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# **SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE**

## **2011 Update**

**Supplemental details to the satellite-based  
component of the “Implementation Plan for the  
Global Observing System for Climate in Support  
of the UNFCCC (2010 Update)”**

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## Executive Summary

The 2010 Update of the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*<sup>1</sup> (GCOS-138, August 2010; the 'IP-10') recognizes the importance of deriving products and data records of physical variables such as wind speed, sea level and soil moisture from the measurements made by satellites. This document provides supplemental details to the IP-10 related to the generation of these products and the associated datasets. It is intended mainly to assist Parties<sup>2</sup> that support Earth observation from space to respond to the requirements of the IP-10. It also has relevance to all Parties that access satellite data records and/or use derived products for climate applications. Furthermore, a wide range of Parties can contribute the *in situ* data needed for the calibration of satellite instruments, for the validation of satellite data and derived products, and for incorporation with satellite data in integrated products, such as provided by reanalysis.

### **The context of the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC***

The IP-10, if fully implemented by the Parties both individually and collectively, will result in a system that provides the global observations of the Essential Climate Variables<sup>3</sup> (ECVs) and their associated datasets and products that are needed to assist Parties in meeting their responsibilities under Articles 4 and 5 of the UNFCCC. In addition, implementation of IP-10 will provide the systematic and sustained observations needed by the World Climate Research Programme (WCRP), the Intergovernmental Panel on Climate Change (IPCC) and the emerging Global Framework for Climate Services.

Specifically, the proposed system will provide information to:

- characterize the state of the global climate system and its variability;
- monitor the forcing of the climate system, including both natural and anthropogenic contributions;
- support the attribution of the causes of climate change;
- support the prediction of global climate change;
- enable projection of global climate change information down to regional and local scales; and
- enable characterization of extreme events important in impact assessment and adaptation and in the assessment of risk and vulnerability.

The IP-10 describes a feasible and cost-effective path toward an integrated observing system that depends upon both *in situ* and satellite-based measurements. Both types of measurement are vital. The emphasis on satellite measurements given in this report is not a reflection of priority but rather a detailing of the opportunities to implement a major and important element of the IP-10 by meeting the specific needs for satellite observations and the products derived from them. Table 1, based on the IP-10, provides the list of ECVs considered particularly feasible for sustained monitoring from satellites.

One of the issues identified in the IP-10, and noted again in this report, is the need for all Parties to be able to benefit from the use of climate data records. This is an important issue in relation to products that depend primarily upon satellite observations: while Earth observation from satellites is a costly activity to which only a limited number of Parties are currently able to contribute, the derived information is generally of global utility. To meet the needs of the UNFCCC, action is necessary to enable global access to these products. Detailed requirements to this effect are given in this report.

The analysis given in the IP-10 showed that many of the required data records that depend upon satellite observations could be obtained with the existing technical capabilities of satellite instruments

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<sup>1</sup> United Nations Framework Convention on Climate Change. (A list of acronyms is provided in Appendix 5).

<sup>2</sup> Parties in the context of this report are signatory countries of the UNFCCC.

<sup>3</sup> These are listed in Appendix 4. Table 1 lists those ECVs that are largely dependent upon satellite observations.

if extra attention were given to the GCOS Climate Monitoring Principles (GCMPs) in the use of such instruments.

For the data records that cannot be generated under current circumstances, this report identifies additional research needs. Furthermore, it is noted that while existing data holdings generally were provided by observing systems that did not meet the GCMPs, appropriate analysis efforts could provide improved records extending over the last two or three decades. This is true particularly for some of those ECVs that can be addressed with data from operational meteorological satellites. In other cases, a data record of some utility could be compiled with current capabilities or data holdings, notwithstanding possible deficiencies in length and/or accuracy.

**Table 1: ECVs for which satellite observations make a significant contribution** <sup>4</sup>

Domain	Essential Climate Variables
<b>Atmospheric</b> (over land, sea and ice)	Surface wind speed and direction; precipitation; upper-air temperature; upper-air wind speed and direction; water vapour; cloud properties; Earth radiation budget (including solar irradiance); carbon dioxide; methane and other long-lived greenhouse gases; and ozone and aerosol properties, supported by their precursors.
<b>Oceanic</b>	Sea-surface temperature; sea-surface salinity; sea level; sea state; sea ice; ocean colour.
<b>Terrestrial</b>	Lakes; snow cover; glaciers and ice caps, ice sheets; albedo; land cover (including vegetation type); fraction of Absorbed Photosynthetically Active Radiation (FAPAR); Leaf Area Index (LAI); above-ground biomass; fire disturbance; soil moisture.

This document does not reconsider the issue of costs. However, as noted in the IP-10, most of the resources needed to achieve satellite-based monitoring of ECVs fall into two categories:

- resources needed to ensure that attention is given to the GCMPs in the sustained operation of the current and planned meteorological satellite instruments; and
- resources needed to initiate and sustain observation capabilities not currently planned in future missions; the required instrument types are in most cases similar to satellite instruments on current research missions.

The Actions falling under the first category have significant costs but amount to only a fraction of the typical cost of a full satellite mission. The second category accounts for the major part of the total satellite-related costs estimated for the IP-10. In addition to climate monitoring, meeting the needs in this second category would also bring substantial benefits to many other user communities, in particular, those concerned with land surface and marine applications. (Note that in the IP-10, for which total additional costs were estimated on the order of USD 2.5 billion per annum, a share of roughly 1 billion was attributed to satellite observations, datasets and related activities.)

### The content of this report

This document provides additional technical detail to the Actions and needs identified in the IP-10 related to satellite-based observations for climate for each of the ECVs listed in Table 1. In particular, it details the specific satellite data records that should be sustained in accordance with the GCMPs, as well as other important supplemental satellite observations that are needed on occasion or at regular intervals. Tables 2-4 provide an overview of the requirements for products and sustained satellite data records that are detailed in this document for the atmospheric, ocean and terrestrial domains, respectively.

<sup>4</sup> Table 5 of IP-10 and covering all ECVs considered in this report.

While sustained climate products and data records are the focus of this document, the vital need for an active and continuing role for space agencies with remits solely for research is also emphasized. The need for research instruments on satellites relates to a number of issues, for example:

- providing intermittent, supplemental detail to sustained observations through (often challenging) new measurements;
- seeking improved and more effective ways of fully meeting observation targets and creating the required satellite data records; and
- exploring new capabilities to extend the number of variables that can be measured from satellites.

Along with scientific and technological progress, ECV product specifications (e.g. accuracy and stability) and associated requirements for satellite instruments and global sampling need to be maintained by expert groups. This document seeks to continue the process started in 2006 by providing updated requirements for datasets and products, with a focus on the detection and attribution of trends over periods upwards of a decade. This focus sets stringent requirements on the accuracy of the measurement and, in particular, on the stability of the measurement bias over time. However, satellite datasets are used for many more applications in the climate domain where requirements may be different from those needed for monitoring. Observational datasets are required for initializing climate model projections and for providing boundary conditions to such models. In various ways, satellite datasets are heavily used in climate model development and validation, especially for regional modelling and downscaling of model prognostic results, as well as in reanalyses which are increasingly used for climate applications. Better climate modelling, both on global and regional scales, underpins some of the key needs of the UNFCCC, alongside continuous climate monitoring.

When stating recommended requirements for Fundamental Climate Data Records (FCDRs) and products, this document attempts to note different climate application areas and to provide requirements in support of these applications. Nevertheless, the expert groups identified under each ECV should have the primary responsibility in further refining and maintaining the requirements stated in this document.

Note is also made of needs for data access and archiving and of issues related to calibration and validation. The key need for representative and high quality *in situ* data for calibration and validation is stressed throughout. All Actions and recommendations have been made traceable to the IP-10.

In addition to the details that apply to each ECV, the report gives an overview of generic, cross-cutting needs. In doing so, some of the recommended Actions from the IP-10 are re-emphasized. These pertain to the need for institutional arrangements to ensure effective links between satellite agencies, end users, and the scientific groups that should be involved in the creation of products. The report recommends that the establishment of these institutional arrangements be done in conjunction with international bodies such as the World Meteorological Organization (WMO), the [UNESCO] Intergovernmental Oceanographic Commission (IOC), the International Council For Science (ICSU), the United Nations Environment Programme (UNEP) and the [UN] Food and Agriculture Organization (FAO), and with other relevant bodies such as the Committee on Earth Observation Satellites (CEOS), the Coordination Group for Meteorological Satellites (CGMS) and the Group on Earth Observations (GEO).

## Key recommendations

Action C8 of the IP-10 is of fundamental importance in the context of this report:

*"Ensuring continuity and overlap of key satellite sensors; recording and archiving of all satellite meta-data; maintaining appropriate data formats for all archived data; providing data service systems that ensure accessibility; undertaking reprocessing of all data relevant to climate for inclusion in integrated climate analyses and reanalyses; undertaking sustained generation of satellite-based ECV products."*

Breaking this Action down in light of the details given in this report results in the following key recommendations for Parties that support space agencies. Parties should:

- 1. Ensure attention to the needs identified in this report related to the planning, initiation and continuity of the satellite missions needed to provide satellite climate data records;**
- 2. Ensure a systematic approach in applying, to the greatest extent possible, the GCOS Climate Monitoring Principles for the generation of satellite climate data records, recognizing, in particular, the need for overlaps in missions and for *in situ* measurements for calibration and validation purposes;**
- 3. Ensure long-term custody of satellite climate data records and their associated metadata, and provide open access to these records;**
- 4. Ensure and encourage the generation of, and access to, products based on the satellite climate data records;**
- 5. Ensure wide and continuing interaction among the international scientific, operational and end-user communities to ensure effective feedback mechanisms and continuing advice on observation and product needs;**
- 6. Sustain active research satellite programmes that address challenging measurement needs and that allow capabilities to advance and to be more cost effective.**

These key Actions can be achieved only partly by space agencies within their current remits. Therefore, a key overarching need is for:

**Parties supporting space agencies to ensure that the remits of those agencies enable them to incorporate the needs for systematic observation of climate as identified in this report (e.g. appropriate structural arrangements and responsibilities within agencies; planning for the maintenance of satellite climate data records, and product generation).**

Collaboration between research and operational agencies in the development of common products, drawing on the observations of both, needs improving.

### **The future role of Earth Observation Satellites for Climate**

Satellites now provide a vital means of obtaining observations of the climate system from a near-global perspective and for comparing the behaviour of different parts of the globe (IP-10, p. 33). It is evident that the future of the global climate observing system depends critically upon a major satellite component. Nevertheless, while there are good expectations for the continuity of data records for some variables linked to meteorological satellites, there is a lack of planning for continuity of measurements of many of the key climate variables needed by the UNFCCC. Moreover, for satellite data to contribute fully and effectively to the determination of long-term records, they must be part of a system implemented and operated so as to ensure that these data are accurate and adequately homogeneous for climate. Finally, in addition to meeting the needs of the UNFCCC, the real-time and near-real-time information obtained through such a system would provide a similarly large benefit to the needs of many other key societal benefit areas.



**Table 2: Overview of Products – Atmosphere**

<b>ECV</b>	<b>Global Products requiring Satellite Observations</b>	<b>Fundamental Climate Data Records required for Product Generation (from past, current, and future missions)</b>	<b>Product Numbers (IP-10 Reference Actions)</b>
Surface Wind Speed and Direction	Surface wind retrievals	Passive microwave radiances and radar backscatter	A.1 (A11)
Precipitation	Estimates of liquid and solid precipitation, derived from specific instruments and provided by composite products	Passive microwave radiances Geostationary VIS/NIR/IR radiances	A.2 (A6, A8, A9, A10)
Upper-air Temperature	Upper-air temperature retrievals Temperature of deep atmospheric layers	Passive microwave and IR radiances GNSS radio occultation bending angles	A.3.1 A.3.2 (A20, A21)
Upper-air Wind Speed and Direction	Upper-air wind retrievals	VIS/IR imager radiances Doppler wind lidar	A.4 (A11)
Water Vapour	Total column water vapour Tropospheric and lower-stratospheric profiles of water vapour Upper tropospheric humidity	Passive microwave radiances; UV/VIS imager radiances; IR and microwave radiances; Limb soundings	A.5.1 A.5.2 A.5.3 (A7, A21, A22, A26)
Cloud Properties	Cloud amount, top pressure and temperature, optical depth, water path and effective particle radius	VIS/IR imager radiances IR and microwave radiances, lidar	A.6.1 A.6.2 A.6.3 A.6.4 A.6.5 A.6.6 (A23, A24)
Earth Radiation Budget	Earth radiation budget (top-of-atmosphere and surface) Total and spectrally-resolved solar irradiance	Broadband radiances Spectrally-resolved solar irradiances Geostationary multispectral imager radiances	A.7.1 A.7.2 (A14, A25)
Carbon Dioxide, Methane and other GHGs	Retrievals of greenhouse gases, such as CO <sub>2</sub> and CH <sub>4</sub> , of sufficient quality to estimate regional sources and sinks	NIR/IR radiances	A.8.1 (A26, A28, A29)
Ozone	Total column ozone Tropospheric ozone Ozone profiles from upper troposphere to mesosphere	UV/VIS and IR/microwave radiances, from nadir and limb sounding	A.9.1 A.9.2 A.9.3 (A26, A32)
Aerosol Properties	Aerosol optical depth Aerosol single scattering albedo Aerosol layer height Aerosol extinction profiles from the troposphere to at least 35km	UV/VIS/NIR/SWIR and TIR radiances UV/VIS/IR limb sounding (scatter, emission, occultation) Lidar profiling	A.10.1 A.10.2 A.10.3 A.10.4 (A33)
Precursors supporting the Ozone and Aerosol ECVs	Retrievals of precursors for aerosols and ozone such as NO <sub>2</sub> , SO <sub>2</sub> , HCHO and CO	UV/VIS/NIR/SWIR and TIR radiances UV/VIS/IR limb sounding (scatter, emission, occultation) Lidar profiling	A.11.1 (A26, A27, A34)

**Table 3: Overview of Products – Oceans**

ECV	Global Products requiring Satellite Observations	Fundamental Climate Data Records required for Product Generation (from past, current and future missions)	Product Numbers (IP-10 Reference Actions)
Sea-surface Temperature	Integrated sea-surface temperature analyses based on satellite and <i>in situ</i> data records	Single and multi-view IR and microwave imager radiances	O.1 (O4, O7, O8)
Sea-surface Salinity	Datasets for research on identification of changes in sea-surface salinity	Microwave radiances	O.2 (O12)
Sea Level	Sea level global mean and regional variability	Altimetry	O.3 (O10)
Sea State	Wave height, supported by other measures of sea state (wave direction, wavelength, time period)	Altimetry	O.4 (O16)
Sea Ice	Sea-ice concentration/extent/edge, supported by sea-ice thickness and sea-ice drift	Passive and active microwave and visible imager radiances, supported by Synthetic Aperture Radar (SAR) altimetry	O.5 (O18, O19, O20)
Ocean Colour	Ocean colour radiometry – water leaving radiance Oceanic chlorophyll-a concentration, derived from ocean colour radiometry	Multispectral VIS imager radiances	O.6.1, O.6.2 (O15, O23)

**Table 4: Overview of Products – Terrestrial**

ECV or supporting variable <sup>5</sup>	Global Products requiring Satellite Observations	Fundamental Climate Data Records required for Product Generation (from past, current and future missions)	Product Numbers (IP-10 Reference Actions)
Lakes	Lake levels and areas of lakes in the Global Terrestrial Network for Lakes (GTN-L)	VIS/NIR imager radiances, and radar imager radiances Altimetry	T.1.1 T.1.2 (T8)
Snow Cover	Snow areal extent, supplemented by snow water equivalent	Moderate-resolution VIS/NIR/IR and passive microwave imager radiances	T.2 (T16)
Glaciers and Ice Caps	2D vector outlines of glaciers and ice caps (delineating glacier area), supplemented by digital elevation models for drainage divides and topographic parameters	High-resolution VIS/NIR/SWIR optical imager radiances, supplemented by microwave InSAR and along-track optical stereo imaging	T.3.1 T.3.2 (T17)
Ice Sheets	Ice-sheet elevation changes, supplemented by fields of ice velocity and ice-mass change	Radar and laser altimetry, supplemented by SAR, gravity	T.4 (T20)
Albedo	Reflectance anisotropy (BRDF), black-sky and white-sky albedo	Multispectral and multiangular imager radiances	T.5 (T3, T24, T25)
Land Cover	Moderate-resolution maps of land-cover type High-resolution maps of land-cover type, for the detection of land-cover change	Moderate-resolution multispectral VIS/NIR imager radiances High-resolution multispectral VIS/NIR imager radiances, supplemented by radar	T.6.1 T.6.2 (T26, T27, T28)
FAPAR	Maps of the Fraction of Absorbed Photosynthetically Active Radiation	VIS/NIR multispectral imager radiances	T.7 (T3, T31, T29)
LAI	Maps of Leaf Area Index	VIS/NIR multispectral imager radiances	T.8 (T3, T29, T30, T31)
Biomass	Regional and global above-ground forest biomass	Long-wavelength radar and lidar	T.9 (T32)
Fire Disturbance	Maps of burnt area, supplemented by active-fire maps and fire-radiative power	VIS/NIR/SWIR/TIR moderate-resolution multispectral imager radiances	T.10 (T35, T36, T37, T38, T39)
Soil Moisture	Research towards global near-surface soil-moisture map (up to 10cm soil depth)	Active and passive microwave	T.11 (T13, T14)
Land-surface Temperature	Land-surface temperature records to support generation of land ECVs	High-resolution IR radiances from geostationary and polar-orbiting satellites; Microwave radiances from polar-orbiting satellites	T.12 (T5, T13, T23, T27, T28)

<sup>5</sup> All variables listed here are ECVs as identified in IP-10, with the exception of land-surface temperature, which has been included as it is a variable whose measurement is important for determining or interpreting other ECVs (cf. section 3.3.12).

# Systematic Observation Requirements for Satellite-based Products for Climate (2011 Update)

## Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)"

### 1. INTRODUCTION

#### 1.1. Purpose of this Document

This document provides supplemental detail to the 2010 Update of the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*<sup>6</sup> (GCOS-138, August 2010, hereinafter called the 'GCOS Implementation Plan' or 'IP-10') related to the generation of global climate data products derived from measurements made from satellites. The detailed specifications, often in conjunction with the need for *in situ* data for calibration and validation, have been made traceable to the GCOS Implementation Plan. The document is intended to assist Parties<sup>7</sup> supporting Earth observation from space, and/or supporting the use of such observations in the generation of climate data products, in responding to the requirements of the GCOS Implementation Plan<sup>8</sup>. Equally, all Parties can play an important role as users and potential generators of climate data products derived from satellites, as well as through the vital contribution of *in situ* observations that are required for the derivation of the climate data products specified in this report. Parties should respond to the needs expressed in the GCOS Implementation Plan, supplemented by this report. They should do so by working, as appropriate, with their space agencies, and in conjunction with international bodies such as the World Meteorological Organization (WMO), the [UNESCO] Intergovernmental Oceanographic Commission (IOC), the International Council For Science (ICSU), the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization (FAO), and other relevant bodies such as the Committee on Earth Observation Satellites (CEOS), the Coordination Group for Meteorological Satellites (CGMS) and the Group on Earth Observations (GEO).

The GCOS Implementation Plan is the consensus document of the international community regarding the global observing system for climate. It has found broad acceptance across a range of international bodies and national organizations, and it meets the needs of the climate research community, notably those acting through the World Climate Research Programme (WCRP) and the Intergovernmental Panel on Climate Change (IPCC), for sustained data and products for climate monitoring. While the present document considers mainly the satellite-based observations, the GCOS Implementation Plan notes the equally vital roles of *in situ* and satellite-based observations, and seeks to balance these to form an effective integrated observing system. Notwithstanding the important needs for *in situ* observations, implementation of the Actions related to satellite-based observations detailed in this supplement would provide a major enhancement to the capabilities for global monitoring of climate. Some new climate observations will meet other societal needs, while in many cases, improved climate observations are extensions of activities that are intended to meet other societal needs, for example for weather forecasting, oceanographic applications, agriculture, and land-use management.

This report also recognizes the important and evolving role of more refined, limited-term observations – often from single 'research' missions – that aid interpretation and understanding of the sustained, systematic observational elements. This research component needs to be discussed on a continuous basis, especially for variables for which additional research is needed to pioneer future monitoring capabilities. In parts, this component will also supplement the creation of climate data records for those variables that are practical and feasible for sustained monitoring today.

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<sup>6</sup> United Nations Framework Convention on Climate Change. (A list of acronyms is provided in Appendix 5).

<sup>7</sup> Parties in the context of this report are signatory countries of the UNFCCC.

<sup>8</sup> Appendix 1 lists all Actions from the GCOS Implementation Plan in which space agencies, CEOS and/or CGMS are listed as "Agents for Implementation".

In the GCOS Implementation Plan, Actions for implementation were assigned to groups with recognized expertise and responsibility, where possible. In other cases, needs for such institutional arrangements were identified. Consistent with this approach, the details provided in this report should be regarded as guidance, subject to review and revision by expert groups that can consider ongoing scientific and technological progress.

This document does not encompass all the ancillary data needed for derivation of end-products from the noted satellite data records, for example data for the determination of the geoid, absolute geodetic reference frames, or digital elevation models.

## 1.2. Basis provided by the GCOS Implementation Plan

The Global Climate Observing System (GCOS), in consultation with its partners, developed the 2010 edition of the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (IP-10)*<sup>9</sup> which replaces a similarly titled Plan (IP-04) published in 2004. The IP-10 and its findings were strongly endorsed through UNFCCC decision 9/CP.15 (see Appendix 2) and, subsequently, by the conclusions of SBSTA 33. Its purpose is to provide an updated set of Actions required to implement and maintain a comprehensive global observing system for climate that will address the commitments of the Parties under Articles 4 and 5 of the UNFCCC and support their needs for climate observations in fulfilment of the objectives of the Convention. This revised GCOS Implementation Plan updates the Actions in the IP-04, taking into account recent progress in science and technology, the increased focus on adaptation, enhanced efforts to optimize mitigation measures, and the need for improved prediction and projection of climate change. It focuses on the timeframe 2010-2015.

Specifically, the system proposed by the IP-10 will meet UNFCCC needs by providing information to:

- characterize the state of the global climate system and its variability;
- monitor the forcing of the climate system, including both natural and anthropogenic contributions;
- support the attribution of the causes of climate change;
- support the prediction of global climate change;
- project the information provided by global climate models down to regional and national scales; and
- characterize extreme events important in impact assessment and adaptation, and to assess risk and vulnerability.

At the same time, the IP-10 builds, wherever possible, on existing observing systems, datasets, infrastructure and institutional arrangements to achieve its goals. Implicit in the IP-10 are the observations and networks needed to support seasonal and, eventually, decadal climate forecasting and a wide variety of other applications in various societal areas.

In its satellite component, the IP-10 considers both:

- the generation of fundamental climate data records of calibrated observations from satellites; and
- the generation of products derived from these data records.

Both of these needs are addressed in this document.

In order to set priorities, criteria for placing items within the current or near-future implementation timeline of the GCOS Implementation Plan include:

- clearly significant and demonstrable benefits toward meeting the needs stemming from Articles 4 and 5 of the UNFCCC for specific climate observations in support of impact assessment, prediction and attribution of climate change, and the amelioration of, and adaptation to, projected future changes;
- feasibility of an observation – determined by the current availability of an observation or by knowledge of how to make an observation with acceptable accuracy and resolution in both space and time;

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<sup>9</sup> GCOS (2010): *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)*, GCOS-138 (GOOS-176, GTOS-84, WMO/TD-No. 1523), August 2010, <http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf> ('IP-10')

- ability to specify a tractable set of implementing Actions (where tractable implies that the nature of the action can be clearly articulated, that the technology and systems exist to take the action, and that an Agent for Implementation, best positioned either to take the action or to ensure that it is taken, can be specified); and
- cost effectiveness – the proposed Action is economically justified. Costs noted in the GCOS Implementation Plan for each Action are indicative and need to be refined by those charged with executing the Actions.

The critical high-priority issues thus identified that should be addressed by the Agents of Implementation, including the space agencies, are:

- continuity and improvement of key satellite and *in situ* networks;
- generation of high-quality global datasets for the Essential Climate Variables (ECVs);
- improvement of access to basic satellite datasets and high-quality global products;
- enhancement of the participation of least-developed countries and small island developing states; and
- strengthening of national and international infrastructures.

The specifications given in this report directly address these priorities as appropriate.

Furthermore, the GCOS has been recognized as the climate observing component of the Global Earth Observation System Of Systems (GEOSS) and provides, through the GCOS Implementation Plan, a mature implementation document supported by a wide consensus of the climate community.

### **1.3. Societal Benefits of Satellite-based Products**

All societies and ecosystems are affected by long-term climate trends, natural climate variability and extreme events. If the satellite data records and products identified in this document were obtained also to support real-time and near-real-time applications, as is largely the case with meteorology today, the resulting observing system would cover a major part of the satellite needs of all GEOSS societal benefit areas. For example, the value of a validated, routinely-produced global precipitation product would not be limited to weather and climate forecasts but would also have a considerable impact on agricultural planning, forestry and water management. The satellite data records and products would also be significant in enabling the emerging Global Framework for Climate Services, which spans observations, modelling, prediction and service delivery across the atmospheric, oceanic and terrestrial domains.

For this reason, Parties and, if applicable, their space agencies need to follow a coordinated, systematic mission strategy in which particular instruments are deployed in a complementary, cost-effective way, and products are developed so as to meet as many application needs as possible.

### **1.4. The Satellite Component of the GCOS Implementation Plan**

As laid down in the IP-10, satellites provide a vital means of obtaining observations of the climate system from a global perspective and assessing the behaviour of different parts of the globe. Table 5 lists the subset of the Essential Climate Variables (ECVs) for which satellites provide a significant contribution to systematic global observation (the full list of ECVs is given in Appendix 4). From this list, which is based on the feasibility of measurement and its relative importance to the overall GCOS, it is evident that a detailed global climate data record for the future will not be possible without a major satellite component. However, for satellite data to contribute fully and effectively to the determination of long-term records, missions must be implemented and operated in an appropriate manner to ensure adequate stability, accuracy, and homogeneity. To assist the space agencies, the GCOS Climate Monitoring Principles (GCMPs) have been extended, in consultation with CGMS, specifically for satellite observations, to address the following key satellite-specific operational issues (see Appendix 3):

- continuity, homogeneity and overlap of satellite observations;
- enhanced orbit control;
- calibration and instrument characterisation, and validation of products;
- sampling strategy; and

- sustained generation of products, data analysis, and archiving.

**Table 5: ECVs for which satellite observations make a significant contribution**

Domain	Essential Climate Variables
<b>Atmospheric</b> (over land, sea and ice)	Surface wind speed and direction; precipitation; upper-air temperature; upper-air wind speed and direction; water vapour; cloud properties; Earth radiation budget (including solar irradiance); carbon dioxide; methane and other long-lived greenhouse gases; ozone and aerosol properties, supported by their precursors.
<b>Oceanic</b>	Sea-surface temperature; sea-surface salinity; sea level; sea state; sea ice; ocean colour.
<b>Terrestrial</b>	Lakes; snow cover; glaciers and ice caps; ice sheets; albedo; land cover (including vegetation type); Fraction of Absorbed Photosynthetically Active Radiation (FAPAR); leaf area index (LAI); above-ground biomass; fire disturbance; soil moisture.

The space agencies have been very responsive to the GCOS Implementation Plan and its Satellite Supplement, and they are advancing their own matching implementation plans (e.g. the 2006 CEOS Response to the IP-04<sup>10</sup> and its planned update in response to the IP-10) detailing the coordinated response of individual satellite operators to the overall GCOS objectives. For example, specific steps have been taken to provide access by all nations to many satellite products. All space agencies have agreed to address the GCMPs for the relevant operational and research satellite systems. Since 2004, there have been some setbacks in ensuring mission continuity; however, remedial action by space agencies has been prompt to fill many of the expected gaps between satellite missions. Current plans still have some likely future gaps that should be addressed by the space agencies. Overall, however, significant progress has been made in responding to climate needs in the mission-planning process.

For "one-off" research spacecraft, the continuity principle as stated in the GCMPs obviously does not apply, but as many of the other principles stated in the GCMPs as possible (e.g. those for rigorous pre-launch instrument characterization and calibration, on-board calibration, complementary surface-based observations, etc.) should be followed.

Sustained attention needs to be given by the space agencies to ensure that the accuracy and consistency of the satellite datasets used to derive products are monitored. Regular reprocessing and re-analysis of archived datasets is generally necessary. Considerable effort has recently been made to this effect, including through the establishment of the CEOS-GEO QA4EO principles, through the instrument calibration activities of the multi-agency GSICS initiative, through the multi-agency SCOPE-CM reprocessing activities, and through the climate reprocessing initiatives by the European Space Agency (ESA) and [USA] National Aeronautics and Space Administration (NASA). This will significantly enhance the value of satellite observations, including past records, for the global observing system for climate. By committing to the requirements for satellite climate data records and products identified in this report (Sections 2 and 3), which each incorporate one or more GCMPs, a major step would be taken by the space agencies toward this end.

The list of ECVs in Table 5, plus other variables for which supporting measurements are needed, is expected to evolve slowly as scientific knowledge and requirements are extended, and as technological developments permit. A small number of variables, specifically groundwater, permafrost, atmospheric constituents in the mesosphere, and surface pressure have been noted in this report as requiring further research for the development of routine monitoring capabilities from space.

The GCOS Implementation Plan contains many Actions that are specifically directed to space agencies, CGMS, and CEOS (Appendix 1). In addition, the text of the GCOS Implementation Plan identifies several

<sup>10</sup> CEOS (2006): *Satellite Observation of the Climate System* - The Committee on Earth Observation Satellites (CEOS) Response to the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, October 2006; [http://www.ceos.org/pages/CEOSResponse\\_1010A.pdf](http://www.ceos.org/pages/CEOSResponse_1010A.pdf).

other needs that were not highlighted as specific Actions. The present report seeks to provide a consolidation of all the satellite-related requirements and Actions from the GCOS Implementation Plan, and it adds more details to these requirements.

The issue of costs is not reconsidered in this document. However, the costs related to satellite missions, datasets and products for climate identified in the IP-10, which are on the order of additional USD 1 billion per year, cover the resources needed for:

- ensuring that attention is given to the GCMPs in the sustained operation of the current and planned satellite instruments;
- initiating and continuing sustained observation capabilities not currently secured in future mission planning; and
- sustaining the generation of products and ongoing reanalysis.

## 1.5. Scientific Coordination

Continuous scientific coordination and guidance related to the generation of required satellite climate data records and products are recommended to be assigned to scientific advisory groups, working in cooperation with the GCOS, GOOS and Global Terrestrial Observing System (GTOS) programmes, the WCRP, and other involved bodies. These groups should, in turn, advise CEOS and its working groups, the WMO Space Programme, and CGMS and other bodies, as appropriate. For all the products called for in this document, engagement and, where necessary, establishment of international working groups is recommended for the comparison and refinement of the products being generated routinely, ideally by independent teams. Periodic overall assessment activities such as initiated by WCRP and GCOS through the recent WOAP Workshop on Evaluation of Satellite-related Global Climate Datasets are a further important requirement.

## 1.6. The Nature of Requirements Considered in this Report

All requirements given in this document are **indicative**, providing a basis for discussion. They need to be kept under review by expert groups, in consultation with the GCOS programme. In general, they are based on the assumption that maximum benefit of the datasets and derived products for climate applications will be reaped if the requirements are met. The applications considered focus on global analyses and do not explicitly include the many detailed physical process studies that the satellite data will usually also support. These applications encompass climate monitoring and detection of climate change, aspects of climate model development and validation, climate impact studies, carbon cycle studies, estimation of emission sources, and reanalyses in support of these applications.

### 1.6.1. Data Records and Products

As mentioned above, the focus of this report will be on Actions related to the Essential Climate Variables (ECVs) for which satellite observations play a significant role in the overall context of GCOS (see Table 5). For each of these variables, the document focuses on the required satellite observations in terms of fundamental climate data records and the need for products. The terms "fundamental climate data record" and "product" are defined for the purposes of this document as follows:

#### **Fundamental Climate Data Record (FCDR):**

The term "Fundamental Climate Data Record" (FCDR) denotes a well-characterized,<sup>11</sup> long-term data record, usually involving a series of instruments, with potentially changing measurement approaches, but with overlaps and calibrations sufficient to allow the generation of products that are accurate and stable in both space and time to support climate applications. FCDRs are typically physical measurements such as calibrated radiances, backscatter of active instruments, or radio occultation bending angles. FCDRs also include the ancillary data used to calibrate them.

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<sup>11</sup> GCOS (2010): *Guideline for the Generation of Datasets and Products Meeting GCOS Requirements* (GCOS-143, WMO/TD-No. 1530)

### **Product:**

The term "Product" denotes long-term data series of values or fields of ECVs derived from FCDRs. Products may be available in the original, instantaneous (often swath-based) satellite projection ("retrievals") or be processed for analysis ("analysed products," often involving averaging over space and time, and gridding). Products are sometimes generated by blending satellite observations and *in situ* data, and physical model frameworks may be used in their generation. The term "Thematic Climate Data Record" (TCDR)<sup>12</sup> is also used in connection with products.

The development of products requires strong collaboration between space agencies and relevant research and operational groups to ensure continuous refinement and extension. Adequate details of the product generation approach need to be documented and made available, along with the products and the underlying FCDRs, to ensure repeatability and incremental improvement. The *Guideline for the Generation of Datasets and Products Meeting GCOS Requirements* (GCOS-143) should be followed.

The following remarks apply to the definition of individual FCDRs and products in this document:

- Specifications of required FCDRs are kept generic, for example in terms of spectral ranges of the data record (e.g. Near Infrared Spectral Range (NIR) or Ultraviolet Spectral Range (UV)) or types of scatterometry that are, given current expertise, considered most relevant for the generation of the product;
- Mention of particular satellite instruments is for illustration only and by itself is not meant to be exhaustive or an indication of preference;
- Analysis by relevant expert groups is necessary to determine the details of the generation of each product and to ensure maximum synergy of the selected approaches, as some FCDRs can benefit more than one product;
- Independent products are usually required for cross-checking of uncertainties and trends; some of these products should be based on independent FCDRs to further enhance the independence in scientific judgment; past experience has also shown that complex climate products should be generated by independent teams in a collaborative manner;
- Note is also made of supplemental non-FCDR-type satellite data records and supplemental products which add value to the FCDRs and products, for example with respect to interpretation and validation, but need not necessarily be sustained according to the GCMPs;
- For many ECVs, two classes of required product have been identified:
  - products needed at relatively high spatial and/or temporal resolution (In the order of hours, days), generally needed in the original instrument projection, often used directly in reanalyses as a starting point for a range of climate applications that all require specific approaches to spatial and temporal averaging or to support the generation of products for related ECVs; and
  - products needed at relatively low spatial and/or temporal resolution (O(months, years)), generally to be made available in a gridded or otherwise processed format, often used for directly analysing variability and trends of the variable at hand (for example, the time series of total column ozone).

Where both are required for a particular variable, a single product is tabulated in this document for the higher temporal resolution.

### **1.6.2. Resolution, Accuracy and Stability**

The **indicative requirements** set out in this document have been determined from a consideration of the user needs for different climate applications, with checks provided by reviewing a number of sources, including the 2006 Satellite Supplement (GCOS-107), the report<sup>13</sup> (and subsequent paper<sup>14</sup>) by Ohring *et al.*, on satellite instrument calibration to measure climate change, the WMO Observing Requirements

<sup>12</sup> For further discussion of the terms "Fundamental Climate Data Records (FCDRs)" and "Thematic Climate Data Records (TCDRs)" see e.g., National Research Council (2004): *Climate Data Records from Environmental Satellites*, The National Academies Press, Washington D.C., USA, 150pp.

<sup>13</sup> Ohring G., Wielicki B., Spencer R., Emery B., and Datla R. (Eds) (2004): *Satellite Instrument Calibration for Measuring Global Climate Change*. National Institute of Standards and Technology, NISTIR-7047, March 2004, <http://www.nist.gov/pml/div685/pub/upload/nistir7047.pdf>.

<sup>14</sup> Ohring G., Wielicki B., Spencer R., Emery B., and Datla R. (2005): *Satellite Instrument Calibration for Measuring Global Climate Change – Report of a Workshop*. Bulletin of the American Meteorological Society, September 2005, 1303-1313.



Database<sup>15</sup> and input from the satellite and satellite user community solicited during community reviews in 2010 and 2011; the accuracy and stability requirements for products are based on the expected variability of ECVs on diurnal, seasonal and decadal timescales.

Setting these requirements is sometimes difficult, due to limited knowledge of the expected variability or likely benefit of the dataset on the application. Where possible, distinctions have been between product requirements for different applications. Requirements are expressed in a largely technology-free manner, i.e., largely irrespective of current observational capabilities and based on current user needs, although the feasibility of meeting the requirements within the timeframe typically envisaged in mission planning has been taken in to consideration.

Product requirements are tabulated in this document under the headings horizontal, vertical and temporal resolution, accuracy and stability:

**Horizontal resolution:**

In most cases this means the sampling distance of analysed products (in some form of gridded or otherwise standardized representation). For products that represent averages over scales upwards of several tens of km, the satellite measurements themselves may need to be much finer in horizontal resolution to facilitate cloud clearing and to allow for non-linearity of the measurements involved. In some cases the horizontal resolution refers directly to retrievals, and in the case of images, horizontal resolution means the image resolution. It should be recognised however that the grid on which a product is supplied or the distance between successive retrieved values may be less than the horizontal scale of the information a product provides, for example due to horizontal correlation of error in retrievals. Different considerations apply to what is quoted for horizontal resolution for a few products such as sea-ice extent and lake area.

**Vertical resolution:**

This means vertical sampling distance or average spacing of independent pieces of information.

**Temporal resolution:**

This is the required interval between two successive instances of a product. Where the stated products are averaged over long periods (such as months), the satellite measurements themselves may need to be sub-daily samples, for example to eliminate aliasing errors due to diurnal effects, or to acquire cloud-free views.

**Accuracy:**

The user requirement for accuracy is a requirement for closeness of agreement between product values and true values. As true values are unknown, users are provided in practice with product values that are estimates of true values, and producers may also provide estimates of the uncertainties of their product values. Product uncertainty may also be assessed by users' own validation activities or by independent evaluation of available products. Each approach has its merits and each is encouraged.

The requirements tabulated numerically in this document under the heading "accuracy" are indicative of acceptable overall levels for the uncertainties of product values. Uncertainty can be influenced by factors such as spatial/temporal sampling, biases introduced by the retrieval method, biases introduced by interpolation methods, calibration errors, geo-location errors, and instrument noise. It may be quantified by the root mean square (or other measure) of the estimated distribution of errors in product values over a spatial domain, a time interval or a set of similar synoptic situations. Uncertainty may accordingly vary in space and time.

The errors in product values, the differences between product values and true values, can be sampled if there are independent, well-characterised, "reference" measurements with relatively low uncertainties that can be compared with a subset of product values. A measure such as the root mean square or the mean has to be chosen to quantify error depending on context. The resulting sample values for error are uncertain due to uncertainty in the reference measurements and uncertainty introduced by any mapping required to construct product equivalents of the reference measurand or vice-versa. Examples of mapping are spatial interpolation of values from the product

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<sup>15</sup> Further information is available at <http://www.wmo.int/pages/prog/sat/Databases.html#UserRequirements>

grid to the measurement site and the monthly averaging of reference measurements for comparison with a monthly-average product.

**Stability:**

The user requirement for stability is in general a requirement on the extent to which the error of a product remains constant over a long period, typically a decade or more.

The relevant component of error of a product for climate application is often the systematic component defined by the mean error over a period such as a month or year. Values quoted under the heading "stability" in this document refer to the maximum acceptable change in systematic error per decade, except for variables for which trends are usually expressed in terms of an annual rate of change, in which case the stability is expressed in terms of this rate of change. Stability of the random component may also be a requirement however, in particular for monitoring long-term changes in extremes.

Accuracy and stability as used here refer not to measurements, but to products, i.e., physical values averaged over or sampled at the spatial and temporal resolutions cited for the product. Definitions and notes given in BIPM (2008)<sup>16</sup> and WMO (2008)<sup>17</sup> for measurements are not fully appropriate for products, but have been used as guidance. No general assumptions have been made on the statistical error distribution of products, given the diverse physical nature of the ECVs. Therefore, the requirements indicated for accuracy are not stated in terms of defined intervals of statistical significance (e.g. they are not stated in relation to the standard deviation from an expected value). Percentage values for accuracy and stability refer to a locally prevailing reference value.

All product requirements are all given as **targets**, i.e. as the resolutions, uncertainties and error variations below which there would be no significant additional value for current climate applications from further reductions. In general, no statement has been made on "minimum" or "breakthrough" requirements<sup>18</sup> (below which there is no use of the data and where the data clearly shows an impact, respectively), since such thresholds are hard to establish for data to be used many years into the future in support of climate applications. Compared with numerical weather prediction, where the impact of a particular data stream or a hypothetical observing system on forecast quality can be readily assessed, such impact studies are not so easily performed for climate applications. In addition, as demonstrated in the context of reanalysis, data that may have been considered poor a few years back can now be usefully assimilated. In the absence of minimum requirements, a statement on the currently known quality level of products has been made in some cases, with the assumption that any effort to generate products should at least try to match this quality.

The following points also need to be considered:

- **Analysis Approach:** Although in some cases the translation of product requirements into satellite mission specifications is fairly straightforward, it is usually a complex undertaking. It often depends on the particular approach taken in the analysis of products, for example, on the extent to which information on the ECV under investigation is available from other measurements. A combination of data records from multiple satellite instruments and/or *in situ* sources, none of which on their own meet any of the requirements given in this report, could usefully meet the needs if applied together in careful analysis. **It is therefore important to note that in general the target requirements given for products in this document should not be mapped directly into instrument requirements.**
- **Sampling strategy:** The suitability of a particular satellite instrument to ultimately contribute in a beneficial manner to a particular product also depends on the instrument sampling strategy, sometimes in connection with other relevant instruments in orbit. Issues regarding spatial and temporal sampling, which depend on the number of satellites, their orbits, and instruments and operating modes are mentioned in this document, but are not discussed in any detail. Although satellite observations provide the only technique to support truly global monitoring, they have limitations in this respect due to sampling issues.

<sup>16</sup> BIPM (2008): Guide to the Expression of Uncertainty in Measurement (GUM), Bureau International des Poids et Mesures. <http://www.bipm.org/en/publications/guides/gum.html>

<sup>17</sup> WMO (2008): Guide to Meteorological Instruments and Methods of Observation (CI-MO Guide), WMO-No. 8.

<sup>18</sup> As included in the WMO Rolling Review of Requirements.

- The WMO Rolling Requirement Review process aids the setting of the priorities to be agreed by WMO Members and their space agencies for enhancing the space-based Global Observing System. In this context, GCOS has provided input for the systematic climate observation elements of the WMO Observing Requirements Database. The requirements in this document are only partly consistent with this process in that they provide target but not breakthrough or minimum requirements. They also provide requirements on stability that are not currently included in the WMO requirements database.

## **1.7. Structure of this Document**

This document identifies cross-cutting needs for systematic climate monitoring that involve space agencies (section 2). Section 3 provides details of the satellite data records and products needed for each of the Essential Climate Variables given in Table 5. For each domain (Atmospheric, Oceanic, Terrestrial) the focus is on the product requirements, the FCDRs needed to sustain long-term records and, where appropriate, the research needed to establish such capabilities. A new section on cross-ECV issues has been added to Section 3. This discusses the importance of satellite climate datasets for estimating surface fluxes, for reanalysis, and for other cross-domain issues. Section 3.5 identifies emerging satellite capabilities in support of climate.

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## 2. CROSS-CUTTING NEEDS

This section identifies common cross-cutting needs that pertain to each of the Essential Climate Variables considered in this report (section 3.4 discusses cross-ECV issues specifically related to fluxes and reanalysis). As noted above, the GCOS Climate Monitoring Principles (GCMPs) provide an agreed statement of the main cross-cutting requirements on climate observations. The main cross-cutting need is therefore the following:

### **C.0 Systematic and continuous attention given to the GCMPs for each of the designated Fundamental Climate Data Records**

C.0.1 Ensure that remits of space agencies include the responsibility for maintaining Fundamental Climate Data Records, including past records;

C.0.2 Establish structural arrangements and responsibilities (within space agencies) to ensure attention to the GCMPs.

Remarks:

- a. The GCOS Implementation Plan and this report provide a list of high priority satellite data records (FCDRs and products) that need to give attention to the GCMPs.
- b. Space agencies have recognized the GCMPs, and valuable and encouraging examples of best-practice within some space agencies can be noted. Agencies are starting to build appropriate mechanisms into their planning and operating processes that are needed to ensure adequate adherence to the GCMPs.
- c. Reference: IP-10 Action C10.

### **C.1 Comprehensive and routine calibration of satellite instruments**

Remarks:

- a. The raw digital counts recorded by a satellite instrument can only be converted into physical quantities (mostly radiance or reflectance) if instrument calibration coefficients are available. These physical quantities can then be used for the derivation of physical parameters. Because instrument characteristics can change with time, absolute calibration and radiometric stability must be determined at regular intervals. The accuracy of any such measurement defines how well a measurement is known compared to an internationally-agreed standard or scale, for example SI units. Well-defined accuracy and stability of individual data records are prerequisites for the generation of homogeneous satellite climate data records and products. They are also vital for consistent comparison and validation of these records with other data sources, such as *in situ* observations.
- b. Reference-type missions such as the proposed Climate Absolute Radiance and Refractivity Observatory (CLARREO) Mission should serve as a key component of the future climate observing system, providing an additional SI-traceable reference-inter-calibration standard for other climate-relevant instruments in space.  
If the signal measured by a satellite instrument cannot be made traceable to an agreed standard, vicarious calibration methods can help specify the radiometric and spectral stability of an instrument over time (such as using stable targets). For example, in the case of visible channels, repeated satellite-based observations of radiometrically-stable calibration sites – typically salt pans and deserts – are compared with contemporaneous high-quality *in situ* radiometric measurements.
- c. The Global Space-based Inter-Calibration System (GSICS), coordinated by CGMS and WMO, is an initiative addressing the needs for instrument calibration. It is being widely adopted by space agencies. The GSICS initiative includes:
  - o ensuring traceable pre-launch and on-board calibration;
  - o exploiting opportunities for calibration against external targets, for example Earth-based reference sites and the Moon; and
  - o exploiting opportunities for instrument cross-calibration, for example by maintaining a database of common satellite viewpoints, including designated radiosonde and surface-based measurement

sites and airborne measurements. Guidance given by the CEOS QA4EO is consistent with GSICS practices.

- d. The effectiveness of the *in situ* observations in this context needs improvement consistent with the recommendations in the IP-10 by, for example:
  - o the continued development of the GCOS Reference Upper-air Network (GRUAN) of high-quality radiosonde and associated ground-based measurements; and
  - o the establishment of the terrestrial reference network, providing measurements of key biomes according to agreed standards.
- e. Reference: IP-10 Action C8.

## **C.2 Archiving and Dissemination**

C.2.1 Ensure adequate data services that:

- handle the increasing volumes of data;
- allow timely feedback to observing network management (e.g. early detection of errors and biases);
- make access to increasingly large volumes of data more effective (especially important for countries with inadequate IT infrastructure or technical skills in using complex data);
- provide version-controlled access to metadata and raw and calibrated physical data; and
- maintain access to historic data;

C.2.2 Ensure that data policies facilitate the exchange and archiving of all products, FCDRs, associated metadata and ancillary data.

Remarks:

- a. Implementation needs, in this context, involve archiving all satellite metadata so that long-term sensor and platform performance is traceable.
- b. The WMO Information System (WIS) is being implemented to achieve interoperable data and information services between meteorological services, space agencies, and a large diversity of other data providers, in collaboration with the International Standards Organization (ISO), the International Telecommunications Union (ITU), and the Open Geospatial Consortium (OGC);
- c. Reference: IP-10 Actions C20, C21.

## **C.3 Detailed Specification of Fundamental Climate Data Records and Derived Products**

Establish detailed specifications for each product in consultation with appropriate scientific and user advisory groups. This document provides a basis for this ongoing process.

## **C.4 Generation of Fundamental Climate Data Records and Derived Products**

C.4.1 Establish and ensure access to Fundamental Climate Data Records (FCDRs);

C.4.2 Update these FCDRs periodically by the addition of new data or by reprocessing complete records when calibration methods or calibration data improve;

C.4.3 Generate products from FCDRs and sustain regeneration (or reprocessing) to derive improved products when FCDRs or generation methods improve;

C.4.4 Sustain the independent generation of derived products as a means of determining the confidence that can be placed in products, in particular in trends estimated from these products; and

C.4.5 When planning missions, form an ECV generation plan, which would entail the development of ECVs records, or the definition of the mission's contribution to extend existing ECV records. This should include consideration of all cross-cutting recommendations made here.

Remarks:

- a. While observations are an essential pre-requisite, users generally require analysed outputs and products.
- b. Whenever possible, the required data records for the generation of products, including historical data records, should cover as many years as possible with the aim of extending over many decades.
- c. Products should be derived on scales which avoid averaging of non-linear effects, for example land cover requires higher spatial resolution of the FCDR and analysis than the final product. ;
- d. International coordination of activities under C.4 is highly desirable to take advantage of progress and to promote efficiency, complementarity and cooperation while recognizing the value of independent product generation (see also C.3).
- e. In many climate applications, the FCDRs themselves are the critical and required type of data record. This necessitates open access to these FCDRs.
- f. It is understood that the derivation of the FCDRs is generally the responsibility of the satellite instrument operators, since in-depth knowledge of the instrument specifics is required.
- g. Although satellite data are a primary source for observing many ECVs, *in situ* and/or other remotely-sensed data are generally needed to (inter-)calibrate, validate and assess the long-term stability of the satellite data. Consistent validation of products is needed, recognizing the physical differences between satellite and *in situ* observations.
- h. The use of observation simulators should be considered. This would allow consistent, radiance-level intercomparisons of model output and satellite datasets.
- i. Reference: IP-10 Action C8.

Additionally, in the context of climate products, the following need has been identified (see section 3.5):

### **C.5 Emerging Products**

Intensify efforts to further develop emerging operational capabilities for research-based variables.

Remarks:

Research is needed to overcome the current scientific and technical limitations to climate-quality measurements (in terms of, e.g., instruments, algorithms, calibration/validation, resolution and cost) of some key – and a few emerging – ECVs (including both *in situ* and satellite-based observations).

- a. Many research satellites (mostly one-off, short-term missions) have demonstrated their potential to overcome these limitations and should therefore make a significant contribution to improvements in the measurement of all ECVs and the creation of reliable FCDRs.
- b. There is a need to ensure, through appropriate scientific coordination, the existence of strong links between research and operational communities.
- c. Reference: IP-10 Action C5.

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### 3. PRODUCTS

GCOS recommends the following products in the atmospheric, oceanic and terrestrial domains for priority action by the space agencies. (Tables 6-8 and Tables 2-4 in the Executive Summary provide the same content.) For all these products, routine creation and early delivery are feasible with today's capabilities, although a continuous research effort and subsequent reprocessing of data and regeneration of products are needed to ensure improving quality and consistency.

For some of the ECVs, in addition to the datasets and products listed here, supplemental observations and products that assist interpretation and analysis have been identified in the text. Systematic adherence to the GCMPs is desirable for these supplemental datasets, but is not as essential as in the case of the noted FCDRs.

**Table 6: Overview of Products – Atmosphere**

ECV	Global Products requiring Satellite Observations	Fundamental Climate Data Records required for Product Generation (from past, current and future missions)	Product Numbers (IP-10 Reference Actions)
Surface Wind Speed and Direction	Surface wind retrievals	Passive microwave radiances and radar backscatter	A.1 (A11)
Precipitation	Estimates of liquid and solid precipitation, derived from specific instruments and provided by composite products	Passive microwave radiances Geostationary VIS/NIR/IR radiances	A.2 (A6, A8, A9, A10)
Upper-air Temperature	Upper-air temperature retrievals Temperature of deep atmospheric layers	Passive microwave and IR radiances GNSS radio occultation bending angles	A.3.1 A.3.2 (A20, A21)
Upper-air Wind Speed and Direction	Upper-air wind retrievals	VIS/IR imager radiances Doppler wind lidar	A.4 (A11)
Water Vapour	Total column water vapour Tropospheric and lower-stratospheric profiles of water vapour Upper tropospheric humidity	Passive microwave radiances UV/VIS imager radiances IR and microwave radiances Limb soundings	A.5.1 A.5.2 A.5.3 (A7, A21, A22, A26)
Cloud Properties	Cloud amount, top pressure and temperature, optical depth, water path and effective particle radius	VIS/IR imager radiances IR and microwave radiances Lidar	A.6.1 A.6.2 A.6.3 A.6.4 A.6.5 A.6.6 (A23, A24)
Earth Radiation Budget	Earth radiation budget (top-of-atmosphere and surface) Total and spectrally-resolved solar irradiance	Broadband radiances Spectrally-resolved solar irradiances Geostationary multispectral imager radiances	A.7.1 A.7.2 (A14, A25)
Carbon Dioxide, Methane and other GHGs	Retrievals of greenhouse gases, such as CO <sub>2</sub> and CH <sub>4</sub> , of sufficient quality to estimate regional sources and sinks	NIR/IR radiances	A.8.1 (A26, A28, A29)
Ozone	Total column ozone Tropospheric ozone Ozone profiles from upper troposphere to mesosphere	UV/VIS and IR/microwave radiances, from nadir and limb sounding	A.9.1 A.9.2 A.9.3 (A26, A32)
Aerosol Properties	Aerosol optical depth Aerosol single scattering albedo Aerosol layer height Aerosol extinction profiles from the troposphere to at least 35km	UV/VIS/NIR/SWIR and TIR radiances UV/VIS/IR limb sounding (scatter, emission, occultation) Lidar profiling	A.10.1 A.10.2 A.10.3 A.10.4 (A33)
Precursors supporting the Ozone and Aerosol ECVs	Retrievals of precursors for aerosols and ozone such as NO <sub>2</sub> , SO <sub>2</sub> , HCHO and CO	UV/VIS/NIR/SWIR and TIR radiances UV/VIS/IR limb sounding (scatter, emission, occultation)	A.11.1 (A26, A27, A34)

**Table 7: Overview of Products – Oceans**

ECV	Global Products requiring Satellite Observations	Fundamental Climate Data Records required for Product Generation (from past, current and future missions)	Product Numbers (IP-10 Reference Actions)
Sea-surface Temperature	Integrated sea-surface temperature analyses based on satellite and <i>in situ</i> data records	Single and multi-view IR and microwave imager radiances	O.1 (O4, O7, O8)
Sea-surface Salinity	Datasets for research on identification of changes in sea-surface salinity	Microwave radiances	O.2 (O12)
Sea Level	Sea-level global mean and regional variability	Altimetry	O.3 (O10)
Sea State	Wave height, supported by other measures of sea state (wave direction, wavelength, time period)	Altimetry	O.4 (O16)
Sea Ice	Sea-ice concentration/extent/edge, supported by sea-ice thickness and sea-ice drift	Passive and active microwave and visible imager radiances, supported by Synthetic Aperture Radar (SAR) altimetry	O.5 (O18, O19, O20)
Ocean Colour	Ocean colour radiometry – water leaving radiance Oceanic chlorophyll-a concentration, derived from ocean colour radiometry	Multispectral VIS imager radiances	O.6.1, O.6.2 (O15, O23)

**Table 8: Overview of Products – Terrestrial**

ECV or supporting variable <sup>19</sup>	Global Products requiring Satellite Observations	Fundamental Climate Data Records required for Product Generation (from past, current and future missions)	Product Numbers (IP-10 Reference Actions)
Lakes	Lake levels and areas of lakes in the Global Terrestrial Network for Lakes (GTN-L)	VIS/NIR imager radiances, and radar imager radiances Altimetry	T.1.1 T.1.2 (T8)
Snow Cover	Snow areal extent, supplemented by snow water equivalent	Moderate-resolution VIS/NIR/IR and passive microwave imager radiances	T.2 (T16)
Glaciers and Ice Caps	2D vector outlines of glaciers and ice caps (delineating glacier area), supplemented by digital elevation models for drainage divides and topographic parameters	High-resolution VIS/NIR/SWIR optical imager radiances, supplemented by microwave InSAR and along-track optical stereo imaging	T.3.1 T.3.2 (T17)
Ice Sheets	Ice-sheet elevation changes, supplemented by fields of ice velocity and ice-mass change	Radar and laser altimetry, supplemented by: SAR, gravity	T.4 (T20)
Albedo	Reflectance anisotropy (BRDF), black-sky and white-sky albedo	Multispectral and multiangular imager radiances	T.5 (T3, T24, T25)
Land Cover	Moderate-resolution maps of land-cover type High-resolution maps of land-cover type, for the detection of land-cover change	Moderate-resolution multispectral VIS/NIR imager radiances High-resolution multispectral VIS/NIR imager radiances, supplemented by radar	T.6.1 T.6.2 (T26, T27, T28)
FAPAR	Maps of the Fraction of Absorbed Photosynthetically Active Radiation	VIS/NIR multispectral imager radiances	T.7 (T3, T29, T31)
LAI	Maps of Leaf Area Index	VIS/NIR multispectral imager radiances	T.8 (T3, T30, T29, T31)
Biomass	Regional and global above-ground forest biomass	Long-wavelength radar and lidar	T.9 (T32)
Fire Disturbance	Maps of burnt area, supplemented by active-fire maps and fire-radiative power	VIS/NIR/SWIR/TIR moderate-resolution multispectral imager radiances	T.10 (T35, T36, T37, T38, T39)
Soil Moisture	Research towards global near-surface soil-moisture map (up to 10cm soil depth)	Active and passive microwave	T.11 (T13, T14)
Land-surface Temperature	Land-surface temperature records to support generation of land ECVs	High-resolution IR radiances from geostationary and polar-orbiting satellites; Microwave radiances from polar-orbiting satellites	T.12 (T5, T13, T23, T27, T28)

<sup>19</sup> All variables listed here are ECVs as identified in IP-10, with the exception of land-surface temperature, which has been included as it is a variable whose measurement is important for determining or interpreting other ECVs (cf. section 3.3.12).

## 3.1. ATMOSPHERE

Satellite radiances provide measurements of several global atmospheric upper air variables, temperature and water vapour in particular. Many of the contributing satellite missions are put in place primarily for weather applications. However, as detailed in this section, a number of additional climate-specific measurements are essential, and, for all measurements, the removal of biases from uncertainties in the sensor calibration and data pre-processing (e.g. cloud removal) is vital for trend detection and other climate applications. The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Mission has been proposed as a key component of the future climate observing system that would provide an absolute calibration traceable to SI standards. Although currently on hold, it is a good example for possible future missions that are specifically designed to most effectively meet climate needs. Such missions would underfly the satellites used for climate monitoring and serve as a tool for satellite inter-calibration in order to provide a climate benchmark radiance dataset. One envisaged component involves the measurement of spectrally resolved thermal infrared and reflected solar radiation at high absolute accuracy. Coupled with measurements from on-board Global Positioning System (GPS) radio occultation receivers, this would provide a long-term benchmarking data record for the detection and attribution of changes in the climate system. It would also provide a source of absolute calibration for a wide range of visible and infrared Earth observing sensors, increasing their value for climate monitoring.

The following sections provide details of the required products and datasets primarily derived from satellites in the atmospheric domain.

### 3.1.1. ECV Surface Wind Speed and Direction

The surface wind field is an important driver of the ocean circulation that is responsible for the global transport of important amounts of heat, freshwater and carbon. Surface drag and momentum exchanges, fluxes of sensible heat, and moisture also depend on wind speed. The surface wind field is a sensitive measure of the state of the global coupled climate system and is valuable for climate change detection and climate model evaluation. Over land, wind contributes to the surface heat balance influencing advective and turbulent heat fluxes.

Spaceborne scatterometer and passive microwave radiometer data (including polarimetric measurements) have been demonstrated to be valuable sources for wind field information over the ocean, especially when coupled with *in situ* observations (e.g. VOS, VOSCLim and the Tropical Mooring and Reference Buoy Networks) in an integrated analysis product. Systematic and sustained deployment of scatterometer or equivalent wind-measuring systems must be maintained. Scatterometers, in particular, provide good coverage and a spatial resolution of wind speed and direction that matches the scales of ocean variability and can also measure the wind field in the vicinity of tropical cyclones.

Reanalysis approaches are of particular benefit to wind analyses, as wind is tightly coupled with atmospheric dynamics, and analysis benefits are obtained from observations of a wide range of other atmospheric variables that are involved in the dynamics.

The following is required for this ECV:

<b>Product A.1 Surface wind retrievals</b>
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#### Benefits

- Forcing of ocean-wave and ocean-circulation models, through improved estimation of air-sea fluxes;
- Climate monitoring;
- Monitoring of the frequency and strength of tropical cyclones;
- Providing climatological information in support of marine operations (e.g. ship design and wind and oil exploration).

## Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Surface wind	10km	N/A	3h	0.5ms <sup>-1</sup> and mean quadratic statistics to 10% of the locally prevailing mean wind speed, for speeds >20ms <sup>-1</sup>	0.1ms <sup>-1</sup>

**Rationale:** Surface wind through the implied stress at the air/ocean interface is critical to ocean reanalysis and is needed at high resolution in time and space. High accuracy is needed to have an impact on ocean circulation models, although uncertainties in surface-drag coefficients need to be taken into account. In the context of climate change, the stability has been set to fully resolve significant changes in mean wind speed over the ocean.

### Requirements for satellite instruments and satellite datasets

FCDRs of appropriate passive microwave radiances and of scatterometry, for example through:

- Continuity of passive microwave imagers;
- Scatterometers on morning and afternoon (AM and PM) polar-orbiting satellites;

FCDRs of passive microwave radiances may also be assimilated directly in reanalysis systems.

### Calibration, validation and data archiving needs

- Buoy data in all climate zones, both open-ocean and coastal;
- Intercalibration of wind FCDRs.

### Adequacy/inadequacy of current holdings

- Scatterometer data record is largely based only on single-satellite coverage;
- Continuity is planned through the Advanced Scatterometer (ASCAT) on the Meteorological Operational Polar Satellite (Metop) series, and new missions;
- No satellite measurements of surface wind over land.

### Immediate action, partnerships and international coordination

- Implementation of two-satellite system of scatterometer measurements;
- Maintenance of passive microwave measurements;
- Reprocessing of [ESA] European Remote Sensing Satellite (ERS)/QuikScat scatterometer data record from 1991 until 2009 and of the Special Sensor Microwave/Imager (SSM/I) passive microwave record since 1987, supplemented by data from Scanning Multichannel Microwave Radiometer (SMMR) from 1979-1984;
- Coordination by CEOS Ocean Surface Vector Winds (OSVW), International Ocean Vector Winds Science Team (IOVWST), [CGMS] International Winds Working Group (IWWG), GCOS and WCRP Panels.

### Link to GCOS Implementation Plan

[IP-10 Action A11] Ensure continuous generation of wind-related products from morning (AM) and afternoon (PM) satellite scatterometers or equivalent observations.

### Other applications

- Assimilation for numerical weather prediction (NWP) and ocean forecasting;
- Transport sector, construction sector, energy production, air-quality management, human health, marine safety and pollution response.

## 3.1.2. ECV Precipitation

Precipitation (rainfall and snowfall) is perhaps the single most important climate variable directly affecting mankind. Even with the efforts of many nations, precipitation observations are still not available with adequate density to define the distribution of precipitation in many parts of the globe, including the oceans and many land areas (cf. Action A3). Estimates of precipitation derived from satellite observing systems have been used to map the distribution of precipitation over some of these regions, and these have

proven essential for global analyses when combined with surface-based measurements of precipitation. There are, nevertheless, fundamental difficulties in monitoring precipitation from space: the very indirect character of the observations, the difficulties imposed by the space/time characteristics of precipitation phenomena, and the consequences of this for retrieval accuracy. The extent to which useful accuracies can be obtained from space, for example for snowfall and light rain during cold seasons, remains uncertain.

Maintenance and enhancement of the satellite systems contributing to precipitation observation (such as passive microwave and, with limitations, high-frequency Infrared Spectral Range (IR) geostationary measurements) is required to ensure continuous accurate global precipitation monitoring. Because of the high societal impact of long-term precipitation changes and extreme events, this is one of the most critical data records for the climate modelling community.

A gridded long-term product of hourly accumulated precipitation at 25-km resolution, or finer in some areas, would be needed to satisfy directly the full range of requirements. Currently, feasible products of lower temporal and spatial resolution may nevertheless satisfy some of the important requirements for monitoring climate fluctuations and change, for validating climate models, and for input data to (or validation of) reanalyses. Over land, ground-based *in situ* measurements form the backbone network, complemented by ground-based radar, with satellite observations used to provide estimates where ground-based measurements are lacking. Over the oceans, satellite observations provide the primary data basis for the generation of products.

The following is required for this ECV:

<b>Product A.2 Estimates of liquid and solid precipitation, derived from specific instruments and provided by composite products</b>
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**Benefits**

- Monitoring of long-term fluctuations and change in precipitation;
- Improvement in the representation of precipitation and the hydrological cycle in climate models and reanalyses;
- Enhancement of the validation of climate models.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Precipitation	25km	N/A	Monthly (resolving diurnal cycles and with statistics of 3 hourly values)	max(10% of daily totals; 0.1mm)	5% of daily totals (regional scale)

**Rationale:** Rainfall has such high societal importance that monitoring its averaged and detailed spatial and temporal variability is critical to all societies. For these impact-related applications, a typical accuracy of about 10 per cent of daily totals is given. For stability, there is a target value of 5 per cent to determine regional, long-term trends. A target related to global precipitation trends linked with changes in the surface radiation budget is impractical to state (given planned capabilities). A hypothetical target stability of 1 per cent would correspond to a change of surface irradiance of 3W/m<sup>2</sup>.

Precipitation rates and spatial scales have a very large dynamic range, and extreme events – which may occur rarely – are of overall significance for monthly and seasonal means. Precise accuracy requirements are therefore hard to set, except for within the context of specific applications and approaches to deriving products.

The requirements for applications other than climate change detection, for example monitoring of variability on sub-seasonal, seasonal and interannual scales and for the analysis of extreme events and their transient behaviour in a changing climate, are also not well defined but entail better than monthly frequency.

### **Requirements for satellite instruments and satellite datasets**

FCDR of passive microwave imager radiances, for example through:

- Passive microwave instruments on a constellation of low Earth orbit satellites to provide adequate temporal coverage over oceans (microwave FCDR accuracy would need to be at least 1.25K for brightness temperature and 0.03K for stability over a decade);<sup>20</sup>
- Spaceborne precipitation radar, essential for improving rain estimates from a microwave imager/sounder;

Supplemented by:

- Complementary precipitation estimates using cloud properties derived in the VIS, NIR and IR bands from geostationary imagers.

### **Calibration, validation and data archiving needs**

- Calibration and validation of satellite measurements and related products by high-quality surface-based instruments is a major issue, not only with regard to the capability of the *in situ* instruments but especially with regard to regional variations in precipitation characteristics and data coverage over the oceans and in high-latitude regions;
- Such validation is required on a continuous, long-term basis, and requires:
  - the free exchange of ground-based precipitation data at high temporal resolution by all countries, ideally in a common format;
  - a strict quality control of such measurements;
- New space-borne salinity-related measurements, such as provided by Surface Moisture/Ocean Salinity (SMOS) and Aquarius, hold the potential to serve as independent validation for precipitation estimates via surface-water budget estimates, i.e. evaporation minus precipitation;
- Expanded use of profiling floats with attached hydrophones is needed to provide alternative products and validate satellite-derived rainfall over the ocean at a large scale.

### **Adequacy/inadequacy of current holdings**

- Current products have been designed for investigation of the global water cycle but not for monitoring climate variability and change. They are not yet adequate for monitoring climate change, as demonstrated by differences in time series from different products and from discontinuities in single products.
- The capability for enhanced detection of light rain and solid precipitation is a specific and important requirement, especially at high latitudes; inclusion of radar observations at 94 GHz enables measurements of snowfall;
- A combination of microwave radiances and precipitation radar with geostationary imagers is needed to obtain an hourly product;
- Assessment initiated by the [WCRP] Global Energy And Water Cycle Experiment (GEWEX) Radiation Panel included only an assessment of the Global Precipitation Climatology Project (GPCP) data set and did not provide an assessment of other precipitation products;
- Uncertainty estimates must be included in future FCDRs;
- Existing data records are inadequate for measuring extremes in precipitation.

### **Immediate action, partnerships and international coordination**

- Research on establishment of requirements for a new generation of datasets and models capable of describing extremes and long-term changes in the frequency and intensity of extremes;
- Analysis of the compliance of the existing and planned observing system to fulfil target requirements;
- Improvement of precipitation climatology through reprocessing of past data, using improved available FCDRs and retrieval methodology;
- Encouraging of multiple realizations of precipitation climatology to assess structural uncertainty, considering the multitude of existing precipitation retrieval algorithms;
- Development of new products, including error estimates, making physically synergistic use of the various available observations rather than simply combining separate products from different types of observation;
- Use of Mesonet gauge reference sites and ground based radar network data; improved use of radar data by employing enhanced validation techniques;

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<sup>20</sup> Ohring et al., 2004.

- Arrangements for global precipitation monitoring continuity beyond the Global Precipitation Measurement (GPM) to include both a low inclination microwave imager in precessing orbit (to serve as calibration anchor) and a space-based precipitation radar, ideally including 94 GHz radar for snowfall detection (the CEOS Precipitation Constellation has been set up to establish an international framework to guide, facilitate and coordinate the continued advancements of multi-satellite global precipitation products);
- Coordination by CGMS, the International Precipitation Working Group (IPWG),<sup>21</sup> CEOS precipitation constellation, GEWEX Hydrometeorology Panel, GEWEX Radiation Panel, SCOPE-CM and GSICS;

#### **Link to GCOS Implementation Plan**

- *[IP-10 Action A7]* Submit all precipitation data, including hourly totals where possible, and radar-derived precipitation products from national networks to the International Data Centres;
- *[IP-10 Action A8]* Ensure continuity of satellite precipitation products;
- *[IP-10 Action A9]* Equip all buoys in the Ocean Reference Mooring Network with precipitation-measuring instruments;
- *[IP-10 Action A10]* Develop and implement improved methods for observing precipitation and deriving global precipitation products that take into account advances in technology and fulfil GCOS requirements.

#### **Other applications**

- Precipitation monitoring essential for use in agriculture, forestry and water resource management (under Global Water System Project (GWSP) and GEOSS);
- Precipitation monitoring and analyses (including snow) essential for managing water, flood and drought alerts;
- Extreme precipitation events over short times (flash floods) and sustained extremes over longer times, as in tropical cyclones, potentially causing major devastation and loss of life;
- Heavy snowfall posing severe disruption for societies, both during the event and when melting.

### **3.1.3. ECV Upper-Air Temperature**

Data on upper-air temperatures are of key importance for detection and attribution of tropospheric and stratospheric climate change. Temperatures measured by high-quality radiosondes are used as a reference for satellite-derived temperatures to characterize their errors and to assist in correction of biases. In turn, there is growing use of satellite data to assist in the identification and correction of biases in radiosonde data. Upper-air temperatures are crucial for distinguishing the various possible causes of climate change and for the validation of climate models, and they can potentially be used for improved understanding of long-term variability in atmospheric circulation. Changes in upper-air temperatures are also crucial for understanding changes in water vapour in the lower stratosphere (Section 3.1.5) and for reconciling ozone trends between different satellite instruments.

Top-of-atmosphere microwave radiances (e.g. from the Microwave Sounding Unit (MSU) and Advanced Microwave Sounding Unit A (AMSU-A)) have become key elements of the historical climate time series, and their measurement needs to be continued into the future to sustain a long-term record. The MSU time series have been used for nearly two decades to estimate temperature trends. They are being continued with data from AMSU-A and other microwave sounders. These time series can be interpreted as deep layer mean temperatures derived from linear combinations of microwave-sounder-brightness temperatures. Layer-mean temperatures in the middle to upper stratosphere are inferred from the Stratospheric Sounding Unit (SSU) (1979-2006) and AMSU-A (1998 to present). Layer-mean temperatures in the mesosphere can potentially be derived from the Special Sensor Microwave Imager (SSM/I/S) (2004 to present). The new advanced infrared sounders such as the Atmospheric Infrared Sounder (AIRS), the Infrared Atmospheric Sounding Interferometer (IASI) and the future Cross-Track Infrared Sounder (CrIS) improve the vertical resolution and stability of satellite-derived temperature soundings.

GPS radio occultation (RO) measurements of bending angle relate directly to temperatures above about 6km altitude (where water vapour effects are small). They provide benchmark observations that can be

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<sup>21</sup> A sub-working-group of CGMS.

used to “calibrate” the other types of temperature measurement. GPS-RO instruments are flown on multiple low Earth orbiting satellites. The COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) fleet of satellites provides real-time data, and the Global Navigation Satellite System (GNSS) Receiver for Atmospheric Sounding (GRAS) instrument is the first of a series of operational GPS-RO instruments. Real-time use of the data has been established and a positive impact on NWP has been demonstrated. Provision of a consistent time series of bending angles is developing for climate applications. The introduction of other GPS constellations (e.g. Galileo) offers opportunities for further improvements in coverage. Atmospheric temperature sounding data, along with radiosonde, GPS-RO and aircraft data also play an important role in reanalyses of temperature and other upper-air variables. High spectral resolution infrared radiances, as proposed for the reference-type CLARREO mission, can be used as anchor points for reanalyses, calibration of other infrared radiometers, and validation of climate models.

Detailed global-scale analyses of temperature are provided by reanalysis for many applications, although retrievals of temperature profiles continue to be used in climate research. In either case, FCDRs of satellite radiances are required. Their characteristics should support the generation of temperature profiles with the following requirements for this ECV:

**Product A.3.1 Upper-air temperature retrievals**

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Tropospheric temperature profile	25km	1km	4h	0.5K	0.05K
Stratospheric temperature profile	100km	2km	4h	0.5K	0.05K

In addition to the temperature records derived from profile retrieval or reanalysis combining different observations (satellites, *in situ*), it is necessary to provide independent satellite-based analyses of temperature for validating variability and trends. These analyses are usually undertaken with an understanding of the regions of the atmosphere where satellites can provide the most accurate measurements (e.g. MSU-equivalent radiances, GPS-RO analyses).

The following is required for this ECV:

**Product A.3.2 Temperature of deep atmospheric layers**

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Temperature of deep atmospheric layers	100km	5km	Monthly averages	0.2K	0.02K

**Rationale:** The resolution and accuracy requirements are set by the need to fully describe and monitor temperature profiles for reanalysis and general atmospheric climatology. There is particular value in layer means of temperature, derived directly from satellite data for which the errors depend primarily on the characteristics of the instrument. Such records provide an independent cross-check on the quality of products from radiosonde records and reanalysis. Four-hourly resolution is needed for profiles to avoid aliasing of the diurnal signal and for synoptic-scale resolution. The stability requirement corresponds to the need for detecting expected tropospheric and stratospheric temperature changes of order 0.2K/decade.

**Benefits**

- Monitoring and detection of temperature trends and variability in the troposphere and stratosphere at global and regional scales;
- Validation of climate model predictions;
- Input to reanalyses;
- Linkage with trends in surface air temperature.



### **Currently achievable performance**

- MSU trends in the troposphere show differences between different data products but are generally in closer agreement with trends from newly homogenized radiosonde data than with trends computed earlier from radiosondes;
- Middle and upper stratospheric trends derived from SSU data show substantial differences between the two currently available data records;
- GPS-RO accuracy is within 0.1K and has exceptional stability, already meeting targets in the upper troposphere and lower stratosphere (although not for spatial resolution).

### **Requirements for satellite instruments and satellite datasets**

FCDRs of passive microwave and IR-based satellite data for use in reanalysis, for example through:

- Ongoing provision of advanced IR sounder capability such as AIRS, IASI and CrIS;
- Homogenized consistent reprocessing of [NOAA]<sup>22</sup> TIROS Operational Vertical Sounder (TOVS/ATOVS) data record;
- Use of other available stable sensors in orbit for determination of absolute biases and intercalibration of operational satellites;

FCDRs of past and future data records from passive microwave and IR sounding and GNSS radio occultation, for example through:

- Passive microwave and IR sounding from at least two satellites in low Earth orbit using instruments with spectral and scanning characteristics to provide global coverage and continuity with the past record;
- A long-term constellation of GPS-RO measurements to continue the limited record established by past and present missions;
- SSU FCDR for middle and upper stratospheric layer mean temperatures from 1979-2006.

### **Calibration, validation and data archiving needs**

- Improved adjustments for effects of instrumental and orbital drifts and inter-satellite differences, as indicated by differences in trends estimated from MSU/AMSU and SSU radiances;
- Use of GPS-RO to validate absolute accuracy of MSU/AMSU mean temperatures;
- Development of SI-traceable standards for absolute calibration of microwave instruments;
- Intercalibrated [NOAA] High Resolution Infrared Radiation Sounder (HIRS) using high quality AIRS and IASI measurements;
- Support for GRUAN and other ground-based observations for validation of future satellite data records;
- Use of GSICS bias-correction coefficients and bias-adjustment information from reanalysis for operational sounders (e.g. MSU, AMSU, HIRS, SSU);
- Use of NWP to monitor sudden changes in measurement biases.

### **Adequacy/inadequacy of current holdings**

- Some uncertainty remains in MSU/AMSU-based temperature trends, despite progress in reconciliation with other estimates; relatively larger uncertainties remain in SSU-based records;
- Accuracy is generally adequate for interannual climate variability;
- Work has started to put together GPS-RO data as a climate-data record.

### **Immediate action, partnerships and international coordination**

- Extension of current microwave FCDRs with additional sensors (e.g. Special Sensor Microwave /Temperature (SSM/T), [NOAA] Advanced Technology Microwave Sounder (ATMS), [CNSA] Fengyun Satellite (FY-3), Special Sensor Microwave Imager/Sounder (SSMIS));
- Assessment of the accuracy of SSMIS for upper stratosphere/lower mesosphere temperature trends;
- Ensuring of the continuation of GPS-RO for reference temperature measurements (e.g. COSMIC-2);
- Construction of an FCDR of bending angles from GPS-RO data;
- Continuation of intercomparisons of advanced IR sounders, imagers and, later, CLARREO, if possible, to assess and monitor accuracy and stability of high spectral infrared radiance data;
- Production of FCDRs of HIRS radiances back to 1979 and Vertical Temperature Profile Radiometer (VTPR) back to 1972;

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<sup>22</sup> National Oceanic and Atmospheric Administration (USA).

- Use of GRUAN to provide reference temperatures;
- Coordination by [WCRP] Stratospheric Processes and Their Role in Climate Change (SPARC), Atmospheric Observation Panel for Climate (AOPC), Working Group on Atmospheric Reference Observations (WG-ARO), International TOVS Working Group (ITWG), [CGMS] International Radio Occultation Group (IROWG), GEWEX Radiation Panel and GSICS for calibration.

#### Link to GCOS Implementation Plan

- [IP-10 Action A20] Ensure the continued derivation of MSU-like radiance data and establish FCDRs from the high-resolution IR sounders in accordance with the GCMPs;
- [IP-10 Action A21] Ensure the continuity of the constellation of GNSS RO satellites.

#### Other applications

- GPS-RO has the potential for monitoring height of inversion layers (i.e. the tropopause and boundary layer).

### 3.1.4. ECV Upper-air Wind

Upper-air wind is a basic element of the climate system that influences many other variables. It is designated an Essential Climate Variable (ECV), but one for which no specific action other than engagement via reanalysis is identified in the GCOS Implementation Plan. Here, attention is given to the provision of FCDRs and products needed to support future improvements in atmospheric reanalysis (see section 3.4).

Geostationary and polar-orbiting imagers provide Atmospheric Motion Vectors (AMVs) by tracking cloud or water vapour features in successive images. AMVs have been available since 1979, and those from European and Japanese platforms have been reprocessed for use in reanalysis. One of the main challenges of AMVs is to accurately assign their height in the atmosphere. The ADM-Aeolus mission is being developed to pioneer wind-lidar measurement from space. If the data from this mission demonstrate significant value for climate purposes, careful and prompt consideration will need to be given to the implementation of follow-on missions. Multiangle Imaging Spectroradiometer (MISR) winds may also be a useful Climate Data Record (CDR) with potentially accurate height assignments.

The following is required for this ECV:

<b>Product A.4 Upper-air wind retrievals</b>
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#### Benefits

Monitoring of fluxes of heat, momentum, moisture and other variables within the climate system, including the long-range transport of pollutants.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Upper-air wind speed and direction	10km	0.5km	1h	2m/s, 20 degrees	0.5m/s, 5 degrees

#### Currently achievable performance

2m/s speed and 30 degree direction, 100hPa in height assignment for single-level AMVs.

#### Requirements for satellite instruments and satellite datasets

FCDR of appropriate VIS/IR imager radiances from geostationary satellites, to enable winds Atmospheric Motion Vectors (AMVs) to be derived from successive images, with capability for reprocessing as wind-derivation techniques improve;

FCDR of appropriate VIS/IR imager radiances from low Earth orbit satellites to enable AMVs to be derived from successive, overlapping swaths from at least one, and preferably two, satellites, with a capability for reprocessing as wind-derivation techniques improve;

FCDR of horizontal line-of-sight wind from Doppler wind lidars, for example through:

- Demonstration data records from the ESA ADM-Aeolus mission;
- Data from follow-on Doppler wind lidar instruments flown on an operational basis, subject to successful demonstration of ADM-Aeolus.

#### **Calibration, validation and data archiving needs**

Validation opportunities are provided by co-located radiosonde and aircraft data, ground-based radar wind and lidar profiling systems, along with data assimilation feedback statistics.

#### **Adequacy/inadequacy of current holdings**

- Improvements in AMV processing, such as reduction in wind-speed biases and better cloud-top-height assignments, have introduced spurious trends in operational products; reprocessing is needed to eliminate these trends;
- Meteosat and GMS data have been reprocessed for the [NOAA] Advanced Very High Resolution Radiometer (ECMWF) Re-analysis Project (ERA) and the Japanese Re-Analysis Project (JRA), but data from other geostationary platforms, notably the [NOAA] Geostationary Operational Environmental Satellite (GOES), have not been reprocessed;
- The [NOAA] Advanced Very High Resolution Radiometer (AVHRR) data record has now been reprocessed to provide polar AMVs from 1982-2009.

#### **Immediate action, partnerships and international coordination**

- Reprocessing of AMV products from geostationary and low Earth orbits (this should be done by the agencies responsible for near-real-time AMV production; the case for repeated reprocessing in the future will depend on the extent of future improvements in AMV production techniques and the extent to which these improvements are applicable to data from older instruments);
- Reprocessing of GOES data records to supplement the initial reprocessing of data from the series of Meteosat and GMS satellites;
- Reprocessing of wind products from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) for the lifetimes of the TERRA/AQUA instruments;
- Investigation of the utility of AVHRR polar winds (since 1980) for reanalysis;
- Assessment of the impact of ADM-Aeolus line of sight winds and preparation for operational follow-on;
- Research towards improved measurement capabilities from space;
- Improvement of coverage of AMVs over polar regions, using Molniya orbits (e.g. (Canadian) Polar Communications And Weather Satellite (PCW));
- Coordination by CGMS/IWWG.

#### **Link to GCOS Implementation Plan**

*[IP-10 Text on page 60]*

#### **Other applications**

- Use of new data sources in data assimilation for NWP should be encouraged;
- Experience has shown that the reprocessing chain for AMV production may enable production of other climate-data products or data for reanalysis from geostationary satellite systems (clear-sky water vapour radiances and ocean and terrestrial products).

### **3.1.5. ECV Water Vapour**

Water vapour is a key climate variable. In the troposphere, condensation of water vapour into precipitation provides latent heating which dominates the structure of tropospheric diabatic heating. Water vapour is also the most important gaseous source of infrared opacity in the atmosphere, accounting for about 60 per cent of the natural greenhouse effect for clear skies, and it provides the largest positive feedback in model projections of climate change.

In the troposphere, the radiative forcing due to direct anthropogenic sources of water vapour (mainly from irrigation) is negligible. Rather, it is the response of tropospheric water vapour to warming itself – the water vapour feedback – that matters for climate change. In GCMs, water vapour alone provides the largest positive radiative feedback, as it roughly doubles the warming in response to forcing such as from greenhouse gas increases.

In the stratosphere, there are potentially important radiative impacts due to anthropogenic sources of water vapour, such as from methane oxidation. In addition, water vapour is a source gas for OH, which is chemically active in the ozone budget. There is recent evidence that the Brewer Dobson circulation is changing in the Tropics. This may alter the balance of water vapour in the Upper Troposphere (UT) and Lower Stratosphere (LS), with potential feedback on climate change. There are also possible stratospheric water vapour feedback effects due to tropical tropopause temperature changes and/or changes in deep convection.

Total column water vapour representative of the water vapour in the lower troposphere can be estimated using microwave radiometers over the ocean and VIS/NIR radiometers over land. Because VIS/NIR observations are limited to clear skies and daylight, the capability to observe continuous total column water vapour with ground-based GPS receivers provides another alternative over land surfaces. The network of GPS receivers needs to be extended to provide coverage across all land areas, and the free exchange of these data needs to be implemented. Upper tropospheric humidity, often used in water vapour feedback studies, can be determined from strong absorption lines in the infrared and microwave spectral range. Infrared estimates are restricted to areas with no- or only low-level clouds, whereas microwave estimates are valid in all non-precipitating areas. This results in a global dry bias of the infrared estimates due to the clear-air-only sampling.

Observational capabilities in the stratosphere are not well co-ordinated. Microwave limb sounding and solar occultation can provide estimates of stratospheric water vapour profiles on a global scale, but these are currently provided by limited-term research missions. Comparisons between instruments flying at the same time (including such *in situ* data as is available) show differences on the order of 20 per cent or greater, and there are problems in measuring water vapour at the lowest mixing ratios, both with remote sensing and *in situ* techniques.

Due to the importance of water vapour and the selective capabilities of different measurement techniques, a number of specialized water-vapour-related products are needed for this ECV:

- Product A.5.1 Total column water vapour**
- Product A.5.2 Tropospheric and lower-stratospheric profiles of water vapour**
- Product A.5.3 Upper tropospheric humidity**

**Benefits**

- Determining of radiative forcing due to water vapour in both the troposphere and lower stratosphere and the nature of the water vapour feedback as greenhouse gases increase;
- Better understanding of the water cycle through water vapour transport estimates derived by using total-column water vapour together with precipitation and evaporation estimates;
- Better understanding of the processes controlling stratospheric water vapour and the links to stratospheric chemistry through Hox;
- Analysis of response of upper-tropospheric water vapour to deep-tropical convection;
- Better structural information on water-vapour distribution from 3-D fields derived from reanalysis.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Total column-water vapour	25km	N/A	4h	2%	0.3%
Tropospheric and lower-stratospheric profiles of water vapour	25km (troposphere) 100-200km (stratosphere)	2km	4h (troposphere) daily (stratosphere)	5%	0.3%
Upper-tropospheric humidity	25km	N/A	1h	5%	0.3%

**Rationale:** The resolution and accuracy requirements are set by the need to fully describe water-vapour (specific humidity) profiles and general atmospheric climatology (monitoring) and for use of data in reanalysis. Total-column accuracy is driven by the need to reliably link humidity changes to changes in precipitation and evaporation. Four-hourly resolution in the troposphere is also needed to avoid aliasing of the diurnal signal and for synoptic-scale resolution. The hourly resolution for upper-tropospheric humidity is needed for the study of variability at synoptic to intra-seasonal scales for water vapour associated with continental tropical convection, including the diurnal cycle. Stability targets for A.5.1 and A.5.2 are based on constant relative humidity and 0.2K/decade temperature trend.

#### **Requirements for satellite instruments and satellite datasets**

FCDR of passive microwave and infrared imager radiances, VIS/NIR spectrometer radiances, for example through:

- Continuity of microwave imager radiances on at least two polar-orbiting satellites;
- Continuity of geostationary water-vapour imager radiances;
- Continuity of VIS/NIR spectrometer radiances over land;

FCDRs of IR and Microwave Spectral Range (MW) sounders, for example through:

- Continuity of polar-orbiting IR sounders (e.g. CrIS, IASI);
- Continuity of microwave humidity sounders on at least two polar-orbiting satellites;
- FCDR of limb sounder measurements (see also section 3.1.8);

Supplemented by:

- Continuous ground-based measurements of GPS zenith total delay.

#### **Calibration, validation and data archiving needs**

- Reference profiles from balloon-borne *in situ* instruments, particularly important for the validation of water vapour profiles;
- Commercial aircraft observations such as those from the Measurement of Ozone and Water Vapour by In-Service Airbus Aircraft (MOZAIC) programme, providing an important validation source for upper tropospheric humidity products;
- Upward-looking MW radiometers for total column-water vapour and Raman and DIAL lidars, used for water-vapour profiles (those instruments are ideally placed at GRUAN sites);
- Ground-based GPS receiver network;
- The proposed CLARREO mission, to provide an SI traceable standard for calibration in the IR;
- Development of SI-traceable standards for absolute calibration of microwave instruments.

#### **Adequacy/inadequacy of current holdings**

- Total column-water vapour over oceans from SSM/I is well established, and different datasets have systematic global mean differences of less than 0.5 kg/m<sup>2</sup>;
- HIRS, Meteosat and AMSU-B/MHS UTH products are used for model validation, climate variability analysis and trend identification;
- Stratospheric water-vapour measurements are available only from research instruments. The principal historical record (SAGE, HALOE) ended in 2005 and has not been adequately linked to the current record (from Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), SMR, ACE-FTS, GOMOS and SCIAMACHY); there are currently no plans for future measurements of sufficiently high vertical resolution.

#### **Immediate action, partnerships and international coordination**

- Maintenance of planned deployment of instruments, to be consistent with existing capabilities/datasets and to improve pre-launch characterization of IR instruments;

Construction of improved FCDRs – from HIRS data from 1979 to present – by using IASI and AIRS;

- Extension of SSM/I FCDR from 1987, with earlier data from SMMR (1979-1984), and with SSMIS data beyond the SSM/I era;
- Extension of MW sounder FCDR datasets with data from Special Sensor Microwave Temperature/Humidity Sounder (SSM/T2) (from 1994);
- Development of a strategy for systematic measurement of lower stratosphere water vapour, building on experience already obtained from limb-sounding and solar occultation;

- Encouragement of new initiatives (e.g. SCOPE-CM) to sustain data set generation and quality assessment;
- Coordination, by GEWEX Radiation Panel and CGMS ITWG climate WG with the GEWEX Radiation Panel, to initiate and perform a formal assessment of existing water-vapour datasets;
- Enhancement of spectroscopy databases to improve radiative transfer for hyperspectral IR sounders;
- Research toward derivation of water-vapour profiles from radio occultation, to clarify the potential of GPS-RO data to benefit the analysis of humidity;
- Free exchange, for research purposes, of data from ground-based GPS receivers, lidars, and MW radiometers used to observe total-column water vapour (via total zenith delay).

#### Link to GCOS Implementation Plan

- *[IP-10 Action A8]* Ensure continuity of satellite precipitation products;
- *[IP-10 Action A22]* Finalize standard and implement exchange of data globally from the networks of ground-based GPS receivers;
- *[IP-10 Action A26]* Establish long-term limb-scanning satellite measurements of profiles of water vapour, ozone and other important species from the UT/LS up to 50km

#### Other applications

- As regards hydrology, surface humidity is important in the calculation of potential evapotranspiration;
- As regards oceans, surface humidity (with surface wind and surface temperature) is a key variable in determining the latent heat flux over oceans.

### 3.1.6. ECV Cloud Properties

Cloud feedback is considered to be one of the most uncertain aspects of future climate projections and is primarily responsible for the wide range of estimates of climate sensitivity from models. The measurement of cloud properties is difficult because it is scene- and instrument-dependent. Passive remote sensing determines in general a 'radiative' height (in pressure coordinates). Observations from VIS/NIR/IR imagers, as well as from IR and MW sounders, have existed for more than 25 years. These are complemented by radiometers determining multi-angle reflection (also polarization) or measuring radiances in the O<sub>2</sub> absorption band (nadir viewing and limb viewing), as well as by some active lidar and radar measurements.

The WCRP International Satellite Cloud Climatology Project (ISCCP) has developed a continuous record of infrared and visible radiances of derived cloud properties since 1983, utilizing both geostationary and polar-orbiting satellite data to resolve a three-hourly diurnal cycle. Additional datasets are available from various other instruments. To improve our understanding of clouds, the synergy of those observations is crucial. For monitoring, an overall strategy has to be developed, and newly developed datasets have to be thoroughly assessed.

Based on published knowledge of cloud radiative transfer and microphysics (precipitation formation), the minimum quantity list (in order of importance) for determining cloud effects on radiation is cloud amount (or cover) (CA), cloud top temperature/pressure (CTP/CTT), and cloud optical depth (COD), and, for determining whether clouds precipitate or not, cloud water path (CWP) or cloud effective radius (CRE). COD can be defined at a specific wavelength (e.g. 550nm) because it is possible to quantify the spectral dependence of optical depth accurately. Adding CRE for radiation would reduce error in COD but only by about 10 per cent. CWP or CRE is sufficient (statistically) to indicate precipitation onset because these two quantities vary together monotonically for non-precipitating clouds up to the onset of precipitation. It is possible to measure two of the three quantities, COD, CWP and CRE, from which the third can be inferred. However, COD can be used to estimate CWP, even without a CRE measurement, because the range of CRE variations is relatively small, i.e. no more than a factor of two. Actual CWP from satellite remote sensing is usually underestimated, even if CRE is measured, because the latter is measured nearer the cloud top and is not as sensitive to the larger particles near the cloud base. CWP can also be used to estimate cloud water content (CWC) because it varies monotonically with CWP, and cloud layer thicknesses for non-precipitating clouds do not vary much – i.e. only by about a factor of three but most of the mass is concentrated near the cloud base.

The following are thus recommended for this ECV:

**Product A.6.1 Cloud amount (CA)**  
**Product A.6.2 Cloud top pressure (CTP)**  
**Product A.6.3 Cloud top temperature (CTT)**  
**Product A.6.4 Cloud optical depth (COD)**  
**Product A.6.5 Cloud water path (liquid and ice) (CWP)**  
**Product A.6.6 Cloud effective particle radius (liquid and ice) (CRE)**

#### Benefits

- Reduction in uncertainty in projections of future climate;
- Improvement in climate monitoring and climate model/reanalysis validation;
- Improvement in knowledge about the interaction between clouds, aerosols and atmospheric gases.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
CA	50km	N/A	3h	0.01 – 0.05	0.003 – 0.03
CTP	50km	N/A	3h	15hPa – 50hPa	3hPa – 15hPa
CTT	50km	N/A	3h	1K – 5K	0.2K – 1K
COD	50km	N/A	3h	10%	2%
CWP	50km	N/A	3h	25%	5%
CRE	50km	N/A	3h	5%–10%	1%–2%

**Rationale:** Targets for accuracy and stability have been determined by assuming a cloud feedback similar to a radiative forcing of about  $0.3\text{W/m}^2$ , which is roughly 20 per cent of current greenhouse gas (GHG) forcing. Since, for radiative forcing, effective cloud amount weighted by cloud emissivity (and not cloud amount itself) is the relevant quantity, target ranges are given, with the lower value for optically thick and low clouds and the higher value for optically thin cirrus (cloud emissivity of 0.2).

Although clouds are one of the most critical factors in the climate system, a precise strategy for monitoring their properties has yet to be developed, and it is recognized that satellite measurements will unlikely meet all of these targets. For example, the ISCCP products, although less accurate, provide a very valuable heritage. As noted in the IP-10, further coordinated research is required, especially for exploring the synergy of different instruments.

Cloud properties involve a complex set of variables, and their uncertainties may depend on the scene (single or multi-layer clouds), on retrieval differences (day/night), and on the instrument sensitivity. Furthermore, cloud height (and therefore also temperature) is only determined at cloud top when using a space-borne active instrument, whereas passive remote sensing determines a ‘radiative’ height.

#### Currently achievable performance

Documented in the GEWEX radiation panel cloud assessment report (WCRP, 2012).

#### Requirements for satellite instruments and satellite datasets

- FCDRs of appropriate VIS/IR imager radiances as well as of IR and microwave radiances from at least two stable low Earth orbit satellites and from five geostationary satellites;
- Exploitation of operational meteorological satellite observations from LEO and GEO;
- Continuous full global coverage;
- Monthly statistics of cloud products, including distributions (e.g. cloud pressure in relation to cloud optical depth), in addition to averages and variability;
- Ongoing programme of research missions, using active and passive instruments to improve observation of cloud properties and to calibrate and characterize long-term products.

#### Calibration, validation and data archiving needs

- Validation against active ground-based and space-based observations (e.g. A-Train, EarthCare);
- Reference-type missions such as the proposed CLARREO, needed for intercalibration of VIS/IR imagers and IR sounders to achieve the accuracy and stability required for decadal time scales.

### **Adequacy/inadequacy of current holdings**

- Current products are adequate for the evaluation of climate models as well as for monitoring large-scale spatial structure and regional variability such as El Nino Southern Oscillation (ENSO);
- Current products are not adequate for monitoring climate change because the existing observing system lacks homogeneity (e.g. orbital drift, change in channel spectral response).

### **Immediate action, partnerships and international coordination**

- Continuation and refinement of products, including reprocessing of the existing geostationary and low Earth orbit satellite data record from the early 1980s onwards;
- Planning of further coordinated satellite missions, like the A-Train, to study the three-dimensional structure of clouds and to assess cloud products from passive remote sensing;
- Development of a strategy/method to better handle satellite-orbit drift;
- Development and implementation of a strategy of how to translate scientific improvements derived from research missions, to enhance the quality of the existing multi-decadal instrument records.
- Extension of the network of measurements at super-sites (e.g. ARM, GRUAN) suitable for validation of cloud properties;
- Sustaining of coordinated assessments of global long-term cloud products, as initiated by GEWEX;
- Continuation of the effort to produce long-term records of cloud parameters in co-ordination with the modelling and observation community (e.g. CFMIP);
- Coordination by GEWEX radiation panel and ITWG.

### **Link to GCOS Implementation Plan**

- *[IP-10 Action A23]* Continue the climate data record of visible and infrared radiances, for example from the International Satellite Cloud Climatology Project, and include additional data streams as they become available; pursue reprocessing as a continuous activity taking into account lessons learnt from preceding research;
- *[IP-10 Action A24]* Research to improve observations of the three-dimensional spatial and temporal distribution of cloud properties.

### **Other applications**

- NWP model validation;
- Assessment of surface UV-B irradiance, with implications on health, biodiversity and agriculture;
- Surface insolation climatology for renewable energy applications.

## **3.1.7. ECV Earth Radiation Budget**

The Earth Radiation Budget (ERB) describes the overall balance between the incoming energy from the sun and the outgoing thermal (longwave) and reflected (shortwave) energy from the Earth. It can only be measured from space, and continuity of observation is essential to detecting changes. The radiation balance at the top of the atmosphere is the basic radiative forcing of the climate system. Measuring its variability in space and time over the globe provides insight into the overall response of the climate system to this forcing. The satellite measurements include solar irradiance observations as well as the broadband directional measurements of reflected solar and outgoing longwave radiation. At least one dedicated satellite ERB mission and one dedicated total solar irradiance (TSI) instrument should be operating at any one time. Satellite observations should be continued without interruption, and operational plans should provide for overlap so that accuracy and resolution issues are resolved to meet climate requirements. This should be a continuing priority for CEOS and CGMS in their planning process.

The top-of-atmosphere ERB also provides an important overall constraint on the surface radiation budget. In order to compute the surface radiation budget, however, high quality observations of clouds (with diurnal sampling), temperature and water vapour profiles, aerosols, trace gases, and surface properties are required. Thus, achieving the requirements for surface radiation budget is quite challenging, as multiple high-quality and temporally consistent observations are needed. This is particularly true for the longwave surface radiation fluxes. In the shortwave the coupling to the radiative fluxes at top-of-atmosphere (TOA) is much closer: the net surface solar radiative flux can be directly estimated from the TOA net flux with ancillary information on atmospheric absorption by gases, clouds and aerosol.



The following is required for this ECV:

<b>Product A.7.1 Earth radiation budget (top-of-atmosphere and surface)</b> <b>Product A.7.2 Total and spectrally resolved solar irradiance</b>
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**Benefits**

- Improved knowledge of basic radiative forcing of the climate system;
- Insight into the response of the system to changes in its forcing and feedbacks (due to changes in greenhouse gases and other factors);

Validation of radiation balance in general circulation models (GCMs).

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Top-of-atmosphere ERB longwave	100km	N/A	Monthly (resolving diurnal cycle)	1W/m <sup>2</sup>	0.3W/m <sup>2</sup>
Top-of-atmosphere ERB shortwave (reflected)	100km	N/A	Monthly (resolving diurnal cycle)	1W/m <sup>2</sup>	0.3W/m <sup>2</sup>
Surface ERB longwave	100km	N/A	Monthly (resolving diurnal cycle)	1W/m <sup>2</sup>	0.3W/m <sup>2</sup>
Surface ERB shortwave	100km	N/A	Monthly (resolving diurnal cycle)	1W/m <sup>2</sup>	0.3W/m <sup>2</sup>
Total solar irradiance	N/A	N/A	Monthly (resolving diurnal cycle)	1W/m <sup>2</sup>	0.3W/m <sup>2</sup>
Solar spectral irradiance	N/A	N/A	Monthly (resolving diurnal cycle)	0.3 % (200-2400nm)	0.1 % (200-2400nm)

**Rationale:** Requirements relate to amounts of radiative forcing significant with respect to global greenhouse gas forcing. The products should be made available as monthly averages of sub-daily values. The diurnal cycle needs to be resolved.

**Requirements for satellite instruments and satellite datasets**

FCDR of appropriate radiances, for example through:

- At least one broadband instrument mission in low Earth orbit at all times, together with at least one instrument providing total solar irradiance and one instrument providing spectrally resolved measurements of solar irradiance;
- Well-calibrated geostationary multispectral imager radiances resolving the satellite measured diurnal cycle of irradiances and thus helping to reduce uncertainties in the integrated daily ERB measurements from a dedicated broadband instrument in a polar orbit.

**Calibration, validation and data archiving needs**

- , Overlapping data records from instruments on different satellites, vital for creating a continuous time series with the highest relative accuracy, owing to the fact that the stability of the instruments employed is often greater than the accuracy of the absolute calibration;
- Onboard calibration sufficient to detect and correct both broadband and spectral instrument stability;
- Reference-type missions such as the proposed CLARREO to provide a calibration reference standard for the decadal record and to be used for intercalibration of other ERB missions;
- A gross validation provided by the consistency of global budgets;
- An updated and extended archive of Baseline Surface Radiation Network (BSRN) measurements to support and supplement the satellite-based measurements, for example with spectral irradiance measurements at the surface.

**Adequacy/inadequacy of current holdings**

Absolute calibration of past multi-satellite data record is inadequate.

### Immediate action, partnerships and international coordination

- Ensuring the continuity of satellite ERB data records, and ensuring reference to a calibration standard for future satellites;
- Support for reprocessing of past data records to improve accuracy of irradiance time series;
- Reprocessing of the past ERB data record extending back to at least 1985 (and to 1978 if feasible);
- Maintaining of high quality observations of clouds (with diurnal sampling), temperature and water vapour profiles, aerosols, trace gasses, and surface properties, required for surface ERB;
- Extending BSRN measurements and updating archive;
- Coordination by GEWEX Radiation panel.

### Link to GCOS Implementation Plan

- [IP-10 Action A14] Ensure continued long-term operation of the BSRN and expand the network to obtain globally more representative coverage; establish formal analysis infrastructure;
- [IP-10 Action A25] Ensure continuation of Earth Radiation Budget observations, with at least one dedicated satellite mission operating at any one time.

### Other applications

- Validation of GCM models;
- Solar energy applications.

### 3.1.8. ECV Carbon Dioxide, Methane and other Greenhouse Gases<sup>23</sup>

Carbon dioxide is the dominant greenhouse gas emitted by anthropogenic activities. The atmospheric build-up is caused mostly by the combustion of coal, oil, and natural gas and reflects to a significant extent cumulative anthropogenic emissions rather than the current rate of emissions.

Methane (CH<sub>4</sub>) is the second most significant anthropogenically emitted greenhouse gas, and its level has also been increasing since preindustrial times. Other long-lived GHGs include nitrous oxide (N<sub>2</sub>O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF<sub>6</sub>), and perfluorocarbons (PFCs). The relative radiative forcing of CH<sub>4</sub> in 2008 was about 18 per cent of the total radiative forcing caused by all long-lived greenhouse gases in the atmosphere since the beginning of industrial time.<sup>24</sup> The Kyoto Protocol of the UNFCCC includes future restrictions on the release of GHGs, including CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, SF<sub>6</sub>, and PFCs. The Montreal Protocol on Substances that Deplete the Ozone Layer includes mandatory restrictions for individual countries on the production and consumption of those CFCs and HCFCs that are also GHGs.

Satellite measurements are emerging as an important component of the overall observing system for CO<sub>2</sub> and CH<sub>4</sub>. Methane was first measured in the stratosphere by SAMS in the 1980s and then by HALOE (1991-2005). The Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) instrument made the first global measurements of tropospheric CH<sub>4</sub>, and its data are being used in inverse modelling studies to quantify CH<sub>4</sub> emissions. Methane data are also provided currently by ACE-FTS. The AIRS, TES and IASI high-resolution IR sounders are providing information on both CO<sub>2</sub> and CH<sub>4</sub>, although with limited vertical range, and their data also have been used in inverting fluxes via data assimilation. The recently launched Greenhouse Gases Observing Satellite (GOSAT) is starting to provide more complete information. Experience in using the data from GOSAT and the future OCO-2 mission will guide the development of the space-based component of the observing system for these two major GHGs. The planned Sentinel-5p and Sentinel-5 missions will also measure CH<sub>4</sub>. Satellite measurements can potentially provide unique information on global emission source identification, which is not possible with ground-based measurements alone.

In the context of this document, detection of sources and sinks of greenhouse gases is the main focus for space-based measurements. Monitoring of global trends of CO<sub>2</sub> and CH<sub>4</sub> as long-lived gases is adequately covered by surface *in situ* measurements.

<sup>23</sup> Including N<sub>2</sub>O, CFCs, HCFCs, HFCs, SF<sub>6</sub> and PFCs.

<sup>24</sup> WMO/ Global Atmosphere Watch (GAW) Greenhouse Gas Bulletin 6, 2010.

The following is required for this ECV:

**Product A.8.1 Retrievals of CO<sub>2</sub> and CH<sub>4</sub> of sufficient quality to estimate regional sources and sinks**

**Benefits**

- Improvement in estimates of global means and facilitation of monitoring of the spatial distribution of the key greenhouse gases.
- Satellite-based observations of column values and vertical profiles of the mixing ratio of carbon dioxide, methane and other greenhouse gases, when coupled with reanalysis, providing a tool for assessment of sources and sinks of greenhouse gases, especially CO<sub>2</sub> and CH<sub>4</sub>;
- Potential provision of additional background information on the measures on stabilization of the mixing ratios of key greenhouse gases at a level that would prevent dangerous anthropogenic interference with the climate system;
- Provision of estimates of localized surface emissions such as those related to wetlands and rice fields for CH<sub>4</sub> and land-use change for CO<sub>2</sub>, where the data products are of sufficient accuracy and resolution.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Tropospheric CO <sub>2</sub> column	5-10km	N/A	4h	1ppm	0.2ppm
Tropospheric CO <sub>2</sub>	5-10km	5km	4h	1ppm	0.2ppm
Tropospheric CH <sub>4</sub> column	5-10km	N/A	4h	10ppb	2ppb
Tropospheric CH <sub>4</sub>	5-10km	5km	4h	10ppb	2ppb
Stratospheric CH <sub>4</sub>	100-200km	2km	Daily	5%	0.3%

**Rationale:** Requirements for tropospheric CO<sub>2</sub> and CH<sub>4</sub> are driven by detection and quantification of the different emission sources via inverse modelling. The primary measurement needed is the tropospheric column, as it provides sensitivity down to the Earth's surface where most of the sinks and sources are located. Research and study of the use of currently available measurements – *in situ* as well as satellite – in reanalysis is needed to provide a more firmly based statement of essential data requirements, in particular on the extent of detail required in vertical sounding. Initial estimates are based on resolving the values of observed column fluctuations. Time scales that extend from the diurnal to the decadal need to be resolved to allow for a complete description of the processes that determine the distributions of these gases. Spatial variability can be substantial in the planetary boundary layer, reflecting the variability of sources and sinks. Products can, however, be useful for source-sink inversion without resolving the shortest space and time scales.

CH<sub>4</sub> is not well mixed in the stratosphere, where it is the main chemical source of H<sub>2</sub>O. The stratospheric product is needed to support the attribution of water-vapour trends and for determining the radiative influences of stratospheric CH<sub>4</sub> and water vapour.

The global trends, seasonal cycle, and latitudinal gradients of the long-lived greenhouse gases N<sub>2</sub>O, CFCs, HCFCs, HFCs, SF<sub>6</sub>, and PFCs in the troposphere are well-monitored, using present-day surface networks. Short-term and regional variability of these long-lived gases is mainly in the stratosphere, in relation to their chemical breakdown at these altitudes. Observing the spatio-temporal variability of these gases is important in the stratosphere, where they also provide information on 'age of air', but these measurements are largely dependent on the limb/occultation type of satellite observations which are not part of the operational suite of satellite measurements. Some monitoring of the stratospheric distribution changes of long-lived gases is needed for the assessment of radiative and dynamical feedbacks in the stratosphere related to composition changes. Future research studies of these greenhouse gases will, at intervals, require future satellite missions.

### Requirements for satellite instruments and satellite datasets

FCDR of appropriate NIR/SWIR<sup>25</sup>/IR radiances, for example through:

- Passive NIR/SWIR operational missions for CO<sub>2</sub> and CH<sub>4</sub>, building on the experience with SCIAMACHY and the specialized missions GOSAT and OCO-2 (simultaneous total column CO, such as provided by SCIAMACHY, adds much value for CO<sub>2</sub> source characterization);
- High spectral resolution IR sounding for the upper troposphere and stratosphere, as provided initially by ACE-FTS, AIRS, and IASI;
- Limb-sounding in IR and MW for distributions in the upper troposphere and stratosphere;
- Active NIR/SWIR systems to obtain tropospheric vertical profiles.

### Calibration, validation and data archiving needs

- The required comprehensive independent ground-based validation measurements can be provided by the WMO Global Atmosphere Watch (GAW) Global CO<sub>2</sub> and CH<sub>4</sub> Monitoring Networks, including ship and dedicated light aircraft profiles up to 8km; both these GAW networks are designated by GCOS as comprehensive networks, and subsets are designated as baseline networks;
- A network of surface-based total column CO<sub>2</sub> and CH<sub>4</sub> instruments (TCCON) and continued routine commercial aircraft observations (e.g. CONTRAIL and observations planned by IAGOS-ERI), needed for validation of products;
- Aircraft observations of CO<sub>2</sub> and CH<sub>4</sub>, needed to validate the transport in the models that are used in the surface emission inversions using total-column data (part of the total-column variability is related to transport in the upper-troposphere/lower-stratosphere and should not be assigned to the lower troposphere affecting the emission inversion).

### Adequacy/inadequacy of current holdings

- Satellite products are still under development, and accuracy requirements have not yet been met (except for CH<sub>4</sub> total column);
- *In situ* observations of the long-lived gases do not provide a complete 3D distribution in the atmosphere and are rather unevenly distributed in space; most networks are designed for trend detection in the background atmosphere, with minimal sensitivity to (nearby) emissions.

### Immediate action, partnerships and international coordination

- Support for the generation of products through retrieval or, in appropriate cases, data assimilation;
- Execution of planned missions and development and implementation of a plan for sustained measurements sufficient to deliver products of the required accuracy;
- Support for the surface and free-tropospheric measurements needed for calibration and validation;
- Derivation of products from AIRS and SCIAMACHY from 2002 onwards, IASI from 2008, GOSAT from 2009 and, in the future, from OCO-2 and from Sentinel-5p/TROPOMI and Sentinel-5 for CH<sub>4</sub>;
- Limb-sounding data for retrieval of stratospheric profiles from current instruments, including those from ACE-FTS (CH<sub>4</sub>, N<sub>2</sub>O), MIPAS (CH<sub>4</sub>, N<sub>2</sub>O), and MLS (N<sub>2</sub>O);
- Additional data provided by TES for the retrieval of tropospheric CH<sub>4</sub>;
- Research towards improved future capabilities, including long-term monitoring of CO<sub>2</sub>, CH<sub>4</sub> and other GHGs such as N<sub>2</sub>O;
- Coordination by WCRP SPARC and IGBP IGAC.

### Link to GCOS Implementation Plan

- [IP-10 Action A26] Establish long-term limb scanning satellite measurements of profiles of water vapour, ozone and other important species from the UT/LS up to 50km;
- [IP-10 Action A28] Maintain and enhance the WMO GAW Global Atmospheric CO<sub>2</sub> and CH<sub>4</sub> Monitoring Networks as major contributions to the GCOS Comprehensive Networks for CO<sub>2</sub> and CH<sub>4</sub>;
- [IP-10 Action A29] Assess the value of the data provided by current space-based measurements of CO<sub>2</sub> and CH<sub>4</sub> and develop and implement proposals for follow-on missions accordingly.

### Other applications

Carbon dioxide and other greenhouse gas distributions may allow improved retrieval of the temperature and water vapour information from IR sounders for NWP and reanalysis; N<sub>2</sub>O measurements are needed for constraining the effects of NO<sub>x</sub> on ozone.

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<sup>25</sup> Shortwave Infrared Spectral Range.

### 3.1.9. ECV Ozone

Ozone is the most important radiatively active trace gas in the stratosphere and essentially determines the vertical temperature profile in that region. The ozone layer protects the Earth's surface from harmful levels of UV radiation. In the troposphere, increases in ozone cause a positive radiative forcing, while in the stratosphere, ozone depletion leads to a negative radiative forcing. Due to its chemistry, which is influenced by the atmospheric temperature and dynamics, ozone is also an important constituent for understanding the interaction between climate and chemistry in the troposphere, stratosphere and mesosphere. In order to study the connection between the climate and chemistry, global measurements of ozone profiles are needed. Additional information of the interactions can be obtained when simultaneous measurements of other constituents participating in ozone chemistry (CH<sub>4</sub>, N<sub>2</sub>O, CFCs, H<sub>2</sub>O, NO<sub>2</sub> and polar stratospheric clouds) are available. Atmospheric ozone amounts declined in the upper and lower stratosphere over the 1980s and 1990s and remain at levels below those present in the 1970s and earlier, largely due to anthropogenic sources of halogens.

Since the 1960s, stratospheric ozone has been monitored *in situ* by wet-chemical ozonesondes and remotely by ground-based spectrometers. Since the late 1970s and 1980s, ozone has also been monitored by optical and microwave techniques from various satellites and ground-based stations. TOMS, (S)BUV, and OMI provide an established data record from the late 1970s onward, and high resolution ozone profile records from SAGE and SAGE II are available for 1979-2005 (with a gap of a few years in the early 1980s). Shorter-term data records are provided by instruments such as HALOE (1991-2005), MLS, GOME(-2), POAM II, POAM III, AIRS, IASI, MIPAS, SCIAMACHY, GOMOS, ACE-FTS, TES, and OSIRIS.

The total column measurements provide information on the overall ozone trends, while the ozone profile information is important for studies of atmospheric processes, as well as for calculations of the radiation balance. High resolution ozone profiles are especially important in the upper troposphere/lower stratosphere (UTLS) region: for example, in the case of an increasing mean meridional circulation, ozone-column reductions in the tropics are observed due to increased upward transport of low ozone amounts from troposphere to stratosphere.

Most ozone measurements use sunlight and are thus restricted to daytime. Thermal emission and stellar occultation measurements have a unique role in measuring ozone at high latitudes during the polar night.

The short-lived ozone and aerosol precursors – in particular NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO – have been added in the IP-10, in recognition of the emission-based view on climate forcing of ozone and secondary aerosols, relevant for climate mitigation and important for processes. The requirements for these precursor variables are given separately below.

Ozone analyses are obtained both from atmospheric reanalysis and as independent products directly from satellite observations as total column analyses and as profiles in the upper troposphere and lower stratosphere.

The following is required for this ECV:

<p><b>Product A.9.1 Total column ozone</b> <b>Product A.9.2 Tropospheric ozone</b> <b>Product A.9.3 Ozone profiles from upper troposphere to mesosphere</b></p>
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#### Benefits

Support in the monitoring and assessment of:

- the impact of the Montreal Protocol and its amendments on the anthropogenically-induced removal of stratospheric ozone;
- the expected radiative influence of ozone on the climate system;
- the role of ozone in the chemistry and dynamics of the climate system.

## Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Total ozone	20-50km	N/A	4h	max(2%; 5DU)	<1%
Tropospheric ozone	20-50km	5km	4h	10-15%	1%
Ozone profile in upper troposphere and lower stratosphere	100-200km	1-2km	4h	10%	1%
Ozone profile in upper stratosphere and mesosphere	100-200km	3km	daily	5-20%	1%

**Rationale:** Resolution requirements in part reflect the use of satellite datasets in reanalysis. For climate analysis, daily to weekly temporal resolution is adequate. Sub-diurnal temporal resolution is needed in the troposphere for air quality applications. The monthly means of total ozone, averaged over diurnal cycles, provides valuable information on long-term ozone trends. Changes in stratospheric ozone since 1850 are roughly 5 to 10 per cent of total column ozone (i.e., 14-29 DU). Tropospheric ozone radiative forcing is significant, with roughly 0.6 W/m<sup>2</sup> (roughly equivalent to 10 DU (3 per cent of total column)). Targets correspond to radiative equivalence to 10 per cent of GHG forcing and should also capture 10 per cent of the expected decadal trend. The higher vertical resolution requirement in the UTLS is driven by the need to monitor the climate-chemistry interaction and especially the vertical transport of ozone.

### Requirements for satellite instruments and satellite datasets

FCDR of appropriate UV/VIS and IR/microwave radiances, for example through:

- Nadir UV/VIS instruments for total column;
- Nadir IR sounding for profiles from lower troposphere to stratosphere;
- Nadir UV/VIS and IR sounding for profiles from lower troposphere to stratosphere;
- Limb sounding in IR/MW/UV/VIS from atmospheric emissions and scattered solar irradiance and occultation for profiles from upper troposphere to mesosphere;

Supplemented by:

- Simultaneous measurements of profiles of other trace gases participating in ozone chemistry in the upper troposphere and stratosphere.

### Calibration, validation and data archiving needs

Comprehensive ground, ship-board, aircraft and balloon-borne measurements are required for calibration and validation, for example through:

- the Network for the Detection of Atmospheric Composition Change (NDACC) and the World Ozone and Ultraviolet Radiation Data Centre (WOUDC);
- the WMO GAW network of ground-based total-column ozone measurements;
- the WMO GAW and NASA/SHADOZ ozone networks of ozone-profile measurements;
- the MOZAIC/IAGOS commercial aircraft programme.

### Adequacy/inadequacy of current holdings

- Total column measurements provide a largely adequate data record of gross change and fluctuations;
- Vertical profile information from present instruments is most often of limited vertical resolution and/or low accuracy in the lower stratosphere and troposphere;
- Planned missions will ensure the continuity of the total ozone CDR, but the continuity of limb viewing and occultation missions is not guaranteed;
- Space agencies have on-going projects to create homogenous data records of total ozone, low-resolution ozone profiles and high-resolution ozone profiles, by combining several instruments;
- There is a need for more routine ozonesonde ascents to support calibration and validation.

### Immediate action, partnerships and international coordination

- Urgent continuation of the limb-viewing measurements of high-resolution ozone (presently only one limb-viewing instrument (NPP/JSS-J2) is planned to measure ozone profiles in the stratosphere, and it is expected that there will be serious gaps in the high-resolution ozone profile datasets in the future; for monitoring ozone at high latitudes it is also important to measure ozone in the dark (during the

polar night); no instruments are planned for continuing the ozone profile records in the mesosphere after the present instruments stop operating);

- Sustaining of current Envisat/Aura (SCIAMACHY/OMI) type missions and their data products to ensure continuity in the data record until the planned Sentinel 5P mission becomes operational;
- Sustaining of current limb missions (MLS, OSIRIS, ACE-FTS, GOMOS, MIPAS) and their data products to ensure continuity or minimize the gap in the data record prior to launch of a future limb mission;
- Reprocessing of identified datasets by improved calibration and retrieval and data merging algorithms, especially with regard to instrumental biases, including effects of drift in orbit;
- Pursuit of the opportunity for reprocessed products from particular instruments or series of instruments, along with the emerging opportunity for provision of integrated products through data assimilation (as provided by the ECMWF reanalyses, for example);
- Continuous research and related intermittent observations are necessary to fully understand ozone chemistry in the troposphere and stratosphere, including precursor trace gases of tropospheric ozone (see section 3.1.11);
- Coordination by WCRP SPARC, [IGBP] International Global Atmospheric Chemistry Program (IGAC), and Integrated Global Atmospheric Chemistry Observations (IGACO) Ozone/UV.

#### **Link to GCOS Implementation Plan**

- [IP-10 Action A26] Establish long-term limb-scanning satellite measurement of profiles of water vapour, ozone and other important species from the UT/LS up to 50km;
- [IP-10 Action A32] Continue production of satellite ozone data records (column, tropospheric ozone and ozone profiles) suitable for studies of interannual variability and trend analysis; reconcile residual differences between ozone datasets produced by different satellite systems.

#### **Other applications**

- Climate-chemistry interaction studies;
- Air-quality forecasting;
- Monitoring and assessment of UV-B exposure at the surface, with its effects on human health and the biosphere;
- Monitoring and assessment of exposure to tropospheric ozone, with further effects on human health and agriculture;
- Enabling the atmospheric correction for several satellite instruments measuring temperature and water vapour profiles and surface and ocean properties.

### **3.1.10. ECV Aerosol Properties**

Atmospheric aerosols are minor constituents of the atmosphere by mass, but a critical component in terms of impact on climate and especially climate change. Aerosols influence the global radiation balance directly by scattering and absorbing radiation and, indirectly, through influencing cloud reflectivity, cloud cover and cloud lifetime. The IPCC has identified anthropogenic aerosols as the most uncertain climate forcing constituent.

Although there is an increasing amount of aerosol data available, more *in situ* and space-based measurements are needed in both the troposphere and the lower stratosphere in order to quantify the radiative forcing by aerosols. A concerted effort to integrate the available measurements of aerosol optical properties and to expand the measurements has begun and may be viewed as an important step in developing an integrated system for global aerosol monitoring. The development and generation of consistent products combining the various sources of data are essential. For improved understanding of the climate impact of aerosols, information on aerosol size and type is important. The physical properties and chemical composition of aerosols need to be routinely monitored at a selected number of globally distributed surface sites. Satellite measurements have been shown to be capable of measuring aerosol optical depth (AOD). They can also provide information on effective size, fine and coarse mode fraction, aerosol type, single scattering albedo (SSA), and aerosol layer height. Single scattering albedo, or rather the absorption aerosol optical depth (AAOD), gives information on the aerosol absorption which is important for radiative-forcing calculations in combination with aerosol layer height. There is likely to be an ongoing need for future operational capabilities for aerosol monitoring from space to be augmented by research missions, and the strategy for an integrated international system for global aerosol measurement

from space needs developing. There is also an ongoing need for reprocessing of past satellite observations, using improved calibration, cloud screening, surface correction and aerosol microphysical models to obtain a historical record.

The short-lived ozone and aerosol precursors – in particular NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO – have been added in the IP-10, in recognition of the emission-based view on climate forcing of ozone and secondary aerosols, relevant for climate mitigation and important for processes. Satellite observations of NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO provide observation-based improvements on bottom-up emission estimates and help to better characterize the different ways in which aerosols force climate. The requirements for these precursors are discussed in section 3.1.11.

Stratospheric aerosol varies naturally, due to episodic volcanic injections of aerosol or its precursor gases (particularly SO<sub>2</sub>), and can have large short-term impacts on climate. The increase in total stratospheric aerosol mass can be by as much as a factor on the order of 100, as in the Mt. Pinatubo eruption of 1991; but even in relatively quiescent periods, a regular succession of minor events is a key – if not the key – source of variability of aerosol in the stratosphere. Stratospheric aerosol is important due to its impact on radiative forcing, warming the lower stratosphere and cooling the troposphere. Its impact on stratospheric chemistry may produce an indirect impact on climate, and high values need to be taken into account in assimilating radiances in reanalysis and in other interpretations of radiance FCDRs. Understanding and monitoring of the role of stratospheric aerosol in climate is also important as artificial enhancement has been proposed as one of the geoengineering approaches to offsetting tropospheric warming due to increased greenhouse gases.

Past stratospheric aerosol measurements from space have primarily been passive measurements of a limited set of optical properties. In particular, much of the backbone of the historical stratospheric aerosol record is based on the solar occultation method. Other approaches include thermal-limb emission, stellar occultation and limb scattering. Active instruments measuring stratospheric aerosol make use of lidar backscatter. Improvement of stratospheric aerosol data quality in the future (for existing datasets and from future measurements) may require a mix of approaches such as UV/VIS/IR occultation measurements and either limb-scatter or lidar measurements. Analysis of these datasets will require on-going corroborative data from robust *in situ* instruments.

Various measures of aerosol properties are possible, including – but not restricted to – aerosol optical depth, light scattering and absorption coefficients, aerosol size distribution, and vertical distributions of aerosol backscattering and extinction. Attention is therefore drawn to four products for this ECV:

<b>Product A.10.1</b> Aerosol optical depth
<b>Product A.10.2</b> Aerosol single scattering albedo
<b>Product A.10.3</b> Aerosol layer height
<b>Product A.10.4</b> Aerosol extinction profiles from the troposphere to at least 35km

**Benefits**

- Improved aerosol products, thereby leading to a reduction in uncertainty as to the quantitative role of aerosols in climate forcing identified by the IPCC;
- Improved products that are needed to validate and improve the capability of climate simulation models and reanalyses to represent aerosol effects.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Aerosol optical depth	5-10km	N/A	4h	Max (0.03; 10%)	0.01
Single-scattering albedo	5-10km	N/A	4h	0.03	0.01
Aerosol-layer height	5-10km	N/A	4h	1km	0.5km
Aerosol-extinction coefficient profile	200-500km	<1km near tropopause, ~2km in middle stratosphere	weekly	10%	20 %



**Rationale:** Resolution requirements allow for estimation of emissions and provision of detailed information on aerosol distribution and chemistry-climate interaction, needed for studies of impacts and extremes as well as radiative forcing. They allow for the use of products in reanalysis. Accuracy and stability targets are judged in relation to detecting radiatively significant regional and global changes in aerosols.<sup>26</sup> Under most circumstances, high spatial and temporal sampling of stratospheric aerosol is not required for climate studies except in the aftermath of a significant intrusion of aerosol from a volcano or other tropospheric event. High vertical resolution in the vicinity of the tropopause is needed to separate tropospheric from stratospheric processes. The proposed spatial resolution and accuracy can only be achieved when occultation aerosol profiles are supplemented with either limb-scatter or lidar backscatter measurements. Both approaches still require substantial averaging or compilation over an extended time period to produce the accuracies required at the resolutions proposed here.

The tabulated requirements are for 550nm extinction, but measurements and products should be based on a multi-wavelength approach in at least the ultraviolet-visible range, and preferably extending into the short-wave infrared. Required aerosol bulk properties in the upper troposphere and lower stratosphere may be derived from the extinction profile product.

#### **Requirements for satellite instruments and satellite datasets**

FCDR of selected wavelengths in UV/VIS/NIR/SWIR and IR, for example through:

- UV/VIS/NIR/SWIR instruments (e.g. NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and AIRS/IASI for dust); using wavelengths in the NIR also gives some basic information on the aerosol layer height;
- Multi-angle measurements providing information on aerosol layer height (e.g. Advanced Along Track Scanning Radiometer (AATSR), MISR) (the combination of multi-view and polarisation measurements provides essential information on SSA, aerosol size, type and aerosol layer height (e.g. [CNES] Polarization and Directionality of the Earth's Reflectances (POLDER) / [CNES] Polarization and Anisotropy of Reflectances for Atmospheric Sciences Coupled with Observations from a Lidar (PARASOL)); in order to quantify not only the effect of aerosol scattering but also the radiative forcing by aerosol absorption, information on the SSA and a measure of layer height is necessary in addition to the AOD);
- Occultation (particularly solar) measurements of aerosol extinction coefficient profiles (this technique has demonstrated strength and should continue to provide the backbone of the observing system for stratospheric aerosol; this data set can be substantially enhanced by measurements in the infrared (2-4 $\mu$ m) to improve determination of aerosol composition and size distribution and thus aerosol radiative properties; a limb-scattering or nadir-viewing lidar system, in conjunction with the above instrument(s), would provide a substantial enhancement; this should include at least two wavelengths and depolarization for the lidar system);

Supplemented by:

- Critical research missions to address the need for the sampling of vertical profiles of aerosol properties at regular time intervals (e.g. CALIOP/LIDAR and EarthCare/LIDAR) and exploitation of other opportunities such as those provided by the potential aerosol measurement capability of the ADM-Aeolus mission.

#### **Calibration, validation and data archiving needs**

Satellite measurements of back-scattered solar radiation require very accurate radiometric calibration. Comprehensive ground-based independent validation measurements are required. These can be provided by existing networks, such as the NASA AERONET or extensions of the NDACC and GAW PFR networks and other lidar networks, with quality assurance coordinated by WMO GAW.

The utility of space-based lidar data is greatly dependent on the ability to calibrate the backscatter measurement with data from an 'aerosol-free' region of the atmosphere, typically above 30km. Calibration needs may be supplemented by ground-based lidar measurements, although that capacity has not been demonstrated. Limb-scattering measurements produce an extinction product similar to that produced by occultation measurements. To produce the most robust stratospheric aerosol data set, there is a strong case for linking limb-scatter/lidar measurements with solar occultation aerosol measurements.

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<sup>26</sup> Similar to Ohring et al., 2004.

### **Adequacy/inadequacy of current holdings**

- Long-term holdings of AOD are limited by the capability of the instruments deployed before 1995;
- Space agencies have on-going projects to produce improved consistent datasets from several instruments; there is a lack of integrated products from recent instruments that have a capability for aerosol-parameter measurements based on similar instrumentation (e.g. MODIS and MISR) and integrated products based on a combination of MODIS-type, POLDER-type, and LIDAR (CALIOP) measurements.

### **Immediate action, partnerships and international coordination**

- Conception and development of operational instruments that will be dedicated to aerosol monitoring (AOD, SSA, aerosol layer height type, size/shape, or phase function) secured for the future (e.g. 3MI-, POLDER-type of measurements); for calculating the effects of aerosols on the radiation balance, AOD, SSA and vertical structure information is needed; although the planned SLSTR and OLCI instruments on Sentinel-3 will provide aerosol information, they will not be sufficient to fulfil these requirements;
- Development of long-term data records based on common methodologies, specifically regarding *a priori* information on the aerosol size distribution and composition, improved cloud flagging, and improved treatment of surface reflection;
- Dedicated effort to radiometric intercalibration for key aerosol instruments such as MODIS, MISR, AVHRR, (A)ATSR and [ESA] Medium Resolution Imaging Spectrometer (MERIS);
- Reprocessing of full AVHRR dataset with respect to AOD over the oceans;
- Development and implementation of composite products from current observations, for example in the A-train (MODIS, POLDER/PARASOL, and CALIOP) or ENVISAT (AATSR/MERIS) and extension of the AVHRR records over land, with some extension back in time using calibrated data from the long-term instruments;
- Sustaining of current limb missions providing information about stratospheric aerosols (OSIRIS, ACE, GOMOS) and their data products as long as possible to ensure continuity or minimize the gap in the data record prior to launch of a future limb mission;
- Continuation of product development through data assimilation (for example as developed for the EU Global Monitoring for Environment and Security (GMES));
- Further exploration of the use of lidar measurements with data from CALIOP and the future ADM-Aeolus and EarthCare missions;
- Exploitation of the IR instruments (e.g. IASI) more fully for information on plumes (e.g. desert dust) and integration of this information in existing datasets;
- Exploitation of SAGE-III occultation data, following launch planned for 2014;
- Further exploration of the use of SWIR and Thermal Infrared Spectral Range (TIR) data together with UV/VIS/NIR, for aerosol retrieval;
- Comprehensive examination of existing stratospheric aerosol datasets to evaluate cross-platform consistency and the potential of mixed datasets whose production may need significant international collaboration;
- Coordination by WCRP SPARC, IGBP IGAC, WMO GAW, and GEWEX Radiation Panel.

### **Link to GCOS Implementation Plan**

[IP-10 Action A33] Develop and implement a coordinated strategy to monitor and analyse the distribution of aerosols and aerosol properties; the strategy should address the definition of a GCOS baseline network or networks for *in situ* measurements, assess the needs and capabilities for operational and research satellite missions for the next two decades, and propose arrangements for coordinated mission planning.

### **Other applications**

- Air-quality forecasting, in particular the effect of anthropogenic particulate matter smaller than 2.5 $\mu$ m on human health;
- Future benefit to NWP;
- Improvement in understanding of the role of aerosols in cloud chemistry, gas-to-particle reactions and precipitation processes;
- Improved knowledge of AOD Aerosols to overcome regional biases in observations of land and ocean surface properties (e.g. SST, ocean colour);
- Furnishing of Aerosol parameters needed for accurate retrieval of several atmospheric trace gases;
- Monitoring volcanic ash and forecasting its dispersion for aviation;
- Surface insolation climatology for renewable energy applications;

- Several instruments provide information on polar mesospheric clouds.

### 3.1.11. Precursors supporting the aerosol and ozone ECVs

NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO are relatively short-lived trace gases in the atmosphere that are not only air pollutants, but also lead to the formation of tropospheric ozone and secondary aerosols. Since ozone and aerosols are radiatively active, the radiation balance is indirectly, but importantly, influenced by the emissions of these so-called *precursors*. Therefore, the requirement for observation of these species has been included in the IP-10, in recognition of the emission-based view on climate forcing of ozone and secondary aerosols, relevant for climate mitigation, and important for chemistry-climate processes. By measuring the emissions of these precursors, tropospheric ozone and secondary aerosols can be better quantified. This also improves knowledge on the aerosol composition, which provides important information regarding the likelihood of aerosols warming or cooling the climate.

Satellite observations of NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO provide observation-based improvements on bottom-up emission estimates and improve the characterization of the different ways in which aerosols force the climate. Measurements in the UV/VIS/NIR/SWIR wavelength range (e.g. from OMI and SCIAMACHY) provide information on all above-mentioned precursors. Recently, thermal infrared measurements (IASI, TES) have been shown to be capable of providing information on SO<sub>2</sub> and CO. Satellite observations to monitor these precursors have now existed for more than a decade, and current and new instruments will continue measuring them operationally for the next few decades (e.g. Metop, GMES Sentinels 4, 5p and 5).

Data on other tropospheric precursor species are currently being derived from measurements made by the IASI advanced high spectral resolution infrared sounder, with good prospects for operational continuity. Profiles of species crucial in understanding stratospheric aerosol morphology are currently being derived from the measurements made by limb-viewing instruments such as ACE-FTS, but in this case there is a lack of planned continuity for such measurements that needs addressing. Detailed requirements for these additional precursor species are not specified in this document.

#### **Product A.11.1 Retrievals of precursors for Aerosols and Ozone such as NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO**

##### **Benefits**

- Improvement in knowledge of changes in tropospheric ozone and aerosol composition, and thus scattering/absorption properties, through monitoring the emission sources of the precursors to support the emission-based view on climate forcing;
- Assimilation in models, thereby improving detection and attribution of changes in aerosols and ozone.

##### **Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
NO <sub>2</sub> tropospheric column	5-10km	N/A	4h	max(20%; 0.03 DU)	2%
SO <sub>2</sub> , HCHO tropospheric columns	5-10km	N/A	4h	max(30%; 0.04 DU)	5%
CO tropospheric column	5-10km	N/A	4h	max(20%; 20 DU)	2%
CO tropospheric profile	10 km	5km	4h	20%	2%

**Rationale:** The requirements are set for retrievals for use of precursor data in reanalysis for improving both the estimates and attribution of derived values of ozone and aerosol, and for the direct use of precursor data in climate process studies, including estimation of emissions. Products at lower spatial and temporal resolution would be sufficient to provide an independent instrument data record of long-term precursor trends to assist in the attribution of changes in ozone and aerosol. SO<sub>2</sub> from volcanic eruptions will also lead to aerosol formation, which is important for climate change. The requirements stated for measuring tropospheric SO<sub>2</sub> will be sufficient for detecting volcanic SO<sub>2</sub>.

### **Requirements for satellite instruments and satellite datasets**

UV/VIS/NIR/SWIR and TIR radiances from sounders and their tropospheric NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO products (currently available types of instrument will be continued on Post-EPS and planned GMES missions: Sentinel 5 precursor (TROPOMI), Sentinel 4 (UV/VIS/NIR) and Sentinel 5 (UV/VIS/NIR/SWIR and TIR)).

### **Calibration, validation and data archiving needs**

- On-ground and in-flight calibration of the space instruments (essential);
- Ground-based systems for validation (e.g. MAXDOAS, TCCON).

### **Adequacy/inadequacy of current holdings**

Measurements of precursors are available for the past 15 to 20 years.

### **Immediate action, partnerships and international coordination**

- Response to the need for ground-based systems for validation that are currently insufficient or lacking (for CO there is the limited TCCON ground-based system (set up for the OCO mission); for tropospheric columns of NO<sub>2</sub>, SO<sub>2</sub> and HCHO there are some validation sites; however, a consistent ground-based network, based on MAXDOAS measurements, is lacking);
- Development of long-term datasets based on the currently available measurements from the past 15 to 20 years;
- Sustaining of current ENVISAT/Aura (SCIAMACHY/OMI)-type missions and their data products to ensure continuity in the data record until future missions that are planned become operational;
- Response to the need for full spectral resolution data from instruments such as CrIS, to enable operational CO measurements from an afternoon orbit to fulfil the temporal sampling requirement;
- Coordination by IGACO, IGAC, and EU GAC IC report.

### **Link to GCOS Implementation Plan**

- *[IP-10 Action A26]* Establish long-term limb-scanning satellite measurement of profiles of water vapour, ozone and other important species from the UT/LS up to 50km;
- *[IP-10 Action A27]* Establish a network of ground stations (MAXDOAS, lidar, FTIR) capable of validating satellite remote sensing of the troposphere;
- *[IP-10 Action A34]* Ensure continuity of products based on space-based measurement of the precursors (NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO, in particular) of ozone and aerosols and derive consistent emission databases, seeking to improve temporal and spatial resolution.

### **Other applications**

- Air quality monitoring and forecasting;
- Observation-based assessment of emission inventories for climate and air quality purposes;
- Monitoring of volcanic eruptions and input to dispersion models for forecasts.

## 3.2. OCEANS

The following sections provide details of the required products and datasets primarily derived from satellites in the ocean domain.

### 3.2.1. ECV Sea Surface Temperature

Sea-surface temperature (SST) is a fundamental indicator of the climate system on a variety of time scales. It is required for climate-model validation, for initialization and constraint of seasonal and decadal prediction systems, for the computation of air sea fluxes of heat, moisture, gas and momentum, for the estimation of net air-sea flux of carbon, for monitoring of marine biodiversity and habitat properties (e.g. at  $T > 301\text{K}$  coral-reef bleaching may occur), as input to atmospheric reanalysis, and for other applications.

There are three distinct sea-‘surface’ temperatures in common use: the traditional *in situ* SST at a stated depth (SST<sub>depth</sub>, where ideally the depth is reasonably well defined and associated with the measurement) measured by *in situ* infrastructure, the ‘sub-skin’ SST (SST<sub>subskin</sub>), assumed to be measured by a passive microwave (MW) radiometer, and ‘skin’ SST (SST<sub>skin</sub>) measured by an infrared (IR) radiometer. Following the Climate Forecast (CF) convention standard definitions for SST, sea-surface-skin-temperature (SST<sub>skin</sub>) should be the primary SST climate data record type for IR- based observations, and sea-surface-subskin-temperature (SST<sub>subskin</sub>) for MW-based observations. The persistence of the inexact term ‘Bulk SST’ (which refers to the SST at or over some arbitrary depth) is problematic in this context and should be depreciated.

Long-term historical climate datasets of “SST” have been traditionally based upon a blend of *in situ* SST data at varied depths and satellite SST measurements. IR measurements provide high spatial resolution (1-5km) and high accuracy ( $< 0.2\text{K}$  in some cases) but are not capable of reliably measuring SST in cloudy conditions or when atmospheric aerosol loads are high. MW measurements currently provide low spatial resolution ( $\sim 25\text{km}$  gridded fields) in all weather conditions except precipitation with reduced accuracy ( $\sim 0.5\text{K}$ ) – particularly in coastal regions where side-lobe contamination prohibits measurement. The relationships between IR, MW, and *in situ* temperatures are complicated by both the surface skin layer, which is seen by satellites, and diurnal thermal stratification. Under almost all conditions, skin temperatures are expected to differ from *in situ* temperatures. The difference can be up to a degree, under certain extremes, but is typically a few tenths of a degree. However, the difference can be significant under certain extremes; for wind speeds less than  $6\text{ms}^{-1}$  thermal stratification in the top metre of the ocean may be significant ( $> 5\text{K}$ ), and the depth of *in situ* measurement becomes increasingly important.

To meet GCOS SST requirements, integrated analysis products are needed that take advantage of the strengths of each data stream (IR, MW and *in situ*), that make best use of our understanding of the limitations of each data stream, and that adjust for variations in uncertainty from region to region, depending on the final application requirements of the derived products.

Global SST fields have been produced on a monthly basis for many years, but comparisons of different analyses reveal regional discrepancies of several K that are unacceptable for many climate purposes, including some of those of the UNFCCC. However, adequate global SST analysis is achievable through enhanced global deployment of existing technology and the improved calibration of satellite sensors, better validation of derived products, and further advancement of blending methodologies capitalizing on the synergy benefit of different SST observations.

The following is required for this ECV:

<b>Product O.1 Integrated sea-surface temperature analyses based on satellite and <i>in situ</i> data records</b>
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#### Benefits

- Providing a fundamental indicator for the state of the climate system;
- Providing a necessary tool for the validation of climate models;

- Computation of air-sea heat, moisture, momentum, and gas fluxes and uptake of carbon by the ocean;
- Quality control of *in situ* data (particularly ship data) [IP-10: Action O3];
- Input parameter for atmospheric reanalysis and seasonal-to-interannual and decadal climate prediction;
- Monitoring of Marine Biodiversity and Habitat Properties [IP-10 Action O23].

### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
SST	10km	N/A	Daily	0.1K over 100km scales	Less than 0.03K over 100km scales

**Rationale:** The requirements have been set to resolve decadal changes on global and regional scales. Known patterns of interannual and longer-term climate variability have amplitudes of several degrees K over basin scales. Mesoscale variability has scales of 10-50km with similar amplitudes over several days. Coastal variability has comparable or larger amplitudes and occurs on scales as small as 1km over several hours. The diurnal cycle in SST can be >5K magnitude in certain regional-local low-wind conditions and can be aliased into lower frequencies if not sampled properly. Diurnal variability signals are important for some climate applications (e.g. air-sea-flux calculations, atmospheric convection). Some current satellite SST datasets may approach 0.1K accuracy on a global average basis but have biases >0.5K for many important regions. If diurnal and seasonal cycle variability is accounted for, comparable SST products should not differ by more than 0.1K between day and night or between seasons.

Global-average surface warming trends (combined land-surface air temperatures and SST) are estimated to be  $\sim 0.165\text{K/decade}^{-1}$  when computed from data between 1979-2005 but with significant hemispheric differences: N. Hemisphere  $\sim 0.235\text{K/decade}$ , S. Hemisphere  $\sim 0.09\text{K/decade}$  (IPCC AR4, Ch3). Trends computed for the period 1901-2005 yield estimates  $< 0.1\text{K/decade}$ , with little difference between hemispheres. Assuming a global surface temperature change signal of  $0.1\text{K/decade}$ , a global average temperature time series should be stable to much better than  $0.1\text{K/decade}$  in order to distinguish the signal from the instability of the time series. To detect such slow and small but significant changes it is prudent to aim for a stability of at least  $0.03\text{K/decade}$  and, if funds and technology allow it, ideally  $0.01\text{K/decade}$ . It is understood that this level of stability is not achievable by current measurement systems, but it remains the target. SST measurement stability should be sought at local spatial scales of  $\sim 1000\text{km}$  or even better in addition to global averages.

### Currently achievable performance (indicative values)

- IR-derived SST: 0.16K at 25km (ENVISAT AATSR);
- Passive microwave-derived SST: 0.42K at 25km gridded (EOS AQUA AMSRE);
- *In situ* buoys: 0.05K;
- SST blended analyses:  $\sim 0.2\text{-}0.5\text{K}$  with regional variation.

### Requirements for satellite instruments and satellite datasets

- FCDRs of appropriate IR (polar orbiting and geostationary) and 'near-all-weather' passive MW satellite measurements capable of supporting climate accuracy in a sustained manner, adhering to GCOS satellite Climate Monitoring Principles (IP-10: Action C6 and C8);
- Properly addressing the long-term future of MW SST observations, which remains uncertain at present;
- Stable well-calibrated high-accuracy and high-temporal stability SST measurements from at least one AATSR-class dual-view instrument (these measurements can be used to monitor variability and tie together wider SST coverage measurements from complementary IR and MW instruments);

Supplemented by:

- Sea-ice edge and concentration observations in high-latitude regions by SST analysis systems;
- Additional information to account for atmospheric aerosol contamination of IR satellite datasets;
- Surface-wind measurements together with SST measurements for diurnal variability estimation;
- Surface-wind vector observations for the retrieval of MW SST;
- For all products, high-quality *in situ* SST observations (to within 0.05 K) on a continuous basis.

### Calibration, validation and data archiving needs

- There is a need to improve instrument calibration of IR and MW sensors;
- Work to improved accuracy and the use of a variety of *in situ* observations for instrument calibration and more general SST validation, for cloud, aerosol, side lobe contamination and other impact characterization is required; comparison of products from independent measurements and analyses remains a priority;
- Routine reporting of the depth of observation from all *in situ* SST data is essential to improve the quality of satellite SST holdings; the ability to exploit historical and contemporary datasets is affected by the limited amount of metadata typically available;
- *In situ* [ship-mounted] radiometers that are accurately calibrated before and after each deployment to traceable national standards must be maintained as a truly independent reference data set for inter-calibration of follow-on satellite missions; this is particularly important where gaps in data exist between follow-on missions; a modest global array of ~10 repeat lines in different atmospheric regimes is required; *in situ* radiometer sampling strategies must consider the variable nature of SST skin dynamics;
- Argo floats that are capable of resolving thermal stratification in the upper 10m of the ocean are required to comprehensively sample thermal stratification and provide a calibration to drifting buoy observations used in satellite validation and quality monitoring;
- Further steps should be taken to strengthen SST data stewardship activities for the satellite SST data record, including tools that provide easy access to multiple-source satellite and *in situ* data. Tools should also be provided for the regular processing and analysis of combined datasets.

**Adequacy/inadequacy of current holdings** SST data holdings are extensive and widely used, but further reprocessing is required to address known problems such as regional biases, cloud, rain, side-lobe and aerosol contamination, and consistently analysed geostationary and polar-orbiting data to resolve the diurnal cycle.

### Immediate action, partnerships and international coordination

- Steps to be taken by satellite SST data providers to make their calibrated radiance observations available for use in the SST reprocessing and re-analysis community;
- A concerted and immediate effort to ensure the sustained continuity of passive microwave SST using a ~6.9 GHz channel (steps should be taken to ensure that better accuracy and high spatial resolution are set as key design goals for future passive microwave satellite radiometers);
- Maintenance and enhancement of coverage by geostationary instruments sufficient to resolve diurnal variability, and improve mechanisms for geostationary SST data exchange;
- A concerted effort to develop a framework to provide robust uncertainty and bias estimates for *in situ* SST datasets used for satellite instrument calibration and product validation;
- Cloud screening of IR data (this remains a significant challenge, despite nearly 30 years of activity, and failure to detect sub-pixel clouds remains the source of substantial uncertainty in IR satellite datasets; further development of cloud-clearing approaches is urgently required to improve the quality of IR SST FCDR);
- Improvement in the performance of IR satellite SST atmospheric corrections in aerosol-rich atmospheres (link to IP-10 Action A33);
- Greater effort to define and implement ice-masking procedures and techniques in polar regions for satellite SST observations (link to IP-10 Action O19);
- Improvement in performance of IR satellite SST atmospheric corrections in polar atmospheres;
- Steps to improve the treatment of side-lobe, ice and rain effects on MW measurements in the coastal zones;
- Continuation of reprocessing of satellite data for providing a homogeneous global SST climate-data record, in particular for all MW datasets and for geostationary and polar-orbiting IR datasets (AVHRR data from 1981 to present requires reprocessing; a systematic framework in which satellite SST datasets can be regularly re-processed and uncertainty estimates provided is required (IP-10: Action C11); the system should foresee multiple re-processing at all levels from engineering data through to physical products to produce the best FCDR for each satellite sensor);
- Sustaining and augmenting of the Argo profiling drifter network, with better capability to resolve diurnal thermal stratification in the surface ocean (Argo profiling floats should be equipped with a capability to make detailed SST vertical profile measurements in the top 10m of the ocean (link to IP-10 Action O26));

- Continuing support for efforts such as the international Group for High-Resolution SST (GHRSSST) Project (and associated CEOS SST Virtual Constellation that is now emerging), which attempts to make optimum use of satellite and *in situ* observations at the highest feasible space and time resolution whilst continuing to support efforts to improve the absolute accuracy of satellite SST measurements and understanding of the characteristics of the uncertainties.

**Link to GCOS Implementation Plan**

- [IP-10 Action O4] Ensure coordination of contributions to CEOS Virtual Constellations for each ocean surface ECV in relation to *in situ* ocean observing systems;
- [IP-10 Action O7] Continue the provision of best possible SST fields based on a continuous coverage-mix of polar-orbiting IR and geostationary IR measurements, combined with passive microwave coverage and appropriate linkage with the comprehensive *in situ* networks noted in O8.

**Other applications**

Numerical weather prediction (NWP) including tropical cyclones, operational oceanography and numerical ocean prediction (NOP), fisheries management, water quality and human health, transport of invasive species, ecosystem dynamics, recreational opportunities, hazardous material spill impacts, the net air-sea flux of carbon, air-sea flux calculations, ecosystem impact (e.g. coral reef) and other marine applications.

**3.2.2. Sea-surface Salinity**

Sea-surface salinity (SSS) is emerging as a new research product from satellite measurements of ocean brightness temperature at L-band (microwave) frequencies. This measurement is important for a number of reasons: sea-surface salinity and sea-surface temperature control the density and stability of surface water. Thus, ocean mixing (of heat and gases) and water-mass formation processes are intimately related to variations of surface salinity. Ocean modelling and analysis of water-mass ventilation should be enabled by new knowledge of surface-density fields, which are again enabled by knowledge of surface salinity. Some ocean models show that sufficient surface freshening results in slowing down the meridional overturning circulation and thereby affecting the meridional oceanic transport of heat. The monitoring of surface salinity from space, combined with the provision of regular surface and sub-surface salinity profiles from *in situ* observing systems such as surface ships and buoys, and the Argo array, provide a key constraint on the balance of freshwater input over the ocean. This allows for better determination of the marine aspects of the planetary hydrological cycle and the possibility of important ocean circulation changes.

The following is required for this ECV:

**Product O.2 Datasets for research on identification of changes in sea-surface salinity**

**Benefits**

Help in the development of coupled climate models. (The importance of the sea-surface salinity field has been demonstrated in hindcasts of El Niño (because of the changes in salinity in the West Pacific Warm Pool region) as well as in the climate of the high-latitude North Atlantic (with respect to the Great Salinity Anomaly and possible implication in the strength of the Atlantic Meridional Overturning Circulation), and for improving estimates of precipitation over the ocean.)

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Seasurface salinity	100km	N/A	weekly	0.05psu	0.05psu

**Rationale:** Detection of regional changes of significance to ocean circulation dynamics.

**Requirements for satellite instruments and satellite datasets**

- Products from research satellite missions (e.g. SMOS and Aquarius/SAC-D), enabling development and demonstration of sea-surface salinity measurements from space;



- Consistent with demonstrated levels of accuracy, an optimal balance of *in situ* and satellite instruments, to be determined and sustained in the future (e.g. an integrated sea-surface salinity observing and analysis system).

#### **Calibration, validation and data archiving needs**

Sea-surface salinity will be calibrated primarily using surface-salinity measurements obtained from salinity profiles from Argo floats, thermosalinograph measurements from ships, and the increasing installation of sensors on surface drifters. Vertical gradients in near-surface salinity are known to exist and must be considered in the development of sea-surface salinity products and uncertainty estimates.

#### **Immediate action, partnerships and international coordination**

- Coordination by science teams for SMOS (ESA) and Aquarius/SAC-D (NASA/CONAE) and WCRP Salinity Working Group;
- Meeting the surface-salinity retrievals requirement for accurate estimates of surface roughness (from surface wind or stress) and SST (partnerships in these areas should be strengthened).

#### **Link to GCOS Implementation Plan**

[IP-10 Action O12] Research programmes should investigate the feasibility of utilizing satellite data to help resolve global fields of SSS.

#### **Other applications**

Hydrological studies.

### **3.2.3. ECV Sea Level**

Sea level is important for both climate science and societal impacts. Change in sea level is a fundamental parameter in the detection of climate change and an indicator of our ability to model the climate system adequately. Sea level is also an indicator of ocean circulation and is an important component in initializing ocean models for seasonal-to-interannual and possibly decadal climate prediction. Current sea-level rise, including the changing frequency and intensity of extreme events, is one of the main impacts of anthropogenic climate change and is particularly important to all low-lying land regions, including many small-island states, for understanding impacts and planning adaptation.

Sea level will continue to rise in the future but the exact amount is presently unknown. Sea level integrates the response to climate change and variability of many components of the climate system (e.g. oceans/atmosphere, land ice, and land waters) and their interactions. Thus sea-level modelling is complex, and current climate models do not adequately reproduce either twentieth century global mean sea-level rise or its regional variability. Projections are also highly uncertain, in particular because of still imperfect understanding of ice-sheet dynamics. Past century sea-level rise is known from tide gauges (a mean rate of 1.7 +/- 0.4mm/yr is recorded for the twentieth century). Since the early 1990s, satellite altimetry has become the main tool for precisely and continuously measuring sea level with quasi-global coverage and a few days revisit time. In addition, satellite altimetry measures 'absolute' sea-level variations (i.e. not contaminated by land motions). Over the past 18 years (1993-2010), the altimetry-based sea-level rise is estimated to 3.3 +/- 0.5mm/yr. This 0.5mm/yr-uncertainty is based on error budget assessments of all sources of errors affecting sea-level measurement using altimetry.

On the regional and coastal scales, changes in sea level are far larger than the globally averaged value and result from many factors, including changes in temperature and salinity and in surface winds. At ocean-basin scale, mass redistributions due to past and current land-ice melt also cause regional variations in sea level. Estimations of changes in coastal sea level, on the synoptic scale and smaller, are undersampled by the current altimeter quality. Reprocessing of altimetry radar waveforms can improve coastal sea-level observations (in the future, wide swath interferometric altimetry will provide 2-D high-resolution coastal sea-level data). Coastal products will be improved by modelling with additional knowledge of winds and tides. Coastal sea level is extremely relevant for understanding societal impacts of climate variability and change.

To monitor global sea-level change, to detect any acceleration in the rate of rise, and to map the regional variability and the temporal variations in spatial trend patterns, satellite ocean surface topography

altimetry of the Topex/Poseidon-Jason class is essential in the long term. For studying coastal impacts of sea-level rise, satellite altimetry measurements in coastal areas should be used in synergy with high-quality tide gauges, corrected for land motion with GPS.

The following is required for this ECV:

**Product O.3 Sea level global mean and regional variability**

**Benefits**

- Estimates of state of the global ocean and its evolution under anthropogenic forcing;
- Evaluation of skill of climate models to reproduce past sea level and provide realistic projections;
- Critical information to coastal communities.

**Target Requirements**

Variable/Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Global mean sea level	50km	N/A	10 days	2-4mm (global mean); 1 cm over a grid mesh	<0.3mm/yr (global mean)
Regional Sea Level	25km	N/A	Weekly	1cm (over grid mesh of 50-100km)	<1mm/yr (for grid mesh of 50-100km)

**Rationale:** The rationale is to assess regional variability and global sea-level trends on decadal time scales, and for the detection of climate change impacts and model improvements. Individual global mean sea-level values are obtained by geographically averaging sea-surface heights measured over the ocean during an orbital cycle (the period needed to cover the whole oceanic domain – ten days for Topex and Jason satellites). To reach the above product accuracy, individual sea-surface-height measurements are expected to be accurate to 1-2 cm.

**Requirements for satellite instruments and satellite datasets**

*Satellite instruments*

FCDR of appropriate satellite altimetry, for example through:

- One high-precision altimeter mission operating at all times in the TOPEX/Poseidon medium-inclination reference orbit, with planned extensive overlaps between successive missions for continuity of global sea-level rise (continuity with Jason-CS and beyond is a goal of primary importance to establish a long-term, climate-related sea-level record);
- Two additional – equally precise – altimeter missions with high-inclination orbits, which would provide needed sampling for the mesoscale and in polar regions;

*Datasets*

- Global mean sea-level curves at ten-day/weekly interval;
- Gridded (50-100km resolution) sea-level time series at ten-day/weekly interval;
- Combined and intercalibrated multi-satellite missions.

**Calibration, validation and data archiving needs**

- Other *in situ* and space-observing systems (e.g. high-quality tide gauges network with co-located GPS, long duration, Argo, highly instrumented calibration sites like the Harvest platform, etc.) are essential to the altimetry missions, as these additional observing systems are used for calibration of altimetric systems;
- To evaluate and understand the sea-level budget, the following observing elements are also necessary:
  - Continuity of space gravimetry missions (e.g. Gravity Recovery and Climate Experiment (GRACE) follow-on missions) to provide estimates of mass exchange between the cryosphere, land water reservoirs and the ocean; and
  - Argo and other *in situ* elements to capture the ocean thermohaline component;
- Geodetic infrastructures (permanent GPS, SLR, and DORIS networks) are needed to improve the terrestrial reference frame in which orbits of altimeter satellites are expressed;
- Continuous precise geoid measurements (e.g. GRACE, GOCE) are required to provide a reference for the altimeter data in order to determine mass redistribution within the ocean (e.g. GRACE);

- Complete reprocessing of altimetry data on a regular basis is a necessary climate system function because continuous improvement in orbit determination, tidal models and atmosphere variability provide improvements to the entire data-record length;
- Altimeter data and tide-gauge data should be referenced within a uniform height system (requiring monitoring for vertical land movements at tide-gauge locations by GPS). In this way, tide gauges recording locally relative sea-level changes can be made consistent with satellite altimetry data;
- In order to compare altimetry with tide gauges and improve knowledge of coastal sea level, there is a need to improve the processing of altimeter missions in the coastal areas (through "retracking" of raw radar waveforms).

#### **Adequacy/inadequacy of current holdings**

- Satellite altimetry, supplemented with tide gauges, has proved adequate to revolutionize the view of global and regional sea-level variability and change;
- Current analysis efforts should be maintained and strengthened;
- Reprocessing of data holdings for the coastal regions could greatly enhance our view of coastal sea-level variability.

#### **Immediate action, partnerships and international coordination**

- Continuation of the precision altimetry satellite time series and regular reprocessing of the global dataset (this is an opportunity to provide the necessary data set to unambiguously monitor and determine if sea level is accelerating and to detect the fingerprint of anthropogenic warming in the spatial trend patterns; in addition, this dataset will serve to constrain, hence improve, coupled climate models used for projecting future sea level (global mean and regional variations); the present >18-year satellite-data record, when compared with twentieth-century tide-gauge data and ice/land data records, suggests that the rate of sea-level rise may have doubled in recent decades; Moreover, independent observing systems indicate that the contributions (ocean warming, land ice melt and waters) are not constant and fluctuate with time; observing sea-level changes is a high priority);
- Partnership and international cooperation include ESA Climate change initiative, some GMES projects, the U.S. Global Change Research Programme, and WCRP activities.

##### *Additional requirements:*

- Performance of intercomparison of sea-level products provided by different groups;
- Reduction in the discrepancies (in particular at interannual and regional scales);
- Development of collaboration between sea-level 'observers' and climate modellers;
- Promotion of the use in synergy of different space and *in situ* observing systems to reduce systematic errors (via sea-level budget and Earth radiation budget studies).

#### **Link to GCOS Implementation Plan**

[IP-10 Action O10] Ensure continuous coverage from one higher-precision, medium-inclination altimeter and two medium-precision, higher-inclination altimeters.

#### **Other applications**

- Operational oceanography: ocean surface topography data provide the core data that enable ocean-state estimates in real-time ocean forecast systems;
- Improved tidal models for coastal communities;
- Planning for adaptation to coastal impacts.

### **3.2.4. ECV Sea State**

Sea-state (variables relating to the height, direction, wavelength and time period of waves) modifies air-sea fluxes of momentum and gas transfer and, to a lesser extent, heat and water vapour, as well as being of high societal relevance in terms of safety at sea (an operational activity) and coastal impacts (e.g. extreme events). There is presently no coordinated sustained effort to deliver global, high-quality sea-state information observations for climate. Present best estimates are provided by direct analyses and via NWP model analysis and reanalysis systems largely on the basis of surface wind, although making use of sparse along-track significant wave-height measurements from altimeters, spectral band-limited directional wave measurements by Synthetic Aperture Radars. Point measurements from the network of moored buoys (which are mostly located in near-coastal margins) are important data for validating NWP

and reanalysis products. A comprehensive strategy for monitoring particular aspects of sea state has yet to be established.

The following is required for this ECV:

**Product O.4 Wave height, supported by other measures of sea state (wave direction, wavelength, and time period)**

**Benefits**

- This product provides required input parameters to ocean-atmosphere coupling schemes of climate models;
- Sea state is fundamental to the corrections required to derive climate-quality sea-surface topography. And, as such, is an essential by-product of the spaceborne contribution to sea-level derivation;
- Wave climatologies influence ship and platform design and coastal infrastructure.

**Target requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Wave Height	25km	N/A	3h	10cm	5cm

**Rationale:** The rationale is for detecting regional changes in waves that are significant to air sea transfers and societal impacts, and for use as input data for reanalysis.

Wave direction and spectrum are also significant parameters, but more work is needed to specify requirements.

**Requirements for satellite instruments and satellite datasets**

FCDR of appropriate altimetry, ideally complemented with Synthetic Aperture Radar (SAR) measurements, for example through a strategy for continuing the current data records of those measurements.

**Adequacy/inadequacy of current holdings**

- Accuracy of the present NWP estimates is known to vary considerably geographically, as well as being of limited utility in shallower coastal regions; knowledge of the uncertainties is limited as a function of both the availability of calibration and validation data and the geographic distribution of reference datasets;
- Reanalyses currently underestimate extreme sea states due to their limited horizontal resolution, but statistical corrections have been developed making use of altimetric wave-height data, and newer reanalyses are running at higher resolution;
- The altimeters on board of past, present and planned missions only provide the significant wave height and wave period, and coverage is limited relative to synoptic scales of variability; Synthetic Aperture Radars (SARs) estimate the spectral properties of the ocean waves and have been flying since 1981; however, SAR has the disadvantage of a strongly distorted image spectrum, caused by the motion of the ocean surface, thereby resulting in a minimum detectable wavelength of about 150-200m; in addition, exchange of SAR data has been limited;
- Sea-state data records exist from many altimeter and SAR instruments, but homogenization is needed if data records from different instruments are to be used together.

**Calibration, validation and data archiving needs**

- It is of the utmost importance to have and maintain a high-quality buoy network measuring sea-state and wave direction for calibration and validation purposes.

**Immediate action, partnerships and international coordination**

- Reprocessing and promotion of use of existing sea-state data records, such as from ERS, Envisat and Jason;

- Efforts to make comprehensive use of planned altimeter- and SAR-bearing satellites in order to ensure the continuity of the existing sea-state information and to build on the existing altimeter and SAR-based decade-long satellite data records;
- New SAR altimeter (Sentinel-3) and swath-altimeter technologies (WSOA) thus allowing advances in near-shore significant wave-height measurement, and their combination with global SAR wave spectral estimates thus allowing more effective coastal zone retrievals of sea state (conventional polar-orbiting altimeters that are presently unable to make effective sea-state retrievals in near-shore regions);
- Proposal that the JCOMM Expert Team on Waves and Surges encourage and coordinate wave measurement systems as part of the Surface Reference Mooring Network.

#### **Link to GCOS Implementation Plan**

[IP-10 Action O16] Implement a wave-measurement component as part of the Surface Reference Mooring Network.

#### **Other applications**

- Near-real-time (<3hr) altimetric sea-state information is presently delivered routinely to operational oceanography users (comprising navies and ocean forecast modellers);
- Near-real-time altimetric and SAR data are used in operational NWP, using coupled atmosphere/ocean-wave models;
- Link to wind observations to improve the stress which forces waves.

### **3.2.5. ECV Sea Ice**

The cryosphere provides indicators of climate change and some of the feedback mechanisms of the climate system, yet it is one of the under-sampled domains in the climate system. Understanding high-latitude climate change requires knowledge of the fluxes between the atmosphere, ocean, and ice. However, efforts to determine surface fluxes at high latitudes face formidable challenges. Observations are sparse and difficult to obtain. Sea ice (SI) has a number of parameters characterizing it.

Sea-ice extent and concentration play a major role in ice-albedo feedback, energy and moisture fluxes between the ocean and atmosphere, and in the temperature and salinity of high-latitude oceans. Ice volume is an important component of high-latitude heat exchange and is needed to quantify the seasonal to interannual variability in freshwater export (in the form of sea ice) from the polar oceans.

Sea-ice concentrations by ice type are determined by operational agencies and can be used to provide rough estimates of ice volume. Improved sea-ice volume estimates require estimates of ice thickness in combination with ice concentrations. Sea-ice thickness is one of the most difficult physical parameters to measure at large scales and, because of the large variability inherent in the sea-ice-climate system, the evaluation of ice thickness trends from the available observational data is difficult.

Sea-ice drift (motion) influences ice mass locally through deformation and creation of open-water areas: regionally, through advection of ice from one area to another, and globally, through export of ice/freshwater from polar seas to lower latitudes where it melts. On time scales of days to weeks, winds are responsible for most of the variance in sea-ice drift. On longer time scales, the patterns of ice drift follow surface currents and the average patterns of wind forcing. Sea-ice drift can be determined from drifting buoys and can be mapped using satellite data.

Estimates of SI extent, concentration, thickness and drift can be derived from combinations of individual space-based instruments, including passive microwave image radiances, visible image radiances, infrared image radiances, SAR, laser and microwave altimetry, and scatterometry. SI motion estimates based on SAR and optical imagery can resolve local scales of motion and deformation, but they lack spatial and temporal coverage. On the other hand, SI motion at regional and global scales can be monitored with passive microwave instruments and scatterometers, but with limited accuracy of both the drift and deformation. *In situ* observations of SI parameters include ship observations, ice profiling sonar measurements and ice buoys (too seldom installed as deformation arrays), and are required to complement satellite data. Very few *in situ* observations are available for satellite SI product validation today.

Many passive microwave, VIS, IR and Active Microwave (SAR, altimetry and scatterometer) satellite instruments are used to retrieve SI parameters. Most of the national SI services base their operational output on individual records and various combinations of these data. SI observations from ships and aircraft cover limited areas, but cannot cover entire ice-covered seas. Satellite observations do provide such coverage on a routine basis, but have limited spatial-temporal resolution, suffer from inconsistencies between datasets, and lack rigorous validation. Until the launch of NASA's Ice, Cloud and Land Elevation Satellite (ICESat) and ESA's Cryosphere Satellite (CryoSat-2), there have been no satellite remote-sensing techniques capable of mapping sea-ice thickness, and this parameter has primarily been determined by drilling or by under-ice sonar measurement of draft (the submerged portion of sea ice). The archive of satellite sea-ice thickness data available to date remains limited but is now being extended.

A major issue limiting the accuracy of ice concentration as well as ice thickness measurements from space is snow cover on the ice. Variability on snow surface and volume properties influence apparent ice<sup>27</sup> emissivity and backscatter and cause errors in estimated ice concentrations (PMR, SAR and VIS/IR). In addition, lack of knowledge of snow load on the ice causes errors in estimated ice thicknesses from satellite freeboard measurements (ICESAT & CRYOSAT).

The following is required for this ECV:

**Product O.5 Sea-ice concentration/extent/edge, supported by Sea-ice thickness and sea-ice drift**

**Benefits**

As noted above, the long-term SI climate-data record represents a fundamental indicator of high-latitude climate change, and information on SI concentration, extent/edge, thickness and drift is required to assess impacts on climate forcing, ocean-atmosphere fluxes and the global thermohaline circulation. SI products are used:

- to improve modelling of sea-ice dynamics;
- in the validation of coupled ocean-atmosphere GCMs;
- to provide precise knowledge of the ice edge location and ice age/type (or stage of development) required for safe navigation and operational support in ice-covered waters (discussion of operational ice observation needs can be found in WMO, 2006).

**Target requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
<b>SI Concentration</b>	10-15km	N/A	Weekly	5% ice area fraction	5%
<b>SI Extent/edge</b>	1-5km	N/A	Weekly	5km	unspecified
<b>SI Thickness</b>	25km	N/A	Monthly	0.1m	unspecified
<b>SI Drift</b>	5km	N/A	Weekly	1km day <sup>-1</sup>	unspecified

**Rationale:** Target requirements have been set to resolve interannual variations and expected trends. Basin-scale observations of SI concentration/extent/edge, thickness and drift are required to understand the large-scale dynamic and thermodynamic evolution of sea-ice cover seasonally and from year to year, and for calculations of ice-mass balance. Continuous time series of these parameters can be used to detect long-term trends in sea-ice cover. Satellite data indicate a continuation of the  $2.7 \pm 0.6$  per cent per decade<sup>-1</sup> decline in annual mean arctic sea-ice extent since 1978. The decline for summer extent is larger than for winter, with the summer minimum declining at a rate of  $7.4 \pm 2.4$  per cent per decade<sup>-1</sup> since 1979 (from IPCC AR4, Section 4.4.2.2). Estimates<sup>28</sup> of average arctic sea-ice thickness over the cold months (October–March) for 1993 to 2001 have been made from satellite-borne radar altimeter measurements and show geographic variation in thickness (increasing from about 2m near Siberia to 4.5m off the coasts of Canada and Greenland) and a significant (9 per cent) interannual variability in winter ice thickness. There are very limited data on sea-ice thickness changes for Antarctic sea ice, much of which is considerably thinner and less ridged than ice in the Arctic Basin (from IPCC AR4, Section 4.4.3.2). However, recent literature show how submarine sonar measurements from the 1950s-1990s can be

<sup>27</sup> SI motion based on SAR and optical imagery are available at 10 km grid spacing. SI motion based on passive microwave imagery and scatterometers is achievable at resolution varying from 50 km to 100 km.

<sup>28</sup> Laxon et al., 2003.

combined with recent satellite measurements (2000s) to provide a longer time trend in ice thickness which indicates an almost 50% decrease over 50 years. Sea-ice drift is variable and wind-dependent, and, overall, there is considerable low-frequency variability in the pattern of sea-ice motion.

Additional product requirements include:

- Coverage: north and south polar region;
- A user-oriented document that describes each analysis product and the choices and assumptions that have been made for the analysis procedure (SI analysis products have a complex derivation, and it is especially important that they be accompanied by such a document);
- Derivation of snow parameters for correction of SIC and SIT estimates.

**Currently achievable performance** are estimated to be in the region of:

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
<b>SI Concentration</b>	10-15km	N/A	Daily	5-20% ice area fraction	unspecified <sup>1</sup>
<b>SI Extent/edge</b>	1-5km	N/A	Weekly	15km	unspecified
<b>SI Thickness</b>	25km	N/A	Monthly	0.5m	unspecified
<b>SI Drift</b>	10-100km <sup>29</sup>	N/A	Weekly	1km day <sup>-1</sup>	unspecified

#### **Requirements for satellite instruments and satellite datasets**

FCDRs of appropriate microwave imagery and visible imagery, for example through sustained existing and planned passive and active microwave and VIS/IR instruments;

Supported by:

- Continuity of satellite SAR altimeter missions and enhancement of techniques for monitoring basin-wide SI thickness; (coordination between radar and laser altimeter missions to obtain near-coincident data will help resolve uncertainties in SI thickness retrievals);
- An ICESat-type follow-on mission to supplement the data delivered by all-weather SAR altimeters;
- Development of algorithms to derive quantitative snow properties from satellite observations (PMR and others).

#### **Calibration, validation and data archiving needs**

Validation of sea-ice products needs improved and shared access to *in situ* observations, which should themselves adhere better to GCOS climate monitoring principles. Validation could also be improved with better use of some satellite data, which is limited in coverage but more precise for some products, for example SAR and high-resolution visible-imager radiances giving sea-ice fraction and coverage samples in summer months, when melting and ponding may be an issue. Among other issues:

- There is a need to develop better inter- and cross-sensor instrument calibration to ensure improved FCDR quality from complementary satellite datasets;
- Further opportunities exist for combining *in situ* data records from Upward Looking Sonars, together with the satellite-derived values of thickness and coverage, so as to quantify estimates of volume and mass variability and fluxes; similar opportunities exist to combine high-resolution VIS/IR image data, SAR, and passive microwave data to reduce uncertainties caused by short-term weather-driven snow-emissivity variations and summer-season meltwater ponding, which requires development/improvement/validation of snow emissivity models;
- The development of physical characteristics of the ice and the ice surface and its interaction with the electromagnetic properties of the ice are not well understood, and fieldwork targeted at understanding physical processes impacting satellite retrievals is important in both the Antarctic and Arctic; although sustained routine complex observations are not practical, such activities are particularly important to provide calibration/validation data for satellites and as inputs for (re)analyses.

<sup>29</sup> SI motion based on SAR and optical imagery are available at 10km grid spacing. SI motion based on passive microwave imagery and scatterometers is achievable at resolution varying from 50km to 100km.

### **Adequacy/inadequacy of current holdings**

- The existing 32-year data record of passive microwave instruments is a unique opportunity to derive uniform information on sea-ice concentration, large-scale sea-ice motion, and sea-ice type. Several sea-ice concentration datasets span the whole data record as of today;
- Extensive satellite data exist from a variety of missions and are available but require further processing, homogenization and integrated analysis.

### **Immediate action, partnerships and international coordination**

- Recovery and reprocessing of long-time series of archived satellite data providing FCDR and a homogeneous SI climate data record (a systematic framework in which satellite datasets can be regularly re-processed and uncertainty estimates provided is required (IP-10: Action C11); the system should foresee multiple re-processing of raw satellite data through to physical products to produce the best FCDR and products for each satellite sensor);
- Improvement and consolidation in existing SI extent and concentration products (1978–present), given the broad range of algorithms being applied to microwave brightness temperatures;
- Development of techniques to capitalize on the synergy of multiple and complementary satellite SI FCDR in order to generate integrated analysis products for the SI ECV, accompanied by uncertainty estimates (methods will need to address resolution, coverage and temporal differences between data types; this applies equally to all the SI variables, that is concentration/extent, thickness and motion);
- A concerted effort to develop a framework to provide robust uncertainty and bias estimates for satellite-based datasets as well as the *in situ* datasets that are used for the calibration of SI-relevant instruments and validation of derived SI products;
- Improved retrieval of sea-ice parameters from SAR (ice drift, shear and deformation, divergence, leads, ice ridging, etc.);
- Promotion of a free-data policy from the space agencies and better coverage by SAR receiving stations for real-time use of the data, in the interest of efficient use of SAR data, especially from the new wide-swath satellites;
- Better exploitation of ice-drift fields from the Radarsat Physical Processor System and PolarView;
- Further development of polarimetric passive microwave instruments and their analysis (e.g. WindSat/Coriolis and SMOS) in order to help support the SI ECV;
- Development of supplemental measurements to assess ice volume and freshwater (i.e. advective) flux and to obtain a global SAR-derived SI drift data record in conjunction with altimetry-derived SI thickness;
- Development of new methodologies to take advantage of the capabilities of dual-polarized SAR sensors;
- Encouragement of the increasing international cooperation between ice agencies (this should include data access and sharing, an agreement on standards in nomenclature and analysis practices and data exchange; such cooperation should also extend to the research community and national funding agencies).

### **Link to GCOS Implementation Plan**

- [IP-10 Action O18] Plan, establish and sustain systematic *in situ* observations from sea-ice buoys, visual surveys (SOOP and Aircraft) and ULS in the Arctic and Antarctic;
- [IP-10 Action O19] Ensure sustained satellite-based (microwave, SAR, visible and IR) sea-ice products;
- [IP-10 Action O20] Document the status of global sea-ice analysis and reanalysis product uncertainty and prepare a plan to improve the products.

### **Other applications**

- Operational ice monitoring and forecasting services supporting ship routing, offshore oil/gas operations, and polar logistics;
- NWP data assimilation;
- SI concentration and edge are required as input to SST analysis systems.

### **3.2.6. ECV Ocean Colour**

Ocean-colour radiance is the wavelength-dependent solar energy captured by an optical sensor looking at the sea surface. The spectral distribution of the water-leaving radiance contains information on the ocean-



albedo and optical constituents of the seawater, in particular the concentration of the phytoplankton pigment chlorophyll-a (a proxy for phytoplankton biomass). Deriving ocean-colour products is not easy because the water-leaving radiance signal is relatively weak at the altitude of a satellite sensor (only 5-15 per cent of incident solar radiation, the remaining light having an atmospheric origin).

Ocean-colour radiometry (OCR) observations from space have revealed decadal-scale changes in the ocean biosphere. Passive ocean-colour sensors observe only the first (top) optical depth of the ocean (40-60m in the open ocean to less than 1m in turbid coastal waters). However, when coupled with *in situ* observations and numerical models, these space-based observations provide a three-dimensional understanding of ocean processes, their complexity, and their interactions with other parts of the Earth system. Therein, enhanced *in situ* sampling of ocean-colour and ecosystem variables is a requirement and complement to satellite-based data.

The FCDR for ocean colour is the time series of calibrated TOA radiances, which are then corrected for the atmospheric contribution to the signal to obtain the water-leaving radiance suite, from which data products such as chlorophyll-a concentration are derived. The most important ocean-colour ECV products are the normalized water-leaving radiances and chlorophyll-a concentration. Other products are in development, such as coloured dissolved organic matter and particulate backscatter (used to estimate total suspended material). OCR products are the only measurements related to biological and biogeochemical processes in the ocean that can be routinely obtained at ocean-basin and global-ocean scales. These products are used to assess ocean ecosystem health and productivity, to understand the role of the oceans in the global carbon cycle, to manage living marine resources, and to quantify the impacts of climate variability and change.

The following is required for this ECV:

**Product O.6.1 Ocean colour radiometry – water leaving radiance**  
**Product O.6.2 Oceanic chlorophyll-a concentration derived from ocean colour radiometry**

#### Benefits

- Climate monitoring;
- Chlorophyll-a linked to carbon-cycling, including between the ocean and the atmosphere;
- Ecological indicators of the marine environment and mapping of marine ecological provinces.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Water Leaving Radiance	4km	N/A	Daily	5%*	0.5%
Chlorophyll-a concentration	30km	N/A	Weekly averages	30%	3%

\*this 5% requirement is specifically for the blue and green wavelengths

**Rationale:** The rationale is based on values chosen to detect global and regional changes of a few percent in ocean chlorophyll cycles. The accuracy of 5 per cent for water leaving radiances for the blue and green wavelengths and 30 per cent for chlorophyll is intended for the concentration range 0.01-10 mg m<sup>-3</sup> in waters in which chlorophyll-a dominates. These are termed Case-1 waters i.e., those whose inherent optical properties can be adequately described by phytoplankton (represented by chlorophyll-a concentration), whereas Case-2 waters are optically complex water where additional in-water constituents considerably influence the optical variability. Four km horizontal resolution and a daily observing cycle are required at the global scale. For regional and coastal applications, 1km or smaller horizontal resolution is preferable. Stability of the OCR ECV has not yet been assessed. Several scientific papers have been published that show the trend in satellite derived chlorophyll concentration being on the order of +/- 2-3 per cent per year with maximums of +/- 5 per cent per year.

#### Currently achievable performance

- Accuracy: 5-15 per cent for water leaving radiances (Product O.6.1) (for the blue and green wavelengths) and 30-70 per cent for chlorophyll (Product O.6.2) in the concentration range 0.01-10 mg m<sup>-3</sup> in Case 1 waters. For coastal waters and regional seas, which are typically Case 2, these errors are considerably higher, typically on the order of 60-70 per cent for chlorophyll-a, but in areas

of extreme optical-complexity as high as 200-300 per cent. For these areas it is recommended that tailored algorithms be implemented;

- Spatial and temporal resolution: 4-9km horizontal resolution, daily, weekly and monthly observing cycles are available at global scale, dependent on sensor. For regional applications 1km horizontal resolution is available.

#### **Requirements for satellite instruments and satellite datasets**

FCDR of appropriate multispectral VIS imager radiances, derived from sensors with spectral and radiometric characteristics, which should be at a minimum of the same class as SeaWiFS, for example through:

- Sustained continuity of current provision of MODIS and MERIS-class, followed by development of a strategy based on advances beyond MODIS, MERIS and SeaWiFS-class capabilities;
- Future satellite observations with higher resolution and accuracy and more spectral bands from polar-orbiting and geostationary satellites; improved capability for ocean-colour observations in optically complex (e.g. coastal and turbid waters) and freshwater systems;
- Ancillary data required for ocean-colour radiances processing, including improved interpretation of sea-ice data from satellites; satellite measurement of salinity;
- Pixel-by-pixel uncertainty information attached to each measurement, where relevant (this is particularly relevant for the products derived from the water-leaving radiances, where large spatial differences are manifested).

#### **Adequacy/inadequacy of current holdings**

- Contributions to OCR ECV data records include current and commissioned polar-orbiting global OCR satellite missions, particularly SeaWiFS, MERIS on Envisat, MODIS-Aqua, OCM-2 on Oceansat-2, OLCI on Sentinel 3A and 3B, SGLI on GCOM-C, VIIRS on NPP and JPSS, as well as future NASA and CNES instruments under consideration; other instruments, such as China's COCTS and Korea's recently launched GOCI on geostationary or geosynchronous orbits, are also of considerable interest, and while these are not collecting global data, a constellation of ocean-colour radiometry on geostationary or geosynchronous platforms would be invaluable for addressing the aforementioned concerns in coastal and regional applications.
- There is no systematic consolidation of a global FCDR based on existing data from SeaWiFS, MODIS, and MERIS (although programmes in this direction have started – e.g. ESA CCI for OCR), and activities to address this need and to derive products should be encouraged; this requires cross-calibrated OCR from multiple satellites which should be merged to provide a data record of water-leaving radiances;
- Planned, next generation, OCR sensors (e.g. PACE and ACE) aim at achieving improved accuracy (i.e. < than 5 per cent for water-leaving radiance and 20 per cent for chlorophyll-a concentration); the OCR time series will undoubtedly benefit from this additional capability.

#### **Calibration, validation and data archiving needs**

- International coordination to establish an integrated network for sensor inter-comparison and uncertainty assessment for Ocean Colour Radiometry;
- Enhancement of the network of *in situ* measurements for calibration purposes, including appropriate planning and coordination to improve the limited spatial coverage of *in situ* measurements;
- Continuation of support, by agencies, of bio-optical systems (e.g. MOBY, BOUSSOLE) for *in situ* data collection, to ensure appropriate vicarious calibration of spaceborne sensors;
- Enablement, by agencies, of the maintenance and expansion of *in situ* measurement networks (e.g. AERONET-OC), providing standardized and spatially distributed time-series for the validation of OCR products;
- Promotion of the collection of comprehensive globally distributed *in situ* bio-optical (both inherent and apparent) properties of sea-water constituents to support algorithm development and assessment;
- Harmonization of the methodologies and protocols for the vicarious calibration of OCR sensors;
- Promotion of the augmentation the Argo profiling drifter network to include the addition of sensors for observing the biological and light-field variables in the surface ocean (separate configurations should be implemented for validation purposes and to improve synoptic knowledge on the 3D structure of the ocean biology and biogeochemistry);
- Improvements in *in situ* platforms for observing the 3-D structure of the light field and biology/biogeochemistry in coastal regions, including improved 'glider' and mooring technology to provide a means of extrapolating the OC data through the water column;

- More international collaboration on establishing centralized data archive and distribution centres for *in situ* data, such as the SeaBASS and MERMAID systems;
- Further steps to strengthen OCR data stewardship activities for satellite OCR data record, including tools that provide easy access to multiple sources of satellite and *in situ* data (tools should also be provided for the regular processing and analysis of combined datasets).

#### **Immediate action, partnerships and international coordination**

- Capitalizing on the OCR community benefits from several international bodies, the IOCCG, which provides the scientific basis and recommendations for advancing OCR science, and the OCR-Virtual Constellation, which provides the coordination for subsequent implementation;
- Revisiting of instrument calibration for historical OC sensors to improve consistency;
- Definition and implementation of an international initiative to establish an integrated network for sensor inter-comparison and uncertainty assessment for Ocean Colour Radiometry;
- Coordination, through user groups, of ocean-colour data such as IOCCP and CMIP and projects (e.g. CMUG and OC-CCI) and GEO initiatives such as SAFARI, ChloroGIN and Global Water Quality Tasks;
- Continuation of research on assimilation of ocean-colour products into ocean-climate models in order to improve carbon-cycle products such as pCO<sub>2</sub> and air-sea CO<sub>2</sub> fluxes; [ANNA: IS THAT "p" A TYPO?]
- Implementation of plans for a sustained and continuous deployment of ocean-colour satellite sensors, together with research and analysis.

#### **Link to GCOS Implementation Plan**

- [IP-10 Action O15] Implement continuity of ocean colour radiance datasets through the plan for an Ocean Colour Radiometry Virtual Constellation.
- [IP-10 Action O23] Establish a global network of long-term observation sites, covering all major ocean habitats, and encourage collocation of physical, biological and ecological measurements.

#### **Other applications**

- Assimilation in ecosystem models for ecological state of the environment applications;
- Monitoring of the health and water quality of coastal seas (including the monitoring of harmful algal blooms).

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### 3.3. TERRESTRIAL

The following sections provide details on the satellite-based datasets and products for climate applications that are required in the terrestrial domain. Land surfaces are generally marked by high spatial variability in their biogeophysical and optical properties, and there is no unified theory describing those properties and their changes over time (as there is, for example, in fluid dynamics in describing atmospheric and ocean variability). This is where the contribution by satellites in providing a synoptic picture is particularly valuable, for example for studying land surface changes in space and time and their role within the climate system. Many terrestrial ECVs are strongly scale-dependent, and inferring them from satellites requires assumptions that are sometimes hard to establish, such as, for example, the structure of a vegetation canopy for deriving its leaf-area index (LAI), the optical effects of the atmosphere for determining the combined surface-atmosphere albedo, or the effect of horizontal sampling and averaging on determining land cover.

When combining different satellite-based terrestrial datasets or products within a climate model, their consistency in space and time is required, implying that the underlying physical assumptions used to generate them should be consistent (e.g. a priori assumptions about atmospheric conditions).

Progress in the establishment of effective internationally agreed standards in observing and documenting many terrestrial ECVs will help in this regard. Facilitated by the GTOS programme, Parties to the UNFCCC reached a consensus to proceed with developing a joint UN/ISO-based framework for setting and maintaining standards for terrestrial observations of ECVs. Implementation of the framework is underway (cf. Action T1 in IP-10). To support this, an assessment of the status of the development of standards for each of the terrestrial ECVs has been made.<sup>30</sup>

Infrastructure to coordinate the collection of data for key *in situ* variables is further being developed (also for validation purposes), and improved mechanisms exist for international consensus-building (e.g. GTOS science panels and a Land Product Validation Group within the CEOS Working Group on Calibration and Validation (WGCV)). Concerted efforts to evaluate and benchmark some of the terrestrial products have started, and space agencies are providing observations for some variables on an increasingly routine basis.

The potential impact of satellite-based datasets and derived products through their assimilation in complex land surface, as well as in combined atmosphere-land-model frameworks, is only beginning to be exploited (see section 3.4.2 on reanalysis).

#### 3.3.1. ECV Lakes

Information on changes in lake level and area (which are surrogates for lake volume) is required on a monthly basis for climate assessment purposes. Approximately 95 per cent of the volume of water held globally in approximately 4,000,000 lakes is contained in the world's 80 largest lakes, which are recognized within the GCOS/GTOS Global Terrestrial Network for Lakes (GTN-L). GTN-L focuses primarily on closed-basin lakes that include major ephemeral lakes and a selection of the largest open lakes. Additional lakes indicative of climate change may be added to the GTN-L at a later stage, including non-permanent water bodies, such as the seasonal lakes appearing with the onset of the rainy seasons throughout the tropics.

Satellite-based observations can substantially contribute to the monitoring of lake level and area using appropriate visible and near-infrared imager radiances, radar imager radiances, and altimetry, especially in remote areas without *in situ* monitoring capability. Direct monitoring of the water surface of each lake of the GTN-L from satellite imager radiances every month at high spatial resolution is currently not realistic, but for each lake, one may calculate the link between water height and area (using 4-5 selected images from low- to high-water-height periods) and then use this relationship (hypsometry) and the monthly height data from satellite altimetry or other tools (*in situ*) to calculate the monthly/weekly lake area. This methodology is under development in the context of the WMO-recognized International Data Centre for

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<sup>30</sup> <http://www.fao.org/gtos/topcECV.html>

Lakes and Reservoirs (Hydrolare), hosted by the State Hydrological Institute of the Russian Federation, St. Petersburg.

Observing lake freeze-up and break-up dates is an important indicator for climate change in boreal and polar regions. Although lake-surface temperature can serve as an indicator for changes in those dates and, more generally, climate change, the most relevant time series for freeze-up and break-up dates come from *in situ* observers. Satellite observations of lake ice cover and temperature are not covered in this section, as the necessary FCDRs are described under other ECVs (e.g. sea ice, SST and land cover). It would be worthwhile to establish trial products of lake-surface temperature and freeze-up and break-up dates to assess their full potential.

Although reservoirs are of undoubted importance in terms of determining terrestrial water storage, fluctuations of the area and level of reservoirs are largely controlled by human activities rather than by climate alone, and reservoirs are invariably being monitored by good *in situ* facilities.

The following is required for this ECV:

**Product T.1.1 Areas of lakes in the Global Terrestrial Network for Lakes (GTN-L)**

**Benefits**

- Assessment of changes in regional climate and better knowledge of the regional water balance, which is an important issue for sustainable development;
- Indication of the volume of the lake water body (through combining lake area with lake level), which is an integrator variable reflecting both atmospheric (precipitation, evaporation-energy) and hydrological (surface-water recharge, discharge and ground-water) conditions.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Areas of GTN-L lakes	Equivalent to 250m	N/A	Monthly	5% (maximum error of omission and commission in lake area maps); location accuracy better than 1/3 of instantaneous field-of-view (IFOV) with 250 m target IFOV	5% (maximum error of omission and commission in lake area maps); location accuracy better than 1/3 of instantaneous field-of-view (IFOV) with 250 m target IFOV

**Rationale:** These targets have been set to detect changes of 5 per cent in annual and decadal averages and seasonal extremes of lake area.

**Requirements for satellite instruments and satellite datasets**

FCDR of appropriate VIS/NIR imager radiances and radar imager radiances, for example through:

- Moderate-resolution optical instruments (e.g. MERIS/MODIS-class);
- Radar instruments (e.g. [JAXA] Advanced Land Observing Satellite (ALOS) L-band in ScanSAR mode and ASAR/Envisat);
- High-resolution optical imager radiances (e.g. Landsat-class).

**Calibration, validation and data archiving needs**

- Validation by high-resolution imager radiances (10-30m) from sample sites and *in situ* measurements (GPS contour of some reference lakes);
- Establishment of a centre with the capability for global data archiving; data documentation, availability and distribution by such a centre (currently under development at Hydrolare) should be given high priority.

**Adequacy/inadequacy of current holdings**

- Current holdings are fragmented; data holdings are not accessible; research databases are no longer supported;

- The designated International Data Centre on Lakes and Reservoirs (Hydrolare) is not yet operational.

**Immediate action, partnerships and international coordination**

- Initiating of the generation of lake-area products using available optical and radar satellite imager radiances and laser altimetry data;
- Coordination by GCOS Terrestrial Observation Panel For Climate (TOPC), GTN-H, WMO Chy and WCRP GEWEX.

**Link to GCOS Implementation Plan**

[IP-10 Action T8] Submit weekly/monthly lake-level/area data to the International Data Centre; submit weekly/monthly altimeter-derived lake levels by space agencies to HYDROLARE.

**Other applications**

- Monitoring of lakes, allowing the prediction of freshwater supplies through the assessment of the regional water cycle;
- Assessment of changes in the regional water cycle and their impact on water quality, biodiversity and health.

**Product T.1.2 Lake level of all lakes in the Global Terrestrial Network for Lakes (GTN-L)**

**Benefits**

(See T.1.1)

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Level of lakes in GTN-L	N/A	N/A	Monthly	50cm	10cm

**Rationale:** These targets have been set, in combination with lake area, with the objective of measuring 1 per cent in water volume change of lakes on annual and decadal timescales. This is based on the assumption that the mean depth of the world's largest lakes is roughly 100m.

**Requirements for satellite instruments and satellite datasets**

- FCDR of appropriate satellite altimetry able to meet measurement requirements;
- Use of laser altimetry instruments, if available.

**Calibration, validation and data archiving needs**

- Ensuring calibration of altimeters to achieve required accuracy;
- *In situ* GPS measurements required for validation;
- Establishment of a centre with the capability for global data archiving; data documentation, availability and distribution by such a centre (currently under development at Hydrolare) should be given high priority.

**Adequacy/inadequacy of current holdings**

- Current holdings are fragmented;
- Global all-weather coverage is lacking;
- Around 1000 lakes have been monitored by Topex/Poseidon (1992-2006), Jason-1 (since 2001) Jason-2 (since 2008), and Envisat (2002-2010);
- Three data centres exist for lake-water-level monitoring from satellite altimetry: Hydroweb (Legos/CNES), the River & Lake (De Montfort University, UK/ESA), and the data centre developed at the University of Maryland, USA.

**Immediate action, partnerships and international coordination**

- Reprocessing of satellite-altimeter data to retrieve lake level;
- Arrangements for Hydrolare currently under development in the context of the Global Terrestrial Network for Hydrology (GTN-H);
- Coordination by GCOS TOPC, GTN-H, WMO Commission for Hydrology (Chy), and SWOT mission stakeholders.

### Link to GCOS Implementation Plan

[IP-10 Action T8] Submit weekly/monthly lake-level/area data to the International Data Centre; submit weekly/monthly altimeter-derived lake levels by space agencies to Hydrolare.

### Other applications

- Monitoring of lakes, allowing prediction of freshwater supplies through the assessment of the regional water cycle;
- Assessment of changes in the regional water cycle and their impact on water quality, biodiversity and health.

### 3.3.2. ECV Snow Cover

The high sensitivity of terrestrial snow properties to changes in temperature and precipitation regimes is recognized as a fundamental indication of climate variability and change and has a significant feedback effect. Projected loss of seasonal snow water storage will strongly affect planetary albedo, soil moisture, growth conditions for vegetation, and other parameters that influence surface water and energy balance. Moreover, changes in the timing, rate and magnitude of snowfall can indicate changing climate conditions, and will modify land-atmosphere fluxes through changes in albedo, latent energy sinks, surface roughness, boundary layer stability and other processes. Snow depth and snow-water equivalent also affect permafrost thermal state, soil temperatures and other characteristics of the ground.

The primary monitoring product is a continuous data record of snow-areal extent. It is also highly desirable to have supplemental global information of three additional terrestrial snow properties: 1) snow depth, 2) snow-water equivalent, and 3) the presence of water in the liquid phase (i.e. wet snow). Combined integrated products linking the four snow products have been generated by space agencies and research groups on a prototype basis, and these activities must continue. Improved resolution passive microwave sensors should be able to provide reasonable estimates of snow depth, water equivalent, and wetness in most areas. Research-mode missions to enhance the retrieval of these variables have been proposed and should be supported over the coming years. The immediate research focus should be to develop reliable capacity to improve measuring global snow-areal extent (especially in complex terrain) and to improve the mapping of snow-water equivalent.

To assist in providing global coverage of snow extent and snow-water equivalent, optimal procedures to generate blended products of surface observations of snow cover with visible and microwave satellite data and related airborne measurements need to be agreed upon and implemented by national services and research groups involved in snow mapping. The Climate and Cryosphere Project (CliC) of the WCRP should take the lead in organizing this with GEWEX and other involved working groups.

Southern Hemisphere snow-extent maps have been available since 1999 from the NASA MODIS sensor. The [USA] National Snow and Ice Data Center (NSIDC) provides a weekly global snow extent product that combines optical (MODIS) and passive microwave (Special Sensor Microwave/Imager (SSM/I)) data for the period 2000 to the present. Agencies currently generating Northern Hemisphere snow-cover products (particularly NASA groups and NOAA/NESDIS) should also routinely generate and archive Southern Hemisphere products. More recently, snow products have also been generated under the auspices of ESA and European Organisation for The Exploitation of Meteorological Satellites (EUMETSAT) Satellite Application Facility (SAF).

Global snow-water equivalent (SWE) products have been available from the NASA EOS Advanced Microwave Scanning Radiometer (AMSR-E) since 2002. Refinements to the retrieval algorithm continue as validation experiments are undertaken. Plans are underway with space agencies to develop new satellite capabilities for measuring snow parameters.

Development of global snow products that blend multiple data sources, including *in situ* observations, need urgent focused attention. Such activities are undertaken in NWP and reanalysis. ESA GlobSnow is an example of a project that has the goal of generating a near-real-time product by interpolating weather-station-based snow-depth and water-equivalent observations and then assimilating the result with spaceborne radiometer based estimates of SWE.



The following is required for this ECV:

**Product T.2 Snow areal extent, supplemented by snow water equivalent**

**Benefits:**

- Better estimate of planetary albedo;
- Indicator of changes in precipitation and temperature regimes;
- Assessment and improvement of regional and global climate-model performance;
- Provision of a key indicator of climate change in cold seasons/regions;
- Assessment of changes in seasonally-frozen ground.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Snow areal extent	1km; 100m in complex terrain	N/A	daily	5% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100m in areas of complex terrain, 1km elsewhere	4% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100m in areas of complex terrain, 1km elsewhere
Snow water equivalent	1km	N/A	daily	10mm	10mm

**Rationale:** The snow-areal-extent requirements stem from consideration of the forcing effect of snow albedo relative to that of greenhouse gases,<sup>31</sup> with a view to supporting climate change assessments and to aid diagnosis of climate-model performance. Spatial resolution is intended to meet regional requirements and impact-related requirements, as well as being necessary to ensure 5 per cent or fewer errors in area estimates. Temporal resolution is needed because of the transient nature of snow cover in mid-latitudes. SWE requirements are based on amounts significant for estimating changes in winter precipitation and associated water availability.

**Requirements for satellite instruments and satellite datasets**

FCDR of appropriate moderate-resolution VIS/NIR/IR and passive microwave imager radiances is required, for example, through:

- Current and planned moderate-resolution, multispectral optical sensors, polar-orbiting (e.g. MODIS) and geostationary;
- Current and planned low-resolution to moderate-resolution, 5km to 20km, passive microwave sensors.

**Calibration, validation and data archiving needs**

- Instrument calibration and refinement of retrieval algorithm to account for changes in sensor characteristics;
- Continuing research, surface observations and field verifications to validate methodologies and satellite products for snow cover, snow extent and snow-water equivalent (*in situ* observations can provide long time series of these variables);
- Product-archiving facilities as provided by NSIDC.

**Adequacy/Inadequacy of Current Holdings**

- Current holdings of historical remote sensing data are available and adequate to generate global reanalysis products for the past 20-30 years, as well as *in situ* data, if national archives make these data freely available;

<sup>31</sup> See e.g. Ohring et al., 2004.

- Current and planned low-resolution to moderate-resolution, 5km to 20km, passive microwave sensors are adequate to provide an estimate of snow-water equivalent for shallow snow packs in simple terrain, and their continuation is desirable; current holdings are inadequate to overcome limitations of low-resolution passive microwave observations and sparse *in situ* observations in areas of complex terrain and deep snow; improved retrieval techniques and higher resolution sensors for complex terrain should be developed;
- Improvements in spectral resolution, calibration, and dynamic range, which are important considerations for future sensors, are needed; more, narrower and better-calibrated bands would help improve observation accuracy and improve snow-cloud discrimination; greater dynamic range is needed to avoid sensor saturation;
- NSIDC produces global snow-cover products from MODIS at 500m resolution and global monthly snow water equivalent from passive microwave data at 25km resolution; NOAA produces daily snow-cover products at 4km resolution;
- SMMR and SSM/I provide soil freeze/thaw states over snow-free ground at 25km x 25km resolution, from 1978 to 2011 (data available from NSIDC).

#### **Immediate action, partnerships and international coordination**

- Continuation of the NCDC archiving of NOAA snow-cover products and the NSIDC archiving of snow-cover and SWE products;
- Meeting the immediate need for continuity and reanalysis of historical areal extent of snow-cover observation datasets that must be maintained for the Northern Hemisphere and extended to the Southern Hemisphere (NOAA/NESDIS has produced daily Northern Hemisphere maps since 1999 and weekly maps since 1966; comparable map products for the Southern Hemisphere are required);
- Integration of multi-sensor (optical, microwave, *in situ*) observations to ensure spatial and temporal consistency for the snow-areal-extent product and the supplemental snow-variable datasets (the NOAA/NWS National Operational Hydrologic Remote Sensing Center has demonstrated a multi-sensor snow-analysis prototype for the conterminous United States since 2003; comparable products are required globally; other examples of integrated datasets include the ESA GlobSnow project and the concept for the CORE-H<sub>2</sub>O Dual Frequency SAR Mission under consideration by ESA);
- Improvement of the near-real-time accessibility of *in situ* observations of snow depth, water equivalent and seasonal frost depth (a central archive for these combined observations needs to be identified and protocols need to be developed for comparing *in situ* observations with satellite derived information);

Coordination by WCRP Climate and Cryosphere Project (CliC), GTN-H (through [NOAA] National Climatic Data Center (NCDC), NSIDC, Global Terrestrial Network for Permafrost (GTN-P) and NOAA/ [USA] National Weather Service (NWS).

#### **Link to GCOS Implementation Plan**

[IP-10 Action T16] Obtain integrated analyses of snow cover over both hemispheres.

#### **Other applications**

- Provision of surface boundary condition for numerical weather prediction;
- Assessment of freshwater resources needed as initial conditions for hydrological forecasts and flood predictions, and for enhanced water supply and reservoir management;
- Snow-water storage, since changes in storage affect water availability in many mountainous areas and in surrounding lowlands in the dry season;
- Improved snow-melt flood prediction.

### **3.3.3. ECV Glaciers and Ice Caps**

Changes in glaciers and ice caps provide some of the clearest evidence of climate change. Their decline will cause serious impacts on the many societies that are dependent on glacier meltwater. The Global Terrestrial Network for Glaciers (GTN-G), based on century-long world-wide observations, has developed an integrated, multi-level strategy for global observations. The strategy combines detailed process-oriented *in situ* studies (e.g., annual mass balance measurements) with satellite-based coverage of large glacier ensembles in entire mountain systems (i.e., glacier inventories combined with digital elevation models, DEMs). The GTN-G is a collaboration among the World Glacier Monitoring Service (WGMS, which operates under the auspices of the ICSU World Data Centre (WDC), the IACS of the International

Union of Geodesy and Geophysics (IUGG), UNEP, UNESCO, and WMO), the Global Land Ice Measurement from Space (GLIMS) initiative, and the NSIDC at Boulder Colorado, USA.)

Glacier inventories derived from satellite remote sensing and digital terrain information should be repeated at time intervals of a few decades (GTN-G, Tier 5), the typical response time of glaciers to climate change. Current efforts for this activity mainly depend on processing of the US Geological Survey (USGS) Landsat Thematic Mapper (TM) / Enhanced Thematic Mapper Plus (ETM+) and [NASA] Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data following the guidelines provided by GLIMS. An important incentive for the completion of a detailed global glacier inventory comes from the recent opening of the USGS Landsat archive and the free availability of global Digital Elevation Models (DEMs) from the Shuttle Radar Topography Mission (SRTM) and the ASTER global DEM (GDEM). Further activities from space agencies moving in this direction, including the use of SAR data and access arrangements by data holders, are strongly encouraged. A DEM is required to derive hydrologic divides for separation of contiguous ice masses into glacier entities and subsequently to obtain topographic information (e.g. mean elevation) for each glacier entity.

Within the GLIMS project a global baseline dataset (2D glacier outlines, outside the two main ice sheets) is being compiled to provide an accurate baseline estimate of global land ice cover and to facilitate assessment of changes in glacier length, area and elevation (i.e., to better assess the ongoing global glacier decline or model future glacier change). Land-ice cover is a primary determinant of sea level, and imperfect knowledge of its state and balance is the principal source of uncertainty about the rate of sea-level change.

Based on these considerations, the following is required for this ECV:

**Product T.3.1 2D vector outlines of glaciers and ice caps (delineating glacier area), supplemented by digital elevation models for drainage divides and topographic parameters**

**Benefits**

- Support for the instrumental data record of climate by providing climate-related information, further back in time, in remote areas and at higher altitude than meteorological stations;
- Input to regional climate models and the validation of impact assessment and climate scenarios on a regional scale;
- Computation of glacier melt contribution to regional hydrology and global sea-level rise.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
2D vector outlines, delineating glacier area	15 - 30 m	N/A	Annual (at the end of the ablation season)	better 5 %	15 m

**Rationale:** To assess changes of glacier extent and mass (for climate change detection and calculation of global sea-level change), a reference dataset that is provided by a glacier inventory (2D outlines) is required. A spatial resolution of 30 m or better and an accuracy better than 5 per cent for the polygons describing the 2D area of individual glaciers is desirable. A clear-sky satellite image from the end of the ablation season in a year with good snow conditions is needed for the mapping. This generally requires repeat acquisition in each year to obtain a scene with appropriate mapping conditions. Where available, multi-year time series can be used for change detection. The elevation data is required to derive drainage divides and topographic inventory parameters for each glacier entity. The accuracy is thus relaxed compared to elevation change measurements.

**Currently achievable performance**

For generating the FCDR of global glacier extents through time, historical archives of Landsat, ASTER and other satellite datasets with spectral bands in the VIS/NIR/SWIR range at approximately 15-30 m resolution are available. The historic Landsat datasets covering the period since 1984 (with the TM sensor), plus the ASTER dataset since 2000, should include several cloud-free images from the end of the ablation period (or dry season) of each glacier in the world. The entire archive can be used to create a

globally complete dataset and perform change assessment where possible. This is a major goal of the GLIMS initiative.

#### **Requirements for satellite instruments and satellite datasets**

Time series of appropriate improved VIS/NIR/SWIR multispectral imager data, for example, through continuity of the Landsat TM/ETM+-class of sensors (e.g. LDCM and Sentinel 2).

Supplemented by:

Accurate DEMs from microwave sensors (e.g. SRTM and TanDEM-X) and along-track optical stereo images (e.g. ASTER and SATELLITE POUR L'OBSERVATION DE LA TERRE (VEGETATION, HIGH RESOLUTION) (SPOT).

#### **Calibration, validation and data archiving needs**

- For accurate orthorectification (better 1 pixel RMSE) of satellite imagery in mountain terrain, a network for ground-reference points is mandatory. Although existing information can be used in some areas, this will require the insertion of new ground-reference points in many remote areas (e.g. in Asia);
- For the use of historical satellite data, archived *in situ* observations/topographic maps might be used (where available) for verification;
- For validation, very high spatial resolution (1 m or better) optical images from selected sample sites are needed;
- In 2008, the global Landsat archives held by USGS (LPDAAC) have been made available to the public at no cost;
- As a common standard format for satellite data, consistent with existing holdings, needs to be agreed, all Landsat data from the USGS archive are orthorectified and available in Geo-TIF format;
- The continuity of existing archives including metadata (from WGMS, USGS, and NSIDC) need to be maintained; this includes *in situ* glacier data (for validation) and satellite data for reprocessing.

#### **Adequacy/inadequacy of current holdings**

- Currently, the World Glacier Inventory provides data from about 40 per cent of the estimated 160,000 glaciers worldwide, but only as point information with limited use for assessment of changes. The GLIMS dataset at NSIDC currently contains more than 100,000 individual glaciers as shape files;
- Simple and robust semi-automatic methods for delineation of debris-free glaciers from multispectral Landsat TM, ETM+, and ASTER data are readily available, but cloud cover and adverse snow conditions set limitations in some regions;
- All Landsat data (MSS/TM/ETM+) in the USGS archive are freely available;
- In most cases, ground-truthing is not possible (apart from careful visual inspection of the satellite image itself; satellite images can be used for glacier mapping only when there is no snow outside of glaciers; debris-covered glaciers and glacier parts in cast shadow need special treatment and editing);
- Landsat 7 lost its scan line corrector in 2003, which reduced the quality of single images at the outer 1/3 of the swath; Landsat 5 has been in operation since 1984 and is still in operation but might fail soon; ASTER is also already beyond its expected lifetime;
- Improved accuracy and spatial resolution of future DEMs are required in regions outside the SRTM coverage; though the ASTER GDEM can be used, it often shows artefacts over low contrast regions like snow and shadow; space-based interferometry with microwave sensors (e.g. the TanDEM-X mission) are expected to improve the situation in the near future.

#### **Immediate action, partnerships, and international coordination**

- The generation of a consistent historical Landsat data record spanning and including the Landsat 4/5 TM and Landsat 7 ETM+ data record, in order to provide major advancement in global monitoring of glaciers;
- Continuation of support by the Global Land Ice Measurements from Space (GLIMS) initiative at the NSIDC for analysis of remotely-sensed products, including mapping of glacier outlines;
- Continuation of support by the NSIDC together with the LPDAAC supports in archiving and long-term availability of the products;
- Pursuance of projects such as the ESA GlobGlacier and Glaciers\_cci in the international context;
- Reporting on Fluctuation of Glaciers (FoG) available from World Glacier Monitoring Service (WGMS), the World Glacier Inventory (WGI) from NSIDC, global vector outlines of glaciers from the GLIMS database, and the Glacier Photograph Collection from NSIDC;
- Guidance is provided from GCOS/WCRP TOPC.

### Link to GCOS Implementation Plan

[IP-10 Action T17] Maintain current glacier-observing sites and add additional sites and infrastructure in data-sparse regions, including South America, Africa, the Himalayas, and New Zealand; attribute quality levels to long-term mass-balance measurements; complete satellite-based glacier inventories in all missing regions.

### Other applications

- Assessment of freshwater resources, particularly critical, in , for example, Central Asia;
- Overall assessment of the hydrological regime, with impact on energy production and agriculture;
- Risk assessment of glacier-related natural hazards.

### Product T.3.2 Elevation change of glaciers and ice caps, from geodetic methods, in regions where outlines are available

### Benefits

- The same as for T.3.1;
- Support the in-situ mass-balance measurements in order to assess their representativeness for entire mountain ranges as well as to extent data coverage in space and time.

### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Elevation data	30 - 100 m	1 m	Decadal	better 5 m	1 m

**Rationale:** Traditionally, in-situ measurement of glacier seasonal or annual mass-balance has been carried out at a few hundred glaciers. They are combined with geodetic volume change assessments based on terrestrial and aerial surveys to asses overall glacier changes in volume and mass (for climate change detection and calculation of global sea-level rise and regional runoff contribution). Combination of space-borne DEMs (e.g. from SRTM and SPOT) with earlier national DEMs opens the possibility to determine glacier specific elevation changes over a decadal time period for entire mountain ranges. This allows (1) to assess the representativeness of the mass balance glaciers in the *in-situ* network for the entire region and (2) to extend the data record in space and time.

### Currently achievable performance

At present, the SRTM DEM with (almost) global coverage fulfils the above target requirements and can serve as a baseline DEM for large-scale glacier volume change assessments based on differencing with earlier and/or later DEMs from other sources. These include national DEMs of sufficient quality, aerial surveys (e.g., digital photogrammetry, laser scanning), and DEMs from other space-borne sensors (e.g. ASTER, SPOT). In some heavily glacierized regions (e.g. Canada and Alaska) also national DEMs are freely available. This allows to calculate the volume changes described above already today with an accuracy meeting the target requirements.

### Requirements for satellite instruments and satellite datasets

Decadal snapshots of global DEM coverage would allow for a most comprehensive assessment of glacier volume changes. The reduced quality of DEMs derived from optical sensors (low contrast over snow and in shadow) and microwave sensors (radar penetration in snow, layover, data voids) have to be considered and corrected where possible. Frequent accuracy assessment of such DEMs should be performed using high-resolution data from aerial surveys (LIDAR). In this regard, the new global high-resolution DEM created by the interferometric SAR mission TanDEM-X is highly promising.

### Calibration, validation and data archiving needs

- The DEMs used for calculation of glacier volume changes need to be properly co-registered and should have the same cell size. If resampling is required, the effects on the elevation should be considered;
- Only DEMs with a proper time stamp can be used for assessing elevation changes of glaciers;

- Elevation values itself can be validated with space-borne (e.g. ICESat GLAS) or airborne LIDAR measurements (outside of glaciers and over flat terrain);
- Data providers should properly document how the DEMs were created (source data, dates, etc.);
- Easy access and easy conversion to software specific data formats are essential for the wide use of a DEM;
- A long-term strategy for archiving and distribution of the data sets should be implemented. Well established standards of current data holdings should be adapted.

#### **Adequacy/inadequacy of current holdings**

- The SRTM DEM from February 2000 covers only the region between 60 N and 57 S, so regions with large ice masses (Alaska, Canadian and Russian Arctic, Greenland) are excluded;
- The GDEMv2 covers these regions but it does not have a time stamp and many artefacts;
- The GLS2000 DEM used by USGS to orthorectify satellite data is also freely available and covers nearly the entire globe. It includes several DEMs from national agencies and is for the regions outside the SRTM coverage from a much earlier period with an unclear time stamp in many cases;
- The SPOT DEM from the IPY project SPIRIT closes some of the gaps in polar regions;
- With the currently available DEMs, decadal glacier elevation changes can already be calculate for some 10,000 more glaciers, but proper repeat coverage in Arctic regions is still not available.

#### **Immediate action, partnerships, and international coordination**

- Encourage national mapping agencies to make their historic DEMs publicly available;
- Support space agencies to make global data sets from on-going mapping missions (e.g. TanDEM-X) freely available;
- Integrate the glacier research and monitoring community at an early step for designing DEM-producing sensors and for pilot studies for product simulation and analysis;
- Help with integrating available data sets (e.g. viewfinderpanoramas.org) in long-term archives.

#### **Link to GCOS Implementation Plan**

*Related themes are: global sea-level rise, water resources, climate change impacts.*

#### **Other applications**

- Assessment of freshwater resources, particularly critical, in, for example, Central Asia;
- Overall assessment of the hydrological regime, with impact on energy production and agriculture;
- Risk assessment of glacier-related natural hazards.

### **3.3.4. ECV Ice Sheets**

Our understanding of the timescale of ice-sheet response to climate change has altered dramatically over the last decade. Rapid changes in ice-sheet mass have surely contributed to abrupt changes in climate and sea level in the past. The mass balance loss of the Greenland Ice Sheet increased in the late 1990s to 50 gigatonnes per year ( $\text{Gt yr}^{-1}$ ), in 2005 to 150  $\text{Gt yr}^{-1}$ , and to more than 250  $\text{Gt yr}^{-1}$  for the most recent observations in 2010. The mass for Antarctica as a whole is close to being in balance, but with a likely net loss since 2000 at rates of a few tens of gigatonnes per year. There are large mass-budget uncertainties from errors in both snow accumulation and calculated ice losses for Antarctica ( $\pm 160 \text{ Gt yr}^{-1}$ ) and for Greenland ( $\sim \pm 35 \text{ Gt yr}^{-1}$ ).

Observations show that Greenland is thickening at high elevations because of a (predicted) increase in snowfall, but this gain is more than offset by an accelerating mass loss, with a large component from rapidly thinning and accelerating outlet glaciers. Recent observations show a high correlation between periods of heavy surface melting and increase in glacier velocity. A possible cause is rapid meltwater drainage to the base of the glacier, where it enhances basal sliding. An increase in meltwater production in a warmer climate will likely have major consequences on ice-flow rate and mass loss. Recent rapid changes in marginal regions of the Greenland and West Antarctic ice sheets show mainly acceleration and thinning, with some glacier velocities increasing more than twofold. Many of these glacier accelerations closely followed reduction or loss of their floating extensions known as ice shelves.

Efforts should be made to (i) reduce uncertainties in estimates of mass balance and (ii) derive better measurements of ice-sheet topography and velocity through improved observation of ice sheets and

outlet glaciers. This includes utilizing existing satellite interferometric synthetic aperture radar (i.e. InSAR) data to measure ice velocity; using observations of the time-varying gravity field from satellites to estimate changes in ice-sheet mass (e.g. GRACE satellite); surveying changes in ice-sheet topography using tools such as satellite radar (e.g. Envisat and Cryosat-2), future laser missions (e.g. ICESat-2), and use of wide-swath altimeters.

Monitoring the Polar Regions with numerous satellites at various wavelengths is essential to detect change (e.g. of melt area) and to understand processes responsible for the accelerated mass loss of ice sheets and the disintegration of ice shelves (e.g. to estimate future sea-level rise). Driven by accelerated ice-sheet mass loss observed today, recent estimates using space-based gravity field measurements show an increase of the ice-sheet contribution to total cryospheric sea-level rise (which includes contributions from the melting of glaciers and permafrost).

In addition to satellite observations, *in situ* measurements (e.g. of firn temperature profile and surface climate) are equally important in assessing surface mass balance and understanding recent increases in mass loss.

The following is required for this ECV:

**Product T.4 Ice-sheet elevation changes, supplemented by fields of ice velocity and ice mass change**

**Benefits**

- Reduction in significant errors to which existing estimates of Antarctic and Greenland mass balance are prone (some parts of Antarctica and Greenland ice sheets are subject to rapid change, especially the Antarctic Peninsula and coastal regions in west and east Greenland);
- State-of-the-ice-sheets is a major unknown factor in determining the pace of sea-level change.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Surface elevation change	100m	N/A	30 days	0.1m/yr	0.1m/yr
Ice velocity	1km	N/A	30 days	10m/yr	10m/yr
Mass change	50km	N/A	30 days	10km <sup>3</sup> /yr	10km <sup>3</sup> /yr

**Rationale:** Requirements for ice sheet-related products are driven by the overall need to determine the mass balance of ice sheets and its change over time, and, more specifically, by: (1) the need for adequate spatial sampling of ice sheet topography and its changes (horizontal resolution can be coarser in the flatter inner ice sheet areas); (2) monthly sampling of total ice sheet behaviour (all parameters) to detect seasonal cycles; (3) the ability to detect rapid elevation changes and to trace a 10 per cent contribution to expected eustatic sea-level rise (i.e. 0.3mm/yr, roughly equivalent to 120 GT/yr mass balance loss), assuming uniform ice loss mainly off the Greenland ice sheet (resulting in 0.1m/yr accuracy); (4) the need for adequate characterization of (potentially non-linear) ice losses through outlet glaciers and other mechanisms through measurements of ice velocity and mass change; (5) the intent to detect 10 per cent of the currently estimated annual rate of mass change due to ice loss (about 100 GT/yr, roughly equivalent to 10km<sup>3</sup>/yr); and (6) the fact that for a lack of a well-established estimated historical trend for all variables, more specific requirements for stability cannot be stated at present.

**Currently achievable performance**

- Surface elevation change: Accuracy 0.2m along satellite track (derived from radar altimetry);
- Ice velocity: Accuracy 25m/year (derived from SAR);
- Mass change: Accuracy 30km<sup>3</sup>/yr with 500km horizontal resolution (derived from gravity measurements).

**Requirements for satellite instruments and satellite datasets**

FCDR of appropriate radar and laser altimetry;

Supplemented by:

- Radar measurements, for example through consideration of the use of SAR, especially interferometric SAR, to provide intermittent sampling of ice velocity and other detailed ice-field properties (surface-height change, densification and vertical ice velocity);
- Satellite-based gravity-field measurements, which should be further explored to detect time-varying changes in mass of water and ice on land.

#### **Calibration, validation and data archiving needs**

- Needs for calibration should be identified by the CEOS WGCV, working with involved partners;
- Validation through mass-balance closure estimates, reference point surveys, airborne laser altimetry, use of other sensors (optical, microwave, etc.) is required;
- Aircraft laser altimeter (NASA ATM) missions are required for validation as well as *in situ* ground observations by automatic stations (surface height change, densification, vertical ice velocity);
- Product archiving by the NSIDC World Data Center for Glaciology is essential.

#### **Adequacy/inadequacy of current holdings**

- Coastal regions of certain outlet glaciers in Greenland are not adequately covered by current satellite data, although surface-height changes in these regions are dramatic (>25m/year);
- 5-km-resolution bed topography data by PARCA, ITASE and DEMs, with appropriate spatial resolution, are available and will be enhanced in the future.

#### **Immediate action, partnerships and international coordination**

- Exploitation of the knowledge base of several research programmes and organisations, including PARCA, CliC, IGOS Cryosphere, SCAR, and NASA Icebridge;
- Identification of the international body that will coordinate this activity and develop a strategy for archiving data.

#### **Link to GCOS Implementation Plan**

[IP-10 Action T20] Ensure continuity of laser-, altimetry- and gravity-satellite missions, adequate to monitor ice masses over decadal timeframes.

#### **Other applications**

- Laser altimeter missions have proven very useful for near-real-time monitoring of major rivers;
- Interferometric SAR allows all-weather detection of land surface movements;
- Gravity mission data have given insight into changes in land-based water storage and ocean currents.

### **3.3.5. ECV Albedo**

The albedo of a land surface is the non-dimensional ratio of the radiation flux reflected by a (typically horizontal) surface in all directions and the incoming irradiance, which is the radiation flux from the upper hemisphere. This is technically known as the bi-hemispherical reflectance factor (BHR), and both fluxes must be relative to the same spectral range. For bare soils and other solid convex objects, the material interface between the ground and the atmosphere constitutes the reference surface. In the case of vegetation, a reference surface is typically defined at or near the top of the canopy and must be specified explicitly. This 'generic' albedo is highly variable in space and time as a result of changes in surface properties (snow deposition and melting, changes in soil moisture and vegetation cover, etc.), as a function of fluctuations in the illumination conditions (solar angular position, atmospheric effects, cloud properties, etc.), and with human activities (clearing and planting of forests, sowing and harvesting of crops, burning of rangeland, etc.). It is thus a joint property of the land surface and of the overlying atmosphere.

Albedo is both a forcing variable affecting the climate and a sensitive indicator of environmental degradation. Given the amount of energy involved in solar radiation fluxes, even a 1 per cent change in land-surface albedo generates fluctuations on the order of  $3.5\text{W/m}^2$  on global and annual averages.

Albedo thus controls the 'supply' side of the surface radiation balance and is required to estimate the net absorption and transmission of solar radiation in the soil-vegetation system. It can be defined spectrally or for spectral bands of finite width with broadband albedos generally referring to the entire 0.3 to  $3.0\mu\text{m}$



range (WMO, 2006) or the two broadband ranges 0.3-0.7 and 0.7 to 3.0  $\mu\text{m}$ . Two simple concepts, corresponding to extreme conditions, have been defined:

- 'Black sky albedo,' technically known as the directional hemispherical reflectance factor (DHR), is the reflectance of that surface when the illumination comes from a single direction. Black sky albedo is the albedo in the absence of any atmosphere. It depends on the angular position of the source of light and on surface properties.
- 'White sky albedo,' technically known as bi-hemispherical reflectance factor under isotropic illumination (BHR-iso), is the reflectance of that surface when the irradiance is isotropic. The surface albedo under an overcast homogeneous cloud deck would be a good approximation of white sky albedo. This value depends only on surface properties.

In practice, the actual instantaneous albedo of a land surface is often approximated from a linear combination of the black and white sky albedos, where the weighing factors are the relative proportions of direct and isotropic diffuse radiation. Such a combination is sometimes referred to as the 'blue sky albedo.' It depends on the angular position of the main source of illumination for direct radiation, the atmospheric condition, and on surface properties.

None of these albedo-related quantities are directly measurable from air- or space-borne platforms. Instead, multiangular reflectance measurements must be interpreted with the help of radiation transfer models to retrieve the desired variables from the actual observations. Significant progress has taken place over the last few decades. The issues of model inversion, as well as angular or spectral integration of directional reflectances into hemispherical values or broad bands, are well-understood, and suites of products (including reflectance anisotropy, black-, white-, and blue-sky albedo estimates) are currently available to satisfy the diverse needs of a wide range of users.

Some albedo measurements (analogous to blue sky values) are acquired *in situ*, for instance, with pyranometers that integrate the incoming radiation reaching the sensor from an entire hemisphere. The coupling of two such instruments back-to-back to measure simultaneously the irradiance from the sky and the reflectance from the surface is the concept of so-called 'albedometers'. Those are deployed to WMO standards<sup>32</sup> on stationary towers as part of the BSRN. Primarily broadband instruments have been deployed although a limited number of spectral measurements do now exist. The footprint characterized by these sensors is driven by the height of the tower above the surface; therefore the applicability of these measurements to satellite derived quantities is governed by the height of the *in situ* instrument above the top of canopy and representativeness of this footprint to the usually larger remotely sensed footprint. While the BSRN tower sites currently provide some of the highest-quality measurements available for radiation at the surface, they are spatially limited and the network needs to be expanded and adequately supported to achieve better representative global coverage.

The following is required for this ECV:

**Product T.5 Reflectance anisotropy (BRDF), black-sky and spectral white-sky albedo**

**Benefits:**

- Climate forcing variable;
- Estimates of net absorption and transmission of solar radiation in soil-vegetation system.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Black-sky albedo	1km	N/A	Daily to weekly	max(5%; 0.0025)	max(1%; 0.0001)
White-sky albedo	1km	N/A	Daily to weekly	max(5%; 0.0025)	max(1%; 0.0001)

<sup>32</sup> McArthur, 2005; WMO, 2006.

**Rationale:** The objective behind these numbers is to detect the change in radiative forcing equivalent to 20 per cent of the expected total change in radiative forcing per decade due to greenhouse gases and other forcing, i.e.  $\sim 0.1 \text{ W/m}^2$  per decade.<sup>33</sup> The requirements are global. More accurate observations over ice and snow would be useful for calculating ice and snow melt.

Although there are issues with respect to radiometer stability and generation of aerosol corrections, the specifications of existing (and planned) space-based instruments meet or largely exceed the spatial and temporal sampling requirements of GCMs, but these higher frequencies of observation are very useful to guarantee the accuracy and stability of the products and to support a host of other downstream applications. Even in the context of climate applications, high spatial resolution supports high-resolution regional models, as well as climate models, and allows studies on the sensitivity of land-surface parameterizations with respect to surface heterogeneity, especially to capture snow events and rapid phenologic, hydrologic, and anthropogenic variations.

#### **Currently achievable performance and threshold requirements**

- Given the role of land surface albedo in the energy balance of the planet over continental areas and the high sensitivity of the scenarios and forecasts to this value, any improvement in the accuracy of systematic albedo estimations will be beneficial;
- Albedo products currently available may meet some or most of the accuracy expectations described in the table above, and future sensors are expected to result in further improvements in accuracy; however, further investigations, especially in the field, are needed to validate these products; in any case, the applicable level of uncertainty should always be reported together with the albedo value itself;
- Various ancillary data may be required to retrieve accurate albedo products. For instance, flags or indicators of the presence of snow on the ground are essential to specify appropriate prior values in assimilation schemes.

#### **Requirements for satellite instruments and satellite datasets**

- The fundamental quantity that is required to estimate any one of a number of albedo-like products (black, white or blue sky albedos, etc.) is the spectral reflectance anisotropy as described by a model of the bidirectional reflectance distribution function (BRDF); this quantity is retrieved by inverting a bidirectional reflectance model against a set of measurements of the same target from different observation angles;
- Instantaneous values of BRDF and albedo products are best generated from FCDRs of multispectral, near-instantaneous multi-angular sensors, such as MISR or POLDER, which do acquire multiple observations of the same location from a range of observation directions within a very short period (minutes), typically in a discrete number of spectral bands.
- FCDRs of multispectral imager radiances: Mono-angular instruments can also be exploited for this purpose, but measurements must be accumulated in time; for instance, MODIS-, MERIS-, (A)ATSR-, VEGETATION class instruments, combining a broad swath and a relatively high revisit frequency (e.g. once a day or so), may provide adequate angular sampling over periods on the order of ten days to two weeks; the main drawback of this approach is that the surface properties must remain stable during that period, so the accuracy of the final products may fluctuate in space and in time, with less reliable products during periods when the surface changes (snow deposition or melting, variations in soil moisture, etc.) or when obscuring of the atmospheric is more frequent (e.g. with high cloudiness).
- FCDRs of multispectral instruments on geostationary platforms can similarly be exploited, even though they observe a given target under a fixed viewing angle and do not sample polar regions; in this case, data accumulation can take place over periods of a day or so (at frequencies on the order of 15 to 30 min), and under the assumption of stable environmental conditions (surface and atmosphere); the reciprocity principle can be invoked to retrieve the surface-reflectance anisotropy from variations in the observations due to changes in illumination angles.

#### **Calibration, validation and data archiving needs**

- As is the case for all surface variables, the accuracy of the products depends on the performance and reliability of all upstream processes, in particular to account for atmospheric effects (cloud detection and masking, aerosol characterization, etc.). Instrument specifications as well as calibration and validation requirements should thus be driven by the most demanding element in the entire process.

<sup>33</sup> Similar to Ohring et al., 2004.

On-board calibration mechanisms are highly desirable to ensure the accuracy of the measurements. Nevertheless, vicarious calibration exercises are also needed to confirm the stability of the measurements over long periods of time and to detect possible degradations or failures of on-board systems;

- The validation of retrieval procedures and the reliability of final products hinge on the availability of *in situ* measurements to characterize both the overlying atmosphere and properties of the surface; this involves, for instance, deploying sun photometers and similar instruments to document atmospheric aerosols, as well as erecting towers or similar infrastructures to support ground-observing instruments (such as those deployed by AERONET (**AE**rosol **RO**botic **NET**work))
- Special attention should be given to the difficult problem of matching measurements obtained from space with those acquired *in situ* because of the wide differences in scale and resolution between these sensors. An integrated strategy to achieve such comparisons may involve the exploitation of high spatial resolution sensors (such as Landsat) or airborne instruments to provide intermediary products. When using *in situ* network data, spatial representativeness of the albedometer footprint has to be tested with regard to the instantaneous field of view of the satellite sensor and the corresponding spatial resolution of the albedo product. A protocol with recommendations for the consistent validation of satellite-inferred albedo products with *in situ* observational data is in preparation by CEOS LPV, including tests for spatial representativeness as described in Roman et al., 2009.
- Whenever multiple instruments are mobilized (e.g. space, airborne and *in situ* instruments), it is essential that observations be acquired contemporaneously. This may be best achieved during dedicated field campaigns, and the latter should encompass the whole range of ecosystems and land cover types to guarantee the accuracy of the products in all environments, from equator to pole.
- Continuous *in situ* network observations are a requirement to perform validation throughout the year, covering all seasons and corresponding land surface dynamics, such as snow cover and phenology of vegetation (e.g. leaf on, leaf off).
- Traceability to international standards is best achieved through round robin calibration exercises and systematic field campaigns over very stable land cover types, such as salt pans, deserts, etc., as well as in deep oceans or other stable dark targets. Effective connections and integration into existing international networks, such as AERONET and BSRN, will further improve the reliability of the distributed products. Similarly, systematic intercomparisons and benchmarking exercises are needed to document, understand, and resolve remaining (or future) small systematic differences between these products
- All Space Agencies and data providers should be encouraged to schedule and implement occasional reprocessing exercises to take advantage of advances in science or to ensure the seamless merging of products derived from different instruments, platforms, or technologies
- Land surface albedo products can be used to document subtle environmental changes over long periods of time. It is thus critical that existing and future archives of such products be preserved and made available on a continuing basis

#### **Adequacy/inadequacy of current holdings**

- Databases of hemispherical-conical spectral reflectance measurements have been made available by space agencies since the early 1980's; some of these data have been analysed to estimate surface albedo, but a much more coherent, integrated, systematic effort should be conducted to ensure consistent accuracy and temporal coverage; in particular, recent measurements and current understanding can be used to reprocess the historical data archives from AVHRR and operational geostationary satellites and to generate a set of products consistent with modern products, thereby delivering a key product over a much extended time line; NASA and NOAA are currently supporting the consistent reprocessing of AVHRR and MODIS data for the production of the Land Long Term Data Records (LTDR) and Climate Data Records (CDR); initial actions with regard to the geostationary satellites by EUMETSAT and CGMS within SCOPE-CM have further demonstrated the feasibility of this goal;
- Albedo products such as DHR and BHR have been generated by major space agencies for over a decade and are routinely used in a range of applications; validation and satellite-product intercomparison efforts have been initiated and should be strengthened, with the financial support of space agencies and research funding bodies; these should also be coordinated with the relevant CEOS Land Product Validation Subgroup as well as other relevant stakeholders.

### **Immediate action, partnerships and international coordination**

- Financial support is required to permit intercomparisons and benchmarking of albedo-type products on a continuing basis, including for field campaigns and partial contributions to established networks, such as BSRN and AERONET;
- Significant benefits would accrue from the albedo reprocessing based on the AVHRR LTDR database in the light of scientific achievements and data acquisitions during the last decade (this would greatly expand the time period for which comparable albedo products would be available and thus facilitate the detection of small but cumulative changes);
- The accuracy, stability and reliability of land surface albedo products generated from multiple instruments on different platforms would be greatly enhanced by the existence of a high-quality dedicated sensor that would provide traceability to international standards and definite transfer functions between instruments;
- Special attention should be given to the development of a traceable quality-assurance system, allowing the acquisition of unbiased and reliable assessments of the compliance of both *in situ* validation methodologies and remotely sensed albedo products with the GCOS criteria on albedo accuracy; ideally, such a system should account for diverging product definitions, spatial resolutions and overpass times.

### **Link to GCOS Implementation Plan**

- *[IP-10 Action T24]* Obtain, archive and make available *in situ* calibration/validation measurements and co-located albedo products from all space agencies generating such products; promote benchmarking activities to assess the quality and reliability of albedo products;
- *[IP-10 Action T25]* Implement globally coordinated and linked data processing to retrieve land-surface albedo from a range of sensors on a daily and global basis, using both archived and current Earth Observation systems;
- *[IP-10 Action T3]* Develop a subset of current LTER and FLUXNET sites into a global terrestrial reference network for monitoring sites with a sustained funding perspective and co-located measurements of meteorological ECVs; seek linkage with Actions T4 and T29, as appropriate.

### **Other applications**

- Critical variable for NWP;
- Useful as an environmental indicator;
- Changes in albedo useful in assessing the extent of burnt areas;
- An indicator of trends in desertification and vegetation variability.

### **3.3.6. ECV Land Cover**

Land cover influences climate by modifying water and energy exchanges with the atmosphere and by changing greenhouse gas and aerosol sources and sinks. Many climatically relevant variables that are difficult to measure at a global scale (e.g. surface roughness) can be inferred in part from vegetation and land-surface types. Thus, land cover can be a surrogate for other important climate variables. Land-cover distributions are linked to the regional climate, so changes in cover can indicate climate change on a regional scale. Current climate models operate on resolutions of 0.5° to 1°, but land-cover information at moderate resolution (250m–1km) is needed to correctly describe the spatial heterogeneity of the land surface within the model cells.

Although land-cover change can be inferred using data from Earth observing satellites, currently available datasets vary in terms of the data sources employed and spatial resolution and thematic content, have different types and patterns of thematic accuracy, and use different land-cover classification systems (although improvements have been made in using common standards). It is necessary, and feasible with present-day technology, to provide satellite-based optical systems at 10-30m resolution with temporal, spectral and data acquisition characteristics that are consistent with previous systems. Commitments to short-term continuity of this class of observations, such as the Landsat Data Continuity Mission and Sentinel-2, are vital steps, although long-term commitments still need to be secured. The CEOS Land Surface Imaging Constellation has been instigated to promote the effective and comprehensive collection, distribution and application of space-acquired imagery of the land surface.

Datasets characterizing global land cover are currently produced at resolutions of between 250m and 1km by several space agencies that closely cooperate with the research community (especially those research

groups participating in the GTOS technical panel, Global Observation of Forest and Land Cover Dynamics (GOFD-GOLD)). The lack of compatibility between these products makes it difficult to measure and monitor climate-induced or anthropogenic changes in land cover. A range of approaches has been adopted, for example centralized processing using a single method of image classification (e.g. MODLAND, GlobCover) and a distributed approach using a network of experts applying regionally specific methods (e.g. GLC2000). Using a single source of satellite imager radiances and a uniform classification algorithm has benefits in terms of consistency but may not yield optimum results for all regions and all land-cover types. Automated land-cover characterization and land-cover change monitoring thus remains a research priority.

It is necessary that land-cover classification systems and the associated map legends adhere to internationally agreed standards.<sup>34</sup> Such standards should eventually be agreed upon by the UN/ISO Terrestrial Framework (see Action T1 in IP-10). In the near term, however, full benefit should be taken of existing initiatives, for example the FAO Land Cover Classification System for legend harmonization and translation and the legends published by the IGBP and the GTOS GOFD-GOLD. The process of harmonization and translation of existing legends will be strengthened with the new FAO Land Cover Meta Language (LCML). The LCML will be an operational tool to formalize the meaning of any existing land-cover classification/legend according to the latest ISO standards.

As a minimum, new land-cover maps should be produced annually documenting the spatial distribution of land-cover characteristics with attributes suitable for climate, carbon and ecosystem models, and using a common language for class definitions (e.g. including wetland information describing forest peat lands (boreal), mangroves, sedge grasslands, rush grasslands, seasonally-flooded forests, and area of land under irrigation) at moderate (250m–1km) resolution. Grid-scale information on the percentage of tree, grass, and bare soil cover should ideally also be made available.

In addition to their use in Earth system models, these global products will help identify areas of rapid change, although the development of automated detection of changes in land-cover characteristics remains high on the research agenda. The production of such land-cover datasets will involve space agencies for processing the satellite data used in the database production, the FAO/science panels to ensure legend relevance and standards, and the research community for optimizing image classification approaches. Mechanisms to fund such partnerships are emerging (e.g. the EU GMES initiative, the proposals from the USGS to the Group on Earth Observations, and the initiative currently underway under the coordination of National Geomatics Center of China); but these are not yet guaranteed on a sustained basis.

Global land-cover databases must also be accompanied by a description of class-by-class thematic/spatial accuracy. The CEOS WGCV, working with GOFD-GOLD and GLCN has published agreed validation protocols which should be used. The current protocols base accuracy assessment on a sample of high-resolution (1-30m) satellite imagery, itself validated by *in situ* observations wherever possible. To better quantify changes in land-cover characteristics, these high-resolution data should also be used for global mapping at resolutions of 10-30m. Maps at this resolution are needed at least every five years, over long time periods (several decades), to quantify land-cover change. Global datasets of satellite imager radiances at 30m resolution have been assembled for selected years (e.g. 1990, 2000, and 2005). Some regional land-cover maps have been generated from these, and China's National Geomatics Center has embarked on a project aiming at creating global land-cover maps from these datasets. The technologies have been developed and tested (e.g. using Landsat, Sentinel-2, and SPOT HRV)), and suitable methods for land-cover characterisation on these scales exist. Space agencies should assure that suitable optical sensors with 10-30m resolution are available for operational monitoring using data acquisition strategies comparable to, and preferably surpassing, those of systems in current operation.

While, at the time of writing, it is not yet clear what methodology would be put in place under the UNFCCC in connection with the proposed implementation of Reducing Emissions from Deforestation and Forest Degradation in developing countries (REDD+),<sup>35</sup> relevant space agencies under CEOS have agreed to

<sup>34</sup> <http://www.fao.org/gtos/ECV-T09.html>

<sup>35</sup> UNFCCC COP decision on REDD, see UNFCCC (2010): *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009*, Addendum, Part two: Decision 4/CP.15 (Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests

supply, on a regular basis, the high-resolution data necessary for the generation of fine-resolution land-cover maps to support such a methodology. Such a commitment would also provide the basis for the observations needed to meet Actions T 27 and T 28 in IP-10.

Systematic global samples of high-resolution satellite imager radiances have also been used to estimate change and are proposed, for example, by the FAO Global Land Cover Network and the FAO Forest Resource Assessment (FRA). Initiatives such as these will provide much needed capacity-building and offer a framework for acquisition of *in situ* observations to support the satellite image-based monitoring. Such *in situ* networks will also provide information on how land is being used (as opposed to what is covering it). Land use cannot always be inferred from land cover.

Two products are therefore required for this ECV:

- Moderate-resolution maps of land-cover type (T.6.1);
- High-resolution maps of land-cover type for the detection, measurement and quantification of land-cover change (T.6.2).

These should be supported by a land-surface temperature product (see 3.3.12).

### Product T.6.1 Moderate-resolution maps of land-cover type

#### Benefits

- Improvement in predictability and accuracy of vegetation and climate models by improved land-surface parameterization;
- Reduction in uncertainty in factors having influence on key climate processes such as deforestation rates and conversion to agriculture;
- Heightened understanding of long-term land-cover change and its link to climate processes.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Maps of land-cover type	250m	N/A	1 year	15% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 250m	15% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 250m

**Rationale:** An exact target for land cover is difficult to set, due to the complex relationship between the number and type of land-cover classes, and physical characteristics that might be consistently linked with these classes, such as roughness, albedo and primary production. The values here are indicative and based on current use of land cover in climate models, and global-climate-change studies. The horizontal resolution is deliberately chosen to roughly correspond to instrument capabilities, recognizing that averaging of land-cover classes and their physical properties to greater scales is generally a non-linear process which is best undertaken with guidance from the end user (e.g. a climate modeller).

#### Currently achievable performance

Published global land cover maps do not meet the target; the reported accuracies range from 67 to 78 per cent (i.e. with the equivalent of 22-33 per cent uncertainty, compared to 15 per cent target); With improvements in image acquisition strategies, classification algorithms and processing power, an accuracy target of 15 per cent is quite achievable.

#### Requirements for satellite instruments and satellite datasets

FCDR of appropriate moderate-resolution multispectral VIS/NIR imager radiances, for example, through:

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and enhancement of forest carbon stocks in developing countries), FCCC/CP/2009/11/Add.1, <http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=11>

- Continuity of moderate-resolution optical data, such as the MODIS/MERIS/SPOT VGT-class;
- Appropriate historical imager radiances, for example through reprocessing of historical Landsat MSS/TM/ETM, SPOT HRV, AVNIR, air photo archives and declassified Argon/Corona imager radiances, in comparison to historical NOAA AVHRR and other coarse-resolution sensors;

Supplemented by:

Radar measurements, for example through SAR.

#### **Calibration, validation and data archiving needs**

- Stringent instrument calibration is essential for land-cover mapping, where globally and regionally tuned approaches are used, and for automated approaches (see for example requirements for FAPAR (T.7));
- For validation purposes, the global land-cover databases must be accompanied by a regional and quantitative robust description of by-class thematic/spatial accuracy; internationally-agreed validation protocols should be used; the current protocols base accuracy assessment on a sample of high-resolution and should include validation of land cover changes;
- 1-30m satellite imager radiances interpreted in terms of land cover and cover change should be validated by *in situ* observations wherever possible;
- Access to the global archives of relevant satellite data and metadata held by relevant space agencies (e.g. daily geo-corrected observations held by NOAA, NASA, ESA, and VITO) and land-cover facilities must be maintained, along with data policies permitting free and open access wherever possible (see also C.7).

#### **Adequacy/inadequacy of current holdings**

- The early IGBP-sponsored DISCover land-cover map from 1992 could be revisited and reworked alongside historical Landsat/SPOT-class data to reconstruct global land cover of around 1990, comparable with estimates provided today;
- The Landsat, SPOT and Argos/Corona archives would need to be systematically accessed and suitable images identified in order to reconstruct early land-cover maps;
- Global land-cover products at 250-500m resolution are currently being generated in the US (MODLAND) and Europe (GLOBCOVER 2005 and 2009), and a pan-global partnership created a 1km-resolution dataset for the year 2000 (GLC2000). The UN Land Cover Classification System (LCCS) for legend harmonization and translation provides a means for developing and comparing legends, although MODLAND products do not currently use LCCS;
- Synergy among existing data sources and integration of continuous land-cover observations from *in situ* to global scales must be ensured.

#### **Immediate action, partnerships and international coordination**

- The GTOS GOFC-GOLD and the UN Global Land Cover Network provides an institutional framework on which an activity to generate historical land cover could be launched, providing space agencies are able to provide appropriate data;
- The GTOS GOFC-GOLD panel working with the CEOS WGCV has established validation protocols, including those of area estimates and land-cover change, and fosters implementation using operational land-cover reference databases;
- The CEOS land constellation should help secure access to other missions, such as from the Disaster Monitoring Constellation and Formosat-2, as well as preparing the way for the Landsat Data Continuity Mission and Sentinel 2;
- ESA and NASA currently support global data acquisitions and pre-processing activities on global land cover and forest carbon tracking; coordinated within GEO, these have the potential to stimulate resources and further country participation in land-cover monitoring initiatives.

#### **Link to GCOS Implementation Plan**

- *[IP-10 Action T26]* Produce reliable accepted methods for land-cover map accuracy assessment;
- *[IP-10 Action T27]* Generate annual products documenting global land-cover characteristics and dynamics at resolutions between 250m and 1km, according to internationally agreed standards and accompanied by statistical descriptions of their accuracy;
- *[IP-10 Action T28]:* Generate maps documenting global land cover, based on continuous 10-30m land surface imagery every five years, according to internationally agreed standards and accompanied by statistical descriptions of their accuracy.

### Other applications

- Land cover and the change of land cover affect the services provided to human society (e.g. provision of food, fibre, shelter, etc.);
- Changes in land availability for agriculture and forestry, as well as for urbanization, are key factors in sustainable development of many regions and a major driver of land use conflicts;
- Land-cover distributions are intrinsically linked to biodiversity, land degradation and ecosystem functioning and services.

### **Product T.6.2 High-resolution maps of land-cover type, for the detection of land-cover change**

#### Benefits

- Provision of a necessary tool for quantifying changes in the area covered by specific land-cover types (see T.5.1);
- Provision of a key level of information – through high-resolution measurements of changes in land-cover type – necessary to integrate *in situ* and global-scale land-cover observations;
- Provision of significant support for national reporting under many chapters of the GHG inventories called for by the UNFCCC (especially those linked to agriculture, grasslands, wetlands and forestry);
- Provision of a neutral basis for verification of carbon trading linked to afforestation, reforestation and eventually, also to avoided-deforestation projects.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
High-resolution map of land-cover change	10-30m	N/A	5 yrs	5% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 10-30m	5% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 10-30m

**Rationale:** An exact target for land-cover change is difficult to set, due to the complex relationship between the number and type of land-cover classes and physical characteristics that might be consistently linked with these classes, such as roughness, albedo and primary production. The values here are based on the main application areas of land-cover-change maps, such as detection of forest and land use (agriculture) change. For global forest areas, the detection of 1 per cent change per decade is relevant to many aspects of the global climate system, including carbon emissions, water resources, and albedo. Global land-cover-change maps at 10-30m resolution should be produced at five-year intervals and synchronized with UNFCCC reporting requirements, although it should be noted that some non-climate applications, such as agricultural yield estimations, would require annual observation at these spatial resolution scales.

#### Currently achievable performance

Global land cover maps at 10-30m resolution currently do not exist, although concrete plans are in place, as exemplified by the efforts of the National Geomatics Center of China and their partners. However, accuracies from regional maps at these scales are rarely better than 10 to 15 per cent error of omission and commission. The 5 per cent error target must remain. Improvements in data acquisition on global scales at 10-30m, with new systems such as the Landsat Data Continuity Mission and Sentinel-2, should make this target realistic.

#### Requirements for satellite instruments and satellite datasets

FCDR of appropriate high-resolution multispectral VIS/NIR imager radiances, for example through continuity of the Landsat ETM-class such as the Landsat Data Continuity Mission and Sentinel-2;



**Supplemented by:**

Radar measurements, for example, through SAR, such as the current ALOS sensor, ENVISAT ASAR, and the planned TerraSAR and ESA Sentinel missions.

**Calibration, validation and data archiving needs**

- Best possible calibration of relevant instruments is a requirement for global mapping of land cover at these resolutions;
- The global land-cover databases must also be accompanied by a description of by-class thematic/spatial accuracy;
- Internationally agreed validation protocols should be used, and a protocol for long-term validation should be elaborated;
- CEOS WGCV, working with the GTOS GOF-C-GOLD, are developing suitable validation guidelines;
- Global datasets of satellite imager radiances at 30m resolution have been assembled and archived for 1990, 2000, 2005, and 2010, and some regional land-cover maps have been generated from these.

**Adequacy/inadequacy of current holdings**

- The current collection of satellite imager radiances is not sufficient to meet the requirements for this Action;
- Scattered regional maps, with varying specification at 30m resolution, exist (e.g. CORINE for Europe, Africover for Eastern Africa, PRODES for the Brazilian Amazonia and EOSD for Canada), but institutional arrangements to ensure operational generation of global land cover maps at these resolutions are not yet in place

**Immediate action, partnerships and international coordination**

Research is needed to develop feasible operational solutions, including the possibility of using moderate-resolution imager radiances as gap fillers and appropriate inter-calibration methods to track the complexity of land dynamics and change; GTOS GOF-C-GOLD and the UN Global Land Cover Network provide an institutional framework on which to launch such an activity, providing that space agencies are able to provide suitable data.

**Link to GCOS Implementation Plan**

- *[IP-10 Action T26]* Produce reliable accepted methods for land-cover map accuracy assessment;
- *[IP-10 Action T27]* Generate annual products documenting global land-cover characteristics and dynamics at resolutions between 250m and 1km, according to internationally agreed standards and accompanied by statistical descriptions of their accuracy;
- *[IP-10 Action T28]:* Generate maps documenting global land cover based on continuous 10-30m land surface imager radiances every five years, according to internationally agreed standards and accompanied by statistical descriptions of their accuracy.

**Other applications**

- Changes in land availability for agriculture, forestry, etc. are key factors in sustainable development of many regions and can be major drivers of societal conflicts;
- Land-cover distributions are also required for studying changes in biodiversity and land degradation;
- Land-cover change, if monitored on high resolutions, such as 10-30m, would support many local-/national-scale land-management and resource-management activities with respect to monitoring of ecosystems, biodiversity, water resources, disasters and public health;
- Non-climate applications such as agricultural yield forecasting and production monitoring (already well-established in parts of the world) would be possible if annual coverage at 10-30m resolution were available.

**3.3.7. ECV FAPAR**

Solar radiation in the spectral range 400 to 700nm, known as Photosynthetically Active Radiation (PAR), provides the energy required by terrestrial vegetation to produce organic materials from mineral components. The part of this PAR that is effectively absorbed by plants is called the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). It is a non-dimensional quantity varying from 0 (over deserts) to 1 (at least for large homogeneous canopy layers observed by medium- to low-resolution

sensors), although such high values are never witnessed in practice because some of the incoming light is always reflected back by the canopy or the underlying ground. FAPAR is related to, but different from, Leaf Area Index (LAI; covered later in the document) because canopy structure affects both ECVs.

FAPAR plays a critical role in assessing the primary productivity of canopies, the associated fixation of atmospheric carbon dioxide, and the energy balance of the surface. As is the case with land surface albedo (see this ECV earlier in this document), FAPAR depends on the illumination conditions, i.e., the angular position of the sun with respect to the vegetation layer and the relative contributions of the direct and diffuse irradiances. Both black-sky (assuming only direct radiation) and white-sky (assuming that all the incoming radiation is in the form of isotropic diffuse radiation) FAPAR values may be considered. Models describing the primary productivity of plants and the energy balance of the land surface require either a characterization of the diurnal evolution of FAPAR or the daily integrated value of FAPAR, depending on the time step used. Other applications may only require cumulative or aggregated values over longer periods.

For the purpose of environmental applications and carbon cycling, estimating the absorption of radiation by leaves is the primary objective, but other plant elements (trunks, branches, etc.) of the canopy also absorb or scatter radiation. The expression 'green FAPAR' is sometimes used to designate the value of FAPAR that is exclusively due to photosynthesizing materials (mostly leaves), i.e. not including scattering and absorption through other processes. FAPAR is difficult to measure directly in the field: *In situ* estimates require the simultaneous measurement of all incoming and outgoing radiation fluxes into and out of the canopy layer, as well as the acquisition of architecture information to account for the absorption by canopy elements other than leaves (in particular for complex three-dimensional canopies such as forests). Specific problems (e.g. poorly designed measurement protocols) and ubiquitous deficiencies (e.g. horizontal fluxes of radiation that are rarely accounted for) frequently plague current experimental setups. They severely limit the feasibility of effectively comparing FAPAR values derived from space-based instruments with those derived from *in situ* measurements:

- While total PAR irradiance is typically monitored as part of the standard observation protocol at ecological and radiation research sites (e.g. FLUXNET, LTER, and SURFRAD), few of these sites generate all the necessary other measurements required to close the radiation budget and derive a reliable estimate of the canopy FAPAR at the scale of the observing space-borne sensor.
- A very detailed sampling strategy (e.g. at spatial intervals much smaller than the typical sampling distance of space-based sensors and consistent with the size of leaves and gaps in the plant canopy) is required in these field campaigns because FAPAR is highly variable in space and time. However, this is rarely implemented.

Information from PAR flux meters or directional PAR meters (e.g. the Ceptometer) inserted at the bottom of the canopy layer can be used to approximate the hemispherically integrated FAPAR (the latter by sampling over several directions in a short time period). Similarly, interception as derived from devices measuring the directional gap fraction (hemispherical photographs, LAI2000) can be used as proxies but with a lower accuracy. Significant improvements could be implemented in field measurements, especially in terms of measuring all relevant radiation fluxes and obtaining more representative spatial sampling statistics to account for the high variability of vegetation. FAPAR is also conditioned by the brightness of both the background and the canopy constituents, such that the accuracy of standard field measurements may decline under snowy conditions.

Global, gridded FAPAR products are routinely generated by Space Agencies and other institutional providers at a typical spatial resolution of 1km. Regional products may be available on finer scales of 250-300m. These remote sensing products are derived by numerically inverting physically-based radiative transfer models against satellite measurements, typically reflectance observations from a wider spectral region than PAR because NIR and SWIR radiances are needed to account for the contribution of the background. By the same token, observations in the blue spectral band, near the edge of the PAR region, are important to help assess the influence of atmospheric aerosols on the measurements.

The obscuring of the surface by clouds introduces spatial discontinuities in the maps of FAPAR derived from single orbital overpasses. To improve the spatial coverage while maintaining the capability of documenting the phenology of vegetation, individual estimates are composited over standard periods, such as a week, ten days or a month.

The following is therefore required for this ECV:

**Product T.7 Maps of the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)**

**Benefits**

- Provision of documentation of the primary productivity of ecosystems and characterization of the phenology of vegetation in space and time;
- Contribution to the estimation of atmospheric carbon dioxide sequestration in terrestrial environments, in combination with vegetation models and other sources of data.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
FAPAR	250m	N/A	2-weekly averages (based on daily sampling)	max(10%; 0.05)	max(3%; 0.02)

**Rationale:** The horizontal resolution (250m) indicated here points to the typical values achievable today and matches land-cover-resolution targets. It is understood that carbon cycling models might be driven by spatially integrated values at a coarser resolution. The frequency of product delivery (no more than two-weekly) is driven by the need to detect changes in primary productivity of ecosystems (e.g. changes in length of growing season) and relies on a minimum observation time resolution of one day, taking into account the presence of clouds and other factors. The accuracy requirements noted in the preceding table are set to resolve significant regional changes and are near the limit of what can be achieved with mono-angular sensors (percentages indicate relative values). The temporal resolution could be significantly improved either by deploying a constellation of polar-orbiting sensors or with instruments on geostationary platforms, but the latter would be useful only if the spatial resolution would match, at least roughly, the indicated requirements (100m to 1km).

**Requirements for satellite instruments and satellite datasets**

FCDR of VIS/NIR multispectral imager radiances, for example from:

- Instruments with a minimum number of three narrow spectral bands (blue, red and near-infrared), although some further improvements might be expected from a few additional bands or from the analysis of data generated by multi-directional sensors;
- Future space-based optical instruments, with spatial resolutions not inferior to current sensors (100m to 1km) and essentially global coverage in one or two days.

All current methods to retrieve FAPAR rely on the availability of co-located simultaneous measurements in multiple spectral bands and from multiple observation angles (when available). Image co-registration must be guaranteed to be no worse than one-third of the instantaneous field of view of a single detector, which translates into stringent requirements for orbital control, including pointing stability and knowledge.

To ensure the continuity of the FAPAR product across multiple sensors and platforms, a minimum overlap of one year (a full seasonal cycle) should be arranged between successive missions to allow for the inter-comparison and inter-calibration of sensors and the eventual adjustment of retrieval algorithms.

**Calibration, validation and data archiving needs**

- Accurate radiometric and spectral calibration mechanisms or procedures to ensure the stability of the measurements are required to guarantee the performance of the FAPAR products, especially in terms of detecting subtle trends and progressive changes that may result from expected climate changes;
- Despite the inherent difficulties of comparing space-based measurements with *in situ* observations, field measurements remain an essential component of the validation process. The availability of higher spatial resolution sensors (1 to 50m) with spectral and directional characteristics similar to the standard global sensors and the establishment of a reference network of experimental sites where FAPAR is measured *in situ*, at scales comparable with the spatial sampling frequency of satellite observations, currently provide the basis for demonstrating the reliability and accuracy of the generated products; further efforts need to be made to develop and promote standard protocols to measure FAPAR in the field, and these must be coordinated with similar requirements arising from the albedo and LAI ECVs;

- Efforts must be undertaken to develop a traceable quality assurance system allowing the provision of unbiased and reliable evaluations of both *in situ* methodologies and EO retrieval algorithms for FAPAR, irrespective of differences in definitions, illumination conditions and spatial resolution.

#### **Adequacy/inadequacy of current holdings**

Space agencies and other institutional providers generate various FAPAR products at different temporal and spatial resolutions over the globe. Over ten years of space-derived FAPAR products are now available from different sources, at spatial resolutions typically in the range of 1 to 2km and temporal resolutions, such as daily, weekly, every ten days or monthly. Comparing these products reveals discrepancies that are mainly due to differences between concepts and definitions, retrieval methodologies or input-data quality. Periodic satellite data re-processing exercises, to take advantage of new findings and especially improvements in instrument calibration, have improved the reliability and consistency of these products. They should be repeated in the future. The following activities would significantly enhance the value and reliability of existing and forthcoming FAPAR products:

- Studies should be carried out to understand and reduce large systematic biases among the magnitudes of existing products, which otherwise exhibit generally consistent seasonal variability;
- Networks of *in situ* experimental sites should be expanded to become representative of a wider range of biomes and consolidated to be more consistent with the spatial scales of satellite observations; this effort should contribute to both an evaluation of field measurements and ultimately a more definitive validation of FAPAR products derived from space measurements;
- FAPAR products at spatial resolutions on the order of 100 to 300m are feasible – though not operationally generated today – from sensors such as MODIS, MISR, MERIS, and the like;
- For some applications, such as diagnostic or prognostic climate models, users may require separate FAPAR values for direct and diffuse incoming radiation, parameterized with respect to the solar zenith angle, although no institution is currently offering such products;
- The documentation associated with FAPAR datasets should include detailed information on the assumptions and models used in the generation of the product and, in particular, on the spectral properties, architectural structure, illumination, and observation angular conditions assumed to facilitate their interpretation in the context of field measurements and user applications.

#### **Immediate action, partnerships and international coordination**

- Space agencies and data providers should continue to generate FAPAR products but with greater emphasis on traceability, clarity of assumptions and documentation;
- Efforts should be directed toward clarifying the explicit or implicit definitions of FAPAR used in the generation of each product, on better defining the specific needs of various users, and on encouraging the convergence toward one or a very limited number of clearly documented products matching these requirements;
- Because of the presence of appreciable interannual variability, small trends in FAPAR can only be detected by analysing long time series; data providers should thus schedule the reprocessing of their archives to generate comparable and consistent products suitable for this purpose, including full documentation and traceability to international standards;
- Further efforts should also be made to reanalyse the historical archives of earlier instruments such as NOAA AVHRR (especially LAC observations, whenever available) and to extend FAPAR records into the past (going back to the mid-eighties), while ensuring compatibility and consistency with current records (see also C.7);
- Building on past and current expertise from existing programmes such as FLUXNET, SURFRAD and LTER, space agencies are encouraged to support a concerted effort to expand and strengthen a reference network of *in situ* field stations to monitor FAPAR (and associated ECVs such as albedo and LAI) that will design and implement observation protocols consistent with the spatial and temporal characteristics of space-based observations; these stations should also acquire ancillary information necessary for the proper interpretation and exploitation of these data for validation purposes;
- The research community can contribute to this effort and improve the FAPAR retrieval methodology by extensively testing the performance of algorithms in computer models of the environment, where all relevant conditions and properties can be controlled explicitly;
- A traceable quality assurance system should be developed, allowing the provision of unbiased and reliable assessments of the compliance of *in situ* and satellite-based FAPAR estimates with the GCOS criteria on accuracy (and precision), ideally taking into account differences in FAPAR definitions, illumination conditions and sensor footprints.

### Link to GCOS Implementation Plan

- [IP-10 Action T31] Operationalize the generation of FAPAR and LAI products as gridded global products at spatial resolution of 2km or better over as lengthy time periods as possible;
- [IP-10 Action T29] Establish a calibration/validation network of *in situ* reference sites for FAPAR and LAI and conduct systematic, comprehensive evaluation campaigns to understand and resolve differences between the products and increase their accuracy;
- [IP-10 T3] Develop a subset of current LTER and FLUXNET sites into a global terrestrial reference network for monitoring sites with a sustained funding perspective and with co-located measurements of meteorological ECVs; seek linkage with Actions T4 and T29, as appropriate.

### Other applications

FAPAR products are useful in a number of applications, ranging from agriculture (e.g. crop-yield forecasting) and forestry to environmental stress and risk assessments (e.g. drought); they have been used to evaluate food-security issues, land degradation (e.g. desertification), and as one of the inputs for land-cover mapping.

### 3.3.8. ECV LAI

The Leaf Area Index (LAI) of a plant canopy or ecosystem, defined as one half the total green leaf area per unit horizontal ground surface area, measures the area of leaf material present in the specified environment. On sloping surfaces, the leaf area should be projected to the underlying ground along the normal to the slope. This dimensionless variable (sometimes expressed in terms of square metres of leaf material per square metre of ground) varies between 0 and values on the order of 10 or so, depending on local conditions. It partly controls important mass and energy exchange processes such as radiation and rain interception, as well as photosynthesis and respiration, which couple vegetation to the climate system. Hence, LAI appears as a key variable in many models describing vegetation-atmosphere interactions, particularly with respect to the carbon and water cycles.

The meaning and measurement of LAI can be subject to interpretations in the case of plant canopies other than crops, grasses and broadleaf forests. Needles are not as easily accounted for and plant organs other than leaves or needles can often contain active pigments and contribute to photosynthesis. Many canopies also exhibit an understory (e.g. grasses, mosses and lichens) that needs to be included in the live foliage area computation. In all environments, LAI is very sensitive to the spatial scale and resolution of the measuring instrument, as well as to the heterogeneity of the plant canopy and the somewhat arbitrary area of reference. The extreme variability of vegetation over a wide range of spatial scales, from clumps of shoots to clusters of plants, and the often unknown spatial distribution of leaves within the volume, further complicate the estimation of this highly scale-dependent variable.

Measuring LAI *in situ* is attempted by a variety of methods. Destructive sampling, where all leaves are individually stripped from the plant and measured, often with the help of statistical relations between weight and area, is very labour- and time-consuming. It can be implemented occasionally on individual plants but is difficult or impossible to deploy over large areas or tall forests and prevents repeated monitoring of the same plants in time. Allometric relations, derived from such individual observations, have been used to estimate the LAI of sets of similar plants. Measurements of light transmittance through the canopy, whether restricted to direct radiation (sun spots) or acquired under largely diffuse irradiance, are subject to somewhat arbitrary thresholds (e.g. with hemispherical photographs). They are, however, non-destructive, cost-effective, applicable to wide areas, and repeatable in time. However, they are sensitive to the presence of plant organs other than leaves (e.g. branches, trunks, etc.), as well as to senescent leaves. The proper interpretation of such measurements requires great attention to the nature of the method, to the particular devices used and their calibration, and to the specific measurement protocol, in particular with regards to spatial sampling.

Space-based observations provide indirect measures of LAI, but are nevertheless essential, as *in situ* measurements provide very limited coverage. LAI is different from, but related to, FAPAR (this ECV is discussed earlier in the document) because it controls the interception of solar radiation in the spectral range relevant for photosynthesis. The retrieval of reliable LAI values from space remains a complex undertaking because it implies sorting out the respective contributions of plant leaves and the underlying ground to the measured radiation flux scattered by the land surface. If the soil reflectance and the canopy

structure (specifically the spatial distribution of leaves in the three-dimensional volume sampled by the satellite sensor) can be assumed (or are known from other sources), then the measurements can be directly interpreted in terms of LAI, provided the influence of woody components has been accounted for. An alternative approach consists in retrieving jointly the background albedo and the effective LAI, i.e. the LAI value that is required by the radiation transfer model to account for the scattered and transmitted fluxes at the spatial resolution of the sensor. Effective LAI (equivalent to a 'Plant Area Index') is retrieved without assuming the structure of the canopy and can be used to estimate the total transmission through the canopy layer, which is directly measurable in the field. The relation between effective LAI and LAI can be explored and determined through simulations that account explicitly for the three-dimensional distribution of leaves within the relevant volume.

When the canopy cover is sparse, reflectance measurements are dominated by soil properties, and when the canopy becomes very dense (i.e. when the underlying soil or background is no longer contributing to the measurements), the sensitivity of retrieval methods based on reflectance measurements diminishes rapidly. Nonetheless, regular global LAI estimates from space are currently being produced, and this effort should be continued (it requires limited additional resources above those required to produce FAPAR). These LAI products have the same requirements in terms of spatial resolution (100m to 1km) and temporal frequency of observation (1 day) as the FAPAR products. Recent research is exploring the feasibility of estimating LAI (and above-ground biomass) from microwave sensors, and these efforts should also be pursued.

Not surprisingly, existing space-derived products exhibit biases between themselves as well as substantial differences when compared to field measurements. Benchmarking between products derived from different satellite instruments and comparing these products with *in situ* measurements are thus essential endeavours to understand and resolve these differences and to ensure their accuracy and reliability. It is recommended that space agencies, in cooperation with CEOS, GCOS, and GTOS, support the establishment or strengthening of reference sites for the specific purpose of validating LAI and similar measurements.

Global gridded LAI products are routinely generated by space agencies at a typical spatial resolution of 1km; regional products may be available for limited areas at a spatial resolution of 250-300m. These estimates are derived from FCDRs that are satellite reflectance measurements in the solar spectral range, by numerically inverting physically-based radiative transfer models. Prior knowledge or assumptions on vegetation structure and leaf and soil properties may improve LAI retrieval for complex heterogeneous canopies.

As is the case for FAPAR and many other surface properties, the frequent obscuring of the land by the presence of clouds necessitates compositing daily measurements into roughly two-weekly maps to provide reasonably complete maps of LAI.

The following is required for this ECV:

<b>Product T.8 Maps of Leaf Area Index</b>
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**Benefits**

- LAI specifies the area of contact between plant leaves (needles, etc.) and the surrounding air and is the locus of mass (water and carbon) and energy (radiation and heat) exchanges between the biosphere and the atmosphere. It is a key variable in the modelling of plant growth and development, in the estimation of productivity, and in the monitoring of phenology in space and time;
- In combination with vegetation growth models and other sources of data, LAI products contribute to the estimation of the rate of sequestration of atmospheric carbon dioxide by the biosphere.

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
LAI	250m	N/A	2-weekly averages	Max(20%; 0.5)	max(10%; 0.25)

**Rationale:** The requirements are driven primarily by the need for LAI maps to better simulate land-atmosphere interactions and to support carbon cycle models. The horizontal resolution (250m) indicated here points to the typical values achievable currently and in the foreseeable future while maintaining frequent and global coverage. It is understood that biogeochemical and climate models are driven by spatially integrated values at a coarser resolution. The time resolution of the desired product (no longer than two-weekly) is driven by the need to detect changes in the state of vegetation (e.g. changes in length of growing season). It usually implies a much more frequent temporal sampling required to account for the presence of clouds and other factors that limit the number of useful observations. The accuracy and stability values assume some prior knowledge of the spatial structure of the canopy as well as of the albedo of the underlying surface.

The accuracy requirements noted in the preceding table are near the limit of what can be achieved with mono-angular sensors. Some further improvements might be achieved from an analysis of a few more spectral bands, although better prospects may be achieved from multi-directional instruments or from new technologies such as satellite-based nadir-pointing lidars. The temporal resolution could be significantly improved either by deploying a constellation of polar-orbiting sensors or with instruments on geostationary platforms, but the latter would be useful only if the spatial resolution would match, at least roughly, the indicated requirements (100m to 1km).

Notable improvements can be expected in field measurements, especially in terms of calibrating the relations between light interception and LAI. The progressive introduction of new technologies, such as the deployment of field and airborne lidars (laser scanners), might lead to more accurate, faster, cheaper and more reliable estimates of LAI, especially in open environments. However, a host of other issues arise with the use of this technology, including dealing with wind during the measurements, occlusion of parts of the plant by other canopy elements, selecting appropriate thresholds to distinguish leaves from branches, and knowing how to effectively scan large areas. In all cases, benchmarking the different direct and indirect methods to estimate this ECV under field conditions should be encouraged, to guide the adoption of standardized instruments and protocols and minimum accuracy requirements.

#### **Requirements for satellite instruments and satellite datasets**

FCDR of VIS/NIR multispectral imager radiances are needed to derive LAI:

- The bare minimum number of narrow spectral bands is two (red and near-infrared), although significant improvements in accuracy can be gained by acquiring observations in the blue spectral region (to help characterize the effect of atmospheric aerosols); further improvements might be expected from a few additional bands and especially from the analysis of data generated by multi-directional sensors;
- Future space-based optical instruments are needed, with spatial resolutions (sampling frequencies in space) not worse than current sensors (100m to 1km) and essentially global coverage in no more than one or two days; all current methods to retrieve LAI rely on the availability of co-located simultaneous measurements in multiple spectral bands; image co-registration must be guaranteed into being no worse than one-third of the instantaneous field of view of a single detector, which translates into stringent requirements for orbital control, including pointing stability and knowledge;
- To ensure the continuity of LAI product across sensors and platforms, a minimum overlap of one year (to encompass the full range of observation conditions globally) should be arranged between successive missions to allow for the inter-comparison and inter-calibration of sensors and the eventual adjustment of retrieval algorithms;
- The introduction of field, airborne and space-borne lidars appears to be very promising and should be fully supported, especially to improve product accuracy and to investigate heterogeneity issues; significant progress is also expected from operating such lidars in conjunction with instruments implementing other current or emerging technologies to measure, for instance, biomass from active microwave sensors or canopy structure from radar tomography or polarimetric interferometry.

#### **Calibration, validation and data archiving needs**

- Accurate radiometric and spectral calibration mechanisms or procedures to ensure the stability of the measurements are required to guarantee the performance of the LAI products, especially in terms of detecting subtle trends and progressive changes that may result from expected climate changes;
- Despite the inherent difficulties in comparing space-based measurements with *in situ* observations, field measurements remain an essential component of the validation process. The availability of higher spatial resolution sensors (1 to 50m), with spectral and directional characteristics similar to the standard global sensors, and the establishment of a reference network of experimental sites where

LAI is measured *in situ* at scales comparable with the spatial sampling frequency of satellite observations, currently provide the basis for demonstrating the reliability and accuracy of the generated products; further efforts need to be made to develop and promote unbiased and reliable protocols to measure LAI in the field, and these must be coordinated with similar requirements arising from the albedo and FAPAR ECVs;

- Each Space Agency or data provider generating LAI datasets at regional, continental or global scales over long periods should produce exhaustive documentation on the algorithm and processing steps involved, including key definitions, assumptions made, and known limitations, together with an assessment of the associated uncertainties.

#### **Adequacy/inadequacy of current holdings**

Space Agencies and other institutional providers generate various LAI products at different temporal and spatial resolutions over the globe. Over ten years of space-derived LAI data are now available from different sources at spatial resolutions typically in the range of 1 to 2km and temporal resolutions such as daily, weekly, every ten days or monthly. Comparing these products reveals discrepancies that are mainly due to differences between concepts and definitions, retrieval methodologies or input data quality. Periodic satellite data re-processing exercises, to take advantage of new findings, especially advances in instrument calibration, have improved the reliability and consistency of these products; they should be repeated in the future and lead to rational methods of establishing the equivalence and conversion factors between these products; the following activities would significantly enhance the value and reliability of existing and forthcoming LAI products:

- Studies should be carried out to understand and reduce large systematic biases between the magnitudes of existing products (biases of >20 per cent, possibly linked to the particular specification of canopy structure and complexity and/or the ability of models to represent it), which otherwise exhibit generally consistent seasonal variability;
- Current *in situ* methodologies should be evaluated in an unbiased and reliable manner across a large number of sites and biomes to assess their conformity with respect to the GCOS criteria for accuracy; results from such quality assurance efforts should form the basis of recommendations for standard protocols;
- Current networks of *in situ* experimental sites are inadequate and should be expanded to become representative of a wider range of biomes and consolidated to be more consistent with the spatial scales of satellite observations; this effort should contribute to a more convincing validation of LAI products derived from space measurements;
- LAI products at spatial resolutions on the order of 100 to 300m are feasible – though not operationally generated today – from sensors such as MODIS, MISR, MERIS, and the like;
- A better dialogue should be established between the providers of LAI products and the modelling community, to ensure that the actual model definitions, assumptions and requirements are clearly expressed and that the products meet those requirements or those of other user applications. This is particularly relevant for the definition of algorithms and products for future platforms such as ESA's Sentinel 3, NOAA's NPOESS, etc.
- The documentation associated with LAI datasets should include detailed information on the assumptions and models used in the generation of the product, and in particular, on the assumed spectral properties and canopy structure or on the illumination and angular conditions, to facilitate their interpretation in the context of field measurements and user applications

#### **Immediate action, partnerships and international coordination**

- Space agencies and data providers should continue to generate LAI products but with greater emphasis on traceability, clarity of assumptions and exhaustive documentation, especially in terms of uncertainty estimates and other indicators of accuracy and reliability that can be easily understood and exploited by users; the same applies to field validation efforts.
- Efforts should be directed toward clarifying the explicit or implicit definitions of LAI used in the generation of each product, better defining the specific needs of various users and encouraging the convergence towards one or a very limited number of clearly documented products matching these requirements; a better understanding of the differences between these products and developing methods to convert one into another would go a long way toward addressing user needs;
- Because of the presence of appreciable interannual variability, small trends in LAI can only be detected by analysing long time series; data providers should thus schedule the reprocessing of their archives to generate comparable and consistent products suitable for this purpose, including full documentation and traceability to international standards;



- Further efforts should also be made to reprocess and re-analyse the historical archives of earlier instruments, such as NOAA AVHRR (especially LAC observations, whenever available), to extend, if possible, LAI records into the past (going back to the mid-eighties), while ensuring compatibility and consistency with current records (see also C.4);
- Calibration and validation activities should build on past and current expertise from existing programmes such as FLUXNET, SURFRAD and LTER, in particular, through exploitation of infrastructural opportunities to benefit the scientific community as a whole; space agencies are encouraged to support, through CEOS WGCV, a concerted effort to expand and strengthen a reference network of *in situ* field stations to monitor LAI (and associated ECVs such as albedo and FAPAR) that will design and implement observation protocols consistent with the spatial and temporal characteristics of space-based observations; these stations should also acquire ancillary information necessary for the proper interpretation and exploitation of these data for validation purposes;
- The research community can contribute to this effort and improve the LAI retrieval methodology by extensively testing the performance of algorithms in computer models of the environment, where all relevant conditions and properties can be controlled explicitly.

#### Link to GCOS Implementation Plan

- [IP-10 Action T29] Establish a calibration/validation network of *in situ* reference sites for FAPAR and LAI and conduct systematic, comprehensive evaluation campaigns to understand and resolve differences between the products and increase their accuracy;
- [IP-10 Action T30] Evaluate the various LAI satellite products and benchmark them against *in situ* measurements to arrive at an agreed operational product;
- [IP-10 Action T31] Operationalize the generation of FAPAR and LAI products as gridded global products at spatial resolution of 2km or better over as lengthy time periods as possible;
- [IP-10 Action T3] Develop a subset of current LTER and FLUXNET sites into a global terrestrial reference network for monitoring sites, with sustained funding perspective and co-located measurements of meteorological ECVs. .

#### Other applications

- Forestry and agricultural crop yield forecasting;
- Estimates of land degradation and desertification;
- Monitoring of phenology and the seasonal evolution of productivity;
- Hydrology and hydrogeology monitoring and assessment.

#### 3.3.9. ECV Above-Ground Biomass

Biomass is defined as total mass of living plant material per unit area, but this ECV adopts a more limited definition, dealing only with above-ground biomass (AGB) in forests and woodlands. This is a pragmatic restriction, since, although a significant proportion of biomass may be stored below ground, this is difficult to measure, even by *in situ* methods, and it is often estimated from AGB using allometric equations. In addition, little is recorded on non-forest biomass, except through agricultural yield statistics. AGB can be measured at stand level in temperate and boreal forests with an accuracy of 10 to 20 per cent using *in situ* methods, but tropical forests present a greater challenge. Estimates of AGB can vary greatly depending on the allometric equations used to convert the *in situ* measurements (for example, diameter at breast height for trees above a certain size in a given area) to AGB.

AGB is an important fraction of the carbon stored in the terrestrial domain, and its dynamics play two major roles in the climate system:

- Photosynthesis withdraws CO<sub>2</sub> from the atmosphere and stores it as biomass, which then provides a source of soil carbon through plant detritus and mortality, with associated respiration;
- The amount of CO<sub>2</sub>, other trace gases and aerosols emitted by fire depends on the quantity of biomass consumed.

Differences in the assumed value of the average biomass gave rise to differences of 1PgCyr<sup>-1</sup> in the range of estimates of emissions from tropical deforestation. Biomass information is also important in the UNFCCC COP's invitation to Parties, relevant organizations and stakeholders to support ongoing efforts, capacity building, demonstration activities and mobilization of resources relating to reducing global greenhouse gas emissions from deforestation and forest degradation in developing countries, and to

enhance forest maintenance, sustainable forestry management and carbon storage by forest lands (REDD+; Bali Action Plan, UNFCCC Decision 1/CP.13).

Many developed countries have national forest inventories that span decades and contain data from a large number of sampling locations; but many forest biomes, in particular those in developing countries, have little or no inventory data. Nonetheless, inventories form the main basis for the periodic (typically five-year) Global Forest Resource Assessments produced by the FAO, the most recent of which was issued in 2010. The annual national reporting on Land Use, Land Use Change and Forestry required by the UNFCCC also mainly relies on inventories.

The labour-intensive nature of establishing an inventory and its requirements for infrastructure have motivated the search for ways to infer AGB from remote sensing data. Both passive optical sensors (such as Landsat or MODIS) and active sensors (lidar and radar) have been used, but each provides fundamentally different information.

Passive optical sensors respond to upper canopy biochemistry and structure and to the topography of the canopy caused by shadows and gaps. The information they provide on biomass is therefore indirect and typically requires the data to be combined with other environmental and forest data, in some form of inference structure. This approach is used successfully, for example, in Sweden, where there is a lot of supporting data, but it is not readily extended to the global scale.

Lidar signals tend to penetrate the canopy and give information affected by both components of the canopy and the ground. Lidars can measure forest-crown sizes, gaps and tree height and, if operated in waveform mode, can also estimate the vertical distribution of material in the canopy from which biomass can be inferred. The ICESat mission (2003-2009) provided a global dataset of forest heights. This has the potential to be combined with other data to infer biomass.

Radar signals can also penetrate the canopy and tend to scatter from elements of the canopy comparable to their wavelength, so longer wavelengths provide information on the larger elements of the canopy. Hence the range and upper limit of biomass they can measure increases with wavelength, as demonstrated by airborne synthetic aperture radars (SARs) using wavelengths from a few cm to several m (and also by scattering models). From space, however, the longest usable wavelength is ~70cm (P-band) because of international regulations and ionospheric effects.

Various radar techniques have been used to measure biomass from space. L-band backscatter measured by the JAXA Daichi (ALOS) satellite is sensitive to biomass up to a saturation level around 60-80t/ha and so has proved useful in mapping biomass in areas such as African miombo forests. Good correlation is observed between biomass and information derived from long temporal sequences of Envisat C-band (6cm) data in large area studies in boreal and temperate forests. In boreal forests, strong correlations have been found between biomass and coherence for pairs of winter images acquired by the ALOS radar (coherence is a measure of pixel correlation between an image pair). Neither of these last two methods displays saturation as biomass increases.

Improved mapping of global AGB from space is likely to require low-frequency radar, preferably in association with a lidar. The first of these technologies is in the advanced planning stage for a space mission, namely the ESA P-band BIOMASS mission (which includes a polarimetric interferometry capability, allowing forest height to be measured); but the lidar capability has recently been dropped from the NASA DesDynI mission, and its retention carrying an L-band radar is under review. The documentation for both missions includes thorough analysis of the case for measuring biomass as an ECV and the properties of the sensors needed to measure it from space. The proposed NASA Icesat-2 mission will carry a lidar; although optimized for land and sea ice applications, it will provide estimates of forest canopy height.

The following is required for this ECV:

#### **Product T.9 Regional and global above-ground forest biomass**

##### **Benefits**

- Biomass information can help to initialize and test the carbon cycle models that are embedded in the latest generation of climate models;

- Biomass provides an estimate of carbon stocks in terrestrial ecosystems and hence carbon emissions due to fire;
- Biomass change is a direct measurement of carbon sequestration or loss.

### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Gridded above-ground biomass (dry weight of woody matter (t/ha))	500m-1km averages based on 100-200m observations	N/A	Annual biomass maps, with coverage of all major forest areas on globe	<20% error for biomass values > 50t/ha, and 10t/ha for biomass values ≤ 50t/ha	10%

**Rationale:** The requirements are driven by the need to quantify the distribution of above-ground biomass (carbon stocks), to initialize and test the carbon cycle models that are embedded in climate models (see ESA BIOMASS report (2008)), and to provide a basis for estimating carbon in the context of national reporting. Changes in forest biomass over time need to be mapped to estimate carbon fluxes, either through emissions (loss of forest) or uptake (forest growth). Horizontal resolution is linked to the typical size of forest disturbance (~1ha), but coarser scale maps averaging this high-resolution information are adequate for some applications. The accuracy and stability requirement is linked to the current ~20 per cent uncertainty of net ocean carbon uptake.

### Currently achievable performance

Current capabilities vary by region, as indicated above. Several of the methods and datasets have not yet been peer-reviewed, and there is considerable variation between products. Threshold requirements are perhaps best specified through the landuse-change emission flux. Recent estimates indicate that the error in this flux is 80 per cent of its mean value, and this error is directly proportional to the error in biomass. This suggests a threshold requirement of ~40 per cent error relative to the mean biomass.

### Requirements for satellite instruments and satellite datasets

FCDRs of long wavelength radar and lidar are needed, supplemented by high-temporal C-band and moderate to high resolution optical data; the radar instruments require polarimetry and an interferometric capability; the BIOMASS mission, if selected by ESA, will meet these specifications; Lidar is highly desirable and will be carried on the proposed NASA Icesat-2 mission but not optimized for forest canopy measurements.

### Calibration, validation and data archiving needs

- For validation, ground-based biomass and height measurements are needed at a range of boreal, temperate, and tropical sites;
- Systematic global measurements of radar and lidar need to be archived; models for this are provided by the ALOS datasets for all the Earth's forest biomes acquired under the JAXA Kyoto Protocol and Carbon Initiative and ICESat datasets of forest height (e.g. as held at Colorado State University).

### Adequacy/inadequacy of current holdings

- Regional maps have been generated, but most of them have not yet been subject to peer-review;
- There are large differences between different products, particularly over tropical regions.

### Immediate action, partnerships and international coordination

- Fostering the systematic acquisition of observations from multiple sensors needed for biomass mapping;
- Increase in coordination between active research and implementation groups (e.g. the GOFC-GOLD Biomass Working Group) in order to (a) ensure proposed missions important for biomass measurement receive strong scientific backing, and (b) develop the combination of multiple data sources to generate biomass products;
- Increase in the amount, access to, and quality of biomass *in situ* data for validating biomass monitoring from space and development of a strategy for independent assessment of existing and proposed biomass products.

### Link to GCOS Implementation Plan

[IP-10 Action T32] Develop demonstration datasets of above ground biomass across all biomes.

#### Other applications

- Dataset valuable for forest management but only at coarse resolution;
- Consistent input for the FAO Forest Resource Assessment Updates.

### 3.3.10. ECV Fire Disturbance

Fires impact several identified radiative forcing agents. They contribute significantly to the build-up of CO<sub>2</sub> through deforestation fires, tropical peatland fires, and areas that see an increase in the fire return interval. They also emit methane and are a major source of aerosols, carbon monoxide (CO) and NO<sub>x</sub>, impacting local and regional air quality. Hence, estimates of GHG emissions due to fire are essential for realistic modelling of climate and its critical component, the global carbon cycle. Fires caused deliberately for land clearance (agriculture and ranching) or accidentally (lightning or human error) are a major factor in land-cover changes, and hence affect fluxes of energy and water to the atmosphere.

Spatially and temporally resolved trace gas emissions from fires are the main target quantities. These can be inferred using both land-surface and atmospheric measurements, preferably in combination (the latter are dealt with in the atmospheric domain, e.g. in A.8). In addition, fire disturbance data are also needed in the following application domains:

- carbon budget assessments, which need frequent update of fire emissions and an assessment of the underlying uncertainties;
- dynamic vegetation modelling, which simulate vegetation birth, growth and death, and replacement of species under different soil and climate conditions; and
- natural hazards management, which aims to reduce the impact of fires on society and natural resources.

Fires are typically patchy and heterogeneous. Measurements of global burnt area are therefore required at a spatial resolution of 250m (currently the maximum resolving power of an instrument that is mapping global fires is 500m) from optical remote sensing, ideally on a weekly, ten-day, or monthly basis, and, if possible, with day-of-burn information. Detection of actively burning fires and measurement of fire-radiative power (FRP) is often adequately done at lower spatial resolutions (1km), but the sensor must have, ideally, mid-infrared (MIR) and thermal-infrared (TIR) spectral channels with a wide dynamic range to avoid sensor saturation. Active fire detection and FRP measurement from Low Earth Orbit satellites should occur multiple times per day and adequately sample the diurnal fire cycle. Some geostationary satellites are capable of active fire and FRP observation at coarser spatial resolutions ( $\geq 3$ km), at temporal frequencies of between 15 and 30 minutes. Geostationary satellites provide the best sampling of the diurnal fire cycle required for certain applications (e.g. for temporal integration of FRP data to estimate total carbon emissions).

The various space-based products require validation and inter-comparison. Validation of medium and coarse spatial resolution fire products involves field observations and the use of high spatial resolution imager radiances in collaboration with local fire management organizations and the research community. The CEOS WGCV, working with the GOFCC-GOLD, is establishing internationally agreed validation protocols that should be applied to all datasets before their release. A fully stratified sampling scheme (designated CEOS level 3) that adequately represents the nature of fire activity over the globe is needed. The validation protocol for burned area products, based on multi-temporal higher spatial resolution reference image radiances, is mature and has been documented. Active fire validation protocol requires simultaneous high spatial resolution airborne or satellite imager radiances, with the latter not readily available, except for the single-platform Terra MODIS/ASTER configuration. An active fire and FRP validation protocol is still required.

Burnt area, as derived from satellites, is currently considered as the primary variable that requires climate-standard continuity. To estimate emissions of trace gases and aerosols, burnt area can be combined with information on 1) available fuel load, 2) the fraction of the fuel loads that is also actually combusted (combustion completeness), 3) information about burning efficiency which, in combination with 4) emission coefficients, governs the partitioning of biomass burned into the multiple trace gases and

aerosols emitted. Ideally, satellite-derived information on vegetation, such as biomass density and vegetation productivity, is derived in concert with burnt-area measurements to facilitate the conversion of burnt area to emissions using computer models. Measurements of burnt area can also be used as a direct input (driver) to climate and carbon-cycle models, or, when long time series of data are available, to parameterize climate-driven models for burnt area simulation.

The following is required for this ECV:

- Burnt area (T.10)
- Active-fire maps (supplemental to T.10)
- Fire radiative power (FRP) (supplemental to T.10)

**Product T.10 Maps of burnt area, supplemented by active-fire maps and fire-radiative power**

**Benefits**

- Burnt area, combined with other information (available fuel load, combustion completeness, burning efficiency and emission coefficients) provides a means to estimate emissions of trace gases and aerosols from vegetation fires;
- Measurements of burnt area can be used as a direct input (driver) to climate and carbon-cycle models, or, when long-time series of data are available, to parameterize climate-driven models for simulating burnt area (fire is dealt with in many climate and biosphere models using the latter approach rather than directly using burned area observations, for example for simulations of future events).

**Target Requirements**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Burnt area	250m	N/A	Daily detection	15% (error of omission and commission), compared to 30m observations	15% (error of omission and commission), compared to 30m observations

**Rationale:** Product requirements are driven by the need to estimate emissions from burnt area and for dynamic vegetation modelling. The requirements are close to original instrument resolution and, with high resolution in space (250 m) and time (daily), provide a basis for weekly and monthly (gridded) products for the various user communities. Error traceability in the provision of aggregated, gridded products is essential.

**Currently achievable performance**

- The current L3JRC product probably has an omission error of between 20 and 40 per cent, depending on the vegetation type. This is at a 1km spatial resolution and with a temporal mapping accuracy of no more than five days.
- The MODIS burned-area product is likely to be more accurate in certain vegetation types. 75 per cent of burned areas are detected within four days. The evaluation of the stability of burned-area products will require multiannual validation datasets, which are currently unavailable.
- The spatial fragmentation of burned areas, when observed at the 250m target resolution, is such that an amount of omission and commission errors is due solely to the presence of burned/unburned mixture in the pixel. With improvements in image-acquisition strategies, classification algorithms and processing power, an accuracy target of 15 per cent is the maximum accuracy achievable at 250m resolution;
- Target requirements may be met under certain conditions, but not in a systematic or consistent way;
- Products in development have not been assessed against requirement thresholds.

**Requirements for satellite instruments and satellite datasets**

FCDR of moderate-resolution multispectral imager radiances, for example, through:

- Sustained moderate-resolution optical data of the MODIS/MERIS-class;
- Instruments acquiring spectral radiances in the MIR/SWIR channel;

- Reprocessing of the AVHRR archive held by NOAA (and NASA), with correction for known deficiencies in sensor calibration and also for known directional/atmospheric problems (see C.4).

#### **Calibration, validation and data archiving needs**

- Relative calibration of VIS, NIR and SWIR channels to within 2 per cent over the full lifetime of each instrument is needed – either overlapping periods of operation or absolute calibration – to provide continuity from instrument to instrument (orbital overpass time drifts should be minimized);
- The space-based products require validation and inter-comparison; validation of medium and coarse-resolution burned area products involves the interpretation of multi-temporal high-resolution imager radiances, as well as field observations, in collaboration with local fire-management organizations and the research community; high-resolution imager radiances (Landsat ETM-class) are needed for sample sites; protocols for the validation of fire products are under development by CEOS WGCV working with GOF-C-GOLD.

#### **Adequacy/inadequacy of current holdings**

- The historical AVHRR archive offers the potential to extend the burnt-area data record back to 1982; calibration, especially of the SWIR channel, is not good enough in most currently available global processed time series;
- Long time-series are needed to quantify the link between climate and burnt area and to detect climate change effects on burnt area;
- Burnt-area products are held by ESA and NASA;
- Standardization of product format, meta-data, and reporting of uncertainty is needed so that modellers can easily understand the structure of the product.

#### **Immediate action, partnerships and international coordination**

- Maintaining of current global burnt-area products as generated by NASA; ongoing development of 300m burned-area products by ESA;
- Maintenance of distribution channels for data held and distributed by the relevant agencies and by the Global Land Cover Facility (GLCF);
- Application before their release – to all datasets – of internationally agreed validation protocols currently being established by the CEOS WGCV, working with GOF-C-GOLD.

#### **Link to GCOS Implementation Plan**

- *[IP-10 Action T35]* Reanalyse the historical fire-disturbance satellite data (1982 to present);
- *[IP-10 Action T36]* Continue generation of consistent burnt area, active fire, and FRP products from low-orbit satellites, including version intercomparisons, to allow un-biased, long-term record development;
- *[IP-10 Action T37]* Develop and apply validation protocol to fire-disturbance data;
- *[IP-10 Action T38]* Make gridded burnt area, active fire, and FRP products available through links from a single International data portal;
- *[IP-10 Action T39]* Develop set of active fire and FRP products from the global suite of operational geostationary satellites.

### **Supplemental Product to T.10 Active fire maps**

#### **Benefits**

- Detection of active fires provides an indicator of seasonal, regional and interannual variability in fire frequency and shifts in geographic location and timing of fire events;
- Detection of active fires serves as part of the validation process for burnt area;
- In some emissions models, active fire detections have been used as a first-order method of estimating burned area;
- For emission modelling, active fire detections have been used as a first-order method of estimating burned area, either because direct burned-area data of sufficient global extent was unavailable or because burned-area measures do not provide sufficiently rapid-fire identification for near real-time services;
- Sensor sensitivity to the presence of active fires is high, with detections being possible even when the fire fills only a very small fraction of the FOV (e.g. <1 per cent).

## Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
ActiveFire Maps	1km	N/A	6h (all latitudes)	5% error of commission 30% error of omission compared to 30m spatial resolution detections (based on per-fire comparisons)	N/A

**Rationale:** The product requirements are set to link with those set for burnt area so that the reasons for the occurrence of new burnt areas may be more effectively recognized

Terrestrial vegetation burning alters the land surface properties and releases large quantities of aerosols and trace gases, which in turn affect the atmosphere's chemical composition and Earth's climate. Quantifying biomass burning emissions, and therefore characterizing the lower boundary condition in atmospheric transport models, typically involves the use of burned area observations (along with fuel load and combustion completeness measures). There are many benefits of the burned-area based approach, although a key limitation is that it can only be applied in retrospective/reanalysis climate simulations. Active fire detections can supplement burnt-area estimates by describing the biomass burning source term in atmospheric transport models. Two further features of active fire observations are that they are available in near real time (NRT) and are able to characterize the diurnal fire cycle.

### Requirements for satellite instruments and satellite datasets

- A data record of appropriate moderate spatial resolution, multispectral imager radiances is needed, for example through moderate-resolution radiometer data from the ATSR-/MODIS-class instruments. (Ideally, these will be supplemented by a higher spatial resolution sensor for validation and error assessment able to be operated simultaneously with moderate spatial resolution imager radiances (e.g. ASTER/ BIRD (Bi-Spectral Infrared Detection)-type).)

### Calibration, validation and data archiving needs

- Absolute instrument calibration to provide thermal channel brightness temperatures accurate to within 1K is important;
- The ephemeral nature of active fires makes validation a real challenge. Controlled burns coinciding with satellite overpass have been used to check detection algorithms and should be periodically repeated; intercomparison to results from higher spatial-resolution instruments should be carried out;
- Global archives held by ESA and NASA should be maintained.

### Adequacy/inadequacy of current holdings

- ESA has been distributing a product (ATSR World Fire Atlas) since 1995, although only of night-time observations;
- NASA distribute MODIS derived active fire counts (year 2000 onwards, day and night) from MODIS;
- Naval Research Laboratory (NRL) archive three-hourly GOES active fire data beginning in 2000.

### Immediate action, partnerships and international coordination

GTOS and GOFC-GOLD should provide coordination and scientific direction.

### Link to GCOS Implementation Plan

- *[IP-10 Action T36]* Continue generation of consistent burnt area, active fire, and FRP products from low-orbit satellites, including version intercomparisons to allow un-biased, long-term record development;
- *[IP-10 Action T37]* Develop and apply validation protocol to fire disturbance data;
- *[IP-10 Action T38]* Make gridded burnt area, active fire, and FRP products available through links from a single International data portal;
- *[IP-10 Action T39]* Develop set of active fire and FRP products from the global suite of operational geostationary satellites.

### Other applications

- Extreme wildfire events have adverse impacts on economies, livelihoods, human health and safety;

- Wildfire events cause changes to ecosystem boundaries, sometimes permanently, with associated consequences for biodiversity;
- Rapid detection of active fires forms part of the remit for natural-hazards monitoring in the United States and Europe;
- Rapid detection of active fires can feed directly into near-real-time assessments of air quality, via an estimate of direct smoke emission sources;
- The detection of static hot-spots, such as oil/gas flares and volcanoes, provides useful information to other communities.

### Supplemental Product to T.10 Fire radiative power (FRP)

#### Benefits

- FRP represents a measurement of the rate of a fire's radiative energy release and provides a means to derive carbon, CO<sub>2</sub> and other emissions estimates directly from remotely-sensed observations, without relying on difficult-to-acquire ancillary data on fuel load and combustion completeness (necessary when basing these calculations on burned area measures);
- Strong empirical relations exist between FRP and rates of fuel combustion and carbon emissions, allowing CO<sub>2</sub> emission rates (and emission rates of other products such as further GHGs, reactive gases and aerosols) from a fire to be estimated directly from FRP observations, even while the fire is still burning, thus providing a link to near real-time atmospheric chemistry modelling;
- Integrating high temporal resolution FRP observations over the lifetime of a fire provides an estimate of the fire radiative energy (FRE) and thus total biomass consumed and, by means of viaapplication of appropriate emissions factors, the total amount of trace gases and aerosols released;
- Geostationary observations of FRP provide the best temporal resolution and thus, in theory, the best means for calculating FRE and for linking emissions to models of atmospheric transport. However, the coarse spatial resolution of geostationary imagers does limit the detectability of small fires. Geostationary observations in high latitude areas (e.g. the boreal zone) are also limited. For these reasons, FRP data from polar-orbiting platforms is also required.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
FRP (polar-orbiting platform)	1km	N/A	Sub-daily (e.g. 6h at all latitudes)	25% down to FRP of 10 MW	10%
FRP (Geostationary platform)	0.1km	N/A	1h	25% down to FRP of 50 MW	10%

**Rationale:** Product requirements are driven by the need to link with burnt area and active fires to improve estimates of greenhouse gas and aerosol emissions from fires.

Terrestrial vegetation burning alters the land surface properties and releases large quantities of aerosols and trace gases, which in turn affect the atmospheres chemical composition and Earth's climate. Quantifying biomass burning emissions, and therefore characterizing the source term in atmospheric transport models, typically involves the use of burned-area observations (along with fuel load and combustion completeness estimates). There are numerous benefits of the burned area-based approach although a key limitation is that it can only be applied in retrospective/reanalysis climate simulations and require estimates of fuel load and combustion completeness, which are difficult to obtain. In contrast, FRP observations can be used to directly estimate carbon emissions from burning and to describe the biomass burning-source term in atmospheric transport models without the need for such additional datasets. They can also work in near real-time and provide information on emission rates as well as totals.

#### Requirements for satellite instruments and satellite datasets

A data record of appropriate multispectral imager radiances, for example through:

- SEVIRI-class instruments, to be extended to the full set of geostationary meteorological satellites;
- ATSR/MODIS-class instruments, to be extended post-Aqua and Terra through VIIRS and Sentinel-3 SLSTR;



- Future BIRD-class instrument, required for high-spatial resolution acquisitions with reduced spatial coverage, to allow the more frequent but lower spatial-resolution datasets to be adjusted for missing smaller and weaker fires.

#### **Calibration, validation and data archiving needs**

- All sensors must be provided with a MIR spectral band (preferably a narrow band, following the design of the MODIS 3.9 $\mu$ m channel);
- High sensor-saturation point is needed, particularly in the mid-infrared and ideally in the thermal-infrared spectral bands;
- Absolute calibration is important across the entire dynamic range of the sensor;
- Validation is challenging due to the ephemeral nature of active fires; the method for validation is still under development and is currently limited to relatively isolated examples/small scales;
- Coincident and near-coincident multi-spatial resolution observations (such as BIRD-type sensors, MODIS and geostationary) are needed to determine differences between data products from different sensors;
- *In situ* observations should be periodically repeated;
- Near-ground and top-of-atmosphere FRP measures should be compared, to ensure consistency;
- MODIS FRP archive should be extended into the future through follow-on instruments;
- Geostationary satellite operators need to commence archiving of FRP products.

#### **Adequacy/inadequacy of current holdings**

- NASA began distributing MODIS-derived daytime and night-time FRP in late 2001; the continuity of this product is needed into the VIIRS era;
- An operational geostationary FRP product is being generated from SEVIRI observations and archived at the LSA-SAF, based on observations every 15 minutes over Africa, Europe and parts of South America; this activity should be expanded to other geostationary sensors covering the Americas (e.g. GOES) and Australasia (e.g. MTSAT); Relocation of Meteosat-8 or Meteosat-9 to Meteosat-7's current position over the Indian Ocean would improve spatial coverage;
- Isolated BIRD data records exist for ~3 years, and a similar replacement system is required.

#### **Immediate action, partnerships and international coordination**

- Continuation of operational production of geostationary FRP, led by geostationary satellite operators or cooperating agencies such as National Meteorological Services, for example through the development of a near global geostationary FRP product;
- Maintenance by NASA of the FRP production capability from MODIS and follow-on sensors;
- SEVIRI, GOES and MODIS instrument currently existing for FRP production; MTSAT and Sentinel-3 SLSTR follow in the near future;
- Provision of coordination and scientific direction by GTOS and GOF-C-GOLD.

#### **Link to GCOS Implementation Plan**

- *[IP-10 Action T36]* Continue generation of IP-consistent burnt area, active fire, and FRP products from low-orbit satellites, including version intercomparisons, to allow un-biased, long-term record development;
- *[IP-10 Action T37]* Develop and apply validation protocol to fire disturbance data;
- *[IP-10 Action T38]* Make gridded burnt area, active fire, and FRP products available through links from a single International data portal;
- *[IP-10 Action T39]* Develop set of active fire and FRP products from the global suite of operational geostationary satellites.

#### **Other applications**

- Extreme wildfire events have adverse impacts on economies, livelihoods, human health and safety;
- Wildfire events cause changes to ecosystem boundaries, sometimes permanently, with associated consequences for biodiversity;
- Rapid detection of active fires forms part of the natural-hazards monitoring in the United States and Europe;
- FRP observations can feed directly into near-real-time assessments of air quality via estimates of smoke-emission rates.

### 3.3.11. ECV Soil Moisture

Soil moisture is an important variable in land-atmosphere feedbacks at weather and climate time scales because of its major effect on the partitioning of incoming radiation (available energy) into latent and sensible heat and on the allocation of precipitation into runoff, subsurface flow, and infiltration. Soil moisture is intimately involved in the feedback between climate and vegetation, since local climate and vegetation both influence soil moisture through evapotranspiration, while soil moisture and climate determine the type of vegetation in a region. Changes in soil moisture therefore have a serious impact on agricultural productivity, forestry and ecosystem health. Soil moisture estimates can also assist gas flux estimates in permafrost regions.

Information on soil-moisture changes and their statistics will also help reduce process uncertainties and improve climate models. On seasonal timescales, improved initial conditions for soil moisture in models should increase the model-prediction accuracy.

Soil moisture is a very heterogeneous variable and varies on small scales with soil properties and drainage patterns. Satellite measurements integrate over relative large-scale areas, with the presence of vegetation adding complexity to the interpretation. The *in situ* measurements do not relate easily to the large-scale measurements. Calibration and validation activities need to be carefully chosen and well-instrumented sites used.

*In situ* soil moisture activities can build on the International Soil Moisture Network (<http://www.ipf.tuwien.ac.at/insitu/>) currently hosted by the Vienna University of Technology (Austria). Satellite-based soil moisture product from scatterometers (e.g. ERS-1/2, ASCAT) and passive microwave (e.g. SMMR, [JAXA/NASA] Tropical Rainfall Measuring Mission (TRMM), AMSR-E and SMOS) have recently been made available and could potentially contribute to a longer-term record by building on data from these different satellites. Space agencies may need to maintain active long-wavelength microwave observation systems with a high temporal and reasonable spatial resolution, possibly with a polarimetric capability, to measure soil moisture and soil-moisture change.

The various ways of representing soil moisture from both satellite and *in situ* measurements, in combination with climate models, need harmonization and, ultimately, standardization. This could be achieved by an expanded network of reference stations to support the validation of satellite measurements with *in situ* data. With this objective, a Global Terrestrial Network for Soil Moisture (GTN-SM) will be initiated with the aid of GCOS/GTOS TOPC.

The following is required for this ECV:

<b>Product T.11 Global near-surface soil moisture maps (up to 5cm soil depth)</b>
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#### Benefits

- Improved accuracy of general circulation models (GCMs) and soil-vegetation-atmosphere transfer schemes;
- Improved understanding of the feedback between climate and vegetation;
- Assistance in gas flux estimates in permafrost regions.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Volumetric soil moisture	50km	NA	Daily	0.04m <sup>3</sup> /m <sup>3</sup>	0.01m <sup>3</sup> /m <sup>3</sup> /year

**Rationale:** The targets are set as an accuracy of about 10 per cent of saturated content and stability of about 2 per cent of saturated content. These values are judged adequate for regional impact and adaptation studies and verification and development of climate models. It is considered premature to consider global-scale changes.

Stating a general accuracy requirement is difficult for this type of observation, as this depends not only on soil type but also on soil moisture content itself. The stated numbers thus should be viewed with some caution.

### **Requirements for satellite instruments and satellite datasets**

FCDR of passive microwave and scatterometer radiances, initially, for example, through:

- The ESA SMOS radiometer, which is expected to provide surface-soil moisture with 30-50km spatial resolution and one- to three-day temporal resolution;
- ASCAT on Metop (2006- present), which is continuing the data record of the scatterometers on ERS-1 and ERS-2, and should provide a continuous and homogenous data record for at least the remainder of the current decade;
- SMMR/AMSR-E-class instruments;
- SAR data from e.g. JAXA ALOS as an additional potential source of data.

### **Calibration, validation and data archiving needs**

- Highly accurate absolute and relative radiometric calibration will be needed;
- Validation studies over diverse types of land cover with representative soil-moisture measurements is critical to the development of retrievals;
- Due to scaling issues and different layer depths, the comparison of *in situ* measurements from individual sites with satellite retrievals is not straightforward; nevertheless, significant advances in the understanding of soil-moisture-scaling issues have been made in the last few years, and there now exist different strategies to deal with scaling (multiple *in situ* instruments, models and advanced techniques such as data assimilation and triple co-location).

### **Adequacy/inadequacy of current holdings**

- There are now many microwave satellites that can provide useful soil-moisture information; however, the higher-level processing and reprocessing capabilities are far from adequate; therefore, much of the capability of the existing space segment remains underexploited;
- There is a long record of passive microwave remote sensing, starting with low-frequency observations from NASA's Nimbus-7 SMMR in the 1970s, TRMM TMI since 1997, and AMSR-E, Windsat, and SMOS in the last decade. By using all these different satellite datasets, and including the scatterometer data (ERS and ASCAT), one could build a long-term soil moisture record;
- ERS scatterometer data have been used for global soil-moisture estimation at a scale of 50km and are now being continued with ASCAT on Metop; data from the latter are available from the Vienna University of Technology and EUMETSAT;
- The passive microwave instruments AMSR-E and Windsat provide C-band and X-band measurements of brightness temperature; several soil moisture datasets derived from these instruments have been released in the last few years; C-band capability is limited, due to radio-frequency interference in many populated regions of the world (e.g. the USA, Europe, Japan);
- AMSR-E-derived soil-moisture results are currently available from NASA for the Aqua time period (2002-2011);
- Over Europe, Asia and some other regions of the world, Radio Frequency Interference (RFI) is strong for the ESA SMOS mission, which results in partly unusable data.

### **Immediate action, partnerships and international coordination**

- International cooperation is needed to improve understanding of the relative performance of different satellite instruments (frequency, active *versus* passive, sampling and radiometric accuracy) and retrieval approaches (empirical approaches, change detection, semi-empirical models and theoretical models);
- Even though the first soil moisture time series based on merging active and passive soil moisture datasets exist, research to blend surface soil moisture observations with satellite observations remains a key challenge.

The SAR C-band radar system on ENVISAT and Sentinel-1 could possibly contribute to the derivation of a global soil-moisture map, although accurate retrieval of soil moisture from these measurements is still a research topic; a fully polarimetric SAR system may be needed to separate the effects of soil moisture and vegetation.

### **Link to GCOS Implementation Plan**

- [IP-10 Action T13] Develop a record of validated globally-gridded near-surface soil moisture from satellites;
- [IP-10 Action T14] Develop Global Terrestrial Network for Soil Moisture (GTN-SM).

### Other applications

- NWP and nowcasting;
- Hydrological modelling, groundwater management, agricultural management and hazard forecasting, including flood and drought prediction;
- Epidemiology, through prediction of water-borne diseases.

### 3.3.12. Land-surface Temperature

Land-surface temperature (LST) is determined by the land-surface energy balance and varies rapidly because of the low thermal inertia of the land surface. The radiative land-surface (skin) temperature can be inferred from space, much like sea-surface (skin) temperature SST, by measuring the thermal emission usually – but not exclusively – at infrared wavelengths. The (radiative) SST can be retrieved more precisely because the angular emissivity is better characterized than is the case for more complicated land surfaces. It is also possible to make a link between the radiative SST and *in situ* bulk water temperature measurements. This consideration also applies to lake surface temperatures.

There is more uncertainty in interpreting the land surface radiative skin temperature than SST, due to more variable angular emissivity and the sometimes complex structures of land surfaces; the radiative skin temperature may relate to the uppermost vegetation canopy or be a mixture of canopy and ground surface temperatures. However, all of these surfaces have low heat capacity so their temperatures respond rapidly to variations in incoming solar radiation due to cloud cover variations (synoptic and diurnal), aerosol variations, and the diurnal variation of insolation. Although thermal infrared emissivities are generally near unity (except for arid soils and rock surfaces), the variations of structure can produce significant spatial variations; because the solar heating varies even more with albedo variations, the temperature itself may vary. Although some work has been done seeking to interpolate *in situ* air-temperature measurement to the scales measured by satellites, there remain uncertainties in relating radiative LST to in-canopy air temperatures and/or soil temperatures. Determinations of LST from thermal infrared are also aliased because most clouds (about 75 per cent) block the satellite view of the surface. However, experimental retrievals of LST from microwave are being investigated, which may help mitigate this problem, especially during the past decade or so when microwave instruments are flown in more orbits with different diurnal phases.

For these reasons, land-surface temperature is not considered an ECV, even its value in determining surface energy and water fluxes and interpretation of surface characteristics – some of which are ECVs – is high. In particular, the nature of the diurnal temperature variations has a relation to vegetation and moisture characteristics of the land surface.

The following is required for this ECV:

<b>Product T.12 Land-surface temperature records to support generation of land ECVs</b>
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#### Benefits

- Relevance to detailed observations of TOA longwave upwelling radiance (see 3.1.3);
- Synergistic with making observations of SST (see 3.2.2);
- Relevance to spatial and temporal characterization of freeze-thaw cycles;
- Land-surface temperature as a driver of vegetation phenology;
- Response of the land surface to radiative and boundary layer forcing, modulated by hydrological conditions;
- Early and sensitive indicator of drought conditions.

#### Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Land-surface temperature	1km	N/A	1h	1K	N/A

**Rationale:** The targets have been set to resolve clear-sky diurnal temperature ranges to ~10 per cent accuracy, but achieving these goals with uniform coverage of the diurnal variation under all weather conditions should be the focus of studies combining infrared and microwave satellite measurements.

**Currently achievable performance**

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Land-surface temperature	5km	N/A	1h	2-3K	1-2K

**Requirements for satellite instruments and satellite datasets**

- A data record of appropriate high-resolution IR radiances from geostationary and polar-orbiting satellites for clear-sky results;
- A data record for microwave radiances from multiple polar-orbiting satellites.

**Calibration, validation and data archiving needs**

Older AVHRR data are being reprocessed to guarantee consistency with MODIS and (A)ATSR-derived LST.

**Adequacy/inadequacy of current holdings**

- Spatial resolution (1-2km) of most current and planned spaceborne sensors is more than satisfactory for climate and weather applications and adequate for other environmental monitoring applications;
- Temporal resolution remains an issue, as surface temperature changes significantly over periods ranging from hours to years and beyond; geostationary satellites provide very adequate temporal resolution under clear conditions; obtaining the full diurnal cycle, which changes amplitude in cloudy conditions, requires combined infrared-microwave analysis;
- Global datasets based on AVHRR and the geostationary weather satellite radiometric data have been available since 1983;
- Global LST maps with an accuracy of 1°K and emissivity maps with an accuracy of 0.005°K will be available from MODIS and ASTER, and AATSR data is available for many surface types.

**Immediate action, partnerships, and international coordination**

Sensor intercomparisons and product validation should be coordinated and executed by existing international mechanisms such as the CEOS WGCV and the CGMS.

**Link to GCOS Implementation Plan**

[IP-10 Action T 23] Implement operational mapping of seasonal soil freeze/thaw through an international initiative for monitoring seasonally-frozen ground in non-permafrost regions.

**Other applications**

- May help in analysis of near-surface air temperature;
- Useful as an environmental indicator;
- Detection of low-intensity fires;
- An indicator of water availability.

*(Intentionally blank)*

## **3.4. CROSS-ECV ISSUES**

### **3.4.1. FLUXES**

Turbulent surface fluxes determine the exchange of momentum, heat, freshwater and gases through the interface between two media (air/sea and air/land interaction). Radiative surface fluxes combine with heat and moisture turbulent surface fluxes to determine the flux of energy through these boundaries. Evaporation and precipitation can be combined to determine a freshwater flux. These exchange processes are critical to a broad range of climate-related processes spanning length scales from metres to thousands of kilometres and time scales from minutes to decades. On all scales, horizontal transport is usually small compared to surface fluxes, but horizontal transport does become important for very long-term processes. The estimation of turbulent surface fluxes from satellites is challenging and a subject for ongoing research.

Ocean-surface fluxes are defined as the rate per unit area at which something (e.g. momentum, energy, moisture or CO<sub>2</sub>) is transferred across the air/sea interface. Typical turbulent flux parameterizations are strongly dependent on surface wind speed (vector wind for momentum transfer), with additional dependence on air/surface temperature differences and sea state. However, there are emerging techniques for retrieving oceanic momentum flux directly from microwave radiance and backscatter data, which would avoid complications associated with sea state and reduce errors associated with air/sea temperature and pressure differences. In terms of flux measurements based on surface variables, progress may also be possible through new techniques for retrieving near-surface atmospheric temperature and humidity.

For land-surface fluxes, the above dependencies on air/surface differences in temperature and humidity apply. However, physics is more complicated in several ways. Soil characteristics can limit the availability of surface moisture. Vegetation also acts to limit the availability of moisture and alter the transfer of heat. At this time, deriving land-surface fluxes from satellite data requires ancillary data and is highly model dependent.

Progress in reducing surface-flux uncertainty and bias may also benefit from satellite missions and integrated observation strategies that seek to improve co-located measurements of the involved variables.

### **3.4.2. RE-ANALYSIS**

Reanalysis by means of data assimilation combines a wide range of data measured over extended periods of time, exploiting the relationships between a number of variables, to provide comprehensive records of many of the ECVs over years and decades, including estimates of air/sea and air/land fluxes. For any instant of time, reanalysis utilizes observations from the immediate past and future to determine the current state. It makes use of as many datasets as possible, usually a combination of FCDRs and products. The quality of the outputs of reanalysis is strongly influenced by the quality of the datasets that are assimilated. For climate analyses, this means that a significant number of the datasets need to be consistent over long periods of time, ideally over decades, to ensure homogeneous reanalysis products. These datasets should include FCDRs, provided in good accord with the GCOS Climate Monitoring Principles and Guidelines, and products derived with the best available approach applied consistently over the whole data record.

Reanalysis utilizes dynamical relations between variables. In the atmosphere and ocean, these are based on the equations of fluid dynamics and engage many variables. Reanalysis for the atmosphere uses weather-forecast models and data sources that are largely adequate to describe the scales of interest. Ocean reanalysis is less well established as, although the oceans have very large-scale mean motions, they are much more variable than the atmosphere in smaller eddy motions that are in general only properly observed (without aliasing) at the ocean surface and not within the ocean. Moreover, the period of adequate observation of the sub-surface ocean is less than that of the upper air. In the terrestrial domain, physical and biogeochemical relations between variables are much less well established and usually relate to the surface only. Reanalysis at this time is well established in the atmospheric domain, is emerging in the ocean domain, and is a matter of mainly research in the terrestrial domain, apart from the few surface variables that are derived as part of atmospheric reanalysis.

Atmospheric reanalysis can use satellite sounding data back to at least 1973 and data for the latest decade from many tens of individual satellite instruments relating to most atmospheric ECVs. The assimilating models include representations of the ocean and land surfaces, and generate sea-state, soil-moisture, and snow-cover products, utilizing observational data related to these variables. They also use sea-surface temperature and land-surface products as prescribed boundary fields. Ocean-data assimilation and reanalysis activities, which utilize *inter alia* altimetry and satellite measurements of ocean-surface conditions, include some climate-oriented efforts that show promising results and are now moving toward coupled data assimilation. Dedicated terrestrial activities have begun but need further development of modelling infrastructure, historical data and institutional engagement. Atmospheric boundary conditions for land data assimilation systems can come either from atmospheric reanalysis or from alternative observation-based products for the required variables. Coupled reanalysis should provide more consistent fluxes between domains but is still largely a research activity.

IP-10 called for a more balanced and sustained reanalysis activity. The international reanalysis programme should give priority to: (a) extending current atmospheric reanalysis activities to meet requirements for monitoring climate variability and trends; (b) consolidating and extending ocean data assimilation research activities by building on the outcome of Global Ocean Data Assimilation Experiment (GODAE) and ongoing and developing WCRP efforts to establish ocean reanalyses for the recent satellite era and for longer, paralleling atmospheric reanalysis periods; (c) establishing and further developing products relating to the composition and forcing of the climate system, (d) developing the high-resolution land reanalyses required to account for the heterogeneity of the land surface, and (e) coupled climate reanalyses.

The following is required for these ECVs:

**Reanalyses, supplying fields of ECVs for all domains, from complementary single-domain systems and increasingly from coupled systems, supported by many of the satellite-based FCDRs and products identified in this report.**

#### **Benefits**

- Widespread availability of sets of integrated products for many ECVs that provide the most comprehensive view of climate variability and change across all domains;
- Availability of products for inter-domain fluxes;
- Dynamically-constrained syntheses of ocean temperature, salinity, current and sea-level variability and change, enabling exploration of the relationship of these parameters with ecosystem and biogeochemical variability and change.

#### **Target requirements**

Requirements are stated in other sections for specific FCDRs and products. An accurate specification of the random component of the uncertainty in the observational datasets to be assimilated is vital, as this determines the weight to be given to the data in the assimilation process. Data assimilation systems attempt to identify and correct for bias (or systematic uncertainty) in the data being assimilated. Small bias is especially desirable for variables and regions when there is little or no independent data to anchor the bias correction

#### **Requirements for satellite instruments and satellite datasets**

- The FCDRs and products relevant to reanalysis should be made freely available to reanalysis centres by the data providers;
- Supplementary information to aid data assimilation, such as averaging kernels used in the generation of some satellite products, should also be provided wherever appropriate;
- Reanalysis centres in turn should make time series of the differences between the observational input values and the corresponding reanalysis values readily available to the scientific community and other interested users of the reanalyses;
- Strong links between reanalysis centres and the space agencies and other product developers need to be maintained, to enable the reanalysis centres to provide comprehensive information on known deficiencies in earlier datasets (including, e.g. metadata, processing algorithms, radiative transfer codes), to identify the relevant datasets and to evaluate trial versions of new datasets.



#### **Calibration, validation and data archiving needs**

- Data need to be stored and maintained in standard modern formats, with quality indicators as appropriate;
- Calibration and validation information on the input data will be provided by feedback from using them in reanalysis systems.

#### **Adequacy/inadequacy of current holdings**

- Inadequacies in input data and in NWP-based data-assimilation systems limit the reliability of trends, low frequency variability, and hydrological and other budgets derived from existing reanalysis products; coordination and collaboration are vital to address these issues;
- Many of the comments on adequacy made for the specific products identified in this document apply also to the related FCDRs or derived products needed for input to new reanalyses;
- Past reanalysis efforts have resulted in identification of specific data deficiencies that are relevant not only to future reanalyses but also to the derivation of observation-based products by methods other than reanalysis.

#### **Immediate action, partnerships and international coordination**

- Most immediate opportunities for action are as identified for the specific FCDRs and products given elsewhere in this report;
- Coordination of reanalysis activities and product intercomparisons may be undertaken by WOAP in collaboration with AOPC, OOPC and TOPC and the expert groups identified for each set of FCDRs and products.

#### **Link to GCOS Implementation Plan**

- *[IP-10 Action C11]* Prepare the atmospheric, oceanic, terrestrial and cryosphere datasets and metadata, including historic data records, for climate analyses and reanalyses;
- *[IP-10 Action C12]* Establish a sustained capacity for global climate reanalysis and ensure coordination and collaboration among reanalysis centres;
- *[IP-10 Action O28]* Develop projects designed to assemble the *in situ* and satellite data into a composite reference reanalysis dataset and to sustain projects to assimilate the data into models in ocean reanalysis projects;
- *[IP-10 Action O40]* Undertake pilot projects of reanalysis of ocean data.

#### **Other applications**

- Testing and calibration of medium-range, monthly and seasonal forecasting systems;
- Development of climate-information products, including regional products for which reanalysis may fill gaps in data-sparse areas;
- Assistance in the interpretation of independent analyses for individual ECVs.

### **3.5. EMERGING CAPABILITIES**

#### **Permafrost**

Satellites give indications of changes in lake area/number in permafrost and non-permanent frozen ground regions. Passive MW time series also allow for mapping areas of frozen and thawed soil. Brightness temperature measurements from microwave radiometers are sensitive to surface moisture because of the relatively high dielectric constant over water. Surface roughness and vegetation cover modulate this sensitivity). Twice-daily coverage of SSM/I (and twice every-other-day for SMMR) have been used to detect the near-surface soil freeze-thaw cycle at regional and hemispheric scales (onset dates of thaw in spring and freeze in autumn and length of the growing season). Research toward – and the demonstration of – permafrost monitoring from space is to be encouraged.

#### **Link to GCOS Implementation Plan**

*[IP-10 Action T 17]* Implement operational mapping of seasonal soil freeze/thaw.

## Groundwater

An appreciable amount – nearly 30 per cent – of the world's total freshwater resources (i.e., including snow/ice) is estimated to be stored as groundwater. Today, groundwater is the source of about one-third of global water withdrawals. Groundwater is by far the largest available reservoir of liquid freshwater (approx. 10.5 million km<sup>3</sup>). Groundwater storage, recharge and discharge are important aspects of climate-change impacts and adaptation assessments.

Over the past several years, important progress has been made, facilitated through the International Groundwater Resources Assessment Centre (IGRAC), in global-scale groundwater monitoring with *in situ* well observations as a foundation. More is expected over the next decade through the establishment of a Global Groundwater Monitoring System (GGMS). In particular, the feasibility of satellite observation of groundwater storage variations using the GRACE mission has been demonstrated. The representation of groundwater storage in land-surface models has advanced significantly, and information on groundwater can now be assimilated. Research into monitoring groundwater by space-based gravity measurements is to be encouraged.

## Surface Pressure

Measuring surface pressure from space is currently not possible, but future sensors measuring high-resolution spectra in near-IR solar absorption bands will measure column densities of the greenhouse gases CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O and N<sub>2</sub>O, along with CO. Observations of O<sub>2</sub> and HF in the same spectra will be used to convert column densities to mean mixing ratios. These measurements can be used to infer surface pressure and will be obtained from the planned OCO-2 instrument and potentially from other future sensors primarily designed for monitoring source and sinks of GHGs. The accuracy specification from OCO-2 for surface pressure is 0.3hPa. Research and demonstration of surface pressure measurements from space is to be encouraged.

## 4. ACKNOWLEDGEMENTS

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## IMPLEMENTATION PLAN FOR THE GLOBAL OBSERVING SYSTEM FOR CLIMATE IN SUPPORT OF THE UNFCCC (2010 Update)

### List of Actions and ‘Agents for Implementation’ for which the ‘Agents’ are Space Agencies, CGMS or CEOS

**(Total: 48)**

**Action C8** [IP-04 C10]

**Action:** Ensure continuity and overlap of key satellite sensors; recording and archiving of all satellite metadata; maintaining appropriate data formats for all archived data; providing data service systems that ensure accessibility; undertaking reprocessing of all data relevant to climate for inclusion in integrated climate analyses and reanalyses; undertaking sustained generation of satellite-based ECV products.

**Who:** Space agencies and satellite data reprocessing centres.

**Time-Frame:** Continuing, of high priority.

**Performance Indicator:** Continuity and consistency of data records.

**Annual Cost Implications:** Covered in the domains.

**Action C21**

**Action:** Implement modern distributed data services, drawing on the experiences of the WIS as it develops, with emphasis on building capacity in developing countries and countries with economies in transition -- both to enable these countries to benefit from the large volumes of data available world-wide and to enable them to more readily provide their data to the rest of the world.

**Who:** Parties' national services and space agencies for implementation in general, and Parties through their support of multinational and bilateral technical cooperation programmes, and the GCOS Cooperation Mechanism.

**Time-Frame:** Continuing, with particular focus on the 2011-2014 time period.

**Performance Indicator:** Volumes of data transmitted and received by countries and agencies.

**Annual Cost Implications:** 30-100M US\$ (90% in non-Annex-I Parties).

**Action A8**

**Action:** Ensure continuity of satellite precipitation products.

**Who:** Space agencies.

**Time-Frame:** Continuous.

**Performance Indicator:** Long-term homogeneous satellite-based global precipitation products.

**Annual Cost Implications:** 10-30M US\$ (for generation of climate products, assuming missions are funded for other operational purposes) (Mainly by Annex-I Parties).

**Action A11**<sup>36</sup> [IP-04 A11]

**Action:** Ensure continuous generation of wind-related products from AM and PM satellite scatterometers or equivalent observations.

**Who:** Space agencies.

**Time-Frame:** Continuous.

**Performance Indicator:** Long-term satellite observations of surface winds every six hours.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action A19**

**Action:** Implement and evaluate a satellite climate calibration mission, e.g. CLARREO.

**Who:** Space agencies (e.g., NOAA, NASA, etc).

**Time-Frame:** Ongoing.

**Performance Indicator:** Improved quality of satellite radiance data for climate monitoring.

**Annual Cost Implications:** 100-300M US\$ (Mainly by Annex-I Parties).

**Action A20** [A19 IP-04]

**Action:** Ensure the continued derivation of MSU-like radiance data and establish FCDRs from the high-resolution IR sounders, following the GCMPs.

**Who:** Space agencies.

**Time-Frame:** Continuing.

**Performance Indicator:** Quality and quantity of data; availability of data and products.

**Annual Cost Implications:** 1-10M US\$ (for generation of datasets, assuming missions -- including overlap and launch-on-failure policies -- are funded for other operational purposes) (Mainly by Annex-I Parties).

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<sup>36</sup> See also Action O19.

**Action A21** [A20 IP-04]

**Action:** Ensure the continuity of the constellation of GNSS RO satellites.

**Who:** Space agencies.

**Time-Frame:** Ongoing; replacement for current COSMIC constellation needs to be approved urgently to avoid or minimize a data gap.

**Performance Indicator:** Volume of data available and percentage of data exchanged.

**Annual Cost Implications:** 10-30M US\$ (Mainly by Annex-I Parties).

**Action A23** [IP-04 A22]

**Action:** Continue the climate data record of visible and infrared radiances, for example from the International Satellite Cloud Climatology Project, and include additional data streams as they become available; pursue reprocessing as a continuous activity, taking into account lessons learnt from preceding research.

**Who:** Space agencies, for processing.

**Time-Frame:** Continuous.

**Performance Indicator:** Long-term availability of global homogeneous data at high frequency.

**Annual Cost Implications:** 10-30M US\$ (for generation of datasets and products) (Mainly by Annex-I Parties).

**Action A24** [IP-04 A23]

**Action:** Research to improve observations of the three-dimensional spatial and temporal distribution of cloud properties.

**Who:** Parties' national research and space agencies, in cooperation with the WCRP.

**Time-Frame:** Continuous.

**Performance Indicator:** New cloud products.

**Annual Cost Implications:** 30-100M US\$ (Mainly by Annex-I Parties).

**Action A25** [IP-04 A24]

**Action:** Ensure continuation of Earth Radiation Budget observations, with at least one dedicated satellite mission operating at any one time.

**Who:** Space agencies.

**Time-Frame:** Ongoing.

**Performance Indicator:** Long-term data availability at archives.

**Annual Cost Implications:** 30-100M US\$ (Mainly by Annex-I Parties).

**Action A26**

**Action:** Establish long-term limb-scanning satellite measurement of profiles of water vapour, ozone and other important species from the UT/LS up to 50km.

**Who:** Space agencies, in conjunction with WMO GAW.

**Time-Frame:** Ongoing, with urgency in initial planning to minimize data gap.

**Performance Indicator:** Continuity of UT/LS and upper stratospheric data records.

**Annual Cost Implications:** 100-300M US\$ (including mission costs) (Mainly by Annex-I Parties).

**Action A27**

**Action:** Establish a network of ground stations (MAXDOAS, lidar, FTIR) capable of validating satellite remote sensing of the troposphere.

**Who:** Space agencies, working with existing networks and environmental protection agencies.

**Time-Frame:** Urgent.

**Performance Indicator:** Availability of comprehensive validation reports and near real-time monitoring based on the data from the network.

**Annual Cost Implications:** 10-30M US\$ (30% in non-Annex-I Parties).

**Action A28** [IP-04 A27]

**Action:** Maintain and enhance the WMO GAW Global Atmospheric CO<sub>2</sub> and CH<sub>4</sub> Monitoring Networks as major contributions to the GCOS Comprehensive Networks for CO<sub>2</sub> and CH<sub>4</sub>.

**Who:** Parties' national services, research agencies, and space agencies, under the guidance of WMO GAW and its Scientific Advisory Group for Greenhouse Gases, in cooperation with AOPC.

**Time-Frame:** Ongoing.

**Performance Indicator:** Dataflow to archive and analyses centres.

**Annual Cost Implications:** 10-30M US\$ (50% in non-Annex-I Parties).

#### **Action A29**

**Action:** Assess the value of the data provided by current space-based measurements of CO<sub>2</sub> and CH<sub>4</sub>, and develop and implement proposals for follow-on missions accordingly.

**Who:** Parties' research institutions and space agencies.

**Time-Frame:** Urgent, to minimize data gap following GOSAT.

**Performance Indicator:** Assessment and proposal documents; approval of consequent missions.

**Annual Cost Implications:** 1-10M US\$ initially, increasing with implementation (10% in non-Annex-I Parties).

#### **Action A32**

**Action:** Continue production of satellite ozone data records (column, tropospheric ozone and ozone profiles) suitable for studies of interannual variability and trend analysis. Reconcile residual differences between ozone datasets produced by different satellite systems.

**Who:** Space agencies.

**Time-Frame:** Ongoing.

**Performance Indicator:** Statistics on availability and quality of data.

**Annual Cost Implications:** 10-30M US\$ (Mainly by Annex-I Parties).

#### **Action A33 [IP-04 A31]**

**Action:** Develop and implement a coordinated strategy to monitor and analyse the distribution of aerosols and aerosol properties. The strategy should address the definition of a GCOS baseline network or networks for *in situ* measurements, assess the needs and capabilities for operational and research satellite missions for the next two decades, and propose arrangements for coordinated mission planning.

**Who:** Parties' national services, research agencies and space agencies, with guidance from AOPC and in cooperation with WMO GAW and AERONET.

**Time-Frame:** Ongoing, with definition of baseline *in situ* components and satellite strategy, by 2011.

**Performance Indicator:** Designation of GCOS baseline network(s). Strategy document, followed by implementation of strategy.

**Annual Cost Implications:** 10-30M US\$ (20% in non-Annex-I Parties).

#### **Action A34**

**Action:** Ensure continuity of products, based on space-based measurement of the precursors (NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO, in particular) of ozone and aerosols and derive consistent emission databases, seeking to improve temporal and spatial resolution.

**Who:** Space agencies, in collaboration with national environmental agencies and meteorological services.

**Time-Frame:** Requirement must be taken into account now in mission planning, to avoid a gap in the 2020 timeframe.

**Performance Indicator:** Availability of the necessary measurements, appropriate plans for future missions, and derived emission data bases.

**Annual Cost Implications:** 10-30M US\$ (10% in non-Annex-I Parties).

#### **Action O4 [IP-04 O7]**

**Action:** Ensure coordination of contributions to CEOS Virtual Constellations for each ocean-surface ECV, in relation to *in situ* ocean observing systems.

**Who:** Space agencies, in consultation with CEOS Virtual Constellation teams, JCOMM and GCOS.

**Time-Frame:** Continuous.

**Performance Indicators:** Annually updated charts on adequacy of commitments to space-based ocean observing system from CEOS.

**Annual Cost Implications:** <1M US\$ (Mainly by Annex-I Parties and implementation cost covered in Actions below).

#### **Action O7 [IP-04 O9]**

**Action:** Continue the provision of best possible SST fields, based on a continuous coverage-mix of polar-orbiting IR and geostationary IR measurements, combined with passive microwave coverage and appropriate linkage with the comprehensive *in situ* networks noted in O8.

**Who:** Space agencies, coordinated through CEOS, CGMS and WMO Space Programme.

**Time-Frame:** Continuing.

**Performance Indicator:** Agreement of plans for maintaining a CEOS Virtual Constellation for SST.

**Annual Cost Implications:** 1-10M US\$ (for generation of datasets) (Mainly by Annex-I Parties).

#### **Action O10 [IP-04 O12]**

**Action:** Ensure continuous coverage from one higher-precision, medium-inclination altimeter and two medium-precision, higher-inclination altimeters.

**Who:** Space agencies, with coordination through the CEOS Constellation for Ocean Surface Topography, CGMS and the WMO Space Programme.

**Time-Frame:** Continuous.

**Performance Indicator:** Satellites operating; provision of data to analysis centres.

**Annual Cost Implications:** 30-100M US\$ (Mainly by Annex-I Parties).

**Action O12 [IP-04 O16]**

**Action:** Research programmes to investigate the feasibility of utilizing satellite data to help resolve global fields of SSS.  
**Who:** Space agencies, in collaboration with the ocean research community.  
**Time-Frame:** Feasibility studies to completed by 2014.  
**Performance Indicator:** Reports in literature and to OOPC.  
**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action O15 [IP-04 O18]**

**Action:** Implement continuity of ocean-colour-radiance datasets through the plan for an Ocean Colour Radiometry Virtual Constellation.  
**Who:** CEOS space agencies, in consultation with IOCCG and GEO.  
**Time-Frame:** Implement plan as accepted by CEOS agencies in 2009.  
**Performance Indicator:** Global coverage with consistent sensors operating according to the GCMPs; flow of data into agreed archives.  
**Annual Cost Implications:** 30-100M US\$ (10% in non-Annex-I Parties).

**Action O19 [IP-04 O23]**

**Action:** Ensure sustained satellite-based (microwave, SAR, visible and IR) sea-ice products.  
**Who:** Parties' national services, research programmes and space agencies, coordinated through the WMO Space Programme and Global Cryosphere Watch, CGMS and CEOS; national services for *in situ* systems, coordinated through WCRP CliC and JCOMM.  
**Time-Frame:** Continuing.  
**Performance Indicator:** Sea-ice data in international data centres.  
**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action O20 [IP-04 O21]**

**Action:** Document the status of global sea-ice analysis and reanalysis product uncertainty (via a quantitative summary comparison of sea-ice products) and prepare a plan to improve the products.  
**Who:** Parties' national agencies, supported by WCRP CliC and JCOMM Expert Team on Sea Ice (ETSI).  
**Time-Frame:** By end of 2011.  
**Performance Indicators:** Peer-reviewed articles on state of sea-ice analysis uncertainty; publication of internationally-agreed strategy to reduce uncertainty.  
**Annual Cost Implications:** <1M US\$ (Mainly Annex-I Parties).

**Action O28 [IP-04 O29]**

**Action:** Develop projects designed to assemble the *in situ* and satellite data into a composite reference reanalysis dataset and to sustain projects to assimilate the data into models in ocean-reanalysis projects.  
**Who:** Parties' national ocean research programmes and space, supported by WCRP.  
**Time-Frame:** Continuous.  
**Performance Indicator:** Project for data assembly launched; availability and scientific use of ocean reanalysis products.  
**Annual Cost Implications:** 1-10M US\$ (10% in non-Annex-I Parties).

**Action O41 [IP-04 O3]**

**Action:** Promote and facilitate research and development (new improved technologies, in particular), in support of the global ocean observing system for climate.  
**Who:** Parties' national ocean research programmes and space agencies, in cooperation with GOOS, GCOS and WCRP.  
**Time-Frame:** Continuing.  
**Performance Indicator:** More cost-effective and efficient methods and networks; strong research efforts related to the observing system; number of additional ECVs feasible for sustained observation; improved utility of ocean climate products.  
**Annual Cost Implications:** 30-100M US\$ (10% in non-Annex-I Parties).

**Action T5**

**Action:** Develop an experimental evaporation product from existing networks and satellite observations.  
**Who:** Parties, national services, research groups through GTN-H, IGWCO, TOPC, GEWEX Land Flux Panel and WCRP CliC.  
**Time frame:** 2013-2015.  
**Performance indicator:** Availability of a validated global satellite product of total evaporation.  
**Annual Cost Implications:** 1-10M US\$ (10% in non-Annex-I Parties).

**Action T8 [IP-04 T6]**

**Action:** Submit weekly/monthly lake level/area data to the International Data Centre; submit weekly/monthly altimeter-derived lake levels by space agencies to HYDROLARE.  
**Who:** National Hydrological Services through WMO CHy, and other institutions and agencies providing and holding data; space agencies; HYDROLARE.  
**Time-Frame:** 90% coverage of available data from GTN-L by 2012.  
**Performance Indicator:** Completeness of database.  
**Annual Cost Implications:** 1-10M US\$ (40% in non-Annex-I Parties).



**Action T10 [IP-04 T8]**

**Action:** Submit weekly surface and sub-surface water temperature, date of freeze-up and date of break-up of lakes in GTN-L to HYDROLARE.

**Who:** National Hydrological Services and other institutions and agencies holding and providing data; space agencies.

**Time-frame:** Continuous.

**Performance Indicator:** Completeness of database.

**Annual Cost Implications:** <1M US\$ (40% in non-Annex-I Parties).

**Action T13**

**Action:** Develop a record of validated globally-gridded near-surface soil moisture from satellites.

**Who:** Parties' national services and research programmes, through GEWEX and TOPC in collaboration with space agencies.

**Time frame:** 2014.

**Performance indicator** Availability of globally validated soil moisture products from the early satellites until now.

**Annual Cost Implications:** 1-10M US\$ (10% in non-Annex-I Parties).

**Action T14**

**Action:** Develop Global Terrestrial Network for Soil Moisture (GTN-SM).

**Who:** Parties' national services and research programmes, through IGWCO, GEWEX and TOPC in collaboration with space agencies.

**Time frame:** 2014.

**Performance indicator:** Fully functional GTN-SM with a set of *in situ* observations (possibly co-located with reference network, cf. T3), with standard measurement protocol and data quality and archiving procedures.

**Annual Cost Implications:** 1-10M US\$ (40% in non-Annex-I Parties).

**Action T16 [IP-04 T11]**

**Action:** Obtain integrated analyses of snow cover over both hemispheres.

**Who:** Space agencies and research agencies in cooperation with WMO GCW and CliC, with advice from TOPC, AOPC and IACS

**Time-Frame:** Continuous.

**Performance Indicator:** Availability of snow-cover products for both hemispheres.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action T20 [IP-04 T14]**

**Action:** Ensure continuity of laser, altimetry, and gravity satellite missions adequate to monitor ice masses over decadal timeframes.

**Who:** Space agencies, in cooperation with WCRP CliC and TOPC.

**Time-Frame:** New sensors to be launched: 10-30 years.

**Performance Indicator:** Appropriate follow-on missions agreed.

**Annual Cost Implications:** 30-100M US\$ (Mainly by Annex-I Parties).

**Action T23 [IP-04 T17]**

**Action:** Implement operational mapping of seasonal soil freeze/thaw through an international initiative for monitoring seasonally-frozen ground in non-permafrost regions.

**Who:** Parties, space agencies, national services and NSIDC, with guidance from International Permafrost Association, the IGOS Cryosphere Theme team and WMO GCW.

**Time-Frame:** Complete by 2013.

**Performance Indicator:** Number and quality of mapping products published.

**Annual Cost Implications:** 1-10M US\$ (10% in non-Annex-I Parties).

**Action T24 [IP-04 T19]**

**Action:** Obtain, archive and make available *in situ* calibration/validation measurements and co-located albedo products from all space agencies generating such products; promote benchmarking activities to assess the quality and reliability of albedo products.

**Who:** Space agencies in cooperation with CEOS WGCV.

**Time-Frame:** Full benchmarking/intercomparison by 2012.

**Performance Indicator:** Publication of inter-comparison/validation reports.

**Annual Cost Implications:** 1-10M US\$ (20% in non-Annex-I Parties).

**Action T25 [IP-04 T21]**

**Action:** Implement globally coordinated and linked data processing to retrieve land-surface albedo from a range of sensors on a daily and global basis, using both archived and current Earth Observation systems.

**Who:** Space agencies, through the CGMS and WMO Space Programme.

**Time-Frame:** Reprocess archived data by 2012, then generate continuously.

**Performance Indicator:** Completeness of archive.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action T27 [IP-04 T26]**

**Action:** Generate annual products documenting global land-cover characteristics and dynamics at resolutions between 250m and 1km, according to internationally-agreed standards and accompanied by statistical descriptions of their accuracy.

**Who:** Parties' national services, research institutes and space agencies in collaboration with GLCN and GOF-C-GOLD research partners and the GEO Forest Carbon Tracking task team.

**Time-Frame:** By 2011, then continuously.

**Performance Indicator:** Dataset availability.

**Annual Cost Implications:** 1-10M US\$ (20% in non-Annex-I Parties).

**Action T28 [IP-04 T27]**

**Action:** Generate maps documenting global land cover, based on continuous 10-30 m land surface imager radiances every 5 years, according to internationally-agreed standards and accompanied by statistical descriptions of their accuracy.

**Who:** Space agencies, in cooperation with GCOS, GTOS, GOF-C-GOLD, GLCN and other members of CEOS.

**Time-Frame:** First by 2012, then continuously.

**Performance Indicator:** Availability of operational plans, funding mechanisms and, eventually, maps.

**Annual Cost Implications:** 10-30M US\$ (20% in non-Annex-I Parties).

**Action T29 [IP-04 T29]<sup>37</sup>**

**Action:** Establish a calibration/validation network of *in situ* reference sites for FAPAR and LAI and conduct systematic, comprehensive evaluation campaigns to understand and resolve differences between the products and increase their accuracy.

**Who:** Parties' national and regional research centres, in cooperation with space agencies coordinated by CEOS WGCV, GCOS and GTOS.

**Time-Frame:** Network operational by 2012.

**Performance Indicator:** Data available to analysis centres.

**Annual Cost Implications:** 1-10M US\$ (40% in non-Annex-I Parties).

**Action T30 [IP-04 T30]**

**Action:** Evaluate the various LAI satellite products and benchmark them against *in situ* measurements, to arrive at an agreed operational product.

**Who:** Parties' national and regional research centres, in cooperation with space agencies and CEOS WGCV, GCOS/TOPC and GTOS.

**Time-Frame:** Benchmark by 2012.

**Performance Indicator:** Agreement on operational product.

**Annual Cost Implications:** 1-10M US\$ (10% in non-Annex-I Parties).

**Action T31 [IP-04 T28]**

**Action:** Operationalize the generation of FAPAR and LAI products as gridded global products at spatial resolution of 2km or better, over as long time periods as possible.

**Who:** Space agencies, coordinated through CEOS WGCV, with advice from GCOS and GTOS.

**Time-Frame:** 2012.

**Performance Indicator:** One or more countries or operational data providers accept the charge of generating, maintaining, and distributing global FAPAR products.

**Annual Cost Implications:** 10-30M US\$ (10% in non-Annex-I Parties).

**Action T32**

**Action:** Develop demonstration datasets of above ground biomass across all biomes.

**Who:** Parties, space agencies, national institutes, research organizations, FAO in association with GTOS, TOPC and the GOF-C-GOLD Biomass Working Group.

**Time frame:** 2012.

**Performance Indicator:** Availability of global-gridded estimates of above-ground biomass and associated carbon content.

**Annual Cost Implications:** 1-10M US\$ (20% in non-Annex-I Parties).

**Action T34**

**Action:** Develop globally gridded estimates of terrestrial carbon flux from *in situ* observations and satellite products and assimilation/inversions models.

**Who:** Reanalysis centres and research organisations, in association with national institutes, space agencies and FAO/GTOS (TCO and TOPC).

**Time Frame:** 2014-2019.

**Performance indicator:** Availability of data assimilation systems and global time series of maps of various terrestrial components of carbon exchange (e.g. GPP, NEP and NBP).

**Annual Cost Implications:** 10-30M US\$ (Mainly by Annex-I Parties).

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<sup>37</sup> See Action T3.

**Action T35** [IP-04 T32]

**Action:** Reanalyse the historical fire disturbance satellite data (1982 to present).

**Who:** Space agencies, working with research groups coordinated by GOFC-GOLD.

**Time-Frame:** By 2012.

**Performance Indicator:** Establishment of a consistent dataset, including the globally available 1km AVHRR data record.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action T36** [IP-04 T33]

**Action:** Continue generation of consistent burnt area, active fire, and FRP products from low-orbit satellites, including version intercomparisons to allow un-biased, long-term record development.

**Who:** Space agencies, in collaboration with GOFC-GOLD.

**Time-Frame:** Continuous.

**Performance Indicator:** Availability of data.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action T37** [IP-04 T34]

**Action:** Develop and apply validation protocol to fire disturbance data.

**Who:** Space agencies and research organizations.

**Time-Frame:** By 2012.

**Performance Indicator:** Publication of accuracy statistics.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

**Action T39**

**Action:** Develop set of active fire and FRP products from the global suite of operational geostationary satellites.

**Who:** Through operators of geostationary systems, via CGMS, GSICS, and GOFC-GOLD.

**Time-Frame:** Continuous.

**Performance Indicator:** Availability of products.

**Annual Cost Implications:** 1-10M US\$ (Mainly by Annex-I Parties).

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UNFCCC Conference of the Parties (COP-15)

**Decision 9/CP.15 - Systematic Climate Observations<sup>38</sup>**

*The Conference of the Parties,*

*Recalling* Article 4, paragraph 1(g–h), and Article 5 of the Convention,

*Further recalling* decisions 8/CP.3, 14/CP.4, 5/CP.5, 11/CP.9, 5/CP.10 and 11/CP.13,

*Having considered* the conclusions of the Subsidiary Body for Scientific and Technological Advice at its thirtieth session,

*Noting* the important role of the Global Climate Observing System in meeting the need for climate observation under the Convention,

1. *Expresses its appreciation:*

(a) To the secretariat and sponsoring agencies of the Global Climate Observing System for preparing the report on progress with the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* (hereinafter referred to as the Global Climate Observing System implementation plan);

(b) To the secretariat and sponsoring agencies of the Global Terrestrial Observing System for developing a framework for the preparation of guidance materials, standards and reporting guidelines for terrestrial observing systems for climate;

(c) To the Committee on Earth Observation Satellites for its coordinated response, on behalf of Parties that support space agencies involved in global observations, to the needs expressed in the Global Climate Observing System implementation plan;

2. *Recognizes* the significant progress made during 2004–2008 in improving the observing systems for climate relevant to the Convention;

3. *Notes* that, despite the progress made, only limited advances have been made in achieving long-term continuity for several *in situ* observing systems and that there are still large areas, in Africa for example, for which *in situ* observations and measurements are not available;

4. *Also notes* that not all climate information needs under the Convention are being met;

5. *Urges* Parties to work towards addressing the priorities and gaps identified in the report on progress with the Global Climate Observing System implementation plan, in particular the implementation of the regional action plans that were developed during 2001–2006, and ensuring sustained long-term operation of essential *in situ* networks, especially for the oceanic and terrestrial domains, including through provision of the necessary resources;

6. *Invites* relevant United Nations agencies and international organizations to do the same;

7. *Encourages* Parties in a position to do so to support activities aimed at sustaining climate observations over the long term in developing countries, especially the least developed countries and small island developing States;

8. *Invites* the Global Climate Observing System secretariat, under the guidance of the Global Climate Observing System Steering Committee, to update, by the thirty-third session of the Subsidiary Body

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<sup>38</sup> UNFCCC (2010): *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009*, Addendum, Part two: Decision 9/CP.15 (Systematic climate observations), FCCC/CP/2009/11/Add.1, <http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=23>

for Scientific and Technological Advice, the Global Climate Observing System implementation plan, taking into account emerging needs in climate observation, in particular those relating to adaptation activities;

9. *Encourages* the secretariat and the sponsoring agencies of the Global Terrestrial Observing System to implement the framework for the preparation of guidance materials, standards and reporting guidelines for terrestrial observing systems for climate, as a joint terrestrial framework mechanism between relevant agencies of the United Nations and the International Organization for Standardization;

10. *Encourages* the Committee on Earth Observation Satellites to continue coordinating and supporting the implementation of the satellite component of the Global Climate Observing System;

11. *Urges* Parties that support space agencies involved in global observations to enable these agencies to continue to implement, in a coordinated manner through the Committee on Earth Observation Satellites, the actions identified in the updated report of the Committee on Earth Observation Satellites, in order to meet the relevant needs of the Convention, in particular by ensuring long-term continuity of observations and data availability.

## GCOS Climate Monitoring Principles

*Effective monitoring systems for climate should adhere to the following principles<sup>39</sup>:*

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.
6. Operation of historically-uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.
10. Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

*Furthermore, operators of satellite systems for monitoring climate need to:*

- (a) *Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system; and*
- (b) *Take steps to sample the Earth system in such a way that climate-relevant (diurnal, seasonal, and long-term interannual) changes can be resolved.*

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<sup>39</sup> The 10 basic principles (in paraphrased form) were adopted by the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) through decision 5/CP.5 at COP-5 in November 1999. This complete set of principles was adopted by the Congress of the World Meteorological Organization (WMO) through Resolution 9 (Cg-XIV) in May 2003; agreed by the Committee on Earth Observation Satellites (CEOS) at its 17<sup>th</sup> Plenary in November 2003; and adopted by COP through decision 11/CP.9 at COP-9 in December 2003.

*Thus satellite systems for climate monitoring should adhere to the following specific principles:*

11. Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained.
12. A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.
13. Continuity of satellite measurements (i.e. elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured.
14. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured.
15. On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored.
16. Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate.
17. Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.
18. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on de-commissioned satellites.
19. Complementary *in situ* baseline observations for satellite measurements should be maintained through appropriate activities and cooperation.
20. Random errors and time-dependent biases in satellite observations and derived products should be identified.



## GCOS Essential Climate Variables

Essential Climate Variables that are both currently feasible for global implementation and have a high impact on UNFCCC requirements

Domain	Essential Climate Variables
<b>Atmospheric</b> (over land, sea and ice)	<p><b>Surface:</b><sup>40</sup> Air temperature; wind speed and direction; water vapour; pressure; precipitation; surface radiation budget.</p> <p><b>Upper-air:</b><sup>41</sup> Temperature; wind speed and direction; water vapour; cloud properties; Earth radiation budget (including solar irradiance).</p> <p><b>Composition:</b> Carbon dioxide; methane and other long-lived greenhouse gases,<sup>42</sup> ozone and aerosol, supported by their precursors.<sup>43</sup></p>
<b>Oceanic</b>	<p><b>Surface:</b><sup>44</sup> Sea-surface temperature; sea-surface salinity; sea level; sea state; sea ice; surface current; ocean colour; carbon dioxide partial pressure; ocean acidity; phytoplankton.</p> <p><b>Sub-surface:</b> Temperature; salinity; current; nutrients; carbon dioxide partial pressure; ocean acidity; oxygen; tracers.</p>
<b>Terrestrial</b>	River discharge; water use; groundwater; lakes; snow cover; glaciers and ice caps; ice sheets; permafrost; albedo; land cover (including vegetation type); Ffraction of Absorbed Photosynthetically Active Radiation (FAPAR); Leaf Area Index (LAI); above-ground biomass; soil carbon; fire disturbance; soil moisture.

<sup>40</sup> Including measurements at standardized but globally varying heights in close proximity to the surface.

<sup>41</sup> Up to the stratopause.

<sup>42</sup> Including N<sub>2</sub>O, CFCs, HCFCs, HFCs, SF<sub>6</sub> and PFCs.

<sup>43</sup> In particular NO<sub>2</sub>, SO<sub>2</sub>, HCHO and CO.

<sup>44</sup> Including measurements within the surface mixed layer, usually within the upper 15 m.

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## Glossary of Acronyms

2AR	GCOS SECOND ADEQUACY REPORT (THE SECOND REPORT ON THE ADEQUACY OF THE GLOBAL OBSERVING SYSTEMS FOR CLIMATE IN SUPPORT OF THE UNFCCC (GCOS-82))
AOD	AEROSOL OPTICAL DEPTH
AAOD	ABSORPTION AEROSOL OPTICAL DEPTH
AATSR	ADVANCED ALONG TRACK SCANNING RADIOMETER
ADM-AEOLUS	ATMOSPHERIC DYNAMICS MISSION AEOLUS (ESA)
AERONET	AEROSOL ROBOTIC NETWORK
AGB	ABOVE-GROUND BIOMASS
AIRS	ATMOSPHERIC INFRARED SOUNDER (NASA)
ALOS	ADVANCED LAND OBSERVING SATELLITE (JAXA)
AM	MORNING
AMSR	ADVANCED MICROWAVE SCANNING RADIOMETER (JAXA)
AMSR-E	ADVANCED MICROWAVE SCANNING RADIOMETER (NASA EOS)
AMSU	ADVANCED MICROWAVE SOUNDING UNIT (NOAA)
AMV	ATMOSPHERIC MOTION VECTOR
ARM	ATMOSPHERIC RADIATION MEASUREMENT PROGRAM (US DEPARTMENT OF ENERGY)
AOD	MEASURING AEROSOL OPTICAL DEPTH
AOPC	ATMOSPHERIC OBSERVATION PANEL FOR CLIMATE (GCOS)
ASAR	ADVANCED SYNTHETIC APERTURE RADAR (ESA)
ASCAT	ADVANCED SCATTEROMETER (EUMETSAT)
ASTER	ADVANCED SPACEBORNE THERMAL EMISSION AND REFLECTION RADIOMETER (NASA)
ATOVs	ADVANCED TIROS OPERATIONAL VERTICAL SOUNDER (NOAA)
ATMS	ADVANCED TECHNOLOGY MICROWAVE SOUNDER (NOAA)
ATSR	ALONG TRACK SCANNING RADIOMETER
AVHRR	ADVANCED VERY HIGH RESOLUTION RADIOMETER (NOAA)
BHR	BI-HEMISPHERICAL REFLECTANCE FACTOR
BHR-iso	BI-HEMISPHERICAL REFLECTANCE FACTOR UNDER ISOTROPIC ILLUMINATION
BRDF	BIDIRECTIONAL REFLECTION DISTRIBUTION FUNCTION
BIRD	BI-SPECTRAL INFRARED DETECTION INSTRUMENT
BSRN	BASELINE SURFACE RADIATION NETWORK
BUFR	BINARY UNIVERSAL FORM FOR THE REPRESENTATION OF METEOROLOGICAL DATA
CALIPSO	CLOUD-AEROSOL LIDAR AND INFRARED PATHFINDER SATELLITE OBSERVATIONS
CASIX	CENTRE FOR OBSERVATION OF AIR-SEA INTERACTIONS AND FLUXES
CA	CLOUD AMOUNT (OR COVER)
CBS	COMMISSION FOR BASIC SYSTEMS (WMO)
CDR	CLIMATE DATA RECORD
CEOS	COMMITTEE ON EARTH OBSERVATION SATELLITES
CIMO	COMMISSION FOR INSTRUMENTS AND METHODS OF OBSERVATION (WMO)
CF	CLIMATE FORECAST
CFC	CHLOROFLUOROCARBON
CGMS	COORDINATION GROUP FOR METEOROLOGICAL SATELLITES
CHAMP	CHALLENGING MINISATELLITE PAYLOAD (GERMANY)
Chy	COMMISSION FOR HYDROLOGY (WMO)
CLARREO	CLIMATE ABSOLUTE RADIANCE AND REFRACTIVITY OBSERVATORY (NASA)
CLiC	CLIMATE AND CRYOSPHERE PROJECT (WCRP)
CLIVAR	CLIMATE VARIABILITY AND PREDICTABILITY PROJECT (WCRP)

CMAP	CLIMATE MODELING, ANALYSIS AND PREDICTION PROGRAM (US NSF)
CMIS	CONICAL SCANNING MICROWAVE IMAGER/SOUNDER (NOAA)
CNES	CENTRE NATIONAL D'ETUDES SPACIALES (FRANCH SPACE AGENCY)
CONAE	COMISION NACIONAL DE ACTIVIDADES ESPACIALES (ARGENTINA)
COP	CONFERENCE OF THE PARTIES (TO UNFCCC)
COD	CLOUD OPTICAL DEPTH
COSMIC	CONSTELLATION OBSERVING SYSTEM FOR METEOROLOGY, IONOSPHERE AND CLIMATE
CRE	CLOUD EFFECTIVE RADIUS (LIQUID AND ICE)
CrIS	CROSS-TRACK INFRARED SOUNDER (NOAA)
CryoSat	CRYOSPHERE SATELLITE (ESA)
CTP	CLOUD TOP PRESSURE
CTT	CLOUD TOP TEMPERATURE
CWC	CLOUD WATER CONTENT
CWP	CLOUD WATER PATH (LIQUID AND ICE)
DAAC	DISTRIBUTED ACTIVE ARCHIVE CENTER (NASA)
DEM	DIGITAL ELEVATION MODEL
DHR	DIRECTIONAL HEMISPHERICAL REFLECTANCE FACTOR
DMSP	DEFENSE METEOROLOGICAL SATELLITE PROGRAM (USA)
ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECAST
ECV	GCOS ESSENTIAL CLIMATE VARIABLE [DELETE: (AS DEFINED BY GCOS SECOND ADEQUACY REPORT (GCOS-82)]
ENSO	EL NINO SOUTHERN OSCILLATION
ENVISAT	ENVIRONMENTAL SATELLITE (ESA)
EOS	EARTH OBSERVING SYSTEM (NASA)
EPS	EUMETSAT POLAR SYSTEM
ERA	ECMWF RE-ANALYSIS PROJECT
ERB	EARTH RADIATION BUDGET
ERS	EUROPEAN REMOTE SENSING SATELLITE (ESA)
ESA	EUROPEAN SPACE AGENCY
ETSI	EXPERT TEAM ON SEA ICE (JCOMM)
ETM+	ENHANCED THEMATIC MAPPER PLUS (USGS LANDSAT)
EUMETSAT	EUROPEAN ORGANISATION FOR THE EXPLOITATION OF METEOROLOGICAL SATELLITES
FAO	FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
FAPAR	FRACTION OF ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION
FCDR	FUNDAMENTAL CLIMATE DATA RECORD
FIR	FAR INFRARED
FoG	FLUCTUATION OF GLACIERS
FRA	FOREST RESOURCE ASSESSMENT (FAO)
FRE	FIRE RADIATIVE ENERGY
FRP	FIRE RADIATIVE POWER
FY	FENGYUN SATELLITE (CNSA)
GAW	GLOBAL ATMOSPHERE WATCH (WMO)
GCM	GENERAL CIRCULATION MODEL
GCW	(WMO)
GCMP	GCOS CLIMATE MONITORING PRINCIPLE
GCOM	GLOBAL CHANGE OBSERVATION MISSION (JAXA)
GCOS	GLOBAL CLIMATE OBSERVING SYSTEM
GEO	GROUP ON EARTH OBSERVATIONS
GEOSAT	GEODETTIC SATELLITE (US NAVY)
GEOS	GLOBAL EARTH OBSERVATION SYSTEM OF SYSTEMS
GEWEX	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (WCRP)
GFO	GEOSAT FOLLOW-ON
GGMS	GLOBAL GROUNDWATER MONITORING SYSTEM
GHG	GREENHOUSE GAS
GLAS	GEOSCIENCE LASER ALTIMETER SYSTEM (NASA)
GLCF	GLOBAL LAND COVER FACILITY
GLIMS	GLOBAL LAND ICE MEASUREMENTS FROM SPACE

GMES	GLOBAL MONITORING FOR ENVIRONMENT AND SECURITY
GMS	GEOSTATIONARY METEOROLOGICAL SATELLITE (JMA)
GNSS	GLOBAL NAVIGATION SATELLITE SYSTEM
GODAE	GLOBAL OCEAN DATA ASSIMILATION EXPERIMENT
GOCE	GRAVITY FIELD AND STEADY-STATE OCEAN CIRCULATION EXPLORER (ESA)
GOES	GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE (NOAA)
GOCF-GOLD	GLOBAL OBSERVATION OF FOREST AND LAND COVER DYNAMICS (GTOS)
GOME	GLOBAL OZONE MONITORING EXPERIMENT
GOMOS	GLOBAL OZONE MONITORING BY OCCULTATION OF STARS INSTRUMENT (ENVISAT)
GOOS	GLOBAL OCEAN OBSERVING SYSTEM
GOS	GLOBAL OBSERVING SYSTEM (WMO)
GOSAT	GREENHOUSE GASES OBSERVING SATELLITE (JAXA)
GPC	GLACIER PHOTOGRAPH COLLECTION (NSIDC)
GPCP	GLOBAL PRECIPITATION CLIMATOLOGY PROJECT
GPM	GLOBAL PRECIPITATION MEASUREMENT
GPS	GLOBAL POSITIONING SYSTEM
GPS/MET	GLOBAL POSITIONING SYSTEM METEOROLOGY
GRACE	GRAVITY RECOVERY AND CLIMATE EXPERIMENT
GRAS	GLOBAL NAVIGATION SATELLITE SYSTEM RECEIVER FOR ATMOSPHERIC SOUNDING
GRUAN	GCOS REFERENCE UPPER-AIR NETWORK
GSICS	GLOBAL SPACE-BASED INTERCALIBRATION SYSTEM
GSN	GCOS SURFACE NETWORK
GSOP	GLOBAL OBSERVATIONS AND SYNTHESIS PANEL (WCRP CLIVAR)
GTN-G	GLOBAL TERRESTRIAL NETWORK FOR GLACIERS
GTN-H	GLOBAL TERRESTRIAL NETWORK FOR HYDROLOGY
GTN-L	GLOBAL TERRESTRIAL NETWORK FOR LAKES
GTN-P	GLOBAL TERRESTRIAL NETWORK FOR PERMAFROST
GTN-SM	GLOBAL TERRESTRIAL NETWORK FOR SOIL MOISTURE
GTOS	GLOBAL TERRESTRIAL OBSERVING SYSTEM
GUAN	GCOS UPPER-AIR NETWORK
GWSP	GLOBAL WATER SYSTEM PROJECT
HALOE	HALOGEN OCCULTATION EXPERIMENT
HCFC	HYDROCHLOROFLUOROCARBONS
HFC	HYDROFLUOROCARBONS
HIRDLS	HIGH RESOLUTION DYNAMICS LIMB SOUNDER
HIRS	HIGH RESOLUTION INFRARED RADIATION SOUNDER (NOAA)
Hydrolare	INTERNATIONAL DATA CENTRE FOR LAKES AND RESERVOIRS
IAGOS	INTEGRATION OF ROUTINE AIRCRAFT MEASUREMENTS INTO A GLOBAL OBSERVING SYSTEM
IASI	INFRARED ATMOSPHERIC SOUNDING INTERFEROMETER (EUMETSAT)
IBAP	ARCTIC BUOYS
ICESat	ICE, CLOUD AND LAND ELEVATION SATELLITE (NASA)
ICSU	INTERNATIONAL COUNCIL FOR SCIENCE
IFOV	INSTANTANEOUS FIELD OF VIEW
IGAC	INTERNATIONAL GLOBAL ATMOSPHERIC CHEMISTRY PROGRAM (IGBP)
IGACO	INTEGRATED GLOBAL ATMOSPHERIC CHEMISTRY OBSERVATIONS
IGBP	INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAMME
IGOS	INTEGRATED GLOBAL OBSERVING STRATEGY
IGOS-P	INTEGRATED GLOBAL OBSERVING STRATEGY PARTNERSHIP
IGRAC CENTRE	THE INTERNATIONAL GROUNDWATER RESOURCES ASSESSMENT
INDREX	INDONESIAN RADAR EXPERIMENT
InSAR	INTERFEROMETRIC SYNTHETIC APERTURE RADAR
IOC	INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (UNESCO)
IOCCG	INTERNATIONAL OCEAN COLOUR COORDINATING GROUP
IOCCP	INTERNATIONAL OCEAN CARBON COORDINATION PROJECT

IOVWST	INTERNATIONAL OCEAN VECTOR WINDS SCIENCE TEAM
IPAB	INTERNATIONAL PROGRAMME FOR ANTARCTIC BUOYS
IPAP	ICE PILOT APPLICATIONS PROJECT
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
IP-04	IMPLEMENTATION PLAN FOR THE GLOBAL OBSERVING SYSTEM FOR CLIMATE IN SUPPORT OF THE UNFCCC - OCTOBER, 2004 (GCOS-92)
IP-10	IMPLEMENTATION PLAN FOR THE GLOBAL OBSERVING SYSTEM FOR CLIMATE IN SUPPORT OF THE UNFCCC (2010 UPDATE), AUGUST 2010 (GCOS-138)
IPWG	INTERNATIONAL PRECIPITATION WORKING GROUP (CGMS)
IR	INFRARED SPECTRAL RANGE
IROWG	INTERNATIONAL RADIO OCCULTATION GROUP (CGMS)
ISCCP	INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (WCRP)
ITASE	INTERNATIONAL TRANS-ANTARCTIC SCIENTIFIC EXPEDITION
ITWG	INTERNATIONAL TOVS WORKING GROUP
IWWG	INTERNATIONAL WINDS WORKING GROUP (CGMS)
JAXA	JAPAN AEROSPACE EXPLORATION AGENCY
JERS	JAPAN EARTH RESOURCES SATELLITE (JAXA)
JRA	JAPANESE RE-ANALYSIS PROJECT
JRC	JOINT RESEARCH CENTRE (EUROPEAN COMMISSION)
LAI	LEAF AREA INDEX
LCCS	UN LAND COVER CLASSIFICATION SYSTEM
LCML	LAND COVER META LANGUAGE (FAO)
LS	LOWER STRATOSPHERE
LST	LAND SURFACE TEMPERATURE
LTDR	LAND LONG TERM DATA RECORDS
LW	LONGWAVE SPECTRAL RANGE
LWIR	LONG-WAVELENGTH INFRARED
MERIS	MEDIUM RESOLUTION IMAGING SPECTROMETER (ESA)
METOP	METEOROLOGICAL OPERATIONAL POLAR SATELLITE
MHS	MICROWAVE HUMIDITY SOUNDER (EUMETSAT)
MIPAS	MICHELSON INTERFEROMETER FOR PASSIVE ATMOSPHERIC SOUNDING
MISR	MULTIANGLE IMAGING SPECTRORADIOMETER
MLS	MICROWAVE LIMB SOUNDER (NASA)
MODIS	MODERATE RESOLUTION IMAGING SPECTRORADIOMETER (NASA)
MOZAIC	MEASUREMENT OF OZONE ON AIRBUS IN-SERVICE AIRCRAFT
MSG	METEOSAT SECOND GENERATION
MSS	MULTISPECTRAL SCANNER (LANDSAT)
MSU	MICROWAVE SOUNDING UNIT (NOAA)
MTSAT	MULTI-FUNCTIONAL TRANSPORT SATELLITE (JMA)
MW	MICROWAVE SPECTRAL RANGE
MWIR	MID-WAVELENGTH INFRARED
NASA	NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (USA)
NCDC	NATIONAL CLIMATIC DATA CENTER (NOAA)
NDACC	NETWORK FOR THE DETECTION OF ATMOSPHERIC COMPOSITION CHANGE (FORMERLY: NDSC – NETWORK FOR THE DETECTION OF STRATOSPHERIC CHANGE)
NESDIS	NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE (NOAA)
NIR	NEAR INFRARED SPECTRAL RANGE
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (USA)
NOP	NUMERICAL OCEAN PREDICTION
JPSS	JOINT POLARSATELLITE SYSTEM
NPP	NPOESS PREPARATORY PROJECT
NSIDC	NATIONAL SNOW AND ICE DATA CENTER (USA)
NWP	NUMERICAL WEATHER PREDICTION
NWS	NATIONAL WEATHER SERVICE (USA)
OCO	ORBITING CARBON OBSERVATIONS
OCR	OCEAN-COLOUR RADIOMETRY

OH	NEED REFERENCE HERE!
OMI	OZONE MONITORING INSTRUMENT
OOPC	OCEAN OBSERVATIONS PANEL FOR CLIMATE
OSVW	OCEAN SURFACE VECTOR WINDS
PAR	PHOTOSYNTHETICALLY ACTIVE RADIATION
PARASOL	POLARIZATION AND ANISOTROPY OF REFLECTANCES FOR ATMOSPHERIC SCIENCES COUPLED WITH OBSERVATIONS FROM A LIDAR (CNES)
PARCA	PROGRAM FOR ARCTIC REGIONAL CLIMATE ASSESSMENT
PCW	POLAR COMMUNICATIONS AND WEATHER SATELLITE (CANADA)
PFC	PERFLUOROCARBONS
PM	AFTERNOON
POLDER	POLARIZATION AND DIRECTIONALITY OF THE EARTH'S REFLECTANCES (CNES)
QUIKSCAT	QUICK SCATTEROMETER (NASA)
REDD+	REDUCING EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION IN DEVELOPING COUNTRIES
RFI	RADIO FREQUENCY INTERFERENCE
RO	RADIO OCCULTATION
SAC	ARGENTINE SATELITE DE APLICACIONES CIENTIFICAS (ARGENTINA)
SAGE	STRATOSPHERIC AEROSOL AND GAS EXPERIMENT
SAR	SYNTHETIC APERTURE RADAR
SBSTA	SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE (UNFCCC/COP)
SBUV	SOLAR BACKSCATTER ULTRAVIOLET RADIOMETER
SCAR	SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH
SCIAMACHY	SCANNING IMAGING ABSORPTION SPECTROMETER FOR ATMOSPHERIC CARTOGRAPHY
SCOPE-CM	SUSTAINED COORDINATED PROCESSING OF ENVIRONMENTAL SATELLITE DATA FOR CLIMATE MONITORING
SEAWIFS	SEA-VIEWING WIDE FIELD-OF-VIEW SENSOR (NASA)
SEVIRI	SPINNING ENHANCED VISIBLE AND INFRARED IMAGER (EUMETSAT)
SHADOZ	SOUTHERN HEMISPHERE ADDITIONAL OZONESONDES
SI	SEA ICE
SIRAL	SAR INTERFEROMETRIC RADAR ALTIMETER
SMMR	SCANNING MULTICHANNEL MICROWAVE RADIOMETER
SMOS	SOIL MOISTURE AND OCEAN SALINITY (ESA)
SOOP	SHIP OF OPPORTUNITY PROGRAMME
SPARC	STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE CHANGE (WCRP)
SPOT (VGT, HRV)	SATELLITE POUR L'OBSERVATION DE LA TERRE (VEGETATION, HIGH RESOLUTION)
SRTM	SHUTTLE RADAR TOPOGRAPHY MISSION
SSA	SINGLE SCATTERING ALBEDO
SSM/I	SPECIAL SENSOR MICROWAVE/IMAGER
SSMIS	SPECIAL SENSOR MICROWAVE IMAGER/SOUNDER
SSM/T	SPECIAL SENSOR MICROWAVE /TEMPERATURE
SSM/T2	SPECIAL SENSOR MICROWAVE TEMPERATURE/HUMIDITY SOUNDER
SSS	SEA-SURFACE SALINITY
SST	SEA-SURFACE TEMPERATURE
SSU	STRATOSPHERIC SOUNDING UNIT
SW	SHORTWAVE SPECTRAL RANGE
SWE	SNOW WATER EQUIVALENT
SWH	SIGNIFICANT WAVE HEIGHT
SWIR	SHORTWAVE INFRARED SPECTRAL RANGE
SWOT	SURFACE WATER AND OCEAN TOPOGRAPHY SATELLITE MISSION (NASA)
TCCON	TOTAL COLUMN CO <sub>2</sub> AND CH <sub>4</sub> INSTRUMENTS
TCDR	THEMATIC CLIMATE DATA RECORD
TES	TROPOSPHERIC EMISSION SPECTROMETER

TIR	THERMAL INFRARED SPECTRAL RANGE
TIROS	TELEVISION INFRARED OBSERVATION SATELLITE (NOAA)
TM	THEMATIC MAPPER (USGS LANDSAT)
TMI	TRMM MICROWAVE IMAGER
TOA	TOP OF ATMOSPHERE
TOMS	TOTAL OZONE MAPPING SPECTROMETER (NASA)
TOPC	TERRESTRIAL OBSERVATION PANEL FOR CLIMATE
TOPEX/POSEIDON	OCEAN SURFACE TOPOGRAPHY ALTIMETER EXPERIMENT (NASA/CNES)
TOVS	TIROS OPERATIONAL VERTICAL SOUNDER
TRMM	TROPICAL RAINFALL MEASURING MISSION (JAXA/NASA)
TROPOMI	TROPOSPHERIC OZONE MONITORING INSTRUMENT (ESA/GMES SENTINEL 5)
TSI	TOTAL SOLAR IRRADIANCE
ULS	UPWARD LOOKING SONAR
UNEP	UNITED NATIONS ENVIRONMENT PROGRAMME
UNESCO	UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
UNFCCC	UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE
USGS	US GEOLOGICAL SURVEY
UT	UPPER TROPOSPHERE
UV	ULTRAVIOLET SPECTRAL RANGE
VIIRS	VISIBLE/INFRARED IMAGER RADIOMETER SUITE (JPSS)
VIS	VISIBLE SPECTRAL RANGE
VITO	VLAAMSE INSTELLING VOOR TECHNOLOGISCH ONDERZOEK (FLEMISH INSTITUTE FOR TECHNOLOGICAL RESEARCH, BELGIUM)
VOS	VOLUNTARY OBSERVING SHIP
VOSCLIM	VOLUNTARY OBSERVING SHIP CLIMATE PROJECT
VTPR	VERTICAL TEMPERATURE PROFILE RADIOMETER
WaTER	THE WATER ELEVATION RECOVERY SATELLITE MISSION
WCRP	WORLD CLIMATE RESEARCH PROGRAMME
WDC	WORLD DATA CENTRE
WG-ARO	WORKING GROUP ON ATMOSPHERIC REFERENCE OBSERVATIONS (AOPC)
WGCV	WORKING GROUP ON CALIBRATION AND VALIDATION (CEOS)
WGI	WORLD GLACIER INVENTORY (NSIDC)
WGMS	WORLD GLACIER MONITORING SERVICE
WIS	WMO INFORMATION SYSTEM
WMO	WORLD METEOROLOGICAL ORGANIZATION
WOAP	WCRP OBSERVATION AND ASSIMILATION PANEL
WOUDC	WORLD OZONE AND ULTRAVIOLET RADIATION DATA CENTRE
WSOA	WIDE SWATH OCEAN ALTIMETER (NASA)





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