→ SATELLITE EARTH OBSERVATIONS IN SUPPORT OF CLIMATE INFORMATION CHALLENGES

Special 2015 COP21 Edition

→ SATELLITE EARTH OBSERVATIONS IN SUPPORT OF CLIMATE INFORMATION CHALLENGES

Special 2015 COP21 Edition

Compiled & edited by: Ivan Petiteville, Pascal Lecomte (ESA),
Stephen Ward, George Dyke, Matthew Steventon & Jennifer Harry (Symbios Spazio)

Layout by: ESA – EOGB (Earth Observation Graphic Bureau)

Jean Jouzel, Climatologist and Research Director at CEA

Every year, the Conference of the Parties (COP) brings together the nations that are signatories to the UN Framework Convention on Climate Change (UNFCCC). This year will be the 21st such meeting, the two most emblematic having been Kyoto in 1997 and Copenhagen in 2009. Copenhagen set a target of capping long-term global warming at 2°C above pre-industrial temperatures. That marked a decisive step, but we now need to translate this commitment into actions. To reach this target, the conference in Paris aims to secure a specific agreement on reducing greenhouse gas emissions after 2020.

To meet the objective of 2°C, we need to start by breaking the emissions spiral by 2020 and then reduce our greenhouse gas emissions by at least a factor of two, ideally three, between 2020 and 2050 to achieve carbon neutrality – i.e., zero net carbon emissions – by the end of the century. The best way to view the problem is to look at our energy requirements, which currently are met largely by burning fossil fuels. To reach the long-term 2°C target, we need to keep nearly 80% of fossil fuel reserves obtainable with current technologies and costs in the ground. We must not use more than 20% of these easily accessible reserves. Seen in that light, it is obvious that we need to completely rethink our current development model.

The role of the Intergovernmental Panel on Climate Change (IPCC) in this process is of the utmost importance. Indeed the IPCC's mission is to provide a diagnosis and scientific elements on how the climate system works, the impacts of disruptions to this system and possible solutions to inform policymakers' decisions.

Satellite data have truly revolutionized how we see the climate system. The most striking example is sea level, which is currently rising at a rate of 3mm a year. Satellite measurements at the polar ice caps and on temperate glaciers have shown that roughly half of this rise is due to ice melt. Slightly less than the remaining half results from expansion of the warming ocean, which stores 93% of excess heat. The remaining proportion comes from extracted groundwater, which obviously ends up in the sea; it is not huge, but it accounts for 13% of sea level rise all the same. Satellite data enable us to precisely calculate these different contributions. Without such data, we would not have that kind of precision, especially when determining regional characteristics. It's the kind of thing we didn't even dare dream about 30 years ago!

Ideally, satellite data will be applied to help reduce the uncertainties in our models. The main uncertainty today concerns clouds. We do not know if they are heating or cooling the climate system. Thanks to their global coverage, satellites can give us new insights into how clouds, aerosols and radiation interact and tell us more about how the physical and chemical make-up of clouds evolves as they warm. The other aspect is our knowledge of the atmosphere's composition. For the purpose of climate negotiations, there is value in being able to determine greenhouse gas emissions in a specific region or sector of the economy. Several satellite projects are looking to determine regional greenhouse gas emissions, but what we need is continuous observations. Lastly, satellites still have a lot to teach us about the consequences of global warming on agriculture, forests, permafrost and more.

Satellite observations therefore provide the fundamental basis of our knowledge of the climate system. The Committee on Earth Observation Satellites (CEOS) together with the Coordination Group on Meteorological Satellites (CGMS) are coordinating the work of space agencies on climate in order that the

global contribution of Earth observation (EO) satellites is greater than the sum of its individual parts. As during the COP negotiations, international cooperation and solidarity are key factors in making concrete progress on sustainable development. I am particularly glad to invite you to read this Handbook that shows remarkable examples of the essential role that satellites play in climate change studies.

Jean Jouzel

Climatologist and Research Director at CEA, the French Atomic Energy and Alternative Energies Commission, Specialist in paleoclimatology.

2002 - CNRS Gold Medal, France's highest scientific distinction

2007 - IPCC is awarded the Nobel Peace Prize while he is Vice Chair

2012 - Vetlesen Prize, equivalent to the Nobel Prize in the field of geophysics and geology

Jean Jouzel is Vice Chair of the IPCC Working Group I and the author of over 300 scientific publications.

Jean Jouzel will be on the French delegation's team of science experts for COP, as he has been every year since 2000. Jean Jouzel will also be involved in the run-up to the event in Paris: he has been asked to sit in the conference Steering Committee by COP21 chair Laurent Fabius and he is also the Chair of the High Level Board for the science conference "Our Common Future Under Climate Change" held in July at UNESCO.

CEOS Message to COP21

CEOS ensures international coordination of the civil Earth-observing programmes of more than 30 of the world's leading space agencies. These agencies are collectively investing billions of dollars in space infrastructure with the capability to provide sophisticated, continuous and sustained observations of the entire planet. The global nature of climate change issues presents special challenges in terms of the need for global information and data on key planetary indicators that can provide the information required for governments and policy makers to make well-informed decisions. Recognising that no single country can satisfy all of the observational requirements necessary for monitoring of the Earth system, governments are taking steps through CEOS to harmonise and integrate their observing network.

This report explores how satellite EO can contribute to the challenges of providing the information that society needs in order to accurately characterise the nature of changes to our climate and to help define the most cost-effective strategies for mitigation and adaptation. Satellite EO data have already proven to be fundamental to the development of the evidence that has persuaded governments to act. Satellite EO data will continue to be an essential source of evidence necessary for informed decision-making, supporting the science that underpins climate policies.

The report has been compiled in support of the 2015 Paris Climate Conference – the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC COP21) – to help develop a broader understanding of the fundamental importance of satellite EO to the information needed to inform our climate policies on all scales. Satellites contribute to more than half of the 50 Essential Climate Variables (ECVs) identified for the UNFCCC by the Global Climate Observing System (GCOS) and provide unique measurements that would not otherwise be possible. The institutional structures and processes already exist to link the information needs of parties to the UNFCCC with the definition of observing requirements and with the planning processes of the space agency observing programmes, but will need recognition and support to evolve effectively in step with any binding agreement and its implementation to ensure society is equipped with the information it needs.

We hope that this CEOS Report might serve as a valuable reference source for a variety of readers from all sectors of society, including those engaged in the COP21 process, as well as decision-makers in political and socio-economic sectors.

David Williams

Executive Director

Commonwealth Scientific & Industrial Research Organisation (CSIRO), Australia

CEOS Chairperson for 2016

Volker Liebig

Director of Earth Observation Programmes

European Space Agency (ESA)

Part I

Space Data Supporting Climate Information

1

Introduction

The governments of the world will converge on COP21, the 2015 Paris Climate Conference, with high hopes that, for the first time in over 20 years of United Nations (UN) negotiations, we might aim to achieve a legally binding and universal agreement on climate, with the aim of combating climate change effectively and boosting the transition towards resilient, low-carbon societies and economies.

To achieve this, the future agreement will focus on both mitigation efforts to reduce greenhouse gas emissions and societies' adaptation to existing climate changes. The COP21 agreement will enter into force in 2020 and will need to be sustainable to enable long-term change. As a new development in international climate negotiations, each country must publish its proposed national contribution and efforts before COP21.

The economic and social implications and costs of the agreement and its underlying commitments will be enormous and not taken lightly by governments. The commitments being made are indicative of the substantial and compelling evidence that has been compiled regarding the nature, scale and impact of changes to the Earth's climate system. This evidence has persuaded societies and their governments that significant and sustained action is necessary.

EO data have proven to be fundamental to the development of this evidence now being acted upon. EO data provide the evidence necessary for informed decision-making – supporting the science which underpins strategies for global decision-making – and for monitoring our progress on all geographical scales as we explore new development paths aimed at sustainable management of the planet.

EO will also be central to the execution of a COP21 agreement that specifies quantitative targets for reduction of emissions, including for: evidence and the basis for scientific advice on the cost-effectiveness of different approaches for governments; baselines against which on-going changes can be measured; monitoring and compliance; assessing progress and improving understanding; and improved predictions of climatic changes.

Many of the quantitative indicators that will be discussed in Paris with regards to environmental and climate change will have been derived largely or exclusively from satellite EO. These data offer many ways to improve the implementation of multilateral environmental agreements, such as the continuous provision of global data; historical data archives; observations of several environmental parameters at global, national and local scales; and the provision of

synoptic and comparable information without infringing on national sovereignty.

This Handbook has been prepared for the stakeholders and delegates supporting the effort towards a legally binding agreement at COP21. It aims to explain how satellite EO are an absolutely essential tool in the development of the information and evidence that has motivated and formulated the anticipated Paris agreement and that will be fundamental to its execution and the monitoring, reporting and verification of the underlying national commitments. The Handbook seeks to improve understanding of readers from all sectors of society as to the role of satellite EO in support of a well-managed planet.

Part I explains the role of EO in support of our climate information challenges – in the assembly of the evidence of climate changes and future monitoring of key indicators.

Part II compiles a number of contributed articles on key activities in space-based climate observations.

Part III focuses on a few case studies where satellites make a unique contribution in support of climate information. Information that we, simply, could not otherwise hope to possess.

2

Climate Context

The IPCC is the leading international body for the assessment of climate change. It was established in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts.

The IPCC is a scientific body under the auspices of the UN. It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate-related data or parameters.

Scientists from all over the world contribute to the work of the IPCC on a voluntary basis. Review is an essential part of the IPCC process, to ensure an objective and complete assessment of current information. The IPCC is an intergovernmental body, open to all member countries of the UN and World Meteorological Organisation (WMO).

The IPCC produces comprehensive assessment reports on climate change every six years or so. The IPCC completed its **Fifth Assessment Report (AR5)** with the release of its Synthesis Report in late 2014. Over 830 scientists from over 80 countries were selected to form the author teams producing the report. They in turn drew on the work of over 1,000 contributing authors and over 1,000 expert reviewers. AR5 assessed over 30,000 scientific papers.

Besides the Synthesis Report, AR5 includes the contributions of IPCC Working Group I (the physical science basis of climate change), of Working Group II (impacts, adaptation and vulnerability) and of Working Group III (mitigation of climate change).

AR5 is the most comprehensive assessment of climate change ever undertaken and represents the best evidence available to inform the negotiations at COP21 with respect to the current state of the Earth's climate system and its future trends. AR5 concluded that:

- Human influence on the climate system is clear and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.
- Warming of the climate system is unequivocal and, since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished and sea level has risen.
- Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century.
- Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify and global mean sea level will continue to rise.
- Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases.
- Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development.

These key findings are from the Summary for Policy Makers of the IPCC 2014 Synthesis Report.

The AR5 Synthesis Report tells a concise story, drawing on all three reports. It says that if governments work to cut emissions and adapt to new conditions, we can still keep the risks of climate change low. Nations have collectively agreed that beyond two degrees of warming, the risks posed by climate change are too high and it is unlikely we could deal with the consequences.

The IPCC concludes that, with the right policies, we can prevent dangerous climate change, allow ecosystems to adapt and ensure countries can develop sustainably, all at the same time.

On the other hand, the slower we take action, the harder it will be and the more expensive it will get. Not acting now puts a very heavy burden on future generations, the report says. It makes it clear that climate change is a collective problem. Because climate change affects everyone, nations must cooperate to limit it. It will only be possible to limit the extent of climate change if nations work together. As the UN Secretary-General has noted in relation to action to reduce climate change, *"this is the planet where subsequent generations will live, and there is no Plan B, because we do not have Planet B"*.

The IPCC is an advisory body – it does not tell the world's leaders what to do. AR5 provides the best available scientific

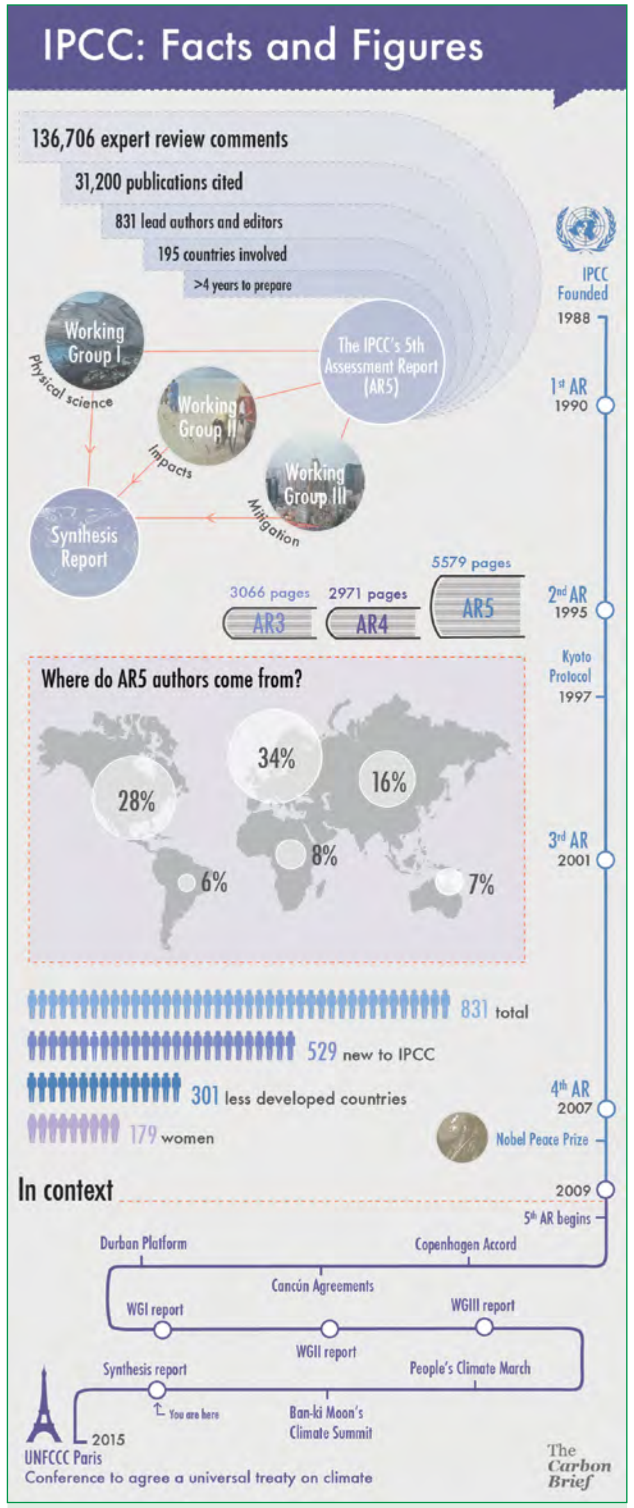


Figure 1: Facts and figures around IPCC's AR5 and the road to the COP21 negotiations

Source: Carbon Brief (www.carbonbrief.org) evidence and guidance for the negotiators at COP21 regarding the observed trends in climate changes and their predicted future paths, depending on the mitigation efforts that are achieved around emissions reduction. AR5 represents the clearest guide yet from scientists about why we need to keep climate risks in check. It concludes that human influence on the climate system is clear and that the more we disrupt our climate, the more we risk severe, pervasive and irreversible impacts.

The globally averaged temperature over land and ocean surfaces for 2014 was the highest among all years since recordkeeping began in 1880. We still have, however, the means to limit climate change and build a more prosperous, sustainable future. COP21 aims to finalise a new global agreement to limit greenhouse gas emissions and to help countries develop low-carbon and climate-resilient economies.

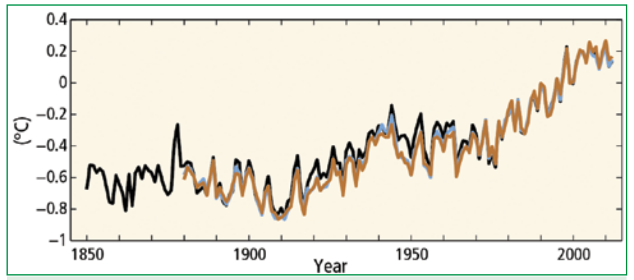


Figure 2: Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986–2005. Colours indicate different data sets.

Source: IPCC AR5 Figure SPM.1

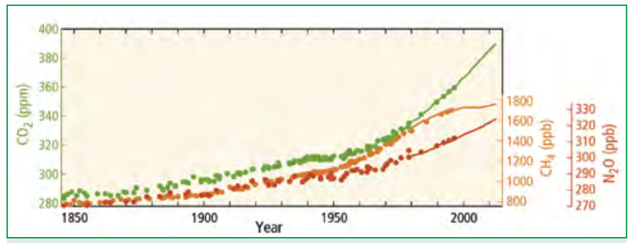


Figure 3: Atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines)

Source: IPCC AR5 Figure SPM.1

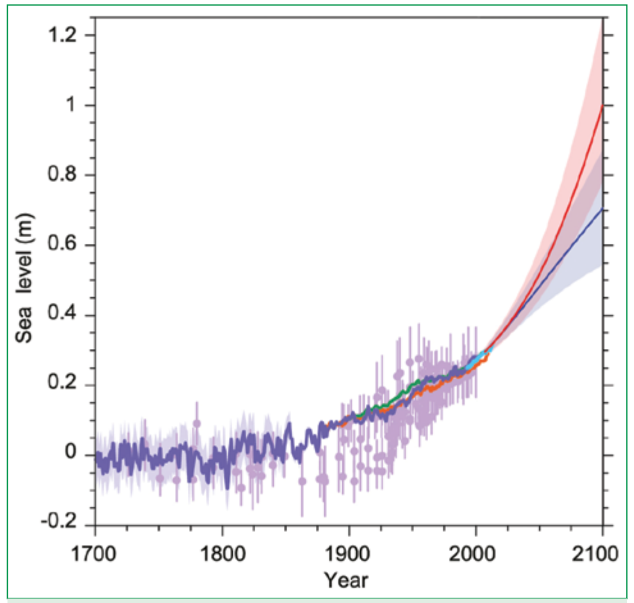


Figure 4: Past and future sea-level rise. For the past, proxy data are shown in light purple and tide gauge data in blue. For the future, the IPCC projections for very high emissions (red, RCP8.5 scenario) and very low emissions (blue, RCP2.6 scenario) are shown.

Source: IPCC AR5 Fig. 13.27

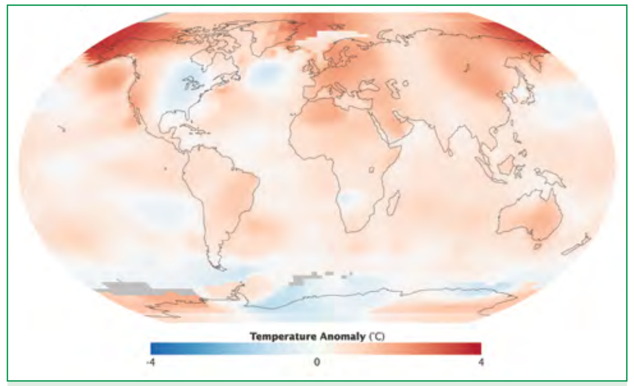


Figure 5: 2014 was the warmest year on record, with global temperatures 0.68°C above the long-term average. 14 of the 15 warmest years on record have occurred since the turn of the century.

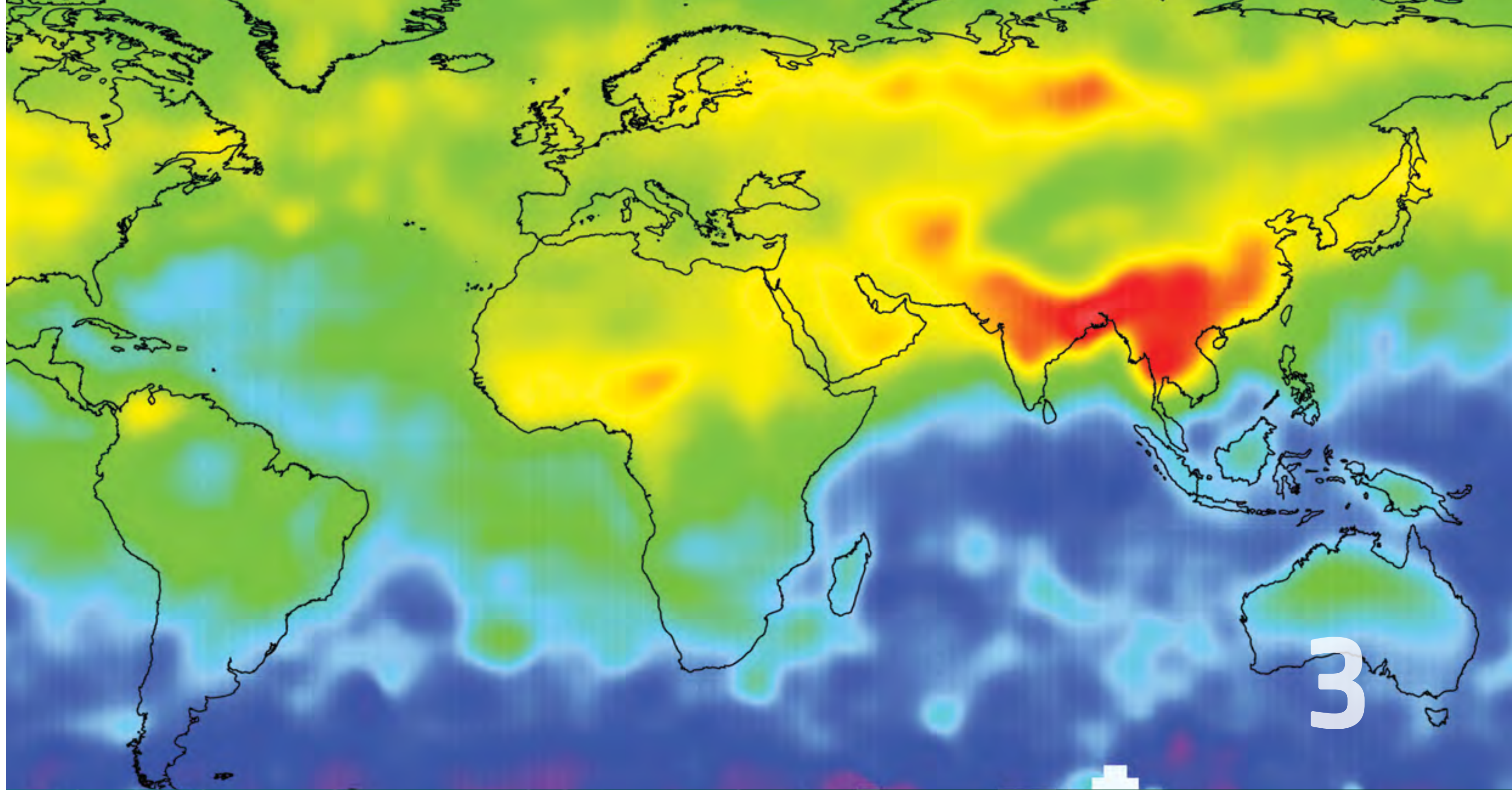
Source: NASA/NOAA

Further information

IPCC:
www.ipcc.ch

UNFCCC:
www.unfccc.int

State of the Climate:
www.ncdc.noaa.gov/sotc



Role of EO Data in Support of Climate Information

3.1 Observations of the Climate System

- **EO data have been central to the formulation of the authoritative scientific advice that the current climate negotiations are responding to.**
- **EO data will be essential in assessing the cost-effectiveness over time of any policy measures agreed, based on changes in the key environmental indicators. Reliable space-based observations can provide the authoritative records of climate change needed to empower governments and the private sector to make informed decisions.**
- **Of the 50 ECVs defined by the Global Climate Observing System (GCOS), more than half have a major contribution from satellite observations.**
- **Without the insights offered by satellite EO, there will be insufficient evidence with which to inform our decision-makers on environmental policies, including those aimed at mitigation and adaptation to climate change.**

Improved understanding of the Earth system – its weather, climate, oceans, land, geology, natural resources, ecosystems and natural and human-induced hazards – is essential if we are to better predict, adapt and mitigate the expected global changes and their impacts on human civilisation. EO data and derived information are essential inputs in the development of this understanding.

Scientists concerned with climate variability and change have, from the very beginning, recognised the importance of observations to our understanding of the atmosphere and the application of atmospheric science to human affairs. Without accurate, high-quality observations on all time and space scales, climate science and services could make only limited progress.

Systematic international coordination of weather and climate observations began around the middle of the 19th century and advanced rapidly in the 1960s and 1970s as the advent of digital computers and EO satellites inspired the establishment of the operational World Weather Watch and the Global Atmospheric Research Programme. The great step forward came in the 1980s with the realisation that understanding and predicting climate would require the involvement of a much wider set of scientific communities and comprehensive observation of the entire atmosphere-ocean-land climate system. This inspired the vision for an integrated **Global Climate Observing System (GCOS)**, which was formally established in 1992 as an international, interagency interdisciplinary framework for meeting the full range of national and international needs for climate observations.

Non-satellite observational systems contributing to the GCOS include atmospheric, oceanic and terrestrial components.

The atmospheric component includes networks for measurement of temperature, humidity and winds aloft, including the WMO Global Atmosphere Watch (GAW) global baseline ozone networks and the WMO GAW Global Atmospheric CO_2 and CH_4 Monitoring Networks.

The surface ocean network provides information about the patterns of ocean surface temperature, pressure, winds, salinity, sea level, waves and sea ice that are important both to the global climate and its regional distribution. Its main systems are: the global networks of tide gauges; moored and drifting buoys; and voluntary observing ships. The sub-surface ocean network provides critical information on ocean climate variability and change and is also based on buoy and ship measurements.

The conventional climate observing system in the terrestrial domain remains the least well-developed component of the global system. Current networks monitor river discharge, glacier hydrology, lake level/area, permafrost, on-going space-based and in-situ observations of forests and other vegetation cover and global and regional change in coastal areas.

3.2 How Satellites Help

While the conventional observing networks provide critical climate measurements at a number of points around the globe and undertake some measurements that are as yet not technically feasible from space at required accuracies, (eg surface air temperature), they have limitations when it comes to observing global climate change. For the most part, the atmospheric observations are limited to the land areas of the Earth and are highly concentrated in the major population centres of the developed countries. Ocean areas – 70% of the globe – are largely under-sampled in terms of atmospheric measurements. And there are also large gaps in the coverage of surface and sub-surface ocean measurements. In-situ terrestrial observation networks also have large gaps. Constructing a reliable picture of global climate change from an observing system that has such large voids is an impossible task.

Satellites and complementary in-situ networks provide the global coverage needed to observe and document worldwide climate change. Space-based remote sensing observations of the atmosphere-ocean-land system have evolved substantially since the first weather satellite systems were launched 55 years ago. EO satellites have proved their capabilities to accurately monitor multiple aspects of the total Earth system on a global basis.

Currently, satellite systems monitor the evolution and impact of the El Niño (including a strong occurrence in 2015), weather phenomena, natural droughts, vegetation

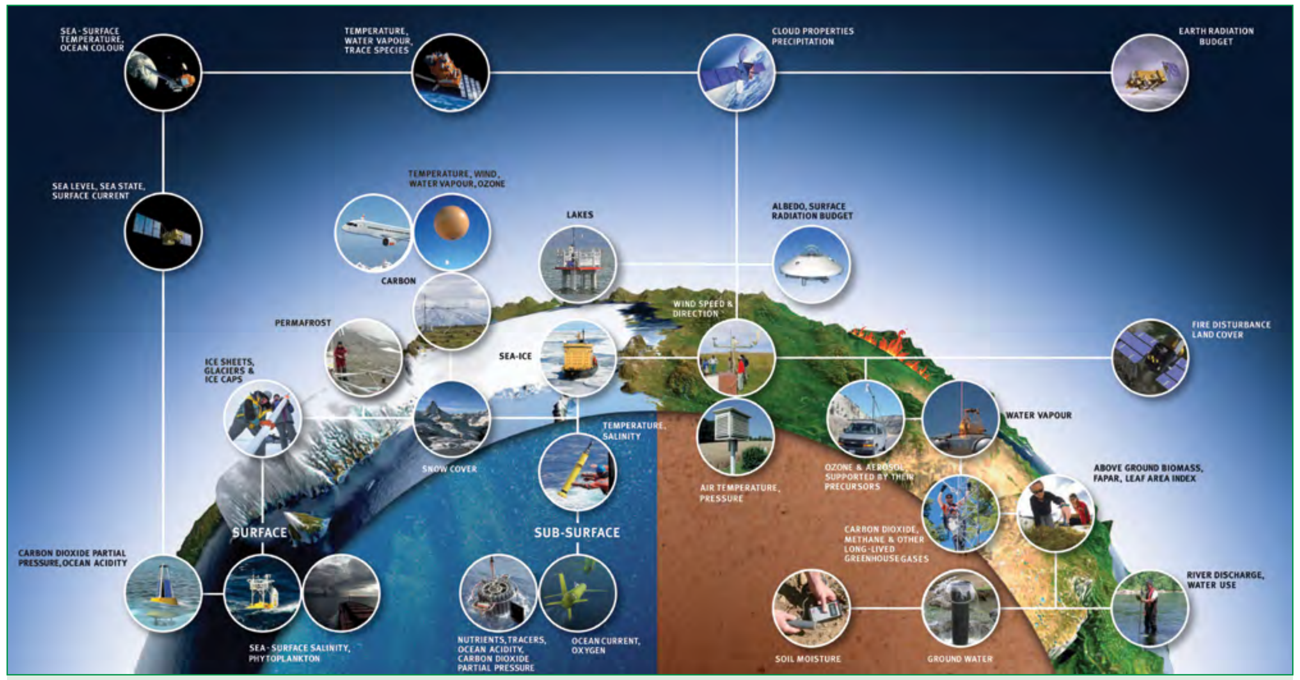


Figure 1: Some of the multitude of observing systems and the observations that contribute to the GCOS

cycles, the ozone hole, solar fluctuations, changes in snow cover, sea ice and ice sheets, ocean surface temperatures and biological activity, coastal zones and algal blooms, deforestation, forest fires, urban development, volcanic activity, tectonic plate motions and more.

EO satellites are being developed and launched in support of climate information needs and their proliferation reflects their unique abilities and benefits:

- **wide area observation capability: a single instrument on a polar orbiting satellite can observe the entire Earth on a daily basis, while instruments on geostationary satellites continuously monitor the diurnal cycle of the disk of Earth below them; together the polar and geostationary environmental satellites maintain a constant watch on the entire globe;**
- **non-intrusive observations allowing collection of data to take place without compromising national sovereignty;**
- **uniformity that enables the same sensor to be used at many different places in the world;**
- **rapid measurement capability, allowing sensors to be targeted at any point on Earth, including remote and inhospitable areas, enabling monitoring of deforestation in vast tropical forests and tracking ice loss in the polar regions year-round;**
- **continuity, with single sensors or series of sensors providing long time series of data suitable for climate studies.**

More than 40 nations are identified as having invested in EO satellites, amounting to government investment of approximately US$7-8 billion per annum, with further and increasing investment coming from the commercial sector and through public-private partnerships. These investments have been made with a view to numerous and diverse applications of the space-based infrastructure and the observing capabilities of the hundreds of satellites involved, including studies of climate, environmental issues, agriculture, meteorology and natural disasters. A large proportion of the EO satellites in operation or planning are dedicated to climate and meteorology observations.

Some of the unique contributions of EO satellites to the development of climate information are presented in Part III of this document. More detailed explanation of the different instrument types and climate measurements that they provide can be found in the online version of the EO Handbook: www.eohandbook.com

3.3 The Essential Climate Variables

Observations are fundamental to advancing scientific understanding of climate and delivering the vetted, timely and purposeful climate information needed to support decision-making in many sectors.

In the 1990s, gaps in knowledge of climate and declining core observational networks in many countries led to calls for systematic observation of a limited set of critical variables. To provide guidance, GCOS developed the concept of **"essential**

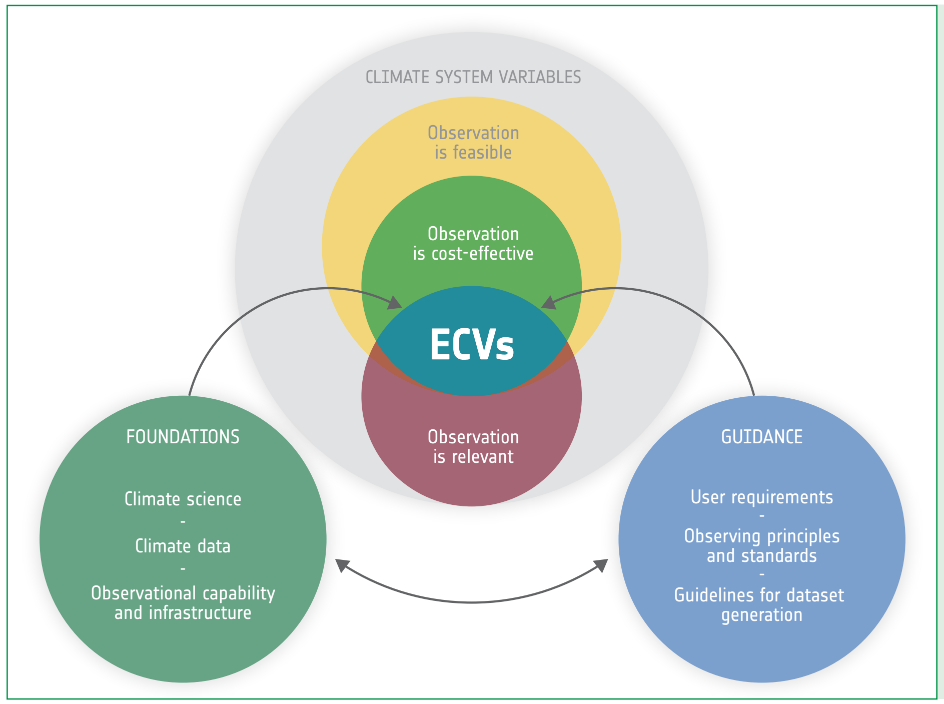


Figure 2: Schematic of the ECV concept: knowing existing climate-relevant observing capabilities, climate datasets and the level of scientific understanding of the climate system are the foundations (lower-left circle) necessary for selecting the ECVs from a pool of climate system variables. In addition, guidance is needed to make practical use of the ECVs (lower-right circle): user requirements capture the data quality needs of science, services and policy; climate-specific principles guide the operation of observing systems and infrastructure; and guidelines facilitate the transparent generation of ECV data records. The latter address the availability of metadata, provisions for data curation and distribution and the need for quality assessment and peer review

Credit: (Bojinski et al., 2014)

climate variables" (ECVs) (Bojinski et al, 2014).

An ECV is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterisation of Earth's climate. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climatic events to underlying causes and to underpin climate services.

ECVs are not a select group of stand-alone variables. Rather they are part of a wider concept and are identified based on the following criteria:

- **Relevance**: the variable is critical for characterising the climate system and its changes;
- **Feasibility**: observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods;
- **Cost effectiveness**: generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

Science and policy circles have widely endorsed the ECV concept. The parties to the UNFCCC acknowledged the need to act upon the plans for implementation. Guidelines for reporting on national programmes contributing to global climate observation are structured along the ECVs. In its planning of global observation for weather, water and climate applications, WMO addresses the ECVs and recognizes GCOS assessment and planning documents as statements of guidance.

Space agencies have responded strongly to the concept, through the Committee on Earth Observation Satellites (see Section 4) and through the broadly developed Architecture for Climate Monitoring from Space (see Section 5).

Of the 50 ECVs identified by GCOS, more than half have a major contribution from EO satellite measurements, with several exclusively derived from EO satellite measurements.

Some of the unique contributions from EO satellites are explained in **Part III** of this document.

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	**Surface**: Air temperature, **Wind speed and direction**, Water vapour, Pressure, Precipitation, Surface radiation budget **Upper-air: Temperature, Wind speed and direction, Water vapour, Cloud properties, Earth radiation budget (including solar irradiance)** **Composition: Carbon dioxide, Methane, and other long-lived greenhouse gases, Ozone and Aerosol, supported by their precursors**
Oceanic	**Surface: Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice,** Surface current, Ocean colour, Carbon dioxide partial pressure, Ocean acidity, Phytoplankton **Sub-surface:** Temperature, Salinity, Current, Nutrients, Carbon dioxide partial pressure, Ocean acidity, Oxygen, Tracers
Terrestrial	River discharge, Water use, Groundwater, **Lakes, Snow cover, Glaciers and ice caps, Ice sheets**, Permafrost, **Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Above-ground biomass**, Soil carbon, **Fire disturbance, Soil moisture**

Figure 3: The ECVs – satellite observations make a major contribution to the ECVs shown in bold

Further information

Measurement capabilities of EO satellites:
www.eohandbook.com/eohb2015/sat_earth_observation.html

Essential Climate Variables:
www.tinyurl.com/p9vywdf

4 Coordinating Climate Information from Space

- **CEOS ensures international coordination of civil space-based Earth observation programmes**
- **GCOS is progressing the systematic definition of climate information needs in support of the UNFCCC, while CEOS is coordinating the planning of the satellite contribution to fulfil them.**

The nature of climate change issues presents special challenges in terms of the need for global information and data on key planetary indicators that can provide the information required for governments and policy makers to make well-informed decisions. No single country can satisfy all of the observational requirements that are necessary for comprehensive and sustained monitoring of the Earth system, so governments are taking steps to harmonise and integrate their observing networks and satellite observing systems so that all the necessary measurements are provided in an affordable and optimised way. CEOS is the mechanism through which governments collaborate on satellite missions, data systems and global initiatives to achieve this.

The definition of the Implementation Plan for GCOS in 2004 provided space agencies with a new clarity, focus and a sense of the priorities in addressing the needs of the UNFCCC. The CEOS-GCOS relationship in service of the UNFCCC has been, and will continue to be, a vital mechanism in managing the definition and operation of the satellite missions required to address society's climate information needs, including the information needed to execute any agreement reached in Paris at COP21. The heritage and importance of the CEOS-GCOS relationship is explained below.

4.1 CEOS

CEOS is the Committee on Earth Observation Satellites, created in 1984 in response to a recommendation by a Panel of Experts on Remote Sensing from Space, under the aegis of the G7 Economic Summit of Industrialised Nations Working Group on Growth, Technology and Employment.

CEOS was established to provide coordination of the EO being provided by satellite missions, recognising that no single programme, agency or nation can hope to satisfy all of the observational requirements that are necessary for improved understanding of the Earth system. Since its establishment, CEOS has provided a broad framework for international coordination on space-borne EO missions.

CEOS has three primary objectives:

- To optimise the benefits of space-based Earth observation through cooperation of CEOS Agencies in mission planning and in the development of compatible data products, formats, services, applications and policies;
- To aid both CEOS Agencies and the international user community by, among other things, serving as the focal point for international coordination of space-based Earth observation activities, including the Group on Earth Observations and entities related to global change;
- To exchange policy and technical information to encourage complementarity and compatibility among space-based Earth observation systems currently in service or development, and the data received from them, as well as address issues of common interest across the spectrum of Earth observation satellite missions.

CEOS membership has reached 31 space agency Members in 2015, comprising most of the world's civil agencies responsible for EO satellite programmes.

CEOS established a new Working Group on Climate (WGClimate) in 2010, as the centrepiece of its contribution to climate change monitoring. WGClimate coordinates and encourages collaborative activities between the world's major space agencies in the area of climate monitoring with the overarching goal of improving the systematic availability of Climate Data Records through the coordinated implementation and further development of a global architecture for climate monitoring from space (see Section 5). The Coordination Group for Meteorological Satellites (CGMS) has co-led the WGClimate with CEOS since 2013, bringing the vital contribution of the meteorological satellite agencies more closely into the coordinated effort and global architecture implementation.

In response to the requirements set by GCOS, WGClimate facilitates the implementation and exploitation of ECV time-series through coordination of the existing and substantial activities undertaken by CEOS Agencies.

4.2 CEOS & GCOS in Support of UNFCCC

GCOS
GLOBAL CLIMATE OBSERVING SYSTEM

Part II of this document includes an article by GCOS on the heritage of its vital work in defining the requirements for information on the Earth's climate and its periodic assessments as to the progress towards implementing a GCOS.

At UNFCCC's COP10 meeting in 2004, the Parties that support space agencies were invited to provide a response to the needs expressed in the first GCOS Implementation Plan. CEOS agreed to respond as the primary international forum for coordination of space-based EO through an initial series of 59 actions covering the atmosphere, ocean and terrestrial domains, and a number of cross-cutting issues. CEOS and GCOS agreed to associate priorities to each one of the 59 actions, based on an evaluation of their ability to deliver significant results in the short (1-2 years), medium (4-6 years) and long term (~10 years).

This interaction was the beginning of an on-going process to assess the adequacy of past, present and future satellite measurements in support of GCOS, with specific reference to the UNFCCC needs for satellite observations. The process continues to this day, with CEOS reporting every two years to UNFCCC through the Subsidiary Body for Scientific and Technological Advice (SBSTA: one of two permanent subsidiary bodies to the Convention; it provides information and advice on scientific and technological matters). This has provided a unique and structured opportunity for space agencies to review the way in which multi-agency cooperation on climate-related observations is prioritised, agreed, funded, implemented and monitored.

GCOS, in consultation with its partners, has developed a credible plan that, if implemented, will lead to a much-improved understanding of climate change. By working with GCOS, CEOS hopes to identify what can be achieved by better coordination of existing and future capabilities, as well as those improvements that require additional resources and/or mandates beyond the present capacity of space agencies. The CEOS reports to UNFCCC (including the latest provided ahead of COP21) are intended to initiate action and assist the Parties in advising and commenting on the planning actions within the agencies.

CEOS recognises that both satellite and in-situ data are required to better monitor, characterise and predict changes in the Earth system. While in-situ measurements will remain essential and largely measure what cannot be measured from satellites, satellites are the only realistic means to obtain the necessary global coverage for climate purposes and, with well-calibrated measurements, will become the single most important contribution to global observations for climate. As a consequence, the cooperation between CEOS and GCOS to define the information requirements needed by UNFCCC and its Parties, and to help plan the implementation of the satellite observing systems needed, is fundamental to the success of the Convention in implementing, managing and measuring the effectiveness of any agreement reached in Paris, as well as the related policies aimed at mitigation and adaptation to climate change.

The next key milestones in this process will be the submission of the latest GCOS Status Report to COP21 and of the latest GCOS Implementation Plan to COP22 in late 2016.

The 2014 Climate Symposium

Space agencies continue to seek opportunities for better coordination and optimisation of their observing strategies for climate information. In 2014, following the completion of the IPCC AR5, it was considered timely to discuss AR5 achievements, to assess future opportunities and challenges with satellite-derived climate information and to provide guidance on future priorities.

A Climate Symposium with the theme of *"Climate Research and Earth Observation from Space – Climate Information for Decision Making"* was organised by the World Climate Research Programme (WCRP) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The Symposium was structured around the "Grand Science Challenges" of the WCRP: Clouds, Circulation and Climate Sensitivity; The Changing Water Cycle; Cryosphere in a Warming World; Ocean Circulation and Regional Sea Level Rise; Prediction and Attribution of Extremes – from Climate to Weather; and Regional Climate Variability and Change – Enabling Climate Services.

The Symposium was an important step towards progressing requirements and the further development of an efficient and sustained international space-based EO system. It brought together international experts in climate observations, research, analysis and modelling to present and discuss results from their studies, with a particular emphasis on the role of space-based EO in improving our knowledge of the current climate at global and regional scales and in the assessment of models used for climate projections.

www.theclimatesymposium2014.com

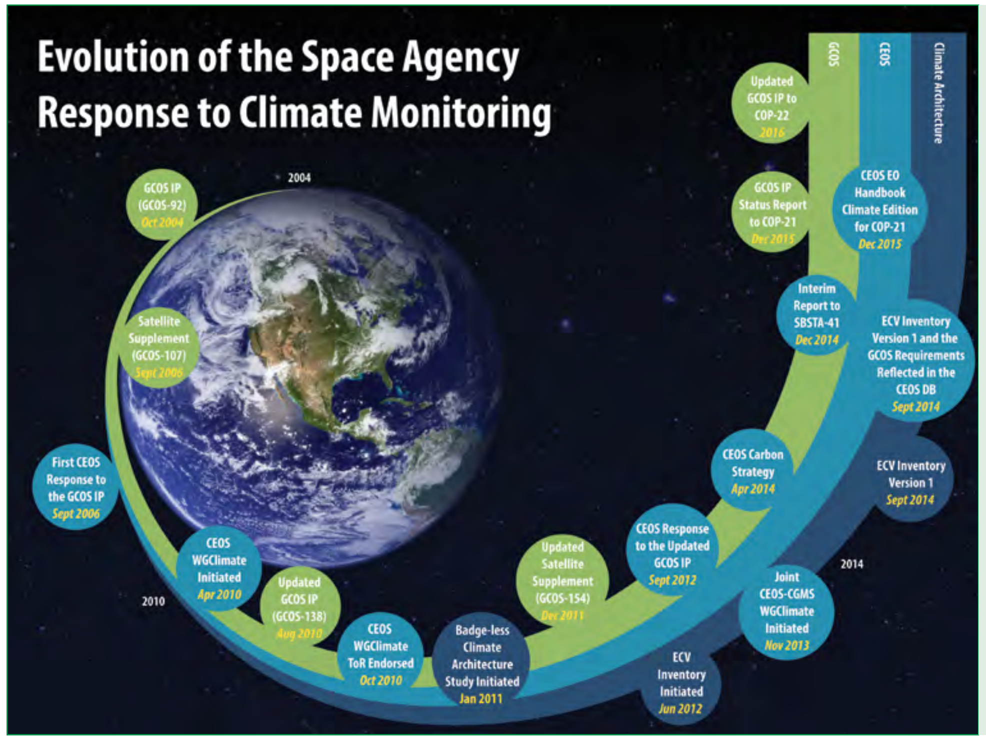


Figure 1: Key milestones in the development and planning of the satellite observations required by the UNFCCC – as defined by the Implementation Plan of the GCOS

Further information

CEOS:
www.ceos.org

Earth Observation Handbook:
www.eohandbook.com

GCOS:
www.wmo.int/pages/prog/gcos

5

The Building Blocks of Climate Monitoring from Space

In order to make decisions on climate change mitigation and adaptation, the UNFCCC requires a systematic monitoring of the global climate system. Satellite data play a crucial role in climate monitoring, research and services.

The journey taken by these data, starting from satellite instruments above to the climate scientists and decision makers on the ground, is a long and varied one. Each step on the journey may be considered as a building block. Each building block works with others on the same journey, building data step by step into a final usable form, a form valuable to policy makers and scientists alike. Together, these building blocks form the **"climate monitoring architecture"**.

5.1 Building Block #1: Gathering Raw Data from Space

Sophisticated instruments flying in space gather valuable geophysical information about the Earth. In contrast to instruments on the ground, the instruments above have the advantage of gathering data on a global scale. **Climate change is a global phenomenon, requiring global data.**

For over 30 years, a broad variety of satellites have gathered, and continue to gather, valuable raw data about the Earth. However, the Earth's climate changes slowly relative to the lifetime of any individual satellite. Therefore, to build a "Climate Data Record", scientists need to stitch together many different sources of raw data spanning many years, satellites old and new, from numerous space agencies. This involves digging into archived data, incorporating new satellite data as it reaches the ground and planning well for the next generation of satellite missions.

Archived Data

Past weather and climate observations have left an enormous legacy of archived data that forms the basis of our current knowledge on climate variability and change. Additionally, although optimised to support real-time weather monitoring and forecasting, operational meteorological programmes of the past have also provided a foundation for long-term climate records of key climate parameters.

Current Data

Approximately 100 satellites are currently operating with an EO mission. Increased frequency of satellite measurements, improved satellite and sensor technology and easier access and interpretation of EO data are all contributing to the increased role of satellite data in our knowledge of the climate system.

As data from currently flying satellites arrive on the ground, they become available to scientists for stitching together, blending and processing with data from other sources.

The new data are then archived for posterity, for use by the next generation of climate projects, programmes, scientists and engineers.

Planning for the Future

Some 140 civil EO satellite missions are planned for launch over the next 15 years. These missions will carry over 400 different instruments to measure components of the climate system, including the atmosphere, ocean and land surface.

The lifetimes of these satellite missions span many years, beginning before their launch. The first step in the life of a satellite mission is consulting with climate science organisations, and many other stakeholders, on their climate science needs.

These needs typically arise from shortfalls in the stitching together, and other processing, for production of Climate Data Records for the international community.

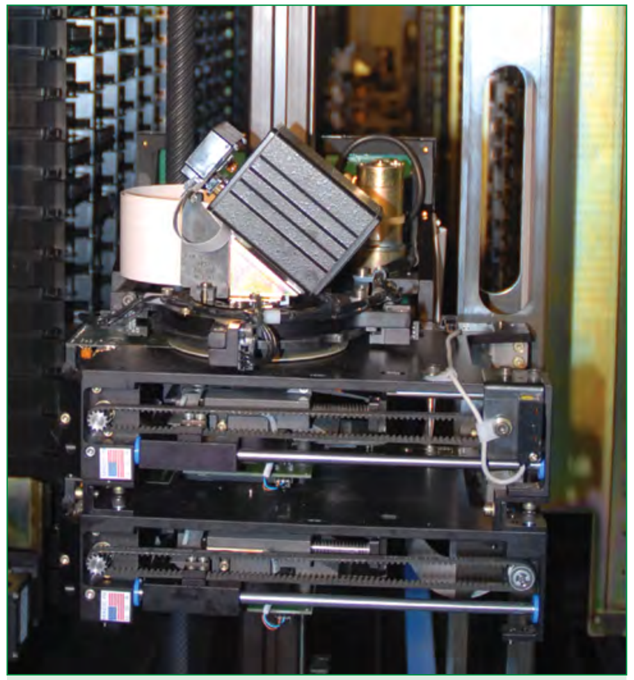


Figure 1: NOAA's robotic archive with packages of tape cartridges with each tape holding 1.5 terabytes of data. Robotic tape libraries allow preservation and ready access to satellite data collected over the past 30 years.

5.2 Building Block #2: Producing and Preserving Climate Data Records

With the gathered raw satellite data in hand, the objective of Building Block #2 is to process this input into Climate Data Records. This building block comprises many mini building blocks to form a "Processing Chain" that shapes this raw input into a final usable form. These mini building blocks include, for example, the computational stitching together of the different sources of raw input data, calculation of numerical uncertainties and the application of state-of-the–art scientific algorithms distilled from the latest scientific reasoning.

Climate Viewpoints

A huge variety of Climate Data Records exist, each formed from a particular viewpoint on climate. Examples include the amount of greenhouse gas in the atmosphere, the height of the oceans or the temperature of the land. Each viewpoint requires a unique blend of raw data and mini building blocks on their processing chain to suitably reflect the viewpoint.

Fifty such viewpoints, termed Essential Climate Variables (ECVs), have been defined by GCOS in support of the UNFCCC, 28 of which have been deemed both technically and economically feasible for systematic observation from space.

To generate Climate Data Records targeted to each ECV, climate scientists strive to gather the right blend of raw data and get the right assortment of mini building blocks to form an appropriate processing chain. In particular, scientists aim to meet the "Target Requirements" defined by GCOS for each ECV.

Reaching for Clearer Views

These GCOS target requirements quantitatively express the desired characteristics of Climate Data Records for each ECV needed by the UNFCCC for the systematic observation of climate.

Climate scientists are striving to bring together their latest scientific thinking, applied to data old and new, to produce Climate Data Records to reach these targets. The science is supported by space agencies and other international bodies working together, enabling the resources required to reach these targets.

Taking a Snapshot

A snapshot of all Climate Data Records, and how each compares against the GCOS target requirements, is compiled by CEOS and CGMS in the form of an ECV Inventory.

The ECV Inventory tabulates the current state of affairs in the production of Climate Data Records taking aim at the GCOS target requirements. CEOS and CGMS use their inventory to further work together to report to the UNFCCC on their progress.

Looking to the future, the ECV Inventory also forms the backbone of material used by CEOS and CGMS in coordinating where to best plan future resources. For example, the

Figure 2: Cryosat-2, now in orbit

exchanging of raw data between two scientists for their processing chains may prove the solution to meeting a currently unmet GCOS requirement, whereas the planning of one new mission for launch in 30 years time may be another.

5.3 Building Block #3: Applying Climate Data Records

Climate Data Records are applicable to hugely diverse and numerous socio-economic areas. Following consultation with stakeholders, sponsors and affiliate scientists over several years, the WCRP published a categorisation of major areas of scientific research, analysis and observation, termed Grand Challenges. The Climate Extremes Challenge, for example, requires decadal data to support adaptation planning, focusing on heavy precipitation, heat wave, drought and storm.

For climate services in societal sectors such as food security, water, energy, and health, the major direct or indirect value of satellite-based climate data records has been demonstrated through case studies developed by the CEOS/CGMS Working Group on Climate. Reference: http://www.wmo.int/pages/prog/sat/documents/ARCH_ClimateServiceCaseStudies.pdf.

Each application of climate data will have its own particular requirements to fulfil the needs of that specific application. Tailoring of climate data products is commonly necessary, in order to hone in to the requirements of the application in question.

This poses significant engineering demands. International coordination is underway in Europe in the form of the Copernicus Climate Change Service and globally via the WMO's Global Framework for Climate Services.

5.4 Building Block #4: Decision Making

Decision makers are engaged by the scientific community in a number of ways. Often there are common regional challenges, for instance shared coastal resources such as a bay or river delta. Alternately, engagement is accomplished by identifying sectors, such as agriculture or energy, that share common needs.

5.5 Putting it all Together

Opposite is an end-to-end example of the climate monitoring, research and services building blocks.

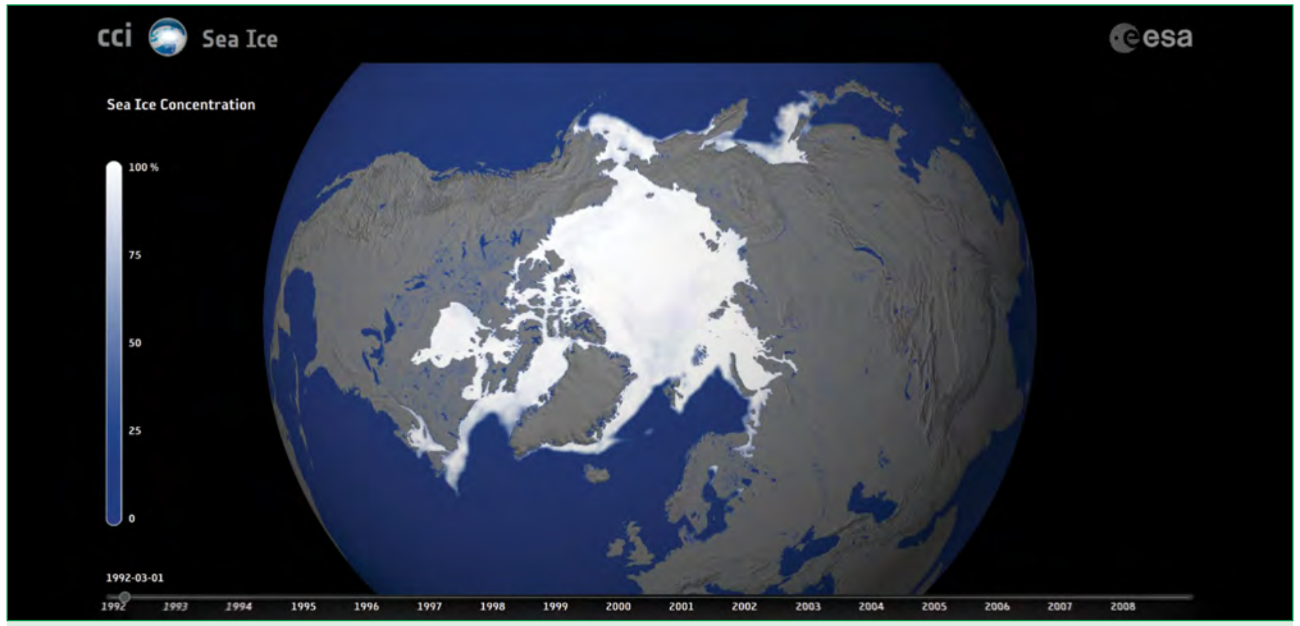


Figure 3: A computer visualisation of sea ice concentration in March 1992, constructed using the ESA Climate Data Record for sea ice

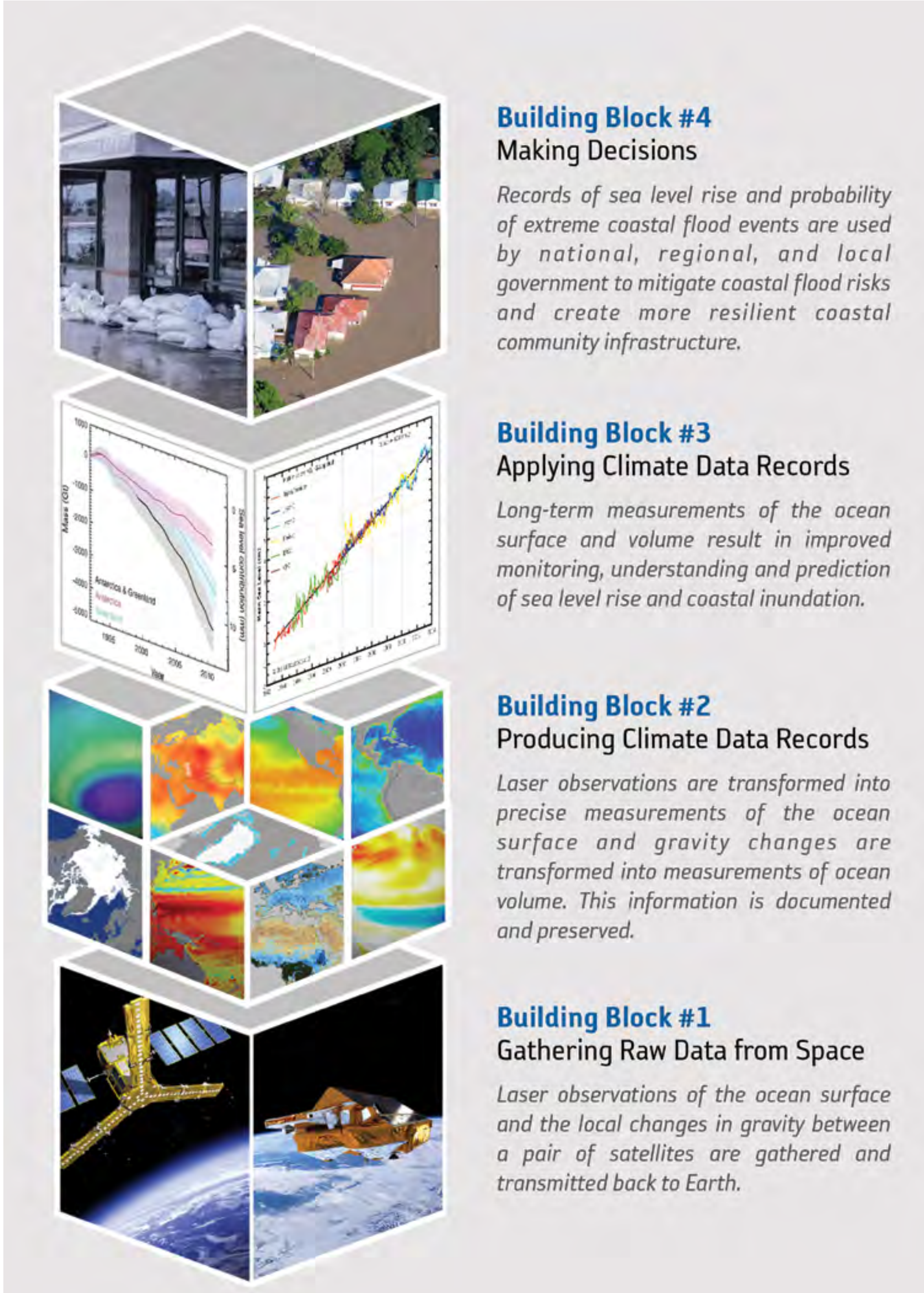


Figure 4: An end-to end-example of the climate monitoring, research and services building blocks applied to Sea Level Rise and Impact on Coastal Regions. Removing any one building block will topple all those above.

Contributors:

Pascal Lecomte (ESA), Ed Pechorro (ESA), John Bates (NOAA)

Further information

Strategy Towards an Architecture for Climate Monitoring from Space:
www.ceos.org/ourwork/workinggroups/climate

GCOS-154 – Systematic Observation Requirements for Satellite-Based Data Products for Climate:
www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf

6 Future Challenges

This Handbook aims to demonstrate that without the capabilities offered by satellite EO, there would be insufficient information for climate change studies and insufficient evidence with which to inform our decision-making on policies aimed at mitigation and adaptation to climate change. Nor would we be able to check the effectiveness of our mitigation strategies in terms of the trends of key ECVs. Earth-based measurement systems alone cannot provide the synoptic global picture that is required.

The work of GCOS, with its sponsors and partners in support of the UNFCCC, has established a clear community consensus on the observations that are required to deliver **50** ECVs needed to detect, monitor, predict, adapt to and mitigate climate change in the Earth system. CEOS and GCOS together have identified **28** of the ECVs that are largely dependent on satellite observations and have specified a number of actions required to ensure the necessary continuity or technical characteristics required for climate studies.

The vision of a global observing system for climate will only be realised through a well planned and sustained international coordination effort, involving a number of challenges.

Effective Institutional Arrangements

Effective institutional arrangements have been proven to be fundamental to the progress achieved to date in establishing consensus on climate information requirements and coordination in the provision of observations to address them. The cooperation between CEOS and GCOS in support of the information requirements of the UNFCCC and its Parties is fundamental to the future success of the Convention and demonstrates the importance of strong partnerships between observation planners and global environmental governance frameworks like the UNFCCC.

CEOS is recognised as the primary international forum for coordination of the EO programmes of space agencies worldwide. Recognising also the importance of long-term space-based observing systems provided by operational satellites that are primarily used for weather observations, CEOS undertakes its climate-related coordination in association with CGMS.

The broad range of scientific challenges and priorities demanded of space-based observations can only be fulfilled through international cooperation. *The Architecture for Climate Monitoring from Space* coordinated by the CEOS-CGMS Working Group on Climate is an appropriate framework for such international cooperation. There is

a need for an integrated observational approach that is strategically designed to be cost effective and sustained over decades, yet remains targeted on key challenges and promotes the fusion of theory, models and observations. Where relevant, this approach should also address the linkage to societal benefits, as this can facilitate greater support and funding for such observation systems.

The importance of these institutional arrangements in support of the UNFCCC must be recognised and suitable political support and resources provided for their continued success. Planning and implementation of satellite observations can take years from inception and efficient processes need to be in place, linking the policy needs of UNFCCC and its parties with the observing requirements defined by GCOS and the planning processes of the space agencies.

Ensuring Continuity of Future Observations

A fundamental commitment by governments investing in space-based EO is needed to ensure continuation of the required observations at an acceptable level of accuracy and coverage.

CEOS will aim to ensure continuity, consistency and inter-comparability of the priority measurements throughout the coming decades, consistent with the requirements of climate studies for trend monitoring and change detection.

The Climate Monitoring from Space Architecture provides a vehicle for comprehensive review of the state of progress towards the full range of ECVs and to establish actions necessary to address shortcomings. Funding and execution of the individual satellite programmes remains the responsibility of individual governments and their space agencies and CEOS will continue to be dependent on their funding and capacity to deliver the EO satellite programmes.

Adopting and Reporting 'Climate Indicators'

Part II of this Handbook contains a substantial article on the need to adopt and popularise the use of a number of climate indicators that can become the recognised lexicon and reference for discussions by both policymakers and the public regarding the symptoms of climate change.

It is widely recognised in the scientific community that the use of global surface temperature as the focus for political messaging is a gross over-simplification and obfuscates significant underlying issues regarding the distribution of energy within the climate system.

The proposed climate indicators would be reliable, simple, have a long-term history, reflect a range of possible symptoms of climate change, integrate as far as possible many wider effects of change, be easily interpreted and conversely difficult to misinterpret. They need not be the same for policy makers and the public, but they must be accessible to both. Candidates include: surface temperature; sea level; atmospheric carbon dioxide; energy content of the climate system; total solar irradiance; measures of extreme climate event occurrence and intensity; and arctic sea ice extent and volume.

Such a dashboard of climate indicators, mostly derived from satellite data, might be included by GCOS in future updates to its Implementation Plan as a way to communicate better and more simply the changes in the Earth system linked to changing climate. Many of the likely measurements are provided by satellite observations and CEOS is ready to ensure that the necessary coordination is put in place to guarantee the observations needed in support of regular and routine updates to the vital signs and their reporting to society. This process must also reflect the political efforts in relation to achievement of the Sustainable Development Goals (SDGs) and support the societal linkages between disaster risk reduction, sustainable development and climate change.

Ensuring Accuracy of Climate Observations

Measuring long-term global climate change from space is a daunting task. The climate signals we are trying to detect are extremely small: temperature trends of only a few tenths of a degree Celsius per decade, ozone changes as little as 1% per decade and variations in the Sun's output as tiny as 0.1% per decade or less.

Accuracy is an important attribute of a climate observing system and helps to advance the understanding of physical processes in the Earth's climate system. CEOS space agencies foresee a series of highly accurate climate-reference instruments in order to measure with high spectral resolution the energy reflected and emitted by the Earth. These instruments would provide reliable long-term records of climate forcings, response and feedbacks to monitor climate change. Their records would also serve as the validation data needed to test and evaluate climate model predictions. The benchmark instruments would also constitute a reference standard, or calibration observatory, in space that can be applied to other environmental satellite sensors that are not as well calibrated, eg the sensors on operational weather satellites. Such calibrations can be performed by comparing coincident observations of the benchmark instruments with the other sensors.

Part II

Key Activities in Space-based Climate Observations

1 GCOS and its Important Role in Observing the Earth's Changing Climate

Observations are fundamental to improving the scientific understanding of climate and to delivering the vetted, timely and purposeful climate information needed to support climate mitigation and adaption decision-making. The demand for information on global climate has been increasing since the inception of the IPCC (Intergovernmental Panel on Climate Change) and the WCRP (World Climate Research Programme) nearly three decades ago. Many regions in the world are clearly impacted by changes in climate and those changes need to be managed now.

Observation and monitoring of the Earth's changing climate is a key element of the emerging Global Framework for Climate Services and, more generally, underpins climate research, assessment of climate change and the development of policy responses.

The Global Climate Observing System (GCOS) was established in 1992 by the World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission (IOC), United Nations Environment Programme (UNEP), and International Council for Science (ICSU) with a comprehensive GCOS plan agreed by mid-1995.

Since then, GCOS, working with national agencies and international organizations such as the sponsors of GCOS, has made significant progress. Routine observations have been improved to meet the exacting demands of climate records, aid provided for the deployment of critical new observing systems and assistance provided to developing countries to improve their observing networks. Significant results include:

– Defining the Atmospheric Observing Network for Climate

– Developing Ocean Observing Networks for Climate

– Facilitating the Expansion of Terrestrial Climate Networks

– Establishing Important Links to the UNFCCC

– Defining the GCOS Climate Monitoring Principles

– Producing the Adequacy and Progress Reports and Implementation Plans

– Promoting the Development of Satellite Observing Systems for Climate

– Implementing a GCOS Regional Workshop Programme

GCOS introduced the widely accepted concept of ECVs and addressed the need for global coverage and timeliness of data. The GCOS Climate Monitoring Principles were adopted by the UNFCCC in 2004. The UNFCCC also emphasised the principle of free and unrestricted exchange for ECV datasets.

1.1 Essential Climate Variables (ECV)

In the 1990s, gaps in knowledge of climate and declining core observational networks in many countries led to calls for systematic observation of a limited set of critical variables. To provide guidance, the GCOS programme developed the concept of ECVs, which has since been broadly adopted in science and policy circles.

An ECV is a physical, chemical or biological variable (e.g. precipitation) or a group of linked variables (e.g. permafrost: area, depth and temperature) that together characterise the Earth's climate. ECV datasets provide the empirical evidence needed to understand and predict the evolution

of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climatic events to underlying causes, and to underpin climate services.

Observing the ECVs and generating climate datasets should be relevant, feasible and cost-effective.

GCOS, together with the WCRP, co-sponsors three climate observation panels (Atmosphere, Ocean and Terrestrial) whose role is to assess the global observing system, review the adequacy of the observing networks, identify measureable key variables (ECVs) and coordinate with other global observing systems.

In addition, the GCOS Co-operation Mechanism (GCM), which once originated from the UNFCCC and its Subsidiary Body for Scientific and Technological Advice (SBSTA) allows developed countries to contribute funds to address specific needs in climate observing networks in developing countries.

1.2 Establishing Observational Systems

The largest observing system, together with operational meteorological satellites, is the World Weather Watch/Global Observing System (WWW/GOS) of WMO. National Meteorological and Hydrological Services (NMHSs) provide the fundamental atmospheric networks. However, there is a need for a worldwide system capable of producing observations of greater accuracy and coverage and comprising additional appropriate climate variables. Among those needed are the atmospheric chemistry variables measured as part of the WMO's Global Atmosphere Watch (GAW).

GCOS defined a subset of the WWW stations of roughly 1000 baseline surface stations that became the GCOS Surface Network (GSN), while a select set of 150 upper air stations was designated as the GCOS Upper-Air Network (GUAN). Designation helped incorporate climate requirements into meteorological service procedures and, for NMHSs, helped sustain support for these long-running sites. These networks provided the foundation for the Regional Basic Climatological Network (RBCN), which provides far greater spatial detail on the variability of climate.

By 2001, annual reports prepared by WMO indicated that the GSN and GUAN were in need of performance improvements. The GCOS System Improvement Programme, which is an element of the GCOS Cooperation Mechanism, has resulted in the renovation of over 30 GSN and 20 GUAN stations, in addition to providing over 25 station-years of radiosondes. The longer-term intent is to apply GCM funds to needs in the oceanic and terrestrial domains in addition to those in the atmospheric domain.

One of the great achievements in climate monitoring over the last 20 years has been the development of ocean observing systems. Knowledge of the global oceans today is partly the result of deployment of both in-situ and satellite systems.

The Pacific Tropical Atmosphere Ocean (TAO) array has been expanded to both the Atlantic and Indian tropics, providing real benefits in seasonal and inter-annual climate prediction. A global network of floats measuring many

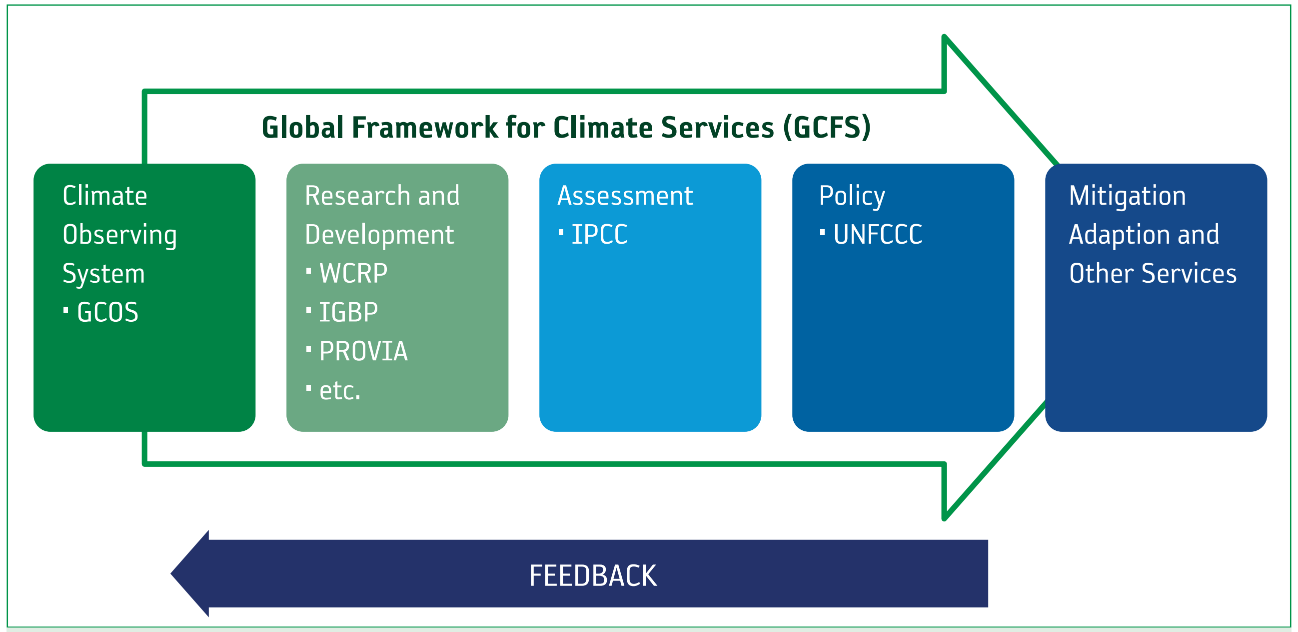


Figure 1: Observing systems underpin climate assessment, policy development and addressing adaption, mitigation and other climate services

parameters, called the Argo Programme, reached its goal of 3000 floats in 2007 and currently has over 3500 floats in the water, measuring the temperature and salinity in the upper 1–2 km of the ocean. In addition a worldwide system of reference stations, known as OceanSITES, provides full-depth coverage at 60 sites for dozens of variables. Overall, the number of in-situ oceanographic reports has gone from roughly 4.5 million in 1999 to more than 16 million in 2009.

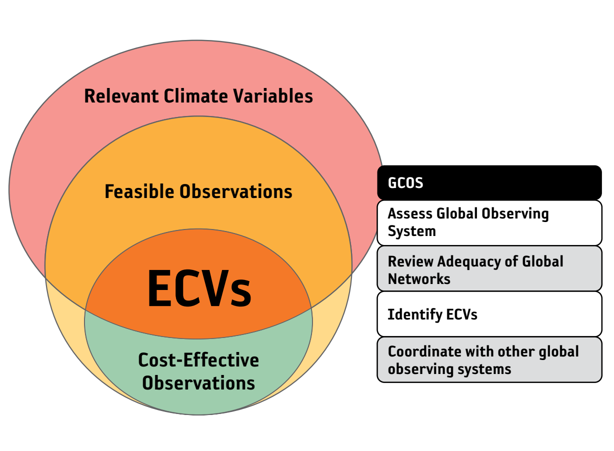


Figure 2: ECVs are relevant to understanding climate change, feasible and cost-effective

The satellite record of global sea level now stretches almost 20 years, from TOPEX/Poseidon through Jason-1 and Jason-2. Analyses from many international groups have converged on global mean sea-level rise rates of 3.1-3.2 mm/year. The far longer Global Sea Level Observing System (GLOSS) network time series provides local variations in sea level and the long-term context of satellite measurements.

There has been notable progress in terrestrial networks for climate over the 20 years since GCOS was founded, particularly in cryospheric measurements. A time series of ice sheet mass balance from space now extends from 1992 to the present. The overall performance of in-situ glacier monitoring networks has been improving, as noted by the World Glacier Monitoring Service, while satellite-based glacier inventories have expanded considerably.

For other terrestrial measurements, the increased commitment of space agencies to produce fundamental climate data records from existing systems has led to improved availability of global datasets, such as of burned area, FAPAR, LAI, above-ground biomass, land cover, lakes and soil moisture. The community now increasingly uses these datasets.

1.3 UNFCCC

Both GCOS and the UNFCCC were established in 1992 and an enduring partnership between them has been in place ever since. Language on research and systematic observations was included in the text of the Convention in 1992 in Articles 4 and 5.

The original GCOS report on the adequacy of the global climate observing systems was requested by the UNFCCC in 1997. Additional interactions include the delivery in 2004 of the *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC* and its 2010 update. The UNFCCC has been and remains a vital mechanism to bring issues of maintenance of the long-term climate record to the attention of governments in an international forum.

1.4 Regions

The GCOS Programme began working with regions to identify priority observing system needs following an invitation by the UNFCCC at the 5th Session of the Conference of the Parties in 1999 to organize a Regional Workshop Programme. This led to the preparation of Regional Action Plans in 10 regions of the world, prepared by experts from each region, and containing 10–15 project proposals addressing regional observing system priorities. In 2006, the GCOS Secretariat helped organise a major meeting with potential donors in Ethiopia to help find funding for these proposals. This meeting led to the establishment of the Climate for Development in Africa Programme, a programme that is now poised to assist funding of African observing system needs.

1.5 GCOS and Satellites

Satellites provide a vital means of obtaining observations of the climate system from a global perspective. A detailed global climate record for the future will not be possible without a major, sustained satellite component. There has been direct and intense interaction between the GCOS Programme and the satellite community over the entire history of GCOS.

One of the highlights of this interaction has been the development of a strong working relationship between GCOS and CEOS, the primary international forum for coordination of space-based EO. In 2006, space agencies, through CEOS, responded to the GCOS climate requirements by identifying 59 separate actions to be undertaken. In addition, CEOS requested, and was provided by GCOS with, a more detailed analysis of satellite climate observing needs in the form of the 2006 Satellite Supplement and its 2011 update.

There has been an increasing interest in long-term satellite observations of climate. Many of the major EO platforms of the 1990s had climate observation as their major driver. However, there has been an increasing concern for continuity of the climate record, following the GCOS Climate Monitoring Principles.

GCOS has also been active recently in defining requirements for climate datasets, particularly in its Guideline for the Generation of Datasets and Products Meeting GCOS Requirements, which has been influential in the development of CGMS and the Global Space-Based Satellite Inter-calibration System (GSICS) implemented by WMO.

Satellite observations have become a fundamental part of GCOS and, when combined with sufficient ground-based measurements, provide a comprehensive view of the global climate.

1.6 Next Steps

In 2014, GCOS was reviewed by a board appointed by its sponsors, ICSU, WMO, IOC and UNEP. Its overall conclusion was:

"There is no doubt the GCOS Programme should be continued. It is indispensible. If it ceased to exist it would need to be re-created."

The review made a number of recommendations for improving GCOS. Improvements are needed to better integrate the sustained observing system and ensure it will meet future requirements. For instance, the Tropical Pacific Observing System (TPOS) has been in place for 20 years. Motivated by challenges in sustaining key components

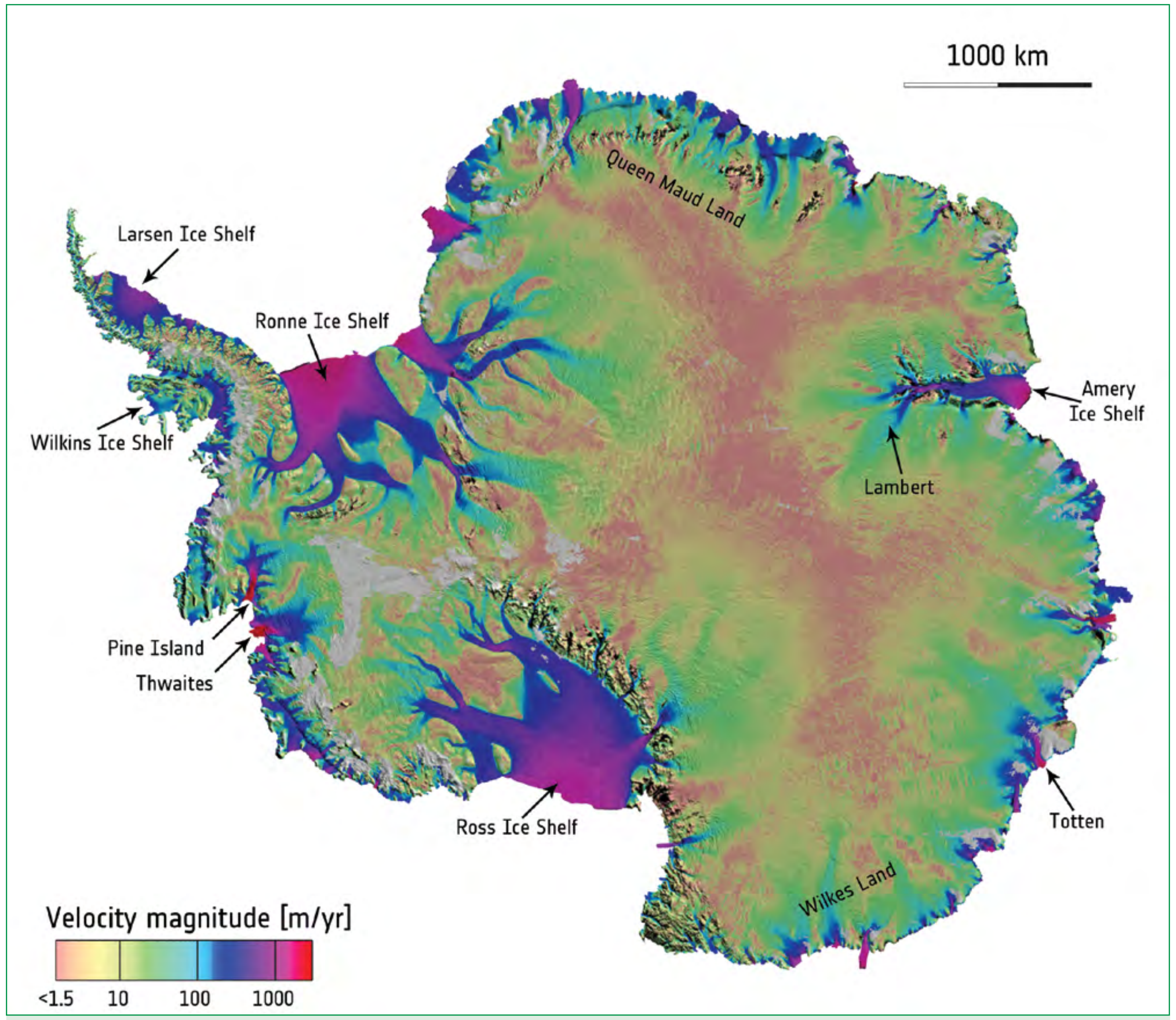


Figure 3: Antarctic ice velocity from Rignot et al., combining multi-mission SAR data acquisitions coordinated by the IPY Space Task Group, with support from ESA, CSA, JAXA and NASA.

of the observing system and evolution in observation requirements and technology, an international review recommended the TPOS 2020 project to make TPOS more robust, integrated and sustainable, and able to meet future needs. TPOS 2020 is now well underway.

GCOS has produced a status report reviewing progress of the Global Climate Observing System and outcomes of actions identified in the Implementation Plan. This Status Report will be submitted to the UNFCCC SBSTA at COP21.

GCOS is also preparing a new Implementation Plan to present to the UNFCCC SBSTA at COP22 in December 2016.

Article contributors:

Carolin Richter and Simon Eggleston (GCOS)

Further information

GCOS:
www.wmo.int/pages/prog/gcos

GCOS publications:
www.wmo.int/pages/prog/gcos/index.php?name=Publications

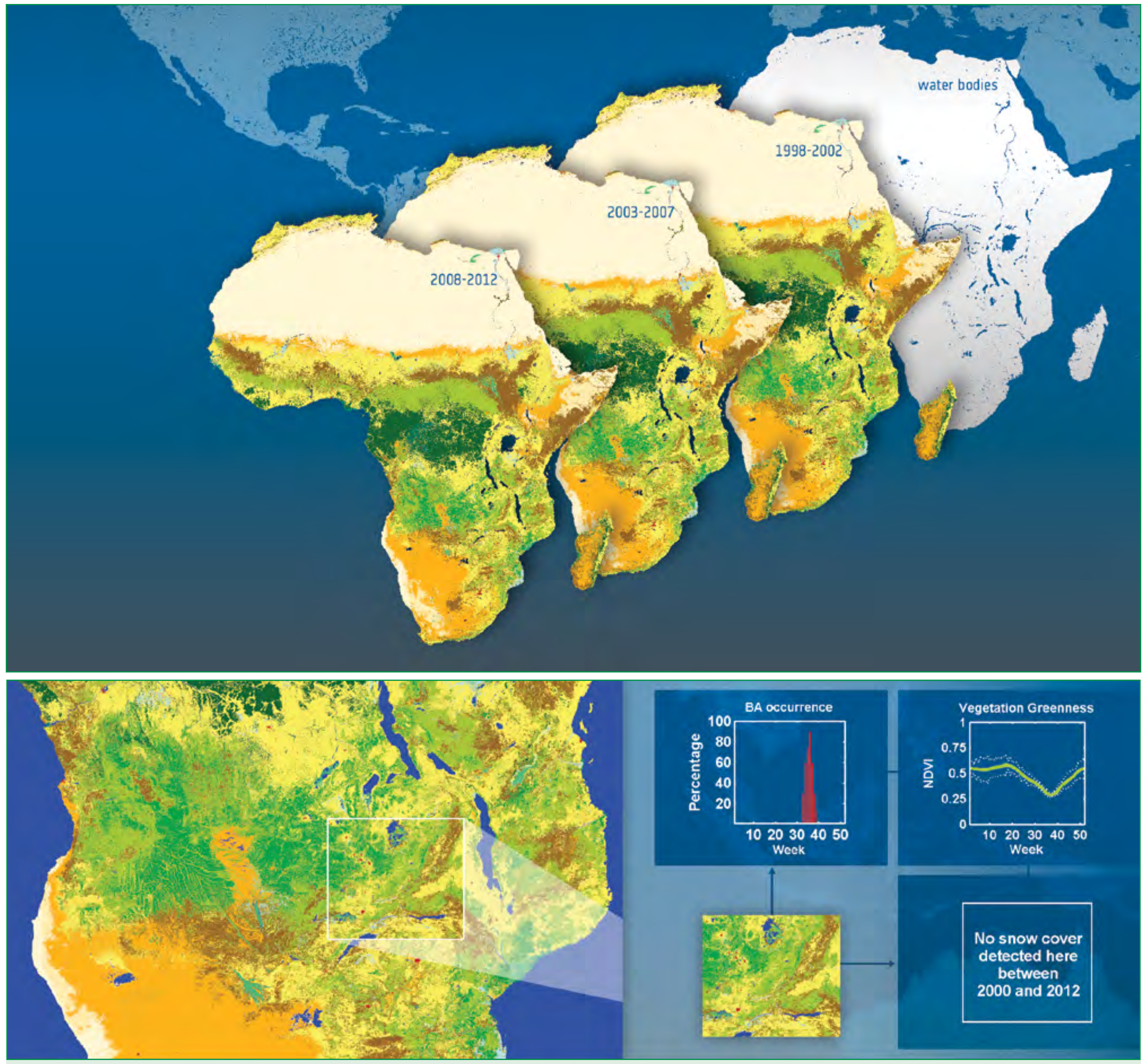


Figure 4: The ESA CCI has released three global LC maps for the 1998–2002, 2003–2007 and 2008–2012 epochs and three global land cover seasonality products describing vegetation greenness, snow and burned area occurrence dynamics. All products can be freely accessed online at http://maps.elie.ucl.ac.be/CCI/viewer (picture: ESA). *Credit: Land Cover_cci Project Team.*

ESA's Climate Change Initiative

2.1 Introduction

All of the major space agencies have programmes dedicated to the development and stewardship of climate data records from satellite observations. This article highlights the programme of the European Space Agency (ESA).

As a contribution to the response from CEOS to GCOS on the need for ECV products, ESA initiated a programme, the Climate Change Initiative (CCI), to bring together European expertise covering the full range of scientific, technical and development specialisations available within the European EO community and to establish lasting and transparent access for global climate scientific and operational communities to its results. The objective of the CCI programme is to realise the full potential of the long-term global EO archives that ESA together with its Member States have established over the last 30 years, as a significant and timely contribution to the ECV databases required by the UNFCCC.

Since 2010, the CCI programme has performed algorithm development, inter-comparison and validation, and large-scale EO data processing for 13 GCOS ECVs where the potential contribution from ESA was considered unique and/or significant. Importantly, all CCI ECV data products are provided with quantitative uncertainty estimates and have been evaluated by leading members of the climate research community. It has contributed to a rapidly expanding body of scientific knowledge, demonstrating new insights in climate research by maximising the scientific benefits that satellite observations can provide to better inform and respond to needs raised by the IPCC.

To achieve this, substantial community building has taken place to strengthen the relationship between satellite data product developers and climate scientists. As a result of the multidisciplinary approach of the programme, strong links have also been forged spanning the land, ocean, atmosphere and cryosphere science communities. The products are being made available through the CCI Data Portal and the intention is that the processing systems are transferred from CCI to operational programmes, such as Europe's Copernicus Climate Change Service (C3S).

2.2 Responding to the IPCC

The IPCC reports synthesise all the published evidence on climate change and produce an assessment of the current state of knowledge. These assessments come with statements on their confidence as well as reporting on changes since the last report. In the fifth IPCC Report in 2013, CCI made contributions in specific areas with direct impact on summary conclusions as a result of improved ECV products and greater community consensus.

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (high confidence) (IPCC 2013).

The Randolph Glacier Inventory (RGI) is the first globally complete inventory of glaciers produced for IPCC AR5, with ESA projects contributing about one-third of all glacier outlines (Figure 1) and consortium members from Glaciers CCI being instrumental in its successful creation.

The RGI has proven vital for global-scale applications, in particular sea level change assessments since the lack of knowledge of the global distribution of glaciers was a significant, but very hard to quantify, source of uncertainty. This has allowed greater agreement on future glacier mass loss.

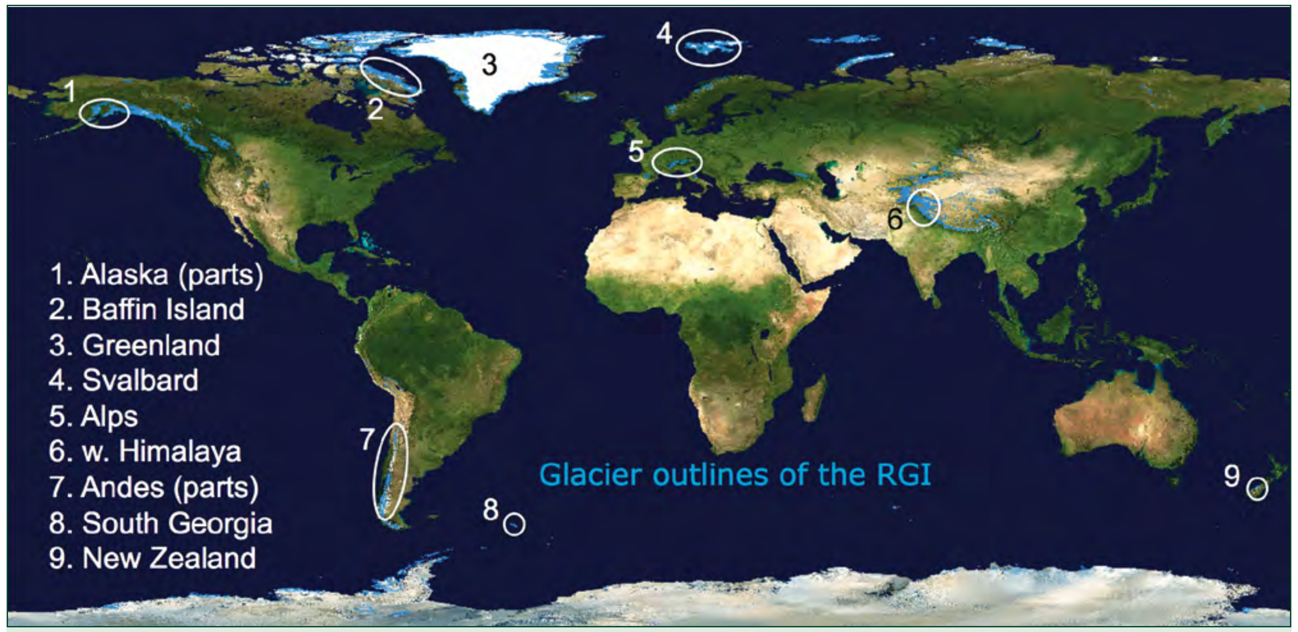


Figure 1: Glacier outlines from the RGI (blue) with contributions from the Glaciers_cci Project Team (Background is MODIS Blue Marble)

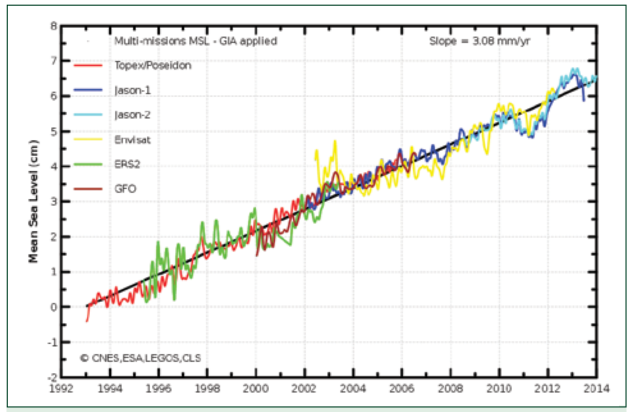


Figure 2: Multi-mission global sea level trend from altimetry. This figure includes all the CCI satellite time series overlaid after being adjusted for biases – 1993 to 2013 (mm/year).
Credit: CNES, ESA, LEGOS, CLS

The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (high confidence). Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (IPCC 2013).

Improved global mean sea level estimates have been produced through evolution of algorithms and homogeneous reprocessing of satellite data from multiple satellites. These products were developed in the framework of the Ocean Surface Topography Science Team (OSTST) and GLOSS. While they cover the period from 1993 to the present, they tie in well with buoy observations from earlier in the 20th century.

By combining the CCI products with other ECVs, improved sea level budget studies have been performed at global and regional scales, allowing estimates of unknown or poorly known contributions (e.g. the deep ocean heat uptake and its role in the current hiatus or the land water storage change due to human activities). The provision of these high quality data has encouraged cross-ECV interaction and hence allowed better knowledge of the components necessary for sea level budget closure. Further work on this is currently being pursued by bringing the CCI teams together to focus on sea level budget closure.

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (high confidence). It is virtually certain that the upper ocean (0–700 m) warmed from 1971 to 2010, and it likely warmed between the 1870s and 1971 (IPCC 2013).

Sea Surface Temperature (SST) datasets have been developed over the period from 1991–2010 using the Along Track Scanning Radiometer (ATSR) and Advanced Very High Resolution Radiometer (AVHRR) satellite data, with Spinning Enhanced Visible and Infrared Imager (SEVIRI) data for diurnal modelling of infrared temperatures. By combining these records with those from passive microwave instruments, SST records and departures from the mean have been produced (Figure 3). The products include both skin SST and SST at standard depth. They are homogeneous and stable throughout the time series, accompanied by context-specific uncertainty estimates and independent from in-situ measurements.

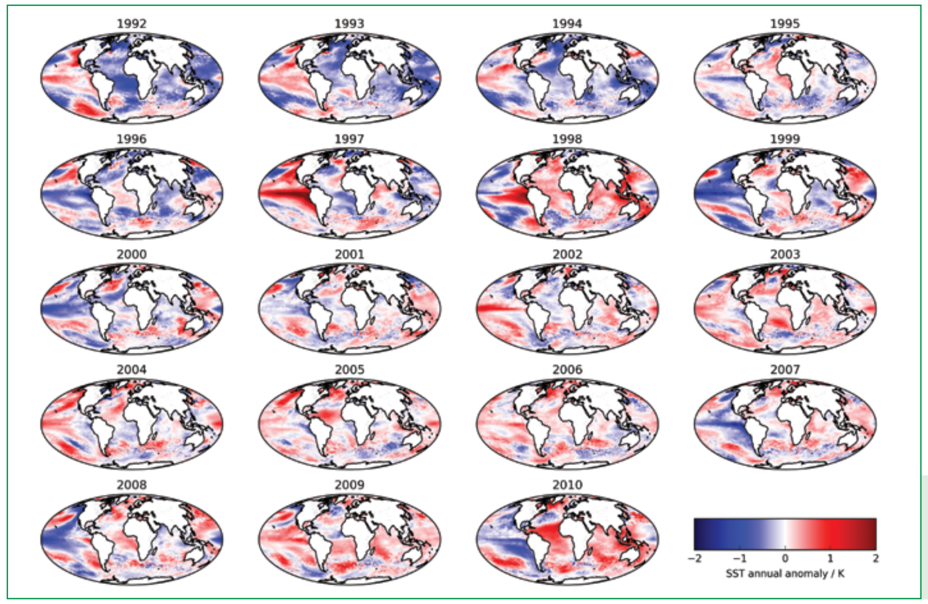


Figure 3: CCI annual mean sea surface temperature (SST) anomaly maps for 1992–2010
Credit: SST_cci Project Team

2.3 Community Building

To achieve the generation of a complete ECV requires the space agencies and the EO science community to collaborate more closely at a scientific level and to coordinate better to ensure data are accessible to all and that the data are adequately preserved over long periods of time. A part of this substantial community building has taken place within CCI to strengthen the relationship between satellite data product developers, EO scientists and climate scientists. Key examples include the development of the RGI for IPCC, the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE), development of close international collaboration on greenhouse gases and the unification of the global satellite aerosol science community through the AeroSAT initiative as a complement to Aeronet and AeroCom.

The RGI was achieved through a major community effort along with international cooperation between the Global Terrestrial Network for Glaciers (GTN-G), the World Glacier Monitoring Service (WGMS) and Global Land Ice Measurements from Space (GLIMS). This is now evolving into development of a global glacier database (gtn-g.org/data_browser.html). IMBIE was a collaboration between ESA and NASA to bring together the key scientists in ice sheet mass balance to end a 20-year disagreement. It produced a reconciled estimate of ice sheet mass balance changes in Antarctica and Greenland, as seen from satellites, and their contribution to sea level rise (Figure 4) is being continued through the second IMBIE experiment.

The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land-use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification (IPCC 2013).

The expertise in greenhouse gas assessment in Europe through the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCHIMACHY) has been coupled with the launches of the Japanese Greenhouse

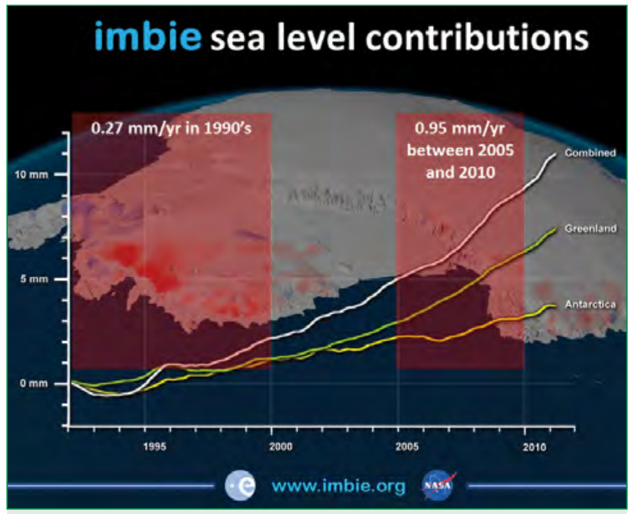


Figure 4: Reconciled sea level contributions due to mass loss from the Greenland and Antarctic Ice Sheets (Shepherd et al. 2012)

Gases Observing Satellite (GOSAT) and US OCO-2 satellites, which took place in the CCI period. This allowed the groups from Europe to work closely together with those from Japan and the US to test multiple algorithms to improve CO_2 and CH_4 retrieval accuracies and coverage and in the process generate column average CO_2 and CH_4 from the SCIAMACHY instrument (2002–2012) and the Japanese Thermal and Near-infrared Sensor for Carbon Observation (TANSO) instrument (2009–2014) and prepare for the Orbiting Carbon Observatory-2 mission (OCO-2).

Total radiative forcing is positive and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750 (IPCC 2013).

One of the greatest uncertainties in climate science is the degree of radiative forcing attributable to aerosols. To help tackle this, the global satellite aerosol science community has been brought together through the AeroSAT initiative as part of the global effort to better understand aerosol behaviour and as a complement to the in-situ Aeronet and AeroCom modelling communities. This has also helped pull together a very disparate community in Europe and thus allowed the development of aerosol property ECV data sets for test years from multiple satellites and an aerosol product from the ATSR-2 and AATSR instruments over the period 1995-2012

2.4 Cross-domain Exchange and EO and Climate Community Collaboration

In addition to improvements in ECV products and collaboration within the communities that generate them, fundamental needs exist to ensure that consistency exists between different ECVs and also that the products are known by and used by the climate community itself. Major successes of the CCI include transparency in production and documentation, estimation of uncertainty and exchange between teams responsible for given ECVs. In addition, the continuous exchange with the climate research and climate modelling communities has been emphasised through their involvement in individual teams and also through the specific Climate Modelling User Group (CMUG), which represents several of the major modelling groups in Europe. These twin elements have allowed the projects to evaluate their products as they proceed. Regular colocation meetings across the CCI Programme, targeting specific topics, have encouraged the traditional boundaries between domains and product-focused communities to be breached. There is therefore a greater willingness to collaborate on common themes and, as a consequence, a desire to tackle larger questions such as how to close the sea level budget, as well as greater openness in model development. These themes need to be continued and developed to spawn better ECV products, such as improved estimates of fire disturbance to help constrain and validate the representation of fire in climate models (Figure 5), and hence go beyond the requirements envisaged by GCOS.

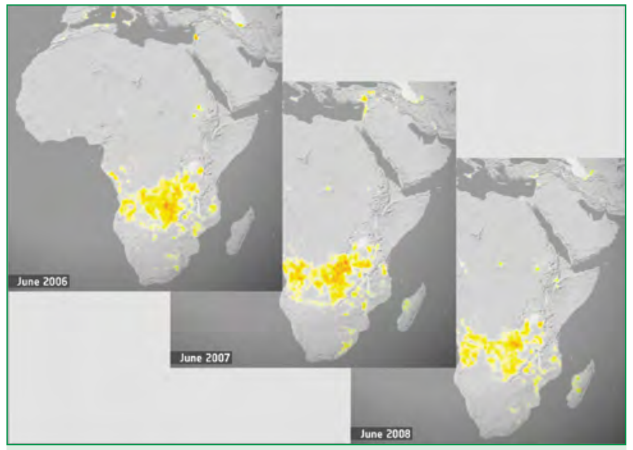


Figure 5: Fire_cci developed spatial distributions of fires at climate model resolution to test the representation of fire in these models.
Credit: Fire_cci Project Team

2.5 Conclusions

The IPCC's AR5 in 2013 highlighted the importance of improvements in both observations and modelling in understanding the Earth as a system and addressing the scientific challenge of monitoring and predicting climate change. Advances in understanding based on better observations and models have been noted and hence there is more confidence in statements made in the report compared with the AR4 released in 2007. These improvements in understanding have been made partly through provision of high quality ECV data products and their availability to the science community. ESA's CCI has taken a lead role in Europe in organising the community and exploiting the data archives accrued in Europe, but the improvements are also a function of the development of structures and fora to exchange information at the international level as well as greater collaboration between science domains and within the EO community.

Despite the successes demonstrated by the CCI so far, considerably more work needs to be done to meet the growing demand for ECV data products to satisfy the increasingly complex scientific challenges presented by change in the Earth's climate and the consequent negative impacts on the environment and human prosperity. While understanding of the Earth as a system has been the focus of the first decade of the 21st century, the next decade for science will be to address the urgent societal challenge to support climate adaptation and mitigation. This is already reflected within Europe in terms of the high priority assigned to climate research and climate service development and the implementation of operational climate services through the EU's Copernicus programme. This new challenge requires even greater effort to go beyond production of high quality observational data sets for climate understanding (i.e. GCOS ECVs) to target information requirements for climate adaptation and mitigation.

Article contributors:

Stephen Plummer, Simon Pinnock, Pascal Lecomte (ESA CCI programme management team)

References

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Shepherd, A. et al. 2012, A Reconciled Estimate of Ice-Sheet Mass Balance, Science 338, 1183, DOI: 10.1126/science.1228102

Further information

ESA CCI:
cci.esa.int

Other International Programmes

EUMETSAT climate products:
www.eumetsat.int/website/home/Data/Products/Climate/index.html

NCDC Climate Data Record programme:
www.ncdc.noaa.gov/cdr/index.html

NASA Climate site:
climate.nasa.gov/evidence

Global Forest Observations for Forest Carbon Tracking

3.1 Our Valuable Forests

Covering around 30% of the world's land area, forests have a crucial role in supporting life on Earth. They support an abundance of ecosystem services, such as providing food and habitat for a variety of species, regulating climate and supporting nutrient cycling, carbon storage and watershed services. Forests also contain scenic landscapes of intrinsic and cultural value.

Human dependence on forests extends their use as a source of food, fuel, medicines and construction materials. Forests are a key driver of industry and economic growth in many parts of the world.

Of perhaps greatest importance is the role of forests in balancing the Earth's carbon budget. Forests have a key role in sequestering carbon and act as a valuable sink to offset other sources of CO_2 in the atmosphere including from deforestation, fire and fossil fuel emissions.

Protecting our forests forms a valuable part of the strategy to mitigate climate change.

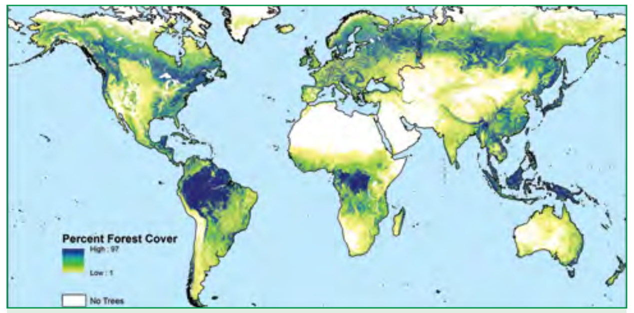


Figure 1: Global tree cover based on MODIS data (M. Hansen, UMD)
Credit: Pan et al. 2013

3.2 Deforestation and Forest Degradation

The extent of forest loss caused by human disturbance has been substantial and progressive. Over 40% of forest area has been cleared, with most occurring during and following the Industrial Revolution. Over the past decade, the greatest losses were felt in the tropical region, with boreal forest loss placed second.

Plantations and regrowth have resulted in a decrease in the net loss of forests in some countries. However, we are still losing around 13 million hectares of forest each year. South America and Africa continue to experience the greatest net loss of forest.

The undervaluing of forests has increased their susceptibility to development pressures and conversion. Degradation of forests occurs where there is a persistent loss in carbon density over time. The drivers are many and varied and involve human pressure (unsustainable logging, shifting cultivation, grazing, urbanization) and natural factors (fire, disease, pests).

Current rates of deforestation and forest degradation are responsible for around 17% of anthropogenic greenhouse gas emissions (www.unep.org/vitalforest/). This is second only to burning of fossil fuels. The impact of forest loss will be felt at all scales, from global climate change to declining economic value of forest resources and biodiversity and threatened local livelihoods.

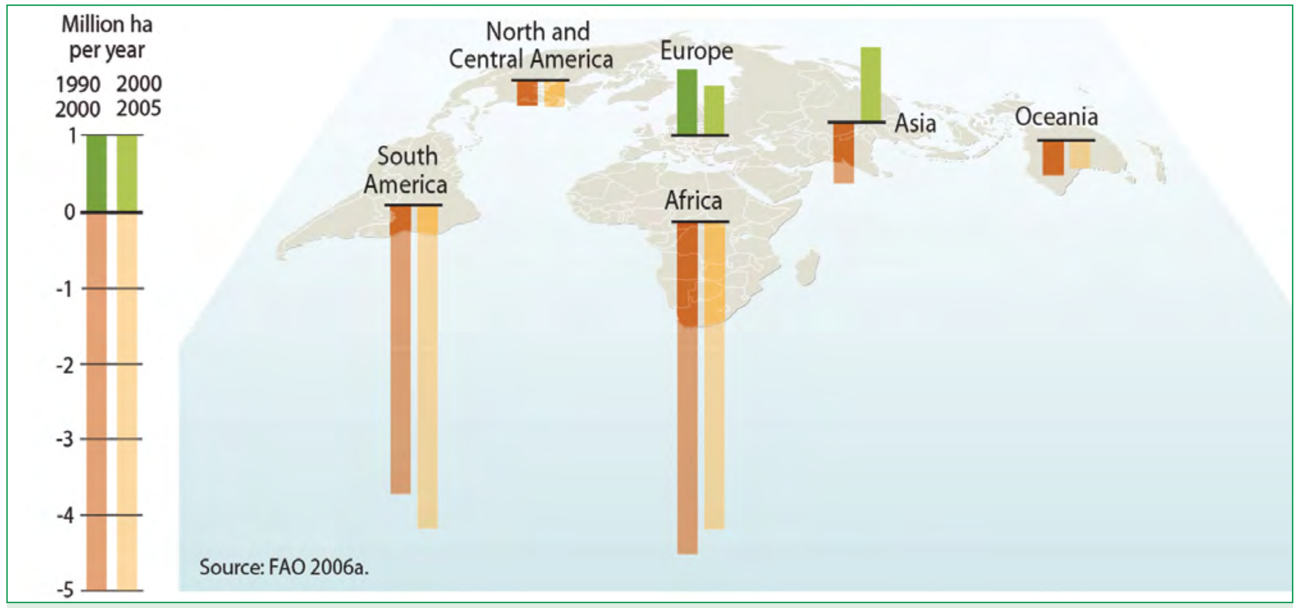


Figure 2: Forest net change 1990–2005 (FAO, 2006: Global Forest Resources Assessment 2005)

3.3 The International Response

A number of global initiatives are underway that aim to improve the sustainability of forest management practices. Collectively, they aim to promote the development of national forest monitoring systems that utilise satellite Earth observations and improve confidence in greenhouse gas emissions estimates.

The adoption of the UNFCCC in 1992 was a significant step towards tackling the issue of global warming. Member countries participate in strategy development at COP on an annual basis. Key agreements to date include:

- The Kyoto Protocol (COP3, 1997)
- Reducing Emissions from Deforestation and Forest Degradation (REDD; COP13, 2007)
- Reducing Emissions from Deforestation and Forest Degradation (REDD+; COP16, 2010)

The Kyoto Protocol required a commitment from developed countries to reduce their greenhouse gas emissions below a specified level within five-year timeframes (first commitment period: 2008–2012). While accounting for forest carbon management practices, including afforestation, deforestation and reforestation, was part of the process, the conservation of forest carbon stocks was not.

REDD was adopted as a means of including developing countries and the protection of forest carbon stocks in negotiations. Financial incentives are offered to developing countries that implement carbon emissions reduction schemes and a low carbon economy.

REDD+ goes beyond REDD and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. REDD+ countries must commit to periodic measurement, reporting and verification (MRV) in the forest and other land-use sectors in accordance with the IPCC Guidelines. Central to the process is the establishment of a robust and transparent MRV system that uses a combination of satellite EO and forest inventory for producing a validated carbon emissions account.

Assisting in the implementation of REDD+ are the United Nations REDD Programme (UN-REDD), the World Bank's Forest Carbon Partnership Facility and the Global Environment Facility. These agencies are engaged in capacity building, developing finance mechanisms and assisting countries in their REDD+ preparedness.

COP21 in December 2015 has the aim of achieving universal agreement on climate change mitigation. Countries will submit their proposed approach to long-term reductions in greenhouse gas emissions and adaptation to change. A binding agreement is foreseen to be entered into force from 2020 onward, providing recognition, at last, of the scale and impact of climate change and the desire to tackle it head on.

3.4 Forest Information Requirements

Primarily as a consequence of the role of forests in regional to global carbon budgets, there is a requirement for annual spatially explicit national mapping of forest cover and carbon stocks. Spatially explicit information is needed to track activities and drivers and support estimation of greenhouse gas emissions and removals.

The IPCC *Good Practice Guidance* in greenhouse gas inventory development mandates the following: transparency, completeness, consistency, comparability and accuracy. National forest monitoring systems should provide data and information that is transparent, consistent over time, and suitable for MRV of REDD+ activities and nationally appropriate mitigation actions. Consistency with historical data is necessary for establishing forest reference (and emission) levels. Methods that minimise bias and allow comparison between countries should be used.

The need for forest information extends beyond national forest monitoring and greenhouse gas inventory. The Group on Earth Observations' (GEO) nine societal benefit areas need some type of information about forests. Information about the status of forest resources is used in forestry operations, natural resource management, conservation and reserve planning, and biodiversity assessment.

3.5 The Role of EO Satellites

To meet the requirement for annual spatially explicit national mapping, the availability of gap-free moderate resolution (10–30m) satellite data is essential. Complementary optical and radar satellite sensors are currently operational and both support the development of forest information monitoring systems.

EO satellites and data processing systems have advanced to the point where it is feasible for countries to produce wall-to-wall assessments of forest and land cover change at national scale. Modelling techniques have also evolved to allow extrapolation of forest inventory measurements and their integration with EO data.

These data will enable countries to produce consistent and comparable annual reports on changes in forest carbon, emissions and removals that can support any binding agreement on emissions reductions targets at COP21.

Satellite EO is considered a valuable source of activity (change) data for mapping land-use. Optical imagery is widely used and offers the most operational capability today. The long temporal archives of the Landsat series are useful for baseline generation and tracking change in land cover/land-use. The existing Landsat Long-Term Acquisition Plans (LTAP) allow frequent observation (ten attempts globally per year) over forested areas.

Figure 3: Landsat-based forest cover change mapping in Colombia
Credit: IDEAM, Colombia

The spectral properties in the optical domain are well suited for forest monitoring, although cloud cover can be limiting. Higher resolution data (RapidEye, WorldView, Pléiades) are suited to detection of fine-scale change. Frequent observations are a requirement for capturing discrete events or rapid change in dynamic environments. The European Sentinel-2A mission, launched in June 2015, provides improved global optical coverage and is expected to be useful for tracking disturbance and subtle changes in forest cover, arising through, for example, forest degradation.

Radar sensors penetrate cloud and operate independently of the weather, so are particularly useful in tropical regions. The different radar wavelengths are sensitive to different forest structures and above-ground biomass. Longer wavelength L-band radar is suited to monitoring changes in forest extent and estimating biomass in low biomass forests. Dense time-series of C-band observations (Sentinel-1) allow tracking of changes in forest cover. High-resolution products (canopy gaps and height) are possible using data from X-band sensors (TerraSAR-X/TanDEM-X).

Data from previous generation (JERS-1, ALOS) and current (ALOS-2) L-band radars can be integrated to observe historic and more recent change in forest cover. The ALOS-2 global

Figure 4: The PRODES Landsat deforestation monitoring programme in the Brazilian Amazon
Credit: INPE, Brazil

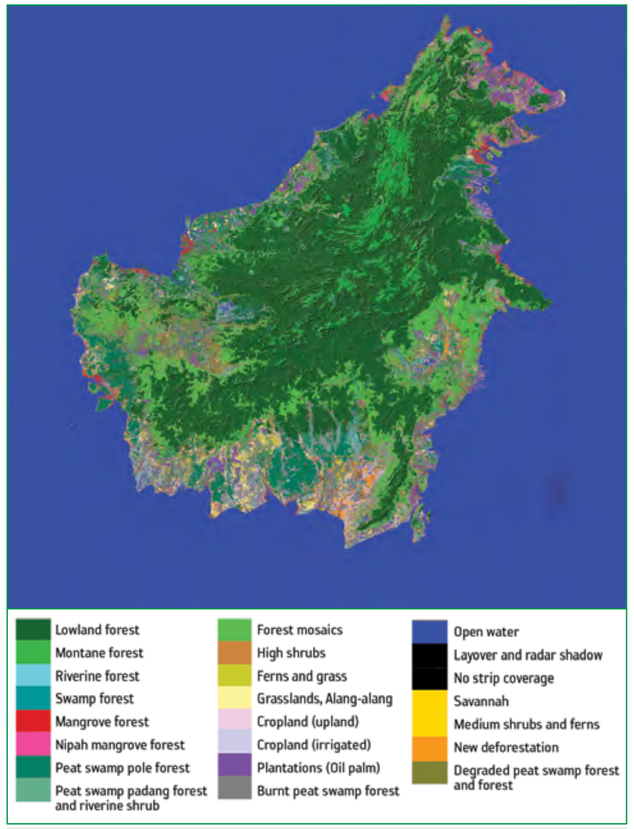


Figure 5: Wall-to-wall land cover map over Borneo island derived from ALOS PALSAR data
Credit: D. Hoekman, Wageningen UR, NL

data acquisition strategy allows two global observation attempts per year and four over tropical regions.

Data from multiple EO sensors are often integrated, as this helps overcome sensor specific limitations such as saturation, operating modes and temporal gaps. Data fusion is often necessary for mapping forest types, degradation and biomass and can improve the detection of change.

Future satellite radars, such as BIOMASS, and space-borne LiDARs (ICESat-2, MOLI and GEDI) may well revolutionise

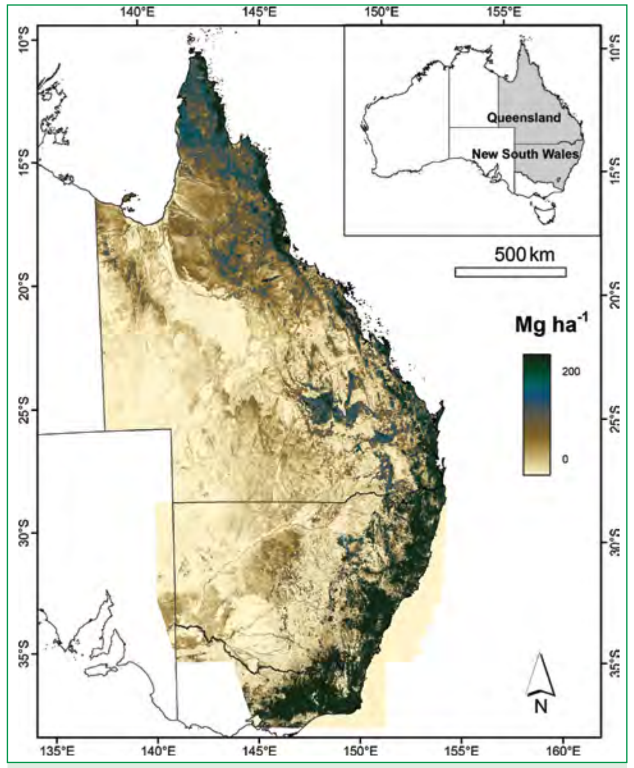


Figure 6: Estimated above ground biomass in eastern Australia, derived from Landsat, ALOS PALSAR and ICESat data
Credit: R. Lucas, UNSW; Credit: JAXA K&C, JRSRP UQ/DSITI, U Aberystwyth

the capacity to monitor changes in forest carbon. By combining long time-series and high resolution data, this will enable better tracking of change as a result of forest dynamics, allowing for better assessments of carbon balances and sequestration potential, as well as habitat quality and biodiversity.

3.6 The Global Forest Observations Initiative

The Global Forest Observations Initiative (GFOI; www.gfoi.org) was set up in 2011 to support the goal of reducing greenhouse gas emissions from the forestry and land-use sectors. National forest information systems are recognised to be essential for effective participation in and reporting to international climate change agreements. GFOI supports governments that are establishing national forest monitoring systems by:

- Fostering the sustained availability of satellite data in support of national efforts to better manage forest resources
- Providing assistance (capacity building) on utilising satellite and ground-based observations
- Developing Methods and Guidance Documentation (MGD) on the use of data for national forest monitoring systems, consistent with IPCC guidelines

– Promoting on-going research and development (R&D) and supporting continuous improvements in forest monitoring and reporting systems

GFOI builds on previous experiences of the GEO Forest Carbon Tracking (FCT) task. It aims to extend national forest monitoring efforts to a global level and promote best practice methods consistent with UNFCCC greenhouse gas reporting requirements. GFOI works in parallel with other global initiatives at the Food and Agriculture Organization (FAO), World Bank, IPCC and Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD).

From the outset, GFOI has encouraged countries to develop national forest monitoring systems that use wall-to-wall time-series of satellite observations to better track changes in forest cover. Such a system allows countries to demonstrate long-term national emissions reductions arising from policy and conservation outcomes.

GFOI has identified seven thematic forest map products, derived using satellite EO data, that will enable countries to routinely and precisely measure forest area and carbon stock changes:

– Forest/Non-forest

– Forest/Non-forest change

– Forest stratification

– All Land-use categories

– Land-use change between forests and other land-uses

– Change within forest land

– Near-Real Time forest change indicators

The products represent intermediate inputs for greenhouse gas emissions estimation that provide improved confidence intervals for country emissions estimates. Their production and use is dependent on monitoring needs and will be greater the more activities are to be monitored within the REDD+ spectrum.

3.7 Implementing a Global Data Acquisition Strategy

Building on associated CEOS satellite data coordination efforts for GEO FCT, CEOS has assumed responsibility for coordinating satellite acquisitions in support of GFOI activities. Approved in 2011, the CEOS Space Data Strategy for GFOI encompasses three key elements:

– A baseline, coordinated global data acquisition strategy involving a number of core data streams that will be supplied free-of-charge for GFOI purposes;

– A coordinated strategy for national data acquisitions in response to national needs assessments;

– Data supply in support of GFOI R&D activities.

Collaboration between CEOS and GFOI has led to a comprehensive strategy that coordinates acquisitions from both optical and radar satellites, and so maximises the interoperable and synergistic use of the available satellite systems.

GFOI will continue to assist countries in building their national forest monitoring systems in support of sound decision-making and sustainable forestry, and so help ensure the preservation and wise use of forests for future generations.

Article contributor:

GFOI Project Office

Further information

GFOI:
www.gfoi.org

4

Tracking Human Perturbation of the Carbon Cycle

4.1 Carbon and Climate Change

Atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4), both components of the carbon cycle, have increased since the beginning of the Industrial Revolution by 42% and 150% respectively. Together they accounted for over 80% of the human-caused increase in the Earth's radiative forcing due to greenhouse gases (GHGs) in 2014 (www.esrl.noaa.gov/gmd/aggi/aggi.html), and therefore are the leading causes of human-induced climate change. These two gases have very unique properties. CO_2 emissions has a very long atmospheric "residence time" once emitted: 40% of today's CO_2 emissions will remain in the atmosphere in 100 years and about 20% will still be airborne in 1000 years (Ciais et al. 2013). Thus, anthropogenic CO_2 emissions cause, to a large degree, irreversible climate change at human time-scales, which justifies a precautionary approach to addressing climate change – given the risks to human wellbeing associated with a warmer world. Second, the CH_4 molecule is a much more powerful GHG than CO_2 (~28 times on the 100 year horizon) but its shorter residence time (~9 years), makes it a good target for efficient mitigation actions on human timescales. Further, CH_4 also impacts ozone chemistry. The Global Carbon Project (www.globalcarbonproject.org) works towards the construction of a more robust global carbon budget and in-depth trend analyses, and has provided annual updates for the past 10 years for CO_2, and more recently the first global CH_4 budget.

4.2 Global Carbon Budget – CO_2

The global carbon budget, here referring to the human perturbation budget of CO_2, includes all changes in the annual CO_2 fluxes of carbon sources and sinks that result from the direct or indirect effects of CO_2 emissions from human activities, mostly fossil fuel combustion, cement production, and land-use changes. This perturbation determines the changes in the atmospheric CO_2 concentration given that we know concentrations were stable at around 278 ppm for thousands of years prior to the Industrial Era. Figure 1 shows the carbon budget for the decade of 2004-2013 (Le Quéré et al. 2015), with emissions from fossil fuels of 8.9±0.4 GtC yr^{-1} (Gigatons or billion tons), and emissions from land-use change of 0.9±0.5 GtC yr^{-1}. Of those emissions: 4.3±0.1 GtC yr^{-1} had accumulated in the atmosphere, and increased the GHG effect; 2.6±0.5 GtC yr^{-1} was removed by the oceans; and 2.9±0.8 GtC yr^{-1} was removed by terrestrial ecosystems. Fossil fuel emissions accelerated and grew at a rate of 2.3% per year on average in the past decade – compared to 1.1% during the 1990s, and are now about 60% higher than those in the early 1990s when international negotiations to address climate change began. Emissions from land-use change seemed to be more stable or declining (in particular in Brazil) during that decade, albeit with large uncertainties associated with its component fluxes. It is worth noticing that due to the smaller land-use change fluxes and, to a larger extent, due to the strong growth in fossil fuel emissions over the past decade, the fraction of anthropogenic CO_2 emissions contributed by

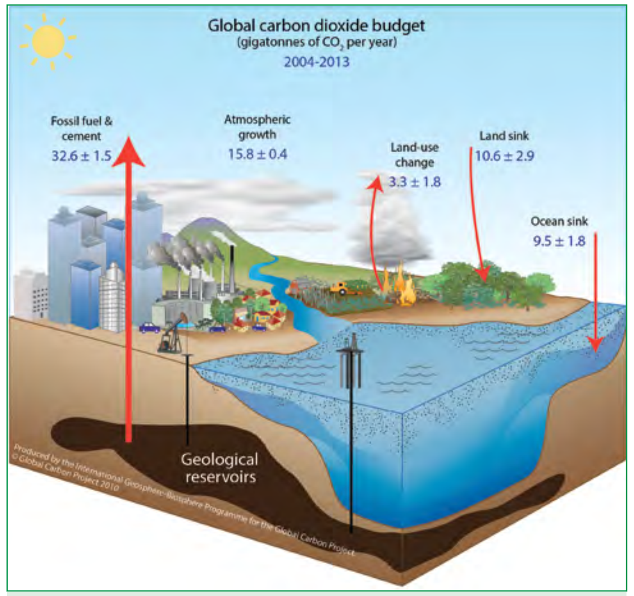


Figure 1: Global carbon budget (CO_2) for the decade 2004 - 2013
Credit: Le Quéré et al. 2015

land-use change is now around 10% of the total, down from 36% in 1960.

Land and ocean sinks are responding to the increasing atmospheric CO_2 by increasing the CO_2 flux being removed from the atmosphere. Natural carbon sinks remove over half of all anthropogenic carbon emissions, thus providing an economic subsidy worth hundreds of billions of dollars annually if an equivalent sink had to be created by currently available financial instruments and technologies (Canadell and Raupach 2011). However, the sink growth is slower than the growth of fossil fuel emissions indicating a loss of sink efficiency and inability of the sinks to keep pace with the fast emissions growth (Raupach et al. 2014). The collective dynamics of all sources and sinks has led to current high atmospheric CO_2 concentrations, now with months-long incursions over 400 ppm and an annual average of 397 ppm in 2014.

4.3 Global Carbon Budget – CH_4

Methane is the second most important GHG – contributing 20% of warming by the well-mixed GHGs. Despite a pause in atmospheric growth, perhaps contributed by better management in the agricultural and energy sectors, growth resumed in 2007 and has since continued. The causes of the new growth are uncertain but likely candidates are a series of wet years in the tropics causing increased wetland emissions and by the rapid growth of the energy sector in Asia. Today, the atmospheric mixing ratio of methane has surpassed 1800 ppb, 1.5 times its pre-industrial value. Anthropogenic emissions in the CH_4 budget now represent about 2/3 of the global methane emissions due to livestock, rice paddies, landfills, and human-caused biomass burning – with significant contributions by leaks from natural gas and oil, coal extraction and distribution. Natural emissions of CH_4 are dominated by natural wetlands and other continental water bodies, with smaller contributions from geological natural venting, wildfires, and termites. 90% of the global sink for atmospheric CH_4 is oxidation by hydroxyl radicals (OH), mostly in the troposphere, with additional minor sinks in soils, stratosphere and marine boundary layers. Figure 2 shows the budget for the decade of 2000-2009 (Kirschke et al. 2013; Ciais et al. 2013). Atmospheric inversions of CH_4 concentrations taken from observational networks estimate total global emissions of 548 Tg (Teragrams) of CH_4 yr^{-1} (526–569) and a global sink of 540 (514–560) Tg CH_4 yr^{-1}. The mismatch between the sources and sinks leads to an atmospheric growth rate of +6 Tg CH_4 yr^{-1}. Interestingly, a combination of national statistics and land based inventories with biogeochemical models show larger global CH_4 emission fluxes and emission trends, not consistent with the atmospheric constraints, and thus highlighting the need for independent observation networks to better constrain national and international based reporting.

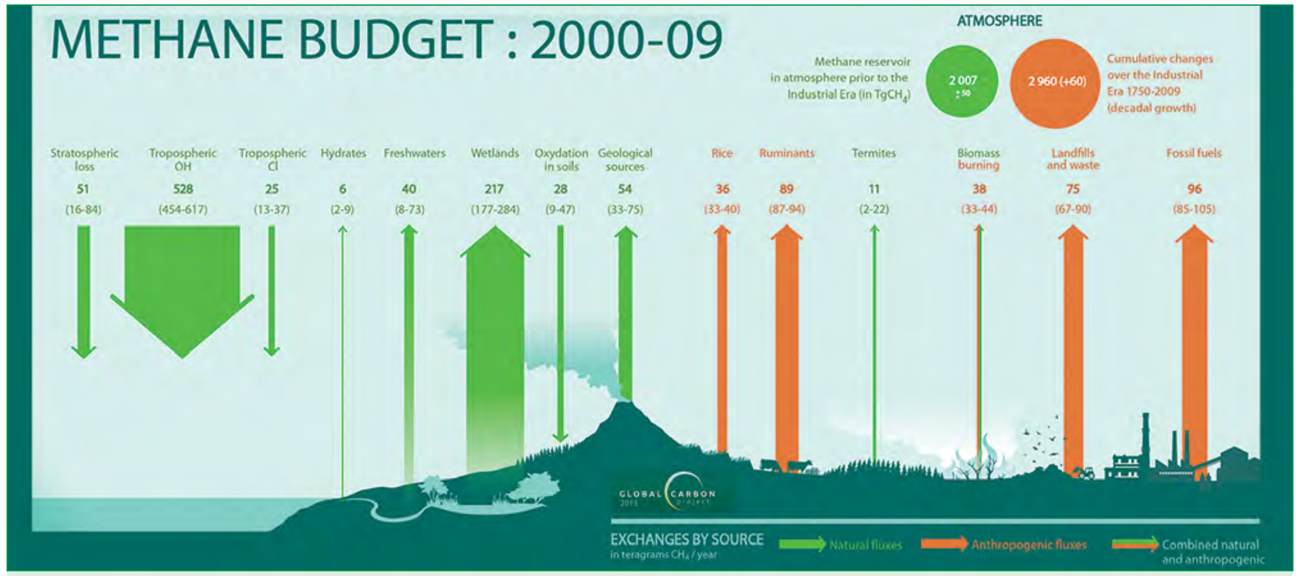


Figure 2: Global methane budget 2000-2009 *Credit: Kirschke et al. 2013*

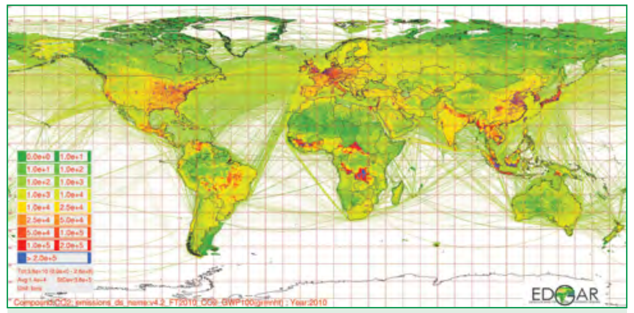


Figure 3: Global tree cover based on MODIS data (M. Hansen, UMD
Credit: EDGAR

4.4 Observing the Perturbation of the Carbon Cycle

Strategies to stabilise the climate require understanding and managing the carbon cycle to control anthropogenic GHG emissions, possibly increase the magnitude of CO_2 sinks on land, and preserve high and vulnerable carbon stocks such as tropical forests and soils (Canadell and Schulze 2014). The global sink cannot be understood without elucidating the contribution of each region. Some land and ocean regions serve as sinks, others as net sources. The fluxes of CO_2 vary across seasons and years, and the processes that explain the sink magnitude and variability of CO_2 (and CH_4) fluxes differ between regions.

Today's global observational networks are able to track, to some degree, changes in concentrations of carbon species, flux exchanges between the land/oceans and the atmosphere, and a number of key indicators of change of the world's land and ocean productivity as climate, CO_2, nitrogen and other quantities change (Ciais et al. 2014).

Atmospheric observations are a key component of a global carbon cycle observing system because, when dense enough atmospheric data can be collected, it is possible to use transport models for quantifying all the fluxes that emit or absorb CO_2 and CH_4 at the surface of the Earth. The atmospheric approach is comprehensive because the atmosphere sees all fluxes impacting the carbon balance of a region. Measurements of fluxes at local scale over specific ecosystems, or ocean regions are more informative about specific processes and fine scale details of fluxes, and they are complementary to atmospheric observations because they help to attribute net fluxes to underlying processes and components.

The current observations of atmospheric mixing ratios of CO_2 and CH_4 include: surface networks continuously monitoring atmospheric concentration of GHGs; observations over the ocean made on ships and moorings; aircraft vertical profile measurements and balloon observations in some locations; and a few instrumented commercial aircraft. Satellite remote sensing of column CO_2 and CH_4 mixing ratio with global coverage offers very promising options to complete atmospheric observations over regions with low surface network density – although they are not yet a substitute for in-situ observations because of less accurate performance and as yet insufficient coverage of cloudy regions. The SCIAMACHY (2002–2012), and GOSAT (since 2009) satellite missions enabled a first mapping of column CO_2 and CH_4 mixing ratio but they have not yet delivered enough data to deliver revolutionary knowledge of the carbon cycle, compared to existing in-situ observation assets. The Orbiting Carbon Observatory-2 mission (since 2014), thanks to its high resolution and target mode allowing comparison of space-borne data against ground based column CO_2 (TCCON), appears to be promising enough to deliver new column CO_2 data that will reduce the uncertainty of CO_2 fluxes, in particular over mid-latitude and tropical continents (Ciais et al. 2014).

On land, observations include the monitoring of land cover change, eddy-covariance carbon exchange between land and atmosphere (FLUXNET), and a number of remote sensed vegetation greening indices that are related to the land's gross primary productivity (Figure 3). CO_2 observations over the ocean are made by ships and moorings, which are used to develop global climatologies and inter-annual variability of carbon exchanges between ocean and the atmosphere; the Surface Ocean CO_2 Atlas (SOCAT) aims to synthesize

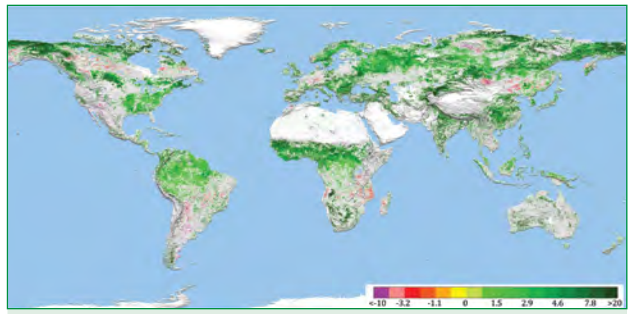


Figure 4: Trend in Growing Season Integrated NDVI (surrogate of Annual Gross Productivity) between 1982 and 2011
Credit: Ranga B. Myneni

these data (Bakker et al. 2014) and revealed that the tropics and southern hemisphere oceans are under-sampled. Observations of changes in carbon concentration in the ocean interior are made from repeat surveys, and provide a synoptic view of the uptake of carbon over decades.

This ensemble of observations is completed by statistical approaches to estimate anthropogenic emissions based, for instance, on energy statistics for CO_2 emissions from the combustion of fossil fuels (Figure 4) and on livestock statistics for CH_4 emissions from cattle.

4.5 Enhanced Policy-relevant Global Carbon Observing System

Despite significant efforts in recent years to develop in-situ, airborne, remote sensing observations and modelling, current capabilities need to be financially consolidated over the long-term (Houweling et al., 2012) and further developed in order to address the Earth system's emerging properties in response to human perturbation, and to support observational capabilities required by climate change policies. The density of observation is still insufficient to accurately quantify the distribution and variability of fluxes in each region, so that models used for future projections cannot be improved and benchmarked against present-day observations.

Mission (agency)	Status (launch)	Mission Objectives
GOSAT series (JAXA) Greenhouse Gas Observing Satellite	Operational (since 2009). 2nd satellite scheduled for 2018	The world's first spacecraft dedicated to measurements of greenhouse gases. Measures CO_2 and CH_4 distribution and how the sources and sinks of these gases vary with seasons, years, and locations
OCO series (NASA) Orbiting Carbon Observatory	Operational (since 2014). 2nd satellite scheduled for 2016	High resolution CO_2 measurements to characterise sources and sinks on regional scales and quantify their variability over the seasonal cycle
TanSat (China)	Planned (2016)	Tansat will improve the understanding of global CO_2 distribution and its contribution to climate change, and monitor CO_2 variation on seasonal time scales
MERLIN (CNES/DLR) Methane Remote Sensing Lidar Mission	Planned (2019)	Global information on atmospheric CH_4 concentration
MicroCarb (CNES)	In definition (2020)	Designed to map sources and sinks of CO_2 on a global scale
ASCENDS (NASA) Active Sensing of CO_2 Emissions over Nights, Days, and Seasons	Considered (2022)	ASCENDS will: quantify global spatial distributions of atmospheric CO_2 on scales of weather models; quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 at weekly resolution; and provide a scientific basis for future projections of CO_2 sources and sinks through data-driven enhancements of Earth system process modeling
CarbonSat (ESA, Germany)	In definition (2023)	Global atmospheric concentrations of CO_2 and CH_4 with high spatial resolution and good spatial coverage – helping to disentangle natural and anthropogenic sources and sinks of CO_2 and CH_4

A number of specialist greenhouse gas observing satellite missions are in orbit or planned by CEOS agencies

At the Earth system level, there is the need to:

– follow and evaluate human emissions of CO_2 using observations independent from energy use statistics used in current inventories;

– monitor the variability and changes in the natural land and ocean fluxes which affect excess atmospheric CO_2;

– be able to provide early detection information on emissions hot spots (e.g. methane from permafrost, hydrates, leaks from the energy sector);

– document CH_4 emissions from natural wetlands given their dominant role in the global budget and large uncertainties;

– monitor emissions pathways to zero for climate stabilisation and the symmetry (or otherwise) of the carbon cycle under negative emissions as required by the low carbon pathways; and

– address all carbon greenhouse gases and N_2O, the latter a gas growing in importance as land-use intensification continues in order to meet growing demands for food, bioenergy and the emerging bioeconomy (Canadell and Schulze 2014).

The carbon observing system needs to be enhanced from a research-based set of observation arrays to a policy-relevant carbon observing system with capabilities to monitor, report and verify policy effectiveness at national and sub-national scales. This will enable nations, provinces, and local municipalities to implement and evaluate the effectiveness of policies that reduce emissions or create sinks of CO_2 and CH_4. Uncertainties in inventories need to be dramatically reduced in order to support such effective policies (Ciais et al. 2014).

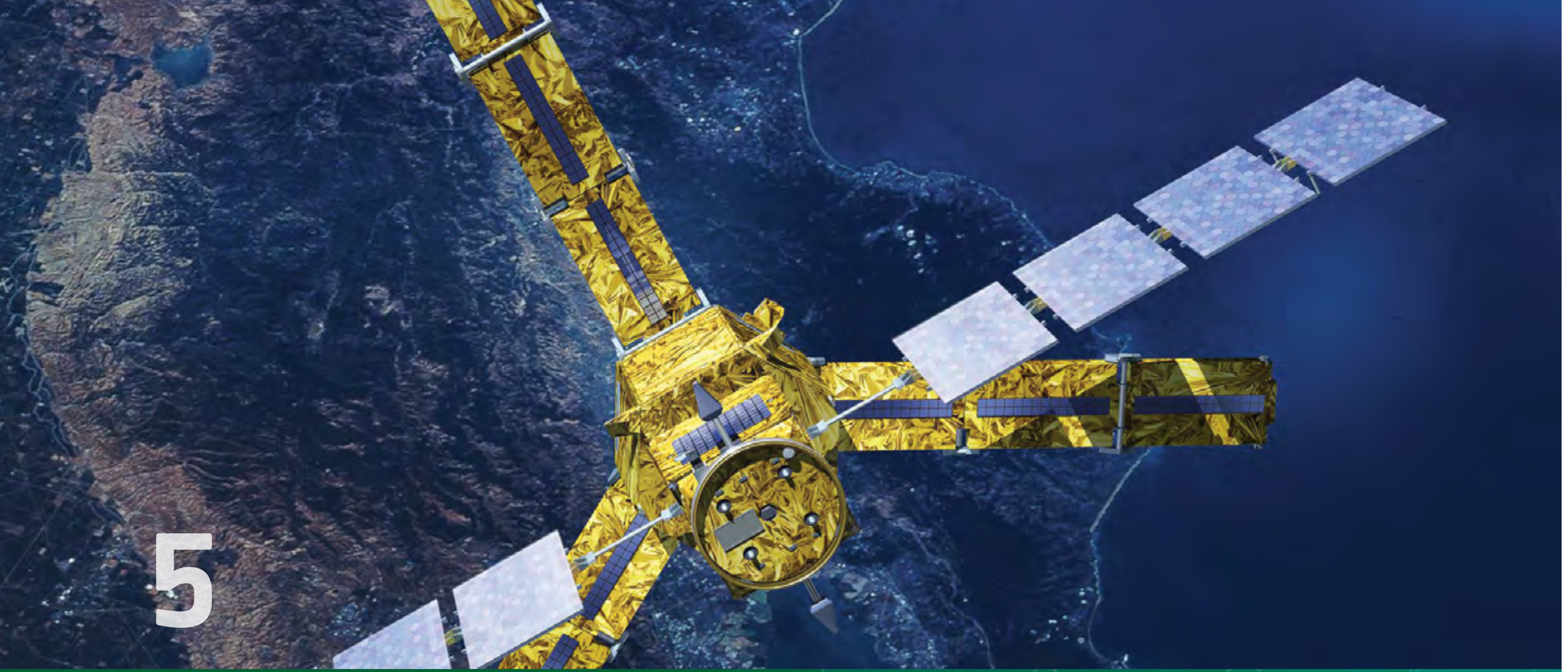
Remote sensing offers the advantage of dense spatial coverage at a global scale. A key challenge is to bring remote-sensing measurements to a level of long-term consistency, high spatial resolution and accuracy so that they can be efficiently and consistently combined in models and inventories with ground-based data in order to reduce uncertainties. Bringing tight observational constraints on fossil fuel related emissions and land-use change emissions is the biggest challenge for deployment of a policy-relevant integrated carbon observation system and one that could begin to be achieved with upcoming and proposed satellite missions. This requires in-situ and remotely sensed data at much higher resolution and density than currently achieved for natural fluxes, including over small land areas (cities, industrial sites, power plants), as well as the inclusion of specific tracers of individual emission processes such as radiocarbon of CO_2 for fossil fuels, isotope ^{13}C in CO_2 for land fluxes, or ^{13}C in CH_4 to separate flux sources (biogenic, thermogenic, and pyrogenic), carbon monoxide to track combustion-related emissions of CO_2 and ethane to methane emissions from the gas industry. Additionally, a policy-relevant carbon monitoring system needs to provide mechanisms for reconciling regional top-down (atmosphere-based) and bottom-up (surface-based) flux estimates across the range of spatial and temporal scales relevant to mitigation policies (Ciais et al. 2014). Uncertainties for each observation data-stream should be assessed. The success of such a system will rely on long-term commitments to monitoring, on the generalisation of the monitoring of "process" tracers, on improved international collaboration to fill gaps in the current observations, on sustained efforts to improve access to the different data streams and to make databases interoperable, and on the calibration of each component of the system to agreed-upon international scales.

Article contributors:

Josep Canadell (CSIRO), Philippe Ciais (LSCE), Corinne Le Quéré (Univ. East Anglia), Philippe Bousquet (LSCE)

Further information

The Global Carbon Project:
www.globalcarbonproject.org



5

Indicators of Climate Change

The world has relied far too long on global temperature as the single indicator of climate change. With the increasing capacity of satellites to provide comprehensive data on the Earth system, it is time for a new approach – a basket of indicators that gives a more complete picture of climate change and its impacts.

Elsewhere in this Handbook you will see described the Essential Climate Variables (ECVs), a complex set of physical quantities that drive the processes that govern climate change on Earth. They were developed by GCOS for the purposes of scientific understanding, modelling and prediction of the world's climate. Some, such as albedo, need a complex discussion of the Earth's radiation balance before their meaning can be conveyed to non-specialists and hence are not always suitable indicators of climate change in a wider context.

Are there a few direct observations that we can make which would give a better picture of change in the Earth system, without necessarily requiring a deep understanding of the physical processes involved? And which do not encourage simplistic interpretations? Sea level rise is already a good indicator. Scientists agree on its meaning, and policymakers and the public can visualize its impacts. Global surface temperature is at first sight a straightforward indicator of climate change and policymakers make use of the concept in negotiations, but science tells us it is an ambiguous indicator. It says something about the weather, since the production of water vapour is a sensitive function of sea surface temperature, but it does not tell you how fast climate is changing despite its frequent use as a reference.

The public controversy on the so-called "hiatus" is a case in point. Had the public been made aware instead of ocean heat content data, it would have seen there was no hiatus in the rate that the energy in the climate system was increasing. Even as policymakers have set temperature as the single most prominent metric for policy success, it is one of the worst real indicators of actual stress.

It is often said that the public will not pay attention to more than one indicator. We think this underestimates the public – it also underestimates policymakers who regularly deal with complex policy challenges, such as employment and economic growth, for which they must rely on many indicators. We would not expect to have a thermometer thrust into our mouths in hospital and have no other investigations of our body to guide a complex differential diagnosis of many possible maladies. We know we can have cancer without running a temperature. We are used to doctors measuring more than one vital sign. We expect to have blood assays, ECGs, tests for liver function, kidney function or others, depending on our symptoms. When we are faced with a serious medical problem, we want them all. Why not treat the planet's health the same way? Why not vital signs for the Earth?

Planetary vital signs should be reliable, simple, have a long term history, reflect a range of possible symptoms of climate change, integrate as far as possible many wider effects of change, be easily interpreted and conversely difficult to misinterpret, either by accident or intent. They need not be the same for policymakers and the public, but they must be accessible to both.

What might be candidates? There are several possible lists already in existence – this idea is not new – and the GCOS ECVs themselves constitute some excellent candidates. However, we should try to define a small set of maybe 6–8 series of observations that reflect in a straightforward manner the state of the Earth's climate. That said, the subject is not simple – hence the need for the fifty ECVs – but we are not here trying to explain the processes involved, but to look for the consequences.

Candidates for such indicators might be:

- **Surface temperature** – for all its faults, this is one sign with which many are already familiar and we should retain it, but not alone.
- **Sea level** is an excellent integrator of many aspects of change – ocean warming, mass loss from the ice sheets, glacier melting and groundwater changes. Half the world's population lives within 100km of a coast, and will be affected by sea level rise. Some small island states and coastal regions are at particular risk.
- **Atmospheric carbon dioxide** – the fundamental driver of anthropogenic climate change. We now monitor from space the spatial distribution of atmospheric carbon dioxide worldwide, but we have over 50 years of observations of global CO_2 content from Mauna Loa. Both the CO_2 emission rate and the cumulative emissions are important to policy.
- **The energy content of the climate system** – largely in the form of Ocean Heat Content (OHC). IPCC AR5 tells us that 93% all the energy increase in the climate system is going into the oceans. This is of greatest importance as OHC is the fundamental driver of the climate system (not a consequence, like surface temperature) and the reservoir of energy that will drive future weather systems.
- **Total solar irradiance** – we need to see whether changes in the Earth system are driven by changes in the solar output, independently of anything humanity is doing to the planet.
- **Measures of extreme climate event occurrence and intensity** – one place to start is an index that measures the total global area during the year in which extreme conditions that depart by three standard deviations from the local and seasonal mean occur.
- **Arctic sea ice extent and volume** – we now have a very reliable means to measure from space the extent (area) of winter and summer Arctic ice, and more recently also to measure its thickness, and hence to calculate the total ice volume at any given time. This record extends in part back to 1979.

Satellites are critical in providing the observations of many of the above. For example, arctic sea ice extent has been measured since the 1970s by passive microwave imaging systems and for the last 20 years or so by active radar imaging sensors also. In addition, dedicated satellites (Icesat, Cryosat) with specific relevant technologies have allowed measurements not only of the extent, but also the thickness and hence total volume of sea ice to be made.

Sea level is now measured most accurately, and globally, by a series of precise altimeters. These measurements go back over 20 years and will continue into the future due to the

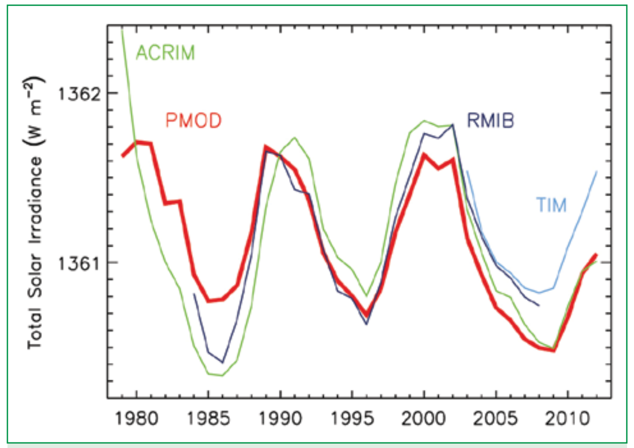


Figure 1: Total solar irradiance – Annual average composites of measured total solar irradiance: The Active Cavity Radiometer Irradiance Monitor (ACRIM) (Willson and Mordvinov, 2003), the Physikalisch-Meteorologisches Observatorium Davos (PMOD) (Frohlich, 2006) and the Royal Meteorological Institute of Belgium (RMIB) (Dewitte et al., 2004). These composites are standardized to the annual average (2003–2012) Total Irradiance Monitor (TIM) (Kopp and Lean, 2011) measurements that are also shown.

Credit: IPCC AR5

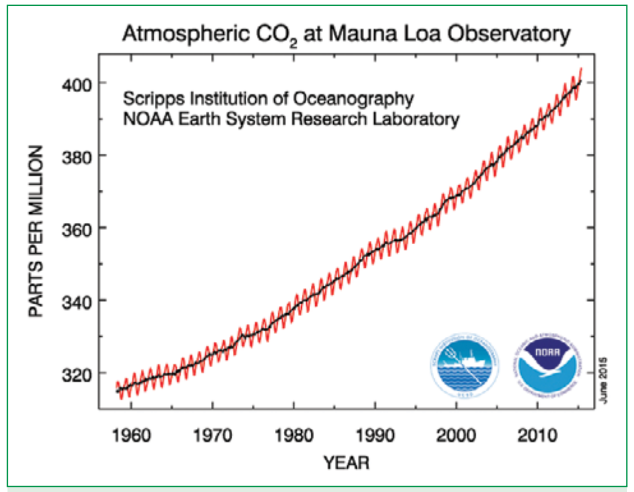


Figure 2: Atmospheric CO_2

Credit: Scripps, NOAA

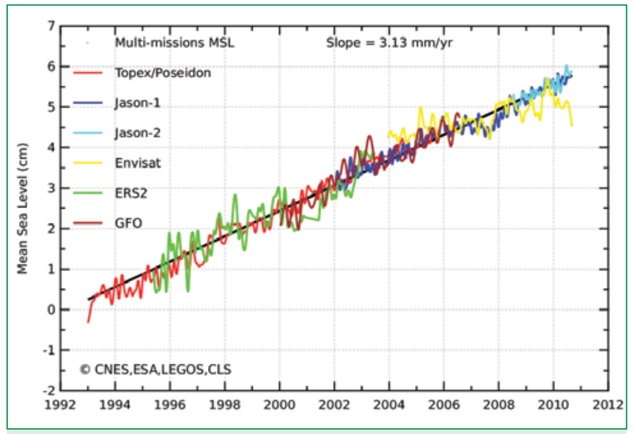


Figure 3: Sea level rise – Multi-mission global sea level trend from altimetry (1993-2010)
Credit: ESA/CLS/CNES/LEGOS

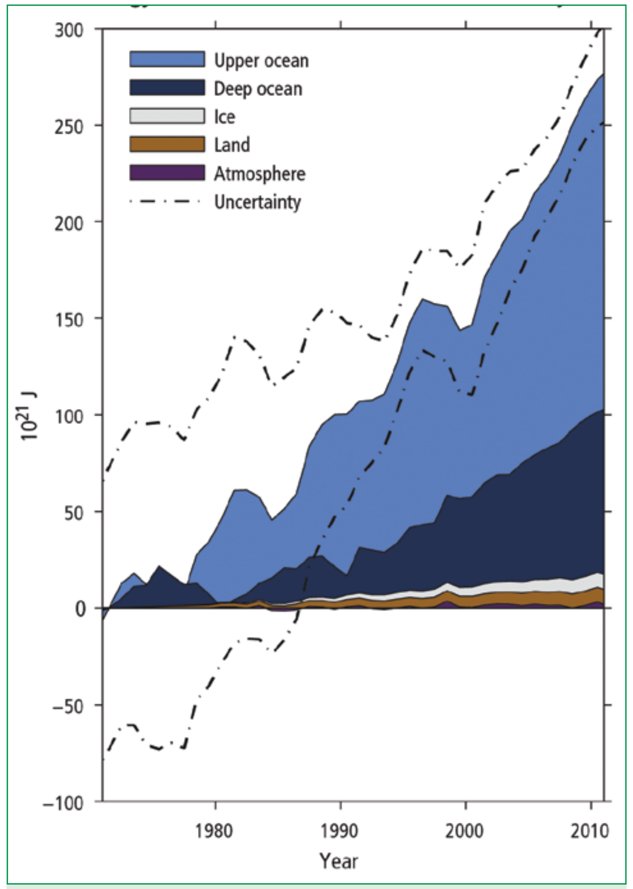


Figure 4: Energy accumulation within the Earth's climate system
Credit: IPCC AR5

Sentinel 6 series of missions. Total solar irradiance is best measured from above the Earth's atmosphere by missions such as the Solar and Radiation Climate Experiment (SORCE). Satellite observations contribute significantly to all the other parameters also.

We could think of more candidate indicators, but we should restrict ourselves, for the sake of simplicity and better communication, to a rather small number such as the above. The climate science community has been generating and using indicators for its own purposes for several decades. It is now time to put this experience to broader use. An indicator is simply a number unless people make use of it. The science community cannot do it on its own. It is essential that policymakers and public communicators participate in the choice, format and dissemination strategy for the world's first set of planetary vital signs.

Let the dialogue begin. We hope that decision-makers call for it and we know that the scientific community can contribute a good panel of indicators if asked. A good first step might be a conference or series of workshops where natural and social scientists, policy specialists and stakeholders frame a proposal on how to start.

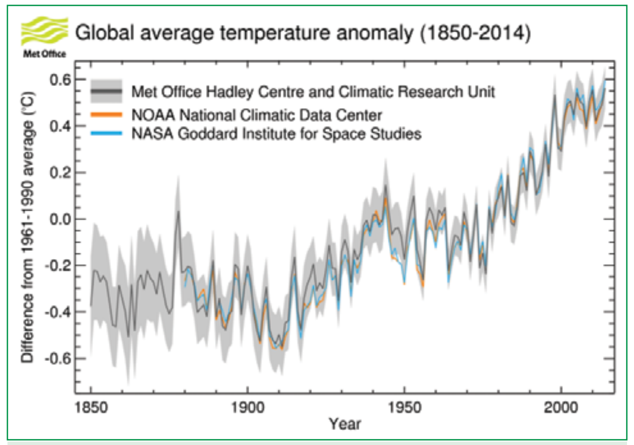


Figure 5: Global average surface temperature anomaly
Credit: UK Met Office Hadley Centre

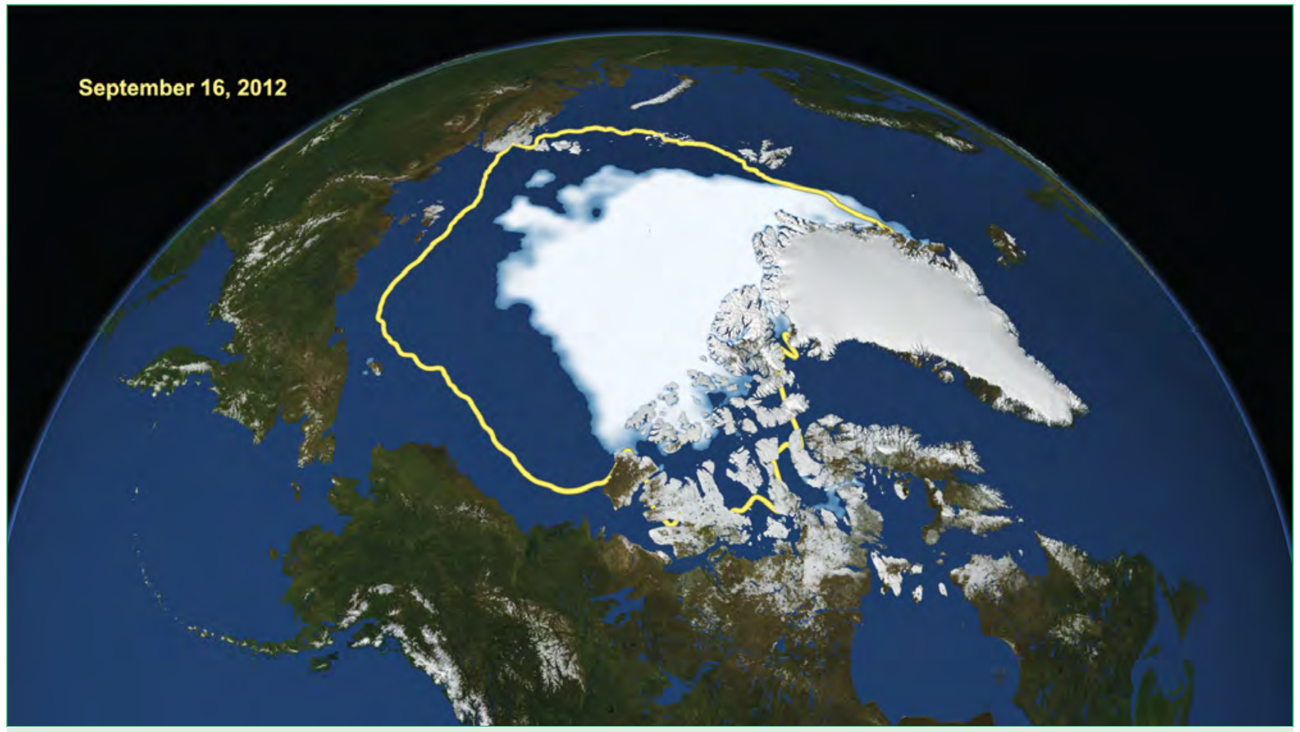


Figure 6: Satellite data supports the study of the long-term variability of polar sea ice cover and its relationship to climate change
Credit: NASA GSFC

Article contributors:

Stephen Briggs (European Space Agency), Charles Kennel (Scripps Institution of Oceanography), David Victor (University of California at San Diego)

Further information

www.nature.com/news/climate-policy-ditch-the-2-c-warming-goal-1.16018

Part III

Unique Contributions from Satellites in Support of Climate Information

Part III focuses on a few case studies where satellites make a unique contribution in support of climate information. Information that we, simply, could not otherwise hope to possess.

Precision Sea Level Monitoring

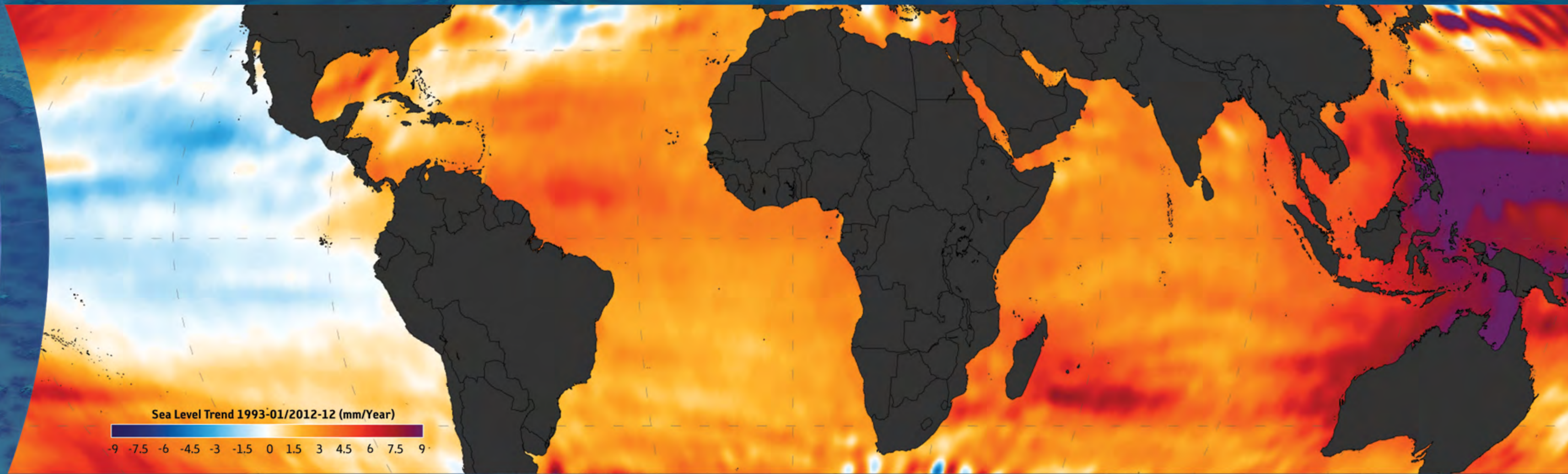
ECV: Sea level

Impact

The change in sea level is one of the main impacts of anthropogenic – or human-induced – climate change and systematic observations over the long term are essential in assessing impacts and planning potential adaptation. This is particularly true in low-lying areas where rising sea level directly threatens damage to coastal infrastructure, more frequent storm-surge flooding, loss of habitat through wetland inundation and, in some cases, potentially the basic viability of entire small island nations.

Sea level is also essential to climate science, serving as a fundamental parameter in the monitoring and tracking of climate change by providing an observable model output for seasonal, inter-annual and decadal climate prediction. Sea level observations provide scientists with important inputs to the modelling of other parameters such global heat exchange via ocean circulation.

Satellites provide spatially explicit, consistent and comparable global-scale observations. These observations have significantly reduced the uncertainty of both global average and regional sea level records. The comprehensive sea level measurements provided by satellites are essential to addressing the monitoring needs of society, government and the science community.



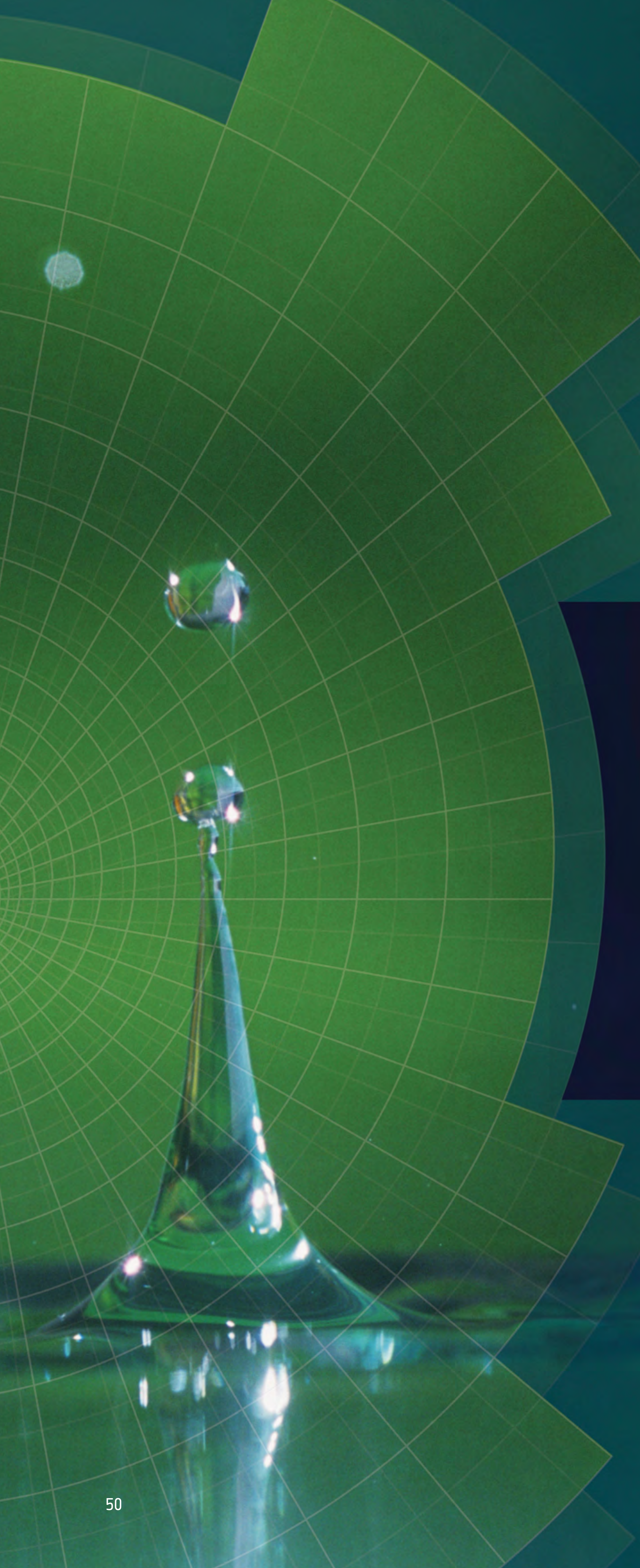
Annual global sea level rise trend from 1993–2012 derived from satellite altimetry

(Credit: NOAA)

The Unique Contribution of Satellite Altimetry

For more than 100 years, accurate sea level records have been maintained by coastal and mid-ocean island tidal gauges. These measurements provide valuable data and have helped to establish long-term trends, but are limited by the nature of their measurements and the coverage area over which they are able to provide them.

In contrast to the sparse network of tidal gauges, measurements by satellite radar altimetry provide near global and homogenous coverage of the world's oceans. Tidal gauges continue to provide important in-situ observations, but since the early 1990s, satellite altimetry has become **the main tool** for precisely and continuously measuring global sea levels. The satellite carries a high accuracy radar altimetry instrument that precisely measures the distance between the spacecraft and the Earth's surface below. These observations are repeated systematically over thousands of points across the ocean's surface every few days. They enable monitoring on global, regional, and local scales, allowing for the assessment of trends in relation to factors like tides, changes in temperature and ocean salinity, and surface winds.



Groundwater Measurements Using Gravitational Instruments

ECV: Groundwater

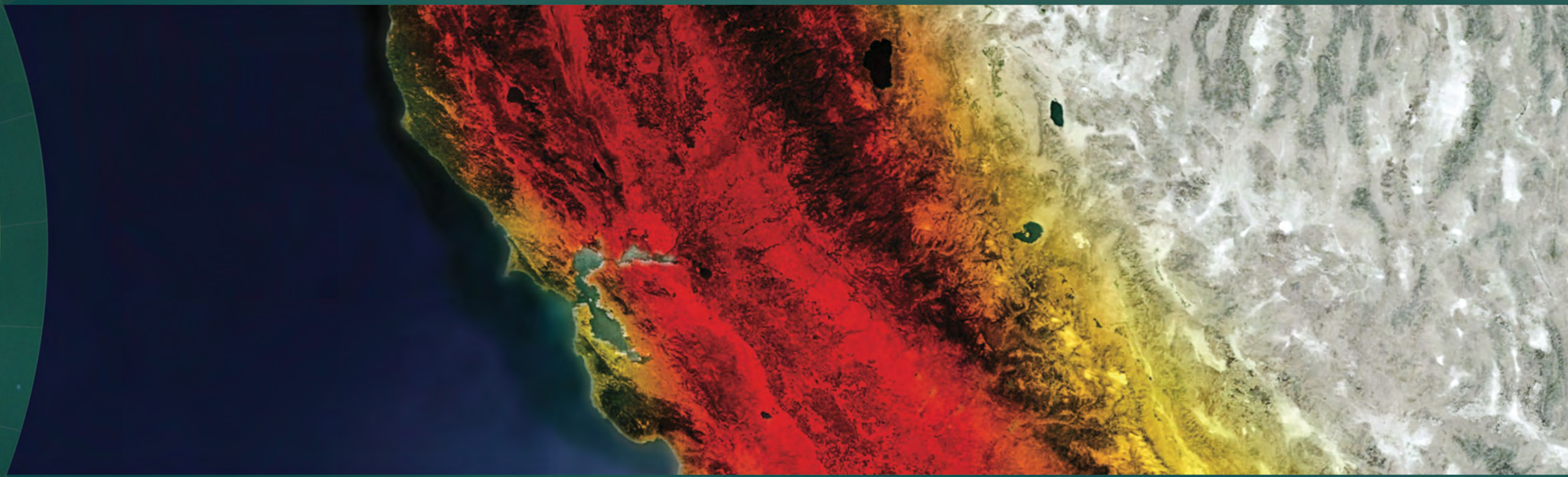
Measuring Groundwater with Gravity

We now measure and monitor almost all aspects of the hydrologic cycle from space. Gravity instruments are used to measure precipitation, ice sheets and glaciers, ocean surface temperature and salinity, soil moisture, surface water and river flows and, importantly, groundwater.

Satellites can map the Earth's gravitational field based on very detailed measurements of tiny changes in spacecraft orbit. In the case of the GRACE mission, the gravity field is measured by taking laser range measurements between two satellites flying together in close formation. The satellites are just over 200km apart and the ranging system is sensitive enough to detect separation changes as small as 10 micrometres, or approximately one-tenth the width of a human hair.

These measurements enable the detection of changes in the mass of sub-surface water over broad areas, effectively weighing the increase or decrease in groundwater. The measurement crosses jurisdictional and national boundaries, providing objective and quantitative environmental information for decision makers.

Groundwater storage, recharge and discharge are important aspects of understanding climate change impacts and assessing the need for adaptation. The UN's International Groundwater Resources Assessment Centre (IGRAC) has established the Global Groundwater Monitoring Information System (GGMIS) to provide an interactive and transparent reference for groundwater-related information. In the coming decade, it is expected that detailed observations from the GRACE mission, and planned follow-on missions, will be incorporated into the GGMIS and become an important part of the basis for long-term groundwater climate data.



Groundwater storage in California as seen by the Gravity Recovery and Climate Experiment (GRACE) mission in June 2014. Colours progressing from green to orange to red represent greater accumulated water loss between April 2002 and June 2014.

Credit: NASA/JPL-Caltech/University of California, Irvine

Managing Extreme Drought

Changes in the climate drive changes in precipitation patterns and these changes have a significant impact on water resources. Water supplies are vital to supporting the health of our communities and to the productivity and prosperity of many sectors of the economy, perhaps most importantly agriculture and food security. It is estimated that nearly 30% of the world's total freshwater resources (including snow/ice) are stored as groundwater.

Observations of groundwater resources are an essential element of any effective water management strategy, as they inform both short-term tactics such as usage restrictions and longer-term adaptation. While groundwater can be measured locally by water resource management authorities, gravity measurements from satellites have enabled unprecedented global observations of groundwater supply. These observations are timely, systematic and independent of local authorities. They also help to support resilience against extreme events like drought.

Global Atmospheric Chemistry Monitoring

ECVs: Carbon dioxide, Methane and other long-lived greenhouse gases, and Ozone and Aerosol supported by their precursors

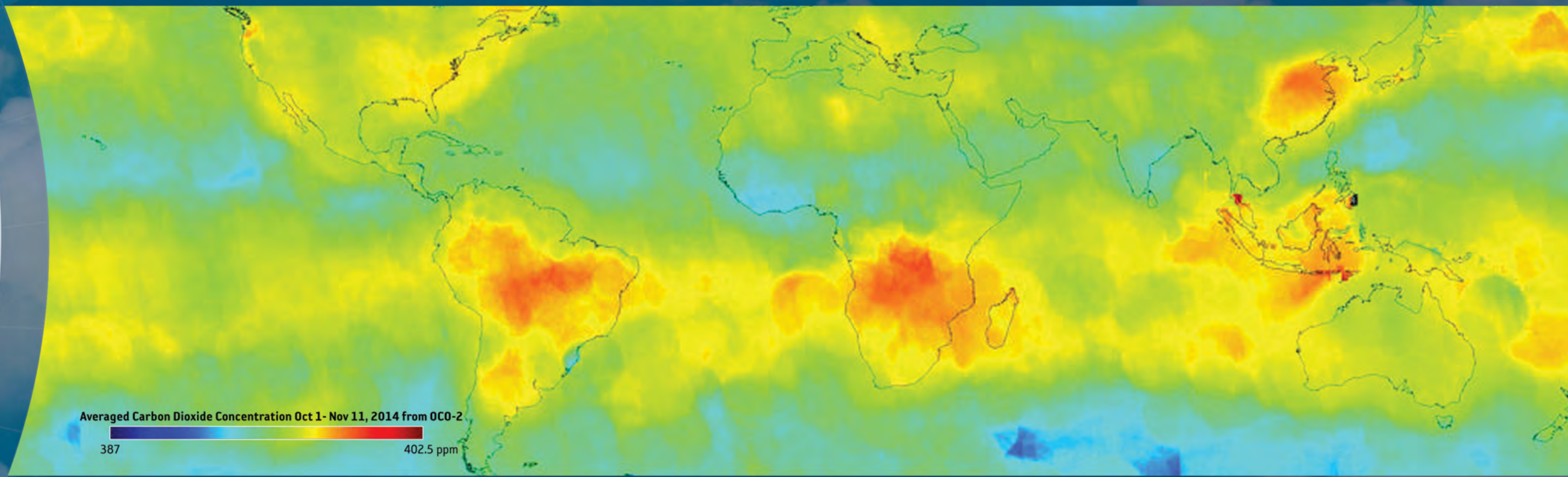
The Role of Satellites

'Atmospheric chemistry instruments' are used to characterise the composition of the Earth's atmosphere, and enable the monitoring of a variety of gases including the greenhouse gases carbon dioxide, methane and ozone. Satellites sense the electromagnetic 'signatures' of these gases, measuring their concentration through the full thickness of the atmosphere, as well as in layers at different altitudes. They provide unparalleled, near-continuous global coverage resulting in a synoptic picture of the atmosphere and how it is changing on a daily, seasonal, annual and decadal basis.

The Earth's atmosphere is a complex, highly interconnected system, with gases produced in one location quickly mixing and travelling vast distances at very high speeds. For example, volcanic eruptions can produce massive gas plumes that are transported in the high atmosphere and impact seasonal weather and climate on a global scale. The only way to provide the comprehensive, consistent and cross-border observations required globally is via satellites.

Tracking the Ozone Hole

Reducing damage to the Earth's ozone layer from chlorofluorocarbons (CFCs) became an important international priority in the 1980s when it was discovered they were partially responsible for thinning the layer worldwide and allowing a large hole to open up over Antarctica during the southern spring. The international community agreed to mitigate the issue by phasing out the use of CFCs under the Montreal Protocol, which came into effect at the beginning of 1989.



This image represents the atmospheric carbon dioxide concentrations from 1 October 2014 through 11 November 2014, as recorded by NASA's Orbiting Carbon Observatory (OCO-2). Carbon dioxide concentrations are highest above northern Australia, southern Africa and eastern Brazil. Preliminary analysis of the African data shows the high levels there are largely driven by the burning of savannahs and forests. Elevated carbon dioxide can also be seen above industrialised Northern Hemisphere regions in China, Europe and North America.

Credit: NASA/JPL-Caltech

Monitoring Carbon Dioxide

Anticipating the policy needs of their governments, space agencies have been developing missions to provide detailed global measurements of greenhouse gases. Two recent missions have focused on the monitoring of carbon dioxide: Japan's GOSAT and the USA's OCO-2.

OCO-2 enables the global tracking of sources and sinks in the carbon cycle, significantly reducing uncertainty about the ultimate destination of carbon dioxide, much of which is thought to be absorbed by the oceans where in–situ observations are limited. In addition, OCO-2 has a 'target' mode that allows for much more detailed observations of a specific location, for example a particular source or sink. Ultimately these observations could be used to produce detailed surveys of sites known to be big emitters of carbon dioxide, such as megacities. Future satellite-based observing systems are envisaged to monitor the evolution of carbon dioxide emissions from local to continental scales. As technology evolves, these systems could also play a role in monitoring the outcomes of adaptation and mitigation actions agreed by governments.

Glaciers and Ice Sheets

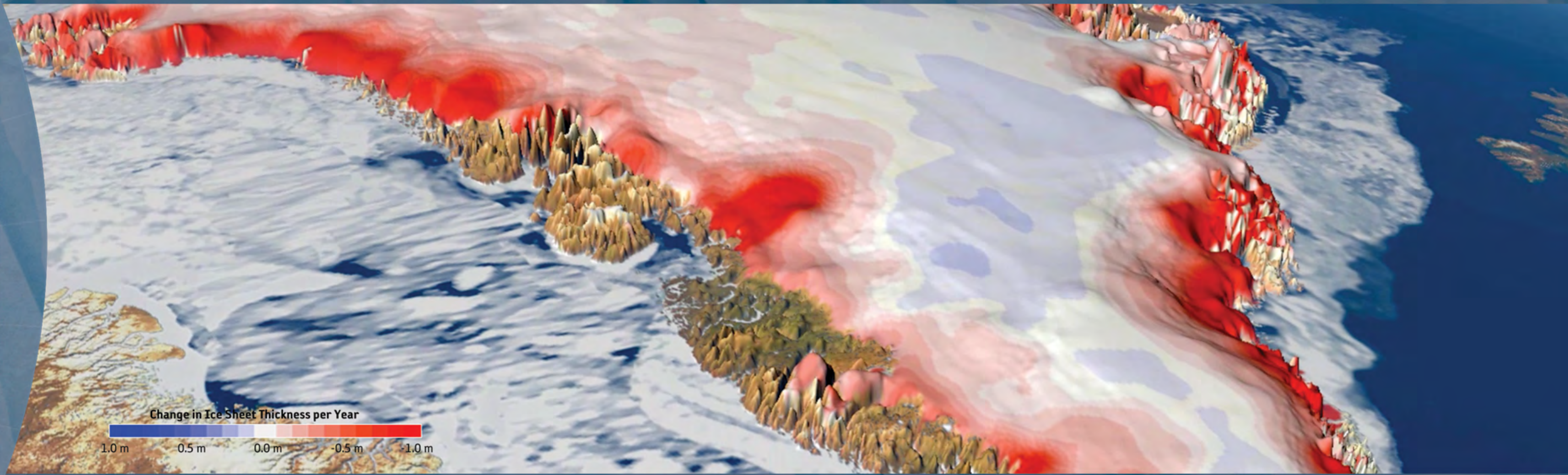
**ECVs: Sea ice,
Ice sheets (terrestrial),
Glaciers and ice caps**

Systematic Monitoring of Remote Locations

The Earth's ice sheets and glaciers cover a vast area and can be remote and difficult to access, which makes their systematic monitoring a significant challenge. While some may be measured by ground instruments, satellites enable regular monitoring on a scale and with a frequency that cannot be replicated in-situ. A number of satellite observations are employed to measure changes in the extent, thickness and density of ice sheets, allowing for improved and reconciled estimates and the assessment of long-term trends.

Altimetry data from radar and laser instruments provide mass balance estimates by measuring surface topography and volume change. Synthetic aperture radar (SAR) imagers also enable the detailed study of changes in the surface through interferometry, which uses the unique range information from successive, closely timed radar observations to detect small changes in topography. SAR also provides valuable all-weather observations in frequently cloudy areas to regularly assess changes in ice sheet boundaries. Measurement of fluctuations in the Earth's gravitational field by the GRACE mission allow regional average changes in ice sheet mass to be measured directly.

These unique measurements have been applied to major ice sheets and glaciers in Greenland and Antarctica, as well as in other locations globally, enabling detailed analysis of change with a frequency of monthly or better. In addition to new measurements, some archives date back more than 20 years, enabling historical comparison.

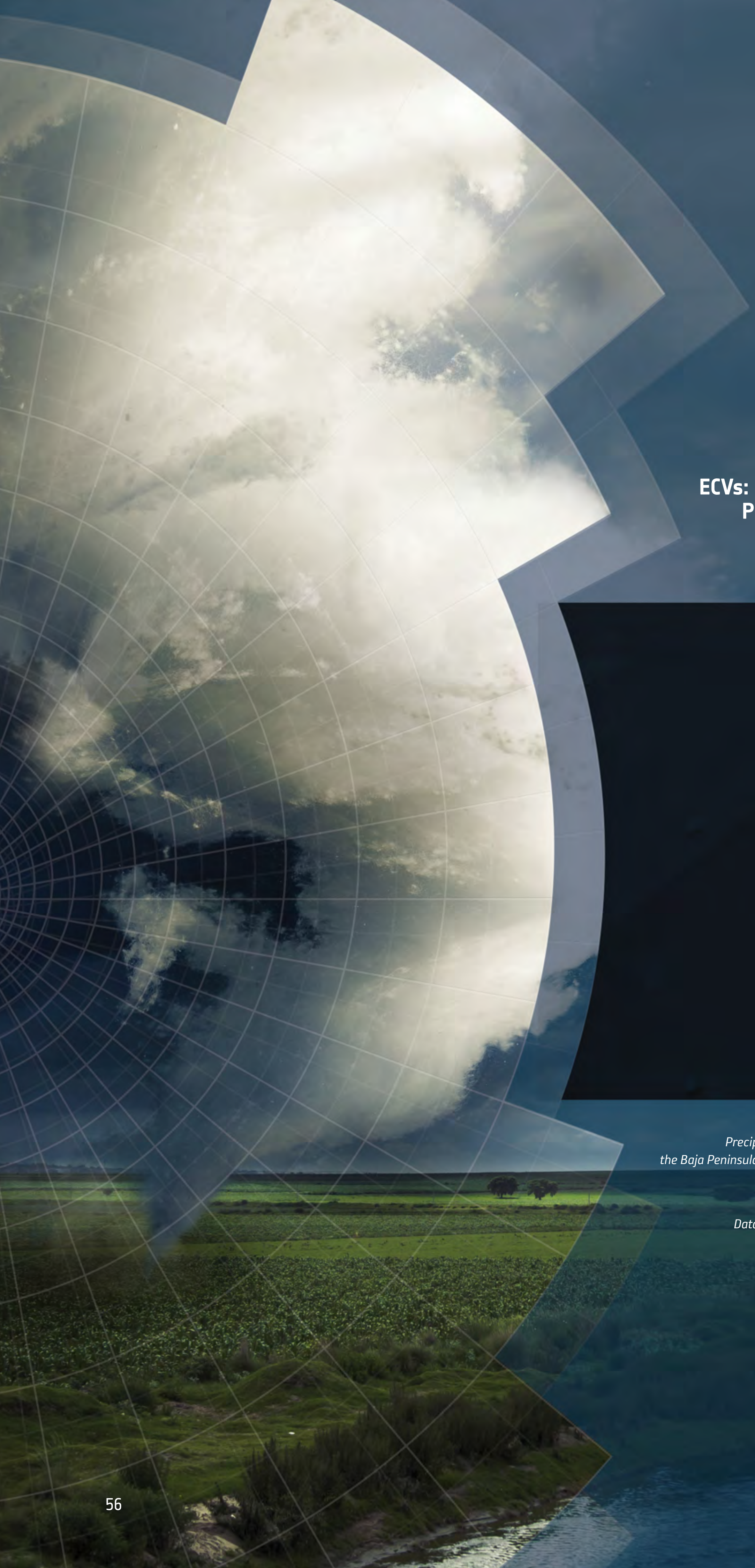


Change in Greenland ice sheet thickness per year
Copyright: Planetary Visions

Antarctic Ice Sheets

Satellite radar imagery of Antarctica's Larsen C ice shelf – which is two and a half times the size of Wales – has shown that it lost four metres from its thickness between 1998 and 2012. As they thin, ice shelves become prone to collapse, with nearby Larsen A and Larsen B collapsing in 1995 and 2002 respectively. While vast, the amount of water contained in these shelves is insignificant in terms of its impact on sea level rise, but the glaciers they help contain are of some concern to scientists and may pose a risk to coastal communities around the world. The glaciers behind Larsen C hold enough water to add a few centimetres to global sea level.

In the nearby Bellingshausen Sea, satellites have observed a sudden dramatic change in the behaviour of glaciers on the Antarctica Peninsula. A Bristol University-led study looked at more than 10 years of satellite observations, noting that these ice streams were broadly stable until 2009, but since then they have been losing on the order of 56 billion tonnes of ice per year to the ocean. Scientists used radar altimetry measurements from the Cryosat mission, with gravity measurements from GRACE used to check the results. While these measurements, and the cause of the changes, need to be interpreted in the broader context of the overall Antarctic climate, signals like these are essential for building knowledge and understanding and for monitoring risk. The role of satellites in the timely detection of these signals is unique.



Extreme Events

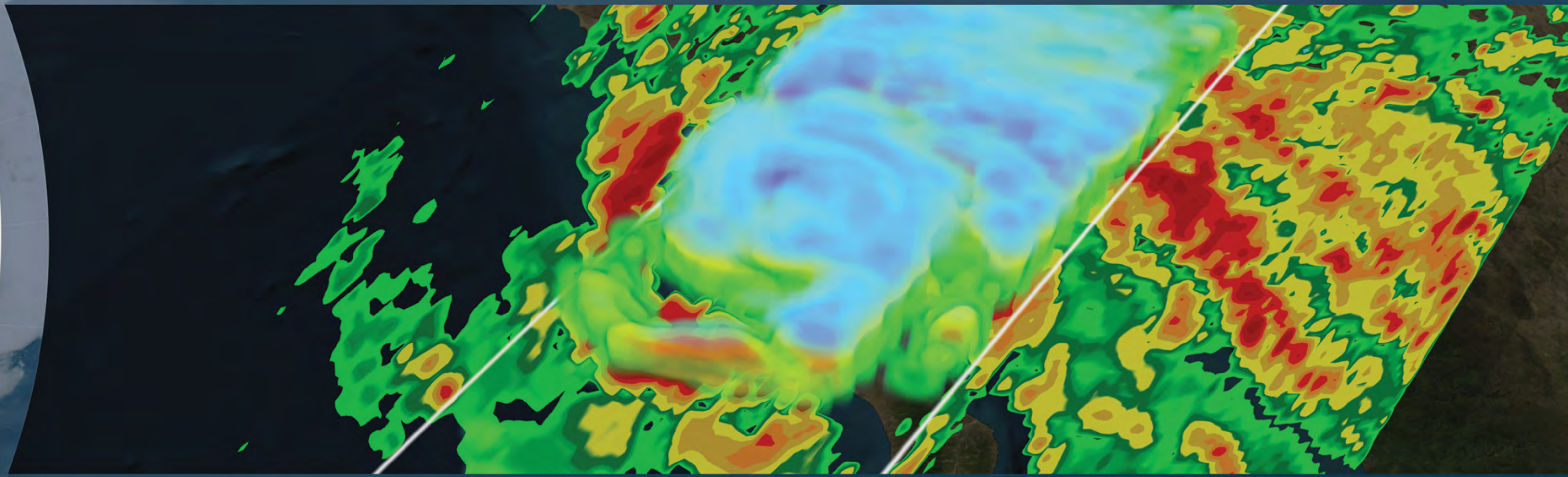
ECVs: Wind speed and direction, Precipitation, Soil moisture, Sea-surface temperature, Sea state, Sea level

Monitoring the Conditions for Tropical Storms

Satellites provide indispensible observations of many of the phenomena that contribute to the development of tropical storms, improving both short-term warnings and forecasts and our understanding of long-term trends. Sea surface temperature (SST) is key for the formation of tropical storms; satellite measurements using both optical and microwave instruments provide forecasters with global views of changing conditions. Increased SST can feed storms by drawing more water vapour into the system, and satellites provide unique global soundings of atmospheric temperature and humidity that greatly improve the accuracy and skill of forecast models. Satellite-based radar scatterometers and altimeters provide key measurements of sea surface wind speed and topography, both of which are key markers of building storm intensity, and also help forecast probable direction.

Tracking Tropical Storms

Tropical storm tracking capabilities have been greatly enhanced since the 1970s - notably with the recent launch of the first of the next-generation of geostationary imagers (Japan's Himawari-8), to be followed by the USA's GOES-R. Storm tracks can now be routinely monitored every 10 minutes and as frequently as every 2.5 minutes during critical periods. New spectral bands, and greatly improved spatial resolution on next-generation geostationary imagers provides meteorologists with a steady flow of composite 3-D colour images showing individual cloud formations, moisture levels and temperature variations. These new data streams represent a revolution in near real-time forecasting, enabling earlier identification of changes in cloud cover and structure, rain, and wind speeds that indicate the formation of a tropical storm. These observations can be translated into earlier warnings and improved forecast accuracy and range.



Precipitation structure of Hurricane Odile impacting the Baja Peninsula in September 2014 as observed by the Global Precipitation Measurement (GPM) mission.

Credit: NASA's Scientific Visualization Studio

Data provided by the joint NASA/JAXA GPM mission

Monitoring Precipitation

A new generation of precipitation monitoring satellites are advancing our understanding of the Earth's water and energy cycle, improving predictions of weather, climate and freshwater resources. Understanding the current variability of precipitation is critical to better modelling future extreme weather events, and satellites provide global observations on sub-daily to decadal time scales.

The Microwave Imager and Dual-frequency Precipitation Radar carried on the GPM satellite enhance our extreme weather monitoring and prediction capabilities, providing unprecedented visibility of precipitation inside complex storm systems. A planned constellation of satellites built around GPM would make possible near real-time estimates of rain and snow every 2–4 hours anywhere on the globe. GPM is also helping to build the long-term record of global precipitation essential to our knowledge and understanding of climate variation. It builds on the legacy of previous precipitation monitoring satellites, extending the time series and advancing measurement capabilities.

The CEOS/CGMS Working Group on Climate

The CEOS/CGMS Working Group on Climate, established in 2010, is the centre-piece of the CEOS contribution to climate change monitoring. This group, a joint group including CEOS Agencies and the Coordination Group for Meteorological Satellite (CGMS), coordinates and encourages collaborative activities between the world's major space agencies in the area of climate monitoring with the overarching goal to improve the systematic availability of Climate Data Records through the coordinated implementation and further development of a global architecture for climate monitoring from space.

The CEOS/CGMS Working Group on Climate facilitates the implementation and exploitation of ECV time-series through coordination of the existing and substantial activities undertaken by CEOS Agencies and via strong collaboration with other CEOS Working Groups and Virtual Constellations.

Further reading and contacts for WGClimate can be found on the CEOS website:

ceos.org/ourwork/workinggroups/climate

EO Handbook Online

The full text of this report is available on the Earth Observation Handbook's website at **www.eohandbook.com/cop21**. A supporting database of the satellite missions, instruments and measurements is available at **database.eohandbook.com** and contains powerful search and presentation tools, with the ability to export customised tables and timelines in support of analyses of current and planned provision of observations for different applications and measurements.

CEOS, the Committee on Earth Observation Satellites, coordinates civil spaceborne observations of the Earth. Participating agencies strive to address critical scientific questions and to harmonise satellite mission planning to address gaps and overlaps.

www.ceos.org

ESA, the European Space Agency, is Europe's gateway to space. It is an international organisation with 22 Member States. ESA's mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world.

www.esa.int

www.eohandbook.com/cop21