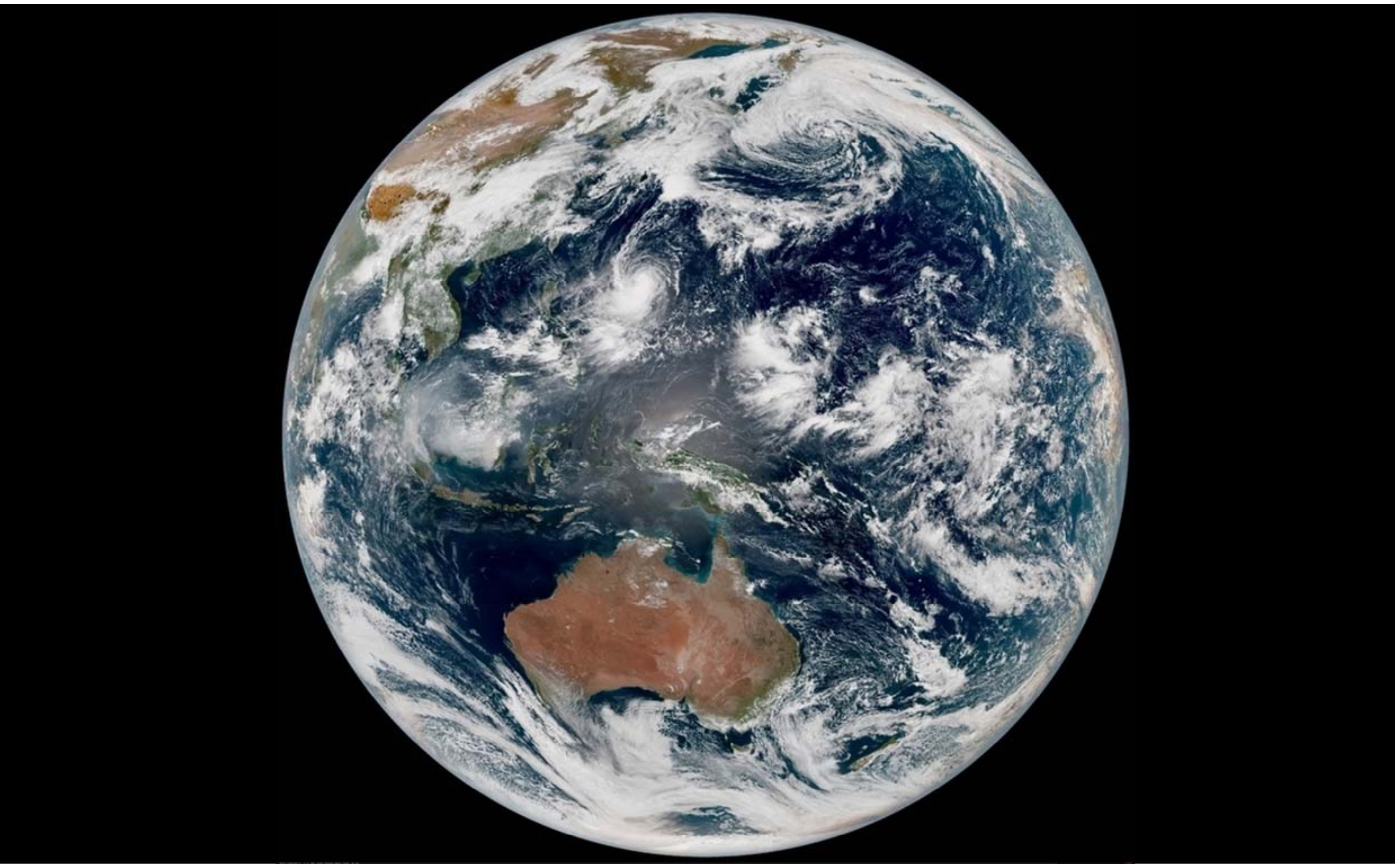
Non-meteorological Applications for Next Generation Geostationary Satellites Study



Cover Image: Himawari-8 full disk observation, image credit Japan Meteorological Agency

Contents

Figures

Tables

1 Introduction

1.1 Overview

The deployment over the next few years of a constellation of advanced meteorological geostationary (GEO) satellites, with their improved spectral, spatial and temporal resolution sensors, opens up a world of new possibilities for continuous monitoring of the high-temporal dynamics of the land, oceans and atmosphere, addressing a broad range of societal challenges and information needs, particularly in combination with moderate resolution low Earth orbit (LEO) observing satellites.

While the primary mission of the new GEO satellites is to support operational meteorological services, they offer opportunities for non-meteorological applications that can enhance and complement the low Earth orbit (LEO)-based applications that have been the primary tool for monitoring of the broader environment.

The Committee of Earth Observing Satellite (CEOS), under the leadership of Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) and supported by the Australian Bureau of Meteorology, conducted a one-year study initiative in 2015-16 to assess the potential of non-meteorological applications of the advanced meteorological geostationary satellites and of synergistic GEO-LEO approaches. This report summarises the initiative's findings. It identifies key issues and opportunities for consideration by CEOS. While the subject of the study is non-meteorological applications, careful consideration is given to developing an understanding of the work planned or underway within the Coordinating Group for Meteorological Satellites (CGMS) and its agencies.

The study was conducted by the CEOS Ad Hoc Team (AHT) on Non-Meteorological Applications for Next Generation Geostationary Satellites (NMA). The AHT was co-led by volunteers from agencies developing non-meteorological applications and space agencies that operate advanced GEO imagers, and the broader team included participants from a range of other CEOS Agencies. The study sought input from groups within CEOS including the Virtual Constellations, the Working Groups and thematic groups.

1.2 Context

1.2.1 THE CAPABILITY

The era of advanced GEO satellites was ushered in with the launch of Himawari-8 by JMA on October 7, 2015. Over the next few years advanced GEO satellites will also be launched by NOAA, KMA, CMA and EUMETSAT. All of the imagers have similar capabilities, with typical specifications being 16 spectral bands, spatial resolution of 0.5 km to 2 km depending on band, and variable image cadence from 30 seconds to 15 minutes with routine full disk imaging every 10 to 15 minutes. Thus the assembly is underway of a GEO-ring of advanced imagers with global coverage outside the polar regions.

These characteristics of the advanced GEO sensors complement current moderate resolution LEO sensors, approaching the LEO sensors in spatial and spectral resolution, while offering far greater temporal resolution and complementary view and illumination geometries. Furthermore, GEO satellites can fill gaps in LEO coverage due to cloud cover. They are particularly well suited to monitoring rapid changes in the land surface (such as snow, burns and harvest), ocean (such as ocean colour including algal blooms and sediment plumes, and sea surface temperature), and characteristics of the atmosphere beyond traditional weather phenomena (such as aerosols including smoke and dust events, ozone and potentially air quality).

GEO sensors promise more cloud free observations resulting in better product availability. Cloud or cloud contamination is a major issue in land data production since most land measurements rely on visible and infrared channels. Applications that will benefit include flood development and surface energy balance.

Furthermore, the fixed observation geometry available from GEO orbit provides consistent measurements, reducing uncertainty due to anisotropic surface reflectance. GEO sensors enable precise measurements of diurnal cycles. Diurnal variation such as of LST and SST can only be comprehensively measured from GEO satellite.

Lastly, besides the "headline" enhancement in sensor characteristics, the new generation refreshes the technology, bringing improved performance. It is worth noting that the SEVIRI imager has been operating over the European sector on EUMETSAT's MSG series of platforms since 2004, with spectral coverage and temporal sampling comparable to the new generation of imagers. As a consequence of this and the well established applications framework within EUMETSAT's network of Satellite Application Facilities (SAFs), SEVIRI applications serve as a valuable guide to maximising the benefit from a constellation of GEO imagers in a so-called GEO-ring.

1.2.2 SYNERGISTIC USE OF GEOSTATIONARY AND LOW-EARTH ORBIT SATELLITES

Further enhancements in observation capability can potentially emerge from applications that use data from both the advanced GEO and LEO sensors together, by exploiting their complementarities. Possibilities include merging the finer spatial resolution of the LEO sensors with the fine temporal resolution of the GEO sensors, exploiting the availability of simultaneous observations with different view or illumination conditions, and the fusion of GEO and LEO products into global products that address sampling issues at high latitudes. The blending of GEO and LEO satellite measurements aligns with a trend in producer agencies towards enterprise algorithms that exploit data from multiple sources to maximise product quality.

1.2.3 THE ENVIRONMENT

CEOS has long served to globally coordinate civilian, non-meteorological Earth Observations from Space (EOS) through practical collaborative activities conducted through its subgroups such as the CEOS Working Groups and Virtual Constellations. CEOS is well placed to build on its well established activities to coordinate application development for the new GEO ring in order to make the best use of the new capability given the resources available. Furthermore, CEOS has links to international agencies such as GEO and the UNFCCC that can support the utilisation of applications for maximum societal benefit

CGMS has similarly coordinated the international exploitation of meteorological satellites, including its past and future coordination of the use of the GEO ring for weather and related applications. Nowadays national meteorological and hydrological services (NMHSs) are active in areas of environmental monitoring other than weather and climate such as water, air quality and marine applications. In this context, the non-meteorological applications considered by this report could be alternatively described as "beyond weather" applications. CGMS has its own international links, such as with WMO with its focus and experience on international cooperation in gathering Earth system data. CEOS and CGMS together are well placed to coordinate international activity to expand the suite of applications from the new GEOs into new non-meteorological areas and build on their links with partner agencies to maximise the societal benefit.

The international EOS community has a rich heritage of experience in developing applications from LEOs with diverse capabilities in terms of spatial resolution, temporal frequency, spectral coverage and angular characteristics. This experience and the algorithms themselves form a solid base from which to develop algorithms for the new GEOs. The existing LEO science teams constitute a valuable resource that could be leveraged to apply this expertise to the new GEOs. The experience with merging LEO data streams with diverse characteristics will be valuable in supporting GEO-LEO applications.

The large data volumes generated by the new GEOs, particularly when used to produce products with global coverage, demands that close attention be paid to current developments in data technologies such as those studied by CEOS-WGISS and the CEOS Future Data Architectures initiative.

Finally, early specific initiatives provide instructive lessons in the management of international collaborations to develop the new applications. An example is the bilateral effort initiated by agencies in

Japan and Australia initiated in 2015 to develop non-meteorological applications from Himawari-8, both alone and in combination with LEOs.

1.3 Purpose

The development of meteorological applications of the advanced GEO sensors is comprehensively addressed by the meteorological community. However, the development of non-meteorological applications from the advanced GEO sensors, including in conjunction with LEO sensors, is a growing area of EO application development that shows much promise but which will benefit from a systematic survey of the potential applications, their benefits, capacity to meet societal needs and their relationship to other EO applications.

This study provides a systematic survey of non-meteorological applications for current and planned GEO missions and provides comprehensive and pragmatic guidance in line with the activities of the Coordinating Group for Meteorological Satellites (CGMS) on how to progress key applications for a quasi-global GEO constellation.

This report identifies the potential non-meteorological applications of advanced GEO satellites alone or in combination with LEO satellites, identifies LEO applications that may serve as a basis for GEO application development, identifies the benefits of applications, identifies where the applications satisfy unmet requirements and fill data gaps, and identifies opportunities for agency collaboration on application development. The report identifies opportunities both to promote the coordinated development, implementation and evaluation of non-meteorological applications by CEOS agencies, and for CEOS engagement with external stakeholders such as meteorological agencies and organisations.

1.4 Structure of the report

The report chapters subsequent to this introduction will address

2. Trends & Outlook for Geostationary EO Satellite Capabilities, providing a catalogue of CEOS/CGMS agency missions, instruments, measurements, data volumes etc.;
3. Inventory of relevant non-met applications and review of initiatives being undertaken by CEOS and related agencies in the atmosphere, land and ocean themes;
4. Benefits of synergistic use of GEO-LEO systems;
5. Coordinating initiatives that are relevant to the further coordination and progression of non-meteorological applications and;
6. Summary and identified opportunities for the way forward tactically and strategically for CEOS and its agencies.

2 Trends and Outlook for Geostationary EO Satellite Capabilities

2.1 Retrospect

Operational geostationary weather satellites have been in service since mid 1970s and these satellites are critical to severe weather prediction. Since 1975, the US National Oceanic and Atmospheric Administration has been operating a series of Geostationary Operational Environmental Satellites (GOES). As of February 2016, three GOES satellites (GOES-13, 14, and 15) are available for meteorological operations, with two operational at any given time. The European Space Agency (ESA) launched Europe's first geostationary weather satellite Meteosat-1 in 1977 and, similar to NOAA, EUMETSAT (the European Organization for the Exploitation of Meteorological Satellites) has two operational geostationary satellites at any given time (METEOSAT Second Generation Meteosat-9 and Meteosat-10 as of February 2016). EUMETSAT is also operating a First Generation geostationary satellite over the Indian Ocean, Meteosat-7 and is now in the process of replacing it with Meteosat-8, which will take over operational services in that region in early 2017. In Asia, the Japan Meteorological Agency, the Indian Space Research Organization, the China Meteorological Administration, and the Korea Meteorological Administration (KMA) have been operating geostationary satellites since 1978, 1983, 1997 and 2010 respectively. The Japanese satellites are called "Himawari" (sunflower), the Indian satellites are known as the Indian National Satellite System (INSAT), the Chinese satellites are called "Feng-Yun" (wind and cloud) and the Korean satellite is called the Communication, Ocean and Meteorological Satellite (COMS). Among the current operational satellites, the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) on MSG is the most advanced Earth imager with twelve spectral bands. The imagers on other satellites have either five or six bands and their functional capabilities are similar.

2.2 The Next Generation of Geostationary Weather Satellites

The next generation of geostationary weather satellites has arrived. The Japan Meteorological Agency (JMA) launched Himawari-8 on 7 October, 2014, which carries the Advanced Himawari Imager (AHI), a new generation sensor that collects imagery of the Earth's hemisphere in sixteen spectral bands every ten minutes at spatial resolutions ranging from half a kilometre to two kilometres. AHI is the first sensor of its kind to be ever launched into a geostationary orbit. NOAA will begin launching its next generation GOES satellites, called the GOES-R series carrying the Advanced Baseline Imager (ABI), in 2016. EUMETSAT is working towards the goal of launching and reaching operational capability of the METEOSAT Third Generation (MTG) geostationary satellites, which will carry the Flexible Combined Imager (FCI). The Korean Meteorological Agency (KMA) plans to launch Geostationary Korea Multi-Purpose Satellite - 2A (Geo-KOMPSAT-2A) which will carry an imager that is identical in design to AHI and ABI and is called the Advanced Meteorological Imager (AMI) in 2018. CMA will launch their Feng-Yun-4 (FY-4) satellite, carrying the Multiple Channel Scanning Imager (MCSI, also known as the Advanced Geostationary Radiation Imager, AGRI), in 2017. All these missions will carry a suite of Earth observing instruments that will provide significantly improved spectral and spatial resolution compared to the legacy satellites. In addition to advanced Earth imagers, several satellites or dedicated geostationary missions also carry other sensors such as lightning sensors, space weather instruments and infrared and ultraviolet/near-infrared sounders. Nevertheless, the discussion here will be only focused on Earth observing geostationary new generation imagers as today there committed plans for the deployment of this capability for the full geo-ring and providing frequent full-disk imagery. Together, these missions provide continuous observations of more than two thirds of the Earth's hemisphere (Figure 1) at much higher temporal cadences than the current satellites. This offers new opportunities for meteorological as well as a wide suite of non-meteorological applications including but not limited to thematic areas such as agriculture, natural and ecosystem monitoring and management, mapping vector borne diseases and aviation safety. Since the spectral characteristics of the new generation GEO sensors is based on well proven legacy remote sensing sensors that have been operational in Low Earth Orbit (LEO) for several decades, combining data from these two platforms opens up new possibilities of combining high temporal GEO observations with moderate spatial resolution LEO sensors. The following sections describe the capabilities of the next generation operational geostationary missions.

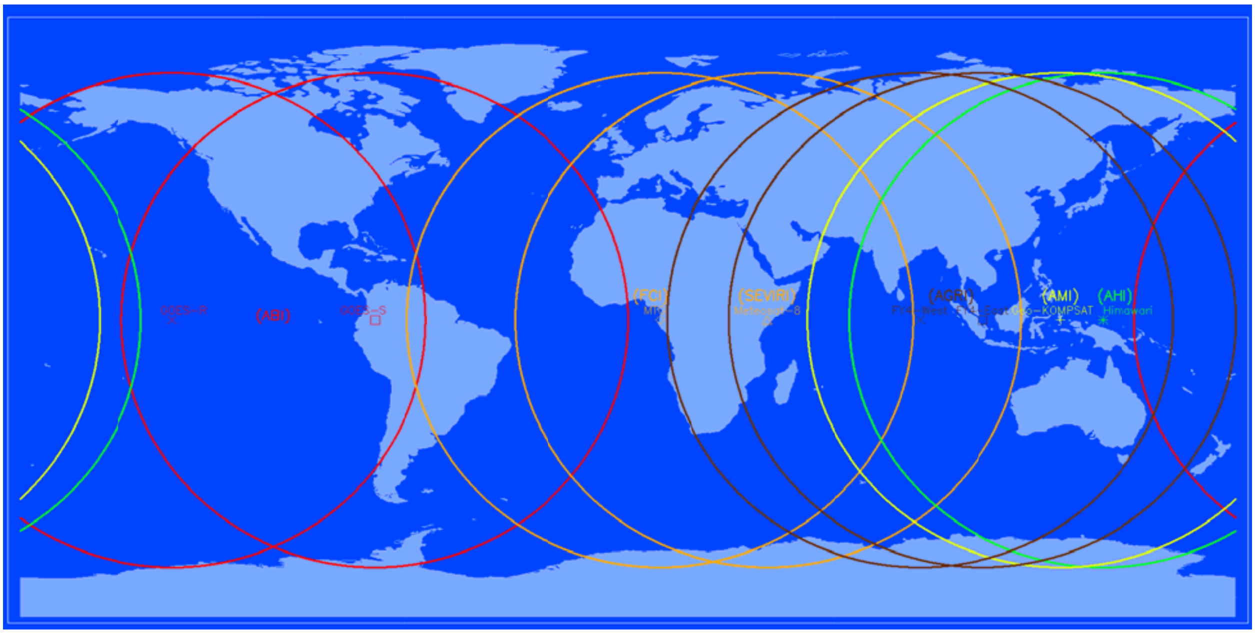


Figure 1: Spatial coverage from the next generation of geostationary meteorological satellites.

2.2.1 AMI/ABI/AHI

The advanced imager is a multi-channel, visible through thermal infrared, imaging radiometer that provides observations in sixteen spectral channels, which significantly exceeds the five-channels of the Imager on the current GOES I/P series (Schmit et al. 2005). All the three advanced imagers (AHI, ABI and AMI) are built by Harris Corporation, and are identical in design apart from minor differences in the choice of spectral bands. Of the sixteen spectral bands, there is a solar reflective band with a 0.5 km spatial resolution, three solar reflective bands at 1 km spatial resolution and twelve NIR/IR bands at 2 km spatial resolution. The spectral ranges of channels among the imagers are configured uniquely depending upon the meteorological agencies requirements (Table 1). All the imagers are flexible in regards to how much of the Earth they can scan and how frequently an area can be scanned. The specific scanning scenarios are defined by the user as a “timeline” and the imaging sequence and frequency follows the timeline. For example, in a given timeline, the entire full disk of the Earth can be imaged in all 16 bands at a 10 minute interval while imaging two separate 1000 km x 1000 km areas every 30 seconds. A timeline therefore defines what to observe and when. Within a given timeline, the imager also observes internal calibration targets such as black body, space looks and stars for radiometric calibration and navigation. All this data is seamlessly interleaved and transmitted to a command and data handling ground station, where the raw data is processed as follows:

1. Uncompressed to detector sample values
2. Radiometric calibration is applied
3. Calibrated detector values are navigated to Earth location
4. Calibrated and navigated values are re-sampled to form pixels, and finally,
5. Generating images in a fixed grid Cartesian projection

Table 1: Comparison of multi-band imagers of geostationary satellites.

Approx. Central Wavelength (µm)	Band Explanation	GOES-R ABI	Himawari AHI	GK-2 AMI	MTG FCI	FY-4 AGRI
		Spatial Resolution (km) @ nadir [Band Number]				
0.47	Visible/reflective	1 [1]	1 [1]	1 [1]	1 [1]	1 [1]
.510		None	1 [2]	1 [2]	1 [2]	None
0.64		0.5 [2]	0.5 [3]	0.5 [3]	1/0.5[1] [3]	0.5-1 [2]
0.865	Reflective	1 [3]	1 [4]	1 [4]	1 [4]	1 [3]
0.91		None	None	None	1 [5]	None
1.378	Cirrus	2 [4]	None	2 [5]	1 [6]	2 [4]
1.61	Snow/Ice	1 [5]	2 [5]	2 [6]	1 [7]	2 [5]
2.25	Particle size	2 [6]	2 [6]	None	1/0.5[1] [8]	2-4 [6]
3.90	Shortwave IR	2 [7]	2 [7]	2 [7]	2/1[1] [9]	2,4[2] [7,8]
6.19	Water vapor	2 [8]	2 [8]	2 [8]	2 [10]	4 [9]
6.95		2 [9]	2 [9]	2 [9]	None	4 [10]
7.34		2 [10]	2 [10]	2 [10]	2 [11]	None
8.5	Water vapor, SO_2	2 [11]	2 [11]	2 [11]	2 [12]	4 [11]
9.61	Ozone	2 [12]	2 [12]	2 [12]	2 [13]	None
10.35	Longwave IR	2 [13]	2 [13]	2 [13]	2/1[1] [14]	4 [12]
11.2		2 [14]	2 [14]	2 [14]	None	None
12.3		2 [15]	2 [15]	2 [15]	2 [15]	4 [13]
13.3		2 [16]	2 [16]	2 [16]	2 [16]	4 [14]

True-color component bands are highlighted in red, green, and blue; [1]Resolution depends on imaging mode; [2]Two bands.

2.2.2 HIMAWARI-8 CONCEPT OF OPERATIONS

Himawari-8 is designed to have an operation life of at least seven years and will be replaced by Himawari-9, which is expected to be launched in 2016 and stored in orbit until needed for operations. Both satellites are therefore expected to provide coverage until 2029. AHI data collection has a 10 minute timeline (Bessho, et al. 2016). Within a 10 minute interval, the full disk is imaged once; two regions (Region 1 and 2) covering Japan are imaged every 2.5 minutes; a "Target Area" (Region 3) is imaged every 2.5 minutes; and two "Land mark" area (Regions 4 and 5) are imaged every 30 seconds (Figure 2).

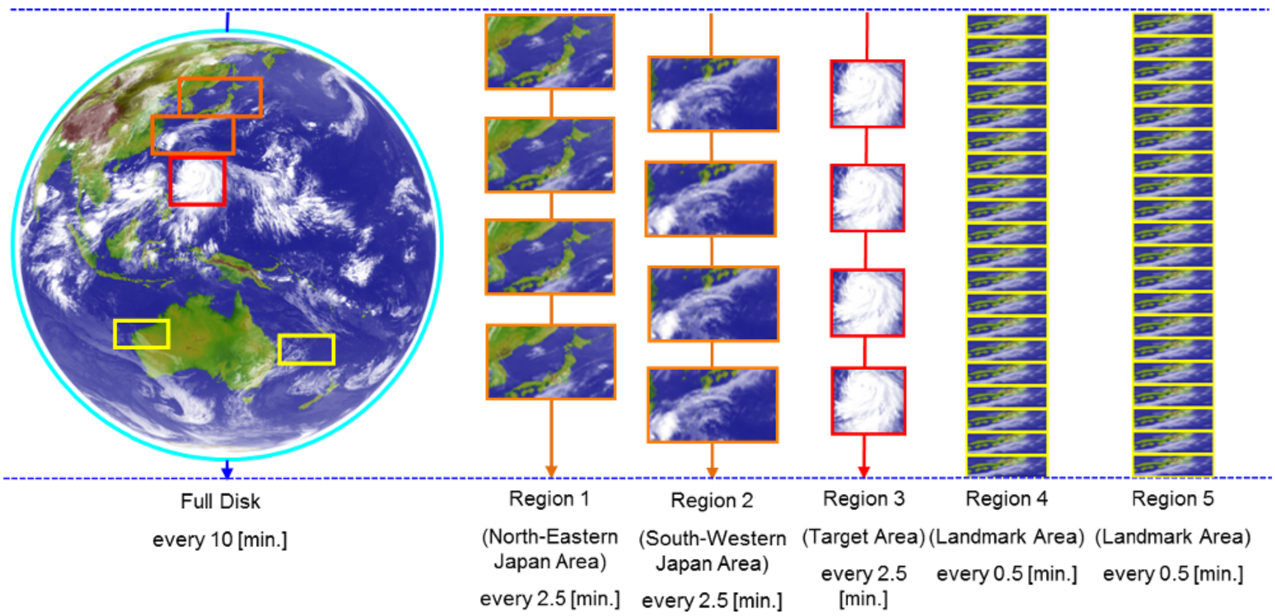


Figure 2: AHI data collection timeline.

Whereas the full disk and spatial coverage of Regions 1 and 2 are fixed, the locations of Regions 3, 4 and 5 can be moved around. Therefore, within a 10 minute timeline, the full disk is imaged once, the Japanese region and the Target Area are imaged four times and the Land Mark areas are imaged 20 times. Regions 1 and 2 that cover Japan are 2000 km x 1000 km each. Region 3 is 1000 km x 1000 km, regions 4, and 5 are 1000 km x 500 km each.

Raw AHI data is down-linked in the Ka-band at two ground stations located at Kanto (primary) and Hokkaido (secondary) (Figure 3). On the ground, raw AHI data processed to Level 1a (known as Himawari radiometric data, which are raw data with calibration and navigation parameters appended). Level 1a data from both the primary or secondary ground station are sent to the Meteorological Satellite Centre (MSC) located in Tokyo (back up facility in Osaka) where it is further processed in to two higher level products: Level 1b Himawari Standard Data (HSD) and the High-rate Information Transmission (HRIT) files. HSD is the full resolution, 16 band calibrated and geolocated AHI data. HRIT data has a lower spatial resolution and smaller data volume compared to HSD, and consists of a visible band at 1 km, three NIR at 4 km and ten IR bands at 4 km spatial resolution respectively. HSD and HRIT data covering the entire full disk in a 10 minute timeline is stored as 10 segment files, where a segment covers an East-West swath. In addition to HSD and HRIT, a true colour full disk RGB image in the Portable Network Graphics (PNG) is created from the three reflective bands at a spatial resolution of 1 km.

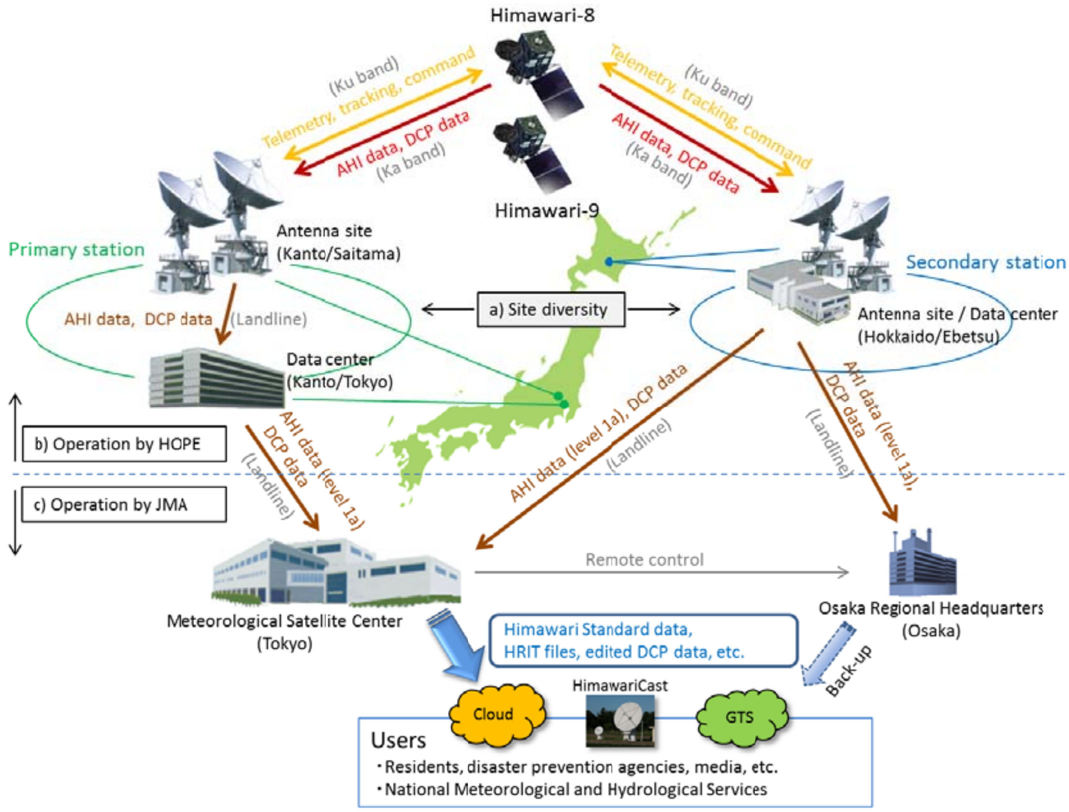


Figure 3: Himawari-8 system architecture.

The primary method for National Meteorological and Hydrological Service (NMHS) users to access the HSD and PNG data is through the internet. Up to 72 hours of data is stored on the HimawariCloud (JMA URL 1, 2016) and users with a subscription can download the data through HTTP1.1/TLS1.0 protocol (JMA URL 2, 2016). Besides the 10 minute full disk data, users can also download the full resolution Target Area files that are collected every 2.5 minutes in HSD and NetCDF formats as well as true color PNG files from the HimawariCloud.

The HRIT data is broadcast as "HimawariCast" using a communication satellite (JCSAT 2A/2B) and the HRIT data format is compatible with the legacy MTSAT HRIT data format. Users need a C band DVB-S2 antenna receiver and computers to downlink and process the HRIT data. Full specifications for the HimawariCast antennas and the computer/software to process the HRIT data can be found at (JMA URL 3, 2016).

2.2.3 **GOES-R CONCEPT OF OPERATIONS**

In 2016, the United States National Oceanic and Atmospheric Administration (NOAA) is expected to launch the first satellite in a new mission of four satellites continuing the Geostationary Operational Environmental Satellites (GOES) series. This next generation of GOES satellites, the GOES-R series, is scheduled to launch in 2016 and, once operational, will provide significant enhancements that go well beyond the current capabilities. Four satellites will be launched (GOES-R, S, T and U) and, in accordance with NOAA naming convention, will be designated GOES-16 through 19 after successful insertion into geostationary orbit. The GOES-R series will carry the Advanced Baseline Imager (ABI) whose design is identical to AHI.

The GOES-R series represents a generational change in geostationary meteorological observation to meet forecasting and environmental monitoring requirements. GOES-R products will be much more advanced compared to the legacy GOES I-P (GOES 8-15) series in terms of spatial, spectral, and, especially, temporal resolution. The two operational satellites will be located at East (75°W longitude) and West (137°W longitude), providing simultaneous, continuous coverage of the entire Western hemisphere 24 h a day.

The Earth and space observation technology improvements embodied in GOES-R will enable a higher science data rate compared to the current GOES satellites. For instance, while the downlink data rate for raw science and telemetry from the current operational GOES satellites is 2.76 Megabits per second (Mbps) 24 hours per day, the peak downlink data rate for raw science and telemetry from the GOES-R series spacecraft command and data handling system is 120 Mbps in the X-band. Under nominal operations, the data content from the six GOES-R series instruments is expected to reach 78 Mbps, offering margin for higher data rates to support instruments operating in diagnostic mode.

While ABI can be configured to image different areas of the Earth at different observation cadence, the launch baseline is configured to operate in two modes or timelines: Mode 3, or flex mode, and Mode 4, or continuous full-disk mode. In Mode 3, the Earth's full hemisphere is imaged every 15 minutes, a Continental U.S. (CONUS) image is collected every 5 minutes, and one mesoscale image (1000 km × 1000 km at the satellite sub point) is collected every 30 seconds. In Mode 4, the Earth's hemisphere is imaged every 5 minutes (Figure 4).

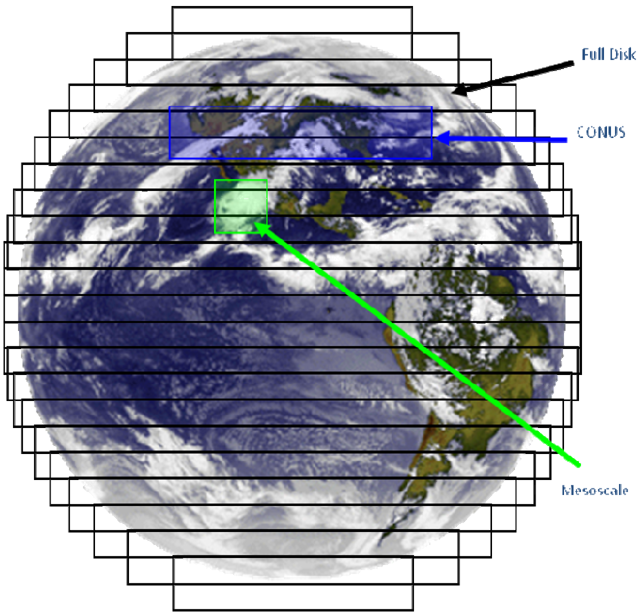


Figure 4: ABI data collection scene definitions.

The GOES-R Ground System (GS) has three geographically separate operational sites (Figure 5). The first of these, the Wallops Command and Data Acquisition Station (WCDAS) in Wallops, Virginia, will provide the primary Mission Management (MM) satellite command and control services and selected Product Generation (PG) and Product Distribution (PD) services (Kalluri et al. 2015). These services convert the raw satellite sensor measurements to L1b data which is rebroadcast over the western hemisphere at L-band frequency as GOES Rebroadcast Services (GRB). The second operational GS site is the Consolidated Backup Unit (CBU) in Fairmont, West Virginia, which performs all MM, PG and PD functions performed at WCDAS as a redundant, secondary "hot backup". The GS is designed to failover from WCDAS to the CBU and transition to operational status within five minutes when directed by the ground operators.

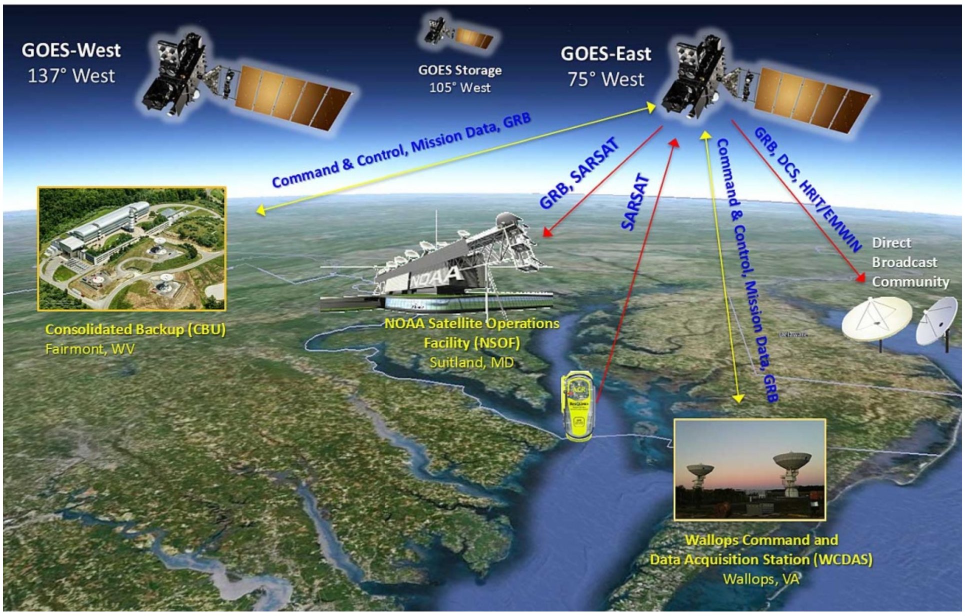


Figure 5: GOES-R series system architecture.

Either WCDAS (primary) or CBU (redundant backup) can broadcast GRB data. Users with a direct broadcast readout receiver antenna can receive this data in real time. The GRB data rate is 31 Mbps in the L-band and is in Digital Video Broadcast Services-2 (DVBS-2) format (http://www.goes-r.gov/users/grb.html). Legacy GOES Low Rate Information Transmission (LRIT)/ Emergency Managers Weather Information Network (EMWIN) data transmission which includes a collection of reduced resolution imagery products will be enhanced for GOES-R and the data rate will increase from 128 Kbps to 400 Kbps (http://www.goes-r.gov/users/hrit.html).

The third operational GS site is the NOAA Satellite Operations Facility (NSOF) in Suitland, Maryland. The GRB data is received at NSOF by the GS. The ABI L1b data is then extracted from the GRB stream and processed into 25 higher-level products (Level 2+), which includes ocean, land and atmospheric products such as land surface temperature, cloud properties and sea surface temperature. All L1b and L2+ products are distributed to external users from NSOF through the internet. All satellite operations at the three sites can be run from NSOF.

In addition to GRB and terrestrial distribution of GOES-R data, there are also plans to distribute a subset of the data (to be determined) through GEONETCast Americas, which is the Western Hemisphere component of GEONETCast, a near real time, global network of satellite-based data dissemination systems designed to distribute space-based, air-borne and in situ data, metadata and products to diverse communities (http://www.geonetcastamericas.noaa.gov/). GEONETCast is a low cost satellite data service that allows users across the hemisphere to receive near real-time imagery and other products for operational meteorology and other applications.

2.2.4 GEOKOMPSAT 2A CONCEPT OF OPERATIONS

GEOKOPMSAT 2A scheduled to launch in 2018, will operate from 128.2°E location and is expected to have a 10 year operational life. AMI will collect full disk data every 10 minutes and will also have the capability to schedule more rapid data collection over regional areas (TBD). The satellite data will have redundant ground processing at two receiving stations operated by the National Meteorological Satellite Center (NMSC). In addition to processing raw AMI data to Level 1b (calibrated and navigated radiances), 52 higher

Level 2 meteorological products are also created for scene & surface analysis, cloud & precipitation, aerosol & radiation, and atmospheric condition & aviation. Data distribution of AMI radiances will be both by satellite rebroadcast as well as terrestrial web based services (http://dcpc.nmsc.kma.go.kr). Table 2 shows that data services plan for GEOKOMPSAT 2A:

Table 2: Data Services Plan for GEOKOMPAT 2A.

Service	UHRIT	COMS-like H/LRIT	
		HRIT	LRIT
Data rate	≤ 31 Mbps	3 Mbps	~512 Kbps
Frequencies	Uplink: S-band Downlink: X-band	Uplink: S-band, Downlink: L-band *Same frequencies band with COMS	
Data type	AMI image (16 channel) Alpha-numeric text Encryption key message * Additional info could be added in the future	AMI image (5 channel) Alpha-numeric text Encryption key message GOCI-II products (TBD)	AMI image (5 channel) Alpha-numeric text Encryption key message Lv2 products GOCI-II image file
Mode	FD	FD, ENH	FD, ENH
Station	LDUS	MDUS	SDUS

[1]HRIT (High Rate Information Transmission); [2]LRIT (Low Rate Information Transmission); [3]MDUS/SDUS (medium/small-scale data utilization stations).

2.2.5 MTG CONCEPT OF OPERATIONS

The METEOSAT Third Generation is a two satellite system in which MTG-I will host two imaging payloads: the Flexible Combined Imager (FCI) and the Lightning Imager (LI); and MTG-S (sounder) will host the Infrared Sounder (IRS), and the Copernicus Sentinel-4 Ultraviolet Visibile-NIR spectrometer (UVN). Four MTG-I and two MTG-S satellites will be launched starting in 2020 and are expected to provide 20 years of continuous on-orbit service for the imagers, and 15.5 years for the sounders. When the system is fully deployed, there will be two imaging satellites and a sounding satellite operating in parallel.

The FCI can scan the full disk every 10 minutes and a European Regional-Rapid-Scan (RRS) which covers one-quarter of the full disk with a repeat cycle of 2.5 minutes (Figure 6).

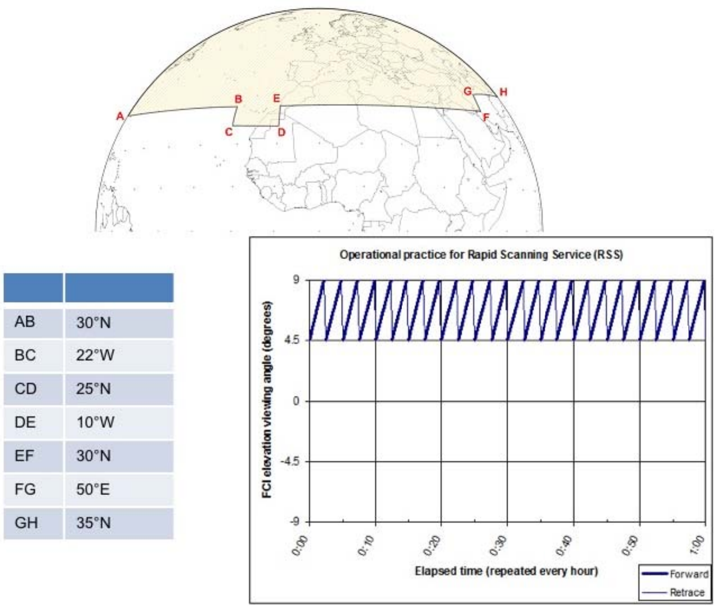


Figure 6: FCI scene types.

Mission data is acquired in the Ka-band frequency at two sites located in Lario, Italy and Leuk, Switzerland. Two sites are necessary for redundancy as well as to cope with occasional signal attenuation in the Ka band due to severe storms. The data is decrypted and sent to the Mission Processing Facility at the EUMETSAT headquarters in Darmstadt, Germany for further processing and distribution of Level 1b, Level 1c and Level 2 products via terrestrial communication networks (Figure 7). Users can either access the data via the internet or receive direct broadcast of EUMETCast data in DVBS-2, in similar manner to legacy Meteosat services.

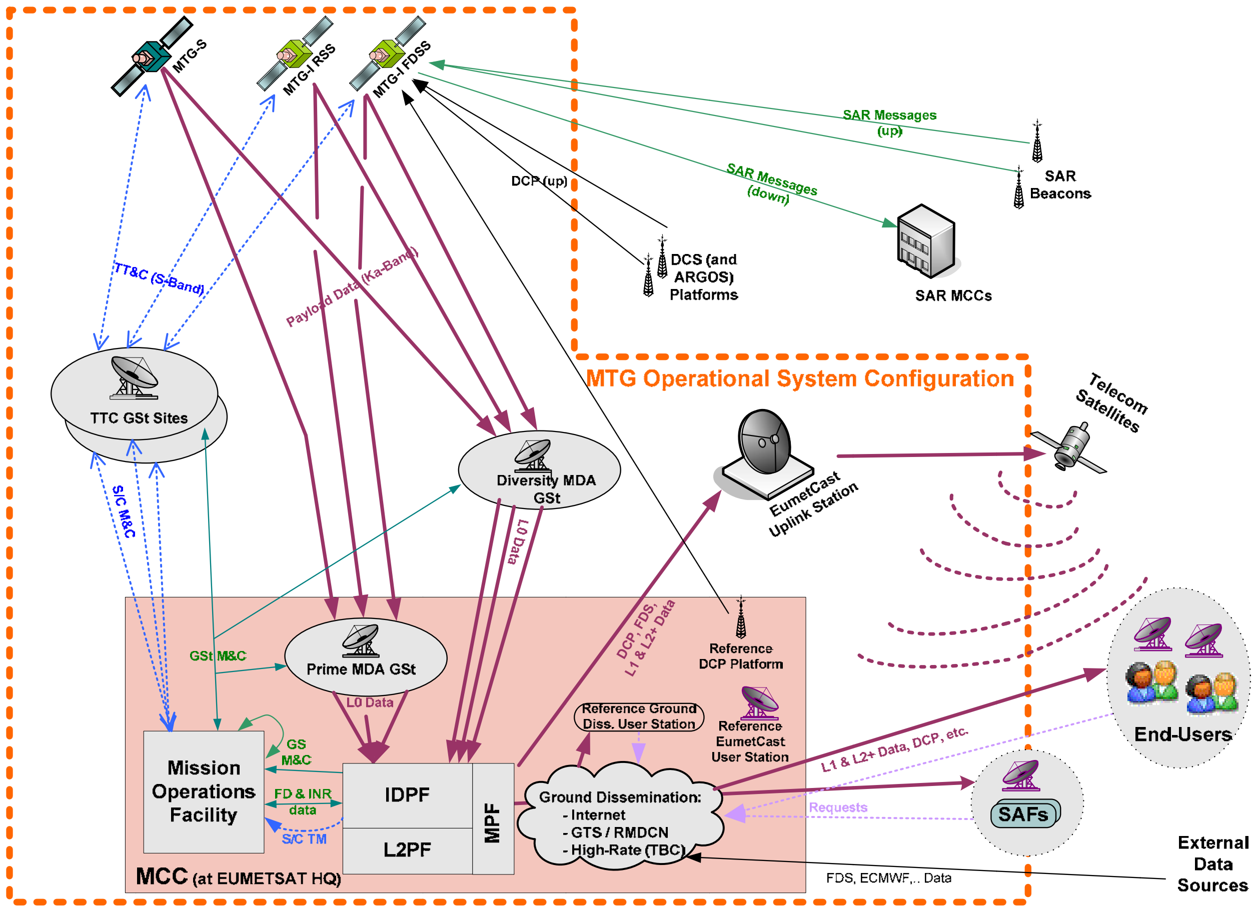


Figure 7: MTG ground system (Legendre, et al. 2010).

2.2.6 FENG YUN-4

The first FY-4 series of satellites, FY-4A is expected to be launched by China by the end of 2016. FY-4A will be a system test and demonstration satellite, and will be followed by FY-4B, FY-4C and FY-4D operational satellites. There will be a Space Environment Package (SEP) and three earth observing sensors which include the Advanced Geosynchronous Radiation Imager (AGRI), Geostationary Interferometric Infrared Sounder (GIIRS) and a Lightning Mapping Imager (LMI). AGRI, the primary instrument of FY-4A, has 14 channels within 0.55-13.8 µm and two observation modes. The temporal resolutions are 1-5 minutes over regional domain and 15 minutes over full-disk domain. AGRI will collect images at 0.5km spatial resolution in one channel, 1 km spatial resolution in two channels, 2km spatial resolution in four channels, and 4km spatial resolution in seven channels. FY-4A is expected to have a design life of five years while the following operational satellites are expected to last for seven years. Two satellites will be operated at 86.5°E and 105°E longitudes, similar to the current operational FY-2 series. GIIRS can be used for vertical atmospheric sounding and it is the first high-resolution sounding sensor onboard the geostationary satellite. There are two observation modes of GIIRS. One mode is designed for China area, whose temporal resolution is 55 minutes and the coverage is 4500 x 4500 km. The other observation mode is Meso-Scale mode, whose temporal resolution is 30 minutes and the coverage is 1000 x 1000 km. Lighting Mapping Imager (LMI) can detect the present of space-based lighting, which is useful for early predictions of storms and severe weather events.

FY-4 data and products will be delivered by the several ways. Near-real time direct broadcast of full resolution data Level 1b data will be available to meet the users' urgent requirements through a dual polarized HRIT (High Rate Information Transmission) with the rate of 21 Mbps. Low Rate Information Transmission (LRIT) broadcasting of image frames and other data will also be available. Higher level data products from FY-4 will also be broadcast to a world-wide community through CMACast, which is a component of the GEONETCast. Based on the mass-data characteristic of FY-4 satellite, CMA will provide a better data-service capability under the cloud framework for the global users after the comprehensive trade-off among the safety of private cloud, cost-to-effectiveness of public cloud and the high-speed wideband internet requirement of cloud technology itself.

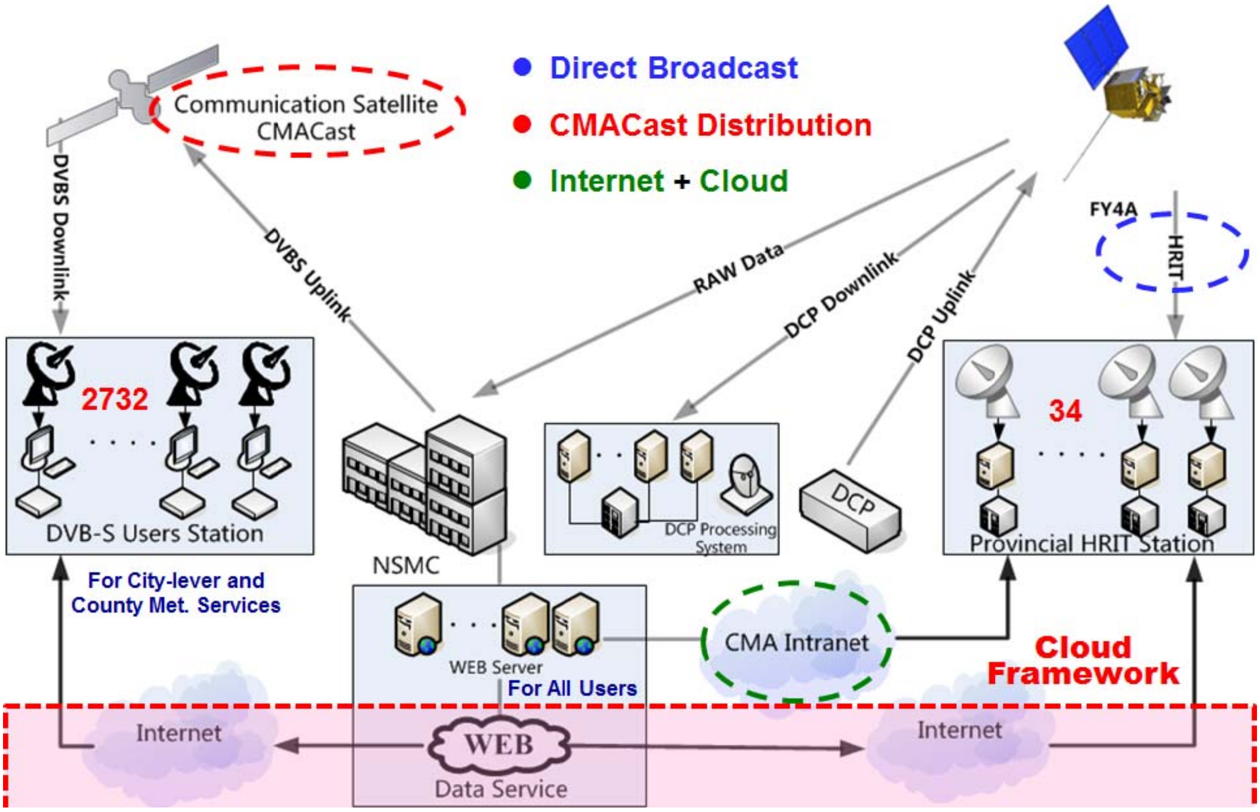


Figure 8: FY-4 Data Distribution and Service.

2.3 Geostationary Satellite Missions with Unique Capabilities

The geostationary missions described earlier in this chapter (e.g. GOES-R, Himwari-8, MTG etc.) are all new missions that provide continuity of legacy systems that have been providing vital remote sensing measurements for operational meteorology for over twenty years. As the existing fleet of operational meteorological satellites reach their end of life, they will be replaced by the new systems to provide uninterrupted coverage. In addition to the new operational meteorological satellites, there are also several new planned missions that have unique capabilities designed to study and monitor specific processes such as atmospheric chemistry and oceanography. This section will briefly review some of these unique missions.

2.3.1 A CONSTELLATION FOR OBSERVING GLOBAL AIR QUALITY

The Committee on Earth Observation Satellites (CEOS) encourages, through its Virtual Constellations (VCs) as thematic or topic-driven working bodies, the coordination of space-based, ground-based, and/or data delivery systems to meet a common set of requirements within a specific domain. The CEOS Atmospheric

Composition Virtual Constellation (AC-VC) focuses on observations needed to improve monitoring and assessment of changes in the ozone layer, air quality and climate forcing. The CEOS AC-VC has defined a vision for a geostationary satellite constellation for observing global air quality[1] that currently includes three ultraviolet (UV) and UV plus visible (UV-Vis) spectrometers in geostationary orbit over Asia, North America, and Europe. While these instruments are separate from the new geostationary meteorological imagers, two of them share platforms with the meteorological imagers, and the constellation serves as an example of a coordination plan for imaging observations from geostationary orbit. The geostationary UV and UV-Vis spectrometers will provide hourly retrievals of ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and formaldehyde (HCHO) columns as well as aerosol optical depth (AOD) over the major industrialized regions of the northern hemisphere (Figure 8). These measurements are directly relevant to urban air quality, trans-boundary pollution transport, and improved air quality forecasting.

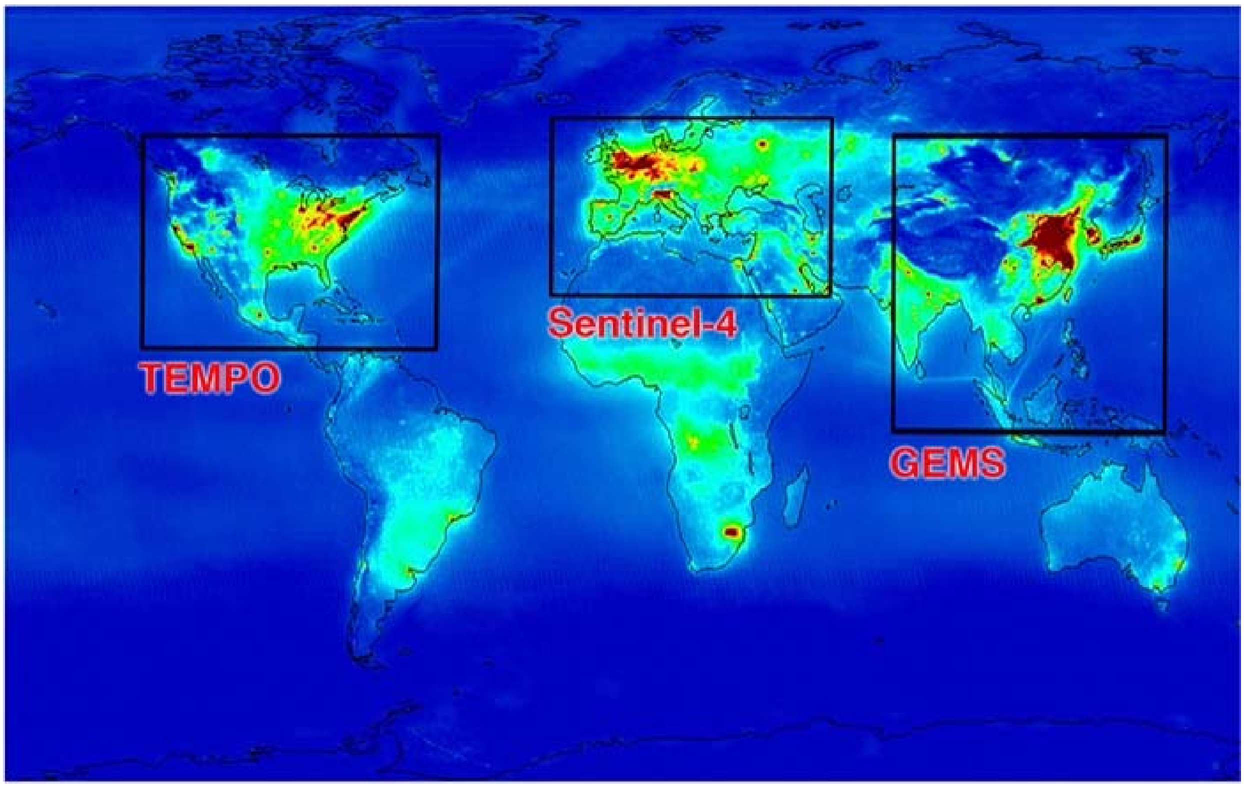


Figure 9: CEOS Geostationary Atmospheric Chemistry Constellation and OMI tropospheric column nitrogen dioxide (NO2) showing high tropospheric NO2 columns associated with major industrialized regions (from http://tempo.si.edu/index.html).

The Geostationary Environment Spectrometer (GEMS) instrument is planned to be launched by the Korea Aerospace Research Institute (KARI) in 2019 onboard the Geostationary Korea Multi-Purpose Satellite (GeoKOMPSAT) and will cover a 5000 km x 5000 km field of regard centred over Korea. GEMS will measure radiances between 300 nm and 500 nm with a spectral resolution of less than 0.6 nm and a spatial resolution of 3.5 km N/S x 8 km E/W at 38°N. The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument is part of the National Aeronautics and Space Administration (NASA) Earth System Science Pathfinder (ESSP) Earth Venture (EV) program[2] and is planned to be launched no later than 2021 as a hosted payload instrument onboard a commercial satellite. TEMPO will cover the continental US, and extend north to the Canadian oil sands, and south to Mexico City and the Yucatan Peninsula. TEMPO will

[1] http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/ACC_White-Paper-A-Geostationary-Satellite-Cx-for-Observing-Global-AQ-v4_Apr2011.pdf
[2] http://science1.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder/

measure radiances between 290-490 and 540-740 nm with a spectral resolution of 0.6 nm (full width at half maximum, 0.2 nm sampling) and will have a spatial resolution of 2.22 km N/S x 5.15 km E/W at 35°N. The European Sentinel-4 UV-Vis and Near-infrared sounder (UVN) is planned to be launched onboard the Meteosat Third Generation Sounding (MTG-S) satellite in 2022[3]. Sentinel-4 will measure radiances in the 305 nm to 500 nm and 750 nm to 775 nm ranges with a spectral resolution of 0.5 nm (UV-VIS) and 0.12 nm (NIR) and a spatial resolution of 8 km x 8 km at 45°N. The additional visible wavelengths (> 540nm) on the TEMPO and Sentinel-4 instruments allows retrieval of both total and tropospheric ozone columns. TEMPO will also retrieve glyoxal **(**CHOCHO).

These geostationary UV-Vis spectrometers have a long heritage on polar orbiting satellites, including the Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite, from the **Sc**anning **I**maging **A**bsorption spectro**m**eter for **A**tmospheric **Ch**artograph**y** (SCIAMACHY), an in-kind contribution of Germany (DLR), the Netherlands (NSO), and Belgium (BelSpo) on the Envisat satellite of the European Space Agency, and from the Global Ozone Monitoring Experiment (GOME) instruments 1 and 2 flown on ESA's ERS-2 and EUMETSAT Polar System (EPS) Metop-satellites, respectively. The CEOS proposed Air Quality Constellation will measure many of the same atmospheric constituents, but geostationary orbit will enable significantly higher spatial and temporal resolutions. The high resolution spatial sampling of the geostationary spectrometers will allow characterization of ozone, ozone precursors, and aerosols on an urban scale (Figure 9). The high temporal resolution of the geostationary spectrometers will allow characterization of morning through evening variations in ozone production associated with rush hour automotive emissions. By combining these geostationary measurements with next generation polar orbiting UV-Vis NIR sensors such as the Tropospheric Monitoring Instrument (TROPOMI), the only payload on ESA's Sentinel-5 Precursor (S5P) mission, we will be able to characterize synoptic-scale long-range transport of pollution from emission sources to receptor regions. The polar orbiting Sentinel-5 Precursor serves as the gap filler between SCIAMACHY and Sentinel-5 and is instrumented with TROPOMI, a spectrometer with bands in the ultraviolet and visible (270 to 495 nm), the near infrared (675 to 775 nm) and the shortwave infrared (2305 to 2385 nm) with a spatial resolution of 7×7 km^2 that will be launched during the fourth quarter of 2016[4,5]. The Sentinel-5 Precursor can be understood as a complement to the European Union Copernicus program which includes Sentinel-5 onboard EUMETSAT's Polar System Second Generation (EPS-SG). Sentinel-5 combines five spectrometers with bands in the UV-Vis (270-370 nm, 370-500 nm), the NIR (685-773 nm), and the SWIR (1590-1675 nm and 2305-2385 nm) with a spatial resolution of 7×7km^2. Sentinel-5 will be operated on the Metop-SG satellite A series from 2021 onwards, with a total mission lifetime of around 21 years on three sequentially launched modules.

In addition to these UV-Vis spectrometers there are also plans to launch geostationary hyper- spectral infrared (IR) sounding instruments over both Europe and Asia. However, there are currently no plans to launch geostationary hyper-spectral infrared sounders over North America. The planned geostationary hyper-spectral infrared sounding instruments include the European Space Agency (ESA) Infra Red Sounder (IRS) onboard Meteosat Third Generation Sounder (MTG-S1) in 2022[4] and the China Meteorological Administration (CMA) Geostationary Interferometric Infrared Sounder (GIIRS) on board the Feng-Yun - 4 (FY-4) in 2016. IRS will provide IR measurements in two wave number (wavelength) regions: 700 - 1210 cm^{-1} (14.3 - 8.26 μm) and 1600 - 2175 cm^{-1} (6.25 – 4.6 μm) at a spectral resolution of 0.625 cm^{-1} and a spatial resolution of 4 km. GIIRS will provide IR measurements in similar wavelength regions: 700 - 1130 cm^{-1} (14.3 - 8.85 μm) and 1650 - 2250 cm^{-1} (6.06 – 4.44 μm) at slightly lower spectral resolutions of 0.8 cm^{-1} and 1.6 cm^{-1} respectively and a spatial resolution of 16 km. These IR sounders are primarily designed for high temporal and vertical resolution retrievals of temperature and water vapor for meteorological applications,

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[3] http://www.wmo-sat.info/oscar/instruments/view/584

[4] http://esamultimedia.esa.int/docs/EarthObservation/SP-1332_Sentinel-5P.pdf (January 2016)

[5] http://www.wmo-sat.info/oscar/instruments/view/232

but will also provide information on upper tropospheric and lower stratospheric ozone. Studies have shown that combining geostationary UV-Vis and IR measurements provides significant improvements in retrieving tropospheric ozone (Natraj et al, 2011).

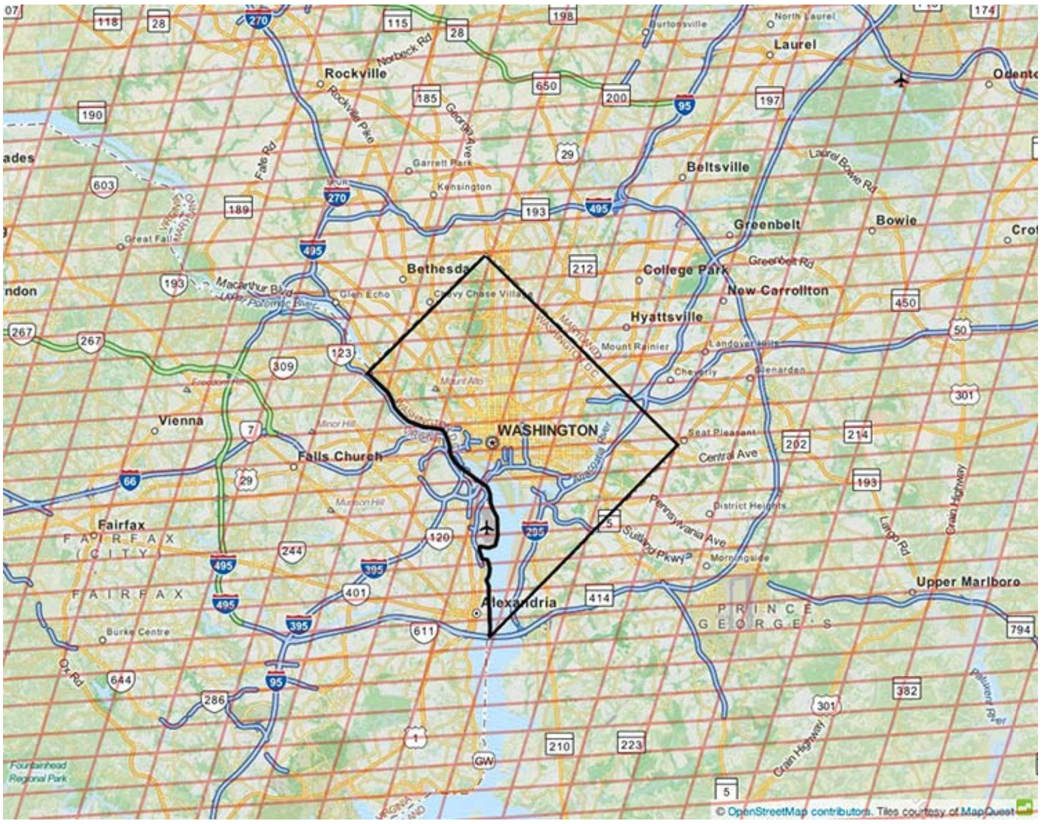

Figure 10: Spatial sampling of hourly TEMPO measurements relative to the Washington DC metropolitan area. Each orange rectangle represents the footprint of a single pixel (from http://tempo.si.edu/index.html).

2.3.2 OCEAN COLOUR SENSORS

The Geostationary Ocean Colour Imager (GOCI) is the first and only ocean colour sensor launched into geostationary orbit. It was developed by the Korean Aerospace Research Institute (KARI) and successfully launched in 2010 on board the Communication Ocean and Meteorological Satellite (COMS). GOCI collects data at 500m spatial resolution in 8 spectral bands (6 visible, 2 NIR) ranging from 412nm to 864nm, every hour (about 8 times daily). The centre of field is at 130°E/36°N, the sensor collects data over a 2500x2500km area (Ryu et al. 2012). Based on the success of GOCI, a follow on mission, GOCI-II, is planned as part of the GEO-Kompsat 2B which expected to be launched in 2019. GOCI-II will increase the spatial resolution to 250m, and collect data 10 times daily in 12 spectral bands (Table 3). Additionally, the entire hemisphere will be observed once a day.

Table 3: Comparison of GOCI and GOCI-II sensors (CGMS-44-KMA-WP-01).

Items	GOCI Specs	GOCI-II Specs
Bus	COMS	GEO-KOMPSAT-2B
Increased band number	8 bands (412~865 nm)	12 bands (380 ~ 865nm)
Improved spatial resolution	500m	250m (at 130E, Eq)
More observations	8 times/day	10 times/day
Pointable & Full Disk coverage	Local Area	Local Area + Full Disk

The GEOstationary Coastal Air Pollution Events (GEO-CAPE) geostationary mission led by NASA to host GEO-CAPE instruments on separate spacecrafts in response to recommendations made by National Research Council’s 2007 Earth Science Decadal Survey. Based on the results of instrument design efforts, science studies, and field campaigns, the Science Traceability Matrix was most recently revised in July 2015 (http://geo-cape.larc.nasa.gov/docs/OceanSTMv4_7_30July2015.pdf). The goals are to design a system that can make hyperspectral measurements in the UV-VIS-NIR region from a geostationary location at $94^{o}\pm2^{o}$ W longitude at a threshold value of ≤2 hours, with the baseline requirement remaining at ≤1 hour. The Coastal Ocean Colour Science Working Group (OSWG) identified that the spatial resolution should be ≤ 375 x 375 m, with a baseline (goal) resolution of ≤ 250 x 250 m. It is envisioned that the GEO-CAPE sensors would be in orbit in the 2020 time frame.

2.3.3 GF-4

The GF-4 satellite was launched on December 29, 2015. It is the first geostationary orbit satellite with a high spatial resolution optical imager in China, acquiring 50-meter visible channels and a 400-meter mid-infrared channel, it’s observation width is 400 meters, and the image mode of the sensor is a staring array. The design life of GF-4 is 8 years. It provides observations for China and surrounding areas by pointing control. GF-4 has two application observation modes, meteorology mode and land mode. Its revisit time is 20s. The GF-4 satellite will play a critical role in natural disaster prevention and reduction, weather forecast and early warning, geologic hazard survey, forest disaster monitoring and environmental protection in China.

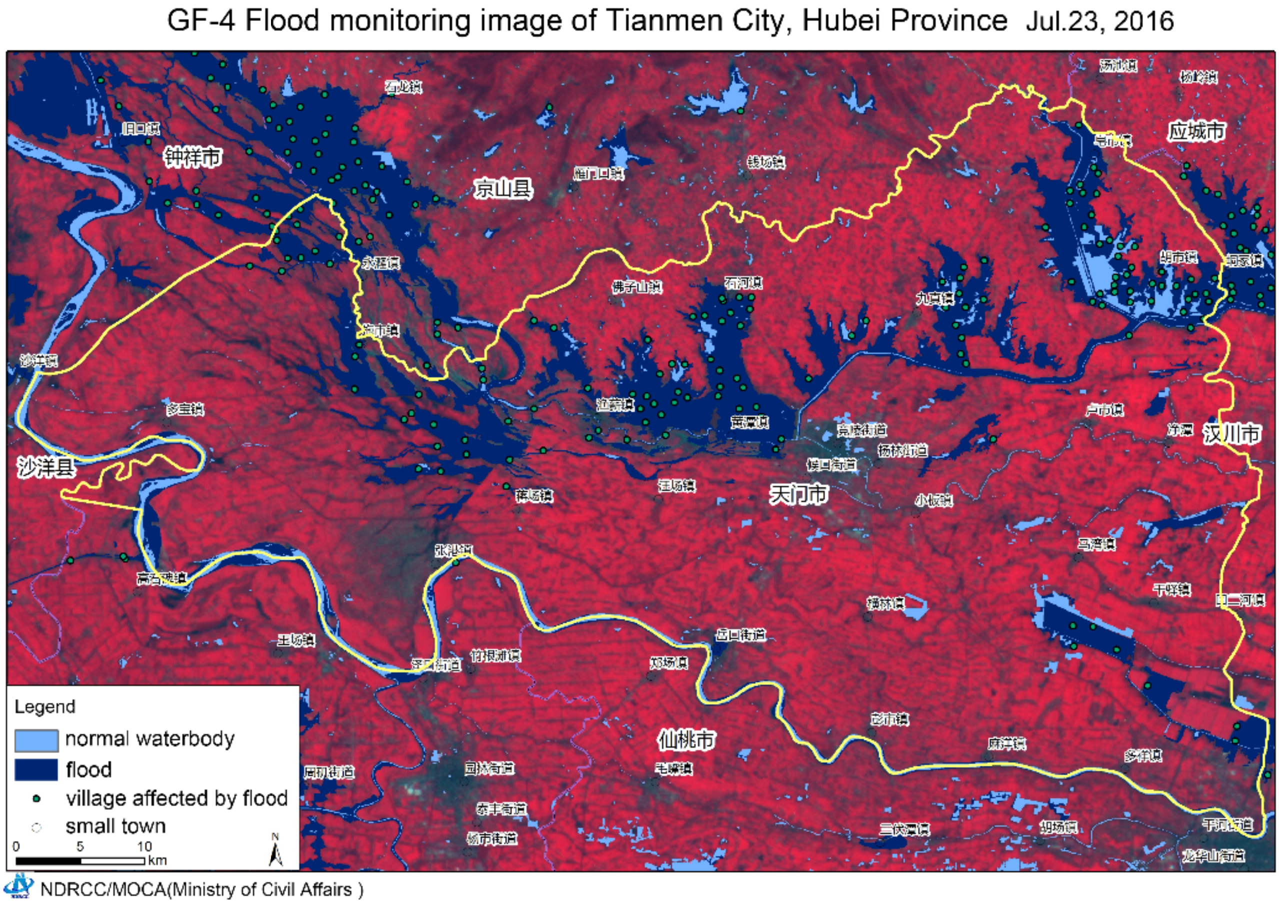

Figure 11: Flood monitoring map of Tianmen City, Hubei Province using GF-4 data acquired on July 24, 2016 (pers. comm. Wu Wei).

3 Potential non-meteorological applications of new generation systems

3.1 Introduction

The generation of non-meteorological application (NMA) products using satellite data has been established for more than forty years and has primarily been based on data from instruments on polar orbiting satellites like AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer), but also from satellites like SPOT and Landsat. The impetus of this study is the improved capabilities of the new generation meteorological satellite imagers that, in terms of spectral coverage and resolution as well as spatial resolution are significantly improving and approaching levels provided by medium-resolution imagers onboard polar orbiting satellites, like MODIS on Aqua and Terra.

It is not surprising that most, if not all non-meteorological application products that can be derived from geostationary imagery data are already today derived with corresponding data from polar orbiting satellites. The instruments on the meteorological polar orbiters can provide global coverage on a daily basis, the higher resolution imagers like Landsat with a significantly lower repeat cycle. Whilst these instruments have a higher resolution than currently available or foreseen from geostationary orbit, they face a challenge of achieving global cloud-free image data due to the frequent presence of clouds. The local overpass times of these sensors often coincide with the periods of maximum cloud built up and coverage. As a consequence, most single day data coverage from polar orbiting satellites are cloud contaminated and cloud-free data can only be achieved using data compositing methods over weeks to months.

The main advantages for the geostationary imagers are that they provide a significantly higher temporal resolution with fixed viewing geometry. The high temporal frequency of observations provide a higher probability of cloud free observations, a prerequisite for most NMA applications as well as the potential to use the information from time-series of data to discriminate rapidly changing phenomenon from static features like dust storms over desert areas. The high temporal frequency also enables early detection and characterization of diurnal variation of rapidly changing phenomenon like wildfires, volcanic ash, flash floods and coastal upwelling. In addition it is only with geostationary data that some specific scientific issues related to the diurnal cycle and irregular variations for instance on the variability of greenhouse gases, vegetation and sea surface temperature can be addressed.

This section gives an overview of geophysical parameters and products that can be derived with the capabilities of the new meteorological geostationary satellite imagers, which for the purpose of this study are not seen as meteorological product. For clarity the meteorological products and the associated parameters are briefly introduced in Table 4. It should also be noted that most, if not all non-meteorological products are also relevant and an integral part of the monitoring and understanding of weather and climate. For the purpose of this report all other products and parameters that are not listed in Table 4 are considered non-meteorological products for associated applications. For solar radiation at the surface, meteorology seems mainly concerned with the upward and downward broadband shortwave fluxes on a horizontal surface. However, as solar energy applications need to discriminate direct and diffuse components, solar radiation is also included as an NMA application. The NMA products are divided into three main groups; atmosphere, ocean and land. The following sections will describe the products for the respective application areas, the main characteristics and parameters and known limitations.

Table 4: Basic meteorological products.

Meteorological product	Associated parameters	Comment
Clouds	Cover, pressure, phase, optical properties, growth rate, temperature, particle size distribution	This, in particular cloud cover, is a critical prerequisite for most other applications including NMA
Atmospheric Motion Vectors	Speed, direction, height/pressure	
Temperature and humidity	Atmospheric temperature and humidity at various levels, Total Precipitable Water	
Atmospheric instability	Various instability indexes	
Precipitation	Rate, QPE, extent	
Radiation	OLR, solar, Downward SFC SW, reflected TOA SW, Absorbed SFC SW, upward TOA LW, Downward SFC LW, Upward SSFC LW, flux, emissivity	
Tropopause folding		

An indication of which instruments of the new generation are currently used or planned to be used to derive the associated products is also given. The instruments considered, together with the associated first platform, are the Advanced Baseline Imager (ABI)/GOES-R, Advanced Himawari Imager (AHI)/Himawari-8, Advanced Meteorological Imager (AMI)/GEO-KOMPSAT-2A, Advanced Geostationary Radiation Imager (AGRI)/FY-4A and Flexible Combined Imager (FCI)/MTG-I1. Furthermore, as a significant pre-cursor with many comparable capabilities, the Spinning Enhanced Visibile and InfraRed Imager (SEVIRI)/MSG is included.

In addition to the requirements of the Level-1 data (see Section 2) on calibration, navigation and stability, a prerequisite for all products is accurate cloud detection. The instruments under consideration are all multispectral imagers that also include infrared channels that enable the implementation of effective cloud detection algorithms.

It should also be noted that Table 4 includes various parameters related to radiation. Whilst these have in addition to **weather** forecasting also an impact on other Societal Benefit Areas (SBAs) like **SBA/Climate** and **SBA/Energy**, these are not further considered in the following sections except for downward solar radiation.

3.2 Atmospheric products

3.2.1 OVERVIEW

The atmospheric products considered in this chapter are aerosol/dust, volcanic ash and the atmospheric constituents ozone and sulphur dioxide. Table 2 gives an overview of all products and an indication of which instruments of the new generation are used or planned to be used to derive the associated products.

Table 5: The foreseen products and parameters for atmospheric NMA products. (Baseline=B, Future capability/potential=F).

Product	Parameter	ABI	AHI	AMI	AGRI	FCI	SEVIRI
Aerosol	Detection	B	B	B	B	B	B
	AOD	B	B	B	B	B	
	Angstrom Coefficient		B	F			
	Particle Size	F		F		B	
	Type				B		
Dust	Detection	B		B	B	B	B
	Optical Depth			B			
Volcanic Ash	Detection	B	B	B		B	B
	Height	B		B		F	
	Concentration			B		F	
Atmospheric Composition	Total Ozone	F		B		B	B
	SO2 detection	F		F		F	

The following sections give a brief overview of the various products.

3.2.2 AEROSOL

Aerosol is an important component of the earth-atmosphere and ocean system. Aerosol particles scatter and absorb solar radiation and therefore have a direct impact on radiative processes. They also serve as the condensation nuclei for the water and ice particles of clouds. Therefore modification of the aerosol properties will cause modification of the cloud properties. Furthermore they directly affect the radiative forcing of climate and weather. Aerosols also play a role in atmospheric chemistry, providing sites where chemical reactions can take place, e.g. for the depletion of stratospheric ozone.

The lifetime of aerosols can be very short (a few days) and their generation very dynamic, varying from hour to hour. They can also have a very strong diurnal cycle, e.g. when generated through biomass burning in the tropics. Aerosols also vary from one region and ecosystem to another. Sulphate aerosols are produced from oxidation of sulphur dioxide emitted by industry and cars, oxidation that requires sun light, and therefore have a diurnal cycle. Dust is generated in desert and desert transition zones (see next section).

Various algorithms have already been employed for the derivation of aerosol parameters from geostationary satellite imagery data. These may rely on separating the fast changing information (aerosol) from slowly changing surface features (surface reflectances). In that respect it is also easier to derive the aerosol information over sea than land. Generating aerosols using geostationary satellite data provides the opportunity to derive aerosols over land exploiting the changing solar illumination angles during the day with a fixed viewing geometry, providing angular sampling of the surface BRDF (Bidirectional Reflectance Distribution Function) and/or aerosol scattering phase function. However, these algorithms may then only provide a daily or three hourly aerosol estimate. Other methods, e.g. based on optimal estimation techniques, can provide aerosol parameters for every repeat cycle.

The high temporal resolution (e.g. every 15 minutes) gives a higher probability to acquire cloud free observations during a day than with polar orbiting satellite data, even taking the slightly poorer horizontal resolution into account.

In addition to the significant role in radiative balance affecting **SBA/Climate** and **SBA/Weather**, aerosols are also directly linked to air quality and hence to **SBA/Health**, e.g. in relation to environmental stress and respiratory problems. Aerosol emissions from strong events like volcanic eruptions and wild land fires are also significant and hence linked to **SBA/Disasters**. In particular for the latter SBA, geostationary data provide significant advantages over polar orbiting data due to the high temporal coverage. However, there are also limitations for the geostationary observations, e.g. on particular matters that emphasize the need of synergetic observations with low Earth orbit satellites.

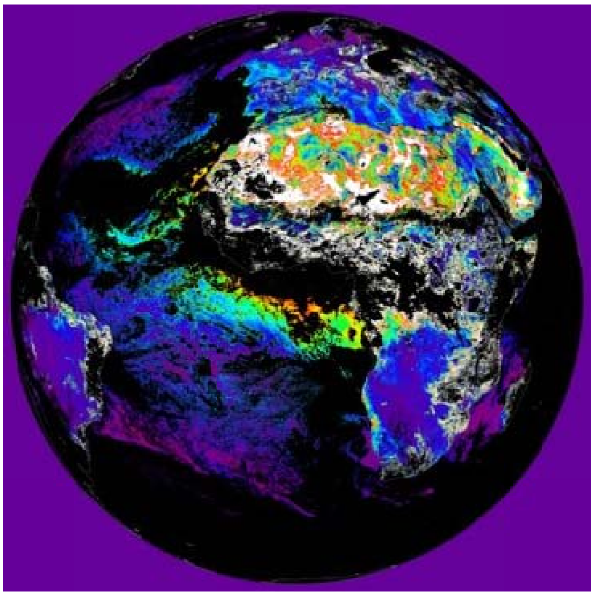

Figure 12: Map of the AOT (colour scale 0-0.7) at 635 nm for the 16th July 2006 at 12:00 UT (Jolivet et al., 2008).

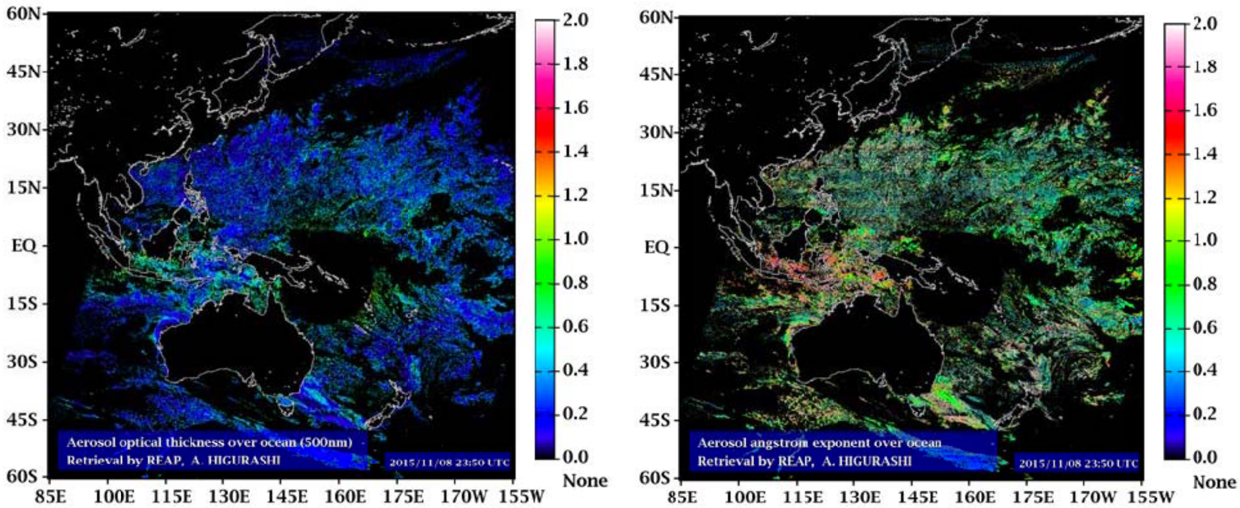

Figure 13: AOT at 500 nm (left and Angström coefficient (right) using Himawari-8 data over ocean (Hashimoto et al., 2015).

Himawari-8 data is also useful for monitoring haze events during winter over East-Asia. It is worth mentioning that the CMA aerosol optical depth (AOD) product based on Himawari-8 proved effective in the China 2015 winter season heavy smog monitoring experiment.

The quality of CMA Himawari-8 AOD product was verified using the MODIS MYD04_L2_3K aerosol product. The MODIS AOD product missed the heavy haze over Northern China. Concurrent Himawari-8 and MODIS observations showed high correlation of the AOD products over land (Figure 13). Ground-based PM2.5 concentration is more closely related to human health impacts. The PM2.5 concentration and air quality classification from Himawari-8 are shown in Figure 13. The spatial distribution of PM2.5 from Himawari-8 and ground observation is in good agreement.

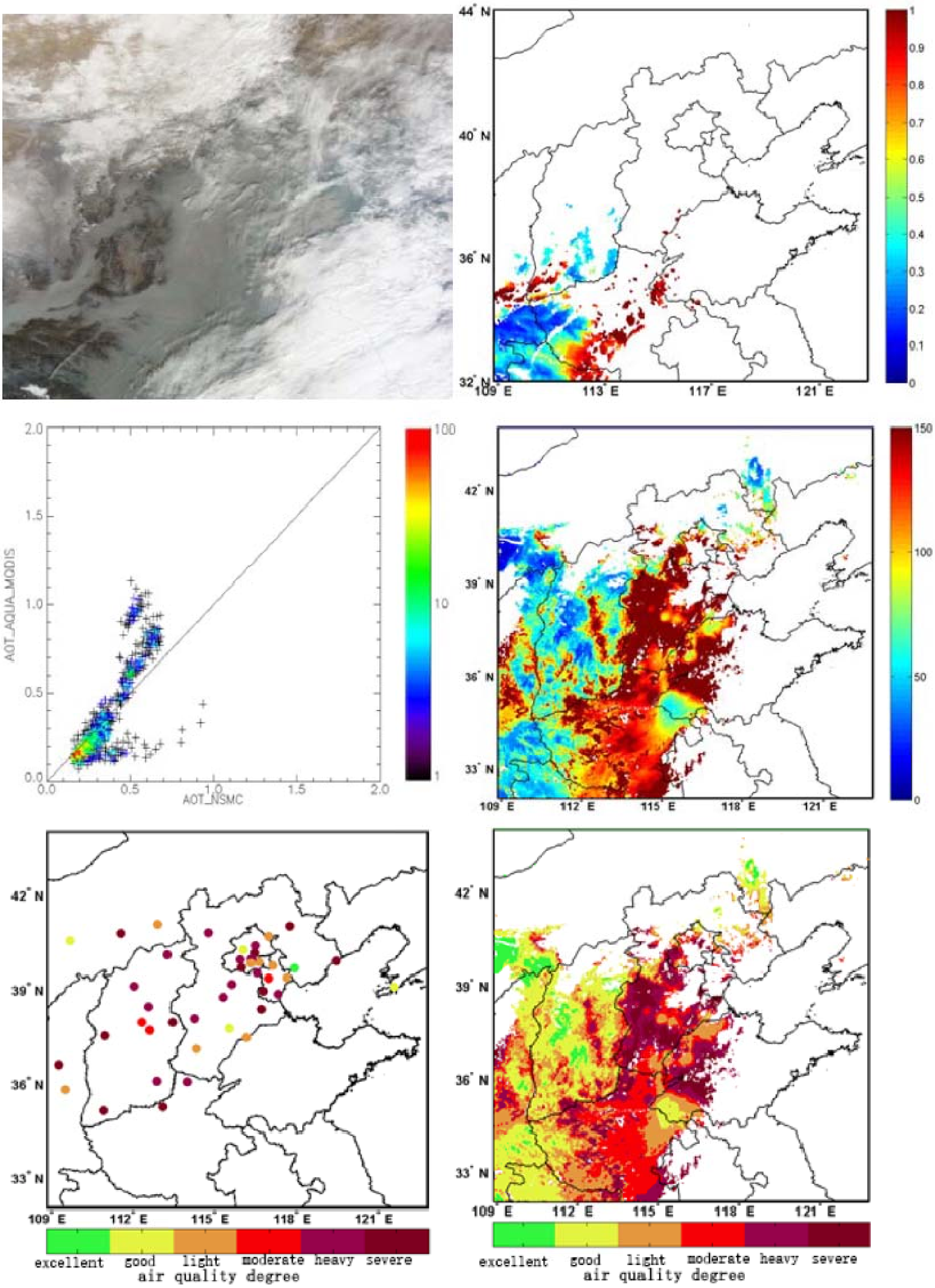

Figure 14: MODIS-Terra observation over China on Dec 20, 2015 (top left) and corresponding AOD product (top right). AOD product from Himawari-8 produced by CMA at 05:30 (UTC) (middle right) and scatter-plot between MODIS and CMA AOD where both retrievals were successful (middle left). Corresponding air quality classification product of Himawari-8 and PM2.5 (µg/m3) data from ground stations are presented bottom right and left respectively. Pers. Comm. Gao Ling.

3.2.3 DUST

The strong impact of dust outbreaks on human activities has significantly increased the interest of scientific community in developing efficient monitoring systems capable of detecting them and supporting activities devoted to mitigation of their effects.

Dust outbreaks have strong implications on climate, environment and human activities. Dust injected into the atmosphere contributes to climate change, impacts human health and, for example, Saharan dust transported to the Atlantic has an impact on cyclogenesis. Visible and infrared Imagery, if properly processed and integrated with information furnished by ground-based systems, can be effectively used to track and characterize dust outbreaks, also in the framework of operational early warning systems. Several methods have been proposed through the years to detect dust from space. Some of these techniques exploit the reverse absorption behaviour shown by silicate particles (the main minerals in the Saharan dust) at 11 and 12 µm wavelengths (split-window), in comparison with ice crystal and water droplets typical of meteorological clouds. More advanced methods have shown that improvements in the identification of dust outbreaks from space are definitively possible, although some limitations still remain.

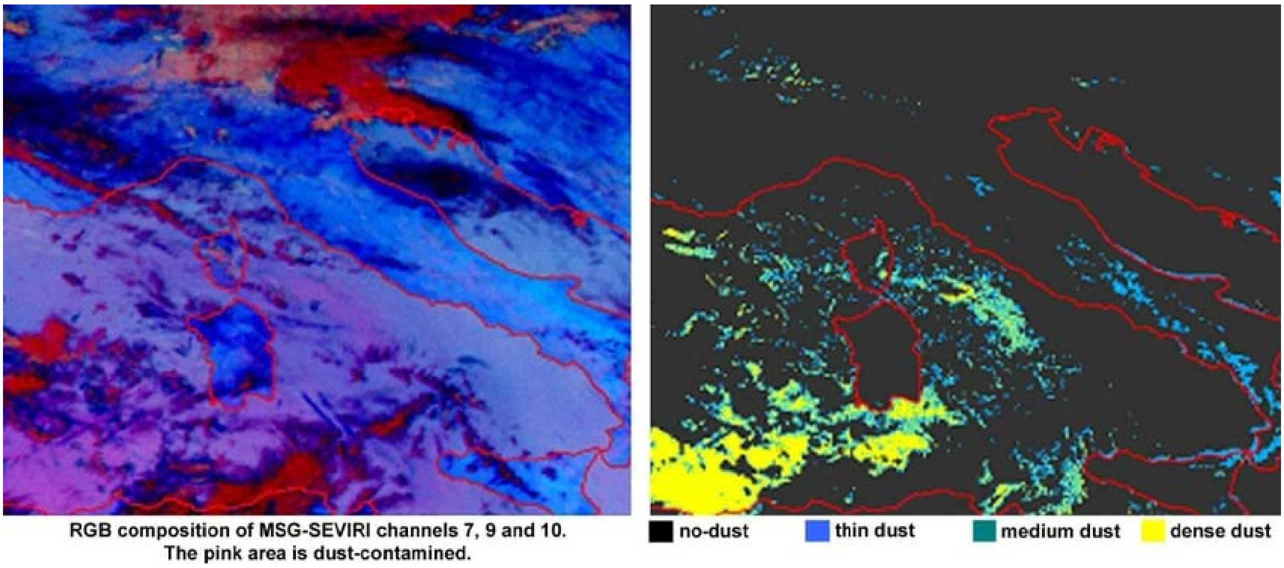

Figure 15: Dust detection using MSG/SEVIRI. Left RGB composition for dust, right quantitative retrieval (channel 7, 9, 10 = 8.70, 10.80, 12.0 micron). (Romano et al.,2013).

With respect to the Societal Benefit Areas, dust has a strong impact on **SBA/Climate** and **SBA/Weather**. It has also a strong important role in air quality, and hence to **SBA/Health**, e.g. in relation to environmental stress and respiratory problems. Dust from strong events like desert storms is also significant and hence linked to **SBA/Disasters**. In particular for the latter SBA, geostationary data provide significant advantages over polar orbiting data due to the high temporal coverage. Furthermore strong dust outbreaks impact solar insolation and can have an impact on the short term availability of solar power, as well as accumulate on the collection surfaces of solar generators and so temporarily reduce their efficiency. Hence it also plays a role in **SBA/Energy**.

3.2.4 VOLCANIC ASH

Volcanic eruptions have been monitored with geostationary satellite imagery data for more than 30 years. The early geostationary imagers had only very limited capabilities for ash detection and basically single channel approaches, using the visible and infrared window bands, were used. Whilst the use of these channels enables the detection of strong eruptions they rely on human interpretation and would only be valid for areas with thick ash clouds. As the capabilities of the geostationary imagers have increased, the detection algorithms have also been improved. Split-window methods based on the temperature difference observed with two infrared channels provided significant improvements in the detection capabilities.

Today, new techniques, that utilize a broader range of multispectral measurements provided by geostationary imagers combined with temporal information and more advanced algorithms, are utilized. These techniques, which are fully automated, also allow ash cloud properties (e.g. mass loading and height) to be estimated. In addition, some current geostationary sensors, and most future geostationary sensors, allow for SO_2 detection and tracking.

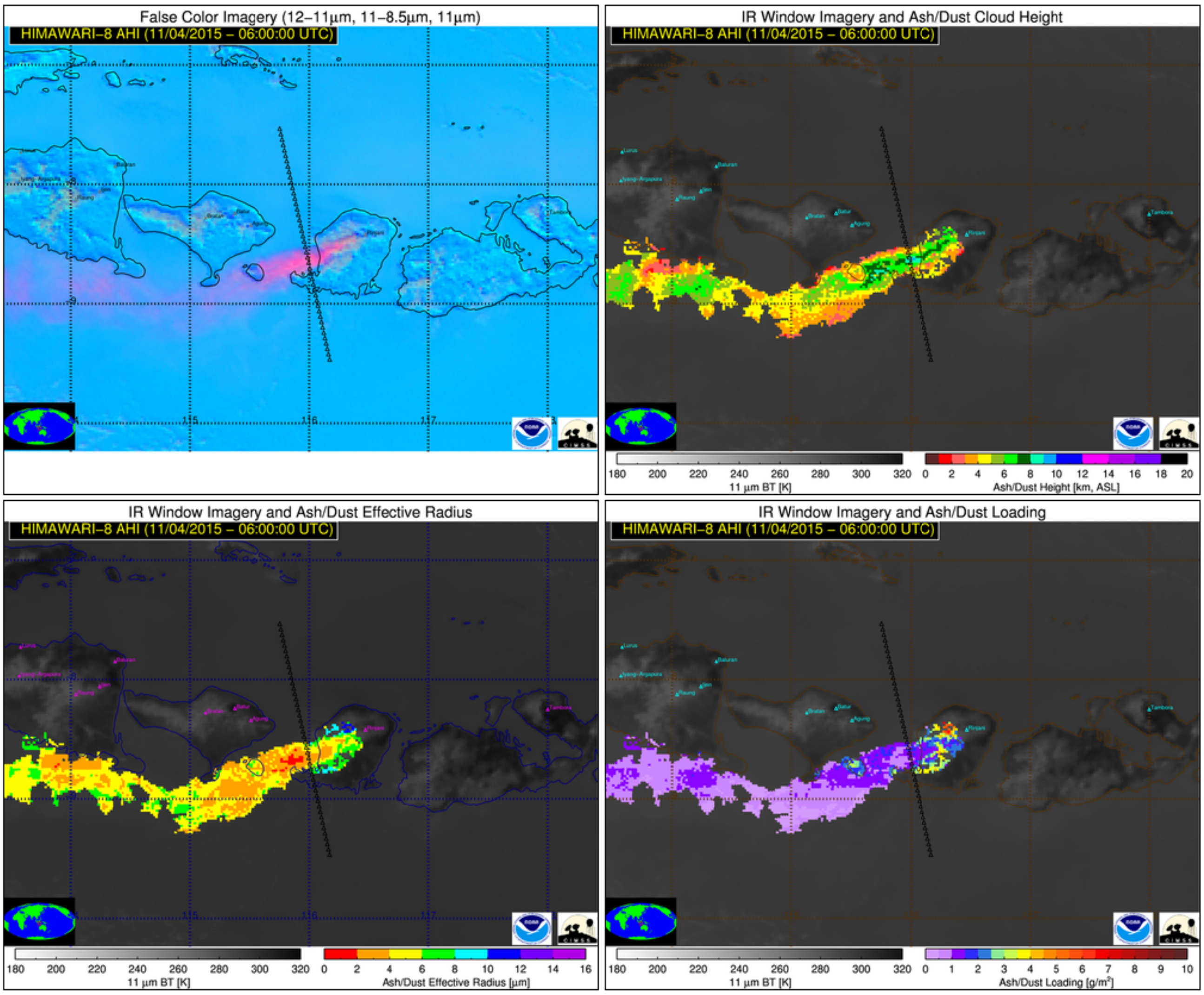

Figure 16: A volcanic ash plume from Mount Rinjani extends westward over Bali, Indonesia on November 3, 2015 (21:40 UTC). The ash emissions from Mount Rinjani, automatically detected and characterized using the NOAA/NESDIS/STAR volcanic cloud algorithms and Himawari-8 satellite measurements, are shown. More specifically, multi-spectral imagery (top left), ash cloud height (top right), ash effective radius (bottom left), and ash loading (bottom right), derived from Himawari-8, are shown. (Images are courtesy of M. Pavolonis NOAA NESDIS Center for Satellite Applications and Research (STAR)).

In order to assess the capabilities of the state of the art algorithms and the current geostationary satellite imagery data, the WMO performed a Volcanic Ash Algorithm Intercomparison as part of a pilot project (SCOPE-Nowcasting PP2) (IPET-SUP-2/Doc. 7.1.2 12.II.2016). As part of the intercomparison, a total of 27 passive satellite-derived volcanic ash data sets, produced by 22 different retrieval methodologies, were intercompared and all passive satellite products were compared to 4 sources of validation data. While volcanic SO_2 satellite remote sensing is also a very important topic, this study was focused solely on volcanic ash due to time and resource constraints. The intercomparison datasets included ash cloud properties derived from MODIS and MSG-SEVIRI data, which gives insight into the capabilities of the new generation geostationary satellite now being deployed. Whilst the intercomparison was quite encouraging, with algorithms able to detect concentration levels of 0.1 g/m3 or better, there is need for more research and only a couple of automated ash detection methods were able to approach the skill of a human analyst. Furthermore, given the uncertainty of aircraft based estimates of mass loading, the uncertainty in satellite based assessments is greater than a factor of 2 and most satellite derived mass loadings differed from aircraft assessments by a factor of 4 or more. The uncertainty in concentration will be greater.

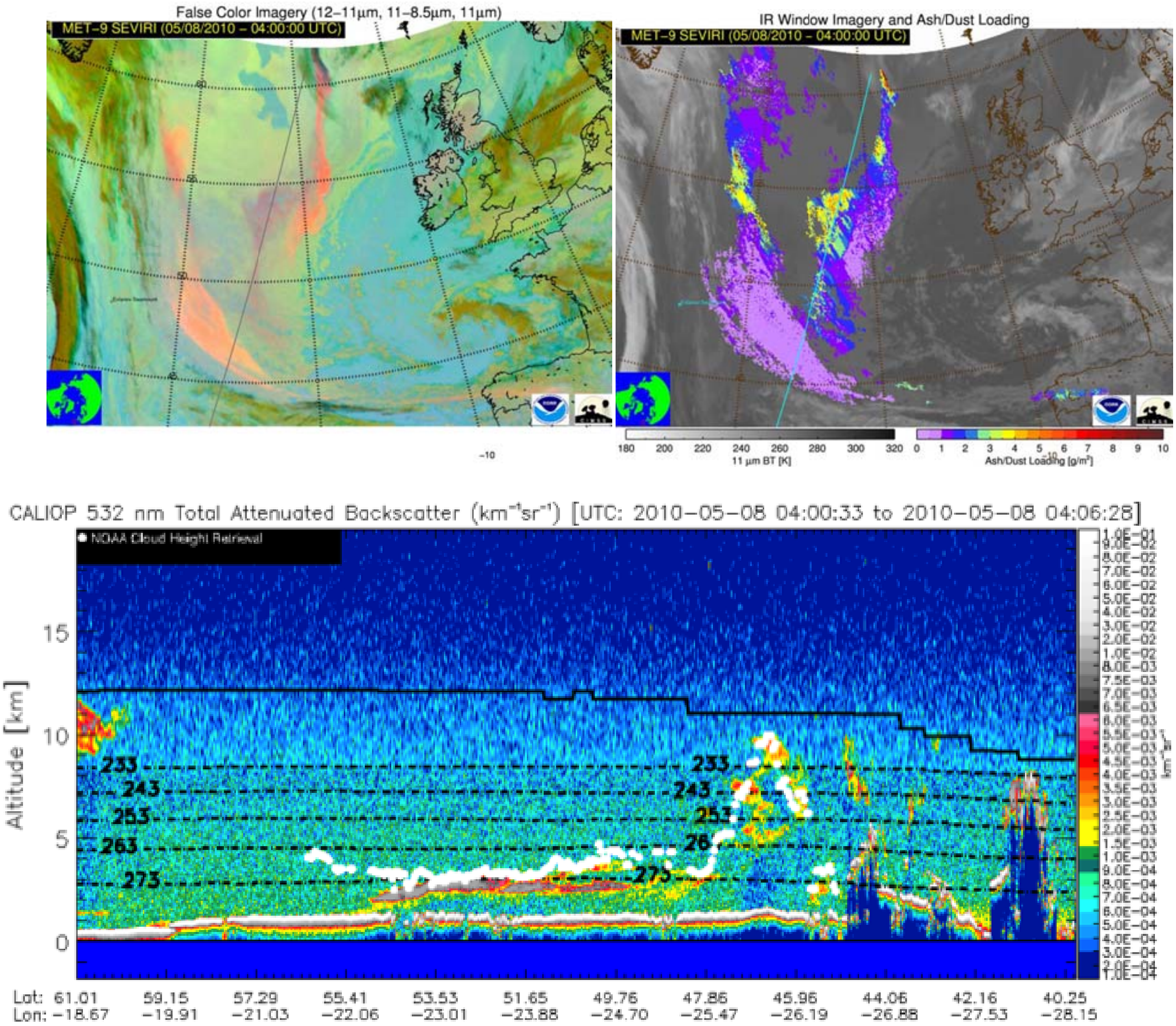

Figure 17: An example analysis from the WMO Satellite-derived Volcanic Ash Inter-comparison Activity: Volcanic ash RGB (left), retrieved Ash/Dust loading (right), CALIOP 532 nm backscatter with retrieved ash cloud heights (bottom). (Pavolonis, 2015).

Volcanic eruptions and the subsequent dispersion of volcanic ash (and SO_2) can have a profound impact on aviation as recently demonstrated by the Eyjafjallajokull eruption in 2010. It should be noted that only about 10% of the 1500+ known volcanoes are routinely monitored with in-situ observations, hence only geostationary satellite data provide the opportunity to continuously monitor most volcanoes around the globe. Furthermore, during an explosive volcanic eruption, volcanic ash can be transported to jet cruising altitudes in as little as 5 minutes. Thus, early detection of volcanic eruptions is critical. Given the large volume of data constantly being collected by the constellation of meteorological satellites in geostationary orbit, volcanic eruption detection cannot solely rely on manual analysis of satellite imagery. Automated detection algorithms are needed to ensure timely detection of significant volcanic eruptions, regardless of the historical activity of the erupting volcano. Hence, quantitative monitoring of volcanoes with geostationary satellites is a critical element in the **SBA/Distaster** for this application.

3.2.5 ATMOSPHERIC COMPOSITION (OZONE AND SULPHUR DIOXIDE)

There are several trace gases important for the greenhouse effect, for atmospheric chemistry, and for human health and safety. The capabilities of the low Earth orbit satellites to detect and measure various species like ozone, carbon monoxide and methane, are better than those of geostationary satellites. Several of these gases have however regional, diurnal, and sporadic behaviour, which is also driven by the local weather. Therefore it is necessary to acquire more frequent and continuous observations which are only possible from a geostationary orbit. The CEOS Atmospheric Composition Constellation group has in 2011 prepared a white paper 'A Geostationary Satellite Constellation for Observing Global Air Quality: An International Path Forward'. In its summary the paper notes:

'Several countries and space agencies are currently planning to launch geostationary satellites in the 2017-2022 time frame to obtain atmospheric composition measurements for characterizing anthropogenic and natural distributions of tropospheric ozone, aerosols, and their precursors, which are important factors in understanding air quality and climate change. Ozone, the ozone precursors NO2 and CO, and aerosols are pollutants that adversely affect human and plant health and the environment. Ozone and aerosols are also the primary short-lived climate forcers, meaning that future air quality and climate are closely linked. Emissions of these pollutants are strongly influenced by human activities. Their distributions in the atmosphere depend on complex physical and chemical transformations that are controlled by sunlight and weather, including the rapidly varying planetary boundary layer and continental- and intercontinental-scale transport of pollution. Understanding and monitoring these processes requires continuous measurements with high temporal and spatial resolution possible only from geostationary Earth orbit.'

Whilst there now is a strong push for deploying a dedicated geostationary mission for air quality and atmospheric composition, there is still a need to complement those missions with data from the new generation meteorological geostationary satellites for better spatial (the dedicated missions tend to have a limited field of view) and temporal coverage as well as increased resolution. The geostationary meteorological imagers are today mainly suited for the detection of total ozone column and SO_2.

The derived ozone data from currently flying geostationary satellites has already been applied to studies of atmospheric dynamics, reflecting the relationship between ozone and potential vorticity in the stratosphere, and air quality, primarily as a source function in air quality and ozone prediction models. The ozone observations are also useful for monitoring and forecasting UV radiation at the ground level

These capabilities will now further increase and for example the GOES-R ABI ozone detection algorithm is being developed within the GOES-R AWG Air Quality team as part of the air quality module processing subsystem. The GOES-R ABI allows for nearly continuous earth observation with an instantaneous ground field of view (IGFOV) at nadir for the visible band and 2 km for the infrared bands. Multispectral ABI data will be available every 5 minutes over the continental United States with full disk coverage of the Western Hemisphere every 15 minutes. GOES-R ABI offers frequent total column ozone measurements at 2 km resolution. Similar capabilities will in the future be available for the full GEO-ring.

Whereas geostationary imagers are capable of detecting SO2, these measurements are due to the low sensitivity of the instruments, mainly useful for qualitative assessments in areas with strong concentrations, like in the case of volcanic eruptions. Nevertheless, they do provide continuous observations and the capability to track SO_2 over extended periods of time.

In summary, atmospheric composition monitoring have an impact on **SBA/Climate**, **SBA/Weather** and **SBA/Health.**

3.3 Ocean products

3.3.1 OVERVIEW

The ocean products considered in this chapter are Sea Surface Temperature (SST), Ice, Currents and Ocean Colour. Table 6 gives an overview of all products and an indication of which instruments of the new generation are used or planned to be used to derive the associated products.

Table 6: Foreseen products and parameters for Ocean NMA products. (Baseline=B, Future capability/potential=F).

Product	Parameter	ABI	AHI	AMI	AGRI	FCI	SEVIRI
SST	Skin Temperature	B	B	B	B		
Ice (and lake ice)	Cover	F		B			
	Concentration	F					
	Motion	F					
	Age	F					
	Skin Temperature	F					
Current		F		F			
Ocean Colour	Water leaving radiance		B				
	Turbidity/TSS					F	F
	Chlorophyll-a		B				
	Blue-green algae				B		

Most of the products and parameters in Table 6 are derived for every repeat cycle and full resolution in Near-Real Time.

3.3.2 SEA SURFACE TEMPERATURE

Sea Surface Temperature (SST) is needed for the accurate understanding of climate variability and weather prediction. Today ocean-atmosphere coupled modelling is mandatory to advance the performance of numerical models with SST as a prime variable, in addition to the dynamic parameters like sea surface roughness and waves.

Whilst SST can be measured accurately with buoys and other methods, satellite data is also required for a full characterisation of the SST. The Group for High Resolution SST (GHRSST; see http://www.ghrsst.org/) combines all various sources for a comprehensive SST product. In this context it is important to note that satellite data provides the so-called skin-temperature which according to GHRSST is defined as the temperature measured by an infrared radiometer typically operating at wavelengths 3.7-12 µm that represents the temperature within the conductive diffusion-dominated sub-layer at a depth of ~10-20 µm. The SST skin measurements are subject to a large potential diurnal cycle.

SSTs has been one of the early non-meteorological applications from meteorological geostationary satellites, but with limited utility due to poor calibration and single infrared band observations. Since the advent of split-window capabilities in the infrared window band, accurate retrieval of SST has become possible. However, with the further improvements in instrumentation geostationary satellite data is also becoming increasingly important due to the improved capabilities of the new generation imagers and their improved calibration and characterisation of the instrument. An important aspect is the availability of multispectral information which is critical for effective thin cirrus detection and moisture corrections.

This improved calibration and instrument characterisation, supported by intercalibration activities (see GSICS in chapter 5) now enable the derivation of the SST with an accuracy of 0.2 K or better. The large scale behaviour of SST can be captured well by polar orbiting satellite data and the general diurnal cycle described by four observations per day satisfying the Nyquist sampling requirements.

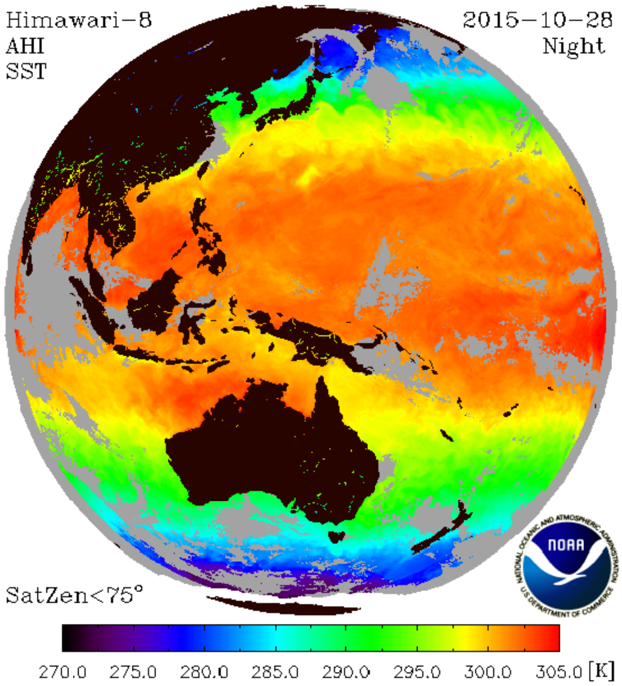

Figure 18: SST from Himawari-8 using GOES-R algorithm (Courtesy A. Ignatov, NOAA NESDIS Center for Satellite Applications and Research (STAR)).

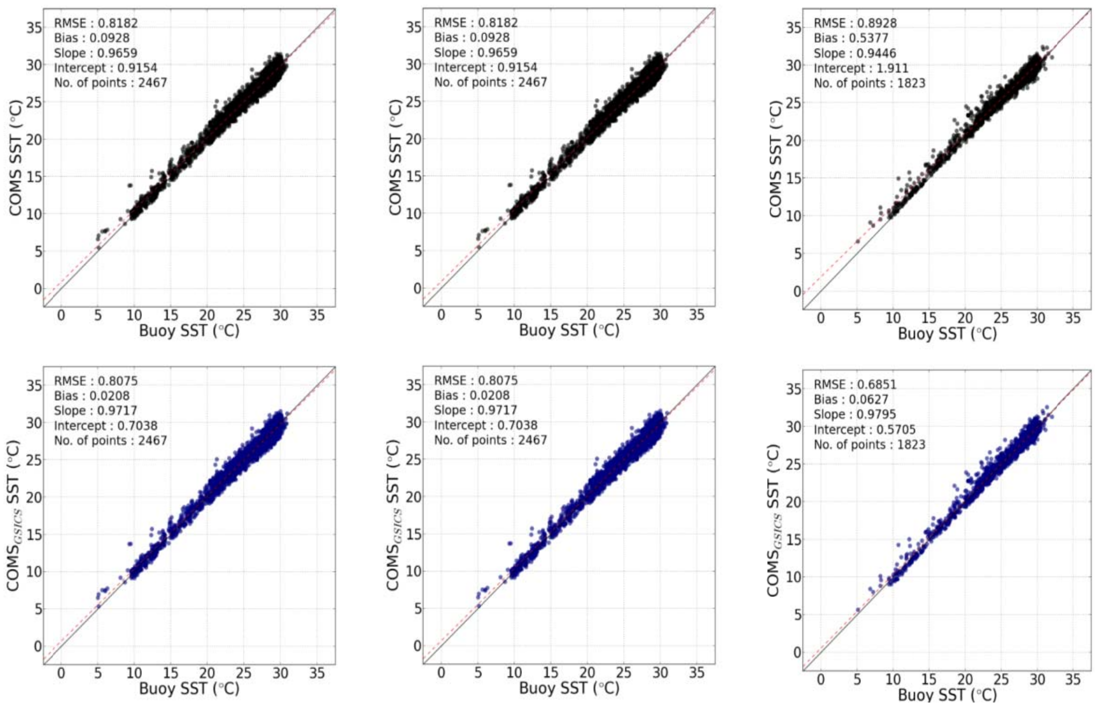

Figure 19: Impact of application of GSICS corrections to the retrieval of SST Uncorrected SSTs observations (top left day-time, top right night-time) and associated GSICS corrected observations (bottom) (Park et al., 2016).

Geostationary satellite data are however also required in order to guarantee sufficient cloud free observations during the day but also for a more accurate depiction of the diurnal cycle. This enables the development of a better understanding of the sea surface process e.g. as shown below, where the diurnal cycle as depicted by satellite data is significantly different from that just below the surface.

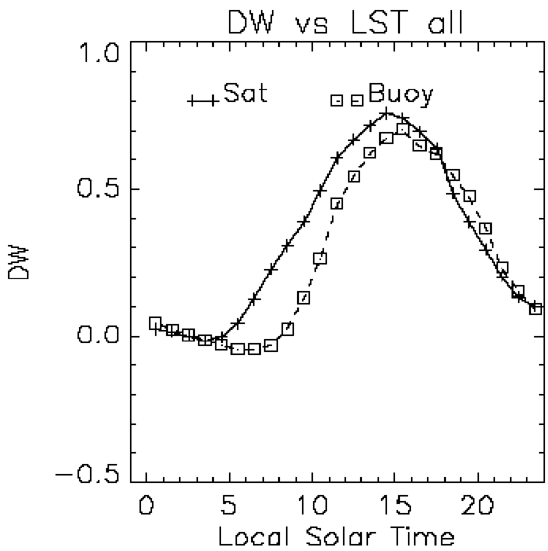

Figure 20: SST diurnal cycle as depicted by satellite data vs buoy data. (Le Borgne et al, 2012).

Furthermore the high temporal resolution also allows the detection and monitoring of cases with rapid changes of the surface conditions like in coastal upwelling events.

Accurate SST retrievals also enable the identification of strong surface gradients. These can be exploited for the identification of SST fronts, currents and eddies. The high temporal coverage with geostationary data, combined the associated increased probability for cloud free observations provide the opportunity to track sea surface structures.

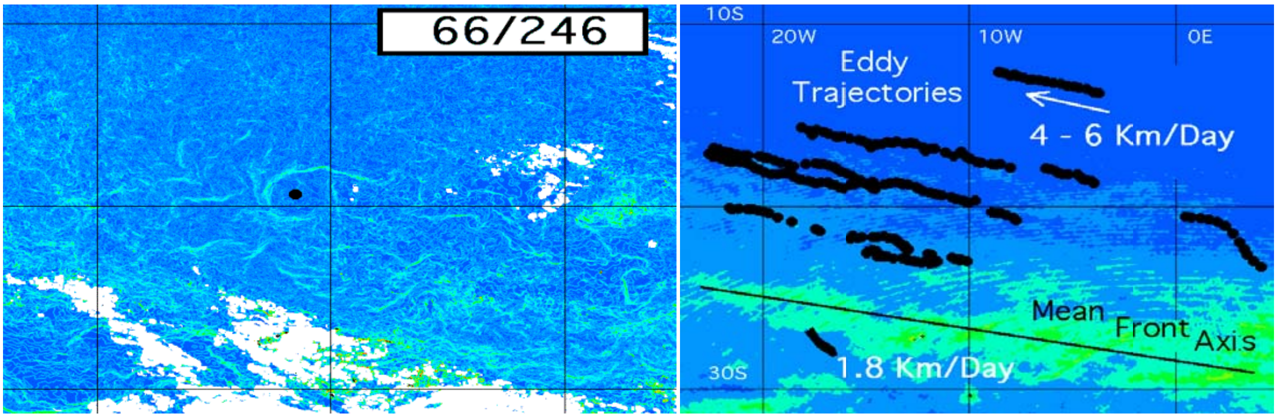

Figure 21: SST gradients (left) and associated eddy trajectories (right). (Legeckis and Le Borgne, 2009).

The applications of SST go however beyond those of **SBA/Climate** and **SBA/Weather** and include **SBA/Ecosystem** assessment, **SBA/Water** (e.g. marine biology, fishery) and tourism. The improved description of the coastal SST is also important for coastal resource management.

Derived from the best available scientific information, the *TurtleWatch* map displays sea surface temperature and ocean current conditions and the predicted location of waters preferred by the turtles. The mapped temperature values represent averages of SST information for the most recently available 3-day period. The maps indicate variations in ocean temperature as well as the direction and strength of the average ocean currents over the most recent week of available data. The maps highlights the areas with temperatures between 63.5°F and 65.5°F that represent the region where more than 50% of loggerhead turtle interactions have occurred during the first quarter of the year and should hence be avoided for fishing. (https://pifsc-www.irc.noaa.gov/eod/turtlewatch.php).

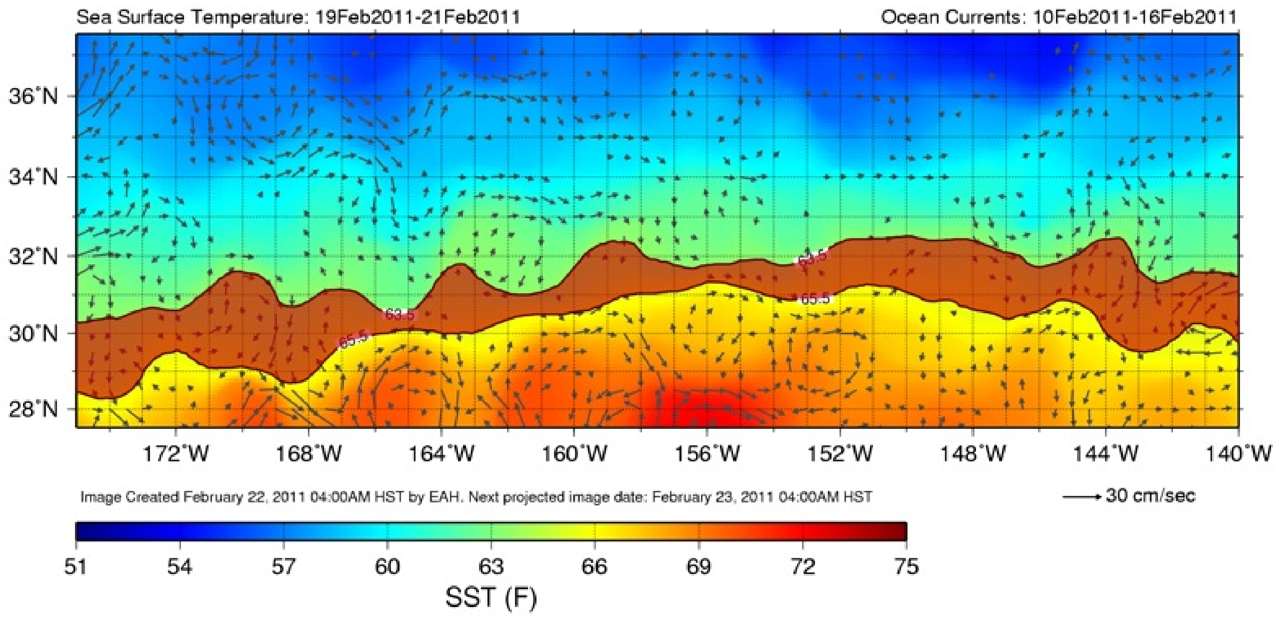

Figure 22: The TurtleWatch map for 19-21 February 2011. The small grey arrows show the direction and strength of the average ocean currents over the most recent week of available data. The solid black lines and the red-brown area in between mark the 63.5°F to 65.5°F temperature area and that should be avoided for fishing.

3.3.3 **ICE**

Ice reflectance depends strongly on its internal structure, such as brine pockets or air bubbles of the near surface layers. These internal structures change with season, state of the near surface layers, and age of the ice, which results in different ice types. Ice surface reflectance is different from snow surface reflectance. Ice consists mainly of sheets, while snow consists of grains. Snow reflectance shows very high values at visible channels, but low values at short-wavelength channels longer than 1.4 microns due to the much stronger absorption and much less back scattering at those infrared channels. This feature is shared by snow-covered ice and many ice types. Most of the ice surfaces show higher reflectance at visible and near infrared channels than water surfaces, which can be used to detect ice cover. However, some ice types, such as clear lake ice and grease ice, can be difficult to detect due to their very low contrast with open water.

The cryosphere has an important socioeconomic impact due to its role in water resources and its impact on transportation, fisheries, hunting, herding, and agriculture. Accurate ice observations from geostationary satellites therefore contribute to **SBA/Water** and **SBA/Ecosystems**. The cryosphere also plays a significant role in **SBA/Climate** for climate studies, and understanding the cryosphere is critical for **SBA/Weather** for accurate weather forecasts. Among the properties of the cryosphere, ice cover and ice concentrations are the most important. Whilst traditionally ice has been monitored using microwave sensors and visible/infrared imagers on low Earth orbit satellites, the frequent (15–30 minutes) observations from geostationary satellites give better chances to observe cloud-clear scenes during. These high frequency images can be used for better tracking of ice motion, particularly at lower latitudes where the image resolution is still reasonable.

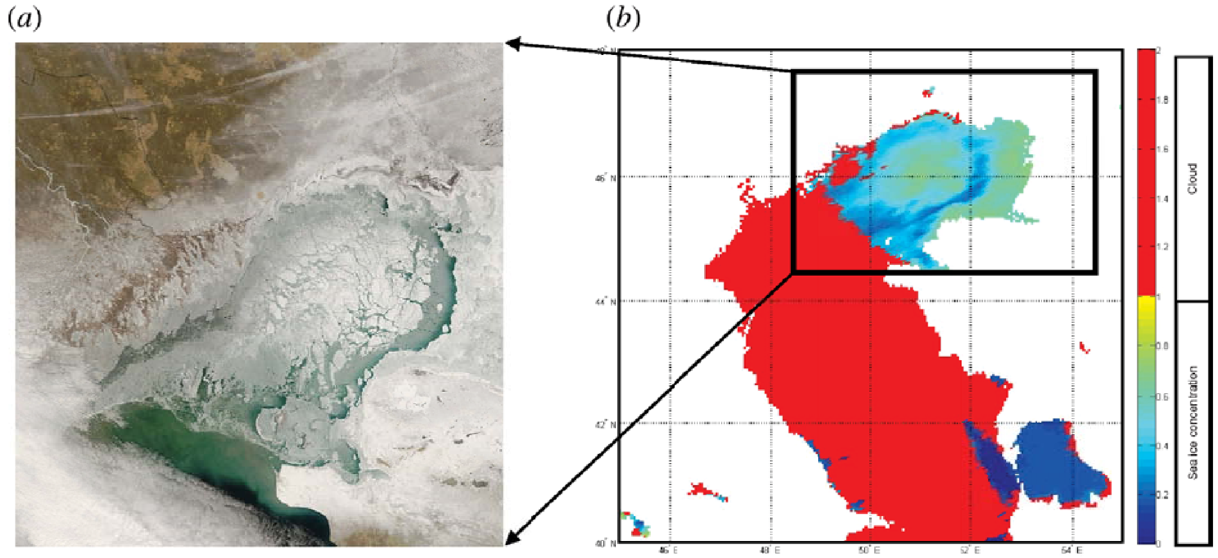

Figure 23: (a) SEVIRI-based sea-ice map over the northern part of the Caspian Sea on 28 February 2007 at 11 h 15m AM UTC and (b) the MODIS true-colour image for the same day. (Temimi et al., 2011).

3.3.4 OCEAN COLOUR

Ocean colour applications from polar-orbiting satellites are now mature and have provided the justification for sustained operational observations of various ocean colour parameters. For instance near real time alerting for harmful algae blooms and the assessment of sediment transport in coastal waters, particularly related to human activities (dredging, offshore construction, etc.), and marine carbon cycle modelling are critical. Polar orbiting satellites however suffer from a lack of information during cloudy periods and from inadequate resolution of quickly-varying processes, e.g. related to the diurnal cycles that drive photosynthesis, or the tidal cycle, which affects sediment transport. Ocean colour remote sensors on geostationary platforms would therefore significantly improve temporal sampling giving some specific advantages like:

- A dramatic improvement in the number of days/year in which cloud-free data can be acquired
- The possibility to resolve high frequency processes during cloud-free periods, thus bringing entirely new marine processes into the realm of ocean colour remote sensing.

Geostationary ocean colour sensors are hence under consideration by a number of space agencies and indeed, Korea launched its first geostationary ocean colour mission GOCI (Geostationary Ocean Colour Imager) in 2010. Whilst dedicated ocean colour missions due to their higher radiometric performance have a significantly better capability for ocean colour applications than geostationary meteorological imagers (IOCCG, 2012), there is still significant potential for the meteorological missions to augment the data from dedicated missions due to better spatial coverage (full disk).

The radiometric performance (e.g. low signal to noise ratio) of the new GEO imagers may limit the application of Ocean Colour in highly absorbing CDOM-dominated and open ocean waters due to the low reflected marine signal in certain spectral bands. However, they offer great potential for monitoring applications in highly-scattering turbid coastal waters.

Ocean colour applications are also highly demanding in terms of calibration, requiring a visible calibration of 1% and better. This is difficult to achieve from geostationary orbit. Hence geostationary meteorological imagers with limited visible calibration capabilities and only a small number of visible spectral bands, provide limited potential. However, there are some parameters that can be derived with meteorological geostationary imagers and the calibration issues can be alleviated using new calibration techniques, like lunar calibration as provided by GSICS, (see section 5).

Indeed it has been shown that already today MSG/SEVIRI can be used to estimate Total Suspended Matter (TSM) concentration and turbidity. In addition coccolithophores, a species of marine phytoplankton, can be detected by MSG/SEVIRI. These capabilities can be further improved with sensors like ABI/AHI/AKI, FCI and AGRI.

Furthermore, until a full geostationary ocean colour constellation is deployed, the geostationary meteorological missions will provide the full geo-ring capability with better temporal coverage than what is available from polar orbiting satellites.

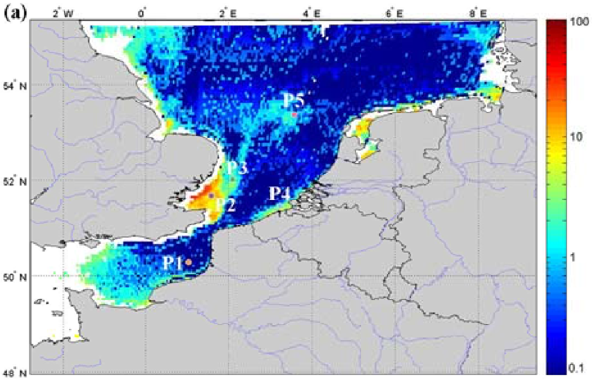

Figure 24: Concentration of Total Suspended Matter (TSM) in the North Sea, derived from SEVIRI imagery (Neukermans et al., 2009).

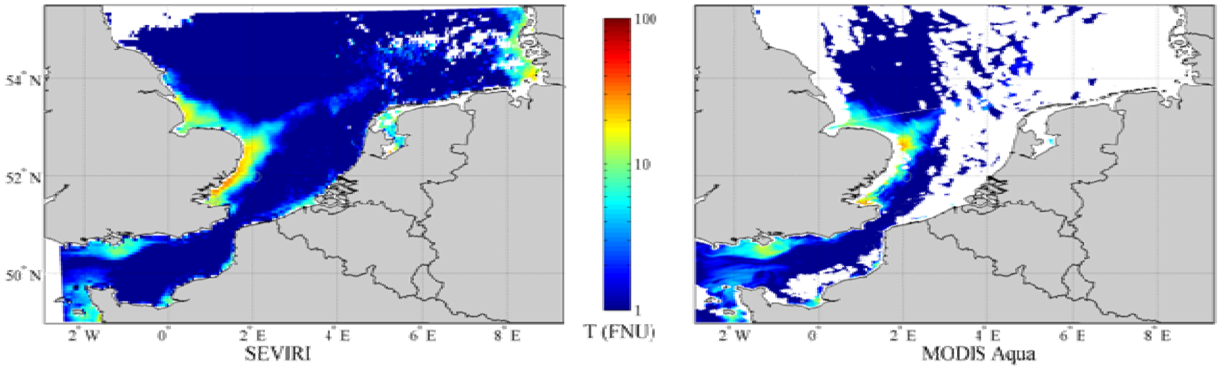

Figure 25: Comparison of a daily composite of SEVIRI turbidity data (T, FNU) with a single daily MODIS-Aqua observation (Neukermans, 2012).

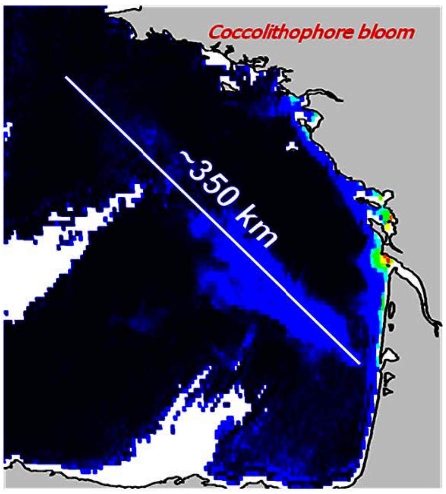

Figure 26: Coccolithophore bloom as observed by MSG/SEVIRI (Vanhellemont et al., 2013).

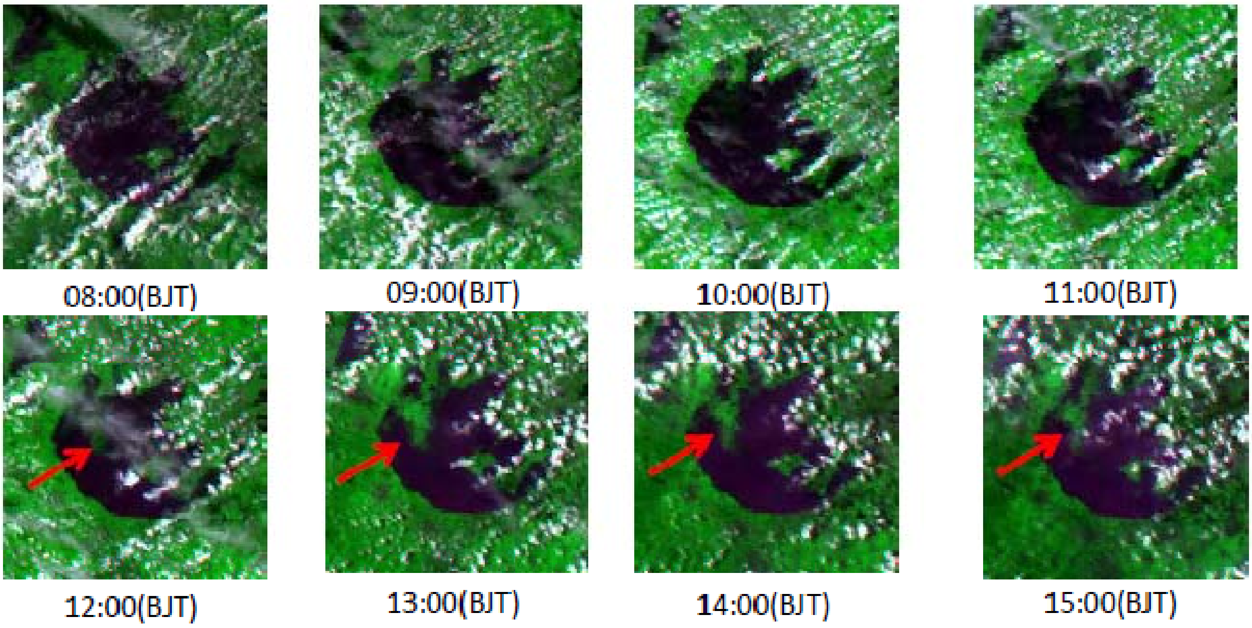

Figure 27: Blue-green algae monitoring of Lake Taihu using Himawari-8 satellite data on Sep 8 2015. (CGMS-44-CMA-WP-01, 2016).

JAXA have developed an ocean colour inversion for Himwari-8 AHI data (Murakami, 2016) by adopting algorithms previously developed for polar-orbiting sensors. For the retrieval of chlorophyll-a these are based on empirical band ratio algorithms using atmospherically corrected remote sensing reflectance as input. The chlorophyll-a products and their browse images are also available from the JAXA Himawari-8 Monitor portal at http://www.eorc.jaxa.jp/ptree/.

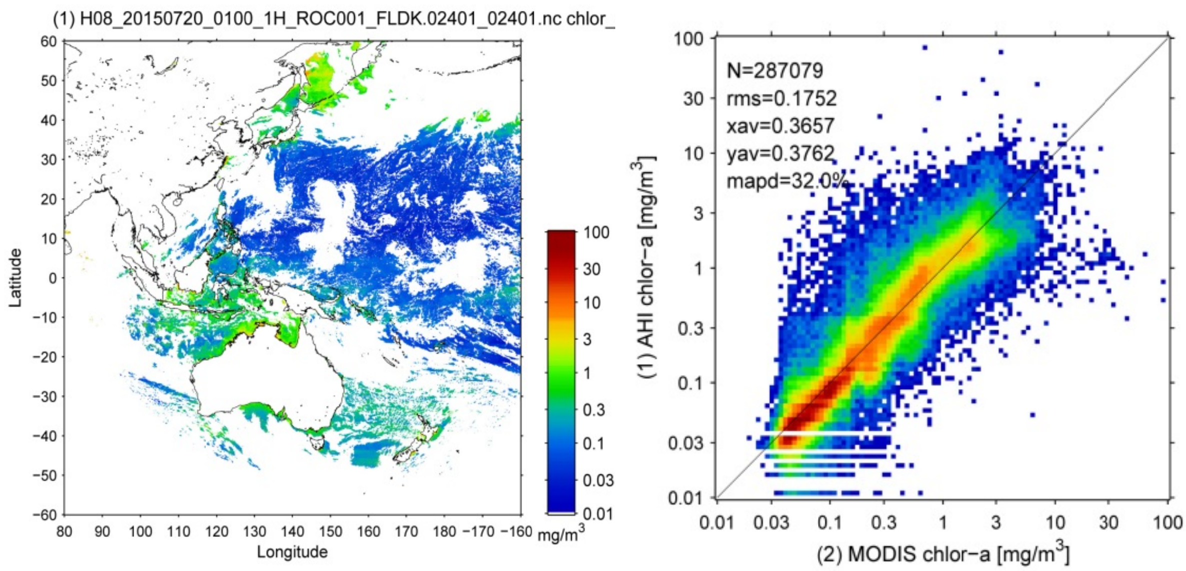

Figure 28: Averaged chlorophyll-a retrieved from Himawari-8 observations 01:00-01:50 UTC on 20 July 2015 for the wider Asia-Pacific region (left) and inter-comparison of Himawari-8 retrievals with MODIS daily Level 3 (right) (Murakami, 2016).

Ocean colour applications and the benefits by geostationary satellite data can have a significant contribution to **SBA/Water**, **SBA/Climate**, **SBA/Ecosystems** and **SBA/Health**.

3.4 Land products

3.4.1 OVERVIEW

The land products considered in this chapter are Fire, Land Surface Temperature, Snow, Flood/Standing water, drought, vegetation and albedo. Table 7 gives an overview of all products and an indication of which instruments of the new generation are used or planned to be used to derive the associated products.

Table 7: Foreseen products and parameters for land NMA products (Baseline=B, Future capability/potential=F).

Product	Parameter	ABI	AHI	AMI	AGRI	FCI	SEVIRI
Fire/(Hot Spot)	Detection	B	B	B	B	B	B
	Fire Radiative Power			F		B	B
Land Surface Temperature	Temperature	B		B			
Snow	Cover	B	F	B			
	Depth (over plains)	F		F			
Flood/Standing water	Detection	F			B		
Vegetation	Green Fraction	F		F			
	Index	F	F	F			
Drought (evapotranspiration)	Detection				B		
	Vegetation Health Index			F			
Albedo	Reflectance			B			
Incident Solar Radiation	Downward Shortwave Radiation	B	F	F		B	B

Most of the products and parameters in Table 7 are derived for every repeat cycle and full resolution in Near-Real Time.

3.4.2 FIRE

Fires are an indication of deforestation and of land use practices that affect both the land productivity and the atmospheric composition. Most fires are man-made, occur in the tropics, are rather small, and have a duration of up to a few hours. Fires of woody material (e.g. in deforestation) are of a longer duration and fires of grasslands and agricultural waste are of a shorter duration. Wild fires in the mid latitudes and northern regions (e.g. USA and Canada, Russia, Australia) are of major ecological and environmental importance. They are also a threat to populated regions directly, as a fire hazard, or indirectly through the emission of polluting smoke.

Forest and wild fires are an important component of the savannah, tundra and boreal forest ecosystems. However, the increasing rate of the occurrence of fires has elevated the concern over their impacts on climate change and fragile ecosystems. This requires efficient and effective methods in forest fire detection for near real-time monitoring so as to minimize these impacts. Remote sensing has been widely used in active forest fire detection. Fire detection has for a long time been performed with polar orbiting data as they have provided imagery information with a 3.8/3.9 micron channel and with sufficient resolution.

However, due to the nature of the fires, their significant diurnal cycle triggered by agricultural practices, polar orbiting satellites only capture a fraction of the fires. Whilst products like fire radiative power (FRP) is approximately proportional to the biomass combustion rate and thus the smoke emission rate, supplementing this information with the geosynchronous data capturing the diurnal cycle, even if with a lower spatial resolution, is very important. Geosynchronous satellites have the capability to provide quasi continuous (e.g. every 15 minutes) observations. They therefore supplement the information from polar orbiting satellites by detecting and monitoring the diurnal cycle of the more energetic fire. Furthermore, the high temporal coverage provides the potential for early detection of strong fire events.

Monitoring and forecasting of the atmospheric composition in atmospheric environmental services, like in the European Copernicus Atmospheric Monitoring Services require boundary condition estimates of the smoke flux to the atmosphere due to biomass burning. This can be done using fire radiative power (FRP)as done for example by the EUMETSAT Land SAF using SEVIRI observations. Therefore the provision of FRP products from the other geostationary satellites currently operating around the globe would be highly beneficial for such environmental services.

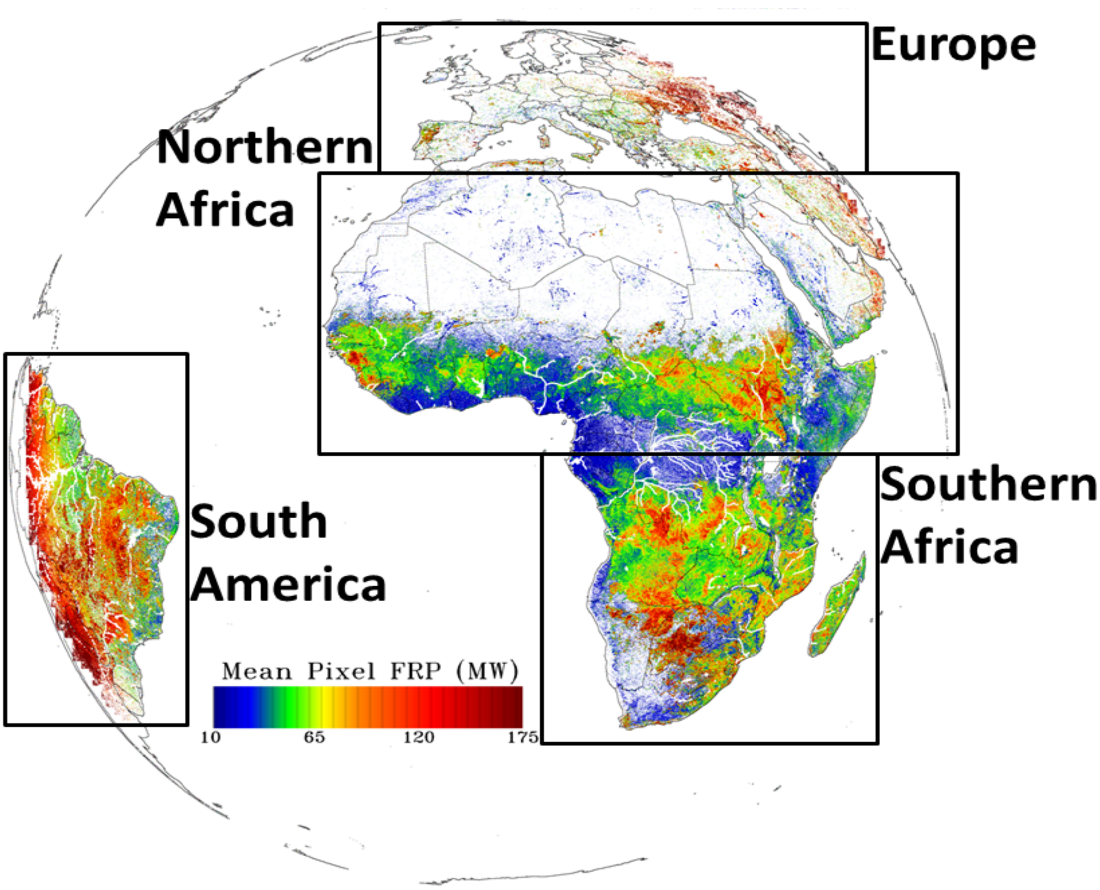

Figure 29: EUMETSAT Land SAF FRP product from MSG/SEVIRI (Roberts et al., 2015).

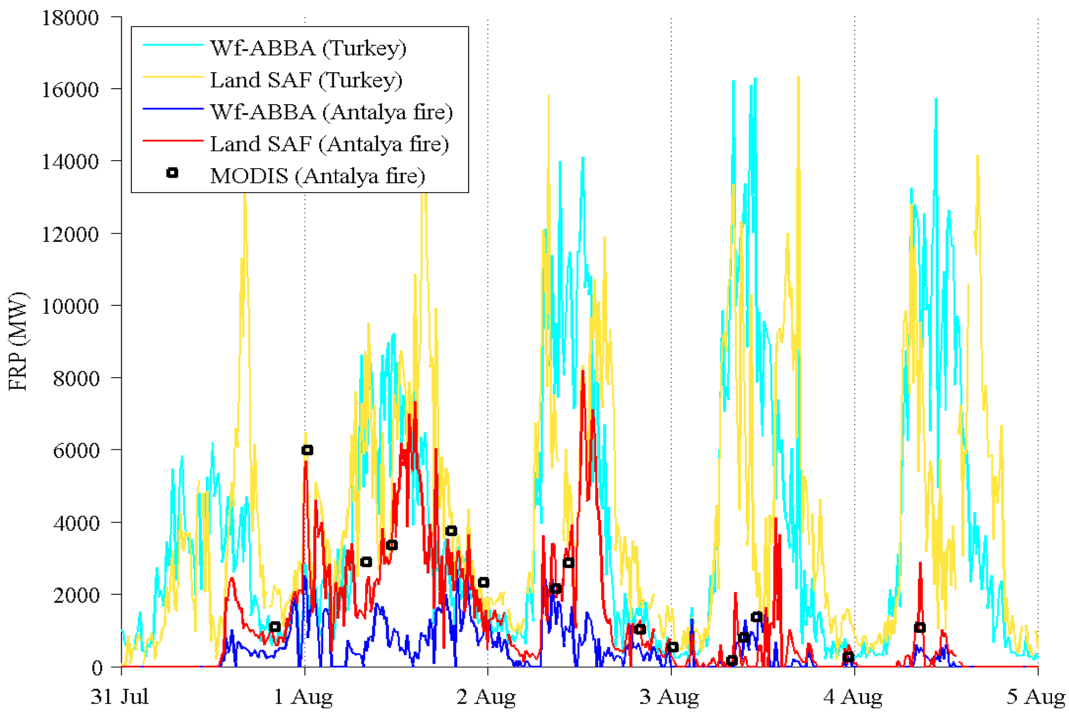

Figure 30: LSA SAF SEVIRI FRP-PIXEL Product captures peaks better than MODIS (Baldassarre et al., 2015).

With high temporal resolution, the new generation geostationary meteorological satellite Himawari-8 plays an important role in fire monitoring. Forest and grassland fire monitoring is an important non-meteorological application carried by CMA. Based on this operation, NSMC/CMA used the meteorological satellite to monitor the crop straw burning. During the crop harvest periods in summer and autumn, there are many fire spots due to crop straw burning in the plain of North China and Huanghuai, which are the major grain producing areas in China. Crop straw burning causes serious air pollution and has a negative impact on aviation and highway transportation safety. Data from Himawari-8 was successfully used to detect the fire spots during the crop harvest. Similar performance in fire and crop straw fire monitoring is expected from FY-4A data.

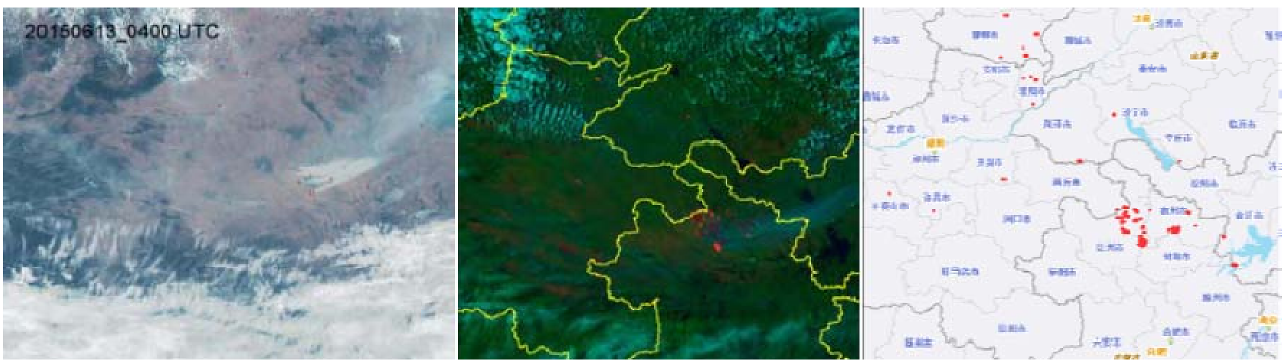

Figure 31: Fire spot detection over China on June 13, 2015 using Himawari-8 (left, 0400 UTC), associated RGB (middle, 0700 UTC) and daily coverage provided by NOAA and FY-3B (right). Pers. Comm. Chen Jie.

Fire detection and FRP are significant contributors to several SBAs including **SBA/Climate**, **SBA/Weather**, **SBA/Health**, **SBA/Ecosystems** and **SBA/Agriculture**.

3.4.3 **LAND SURFACE TEMPERATURE**

The diurnal cycle of land surface temperature (LST) is an important element of the climate system. LST and its diurnal variation are crucial for the physical processes of land surface energy and water balance at regional and global scales. The diurnal cycle of LST is closely related to solar insolation, the state of the atmosphere, and surface characteristics, e.g., soil type, soil moisture, and vegetation cover. Satellite remote sensing provides the unique way to measure the diurnal cycle of LST over extended regions and is sensitive to heat waves, but can also be used over small areas like for monitoring urban heat island (UHI) effects.

Whilst urban heat island studies have generally been conducted using air temperatures these have focused mostly on the features and causes of UHIs and the relation between weather conditions and UHI intensity. Alternatively, remote sensing data from satellites can be used to study UHIs. As the quality of background data, such as the surface spectral emissivity, has increased and the retrieval algorithms for land surface temperature (LST) have become more sophisticated, the quality of LST data retrieved from satellites has greatly improved in recent years. Therefore the capability of geostationary satellite data to support the assessment of the impact of heat waves in urban environment is increasing and is important in mega-city areas, in particular when combined with other data like geospatial information or polar orbiting data.

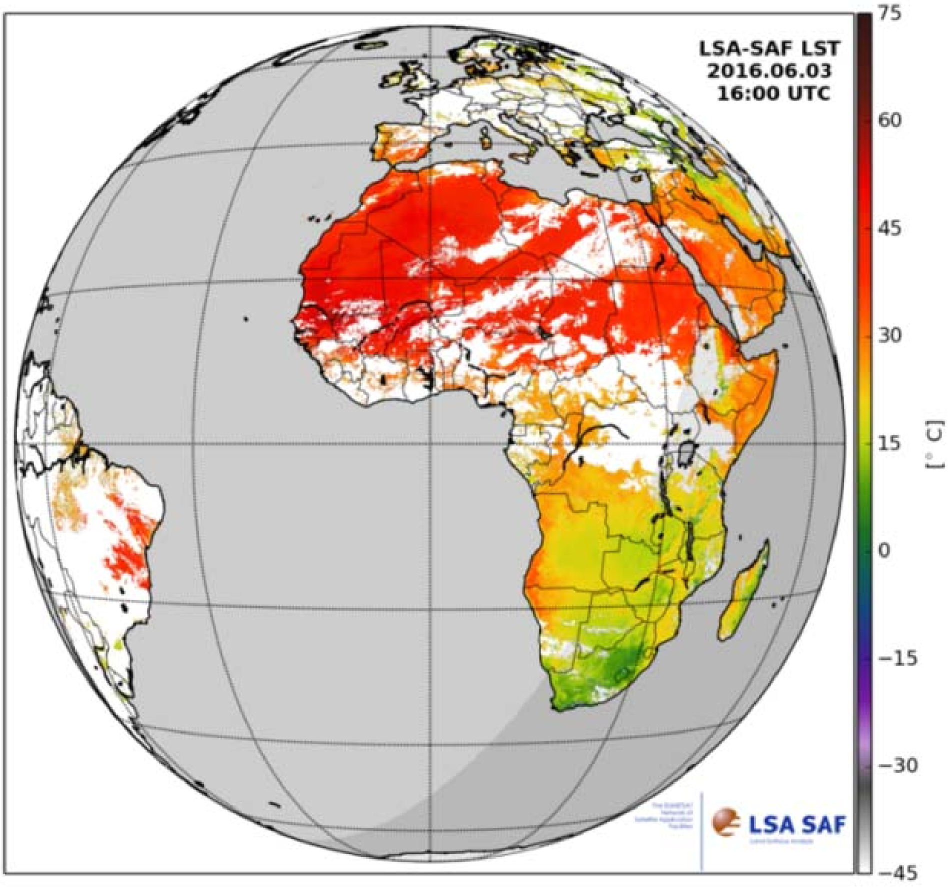

Figure 32: Land Surface Temperature for derived from MSG/SEVIRI (CGMS-44-EUMETSAT-WP-34, 2016). As geostationary satellite imagers have since the very beginning contained observations in the infrared window region and today also with split window capabilities it is possible to derive consistent LST for the geo-ring. The accuracy and consistency of those observations will improve with the enhanced capabilities of the full geo-ring that enables higher temporal and spatial resolution observations with multispectral capabilities for cloud detection.

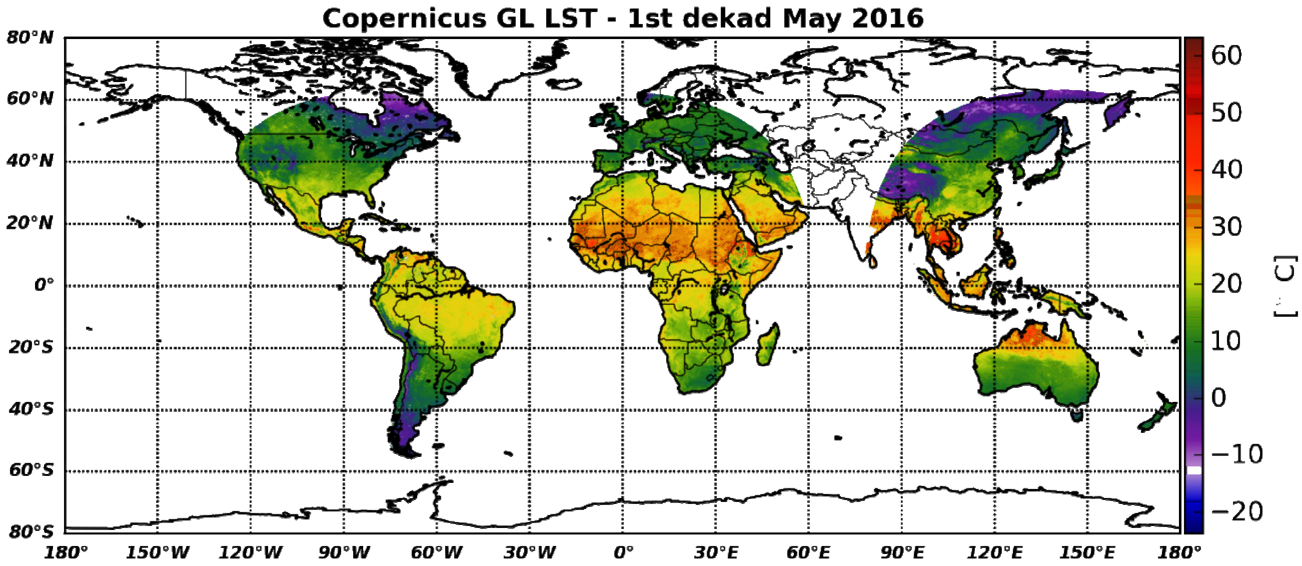

Figure 33: In the framework of the Copernicus GL, besides the hourly LST, also dekad composites are provided together with the Thermal Condition Index based on a multi-year climatology. (CGMS-44-EUMETSAT-WP-34 , 2016).

LST is a direct indicator of the instantaneous land stress affecting the hydrological cycle and hence it contributes to **SBA/Agriculture** as well as to **SBA/Ecosystems**. As a component in drought monitoring, and the potential for supporting the monitoring of strong temperature anomalies over land, it also contributes to **SBA/Disasters**.

3.4.4 SNOW

The potential to estimate the depth of the snow pack from satellite observations in the reflective part of the electromagnetic spectrum is limited and, there is no direct physical relationship between the snow depth and reflectivity of the snow surface. However, due to the structure of vegetation and terrain roughness, changing snow depth causes a gradual change of the fraction of the land surface masked by snow. Along with the snow fraction, the reflectance of the land surface also increases with the increasing snow depth up to some depth where the underlying land surface is completely masked by snow. This relationship between the snow depth and the surface reflectance or the fractional snow cover is quite pronounced for thin to medium thick snow packs and thus provides means for estimating snow depth. This would be obscured in the presence of trees that mask and cast shadows and therefore providing the potential to estimate snow depth in areas with no or very little forest cover.

The relationship between the snow fraction and the snow depth is actively used in climate and land surface models to predict the fractional snow cover when the depth of the snowpack is known. An empirical approach matching snow fraction derived directly from GOES Imager observations with synchronous in situ measurements of snow depth is the basis for the snow cover product planned for GOES-R. The ABI sensor, and hence all other instruments of that class, with their high spatial resolution and multi-sensor capability in both the solar and thermal spectrums, are well suited to modern Snow Cover retrieval algorithms that are capable of detecting snow at sub-pixel levels.

Today's Snow Cover products can accurately determine not only what fraction of a pixel is covered in snow but also snow grain size and reflectivity. The new generation geostationary imagers can inform us about extent and morphology with a frequency and accuracy never before enjoyed - characteristics that are critically important to climatologists and hydrologists. Hence these products have the potential to support **SBA/Climate** and **SBA/Water**.

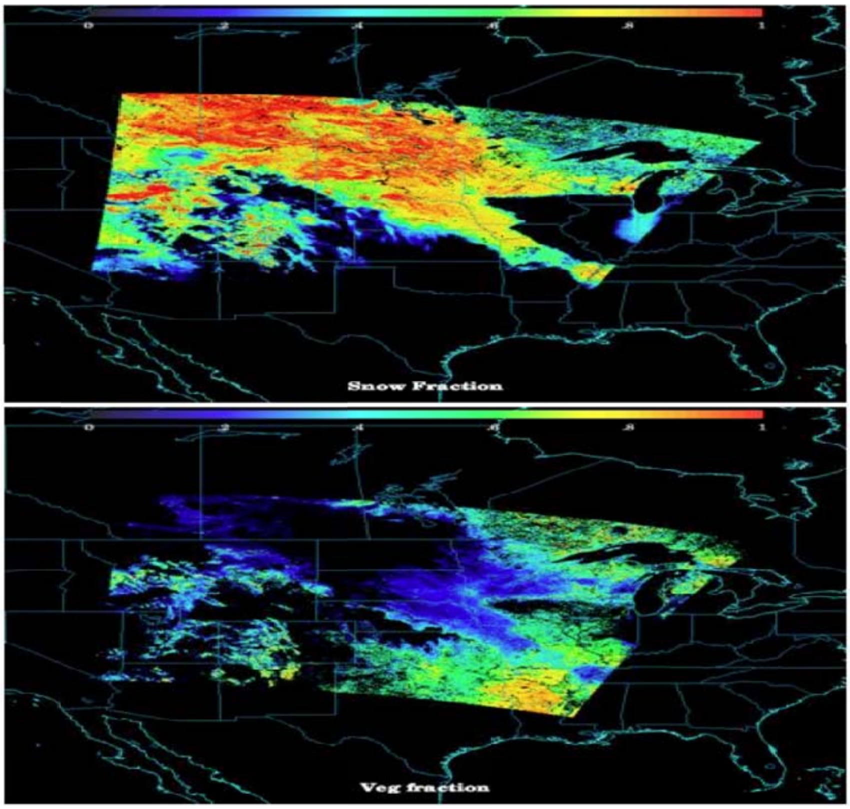

Figure 34: Simulated GOES-R ABI Fractional Snow Cover from GOESRSCAG processing of proxy ABI data from Moderate Resolution Imaging Spectroradiometer (MODIS), March 1, 2009 (Cline et al., 2010).

3.4.5 FLOOD/STANDING WATER

Floods are the most frequent of natural disasters affecting millions of people globally. Despite this, few techniques exist for the rapid detection and monitoring of flooded land. Whilst in-situ methods produce good quality results they are expensive, which is a particular concern in the developing world, where the majority of people affected by such flooding events live. It is therefore important to develop global techniques for flood detection, particularly as it is predicted that climate change may lead to more frequent and more severe flooding in the future. Whilst again the use of polar orbiting satellite data with their diverse instrumentation provide significant capabilities for flood monitoring, in rapidly changing situations more frequent observations, as provided from geostationary orbit, are needed.

Limited flood mapping from space has been achieved by examining changes in the Normalised Difference Vegetation or Water Indices (NDVI and NDWI), but NDVI is designed to monitor vegetation, and so is unsuitable for flood mapping if very sparse or dense vegetation is present. With the advent of new geostationary sensors it is now possible to gain cloud-free VNIR observations of land surfaces much more rapidly than before. It has been shown that the land surface can be viewed on multiple occasions on a better than 3-day timescale, e.g. with SEVIRI.

Analysing the variation in surface reflectance as a function of the sun's position allows for examination of the properties of the land and, in particular, the ability to map areas that are flooded at a given time. Water displays a very distinct set of scattering patterns and these can therefore be used to identify areas that are wholly or partially submerged. Due to the dynamic and transient nature of flooding events, it is vital to examine them with an instrument capable of rapid data acquisition which the new generation geostationary satellites with their improved capabilities now provide. This is well demonstrated in Figure 31 where one day of Himawari observations gives a more complete overview over the flooding event in China in July 2016 than the corresponding SNPP/VIIRS data.

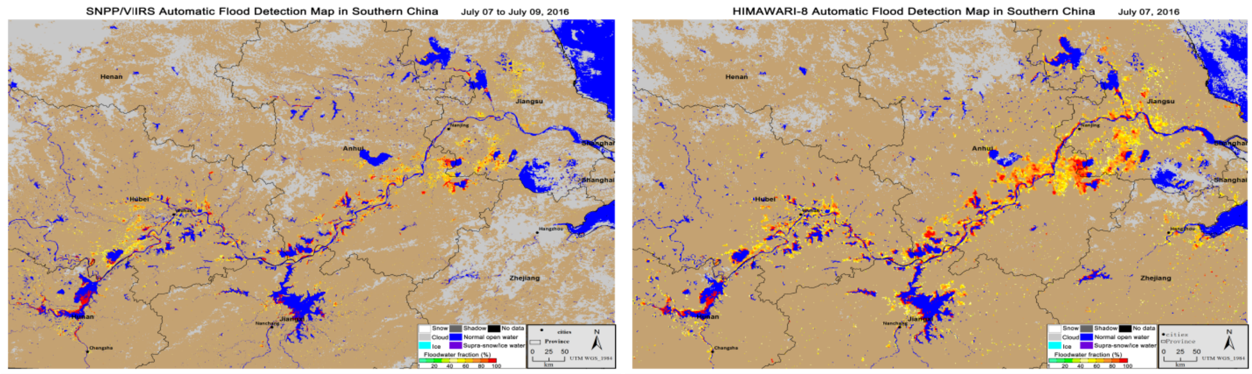

Figure 35: Flood mapping over China using SNPP/VIIRS three-day composite(7-9 July 2016, left) and Himawari 8 one-data composite (7 July 2016, right). (Goldberg, 2016).

Flood and standing water monitoring can therefore essentially contribute not only to **SBA/Disasters**, but also support **SBA/Agriculture** and **SBA/Ecosystems**.

3.4.6 VEGETATION/DROUGHT/EVAPOTRANSPIRATION

The distribution of vegetation, its properties and state, is of major importance for a wide range of applications, namely:

- Environmental management;
- Natural Hazards monitoring;
- Agriculture and forestry;
- Climate change studies;
- Numerical weather forecast models.

Changes in the land cover either caused by changes in land use, climate change or natural hazards (like forest fires or droughts, for instance) may have a huge social and economic impact. Remote sensing provides the best means to monitor changes in vegetation over a wide range of temporal scales over large areas.

Several empirical indices have been proposed and used through the years, which allow an easy identification and monitoring of the vegetation conditions from satellite measurements. However such indices have several disadvantages. Because they are ratio-based, they are nonlinear, have noise effects and are not structural properties of land surface areas. There are several key variables that can be use for a wide range of land biosphere applications that are more directly related to vegetation properties and health than conventional empirical indices. The Satellite Application Facility on Land Surface Analysis (LSA SAF) produces several of those variables, making them available both in near real time and off-line.

The following time series of 16-day NDVI composites have been computed from daily NDVI to analyze the spatio-temporal dynamics of NDVI for a growing season over different land cover categories from June 2008 to March 2009. In agriculture, NDVI showed quite high dynamics as compared to desert and forest, respectively. It can be seen that in the Indo-gangetic plain, NDVI showed high dynamics of intensive agricultural activities from June 2008 to March 2009. Also in the Indo-gangetic plain, overall spatial NDVI was low during June but it increased from July due to increase of vegetation cover with the progression of monsoon rainfall over the Indian landmass. The NDVI shows a decreasing trend during October with the maturity of kharif crops but shows increasing trend in November, with a peak in February, due to the progress of rabi crops.

Monitoring evapotranspiration and the extent and severity of agricultural drought is an important component of food and water security. An example of this was the severe drought that struck Eastern Africa in 2009, causing crops to shrink and threatening millions of people with starvation (Independent, 2016).

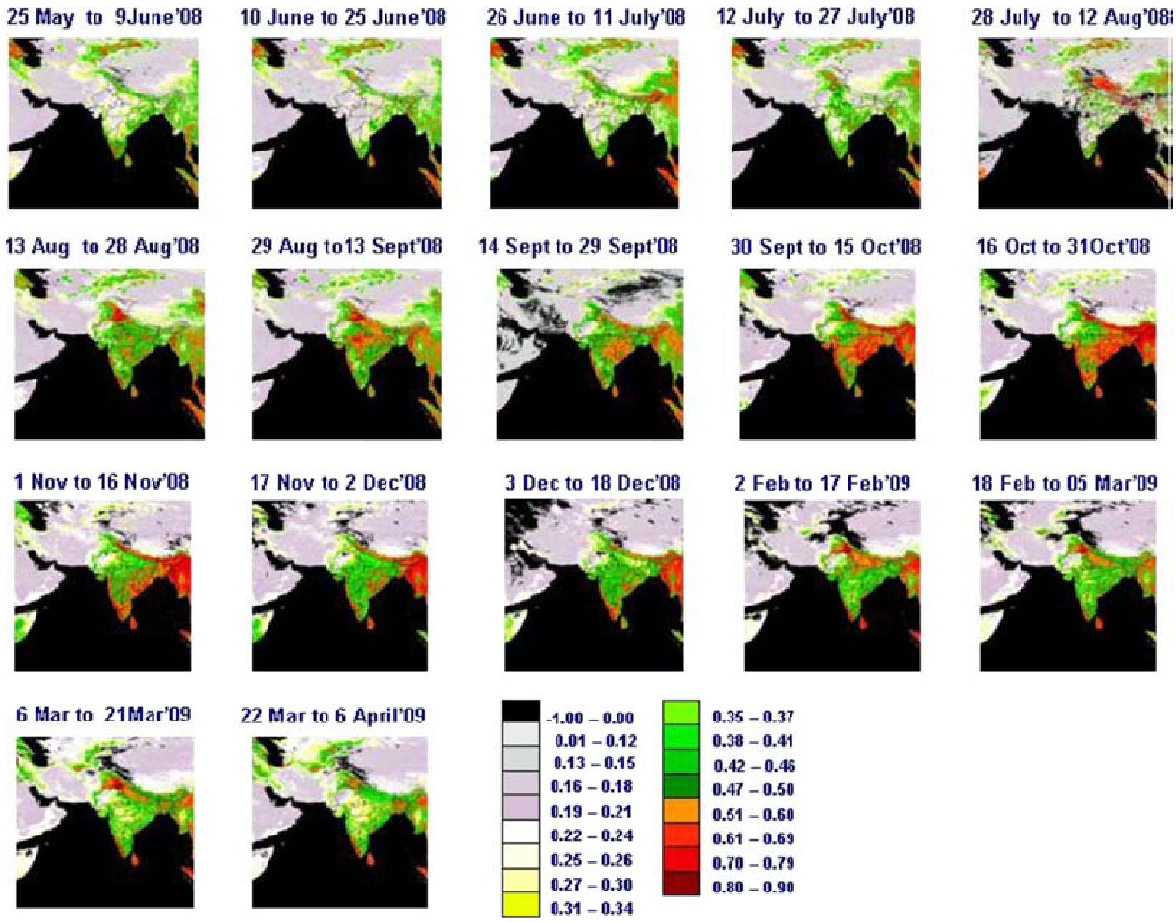

Figure 36: Spatio-temporal dynamics of NDVI during a growing season using Insat-3A data. [Nigam et al., 2011).

Another example of drought monitoring is given below using Chinese FY-2 over China. This is compared with the average surface evapotranspiration during the same period for more than ten years. The yellow color means no obvious evapotranspiration change during the monitoring period, and no drought occurs. Red, brown and black areas mean surface evapotranspiration during the monitoring period is lower than the average evapotranspiration, and drought occurs (the deeper the color, the drier). In contrast, the green and blue colors mean surface evapotranspiration during the monitoring period is higher than the average evapotranspiration; it shows that water supply to the land surface is enough (the deeper the color, the wetter).

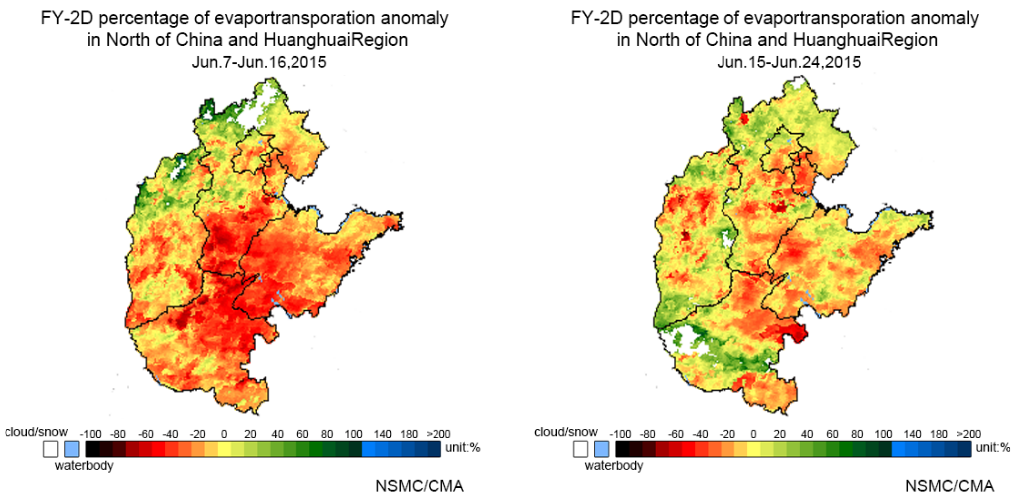

Figure 37: Drought monitoring in China using FY-2. FY-2D Percentage of evapotranspiration anomaly in North of China and Huanghuai Region on 7-16 June 2015 (left) and 15-24 June, 2015 (right). Areas in white are cloud/snow, areas in light blue water. (CGMS-44-CMA-WP-01, 2016).

Agricultural systems are climate-sensitive, and conventional surface instrument networks are sparse and sometimes with significant latency, in particular in developing countries. Satellite monitoring therefore provides the potential for global efficient and timely monitoring of water balance and deficits and can be used to supplement coarser resolution data from weather and precipitation networks to assess drought conditions. Whilst traditionally polar orbiting satellite data would be used, the new generation geostationary satellites provide the potential to support evapotranspiration and water stress modelling as well as drought and water stress monitoring. Because land-surface temperature (LST) is strongly modulated by evaporation, thermal infrared (TIR) remote sensing data carry valuable information regarding surface moisture availability and therefore have been widely used to map ET, drought, and vegetation stress. Signatures of vegetation stress are manifested in the LST signal before any deterioration of vegetation cover occurs, for example as indicated in the Normalized Difference Vegetation Index (NDVI), so TIR-based drought indices can provide an effective early warning of impending agricultural drought.

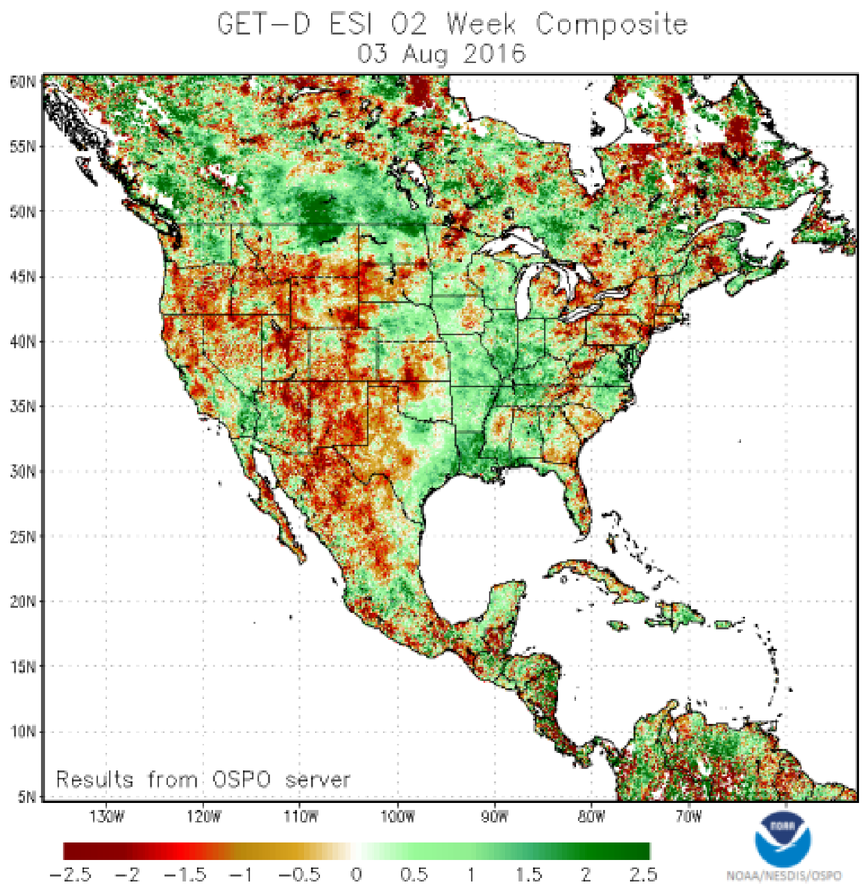

Figure 38: GOES evapotranspiration GET-FD product. [http://www.ospo.noaa.gov/Products/land/getd/].

The GOES Evapotranspiration and Drought (GET-D) products are derived from the Atmosphere-Land Exchange Inversion model (ALEXI). ALEXI computes principle surface energy fluxes, including Evapotranspiration (ET), which is a critical boundary condition to weather and hydrologic modelling, and a quantity required for regional water resource management.

Satellite derived ET data products are critical to improving land surface model simulations and in order to improve numerical weather/climate forecasts; more accurate and complete ET and drought data products are critical for agricultural management forecasts.

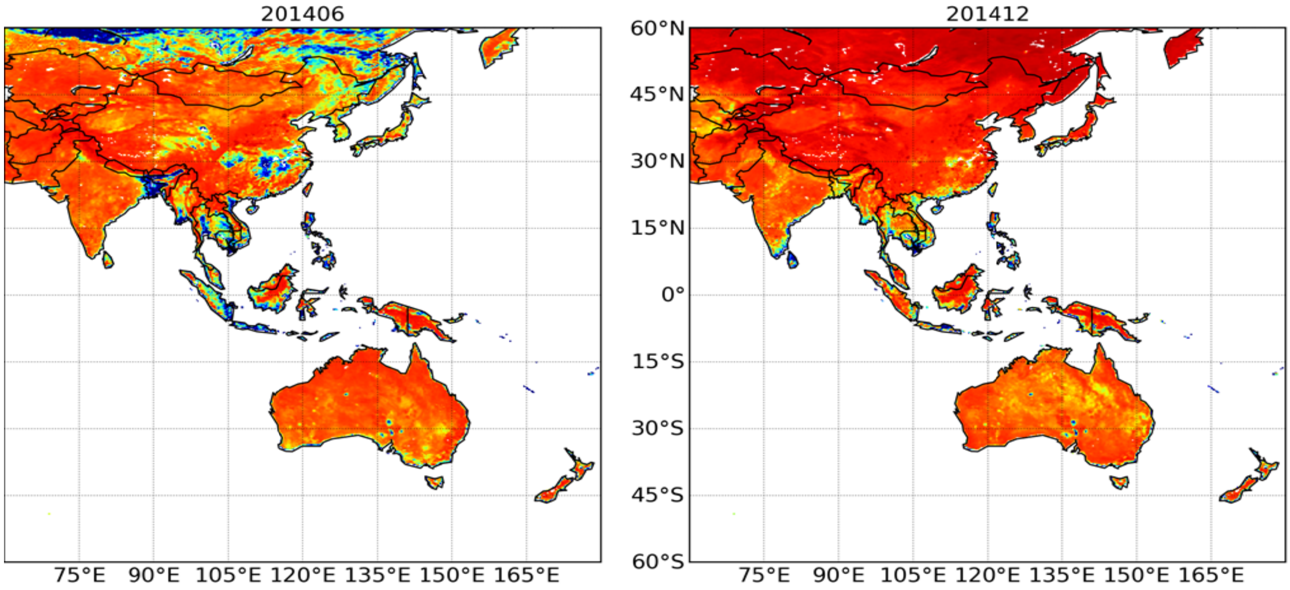

Figure 39: Drought determination using VHI (Vegetation Health Index) (CGMS-44-KMA-WP-01, 2016).

3.4.7 EPIDEMIOLOGY

Associations between satellite-derived environmental variables such as temperature, humidity, and land cover type and vector density have become standard techniques to identify and characterize habitats of disease causing vectors such as mosquitoes and ticks. There has been a significant evolution in modelling approaches over the past twenty years to map vector presence/absence and abundance, to create risk maps for epidemiology. Earlier methods relied on statistical correlations between time series of Normalized Difference Vegetation Index (NDVI), and Land Surface Temperature (LST) measurements from AVHRR with entomological and epidemiological data because of the availability of a long term global AVHRR data set from the late 1970s. A few studies also used Cold Cloud Duration (CCD) from Meteosat satellites as a proxy for rainfall along with AVHRR data. The next generation of geostationary satellites will provide improved satellite based environmental variables for epidemiology and provide new opportunities for modelling vector borne diseases. Frequent temporal resolution and multispectral observations will improve cloud free observations of land such as NDVI and LST compared to polar orbiting satellites, especially in tropical areas. The enhanced spectral measurements in the infrared (IR) bands will improve rainfall estimates by providing increased sensitivity to cloud top properties such as phase and particle size compared to legacy geostationary sensors. When geostationary IR measurements are combined with microwave measurements from polar satellites, the precipitation estimates are better than those that are derived from legacy geostationary IR measurements alone, and result in more frequent and low latency estimates of rainfall, especially in data sparse regions that do not have a dense network of either ground based radar or rain gauges.

Vectorial Capacity that defines precipitation and temperature as the limiting factors of malaria incidence is the daily rate at which future malaria inoculations could arise from a currently infected case. It is used as a convenient way to express malaria transmission risk or receptivity of an area to malaria. (Grover-Kopec et al., 2006).

The new generation geostationary satellites will provide more rapid temporal update, higher spatial resolution and more channels which will improve the precipitation measurements. A good example of this is the recent JMA Himawari-8 satellite. Additionally, the future geostationary satellites (beginning with GOES-R in late 2016) will fly lightning mappers which will greatly improve the precipitation estimation by better delineating regions of active convective rainfall. Therefore the data will have a direct impact on **SBA/Health**.

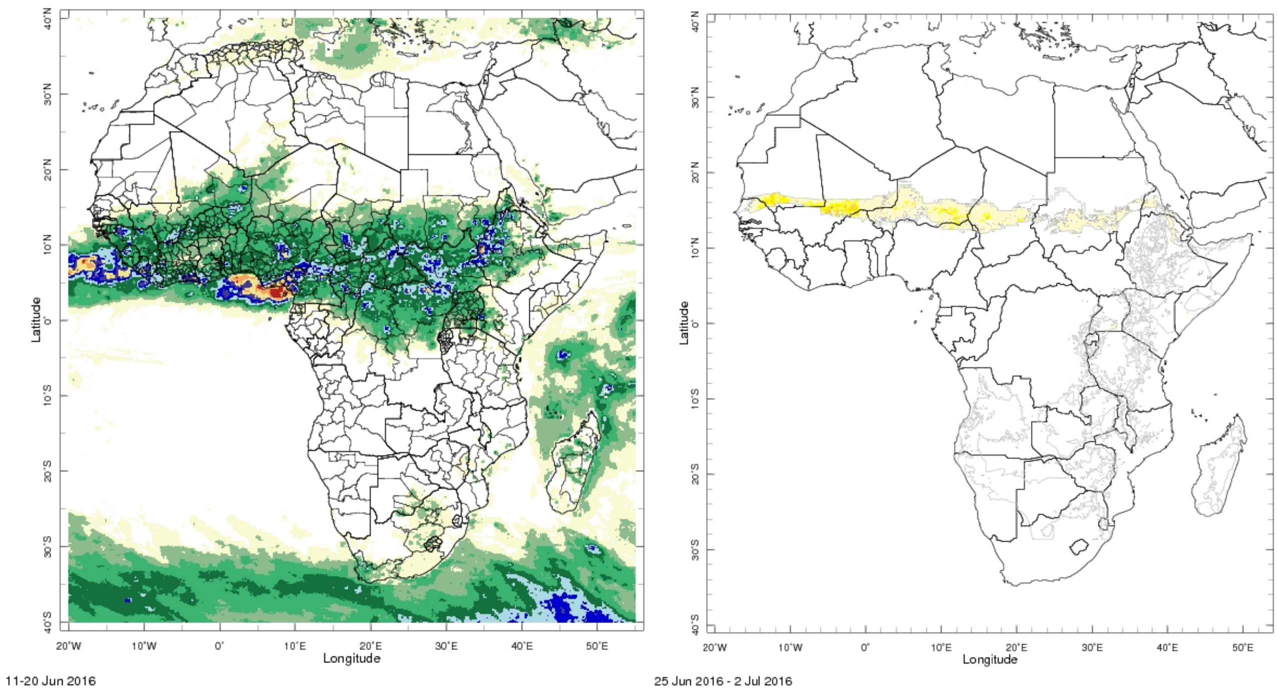

Figure 40: Decadal (10-day) precipitation estimates from NOAA's Climate Prediction Center derived from merging measurements from three satellites sensors (IR from Geostationary every 30 minutes and passive microwave from two polar orbiters up to four times a day) and rain gauge measurements (left, Xie, and Arkin, 1996) and Vectorial Capacity (right, Ceccato et al. 2012).

3.4.8 ALBEDO

Anthropogenic changes to the physical properties of the land surface can perturb the climate by modifying processes such as the fluxes of latent and sensible heat and the transfer of momentum from the atmosphere. Anthropogenic changes in the large-scale character of the vegetation covering the landscape ('land cover') can also affect physical properties such as surface albedo. Albedo is therefore inversely a good tool to monitor these changes as well as in general land use, and can depict well regional changes and differences. Albedo is also, through its direct control of the surface radiation budget, an important input to weather and climate models.

Albedo is one of the Essential Climate Variables listed by GCOS and the requirement for long-term, global, homogeneous, and complete datasets is high. The Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring (SCOPE-CM) initiative aims at coordinating cooperation among operational space agencies. One of the data sets derived under SCOPE-CM is the land surface albedo. Albedo changes in space and time, depending on both natural processes (vegetation growth, rain and snowfall and snow melting, wildfires, etc.) and human activities (forestation and deforestation, harvesting crops, anthropogenic fires, etc.).

Ground based measurements are of great importance for the assessment and evaluation of local and regional variability and change, while satellite remote sensing offers a unique opportunity for documenting and monitoring the spatial surface albedo distribution, its variability, and changes at continental scales. Observations acquired by geostationary satellites have the advantages of offering both a long-term dataset and an angular sampling of the surface, as well as providing diurnal sampling of key parameters influencing the retrieval, such as cloud cover and aerosol load.

Albedo monitoring contributes directly to **SBA/Climate** and **SBA/Weather** but also support **SBA/Agriculture** and **SBA/Ecosystems**.

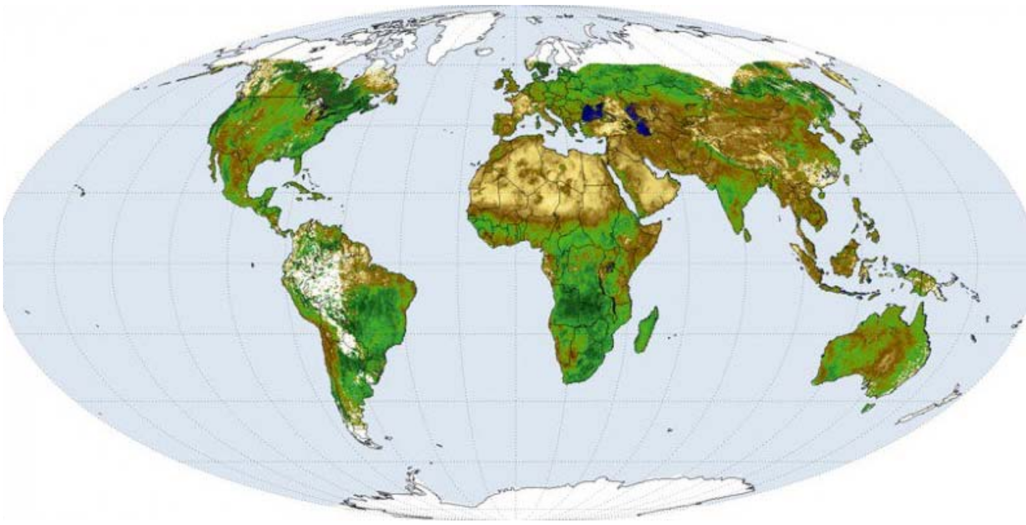

Figure 41: Broadband black sky albedo spatial composite product for the period 1-10 May 2001 [http://www.scope-cm.org/].

3.4.9 INCIDENT SOLAR RADIATION

Downward Short-wave Radiation (DSR) is essential to climate studies and to understand the radiative forcing of clouds and aerosol. It is a key component in the surface energy budget and can be used either as an assimilated quantity in numerical climate and weather prediction models or as an independent source for validation and verification. However, DSR can also be used in non-meteorological applications directly. It is important for applications in solar power generation, building thermal management, water balance modelling and agricultural and ecological modelling. In hydrology, it is used in watershed and run-off analysis, which is important for determining flood risks and dam monitoring. High irradiance values also result in surface drying and DSR can therefore also be used in monitoring fire risk.

Many applications require more detailed information than the total flux on a horizontal surface, referred to as the global irradiance. Most commonly this is the split of the global irradiance into its direct and diffuse components, which arrive from the sun's disk and the rest of the sky respectively, and in some cases also the spectral or angular distribution of the radiation. For instance, concentrating solar power requires the direct beam component, while photovoltaic power and design and control of building heating and cooling both require the direct and diffuse components to calculate radiation on a surface at an arbitrary orientation. Models of plant function and diverse photovoltaic technologies require the irradiance over particular spectral bands.

Clouds exert the strongest non-geometric control over the solar irradiance, while in clear skies aerosol strongly influences the direct beam component. The high frequency sampling of the GEO platform is required to track the cloud variations throughout the day. Near-real time observations at high frequency are essential for short-term forecasts of solar energy production as well as for building energy usage modelling and optimization. Solar radiation algorithms with the older generation of GEO imagers have tended to use empirical relations between satellite observed cloud brightness and the surface global irradiance, which is partitioned into direct and diffuse components by means of empirical models. The increased spectral coverage of the new GEO imagers enables a physical approach in which retrieved cloud physical and microphysical properties are input to a radiative transfer scheme that yields direct and diffuse components explicitly and which can potentially yield spectral information. The aerosol information retrieved from the new GEOs can potentially improve the estimate of the direct irradiance.

Solar radiation is the major driver of many physical, biological and technological processes on Earth, and consequently its monitoring and forecasting contributes to many of the SBAs. GEO observations of DSR will grow in importance for **SBA/Energy** as long-term historical data support the planning and financing of solar power generation, while solar forecasts based on cloud motion support the operation of generators, electricity grids and energy markets, as well as active building thermal management. As one component of the surface energy budget, DSR is important for **SBA/Weather** and **SBA/Climate**, as well as in hydrological modelling that has a role in **SBA/Water**. As an input to models of plant growth, including crops, DSR plays a part in **SBA/Agriculture** and **SBA/Ecosystems**. Finally, cloud-adjusted radiation in the UV band has impacts in **SBA/Health**.

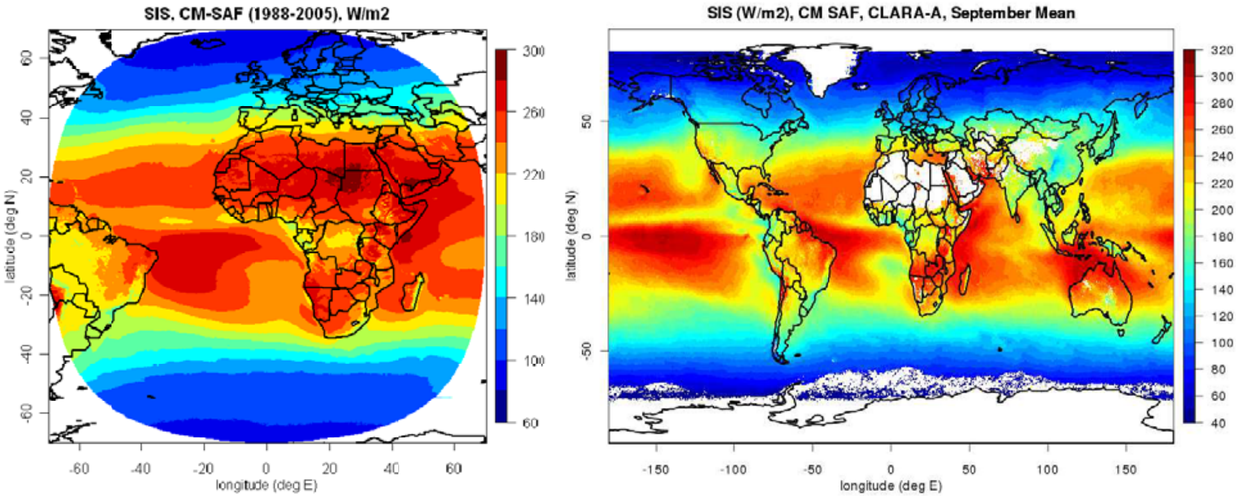

Figure 42: Regional Surface Radiation from Meteosat (left) and Global Surface Radiation from multiple geostationary and polar orbiting satellites (right). (Trentmann et al., 2013).

3.4.10 THE USE OF RGBS

Until recently imagers on geostationary satellites were limited to 2-3 spectral channels, i.e. VIS, IR (and WV). Imagers on satellites in polar orbits offered a couple of additional channels, e.g. 3.9 micron and split window. Traditionally RGBs have been used in weather forecasting as an easy means to emphasise certain aspects captured by the satellite data. However, this technique can also be expanded to NMA application. Various schemes exist for displaying the imagery, and interpretation is sometimes difficult when not being acquainted with the particular colouring.

The advent of true multi-spectral imaging in geostationary orbit is offering the use of false-colour multichannel RGB imagery for easier image interpretation. On RGB displays some characteristics may be easily evidenced with a minimum of processing by attributing a selection of channels and/or channel differences to the individual RGB colour planes. Such RGB composites convey very useful additional information to duty forecasters and image analysts, in particular when looking at animated image sequences. Besides processing on the fly another advantage of RGB compositing (as opposed to more sophisticated processing using classification algorithms) is that the images preserve the “natural” look-and-feel of “traditional” satellite images, e.g. they preserve texture and patterns are continuous in time. Any classification scheme tends to flatten texture (down to chessboard-like patterns and mis/unclassified fringes) and to introduce temporal inconsistencies. These defects hamper reliable interpretation in an operational environment. In particular image sequences are not sufficiently smooth when animated, so important for the appraisal of dynamical aspects.

In the multi-spectral imager era RGB composites are an excellent addition to the tools available for image interpretation. In an operational environment it is important of course, to judiciously select the RGB composites and limit their number to a strict minimum in accordance with the problems at hand. At the same time one should strive for composites being available night and day (i.e. IR only) and maximising feature identification. Depending of the particular multi-spectral imager RGB composites may support the identification of:

- solid and liquid water particles (snow – ice crystals – cloud droplets) and of their relative size at, close to, the cloud tops;
- weak-moderate and strong convection;

- dust and smoke plumes;
- air mass type in middle and high troposphere;
- evolution of snow cover and vegetation;
- oceanic features such as turbid flood plumes and algal blooms.

Further details, information and training material can be found e.g. at:

- http://oiswww.eumetsat.org/WEBOPS/msg_interpretation/index.php
- http://oiswww.eumetsat.int/~idds/html/doc/best_practices.pdf
- http://www.goes-r.gov/users/comet/npoess/multispectral_topics/rgb/print.htm
- http://www5.bom.gov.au/files/7013/5580/7378/RGBWebinarforWebNoRefs.pdf
- https://www.meted.ucar.edu/training_module.php?id=568#.V6SbyKJHCFs
- http://www.eumetrain.org/RGBguide/rgbs.html

3.4.11 RESOURCES

Many of the main findings, results and conclusions presented in this chapter have been derived from the associated Algorithm Theoretical Basis Documents for the new generation meteorological satellites, e.g.:

GOES-R ATBDs:
http://www.goes-r.gov/resources/docs.html#ATBDs

MTG ATBDs:
http://www.eumetsat.int/website/home/Satellites/FutureSatellites/MeteosatThirdGeneration/MTGResources/index.html

4 Synergistic use of LEO systems – benefits and issues

The focus on expanding GEO measurements into Earth Observation applications beyond the traditional core meteorological applications can encompass the recognition that additional Earth Observation applications can arise from synergistic information derived from GEO and LEO satellite systems used in combination. The focus of this chapter is to elaborate what is possible for this class of Earth Observation applications, taking into account the advantages and limitations of each orbit configuration.

After first defining several categories of approaches to the synergetic use of GEO and LEO, a general overview of GEO and LEO characteristics is presented, emphasising similarities and differences, in terms of spatial resolution and coverage, temporal resolution and coverage, viewing and illumination conditions, and spectral resolution and coverage. A brief section summarizes the key figures that characterise GEO and LEO observation geometry individually. Then, taking these characteristics into account, different approaches to deriving geophysical parameters from a GEO-LEO combination are laid out with suggestions of applications that can benefit. It is important to recognize that certain prerequisites and requirements must be fulfilled in the usage of algorithms, calibration, harmonization, and validation to deduce a geophysical quantity from GEO and LEO observations jointly, and a subsection is dedicated to these topics. Finally, we briefly note some existing studies that have made synergistic use of GEO and LEO satellite systems, and present one case study in detail.

Note that while the present study is focused on applications that use LEO imagers, which have been the basis of many non-meteorological applications in the past, there is also a lot of potential in other sensor families and many of the considerations raised in this chapter will apply to them.

4.1 Synergistic use – what kind of synergy is meant

It is worth prefacing a discussion of synergistic use by clarifying the nature of the synergy, identifying the nature of the inputs and the output. There are in fact several approaches to synergistic usage which differ in the type of measurements drawn from the different orbit configurations and in the kind of information they produce. Finally, it is a question of merging different single information content into another information context.

The following list, though probably not exhaustive, offers a structure for the discussion in terms of successive levels of satellite data processing beginning with level 0.

a. The approach closest to level 0 is to combine measurements of the same or similar sensor type from GEO and LEO orbit. However, the choice of the orbit usually dictates differences in sensor specifications, so the ideal case of identical sensors with identical characteristics is not realized in practice and modifications in data processing must be introduced to combine such data;

b. Another approach would be to combine level 1 data (radiances) which are defined in absolute physical quantities to make them compatible. These can be input into a single algorithm in order to derive higher level products and information;

c. Geophysical quantities measured from GEO and LEO (usually level 2 and higher) can be also the taken as inputs for a synergistic approach. In this particular case, a merge of one geophysical quantity derived from GEO and LEO into one derived product is one approach. However, an alternative is the complementary use of different geophysical quantities to derive new, synergistic information, possibly using new measurement techniques that exploit the availability of the complementary data streams. One such example is the case study discussed below of CSIRO's retrieval of aerosol and land surface reflectance from GEO and LEO together.

d. Information derived from level 1 (for example cloud masking) can be also used to merge with a geophysical quantity (level 2) to derive another geophysical product.

Approaches a) and b) can be discussed together as merging the data before performing the geophysical retrieval. Likewise, c) and d) can be considered together, because in these cases higher level information is derived from the GEO and LEO measurements individually and then merged into new information. It is worth noting that this discussion can be applied not only to merging GEO and LEO, but is independently applicable to LEO/LEO or GEO/GEO synergistic usage. However, the following discussion of the benefits and issues arising from the different characteristics of orbit configurations is confined to the synergistic use of GEO and LEO systems.

4.2 GEO and LEO observation geometry

GEO satellites were originally designed to monitor meteorological conditions with frequent imaging in order to improve weather forecasts[5]. Thus, the GEO orbit offers the opportunity of measuring with a very high frequency over an unchanging region of interest. GEO observations are, however, restricted to a disc projected on the earth surface and limited to approximately 60° north to 60° south latitudinal coverage. The viewing geometry is the same for all measurements carried out for a specific point of interest while the illumination changes with diurnal and seasonal cycles. The new GEO sensor designs feature a footprint with a spatial resolution of around 250 m to 2 km and so this will be the resolution of the image data for the present discussion of synergistic use with LEO observations. It is worth noting that GEO imagers can employ longer integration times or co-adding over a single scene to compensate for the disadvantage of the lower photon flux and hence the lower sensitivity compared to the sensors in LEO orbits.

A sun-synchronous LEO orbit offers a global coverage of the earth including the polar regions within a defined time span of typically half a day to several days. On the other hand, flying in a lower orbit allows the measurement of scenes with a spatial resolution down to 1 m at the cost of spatial coverage. Thus measurements from LEO orbit on timescales relevant to environmental monitoring are, with current technology, constrained to approximately the range 10 m to 1 km, with a trade-off between spatial resolution and the time to acquire global coverage. However, the combination of several satellites of the same type in LEO orbit as a constellation (for example DMCii and RapidEye) can achieve daily global coverage with fine spatial resolution. The LEO orbit provides the opportunity to observe each individual scene under similar illumination geometry at the same time of day, but the viewing geometry is different for each spatial pixel and varies from day to day. Long term variations in geophysical quantities can be tracked if a long time series is available from a sensor. Finally, it is worth noting that most active remote sensing techniques are restricted to LEO orbit because of technical constraints such as, for example, size of telescopes and sensitivity.

Summarizing this brief comparison of GEO and LEO imagers, the characteristics discussed above are coarsely contrasted in Table 8.

We can conclude from Table 8 that, broadly speaking, some of the characteristics support exploiting complementarity (e.g. spatial resolution and technique) and others similarity (e.g. spectral coverage and resolution). This has been noted in many activities and will be starting point for the discussion of possible Earth Observation applications below.

Before discussing synergy approaches, some basic pre-requisites and requirements that must be understood are discussed, because the combination of information from different sources needs some care in order to avoid incompatibilities and to retrieve high quality information from the synergy.

[5] See also page 19, ".....the oracle of Meteosat“ in Asterix and the Magic Carpet, Vol. 28, 1987

Table 8: GEO versus LEO characteristics.

	GEO	LEO
Spatial coverage	Disc	Global
Spatial resolution	Coarse	Fine
Temporal resolution	Fine	Coarse
Spectral coverage	Similar	Similar
Spectral resolution	Similar	Similar
View geometry	Fixed	Varying
Illumination geometry	Varying (full diurnal cycle)	~Fixed
Technique	Passive (predominantly or only)	Passive and active

4.3 Pre-requisites and requirements

When considering deriving an EO application from the synergetic use of a GEO and LEO product (or several products), levels of uncertainty, from the perspective of the target information of the application, must be understood in order to first decide whether a merging of different information is in principle possible. It is clear that an input with an uncertainty level around 10% will not produce an output with an uncertainty level of around 1%. It makes no sense trying to derive of data product with lower uncertainty than the input allows. However, one can turn around this paradigm into the formulation that from high quality input one may estimate the expected quality level of the output. This quality level is not only dependent on the quality level of the input but also dependent on the merging process which will usually be influenced by different issues:

- The quality of the input and the algorithms has not been sufficiently evaluated;
- Sensors must be calibrated against the same standards so that their results become comparable;
- Typically, sensors do need corrections in order to be matched. The spectral response function is a typical sensor-specific quantity which may lead for two sensors to different results in similar bands. Similarly, cross-sensor co-registration errors must be taken into account. It shall not be overlooked that these can be found also on one satellite platform between two optical parts of one spectrometer.

The first item is related to the validation of data products and the underlying algorithms. In order to clearly quantify how good a derived data product is, the validation is carried out versus independent measurements of the same quantity from which the uncertainty is determined so that an error budget can be derived for this data product.

The CEOS WGCV is currently developing principles, rules, and metrics—ultimately based on the QA4EO principles—for the calibration and validation of data products in several domains. The different activities encompass the definition of validation protocols (for LAI, for example), the establishment of the “fiducial reference measurement” system which is currently successfully applied to Sea Surface Temperature together with the SST-VC and will be extended to additional systems, and establishment of vicarious calibration sites into networks with a unified processing approach (RADCALNET).

Aside from these activities, further efforts exist with an emphasis on the quality characterization of both level 1 and level 2 data for individual sensors, traditionally mostly from LEO platforms. From this perspective, the calibration of sensors against an acknowledged standard, the discussion of mismatch between the spectral response function of two sensors, and co-registration errors are part of the discussion in several parts of CEOS WGCV. These activities are basic knowledge which underpin the evaluation of emerging algorithms.

In contrast, the activities of WMO/GSICS have been dedicated from its early inception to the harmonization of the calibration of different meteorological sensors. This intercalibration approach, which is usually tied to one sensor as a reference for the others, allows the comparability of sensors on different GEO platforms and in its ideal application enables synergistic use of GEO and LEO measurements of similar type/quantity. For global products derived from the GEO ring, there is an additional requirement to inter-calibrate the GEOs, possibly via the LEOs. Much work has already been done to use LEOs to calibrate GEOs and such work becomes critical for applications that merge GEO and LEO data. CEOS WGCV and WMO/GSICS have expertise to offer in this area, and the GSICS framework for routine collection and analysis of simultaneous observations by spacecraft pairs will be a valuable resource. Also, related to the discussion of sensor matching above, a secondary effect to consider is that the target spectral shape influences the effective calibration (Vermote and Kaufman, 1995; Minnis et al., 2002), and that this effect is complicated by differences between sensor spectral response shapes.

We should also note that GEO and LEO observations can be used for cross-validation of geophysical products.

An issue which is familiar for imagers with separate optical paths in different spectral channels is the co-registration between the different spectral channels. Usually pre-flight characterization is used to minimize that effect. However, such an effect must also be taken into account for cross-sensor comparisons. There is some experience within CEOS and CGMS for cross-sensor co-registration in order to reduce the noise introduced by misalignment.

The adoption of data standards to facilitate the development and operational processing of joint algorithms is another issue which must be taken into account. This is because Earth Observation applications are no longer simply research resources but are today instead thought of as a societal benefit, always developed with the goal to deliver a service to mankind. The size of the data infrastructure required to produce and deliver large global datasets from the new GEOs is, if anything, greater when extended to synergistic use with LEOs. Consequently it will be necessary to take advantage of modern data approaches as guided, for instance, by the CEOS Initiative on Future Data Architectures.

4.4 Potential fields of Earth Observation applications

As we begin an outline of the potential applications from a synergistic use of GEO and LEO, table 8 suggests different approaches that combine different characteristics: combination of spatial and temporal coverage, viewing and illumination conditions, latitudinal coverage, and synergies with other platforms. Note that the present discussion is limited to imagers, but could be extended to other sensor systems to systematically include the combination of active and passive sensor systems.

4.4.1 COMBINATION OF SPATIAL AND TEMPORAL COVERAGE

The LEO imagers with daily coverage have spatial resolutions of around 250 m to 1 km, depending on spectral band, compared with 500 m to 2 km for the new GEO imagers. Table <XX Chapter 2 table “Comparison of multi-band imagers of geostationary satellites”> gives the details for some specific sensors. Thus, for nominally equivalent spectral bands, the GEOs provide a data stream comparable to that from the LEOs with somewhat coarser resolution but far denser temporal sampling. This complementarity raises the possibility of creating a merged data stream with the LEO spatial resolution and GEO temporal resolution.

The following are examples of applications that can potentially benefit from the combination of spatially detailed information on a dense grid with high temporal resolution that captures dynamics on short timescales:

For land surface applications based on surface reflectance this includes:

- agriculture such as harvest, crop monitoring;
- burned area monitoring;
- transient snow;
- enhance LEO flood monitoring with sub-daily resolution;
- Fire hotspots: LEOs have finer resolution and hence typically better sensitivity to small fires but GEOs are better able, for large enough fires, to capture fires early after ignition, and monitor their spread.

For ocean application this includes:

- Currents traced by ocean colour; sediment plumes;
- SST fine scale dynamics.

Approaches similar to those required have been developed for merging, for instance, MODIS and Landsat for the land surface, albeit at the slower sampling periods of daily and 16 days (Emelyanova et al. 2013; Gao et al. 2006).

4.4.2 VIEW AND ILLUMINATION CONDITIONS

As described above, observations from GEO and LEO sensors differ in the characteristics of the view and sun directions at which they are made. Over a pseudo-regular cycle of several days the view zenith angle at the surface varies over a large range and the solar zenith angle over a small range, while a GEO-based sensor observes a surface location from a constant view direction and samples the full diurnal cycle of sun direction at that location over a single day.

Potential applications of the complementary angular geometries include:

- Using the extra angular information of simultaneous GEO and LEO observations to decouple aerosol and BRDF effects on land surface reflectance. This will be discussed further in a case study below. Aerosol and BRDF have been simultaneously characterised from LEO platforms by multi-view research sensors such as POLDER, MISR and the (A)ATSR series. Simultaneous GEO and LEO observations from different directions provide a pair of similarly diverse views.
- Using the diversity of scattering angles to obtain aerosol properties such as particle shape.
- Using GEO-based BRDF models to normalise higher resolution but less frequent LEO observations for angular effects. This could be particularly useful for tracking reflectance and albedo dynamics in persistently cloudy situations such as common in the tropics, and in cases of rapid surface changes such as transient snow and burns, but could potentially improve the quality of all LEO-based land cover dynamics. The application of coarse resolution BRDF models to finer resolution, less frequent observations has been developed in the case, for instance, of MODIS BRDF applied to Landsat (Li et al. 2010).
- Using GEO observations to extend the angular sampling of LEOs, thus better constraining BRDF models and reducing the uncertainty of albedo estimates.
- Stereo heights of atmospheric features such as clouds and volcanic plumes.
- Observations of three-dimensional effects such as cloud structure.

4.4.3 LATITUDINAL COVERAGE

As noted above, the latitudinal coverage of effective GEO-based observation extends from approximately 60° North to 60° South. On the other hand, the overlap of LEO image swaths increases towards the poles, so that the frequency of temporal sampling of a wide-swath sensor increases from approximately daily at the equator and mid-latitudes to every orbit for a large fraction of the day in the Polar Regions. Thus GEO and LEO data taken together can provide global coverage with at least the LEO orbital frequency (approximately 100 minutes), particularly if a constellation of LEOs is used to cover all local time sectors.

Applications that could benefit from merging GEO and LEO products include:

- Sea-ice and weather monitoring for transportation
- Cloud and ice monitoring for climate
- Ocean colour and SST

Furthermore, at the intermediate latitude bands of 60°–70° where both GEO quality and LEO temporal sampling are marginal, observations can be combined to create products that are not feasible with either platform alone. An example is the combined LEO/GEO high latitude atmospheric motion vectors developed by the University of Wisconsin-Madison and NOAA (Lazzara et al. 2014) that fill the latitude gap between GEO AMVs and polar winds from LEOs.

4.4.4 SYNERGIES WITH OTHER PLATFORMS

This discussion of the means by which GEO platforms can be used in synergy with LEO platforms concludes by briefly noting the potential to similarly combine GEOs with platforms in other orbit types.

The L1 Lagrange point is located 1.5 million km sunward of the Earth and imagers stationed there have a continuous view of the Earth's dayside. The US DSCOVR satellite carrying the EPIC imager is currently situated at L1, capturing 25-km imagery in 10 bands up to hourly. Simultaneous GEO imagery will have different view directions and consequently scattering angles and atmospheric path lengths (but identical Sun directions), thus offering extra information to constrain BRDF models and estimates of aerosol, atmospheric composition and air quality, analogous to the extra angular information available from the combination of GEO and LEO platform measurements.

Molniya orbits enable a platform to linger at high latitudes for the majority of the 12-hour orbital period. They thus offer high frequency sampling of Polar Regions that in conjunction with GEOs can complete global coverage, analogous to the GEO and LEO combination.

4.5 Examples of GEO and LEO Earth Observation applications

Some agencies and scientific institutions have, in the past, researched what is possible with the synergistic use of GEO and LEO. These efforts serve as impressive demonstrators of the potential for further Earth Observation applications. This section collects some of the existing studies as exemplars, and also includes some of the obvious but unimplemented possibilities.

GEO and LEO Level 1 data input to a single algorithm

- Aerosol and surface reflectance: Australia's CSIRO uses the GEO-LEO angular complementarity to simultaneously retrieve aerosol and surface reflectance over land.

Merging of GEO and LEO Level 2 and higher data

- Fire hotspots: CMA has developed mapping of fire hotspots using data from its FY-2 meteorological GEO satellites as well as LEO satellites. Geoscience Australia is adding Himawari-8 fire hotspots to the AVHRR and MODIS hotspots already on its Sentinel service (https://sentinel.ga.gov.au) for the public and operational fire management agencies. JAXA's fire monitoring service (http://www.eorc.jaxa.jp/ptree/) draws on data from Himawari-8 and several LEOs to map hotspots at a broad range of spatial scales.
- Sea Surface Temperature: Several groups within GHRSST merge GEO and LEO SST products, typically imposing the GEO-observed diurnal variations on the fine resolution LEO data.
- Atmospheric chemistry: The CEOS proposed GEO-based Air Quality Constellation can be used in combination with the Sentinel-5P and Sentinel-5 LEO missions that was described in Chapter 2 to yield

compatible information on atmospheric constituents with both fine spatial and temporal spatial resolutions.

- Land surface reflectance: A land surface reflectance product that combines GEO temporal resolution either maximum frequency or daily with better cloud-free coverage with LEO spatial resolution is a potentially very useful product, mainly because it can support improved downstream products such as land cover and vegetation parameters. However, as far as the authors of this report are aware such a product has not yet been implemented.

GEO product input to LEO production or vice-versa

Even without merging the low level data or products, GEOs and LEOs can be used in combination for purposes of, for instance, algorithm tuning.

- Sea surface temperature: The Australian Bureau of Meteorology has tuned its initial Himawari-8 SST product to VIIRS SST observations, owing to the short record and sparseness of the buoy network.
- Evapotranspiration: The Universities of Maryland and Wisconsin have developed Landsat-scale evapotranspiration (ET; 30-m) products for which GOES-based ET (4-km) serves as the boundary condition, thereby supporting field-scale assessments of consumptive water use.

There is an emerging trend to use all relevant satellite sensors (including spectral, spatial, and temporal information) and relevant non-satellite data sources to provide a “best” analysis of geophysical parameters. NOAA is aiming to apply such “enterprise algorithms” to, for instance, mapping the horizontal extent of volcanic ash clouds.

The common use of the same LEO satellite in synergistic applications by the different GEO satellites both motivates and provides a mechanism for harmonisation of the GEO and LEO synergistic products derived from the various GEO satellites, including through intercalibration of GEO level-1 products with LEO products, intercalibration of GEO level-1 products with each other via LEO products, correction for spectral differences between GEO level-1 products and between GEO level-1 products and LEO level-1 products, and adoption of common algorithms. Adoption of common data standards is also desirable. GSICS has results and expertise to apply to the intercalibration and spectral correction issues. The SCOPE-CM activity for globally consistent production of GEO-ring surface albedo distributed across three centres provides a model for global coordination of algorithms and formats.

4.6 Case Study

A recent example of a synergistic algorithm that illustrates the new possibilities but also highlights the harmonisation issues is the recent development of a GEO and LEO joint retrieval of aerosol optical depth and surface reflectance by Yi Qin (CSIRO) and colleagues in Australia. The technique was originally developed for the dual-view AATSR and has subsequently been applied to Himawari-8/AHI in combination with either MODIS or VIIRS, and is now being adapted to AHI with SGLI on GCOM-C.

The retrieval of aerosol parameters over the land surface is challenging, particularly over bright surfaces such as deserts. The inhomogeneity and variable anisotropy of the surface reflectance contributes to the challenge: it is difficult to distinguish the effects of aerosol and BRDF on reflectance variations at the top of the atmosphere. The CSIRO method relies on the different view directions of the near simultaneous observations that occur once per day at the time of LEO overpass to decouple the BRDF and aerosol effects on the TOA signal. Radiative transfer modelling links surface BRDF and top of atmosphere (TOA) reflectance. The method requires an aerosol classification providing representative aerosol types, and models the surface BRDF on the assumption that the BRDF shape is stable over a long period of time. Figure 43 shows example outputs and validation results over Australia. The retrieved AOD has good spatial coverage, even over the bright arid inland regions of Australia, and the AOD time series validates well against ground-based observations from the CSIRO’s AeroSpan network that is affiliated with AERONET.

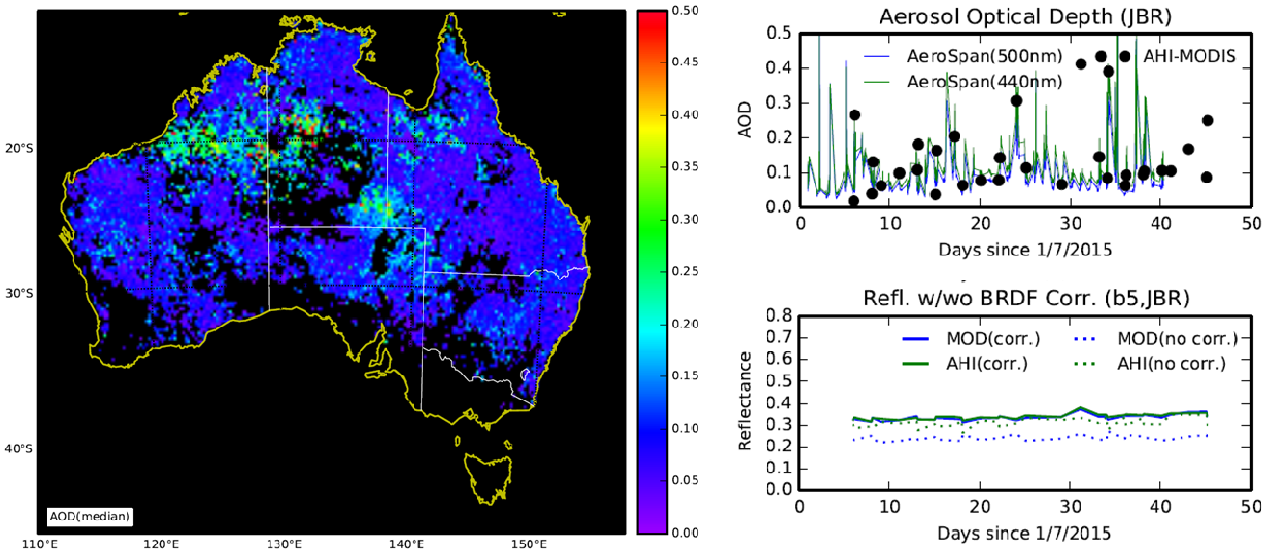

Figure 43: The simultaneous retrieval of aerosol optical depth (left) and surface reflectance jointly from AHI and MODIS. The AOD is compared with AeroSpan data from Jabiru in northern Australia (top right). The surface reflectance at Jabiru in AHI Band 5 is compared with that in the corresponding MODIS band, with and without the derived BRDF normalisation (Qin, 2015).

A prerequisite for the CSIRO method is calibration harmonisation of the GEO and LEO, accounting for residual calibration differences and differences in spectral response functions. For AHI and MODIS both effects were modelled together by linear models that were regressed against 2700 hyperspectral images from Hyperion onboard EO-1 that were processed to equivalent multiband responses for the two sensors (Figure 44). Regression slopes differed from unity by as much as 5% but were well constrained with squared correlation coefficients r^2 over a wide range of scene brightnesses in the range 0.990–0.997.

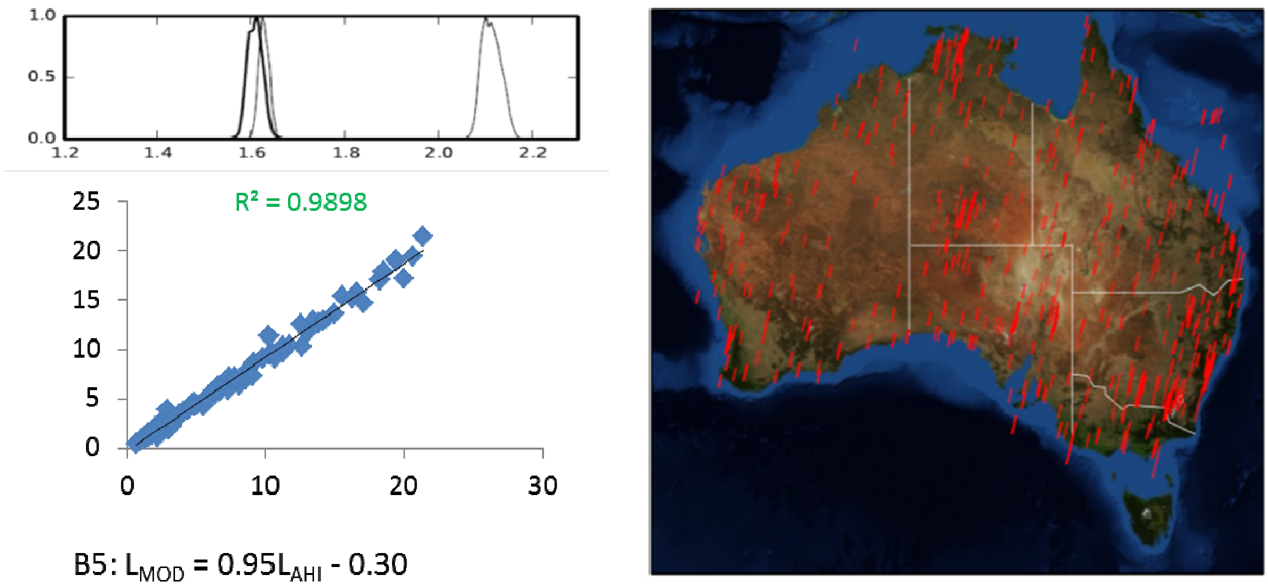

Figure 44: The relative spectral responses (top left) of AHI Band 5 (black) and MODIS Bands 6 and 7 (grey), the regression relation (bottom left) to convert AHI Band 5 radiance into equivalent MODIS Band 6 radiance, and the location of the Hyperion scenes used to develop the regression (right). (Qin, 2015).

4.7 Conclusion

The image data from the new generation of GEO imagers has spatial resolution and spectral coverage approaching those of the polar orbiting LEO imagers that have until now formed the backbone of satellite-based monitoring of dynamic environmental variables, but with much greater temporal frequency and with different geometry. This creates an opportunity to combine the complementary measurement characteristics of the two platforms to strengthen or extend the LEO-based measurements or apply new algorithms that are not feasible for either platform alone.

Specific strategies for the fusion of GEO and LEO data include:

- LEO fine spatial resolution and GEO fine temporal resolution;
- Simultaneous observations with different viewing or illumination conditions;
- Low- to mid-latitude GEO and High-latitude LEO.

Supporting strategies that can be enabled by inter-agency coordination include:

- Building on LEO algorithm experience and teams;
- Taking advantage of modern data approaches;
- Harmonisation of GEOs and LEOs, particularly in regard to calibration standards and relative calibration methods between GEO and LEO;
- Common data product validation approaches and standards.

CEOS has the potential to significantly contribute through its Working Groups and Virtual Constellations in carrying out the preparation for such synergistic use on different levels. An asset is also the cooperation between WMO/GSICS and CEOS WGCV in combining their knowledge for calibration and validation.

5 Coordinating initiatives

This chapter provides a short non-exhaustive overview of CGMS and other agency initiatives that are relevant to the further coordination and progression of non-meteorological applications from GEO orbit and their full exploitation in combination with LEO observations (GEO-LEO synergies) as described in the previous chapter. In view of multi-sensor non-met products from a constellation of GEO imagers (Figure 1) on-going inter-calibration efforts of satellite operators under GSICS should be expanded to cover these new products. In addition, satellite operators need to engage more broadly with user community to progress non-met algorithm developments and to drive data uptake from new stakeholders.

5.1 User engagement – SATURN, EUMETRAIN, WMO-CGMS VLab

To provide the user community with a single point of access to information about the new generation of meteorological satellites planned to enter operation in the 2015-2020 timeframe the WMO-CGMS Satellite User Readiness Navigator (SATURN) portal has been established by WMO (TBD add URL to References). In detail, the portal provides information about the technical specification of recently launched and to-be-launched GEO satellites, an overview of ground segments and operations, data access and use, as well as information on user readiness planning to guide the introduction of new satellite data into the operations of meteorological services and other users. Through user readiness planning all WMO members and satellite operators should assist users in preparing them for using the new generation of operational satellites through detailed list of actions outlined in the “CBS Guideline for Ensuring User Readiness for New Generation Satellites”. However “users” in this context are mainly the National Meteorological and Hydro-meteorological Services (NMHS) and operational user organisations.

Another online resource for training to support and increase the use of meteorological satellite data is the EUMETSAT sponsored EUMETRAIN portal (TBD add URL to References) that provides users specifically of EUMETSAT satellite data and products (e.g. NMHS) with training resources that enable them to make more effective use of this satellite data. If satellite operators were to expand their GEO operational product list to include non-met applications additional training requirements need to be accommodated.

Also the WMO-CGMS Virtual Laboratory for Training and Education in Satellite Meteorology (VLab) through its global network of training centres and satellite operators aims to improve data utilization not only from meteorological (GEO) satellites but also from environmental (LEO) satellites.

However, the fleet of EO satellites is continuously expanding and becoming more diversified. Therefore it is critical to ensure inter-comparability of observations from instruments on different satellite platforms.

5.2 The Global Space-based Inter-Calibration System (GSICS)

Since 2005 satellite operators and science teams collaborate under GSICS to monitor, improve and harmonize the calibration of a range of instruments onboard operational GEO and LEO satellites of the Global Observing System (GOS). Consistent inter-calibration of instruments onboard different satellites is of importance to ensure reliability of EO data in particular for monitoring of climate variability and change. Specifically globally-merged “multi-satellite” products, e.g. from a constellation of GEO imagers, require consistent inter-calibration to ensure seamless product quality and comparability of observations across different satellite platforms. Dedicated GSICS Processing and Research Centres (GPRC) operated by NOAA, CMA, EUMETSAT, JMA and KMA deal with monitoring of instrument performances and operational inter-calibration of satellite instruments. To quantify sensor performance GPRCs deploy satellite inter-calibration algorithms for GEO-LEO observations. Whilst GSICS aims to cover all spectra regions, the following sections will only highlight the activities performed for infrared and visible channel calibration activities as they are the relevant ones for the meteorological geostationary imagers.

5.2.1 **INFRARED**

One of the first objectives of GSICS was to support the development of consistently calibrated geostationary infrared imagery data. A prerequisite for successful exploitation of infrared radiances is an accurate instrument pre-launch characterisation and onboard calibration. However, it is also mandatory to have an independent mechanism to verify and monitor the performance of the onboard calibration system. The advent of highly accurate hyperspectral instruments with a calibration accuracy of 0.1-0.15K, like AIRS onboard Terra and Aqua, CrIS onboard Suomi-NPP and IASI onboard the Metop-satellites has enabled the intercalibration of the geostationary satellites against these reference instruments. Monitoring of the calibration of the geostationary imagers is now provided routinely by most satellite operators and provides also the means for improved satellite in-orbit check-out as well as the derivation of accurate and consistent products across different platforms.

The Meteorological Satellite Centre (MSC) of JMA supports GSCIS by operating a GPRC that, amongst other satellites, ensures calibration monitoring of Himawari-8 AHI.

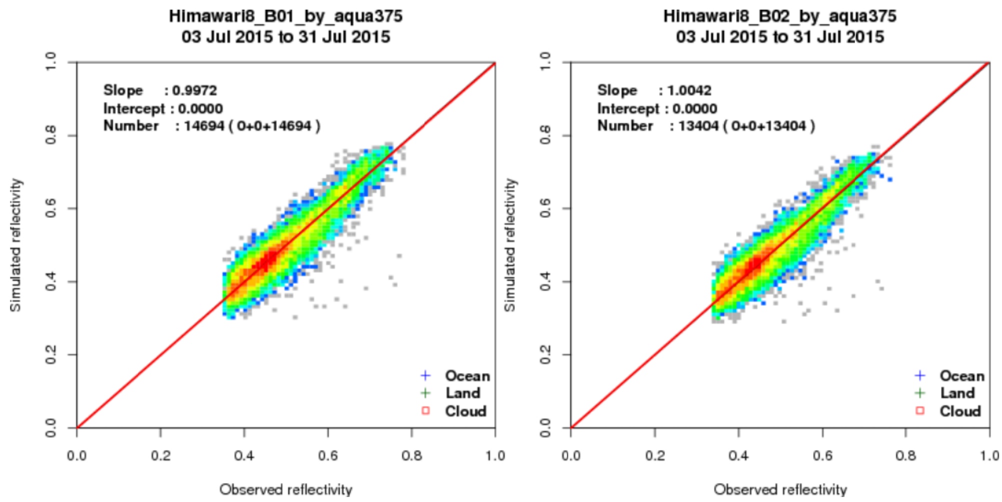

Figure 45: Himawari-8 AHI band 1 and 2 vicarious calibrations statistics July 2016. (Courtesy JMA, Himawari-8 Calibration Portal).

Whilst the imagers on the new generation meteorological geostationary satellites have accurate onboard calibration, the calibration of the visible channels relies on various methods. Several approaches have over the years been adopted: e.g. desert targets in vicarious calibration methods, cross-calibration with other satellite e.g. over Deep Convective Clouds and Lunar calibration methods. In particular the latter method, provided that the instruments are capable of Lunar observations, has the utility to provide highly accurate calibration of the visible channels. Whilst today, lunar calibration provides and absolute accuracy of 5-10%, a significantly better accuracy can be achieved. Lunar calibration has the potential to provide absolute radiometric calibrations of solar band sensors in orbit with SI-traceable accuracy better than 1.0% (k=2). Whilst this is beyond current capabilities, it would be achievable if high-accuracy, SI-traceable absolute measurements of the Moon are acquired and developed into an absolute lunar reference standard. The availability of such a high-accuracy absolute reference has significant implications for the utility of data acquired from solar band instruments, particularly with regard to consistency and inter-operability across sensors and platforms, and the construction of climate records. With this reference standard, absolute accuracy requirements for visible and near-infrared channel sensors could be set to a similar level.

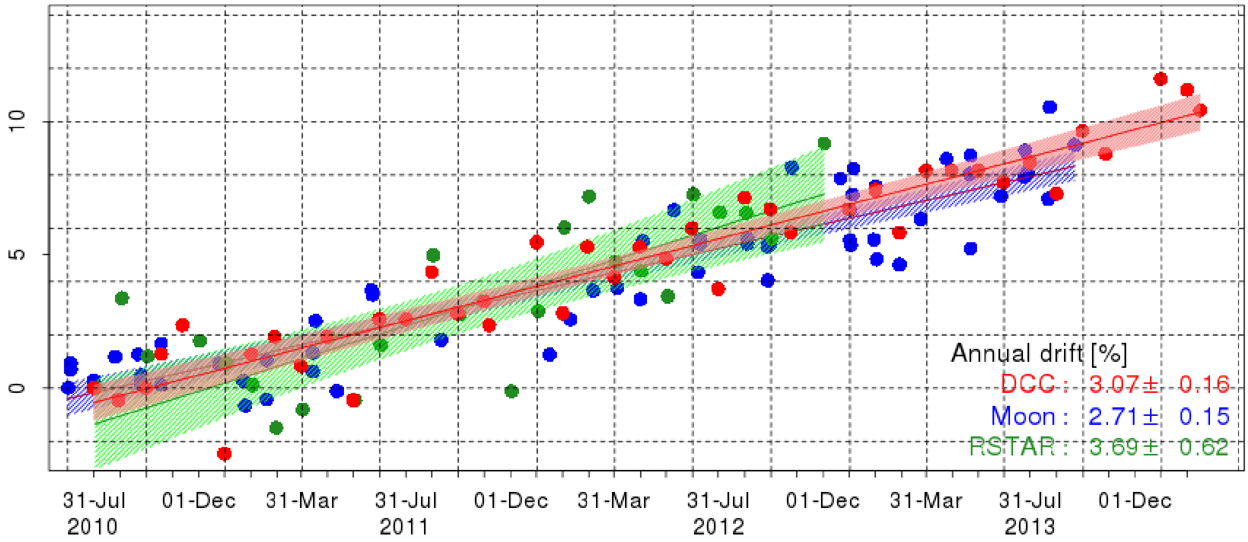

Figure 46: A comparison of various calibration methods. Time series representation of variation in the MTSAT-2 visible calibration slope as derived using three calibration methods (DCC = Cross calibration using Deep Convective Clouds, Moon = Lunar calibration, RSTAR = Vicarious Calibration using radiative Transfer Model simulations). Each result is normalized against the first calibration result. The shaded are shows the 95% confidence interval of the linear regression. (Takahashi and Okuyama, 2015).

5.3 EUMETSAT Satellite Application Facilities (SAFs)

The EUMETSAT Satellite Application Facilities (SAFs) provide users with operational data and software products, with each one being dedicated to a particular user community and application area. The SAF activities are centrally coordinated so as to ensure that the SAFs provide reliable and timely services to their respective user communities. Their deliverables range from a specific piece of software to be made available to users for use in their own environment, to data and products made available in near real-time or offline. The SAFs that provide software/tools and monitoring capabilities could be used as a model for collaboration and joint development activities as well as enabling simple software packages to be developed and distributed to NMA users with limited resources in satellite remote sensing.

The SAFs are located within the National Meteorological Services (NMS) of EUMETSAT Member States, or other agreed entities linked to a user community, and carry out relevant research, development, and operational activities not carried out by EUMETSAT centrally.

The network of EUMETSAT SAFs consists of the:

- Nowcasting SAF (NWC SAF);
- Numerical Weather Prediction SAF (NWP SAF);
- Ocean and Sea Ice SAF (OSI SAF);
- Climate Monitoring SAF (CM SAF);
- Land Surface Analysis SAF (LSA SAF);
- Ozone and Atmospheric Chemistry Monitoring SAF (O3M SAF);
- Radio Occultation Meteorology SAF (ROM SAF);
- Hydrology SAF (H SAF).

NWC SAF

The main goal of the NWC SAF is to produce software packages that support Nowcasting and Very Short Range Forecasting. The software, which is for local installation at the user's site, processes data from operational meteorological satellites flying in geostationary orbits (e.g. Meteosat Second Generation (MSG)) or polar orbits (e.g. Metop or NOAA) as well as their successors.

NWP SAF

The main objective of the NWP SAF is to increase the benefits derived from numerical weather prediction by developing techniques for more effective use of satellite data, and to improve the exploitation of data and products from EUMETSAT satellites programmes, and the related programmes of other agencies. To achieve this objective, the NWP SAF updates, assesses and prioritises user requirements and develops the satellite data processing modules needed to meet those requirements. The NWP SAF is similar to the NWC SAF, in the sense that the NWP delivers processing modules to European NWP operators, rather than operational products and data.

OSI SAF

The OSI SAF is a response to requirements, from the meteorological and oceanographic communities of EUMETSAT Member and Cooperating States, for comprehensive information derived from meteorological satellites at the ocean-atmosphere interface. The OSI SAF offers a precious complement to in-situ data, based on continuously increasing temporal and geographical resolution products from coastal to global coverage.

CM-SAF

The CM SAF generates and archives high-quality datasets for specific climate application areas, through the exploitation of satellite measurements with state-of-the-art algorithms, to derive information about the climate variables of the Earth system. The application areas cover the objectives of various international programs such as the Global Climate Observing System (GCOS), the World Climate Programme (WCP) and the World Climate Research Programme (WCRP), and are also vital for activities within the Group on Earth Observations (GEO) and Copernicus framework.

LSA SAF

The objective of the LSA SAF is to take full advantage of remotely sensed data on land, land-atmosphere interactions and biosphere applications. A strong emphasis is put on developing and implementing algorithms that will allow an operational use of data from EUMETSAT satellites. The LSA SAF addresses a wide user community, ranging from surface processes modelling e.g. Numerical Weather Prediction (NWP), seasonal forecasting and climate models to agriculture and forestry applications e.g. fire hazards, food production and hydrology.

O3M SAF

The O3M SAF develops, produces, archives, validates and disseminates ozone and atmospheric chemistry products, to support the services of the EUMETSAT Member States in weather forecasting, as well as monitoring of ozone depletion, air quality and surface UV radiation.

ROM SAF

The ROM SAF generates and archives high-quality GPS Radio Occultation (RO) datasets for Numerical Weather Prediction (NWP) applications and specific climate application areas, through the exploitation of satellite measurements with state-of-the-art algorithms, to derive information about the atmosphere and climate variables of the Earth system. The ROM SAF is also engaged in developing an RO processing software package containing modules for assimilation of RO data in NWP models.

H SAF

The H SAF operationally generates, validates, distributes and archives high-quality datasets and products for operational hydrological applications, starting from the acquisition and processing of data from Earth observation satellites in geostationary and polar orbits, operated both by EUMETSAT and other satellite organisations.

The H SAF mainly focuses on:

- The generation of precipitation products, soil moisture products and snow parameters;
- The independent validation of new products for hydrological applications with special relevance attached to those initiatives which want to mitigate hazards and natural disasters, such as flash floods, forest fires, landslides and drought conditions, and improve water management.

5.4 Bilateral collaboration Japan-Australia

Satellite application developers from Japan and Australia have established a collaboration on the development of applications from Japan's Earth Observation satellites, primarily Himawari-8 but also LEOs such as GCOM-W and GCOM-C. This initiative is intended to make the most of Japan's satellite data streams and Australia's application capabilities. The joint effort is particularly focused on applications that benefit from the high temporal and spatial resolution of combined GEO and LEO observations, and hence is often referred to by its participants as the "GEO-LEO" collaboration.

The collaboration commenced with a workshop held in Brisbane in August 2015. Participants from Japan included representatives from JAXA, JMA and universities, while the Australian representatives came from CSIRO, the Australian Bureau of Meteorology (ABoM), Geoscience Australia and universities. The workshop established product teams and identified target products and applications within the themes of land, ocean and atmosphere. These structured plans and workshop presentations can be seen at the collaboration website at http://geoapplications.org/.

A second workshop, held in Tokyo in September 2016, established demonstration projects for the GEO-LEO collaboration around two application areas: fire hotspot and smoke haze monitoring over land, and ocean parameter monitoring (SST, Ocean Colour) targeted particularly towards reef health monitoring. The objective of this focusing of the collaborative work was to develop new applications that would practically demonstrate societal benefits in the Asia-Pacific region flowing from the Japan-Australia GEO-LEO collaboration. It was recognised that the new capabilities offered both potential commercial and public good opportunities.

The second workshop agreed that the best approach to achieving the overall goal of providing information (derived using combined GEO and LEO data) that delivers societal benefits to users in the Asia-Pacific region is to identify some achievable first steps that will help improve the independent systems being developed on both the Japanese and Australian sides, and facilitate the generation of compelling case studies and examples that can be presented to other Asia-Pacific countries and donor bodies to generate interest and involvement.

Recognising that both Australian and Japanese agencies have established independent algorithms and production systems, opportunities were identified for cross-validation of products, working towards the sharing of validation data and establishment of common validation protocols. Most importantly, the participants agreed on the importance of establishing relationships with user groups, and that an efficient path to achieving this is to assess the potential contributions of GEO-LEO applications to existing user frameworks.

The aims and activities of each of the two focus areas will now be discussed, followed by a summary of the most important lessons coming out of the initiative for such collaborative application development.

5.4.1 **HOTSPOTS AND HAZE**

The hotspot detection systems on each side were identified: Australia's Sentinel bushfire monitoring system for which the sources of hotspot information are being extended from AVHRR and MODIS to include Himawari-8, and Japan's system to be released at the end of 2016 that integrates hotspot information at multiple scales from CIRC, GCOM-C and Himawari-8. Sources of aerosol validation data were also identified: AERONET which includes data from CSIRO's AOD network, WMO's Global Atmosphere Watch which is expected to include ABoM AOD data, and Japan's SKYNET network.

Specific activities planned for the hotspot and haze focus are:

- Communication of each side's independent validation of aerosol products, and then later discussion of a common validation protocol which could agree on sites, dates and metrics.
- Use of MODIS hotspot products to validate those from Himawari-8 and JAXA's high-resolution CIRC sensor on ALOS-2 and ISS.
- Identification of potential end user groups and possible contributions to existing frameworks, in particular those related to public health, fire management, aviation etc.
- Prepare case studies that demonstrate the potential societal benefits of GEO and combined GEO-LEO products, in coordination with user groups such as fire managers and public health bodies.
- Investigate the integration of local satellite-derived hotspot products into existing smoke transportation models (such as those from Kyushu University and CSIRO) as improved initial conditions.
- Pursue the advanced notice and planning of prescribed burning events so that CIRC acquisitions can be coordinated.

5.4.2 OCEAN COLOUR AND SEA SURFACE TEMPERATURE

The focus region proposed for this work was the "Coral Triangle" marine area, which extends from Indonesia, Malaysia and Philippines to Papua New Guinea and Solomon Islands. Potential applications could be targeted to support fisheries and navigation, as well as conservation needs around coral and mangrove ecosystems, development impacts and detection of harmful algal blooms. Some of these applications require high spatial and spectral resolution data, however there is the potential for blended GEO-LEO products to overcome the temporal limitations of LEO sensors, as well as the potential to exploit high temporal resolution Himawari-8 data in models to provide forecasts (e.g., algal blooms, stress related to coral bleaching) and diurnal cycle information. Research will be required in several areas, including blended GEO-LEO products and assimilation by biogeochemical models, besides the fundamental EO tasks such as atmospheric correction and understanding of atmospheric and in-water optical properties and variability for algorithm parameterization. The requirement for information delivery offers an opportunity to prototype a product distribution system for delivery of data for the entire Coral Triangle marine area.

Specific activities contributing to the collaboration include:

- Engagement with user bodies in the target region to identify their needs, interest in remote sensing data, potential societal benefits, relevant user groups, collaborations and potential for demonstration projects and sharing of validation data.
- Identification of funding to initiate demonstration projects as well as the most appropriate countries for cooperation.
- Independent development of products in Japan and Australia using different algorithms and joint inter-comparisons to access accuracy, using in-situ and other satellite data.
- Supply of in situ data for parameterization and validation applicable to the Australian region, and further sources of in situ data for the region of interest will be assessed.

5.4.3 CONCLUSION

The intention is that once these bilateral pilot projects have demonstrated their usefulness, user groups and funding bodies will engage more deeply and the projects will be expanded to involve other nations of the region through existing coordination mechanisms such as the Asia-Pacific Regional Space Agency Forum (APRSAF).

The key consensus lessons on productive collaborative development of applications to come from the Japan-Australia GEO-LEO initiative are, besides the need to maintain regular and active communication:

- Engage with user groups in the target region to identify their needs for Earth observation data and existing frameworks for system implementation, information delivery and funding.
- Identify specific joint activities that will contribute towards the overarching goal of delivering societal benefits to the targeted user sector and which recognize the independent activities that the collaboration partners will each continue.

6 Summary and opportunities

This study has highlighted the value of non-meteteorological applications from GEO orbit both to CEOS agencies as data providers and to existing and prospective users of EO satellite data. Agencies can get a better return on their existing substantial investment in GEO and LEO infrastructure and applications, by applying their infrastructure and expertise to non-meteorological GEO applications. This will strengthen the science and environmental monitoring that is the aim of their programmes, and thereby deliver increased benefit to society. In implementing these applications, agencies will further benefit from collaboration and inter-comparisons with other agencies but also from the user community of non-meteorological applications. Engagement with the user community, for instance dedicated workshops will advance algorithm developments as well as increase uptake of the new and/or improved non-meteorological GEO products. A good example is the Japan-Australia collaboration on non-met applications from Himawari-8 (see Chapter 5).

The progressive implementation of non-met applications from GEO orbit also supports the Global Earth Observation System of Systems (GEOSS) by addressing many of the Societal Benefit Areas (SBAs) mainly Disasters (e.g. pollution events, floods, fire), Climate (e.g. predicting, mitigating change), Ecosystems (e.g. land, coastal and ocean management), Biodiversity (e.g. conservation), Health(e.g. harmful algal blooms, spread of infectious diseases) and Water (e.g. fisheries and habitat) – a range of these applications were highlighted in Chapter 3. Optimization of the social benefit of space-based Earth observation is also in alignment with the CEOS Strategic Guidance.

Many environmental studies would benefit from global coverage of satellite observations, which given the technical similarity of the current and to be launched advanced GEO sensors (see Table 1) could be achieved from a constellation of GEO imagers in a so-called GEO-ring. A key challenge in terms of data quality is the production of consistently inter-calibrated products against reference instruments or calibration sites. This is an area that is already well addressed by CGMS/GSICS and the CEOS Working Group on calibration and validation that are working on inter-agency data harmonization and inter- and vicarious calibration of GEO using LEO sensors.

A series of opportunities were identified by this study that may help to achieve better integration and uptake of non-met GEO observations across the full range of Earth observation applications. In the following these opportunities have been grouped into thematic areas such as user engagement, application development, data calibration, validation and harmonization, as well as data management and outreach.

User engagement

1. **The determination of user requirements and priorities would benefit from developing strong links with the relevant non-weather communities.**

   NMA applications should respond to, and be driven by, user requirements. However, NMA data producers cannot prioritise independently and need to consult with users. This might be done effectively by engaging with user groups such as IRENA for Energy. Such engagement could be facilitated by a single access point for data products such as through GEOSS.

2. **Study in detail the suitability of GEO observations to contribute to UN Sustainable Development Goals (SDG).**

   It is worth noting in this context that the Group on Earth Observation encourages the exploitation of geostationary applications in support of all nine defined Societal Benefit Areas (SBA).

Application development

3. **Support collaborative efforts for algorithm development and inter-comparison activities to achieve consistent GEO-ring products.**

4. **A broad engagement with the EO community and LEO science teams to foster collaborative developments of advanced algorithms, and identify potential non-meteorological applications for coordinated GEO-ring implementation.**

   The existing LEO science teams constitute a valuable resource on which to build applications from the new GEOs. International collaboration will be necessary to reach consensus on suitable algorithms types and application priorities for coordinated GEO-ring implementation.

5. **Continue working towards the operational delivery of NMA geophysical products to achieve quasi-global consistent coverage, particularly radiometric products that underpin downstream products.**

   NMA data producers should consider to working towards the operational delivery of radiometric (Level 2) products such as Land Surface Reflectance (LSR) and Ocean Colour Radiometry (OCR, for example, water-leaving radiance) from a constellation of GEO imagers (GEO-ring) to achieve quasi-global coverage from merged products. These key non-met radiometric applications will enable the development of higher-level non-met products for various terrestrial and oceanic applications.

   A question to be resolved is whether GEO-ring products are produced by a common algorithm adopted by community consensus or by independent algorithms for each GEO with appropriate harmonisation and uncertainty characterisation.

6. **Consider identifying a suitable pilot project for a new GEO-ring product within existing coordination activities.**

7. **Synergistic use of data from GEO and LEO imagers is encouraged.**

   GEO and LEO imagers each have their own advantages: GEOs have higher temporal resolution which allows more frequent observations which both increase the probability of observing surface without cloud cover and enable the observation of diurnal cycles and dynamic phenomena; LEO have higher spatial, spectral resolution and global coverage. The combination of data from GEO and LEO platforms, at any product level, is in the spirit of "enterprise" approaches that use all available data (GEO, LEO, in situ observations, modelling, etc.) to make the best products. Successful demonstrations will encourage the synergistic use of GEO and LEO data.

8. **Study in detail the suitability of GEOs to contribute to the climate monitoring framework.**

   GEOs could potentially contribute to the climate records of some Essential Climate Variables. The Sustained and COordinated Processing of Environmental satellite data for Climate Monitoring (SCOPE-CM) initiative has demonstrated the capacity to exploit new applications from both GEO and LEO satellites.

Data calibration, validation and harmonization

9. **Promote consistency of products and algorithms between platforms.**

   This includes between GEOs and between GEO and LEO.

10. **To achieve consistent products continued strong inter-agency coordination and engagement in various calibration and validation initiatives, like GSICS and CEOS WGCV, is encouraged.**

    GSICS has demonstrated its value as key to early post-launch refinement of calibrations, and its continued use for this purpose is encouraged.

GEO-GEO harmonisation of calibrations (perhaps via LEOs) is required for consistent GEO-ring products, and GEO-LEO harmonisation for merged products. Established facilities such as the GSICS inter-comparison infrastructure can contribute here.

11. **Algorithm development and validation benefits from openly shared in-situ validation data and simulated test data sets. Coordination of validation data acquisition such as from field campaigns, which are often resource intensive, would be highly beneficial.**

12. **Support to cal/val infrastructure for validation of radiometric products such as the RadCalNet or AERONET(-OC) networks including system vicarious calibration sites, fosters interactions with the user community in support of validation and accuracy assessments.**

Data management

13. **Promote uniform data and metadata formats across missions.**

    Common formats facilitate the generation of quasi-global products and the merging of diverse data sources. They also promote data sharing which in turn supports early and efficient development of applications. Past demonstrations of this include the use of MODIS and SEVIRI data to develop ABI algorithms and the use of AHI data to test them.

14. **Take advantage of modern data approaches such as those identified by the CEOS Ad Hoc Team on Future Data Architectures.**

    The large data volumes that potentially result from the high temporal frequency and global coverage of the new GEOs, as well as the need to customise products to users' needs to encourage uptake, necessitate modern approaches to data management and delivery.

15. **Emphasise the generation of information rather than product files.**

    The volume of GEO data for the new satellites is much larger than LEO and legacy GEO data. However, the temporal frequency of provided products will depend on the application. Not all applications require data at 10 minute intervals.

16. **Consider how the “Analysis-Ready Data” concept would apply to GEO-ring products and GEO-LEO integration.**

17. **Create data that is readable by non-meteorological application software such as GIS to broaden the user base.**

    Data from the earlier generations of GEOs have generally been available in formats used by the meteorological community such as NetCDF, McIDAS, BUFR and GRIB. LEO data are often provided in additional formats such as GeoTIFF and shapefiles that can be read by GIS software widely used in non-meteorological applications.

18. **Develop common tools so that GEO data and applications can be integrated into commercial or open source software.**

    Several non-meteorological users tend to be local and regional users with limited computing resources. Having software tools for common tasks such as sub-setting regional data from full disk data, reprojection and GEO-LEO blending or merging would be of great benefit to them. Some of these functions can be supported on the supply side, and data providers are encouraged to adopt modern approaches that support user-driven customisation of product delivery. Great potential offers the integration of new GEO sensors into the ESA Sentinel Application Platform (SNAP) toolbox that already supports a wide range of generic data formats and LEO sensors.

Outreach

19. **Explore opportunities to promote non-met GEO products widely.**

There is a long history of applying satellite data from polar orbiters for applications in studying land cover dynamics related to applications such as agriculture, forestry, natural resource management, etc. because of the higher spatial and spectral resolution of polar data compared to geostationary data. However, as capabilities of next generation GEO imagers and polar imagers converge, increasing awareness of the enhanced capabilities of GEO data among non-meteorological users will go a long way towards increased adoption of this data. The radiometric GEO products could in particular be promoted to raise awareness of the potential for non-meteorological users to develop new applications.

20. **Consider including appropriate non-meteorological products and applications into training activities such as SATURN, EUMETRAIN and WMO-CGMS Vlab.**

Appendix A List of contributing authors

(In alphabetical order)

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Appendix B Glossary of acronyms

Abbreviation	Description
AATSR	Advanced Along Track Scanning Radiometer
ABI	Advanced Baseline Imager
AC-VC	Atmospheric Composition Virtual Constellation
AGRI	Advanced Geostationary Radiation Imager
AHI	Advanced Himawari Imager
AHT	Ad-hoc Team
AMI	Advanced Meteorological Imager
AOD	Aerosol Optical Depth
AHVRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
CEOS	Committee on Earth Observation Satellites
CGMS	Coordinating Group for Meteorological Satellites
CMA	China Meteorological Administration
COMS	Communication, Ocean and Meteorological Satellite
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSR	Downward Shortwave Radiation
EO	Earth Observation
ESA	European Space Agency
FCI	Flexible Combined Imager
FY-4	Fengyun-4
GCOM-C	Global Change Observation Mission - Climate
GEMS	Geostationary Environment Monitoring Spectrometer
GEO	Geostationary Earth Orbit (also Group on Earth Observations)
GEO-CAPE	GEOstaionary Coastal Air Pollution Events
GIIRS	Geostationary Interferometric Infrared Sounder
GHRSST	Group for High Resolution SST
GOCI	Geostationary Ocean Color Imager
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GSICS	Global Space-based Inter-Calibration System
HRIT	High-Rate Information Transmission
HSD	Himawari Standard Data
INSAT	Indian National Satellite
IRS	Infrared Sounder
JMA	Japan Meteorological Agency
KARI	Korean Aerospace Research Institute
KMA	Korea Meteorological Administration
LEO	Low Earth Orbiting
LMI	Lightning Mapping Imager
LRIT	Low Rate Information Transmission
LST	Land Surface Temperature
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NMA	Non-Meteorological Application

NMHS	National Meteorological and Hydrological Services
NMSC	National Meteorological Satellite Center
MCSI	Multiple Channel Scanning Imager
MISR	Multi-angle Imaging Spectro Radiometer
MODIS	Moderate Resolution Imaging Spectro-radiometer
MSC	Meteorological Satellite Center
MSG	Meteosat Second Generation
MTSAT	Multi-functional Transport Satellite
NIR	Near-infrared
NOAA	National Oceanic and Atmospheric Administration
OMI	Ozone Monitoring Instrument
PNG	Portable Network Graphics
POLDER	Polarization and Directionality of the Earth's Reflectance
SAF	Satellite Application Facility
SATURN	Satellite User Readiness Navigator
SBA	Societal Benefit Area
SCOPE-CM	Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring
SEVIRI	Spinning Enhanced Visible and Infrar-Red Imager
SCIAMACHY	Scanning Imaging Absorption spectrometer for Atmospheric Chartography
SST	Sea Surface Temperature
TSM	Total Suspended Matter
URL	Uniform Resource Locator
WGCV	Working Group on Calibration and Validation
WGISS	Working Group on Information Systems and Services
WMO	World Meteorological Organisation

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