SATELLITES FOR CLIMATE SERVICES

CASE STUDIES FOR ESTABLISHING AN ARCHITECTURE FOR CLIMATE MONITORING FROM SPACE

GFCS
GLOBAL FRAMEWORK FOR CLIMATE SERVICES

European Commission

World Meteorological Organization
Weather • Climate • Water

WMO-No. 1162

EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at http://www.wmo.int/pages/prog/lsp/meteoterm_wmo_en.html. Acronyms may also be found at http://www.wmo.int/pages/themes/acronyms/index_en.html.

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EXECUTIVE SUMMARY

The report describes case studies that demonstrate the direct or indirect value of Earth observation satellites for climate services. Climate services (climate information prepared and delivered to meet a user's needs (WMO, 2011)) are recognized as vital for decisionmaking in climate-sensitive societal sectors, such as food security, water management, disaster risk reduction and health. Against a backdrop of human-induced climate change and the need for adaptation and mitigation, reliable, quality-controlled climate information at a global level is essential to inform decisions. Satellites are uniquely placed to provide a global perspective on the climate system, to contribute to the monitoring of the 26 Essential Climate Variables (ECV) (GCOS, 2011), and to inform regional and local climate analyses.

The 13 case studies in this report start from a wide range of end users' perspectives and their needs for climate services, including those of farmers, house owners, ecosystem managers, agriculture and health authorities, river basin managers, coastal protection agencies, energy companies, the finance and insurance industry, development fund agencies, and government and other policy decisionmakers. The case studies then demonstrate the importance of satellites for preparing the climate services needed by these communities. Satellite-based climate data records provide both a critical baseline and new input into the reanalyses that underpin climate services. In many examples, climate services are generated using a combination of data records from satellites, surface-based observing systems and other sources of information (models, socioeconomic data). The importance to climate services of near-real-time satellite data that do not, or only partially, meet climate standards is also shown.

The coordination of climate observing and modelling systems, the integrated use of climate data and effective user-provider feedback mechanisms in all climate-sensitive sectors are therefore essential for advancing the development of climate services.

The objectives of this report are (i) to demonstrate the value of satellite-enabled climate services to decisionmakers, funding agencies and climate service users; (ii) to demonstrate to satellite agencies the need for an enhanced coordination within the Architecture for Climate Monitoring from Space (ACMS) that will address the thematic breadth of climate services.

This report supplements the *Strategy Towards an Architecture for Climate Monitoring from Space* (Dowell et al., 2013), a joint coordination effort by space agencies and the World Meteorological Organization (WMO) in support of the Global Framework for Climate Services (GFCS), and provides a basis for validating the logic of the proposed end-to-end Architecture.

INTRODUCTION AND CONTEXT

The last decades have seen an increasing demand for reliable climate information and services from key sectors, including insurance, agriculture, health, water management, energy and transportation. This demand is expected to grow further against the backdrop of a changing climate (IPCC, 2014). Planning, investment, and policy decisions in climate-sensitive sectors reflect the increasing societal readiness to mitigate greenhouse gas emissions (Lima Call for Climate Action, UNFCCC, 2015) and the urgent need to adapt to the unavoidable ("locked-in") impacts of climate change (World Bank, 2012).

The importance of high-quality, reliable and timely climate services has been recognized in the Global Framework for Climate Services (GFCS), a UN-led initiative instigated at the World Climate Conference-3 (WCC-3, 2011). In the GFCS high-level plan (WMO, 2011), a climate service is defined as "climate information prepared and delivered to meet a user's needs". A climate service includes the timely production and delivery of science-based trustworthy climate data, information and knowledge to support business, policy and other decisionmaking processes. To do so effectively, climate services should be primarily end-user driven, designed in collaboration with customers and stakeholders, based on free and open access to essential data, and including user feedback mechanisms. In addition, research is essential to better understand and predict the climate and thus improve many climate products, applications and services. By exploiting the full potential of the climate observing system, and through improved climate modelling, climate research innovates and stimulates new areas of service development. All of the above mentioned elements of climate services are reflected in the five components ("pillars") of the GFCS (WMO, 2011): User Interface Platform; Climate Services Information System; Observations and Monitoring; Research, Modelling and Prediction; and Capacity Development.

Climate services require data from observing and monitoring systems such as ground-based weather stations, ocean buoys, and Earth observation satellites. Observational

BOX 1. What are components of a climate service?

Core elements of a climate service include:

- Monitoring
- Reanalyses
- Attribution of phenomena and events, including extremes
- Indicators and indices
- Forecasts (predictions and projections)

Downstream elements of climate services could include, for example:

- Seasonal climate outlooks (3–6 months) over the south-east United States to inform livestock and fruit farmers
- Expected trend in annual rainfall over the next three decades in support of hydropower infrastructure decisionmaking in India
- Assessment of whether a recent drought in the Greater Horn of Africa, by its length and severity, has been a 1–in–10, 1–in–30 or 1–in–50 years event, to inform the building of resilience against famine and to manage risks
- Insight into how sea-ice parameters are likely to change along the North-east passage in September over the next 20 years
- Food security outlooks, malaria outlooks, etc.

datasets are the basis for long-term climatologies and statistical analyses of climate; they are essential for detecting climate trends, and for the understanding of processes that enable climate modelling and prediction. Human-induced climate change leads to shifting probability distributions of some climate variables, with proven increases in the likelihood of "climate extremes", such as heat waves and heavy rainfall events (Zwiers et al., 2013). The changing climate baseline can only be reliably detected using observations, and poses additional challenges for monitoring, modelling and predicting the climate system. Improved knowledge in these areas is a prerequisite for adaptation decisions, and effective disaster risk reduction: an assessment of the risk of extreme events is required, followed by measures to reduce exposure and vulnerability, for example, through planning and policymaking, infrastructure design, and the introduction of insurance schemes.

Climate information can be classified by its update frequency, from static (e.g. climatologies) to dynamic (e.g. near-real-time operational climate monitoring) (Pulwarty and Zillman, personal communication, 2015). Such information has different applications and requires different delivery mechanisms to users. In all cases, the best possible climate information optimizes decisions and translates directly into lives saved, property protected, improved economic resilience, enhanced security and the well-being of the public.

Climate services are distinct from other operational services (such as for weather and environmental assessments) in that the requirements for uncertainty characterization, documentation, traceability and accuracy are particularly demanding. Users expect to be able to assess whether the quality of climate information (for example, resolution in time and space) is adequate to support their decisionmaking, or to assess the risks associated with taking a decision based on climate information in terms of, for example, financial implications, or safeguarding property or human life. Establishing best practices and standards for characterizing and describing climate datasets is subject of ongoing investigation, often in collaboration with the metrology and computer science communities (WMO–BIPM, 2010; QA4EO, CHARM).[1]

Climate monitoring from space

Climate is determined by the combination and statistical aggregation of Earth system processes at a wide range of spatial and temporal scales. It is important to monitor climate so that the causes of climate variability and change can be traced, and the predictability of future changes improved. A complete characterization of the Earth's climate system requires observations of the coupled ocean, land, cryosphere and atmosphere, all of which involve many individual variables. The Essential Climate Variables (ECV) defined by the Global Climate Observing System (GCOS)[2] provide an internationally agreed priority list to guide the sustained observation of the Earth's climate (Bojinski et al., 2014).

To characterize climate and climate change, data need to be accurate and homogeneous over long timescales. The signals that are important for climate monitoring and the detection of climate variability and change can easily be lost in the "noise" of an evolution observing system.[3] This emphasizes the need for continuity in an observing system where observations can be tied to an invariant reference. Such a system needs to be maintained over at least several decades (see the GCOS Climate Monitoring Principles (GCOS, 2010)).

The GCOS Climate Monitoring Principles are well recognized for establishing the climatology of traditional meteorological parameters (such as air temperature and rainfall), which are measured from the ground using standard meteorological stations. However, for global observations of the coupled land-ocean-atmosphere system and of all GCOS ECVs, a multitude of observation systems is required and satellites are indispensable. For the global observation of 26 out of the 50 ECVs, satellites make a significant, or the only, contribution to the observational record (GCOS, 2011). Space-based Earth observation has reached a good level of maturity in performance and data-record length: some of the records span 40 years and sensor technologies are increasingly sophisticated and stable. As a result, many of the GCOS requirements can technically be met. The evolving role of satellites for climate monitoring has been recognized by space agencies (CEOS, 2008), the United Nations Framework Convention on Climate Change (UNFCCC) (2008) and within the GFCS (WMO, 2011; 2014*a*).

It is within this context that the necessity emerged for a coordinated approach for observing climate and generating climate data from space. In turn, this resulted in the call for an Architecture for Climate Monitoring from Space (ACMS).

Global and regional actors

The World Climate Conference-3 in 2009 unanimously decided to establish a Global Framework for Climate Services (GFCS). It is an initiative to guide the development

[1] See: www.qa4eo.org and http://charme.org.uk/

[2] Sponsored by WMO, the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme and the International Council for Science.

[3] Such evolution results from changes in observing systems and data over time. Those changes are themselves due to technological evolution, modifications in measurement approach and spatio-temporal coverage, and the shifting, interruption or discontinuation of operations.

and application of science-based climate information and services in support of decisionmaking in climate-sensitive sectors. The Framework is an intergovernmental partnership, which is spearheaded by WMO and supported by the United Nations and other international organizations with diverse, cross-cutting mandates and competences.

The four initial priority areas of the GFCS are water, disaster risk reduction, health, and agriculture and food security, which are also Societal Benefit Areas of the Group on Earth Observations (GEO). In November 2014, the Intergovernmental Board on Climate Services (the GFCS main governing body) decided to add the energy sector as an additional priority,[4] and urban activities related to climate as a cross-cutting element. The GFCS provides a framework which envisages service provision at global, regional and national levels. In many areas, these efforts are not starting from scratch as there are already existing service components at different scales in several countries and regions. Implementation of the GFCS is underway, with project-based activities being implemented in various countries in Africa, the Caribbean, Asia, and Pacific small island developing States.[5]

Although all five components of the GFCS are important, the basis for the provision of climate services on global, regional and national levels is a strong observation and monitoring pillar (WMO, 2014*a*). Core contributions to this pillar are the WMO Integrated Global Observing System (WIGOS) and GCOS. Information on current and planned observing systems, including satellites, can be found in the WMO Observing Systems Capability Analysis and Review (OSCAR) tool.[6] A significant part of the required observations can only be provided by satellite systems, especially in less developed regions. The implementation plan for the GFCS (WMO, 2014*b*) therefore calls for the implementation of the ACMS. One of the major driving forces for the ACMS will be the observational requirements of climate services, such as within the GFCS. This report helps build the foundation for identifying and formulating those requirements.

4 Subsequently endorsed by the Seventeenth World Meteorological Congress in 2015

5 http://gfcs.wmo.int/projects-list

6 http://www.wmo.int/oscar

Table 1. Key policy areas of the European Union, linked to applications, climate data records, and Earth observation data sources

Policy area	Application	Climate data record generation	Earth observation data sources
Climate Risk Management	Floods	Surface water	AMSR-E and TRMM Visible imagery – Copernicus emergency management service
		Meteorology/precipitation	ECMWF forecasts/analyses
Climate Risk Management	Flash floods/ landslides	Landslide scar/ surface water	Visible imagery – Copernicus emergency management service
Climate Risk Management/ Adaptation	Droughts	Normalized Difference Water Index	MODIS
		FAPAR	MERIS, SPOT-VGT
		Standardized Snowpack Index	Nimbus-7, DMSP
		Standardized Precipitation Index	In situ synoptic stations, GPCC
		Soil moisture	ECMWF-Lisflood, SMOS
Adaptation	Sea-level rise	Sea-surface height	Poseidon, Jason
Adaptation	Agriculture	Meteorology/precipitation, FAPAR	Meteorological forecasts/analyses, In situ stations, MERIS, SPOT-VGT
Adaptation	Forestry	Meteorology/precipitation, FAPAR	Meteorological forecasts/analyses, In situ stations, MERIS, SPOT-VGT
Adaptation	Air quality	Short-lived gases, aerosols	SCIAMACHY, GOME, OMI, In situ stations
Mitigation	REDD	Land cover	Landsat, Sentinel-2

One example of a regional actor is the Copernicus Climate Change Service (C3S) of the European Union Copernicus programme. The Service responds to environmental and societal challenges associated with human-induced climate change. It will give access to information for monitoring and predicting climate change, and will therefore help to support the adaptation and mitigation policies of the European Union. The Service will benefit from a sustained network of in situ and satellite-based observations and reanalysis of Earth climate and modelling scenarios based on a variety of climate projections. Table 1 links key policy priorities of the European Union to applications, related climate data records and underlying Earth observation data sources.

The Architecture for Climate Monitoring from Space

Initiatives to address gaps in satellite-based climate observation and climate dataset generation in a coordinated fashion have been taken over the past ten years by space agencies through the frameworks of the Committee on Earth Observations (CEOS) and the Coordination Group for Meteorological Satellites (CGMS), as well as by WMO in response to GCOS requirements.

With the objective of more efficient coordination, a strategy report (Dowell et al., 2013) was produced by a joint CGMS, CEOS and WMO team. The report forms the basis of the Architecture for Climate Monitoring from Space (ACMS) and provides the background to the present document. The strategy report focuses on satellite observations for climate monitoring and the need for an international architecture that ensures delivery of these observations over the timeframes required for the long-term analysis of the Earth's climate system.

The strategy report describes the ACMS in terms of information flow and logical dependencies, which includes: measuring relevant quantities from satellites ("sensing"); the production of climate data records; and the application of those records by various end users, often for policy and decisionmaking purposes (Figure 1).

The proposed ACMS specifically calls for a constellation of research and operational satellites, for broad, open, data-sharing policies and for contingency planning and agreements. Such arrangements are considered essential to secure the same continuity of long-term, sustained climate observations that we have today for weather observations. While the longevity of essential climate records needs to be ensured, observing systems also need to evolve, taking advantage of scientific and technological progress. Research and operational agencies need to closely collaborate in the framework of the ACMS to achieve this goal.

Furthermore, whilst the emphasis of the initial strategy report had been on space-based observations, it was also recognized that, during the implementation phase, space agencies and associated programmes would start to address in earnest how the in situ components of the climate monitoring system could be represented within the ACMS. That integration process should take advantage of existing international activities and frameworks which independently coordinate the in situ observation networks. With this long-term ambition in mind, the Architecture presented in this document has been made intentionally generic, so that it can be readily adjusted to describe the functional components of an integrated, in situ space-monitoring system in the future.

The strategy report identifies a way forward and the associated roadmap is currently being implemented through the joint efforts of CEOS, CGMS and WMO. Implementation activities include specifying a physical architecture that captures, among others, the current and planned availability of datasets of each ECV. An initial step in this process is the population and maintenance of an ECV inventory to provide a detailed overview of current and planned capabilities. The inventory is available at http://ecv-inventory.com/.

The World Meteorological Congress at its seventeenth session (WMO, 2015) stressed the linkage of the ACMS to the policy framework of the UNFCCC and highlighted the

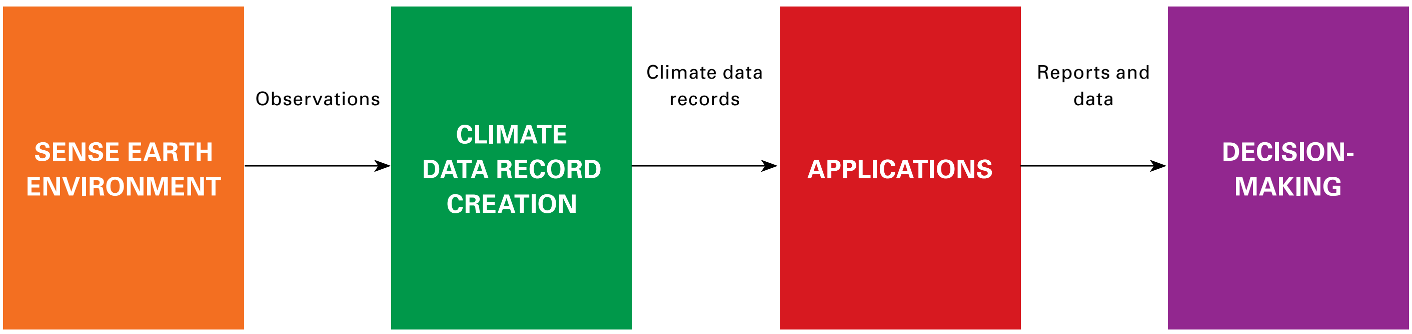

Figure 1. Architecture for Climate Monitoring from Space (ACMS), "Logical view" (Dowell et al., 2013)

important role of the Joint CEOS-CGMS Working Group on Climate. The session further identified the following as key objectives of the ACMS: seamless continuity of climate monitoring satellite programmes; comparability of measurements; provisions for continuity and contingency; and traceability to reference standards.

Additionally, it is recognized that a fundamental value of the Architecture is its end-to-end nature. For the user, that nature flows from a decisionmaking/policy perspective, back through the required applications, to the necessary datasets and ultimately the required observational capacity needed to sustain this information chain. Furthermore, the section of the strategy report about the way forward concludes by underlining that *"as the architecture matures and the development of climate services at the global (i.e. the Global Framework for Climate Services), regional and national level becomes further defined, then the continued mapping of dedicated case studies resulting from the climate service requirements onto both the logical and physical views should be undertaken"*.

The relevance of performing such case studies was emphasized during a February 2013 meeting, entitled "Climate from Space Week", held at the WMO headquarters in Geneva, Switzerland. The WMO Expert Team on Satellite Utilization and Products (seventh session, May 2013) discussed the matter and decided to develop case studies to demonstrate the value of satellite data for climate services. A task group of the Team, together with the Joint CEOS-CGMS Working Group on Climate, subsequently led the preparation of the present report, jointly produced by WMO, the GFCS and the European Commission Joint Research Centre.

Scope and purpose of the report

Using 13 case studies (Table 2 and Figure 3), the present report illustrates the fundamental importance of satellite observations for climate monitoring and building climate services. In doing so, the report supplements the *Strategy Towards an Architecture for Climate Monitoring from Space* (Dowell et al., 2013).

The objectives of this report are (i) to demonstrate the value of satellite-enabled climate services to decisionmakers, funding agencies and climate service users; (ii) to demonstrate to satellite agencies the need to address a wide range of climate service requirements, and to provide for enhanced coordination within the Architecture that will enable the agencies to effectively address those requirements.

The material presented also assists in the efforts of the GEO to demonstrate the benefits of Earth observations to society and to play a brokering role in the incubation and enabling of end-to-end systems and services.

The case studies have been selected to be representative and include examples of: services provided at global, regional and national levels; services in developing and developed countries; services used in research, operational and policy arenas (Figure 3). The case studies also include: a description of the end users' needs for climate-related information in a particular societal sector, where possible through user testimonials; an identification of the importance of satellite-based (and other) climate datasets for generating climate-related information; and a description of the observing system(s) required to generate those datasets.

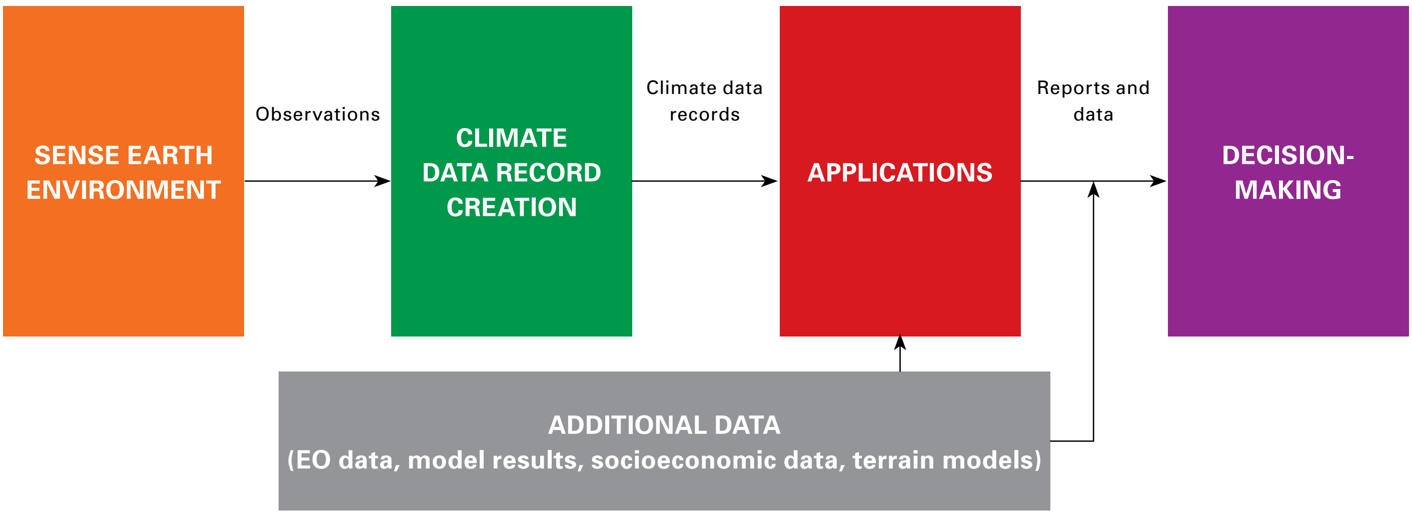

Figure 2. Case studies analysed in this report show the need for additional data sources in preparing and delivering a climate service (modified Figure 1).

Table 2. Overview of case studies (see appendix for author affiliations)

No.	Title	Author(s)	Geographic focus	Thematic area
1	Marine environmental monitoring (Great Barrier Reef)	Anthony Rea	Australia	Marine ecosystems, agriculture/fisheries, tourism
2	Sea-level rise and impact on coastal regions	Anny Cazenave	Global	Adaptation, mitigation, coastal management, disaster risk reduction (DRR)
3	Estimating flood climatologies and prediction skills	Guy Schumann, Stephen English	Australia	Flood management, DRR
4	Drought monitoring in Eastern Africa	Ignatius Gitonga, Peter Omeny, James Muhindi	East Africa	Food security, DRR
5	Crop monitoring in Eritrea	Mark Dowell	Eritrea	Agriculture, DRR
6	Drought monitoring and assessment in China	Xiang Fang and Yiping Zhang	China	Food security, DRR
7	Renewable energy resource assessment in the USA and Japan	Richard Eckman, Terry Nakajima, Toshiyuki Kurino	USA, Japan	Energy
8	Solar energy assessment in complex terrain	Reto Stöckli	Switzerland	Energy
9	Projecting natural gas demand in NE United States	Ed Kearns, John Bates	USA	Energy
10	Monitoring tropical deforestation in support of REDD+	Mark Dowell, Frédéric Achard	Sub-tropics, global	Mitigation
11	Sea-ice edge monitoring for polar navigation	Pascal Lecomte, Marcus Engdahl	Canadian Arctic	Adaptation (agriculture/ fisheries, transport, water)
12	Prototype malaria early warning system in the Solomon Islands using seasonal climate outlooks	Yahya Abawi and BOM Australia co-authors; Lloyd Tahani	Solomon Islands	Health
13	Stratospheric ozone monitoring and assessment for the Montreal Protocol	Paul Newman, Richard Eckman	Global	Protocol monitoring, mitigation, health

The case studies include end users' perspectives from farmers, house owners, ecosystem managers, agriculture and health authorities, coastal protection agencies, energy companies, the finance and insurance industry, development aid agencies, researchers, and government policy and decisionmakers.

The case studies provide a practical demonstration of the logical structure of the ACMS in terms of its functions, information flows and dependencies. It is intended to demonstrate the validity of the Architecture, its robustness to new applications and its possible shortfalls. The case studies follow a common template:

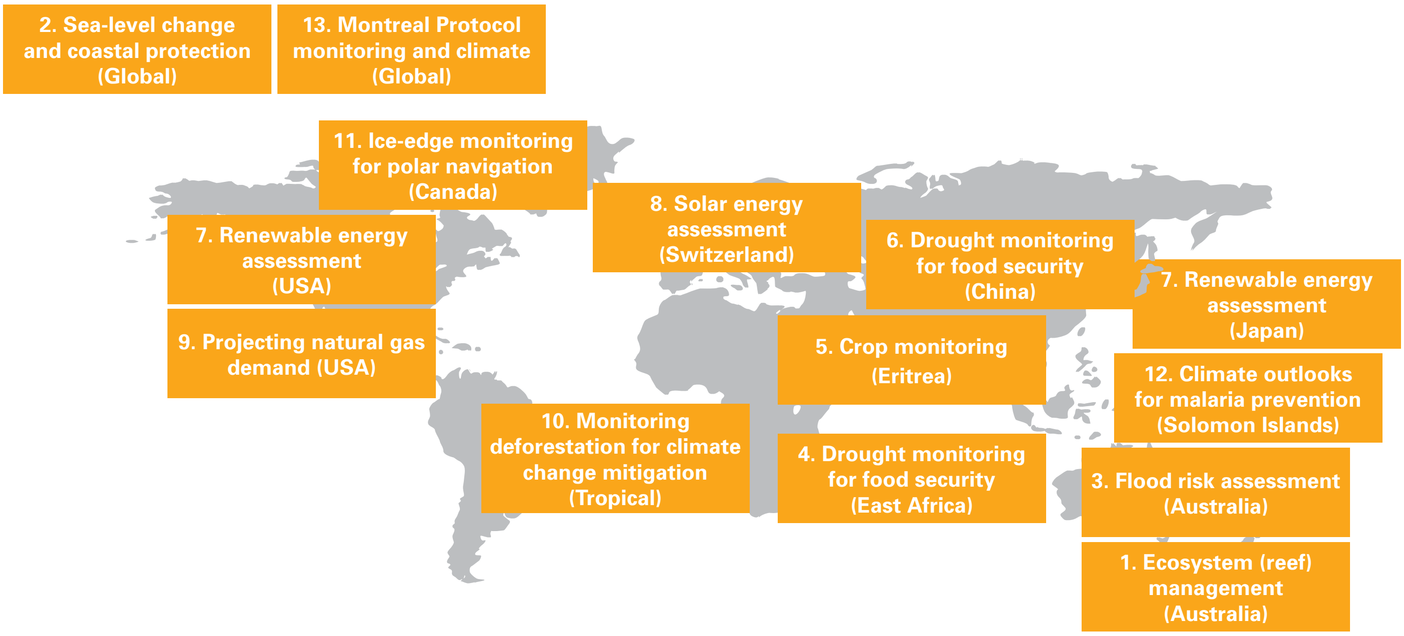

Figure 3. Geographic scope of the case studies considered in this report

functional elements of each case are mapped against the logical view of the ACMS.

The case studies show that satellite-based climate data records provide a critical baseline and input to reanalyses that underpin climate services. In several cases, satellite data records (climate and non-climate) are complemented by climate data records from surface-based observing systems and other sources of information (models, socioeconomic data) to generate the service. To account for the importance of complementary information, Figure 2 (an adapted version of Figure 1) maps the information flow and dependencies within each case study. The geographic scope of the case studies is shown in Figure 3.

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CLIMATE SERVICE CASE STUDIES

CASE STUDY 1

MARINE ENVIRONMENTAL MONITORING (GREAT BARRIER REEF, AUSTRALIA)

SUMMARY

Title
eReefs

Service
Marine environmental monitoring

End users
Government agencies, reef managers, policymakers, researchers, industry, local communities

Intermediate users
- Queensland and Australian governments (Reef Report Card)
- Integrated Marine Observing System

Application(s)
- Marine ecosystem monitoring through Marine Water Quality Dashboard and ReefTemp tools
- Climate impact monitoring and assessment
- Adaptation to climate change

Models used
Water optical property models for deriving in-water optical properties and concentrations of optically active constituents from satellite imagery

Climate data records used
- SST
- Ocean colour (chlorophyll levels, suspended sediments, dissolved organic matter)

Satellite observations used
- MODIS daytime cloud-free VIS/NIR imagery (1x1km) (for ocean colour)
- AVHRR cloud-free imagery (2x2 km) on board NOAA-18, -19 (for SST)

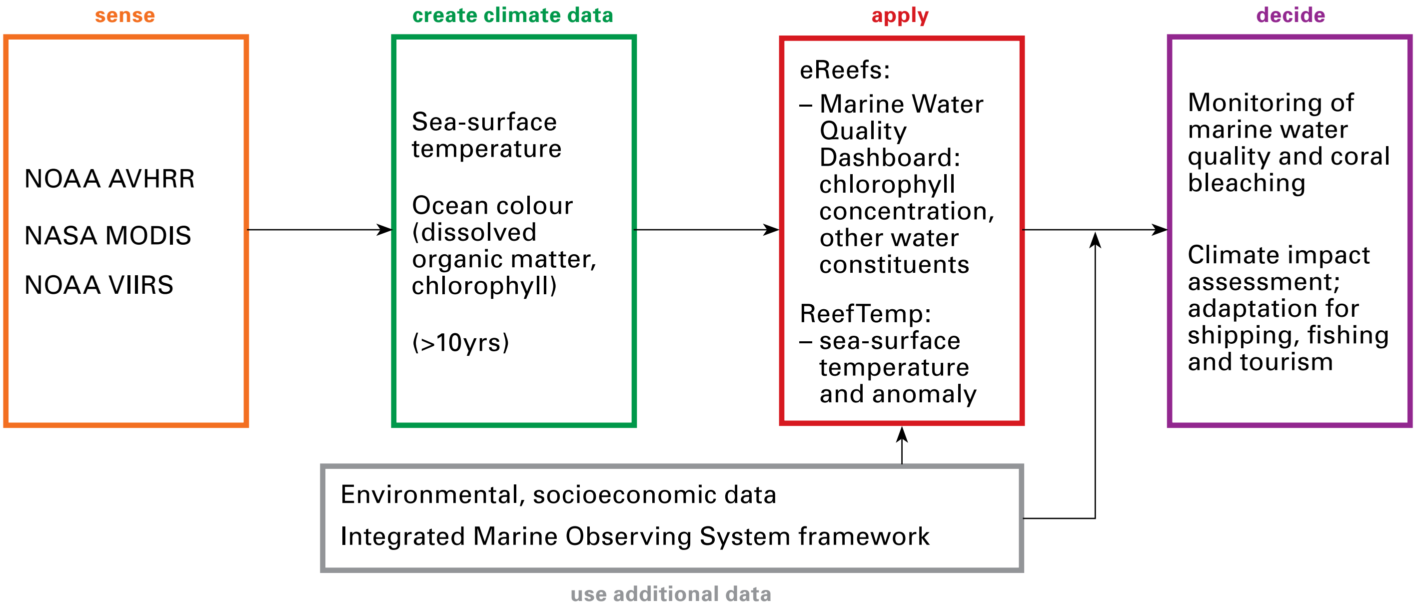
Agencies that produce records
- Bureau of Meteorology as implementing agency, in conjunction with CSIRO, Australian Institute of Marine Science, Great Barrier Reef Foundation and the Queensland Government
- NASA (MODIS), NOAA (AVHRR)

Sustainability of service (demonstration or ongoing)
eReefs commenced in 2012 and is a five year project; it is expected to successfully move to a fully operational information and modelling system

MIKE MCCOY

Hardy Reef on the Great Barrier Reef, Australia

INFORMATION FLOW



DESCRIPTION

The eReefs project is a collaboration that contributes to the protection and preservation of the iconic Great Barrier Reef. A number of threats, including water quality, climate change, shipping, fishing and coastal development have the potential to detract from the Reef's natural, cultural and economic value. It combines government commitment to Reef protection and science innovation and operation with contributions from leading Australian businesses. Using the latest technologies to collate data and leading-edge integrated modelling, eReefs produces powerful visualisation, communication and reporting tools.

The Marine Water Quality Dashboard (Figure 1) is a tool designed to access and visualize a range of water-quality indicators, including near real-time data, more than ten years of records of sea-surface temperatures, chlorophyll levels, sediments and dissolved organic matter derived from ocean-colour observations for the entire Great Barrier Reef. Data from the Dashboard can be displayed in various formats including maps, tables and charts. Users are able to download data for further analysis and interpretation.

Using data captured through satellite remote-sensing, water quality indicators help to determine the type and amount of matter in the water and consequently, how much light is available in the water. The amount of light in the water, and concentrations of chlorophyll and sediments can assist in managing sea grass beds and the production of large algae, which may compete with coral for space.

These indicators are important to monitor as they can have a great impact on the state and health of the Great Barrier Reef ecosystem.

ReefTemp Next Generation is a high-resolution mapping product that provides information on coral bleaching risk for the Great Barrier Reef region. Bleaching is a stress response of coral in unfavourable conditions. High ocean temperatures are the primary cause of mass coral bleaching events. Coral mortality appears to increase with the intensity of the bleaching event; intensity is determined by how much and for how long temperatures remain above the maximum mean summer temperatures. With future climate change projections indicating increased frequency and severity of mass coral bleaching events, ReefTemp improves our ability to monitor heat stress on the Great Barrier Reef.

Linking temperature characteristics to measures of bleaching response severity has revealed that multiple heat stress indices allow for a better estimate of bleaching risk than any single measure. ReefTemp indices include SST, SST anomaly (+SST), Degree Heating Days (DHD) and Heating Rate. DHD are a measure of the accumulation of heat stress, while Heating Rate represents the rate of accumulation of heat stress. The combination of indices used has provided consistent and effective estimates of bleaching risk during recent bleaching events in the Great Barrier Reef Marine Park (Figure 2).

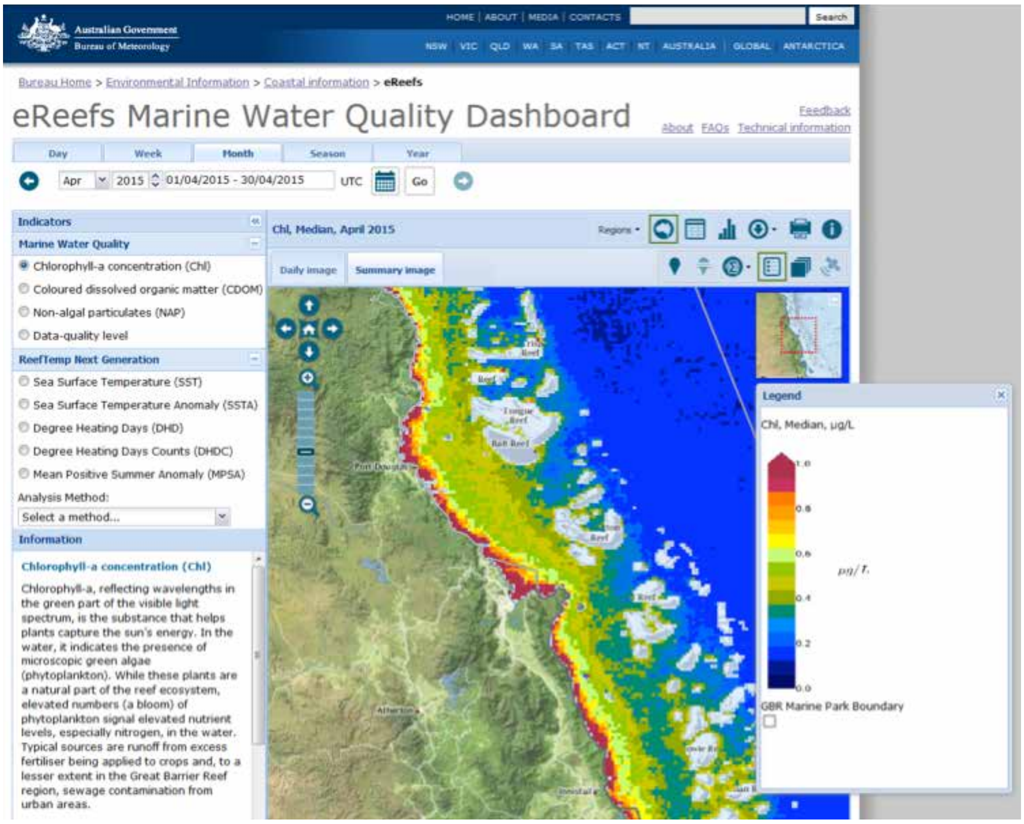


Figure 1. Marine Water Quality Dashboard displaying a monthly composite image of chlorophyll-a concentration, an important indicator of the presence of green algae (phytoplankton) in the Great Barrier Reef region (April 2015)

The eReefs project started in 2012 and is being implemented in three phases over five years. Phase one focuses on delivering the building blocks for the project. Monitoring, modelling and visualization platforms form the basis of eReefs: they enable the delivery of primary datasets and information to reef managers, scientific researchers and the broader public. A key deliverable of phase one was the release of the Marine Water Quality Dashboard and ReefTemp Next Generation products.

Phase two of the project comprises extending the capabilities established in phase one, including the application of VIIRS spectral data to replace MODIS Aqua. Secondary products and services will be developed in consultation with various end users. Phase three will incorporate the transition to a fully integrated operational information and modelling system. The eReefs project will deliver:

- Expanded and improved monitoring data through the application of the latest measurement technologies and data delivery tools, such as mobile and internet applications;
- A suite of new and integrated models across paddock, catchment, estuary, Reef lagoon and ocean;
- A framework to research the impact of multiple factors such as temperature, nutrients, turbidity and pH, and to communicate the results of that research to those who will be affected;
- An interactive visual picture of the Reef and its component parts, accessible to all;
- Public science initiatives to engage the broader community on the health of the Reef;
- Targeted communication products to allow the public to interact with and learn about the Reef, and to contribute monitoring information.

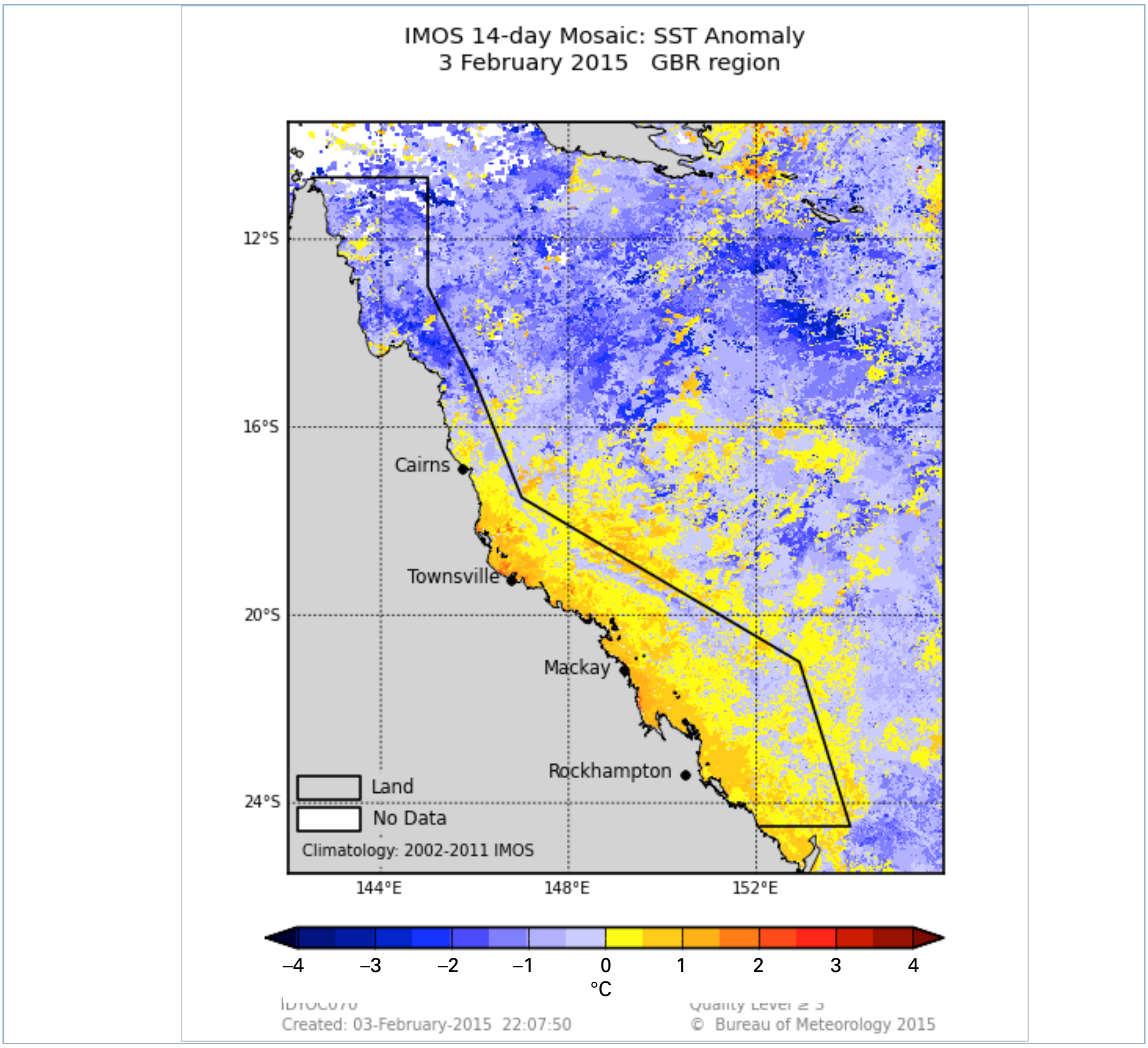


Figure 2. Example of an SST anomaly map for the Great Barrier Reef region obtained through the ReefTemp Next Generation system (http://www.bom.gov.au/environment/activities/reeftemp/reeftemp.shtml)

CASE STUDY 2

SEA-LEVEL RISE AND IMPACT ON COASTAL REGIONS

SUMMARY

Title
Sea-level rise and impact on coastal regions

Service
Global, regional, and coastal sea-level change information (trends, rates of change, spatial patterns); and associated uncertainties

End users
Policymakers (government to coastal city authorities), state offices, coastal management agencies, stakeholders, general public

Intermediate users
Scientific community, international bodies (WCRP, IPCC)

Application(s)
Climate change monitoring, coastal management, adaptation to extreme events (storm surges and flooding), urban development, recreation and tourism

Models used
- Earth gravity fields models for orbit computations
- Solid earth and ocean tide models, ionospheric and wet/dry tropospheric models
- Mean sea-surface (marine geoid) models
- Glacial isostatic adjustment models
- Global hydrological models

Climate data records used
- Sea-level record from satellite altimetry (multi-sensor gridded time series at 0.25° daily resolution, 1993–present)
- Ocean temperature and salinity records from Argo and XBT devices
- Glaciers and ice-sheet mass balance records
- Atmospheric and oceanic reanalyses 30-year average of historical sea-ice edge locations

Satellite observations used
- Topex/Poseidon, Jason-class, ERS-1/-2, Envisat ASAR, SARAL/AltiKa, Cryosat (altimetry)
- GOCE, GRACE (gravimetry)

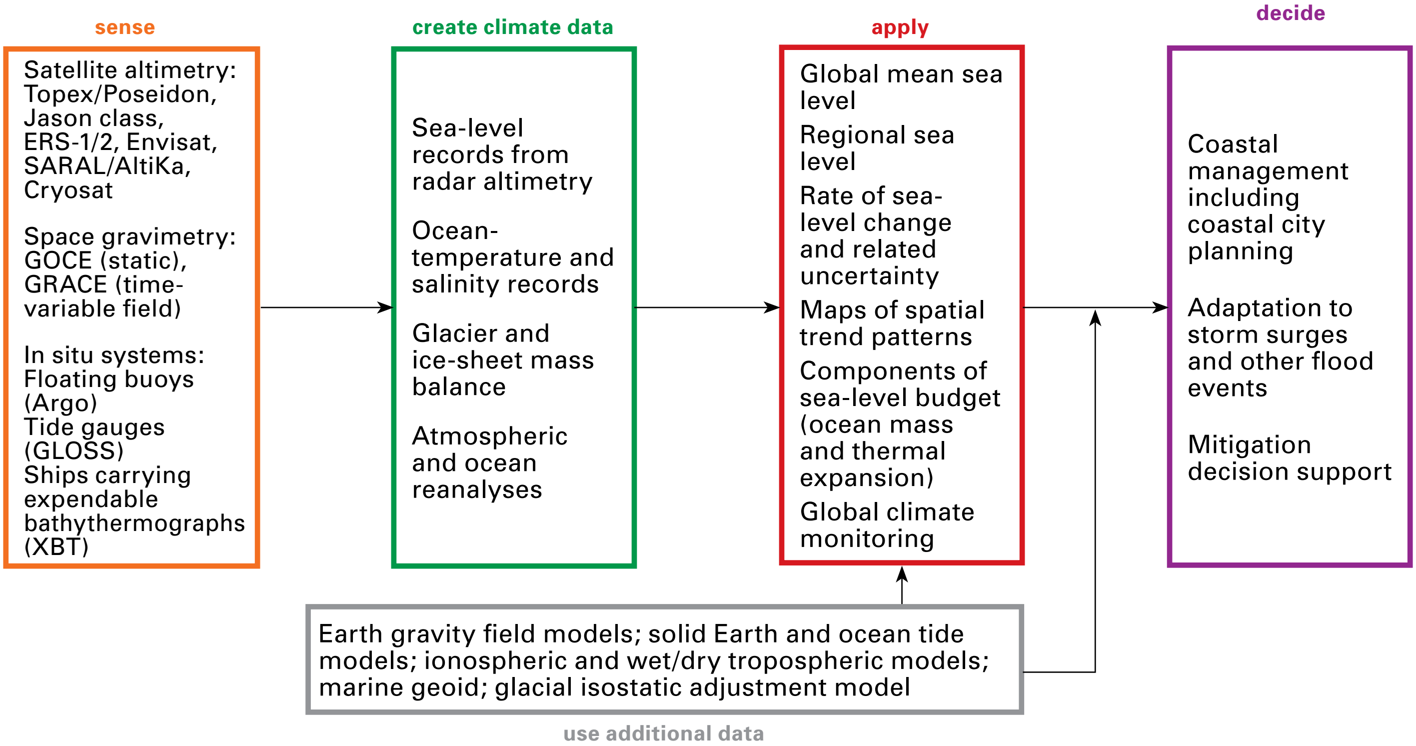
Agencies that produce records
- CNES/AVISO, ESA (CCI), NASA (GRACE), NOAA, CSIRO, University of Colorado (USA)
- Copernicus Marine Service, Climate Change Service (Europe)

Sustainability of service (demonstration or ongoing)
Ongoing service (partially operational)

FLICKR

Stilt houses, Pulau Sibuan, Sabah, Malaysia

INFORMATION FLOW



DESCRIPTION

Sea levels are presently rising at a sustained rate. They will continue to do so in future decades and centuries in response to anthropogenic climate change. Sea-level rise is one of the most threatening consequences of global warming and a major concern for populations living in low-lying coastal regions (about 25% of the world's population). Sea-level rise causes in permanent inundation, shoreline erosion, wetland loss, saltwater intrusion into surface water bodies and aquifers, and rising water tables. Figure 1 (IPCC SREX, 2012) shows current and future population exposure to inundation in low-level coastal areas in the case of a 1-in-100-year extreme storm for different sea-level rise scenarios. Moreover, in many coastal regions of the world, the impact of sea-level rise is exacerbated by other natural and/or anthropogenic factors (for example, decreased rate of fluvial sediment deposition in deltaic areas, ground subsidence due to tectonic activity or ground-water pumping and hydrocarbon extraction).

Monitoring sea-level variations from global to local levels is essential to estimate how fast sea levels are rising, to understand the physical processes at work and to validate climate models used for projecting future changes. This is a major goal and an essential need for the development of coastal adaptation to climate change. The service therefore consists of:

- Sea-level records at global, regional and coastal levels (with associated uncertainties);
- Secondary products:
  - Rate of sea-level rise with associated uncertainties;
  - Maps of spatial trend patterns in sea levels with associated uncertainties;
  - Components of the global mean sea-level budget (ocean mass based + ocean thermal expansion changes) with associated uncertainties.

Background

Sea level is the height of the sea surface expressed either in a geocentric reference frame (absolute sea level) or with respect to the moving Earth's crust (relative sea level). Absolute sea-level variations result from changes in the volume of water filling ocean basins (either due to water density or mass changes). Relative sea-level variations denote sea-surface height changes with respect to the ground (thus accounting for both absolute sea-level changes and vertical ground motions). Sea-level variations occur on a very broad range of spatio-temporal timescales. Sea level is a very good indicator of climate change and variability. As the ocean heats up in response to global warming, sea waters expand, which causes sea levels to rise. Mountain-glacier melting and ice-mass loss from the ice sheets also

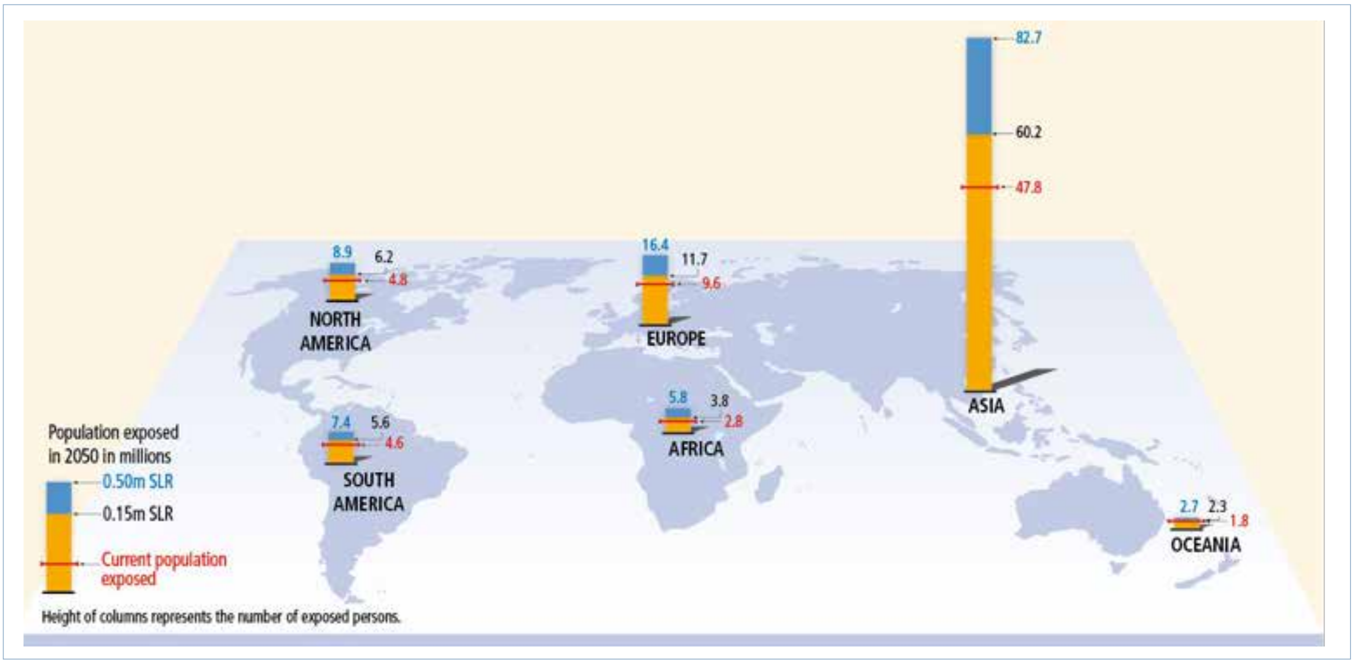


Figure 1. For low-elevation coastal areas, current and future (2050) population exposure to inundation in the case of the 1-in-100-year extreme storm for a sea-level rise of 0.15 m and for a sea-level rise of 0.50 m due to the partial melting of the Greenland and West Antarctic Ice Sheets (Handmer et al., 2012; data from Lenton et al., 2009)

cause sea levels to rise. In addition, modifications of the land hydrological cycle due to climate variability and direct anthropogenic forcing lead to sea-level variations.

Since the early 1990s, satellite altimetry has become the main tool for precisely and continuously measuring absolute sea level with quasi-global coverage and a few days' revisit time. The concept of satellite altimetry measurement is simple: an on-board radar altimeter transmits microwave radiation towards the sea surface, which partly reflects back to the satellite. Measurement of the round-trip travel time provides the height of the satellite above the instantaneous sea surface (called 'range'). The relevant measurement is the sea-surface height above a fixed reference surface (e.g. the mean sea surface). Sea-surface height is obtained by calculating the difference between the altitude of the satellite above the reference surface (deduced from precise orbitography) and the range measurement. The estimated sea-surface height needs to be corrected for various factors due to atmospheric delays, instrumental drifts and bias between successive altimetry missions. Other corrections due to geophysical effects, such as solid-Earth, pole and ocean tides are also applied.

High-precision satellite altimetry started with the launch of Topex/Poseidon in 1992, followed by several other missions. The precision of an individual sea-surface height measurement has now reached 1–2 cm, allowing the global mean rate of rise to be estimated to within ~0.4 mm/yr. The temporal evolution of the global mean sea level from satellite altimetry since early 1993 shows an almost linear increase, at a mean rate of 3.2 ±0.4 mm/yr (Figure 2). For the altimetry period, rises in the sea level result from ocean thermal expansion (~38%), land-ice melt (~50%) and land-water storage change (~12%, mostly due to ground-water pumping). As evidenced by satellite altimetry, sea levels are not rising uniformly (Figure 3). The regional variability in sea-level trends is dominated by large-scale changes in the density structure of the oceans (mainly temperature changes). Those changes are a response to forcing factors (e.g. heat and fresh water exchange at the sea-air interface and wind stress) and their interactions with the ocean circulation.

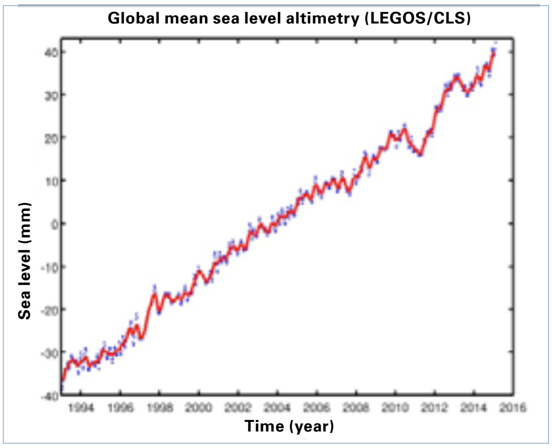


Figure 2. Global mean sea-level evolution from multi-satellite altimetry (1993–2015)

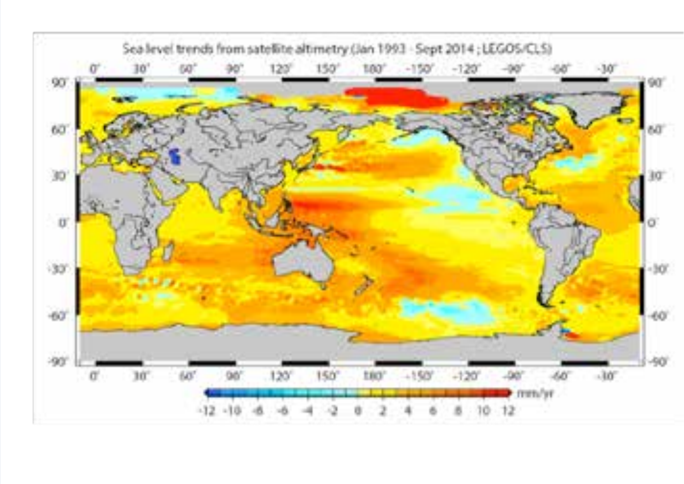


Figure 3. Spatial trend patterns in sea level from multi-satellite altimetry, 1993–2014 (mm/yr)

Figure 4. Maeslant storm surge barrier (near Rotterdam) and the Eastern Scheldt barrier (Rijkswaterstaat, 2009 and Jonkman et al., 2013)

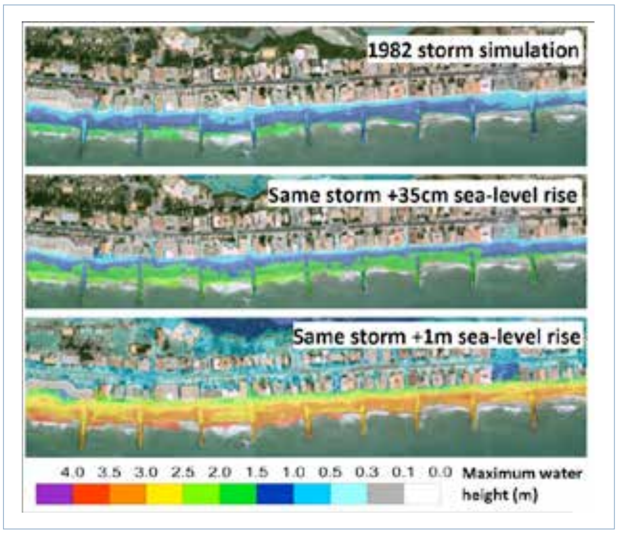


Figure 5. Simulation of local coastal flooding in a low-lying area of the north-western Mediterranean (Languedoc-Roussillon, France) during a storm surge event (the 1982 storm) for different sea-level rise scenarios; maximum water height (m) reached for each scenario is shown (By permission, BRGM; Pedreros et al., 2011)

Coastal cities adapting to sea-level rises

With sea-level rise adding to the risk of coastal inundation, in particular during storm surges events, a number of cities have decided to reinforce their coastal protection schemes. An illustration is given in Figure 4 of the Netherlands coastline near Rotterdam (Jonkman et al., 2013). More generally, as concerns grow over sea-level rise impacts in coastal areas (temporary and permanent submersion, shoreline erosion), more precise information on projected sea-level rises and the probability of storm surges need to be developed to better inform coastal planning policies. Available simulations show that sea-level rises drastically increase storm surge-related flooding in low-lying coastal areas (Figure 5, Pedreros et al., 2011). For efficient and timely adaptation planning, coastal managers require a range of advanced sea-level products based on observations and modelling, including regional and/or probabilistic projections and global to local observations.

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CASE STUDY 3

ESTIMATING FLOOD CLIMATOLOGIES AND PREDICTION SKILLS (AUSTRALIA)

SUMMARY

Title
Establishing flood climatologies and prediction skills

Service
Flood management and climate change; disaster risk reduction in high-impact weather

End users
Governments (Australia initially), river basin management authorities, Global Flood Partnership, European Flood Awareness System, provincial and local authorities, international donor agencies such as the World Bank, humanitarian relief services such as the World Food Programme

Intermediate users
Research institutes and academia

Application(s)
Flood risk assessment and forecasting

Models used
- Variable Infiltration Capacity (VIC), a macroscale hydrological model which solves full water and energy balances and uses reanalysis precipitation datasets to simulate flows into the coupled
- LISFLOOD-FP, a 2D hydrodynamic model, specifically designed to simulate floodplain inundation in a computationally efficient manner over complex topography (Bates et al., 2010; Neal et al., 2012)

Climate data records used
- Benchmarking with continent-wide flow gage records spanning 40 years (1973–2012)
- Reanalysis of precipitation incorporating a range of climate data records
- ICESat canopy (Simard et al., 2011)
- Lakes and reservoirs from the Global Lakes and Wetlands database

Satellite observations used
- Landsat flooded area, MODIS flood product, MODIS snow, MODIS evaporation, SAR flood maps, radar and ICESat altimetry for water levels and canopy heights, SRTM-DEM topography
- Planned within the VIC model: SMAP soil moisture, MODIS snow cover

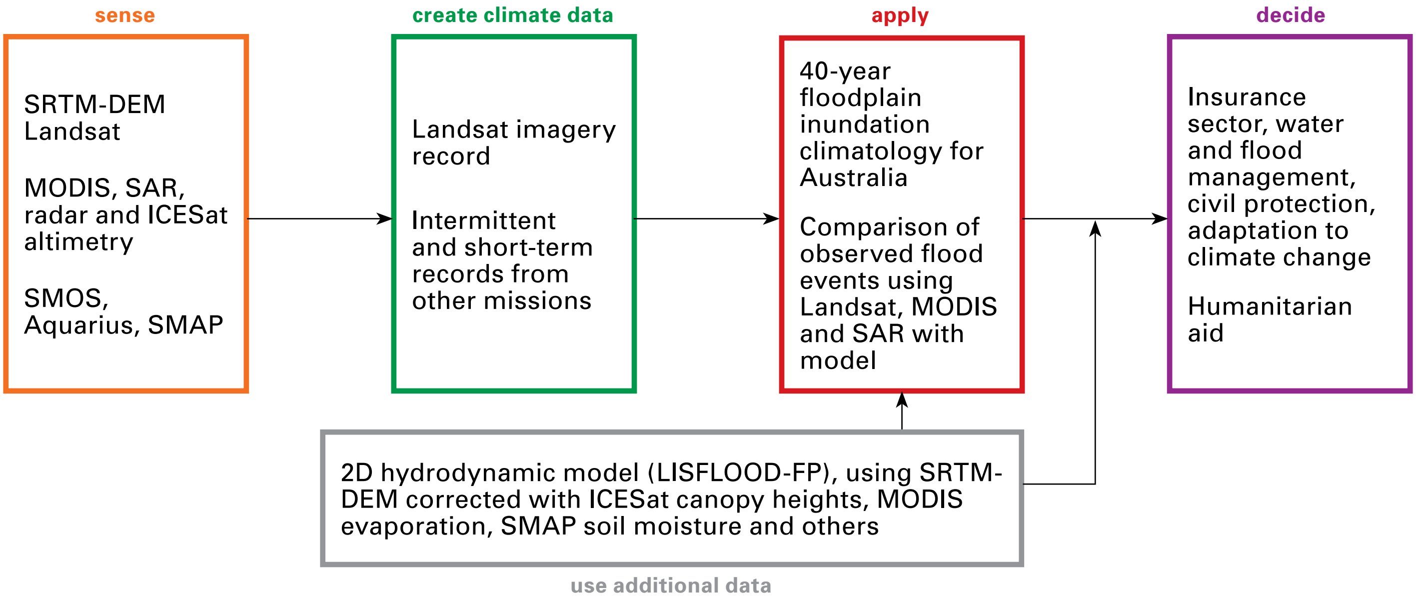
Agencies that produce records
JPL, NASA, WWF

Sustainability of service (demonstration or ongoing)
Proof of concept; intended for open-access use of flood-event climatologies

MICHAEL SPENCER

Flash flooding in Perth, Australia, 2010

INFORMATION FLOW



DESCRIPTION

To improve flood climatologies and flood prediction skills, a database is being generated new which deals with observed or simulated flood-event inundation and magnitude at continental to global scales. The only dataset compiled to date which shows a consistent but spatially and temporally discontinuous history of flood-inundation area and extent at a near-global scale is provided by the Dartmouth Flood Observatory at MODIS and the NASA GSFC near real-time flood mapping archive. The proof of concept study for the flood event database was presented by Schumann et al. (2014*a*). It uses a computationally efficient 2-D hydrodynamic model (LISFLOOD-FP; Bates et al. (2010), Neal et al. (2012)) complemented with a sub-grid channel formulation to generate a complete flood inundation climatology of the past 40 years (1973–2012). It will initially be for the entire Australian continent (Figure 1) at 1-km floodplain resolution and based on gauged stream-flow records. This dataset can easily be downscaled if a higher-resolution digital elevation model is available (Schumann et al., 2014*b*).

Generating the flood-event database is based on SRTM-DEM topography, MODIS and Landsat flood records, ICESat and radar altimeters (water levels), SAR-derived flood maps, and a range of other snow and soil moisture-related products. Use of SMOS and SMAP soil moisture data and the planned SWOT mission is being explored. The floodplain inundation climatology has been compared to Landsat flood-event observations.

The modelling chain used for generating the flood-event database is similar to that used for the operational European Flood Awareness System (EFAS (Thielen et al., 2009)) and the Global Flood Awareness System (GLOFAS (Alfieri et al., 2013)). EFAS was improved by assimilating satellite data, such as MODIS snow cover (Thirel et al., 2013). EFAS has been operational since 2012 and works under the auspices of the European Copernicus emergency management service.

The flood-climatology database allows for the continental-scale assessment of flood-event impacts, improves forecasting and reanalysis of such events and is potentially very useful for the research, industrial and humanitarian sectors.

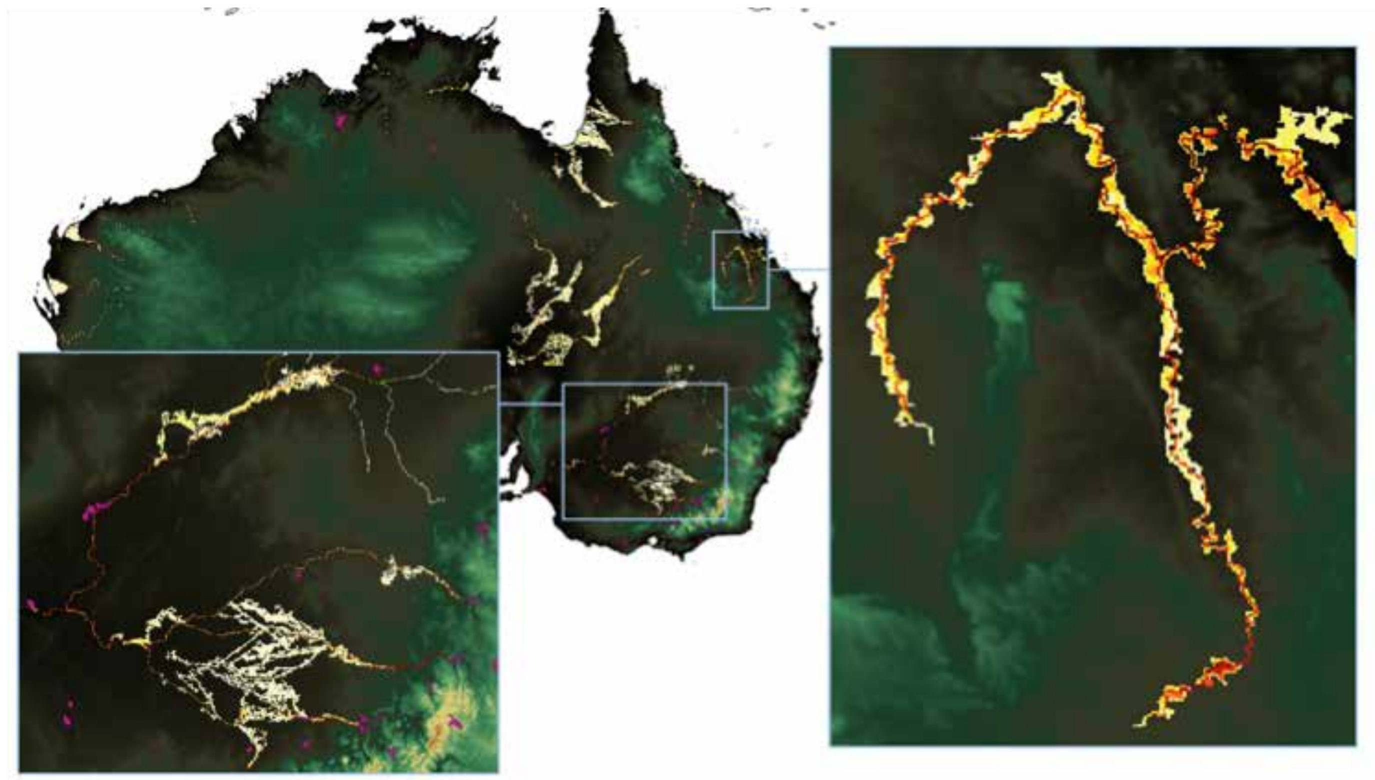


Figure 1. Maximum flood hazard in Australia over 40 years based on gauged flow records. Maximum hazard is here defined as H(V+1.5), where V is the maximum velocity in each cell over the simulation time and H is the water depth in each cell at the time of maximum velocity. Hazard is increasing from white-yellow-orange to red; the purple patches are lakes and reservoirs that do not represent a hazard.

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CASE STUDY 4

DROUGHT MONITORING IN EASTERN AFRICA

SUMMARY

Title
Drought monitoring in Eastern Africa

Service
Seasonal climate outlook for the Greater Horn of Africa countries

End users
Decision- and policymakers from a variety of sectors in the member countries of the Intergovernmental Authority on Development (IGAD)

In Kenya:
County directors of meteorology, hydroelectric power sector, Ministry of Agriculture, Ministry of Water and Irrigation, farming community (large- and small-scale), general public, commerce sector, transport sector, researchers, academia, Red Cross, Ministry of Health, Ministry of Devolution and Planning, private sector

Intermediate users
NMHSs in IGAD member countries, ICPAC, ACMAD, UKMO, International Research Institute for Climate and Society, University of Nairobi

Application(s)
Seasonal forecasting, adaptation to climate variability and change

Models used
- Empirical statistical models
- Models from Global Producing Centres (UKMO, NCEP)

Climate data records used
- Precipitation, air temperature, wind speed and direction, water vapour, pressure, sea-surface temperatures, cloud cover, NDVI, outgoing longwave radiation
- Derived climate indices (e.g., Indian Ocean Dipole)

Satellite observations used
In addition to the use of many satellite data used in Global Producing Centres, the service uses:
- Quantitative precipitation estimates (SEVIRI, TRMM);
- Cloud cover, NDVI (SEVIRI)

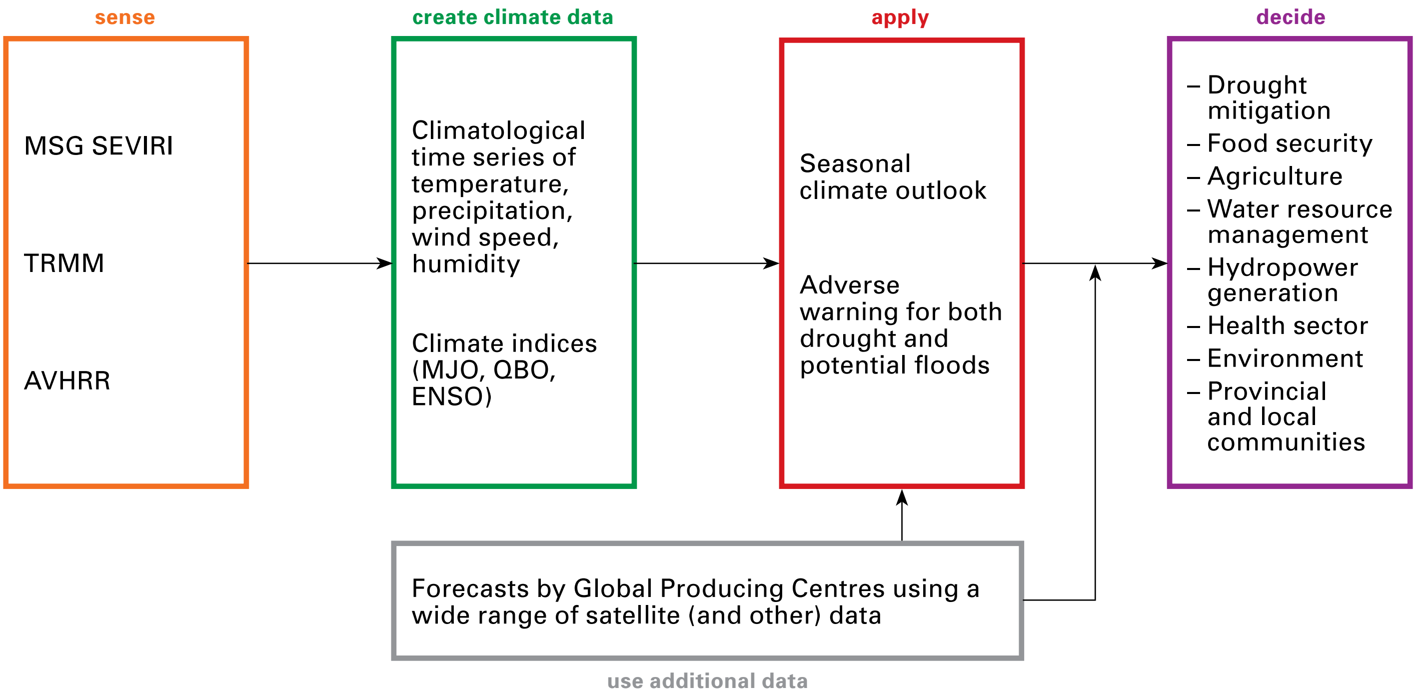
Agencies that produce records
- All satellite operators providing data to Global Producing Centres
- NASA (TRMM), NOAA (AVHRR), EUMETSAT (SEVIRI)

Sustainability of service (demonstration or ongoing)
Operational and ongoing

OXFAM EAST AFRICA

The village chairman, Waridaad, Somalia

INFORMATION FLOW



DESCRIPTION

Context

Drought leads to serious consequences. The severity of drought, often defined by its length, affects many sectors of society, such as agriculture (in terms of crop production and livestock rearing: Figure 1), water resource management, hydropower generation, and the health sector. This can lead to significant economic, environmental and societal loss if preventive or mitigating measures are not taken in time. Seasonal forecasts, together with satellite monitoring products such as a vegetation index, can help to detect drought conditions at an early stage and to assess the likelihood and extent of droughts in the Greater Horn of Africa region.

Satellite-derived sea-surface temperature measurements play a major role in seasonal forecasting in the region, especially when extreme climate events take place. A La Niña occurs when sea-surface temperatures fall below average over the eastern and central Pacific Ocean. This is usually echoed by a similar fall over the western Indian Ocean. The net effect is a decrease in precipitation over most of the Greater Horn of Africa region, which in turn leads to drought. When similar conditions occur in consecutive seasons, the result is a devastating drought.

The opposite conditions during El Niño result in increased rainfall over the region. Sea-surface temperatures rise above average over the eastern and central Pacific while similar conditions occur in the western Indian Ocean.

Empirical statistical models usually derived from linear regression analyses make use of independent variables or predictors to estimate seasonal rainfall probability. Those include sea-surface temperature, sea-surface temperature gradients, other climate indicators (such as the Indian Ocean Dipole, the Southern Oscillation Index, and the Quasi-Biennial Oscillation) and outgoing longwave radiation. Seasonal forecasts provided by WMO Global Producing Centres for Long-Range Forecasts (GPC) assist further.

The position, orientation and intensity of the intertropical convergence zone, which is a seasonal weather-determining feature, is easily identified by cloud imagery from the EUMETSAT geostationary satellite, Meteosat. Though such imagery is best for short-range weather forecasts, its strength, activity and evolution in a given season is a good indicator of the likely severity of an impending drought or flood.

The satellite-derived normalized difference vegetation index (NDVI) is a biomass indicator over a region and

Figure 1. Impacts of drought: herdsmen in search of water in a drying well for starving cattle, with vegetation also in dry condition

is obtained from a climate time series derived from the geostationary Meteosat. The NDVI and its anomalies play a big role in the determination of the amounts of vegetation likely to grow. In case of impending drought, vegetation indices from previous season(s) can be used to project the degree of the drought severity.

Flow of information

Satellite data from a wide range of instruments contributing to the WMO Global Observing System are received by various data-processing and numerical weather prediction centres, including GPCs. It is from these centres that the described service receives various datasets relevant to seasonal forecasting. Besides satellite observations and derived products, the service makes use of a variety of climatological data from in situ observation stations.

Long-term datasets of measurements derived from satellite observations of relevant variables are combined with atmospheric models and the model output from GPCs to generate tailored datasets of measurements relevant to drought, flood or general seasonal forecasting. In conjunction with ICPAC, the Kenya Meteorological Department and all other IGAD members organize regular sessions, usually corresponding to the main seasons in the Greater Horn of Africa region. There are normally two rainy seasons in most of the eastern African countries, corresponding to the seasonal shift of the Inter-Tropical Convergence Zone.

The seasonal forecasts start with a meeting known as Pre-COF, which is to prepare for a main meeting, the Climate Outlook Forum. Weather experts share their knowledge and make use of all the available tools, expertise and data to develop a seasonal outlook for the IGAD region.

Pre-COF plays the double role of developing the seasonal forecasts and delivering training to new professionals from the IGAD region. Local and international forecasters from the region thus ensure that professional capacity continues to be built up across the region. During pre-COF, prognoses are also referred to as a consensus forecast, since they involve resources and expertise from many countries.

Pre-COF is followed by the main Climate Outlook Forum usually held on a rotational basis in one of the IGAD member countries. Other partners are from time to time invited to the Forum, including NCEP, IRI, UK Met Office and WMO.

Based on the outcomes of the Forum, the Kenya Meteorological Department immediately calls a wide variety of meteorological application users for a briefing on the seasonal forecast. These include county directors of meteorology and radio and television media organizations. The Department goes a step further and translates the seasonal weather forecast into various local languages which are then aired on television and radio channels. The Department also broadcasts weather briefings via internet radio to local communities in their mother tongues, of which there are so many in Kenya.

Seasonal climate monitoring and forecasting has been going on for a long time in the region. Since the formation of ICPAC in the 1980s, both the Kenya Meteorological Department and ICPAC have always joined hands in developing seasonal forecasts for the Greater Horn of Africa region. Sustainability is achieved via funding from ICPAC member countries and other funding organizations and partners.

CASE STUDY 5

CROP MONITORING IN ERITREA

SUMMARY

Title
Crop monitoring in Eritrea

Service
Bulletins of crop yield forecasts

End users
- Local authorities in the region concerned (Eritrean institutions, national agencies)
- European policy entities and development funds providers such as DG DEVCO

Intermediate users
European Commission Joint Research Centre (EC-JRC)

Application(s)
- Anomalies of meteorological and vegetation conditions for Eritrea in the Kremti season (main annual harvest)
- Climate monitoring

Models used
ECMWF reanalysis data for precipitation

Climate data records used
Time-series and climatologies for precipitation and NDVI

Satellite observations used
- Satellites (and other) data used in ECMWF reanalysis
- Metop, SPOT-VGT, AVHRR (for NDVI), PROBA-V

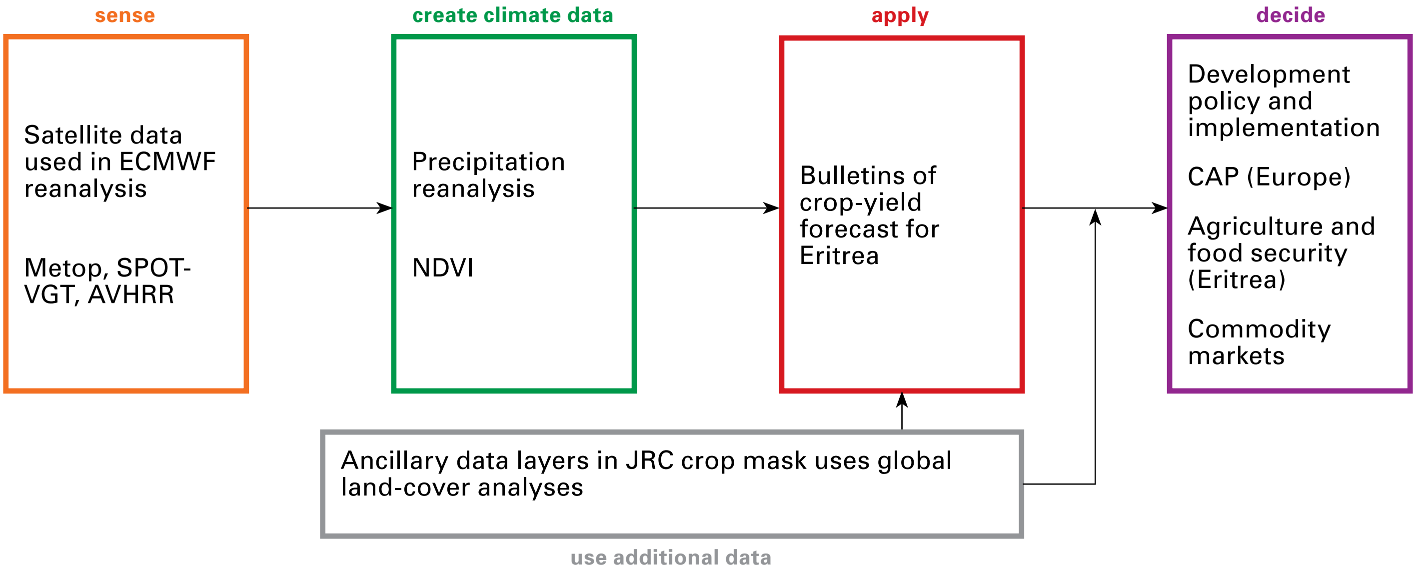
Agencies that produce records
- All satellite operators providing data to ECMWF
- EUMETSAT (Metop), NOAA (AVHRR), SPOT-Image (SPOT-VGT)
- EC-JRC (crop products)

Sustainability of service (demonstration or ongoing)
Sustained service for European users; ad-hoc service to third-party countries

NEIL PALMER (CIAT)

A farmer at work, Eritrea

INFORMATION FLOW



DESCRIPTION

The Monitoring Agricultural Resources (MARS) Unit of the European Commission Joint Research Centre has been developing and running a crop-yield forecasting system since 1992 in order to provide timely crop production forecasts at European level. The Unit, also known as the MARS Crop Yield Forecasting System, monitors crop vegetation growth (including cereal, oil seed crops, protein crops, sugar beet, potatoes, pastures and rice). It also monitors the short-term effects of meteorological events on crop production, and provides seasonal yield forecasts of key European crops. The Unit's activities contribute to the evaluation of global production estimates for crops such as wheat and maize and support the management decisions of the Common Agricultural Policy (CAP). The MARS Crop Yield Forecasting System is a complex, integrated analysis tool, comprising remote sensing and meteorological observations, meteorological forecasts, agrometeorological and biophysical modelling, and statistical analysis capabilities.

While the crop-yield forecasts for Europe are produced on a regular basis, other main producing areas of the world receive increasing attention, since global commodity markets increasingly influence the CAP. Therefore, the MARS Crop Yield Forecasting System is being extended in its simulation capacities to methodologies tailored to other crop-producing regions. Its crop-yield forecasts are also being gradually extended towards key regional production areas across the world.

The present example focuses on Eritrea. The country's economy largely depends on subsistence agriculture, with two thirds of the population earning their living through subsistence farming and pastoralism. This makes them vulnerable to climate variability.

There are three distinct rainy seasons in Eritrea: Bahri rains from December to February in the eastern coastal lowlands, Azmera rains between March and May in the highlands (Debub and Maekel regions) and the Kremti rains from June to September over the whole country apart from the coastal plain. The Kremti crops form the basis of the main annual harvest.

Bulletins of crop-yield forecast for Eritrea provide a rapid overview of the meteorological and vegetation conditions of the Kremti season, focussing on cultivated areas, due to the Kremti's importance for agricultural production. Major crops that grow during that season include wheat, barley and teff in the highlands, maize at intermediate altitudes, short-cycle sorghum and pearl millet at lower altitudes and sesame, which is mainly grown in the Gash Barka region.

The analyses based on satellite imagery and meteorological data (Figure 1) indicate above-average vegetation conditions and no major concerns for the 2014 Kremti season. Moreover, the abundant and well-distributed rains throughout the season could ensure the first good harvest in years. Harvesting is expected to start normally at the beginning of November with a good production forecast for the main agricultural areas.

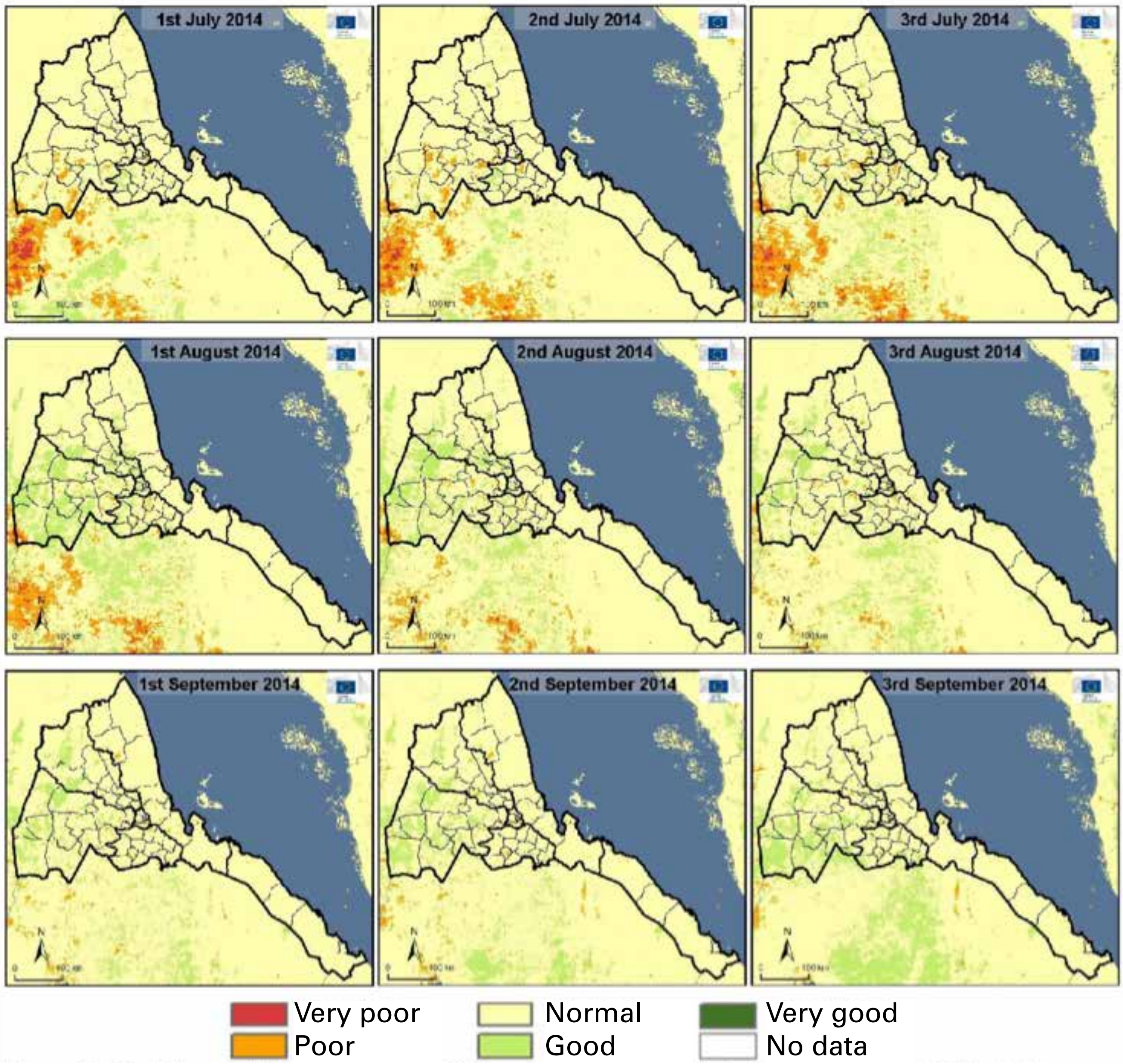


Figure 1. Monthly vegetation conditions (NDVI) compared to the historical average (2007–2013). "1st July 2014" denotes the first 10 days of July 2014, "2nd July 2014" the second 10 days of July 2014, etc.

Source: METOP-NDVI

CASE STUDY 6

DROUGHT MONITORING AND ASSESSMENT (CHINA)

SUMMARY

Title
Drought Monitoring and Assessment (China)

Service
Monitoring of drought indicators (basic service), generation of additional products and analyses in case of drought (special service)

End users
Decisionmaking service of the China Meteorological Administration (CMA); provincial governments and agriculture services

Intermediate users
National Climate Centre; provincial meteorological bureaus

Application(s)
Operational climate monitoring

Models used
Thermal inertia soil model

Climate data records used
– Land surface temperature (2002 onwards)
– NDVI (2002 onwards)

Satellite observations used
– NOAA AVHRR, FY-2E (basic service)
– FY-3 MWRI (special service)

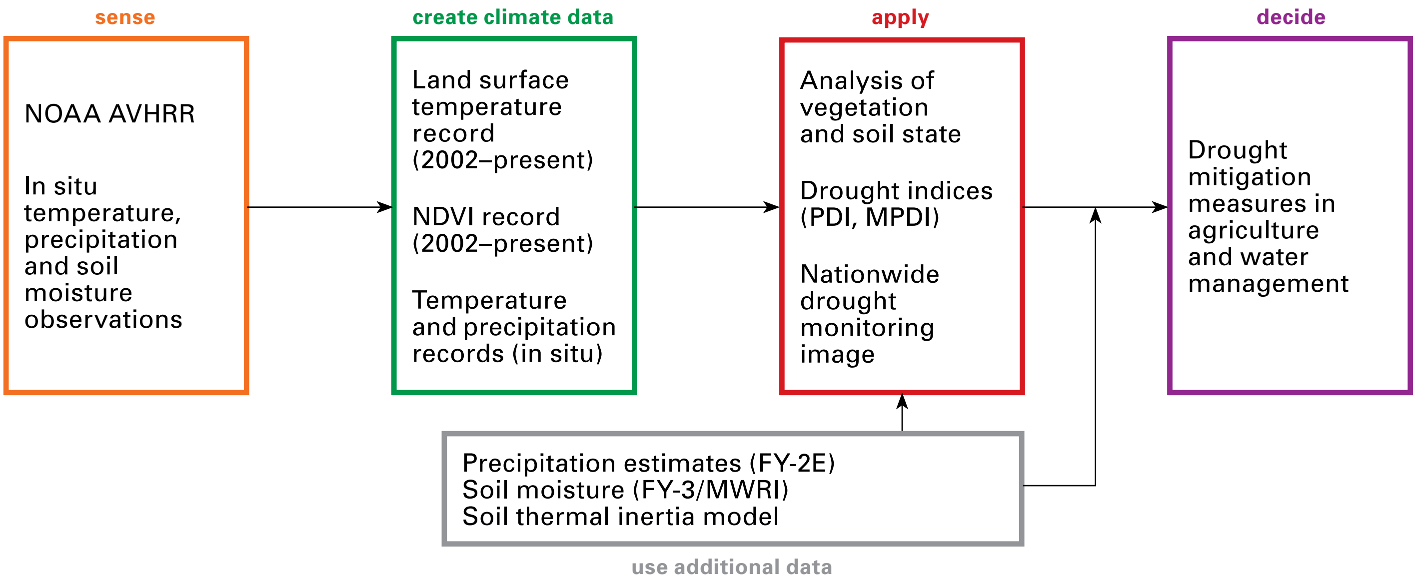
Agencies that produce records
National Satellite Meteorological Center, National Climate Center

Sustainability of service (demonstration or ongoing)
– Operational service
– Dissemination of information via reports and website
– Improvements concerning spatial, seasonal and physical geography
– Construction of long-term drought monitoring database

AUSAID, AUSTRALIAN GOVERNMENT

Blowing sand, China

INFORMATION FLOW



DESCRIPTION

Introduction

The National Satellite Meteorological Center (NSMC) of the China Meteorological Administration (CMA) began to devise a drought-monitoring operation involving satellite-based remote sensing in 2002. A complete drought-monitoring system is now operating, including research into and the application of several drought-monitoring methods, the development of software, optimization of data-process flow and the dissemination of drought-monitoring products and services.

Services provided

The goal of the NSMC/CMA drought-monitoring operation is to provide satellite remote sensing products and services to the public and to support national and local governments to plan prevention measures. End users of NSMC/CMA satellite drought-monitoring products include the CMA department of decisionmaking, the Ministry of Agriculture of China and the general public. Intermediate users of the products include the CMA National Climate Center and provincial meteorological bureaus. The application division of the Center uses surface observation data to monitor and assess the effect of severe climate events, including severe drought.

Two kinds of service are provided:

(1) Basic services

Under normal conditions, a nationwide drought-monitoring remote-sensing image using polar-orbit meteorological satellite data and a corresponding analytical report are generated and disseminated by the NSMC every ten days. The image and report are published on the website of the NSMC remote sensing application and released to several operational service systems. The products can therefore be explored and referred to by decisionmakers at the CMA, drought-monitoring and early warning specialists at the National Climate Center and staff at provincial meteorological bureaus.

(2) Special services

If a severe drought event occurs, the CMA pays special attention to the drought area and monitors and assesses the intensity and the development of the drought. CMA increases monitoring frequency in the drought area and deploys other satellite products, such as those that deal with precipitation estimation, land-surface temperature, evapotranspiration, vegetation, fire spot and water body area. This enables CMA to monitor the change of the severe drought and evaluate its effect. NSMC disseminates analytical reports to the CMA department of decision-making. Within two days, CMA provides a special report to the Ministry of Agriculture and the State Council of

China with recommended actions for drought mitigation. The provinces and local meteorological bureaus where the drought has occurred are then advised to take action. Monitoring information is therefore useful to help decisionmakers to understand the impact of the severe drought in order to propose effective prevention measures.

Example

The benefits of the service are illustrated using the example of a severe drought that occurred in south-west China from autumn 2009 until early summer 2010.

The extreme lack of precipitation during that period caused a severe and lasting drought in the provinces of Yunnan, Guizhou and Sichuan, in Chongqing City and the Guangxi Autonomous Region. Water supplies from reservoirs were insufficient and many rivers, brooks, wells, springs and lakes dried out. Residents and livestock suffered from the shortage of drinking water, and local agriculture sustained significant losses.

According to the accumulation of precipitation estimation using data derived from the FY-2E geostationary meteorological satellite (Figure 1), total rainfall from 1 November 2009 until 28 February 2010 in the south of Sichuan, most of Yunnan, the mid-west of Guizhou and Guangxi, was less than 100mm.

Images of ten-day land-surface temperature anomalies (Figure 2) demonstrated that temperatures between 1 September 2009 and the end of March 2010 had been higher than the average for the same period since 2002 in the south-west of China.

The drought began to develop from the beginning of November 2009. The meteorological satellite drought-monitoring images (Figure 3) showed that there had been a mild drought on a large scale in the north and middle part of Yunnan in the first ten days of January. Since then, the drought area in the south-west of China enlarged and the drought gradually intensified. The severe phase of the drought reached its peak during the middle ten days of March 2010. After light precipitation in the last ten days of March, the drought began to weaken. The severe phase weakened dramatically in early May and ended completely in the first ten days of July 2010. The anomalies in the vegetation index images (Figure 4) showed that vegetation growth was affected by the long-term phase of the drought. The drought also caused a significant increase fire risk. According to NSMC satellite monitoring results, from January until March 2010, fire spots in Yunnan and in Guizhou reached an eight-year high (Figure 5).

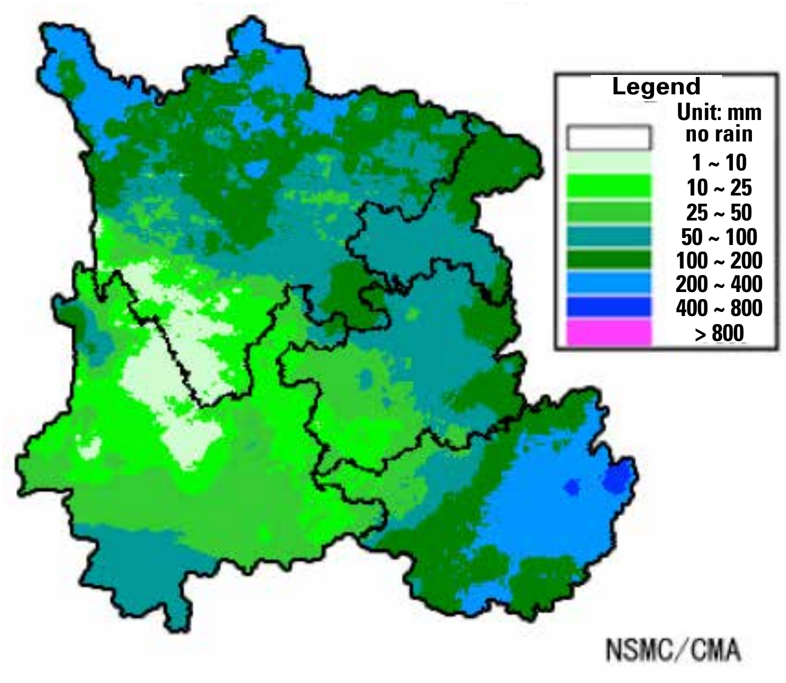


Figure 1. Accumulation of precipitation estimation in south-west China for the period 1 September 2009–28 February 2010, based on data from the geostationary satellite FY-2E

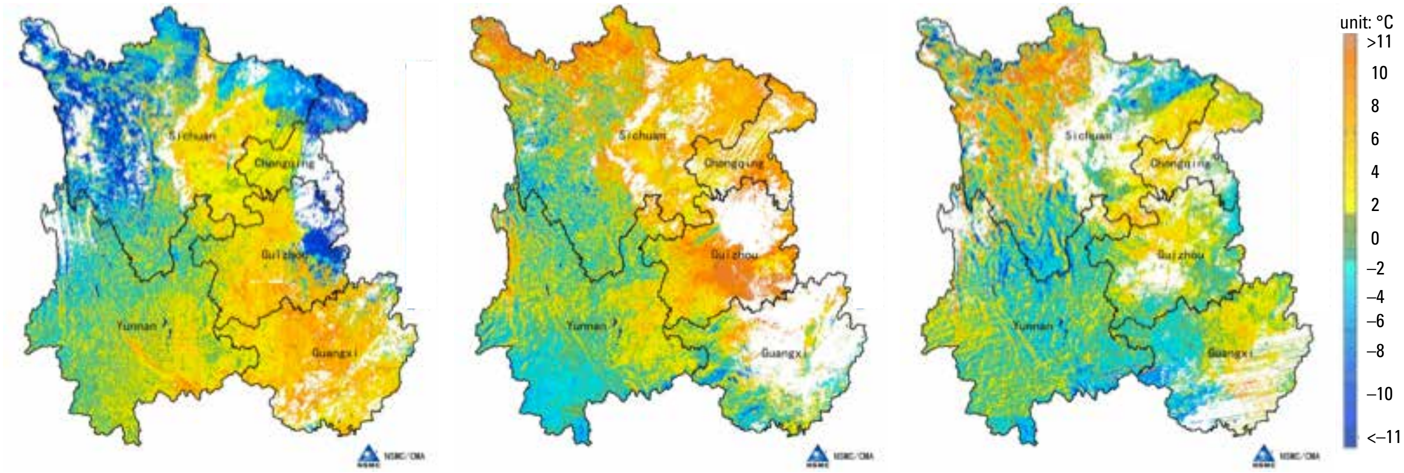


Figure 2. Anomaly of land surface temperature in south-west China for March 2010 (left: first ten days, center: middle ten days, right: last ten days)

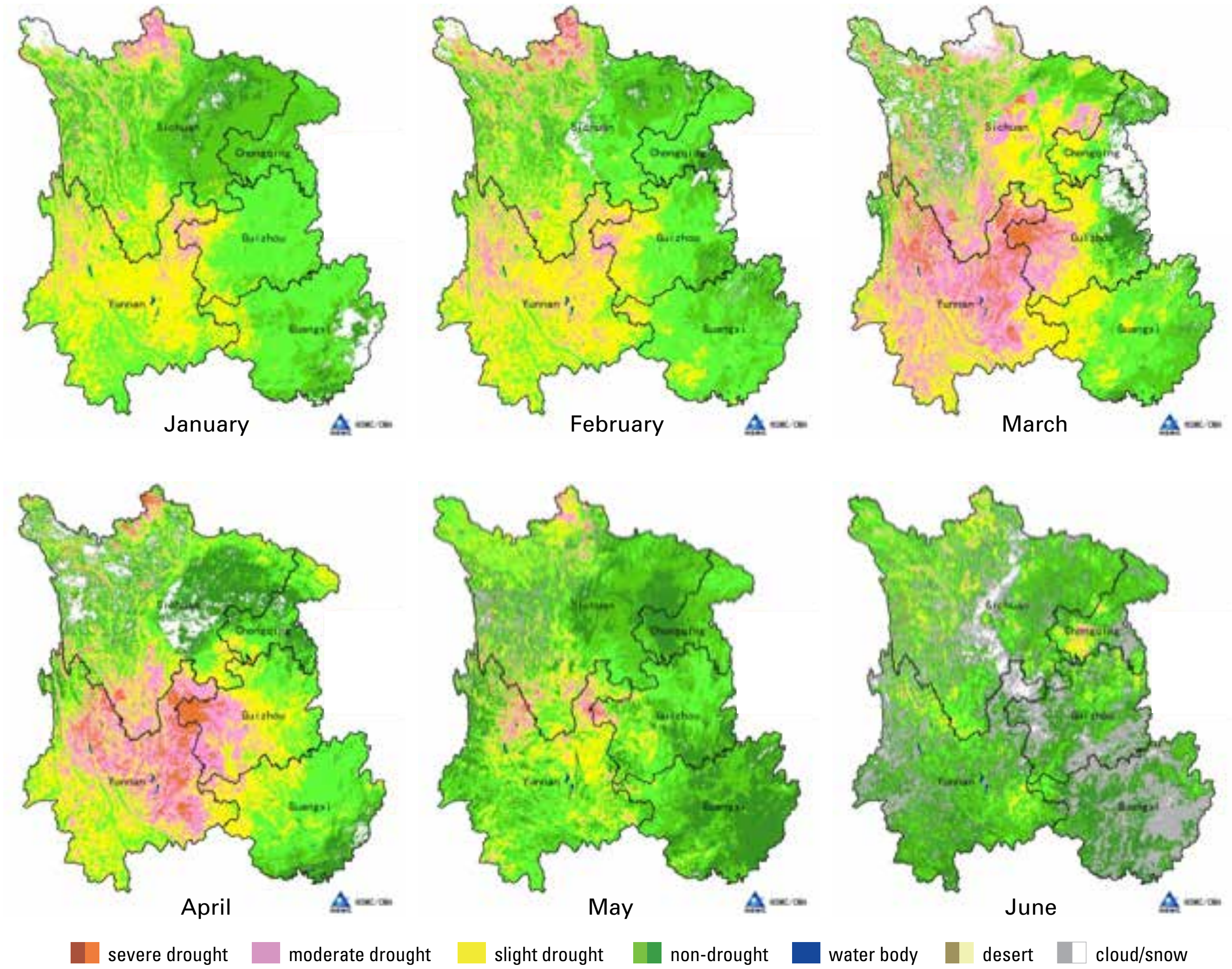


Figure 3. Drought monitoring image for south-west China using NOAA/AVHRR (first ten days of each month, 2010)

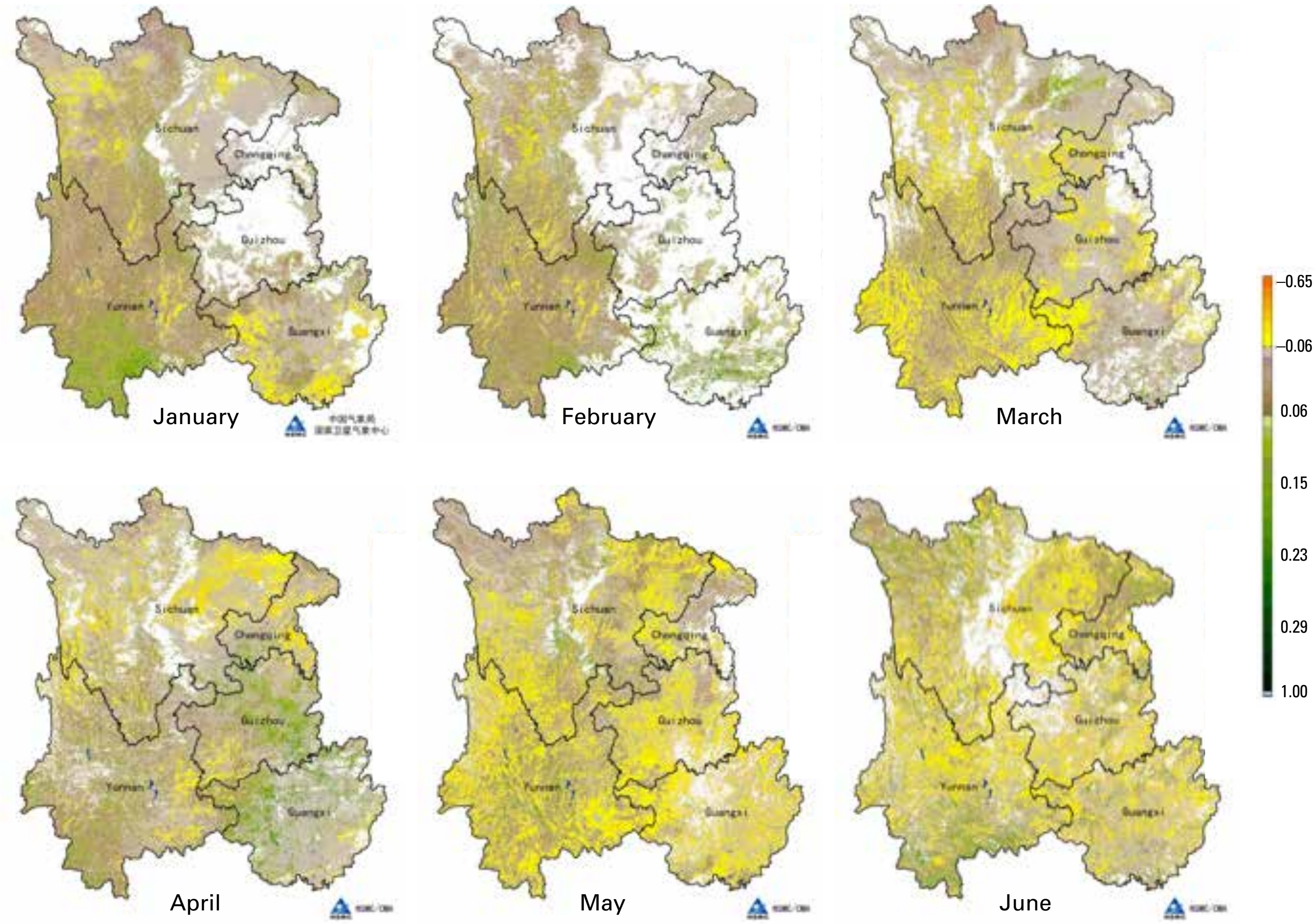


Figure 4. Vegetation monitoring image for south-west China using NOAA/AVHRR (first ten days of each month, 2010)

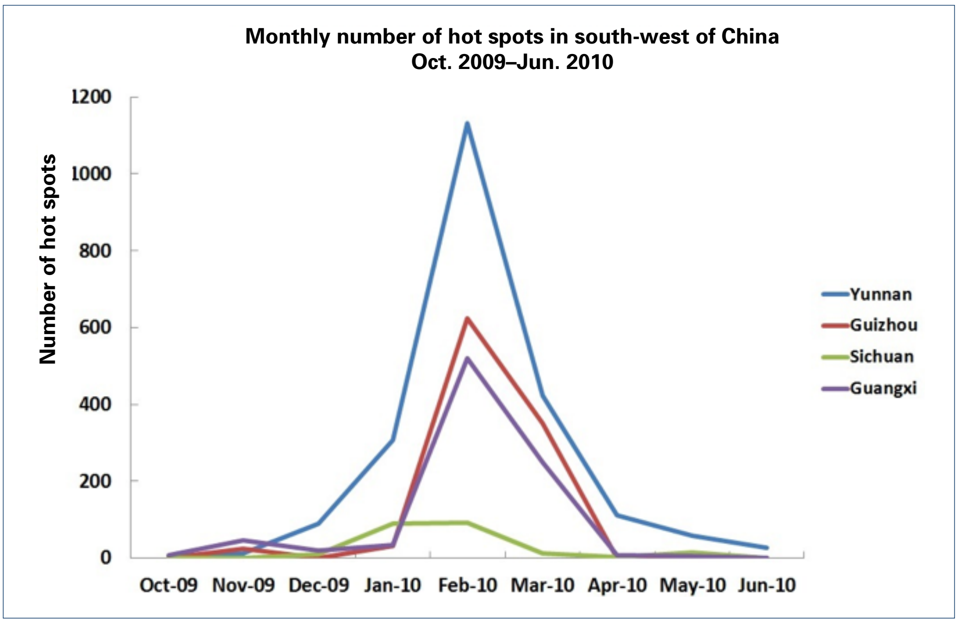


Figure 5. Fire hot-spot statistics using meteorological satellite (October 2009–June 2010)

Models and satellite data used

In drought-monitoring operations CMA applies a thermal inertia model (resistance of soil to thermal change). Soil moisture correlates positively with thermal inertia in the soil but negatively with diurnal temperature difference of the upper soil layers. Diurnal temperature difference of the upper soil layers can be obtained from meteorological satellite data. CMA uses the regression method to construct a model that integrates agrometeorological sample observing data and remote satellite data.

CMA also tries to adopt the Perpendicular Drought Index and the Modified Perpendicular Drought Index by using reflectances in the Red and near-infrared spectral bands to monitor severe drought events. Soil moisture data from FY-3/MWRI has been used to monitor severe drought events since 2012.

Land-surface temperature (2002 until the present, NOAA/AVHRR, NSMC, 1.1 km) and NDVI (2002 until the present, NOAA/AVHRR, NSMC, 1.1 km) are used to compile satellite-derived climate data records. If a severe drought occurs, FY-3/MWRI is used.

Further developments

(1) Improvements in remote sensing drought-monitoring methods and its accuracy. The construction of specific models that take into consideration spatial, seasonal and physical geographical differences.

(2) Construction of a long-term drought database using remote sensing products, such as NDVI, LST and evapotranspiration.

CASE STUDY 7

RENEWABLE ENERGY RESOURCE ASSESSMENT (USA, JAPAN)

SUMMARY

Title
Renewable Energy Resource Assessment (USA, Japan)

End users
Decision-support tool developers, research scientists, government agencies, industry organizations, international coordination agencies, power companies, energy management system companies, weather forecasting service companies

Intermediate users
Decision-support tool developers, research scientists, government agencies, industry organizations, international coordination agencies, power companies, energy management system companies, weather forecasting service companies

Application(s)
Climate monitoring, short-term forecasting and climatology

Models used
- USA: NASA Goddard Earth Observing System Model (GEOS-4), NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis, NASA Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB)
- Japan: MIROC General Circulation Model (GCM) and NICAM non-hydrostatic cloud resolving model

Climate data records used
Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget, ozone, aerosols, albedo, snow/ice coverage
International Satellite Cloud Climatology Project (ISCCP) datasets

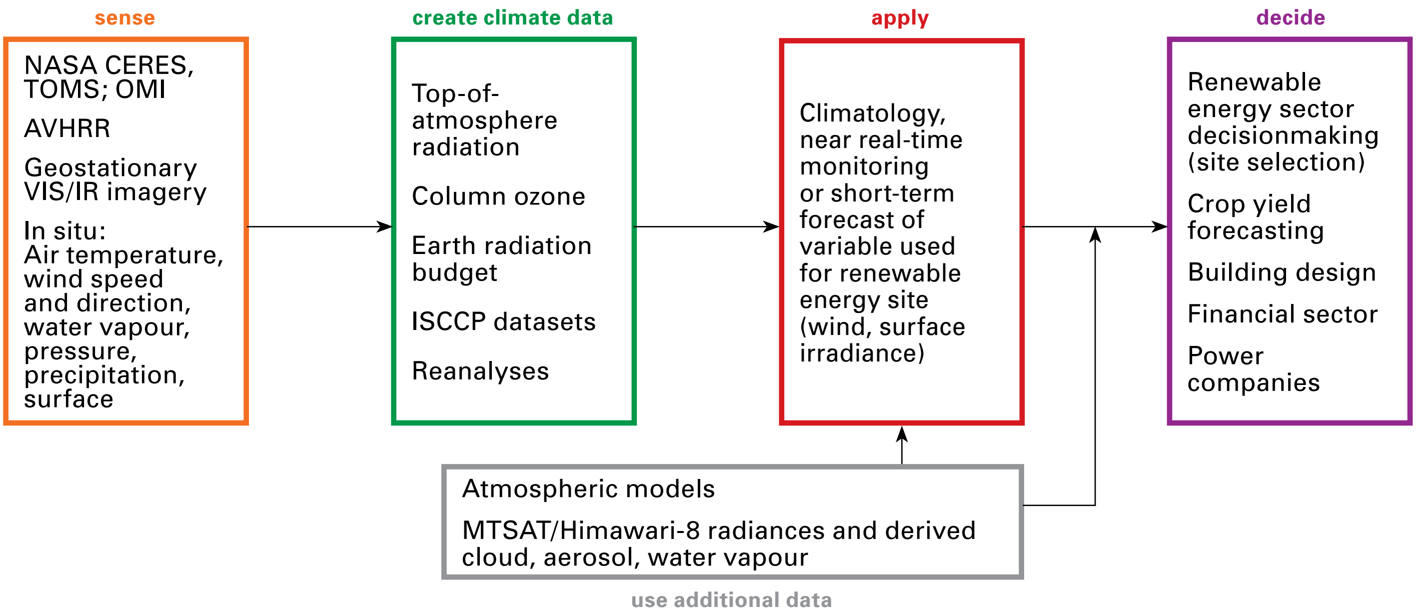
Satellite observations used
- Imager Radiances and Cloud Retrievals: Geostationary and AVHRR VIS and IR channel radiances
- Top of Atmospheric radiation measurements: NASA Clouds and the Earth's Radiant Energy System (CERES), Geostationary weather satellites (Himawari, GOES, Meteosat series)
- Temperature and moisture profiles: indirect use of satellite measurements through data assimilation systems from NASA Global Modelling and Assimilation Office
- Column ozone: NASA Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI)

Agencies that produce records
- USA: NASA and NOAA
- Japan: Cooperative organization of Tokai University, University of Tokyo, Chiba University, Japan Meteorological Agency, and Toyama University

Sustainability of service (demonstration or ongoing)
- USA: Generation and delivery ongoing activity by NASA; some end-user engagement projects of limited duration
- Japan: Data are provided to research and education users free

Renewable energy

INFORMATION FLOW



DESCRIPTION

Background

As renewable energy is increasingly used in electric power systems, there has been increasing interest in the instability of renewable energy sources such as solar radiation and wind. The availability of these resources varies over time, independent of power demands; meteorology and geophysics can contribute to solving this problem. Clouds, aerosols, and water vapour are the most important atmospheric components that affect levels of solar irradiance reaching the ground. These components have been well examined and can be estimated.

Satellite-derived measurements

- Estimates of solar radiation (derived from multiple imagers and Earth radiation budget satellite sensors) scaled to the Earth's surface using measurements and satellite-derived climatologies of clouds, ozone, and aerosols;
- Measurements of surface winds (derived from meteorological reanalyses);
- A range of other atmospheric parameters, such as temperature and relative humidity used to assess the potential of renewable energy resources at a given location across a variety of scales ranging from the individual household to large solar thermal power generation projects.

Cloud cover is an important atmospheric phenomenon that affects ground-level solar radiation. The optical thickness and particle size of clouds are primary parameters for estimating solar irradiance. They are retrieved from multi-spectral images obtained from satellite sensors. One application for such cloud properties is to estimate the solar irradiance penetrating the atmosphere which subsequently reaches the ground. Ground-level solar irradiance can be estimated by fast radiative transfer calculations using inputs of cloud properties retrieved from satellite imagery.

In addition to the constellation of low Earth orbiting satellites, the constellation of meteorological geostationary satellites are useful for gathering such information because they observe the Earth (except for the Polar Regions) at high temporal frequency and moderate spatial resolution (around 1 km). A new generation of geostationary satellites, due to be introduced between 2015 and 2020 will dramatically improve performance. They will observe 16 spectral bands from visible to infrared every 10 minutes or more frequently. Satellite measurements such as from Himawari-8 will therefore be increasingly useful for wide-area monitoring of ground-level solar radiation at high spatial and temporal resolutions (Takenaka et al., 2009).

Global models

Developing global models that investigate cloud systems and solar radiation is important for renewable energy-related short-term forecasting. Non-hydrostatic cloud-resolving models are efficient for this purpose. Japan has been developing a model that is composed of the Nonhydrostatic Icosahedral Atmospheric Model and the Spectral Radiation-transport Model for Aerosol Species for estimating solar irradiance for a given time and location. Since the cloud evolution process is influenced by the existence and species of aerosols, it is important that models consider aerosol inventories and transport in addition to cloud evolution processes. Ground-level solar irradiance is currently estimated using global models. However, further improvements related to the cloud evolution process are needed, such as the downsizing of the grid system and assimilation of in situ data and other data sources. A general circulation model commonly used for estimating the climate system is also used for estimating solar radiation over ten-day time periods. Output from the general circulation model is useful for investigating power demands and estimating potential renewable energy over tens or hundreds of years. Models for short- and long-term forecasting of solar radiation need to be used for energy management systems, and relevant methods are still being improved (Nakajima et al., 2013). Those questions are addressed in the Terrestrial Energy Estimation by Diurnal Data Analyses project. The project investigates energy management systems and forms part of a research programme under the Japan Science and Technology Agency.

Weather forecasts at various time scales (from daily to seasonal to climatic) are used to optimize load forecasts by power utilities, to better integrate intermittent sources of energy into the electrical grid and to aid longer-term infrastructure planning. While not strictly related to terrestrial climate change, space weather observations (made in the near space environment) assist in the prediction of potential damage to national grids, due to solar energetic particle precipitation, a phenomenon which follows multiple time scales.

Validation

Validation of solar radiation estimated from satellite measurements and model simulations is important for the quality control of data. Japanese researchers use the SKYNET ground validation system, which includes pyranometers, sun photometers and other kinds of radiometers. This provides not only measurements of direct and diffuse components of solar radiation, but also measurements of atmospheric parameters, such as aerosol and cloud properties that affect solar irradiance due to scattering and absorption. Solar radiations obtained from SKYNET have been compared with results estimated from geostationary weather satellites. The results showed that the root mean square error (RMSE) was around 80 W/m^2. Cumulus clouds with a spatial scale of several hundred metres increase the RMSE, because the horizontal spatial resolution of geostationary weather satellite imagery is generally 1 km or larger. More information about SKYNET can be found at http://atmos.cr.chiba-u.ac.jp/.

Research and end-use examples

In the United States of America, the need for customized data projects that are easily accessible and useable by non-technical end users was recognized through stakeholder engagement (Zell et al., 2008). The NASA Langley Research Center produced a 22-year dataset of energy-relevant quantities called the Surface Meteorology and Solar Energy (SSE) dataset. The long data time series allows for examination of the effects of interannual variability and long-term trends which are possibly related to climate change impacts. NASA is presently funding a project to add Geographic Information System capability to SSE and support mobile device access. The project will enable expanded usage while still supporting the older text based delivery systems and will provide simpler pathways for future data enhancements.

NASA, DLR, the École des Mines de Paris and other organizations have worked with the International Energy Agency to improve solar resource standardization using space-based and surface-based data sources (http://task46.iea-shc.org/). As a boundary organization with connections to multiple government and industry end users International Energy Agency can improve the uptake and enhance the value of space-based measurements for a large set of decisionmaking purposes.

The RETScreen clean energy project analysis software is run by Natural Resources Canada. It is an example of an end-to-end project where data from Earth observations are directly ingested into a decision support tool. NASA has partnered with Natural Resources Canada since 2000 by providing data from the SSE dataset as input into the RETScreen system. The global NASA SSE dataset augments input parameters in regions where ground-based data are sparse or non-existent. RETScreen uses both ground-based and satellite-derived climate data in a seamless fashion, via a city database or a direct query to SSE in the case of queries submitted online. As a result, the end-user is not concerned with the IT challenges of importing unfamiliar datasets into the decision support system. RETScreen is freely available on the Web at http://www.retscreen.net and is used globally. Natural Resources Canada provides manuals, video tutorials, and on-site training throughout the world. The decision support tool is used to evaluate a wide range of renewable energy and energy efficiency technologies from resource assessment, emission reduction and financial viability perspectives for small-scale projects to large-scale power generation projects (Eckman and Stackhouse, 2012).

RETScreen director Greg Leng commented: "The RETScreen Clean Energy Management Software now has more than 430 000 users in every country and is available in 36 languages that cover two-thirds of the world's population. Solar and climate data are key inputs into the software. Satellite-derived data provided by NASA has been used by most of these users to implement thousands of renewable energy, energy efficiency, and cogeneration projects across the globe."

NASA has also maintained a partnership with the United States National Renewable Energy Laboratory (NREL) and provided data products for use in the HOMER distributed power optimization model. While this decision support tool is now being developed privately, a version continues to be available free of charge at http://www.homerenergy.com/. HOMER is a computer model that enables the evaluation of design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. HOMER uses a variety of NASA data products, including the SSE dataset, as meteorological and solar energy inputs to the model. These data products are obtained via a direct query to the SSE web service (similar to the RETScreen link to SSE) making them readily available to the user. The HOMER system is now maintained and distributed by Homer Energy LLC and has been downloaded by over 50 000 users worldwide.

Researchers at the NASA Langley Research Center are working with the heating and air conditioning industry, and the United States Department of Energy to explore the utility of space-based observations to improve and update standards manuals for the heating and air-conditioning industries.

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CASE STUDY 8

SOLAR ENERGY POTENTIAL IN COMPLEX TERRAIN (SWITZERLAND)

SUMMARY

Title
Solar energy potential in complex terrain (Switzerland)

Service
MSG SEVIRI-based Solar Energy Mapping including the radiative effects of topography and bright surface targets, by use of the Heliomont algorithm

End users
Renewable energy companies, communal and regional infrastructure planners, home owners, architects, climate research scientists, agriculture (farmers, wine growers), regional NWP and climate modellers

Intermediate users
- Solar energy professionals
- Electricity grid operators
- Government agencies
- Agricultural and hydrological modellers
- Solar cadastre builders
- Private meteorological companies


SHUTTERSTOCK.COM

Solar panel

Application(s)
Climate monitoring and analysis; generation of climatology

Models used
Total column water vapour and ozone data from the operational forecast and the ERA interim reanalysis provided by the European Centre for Medium Range Weather Forecasts (ECMWF)

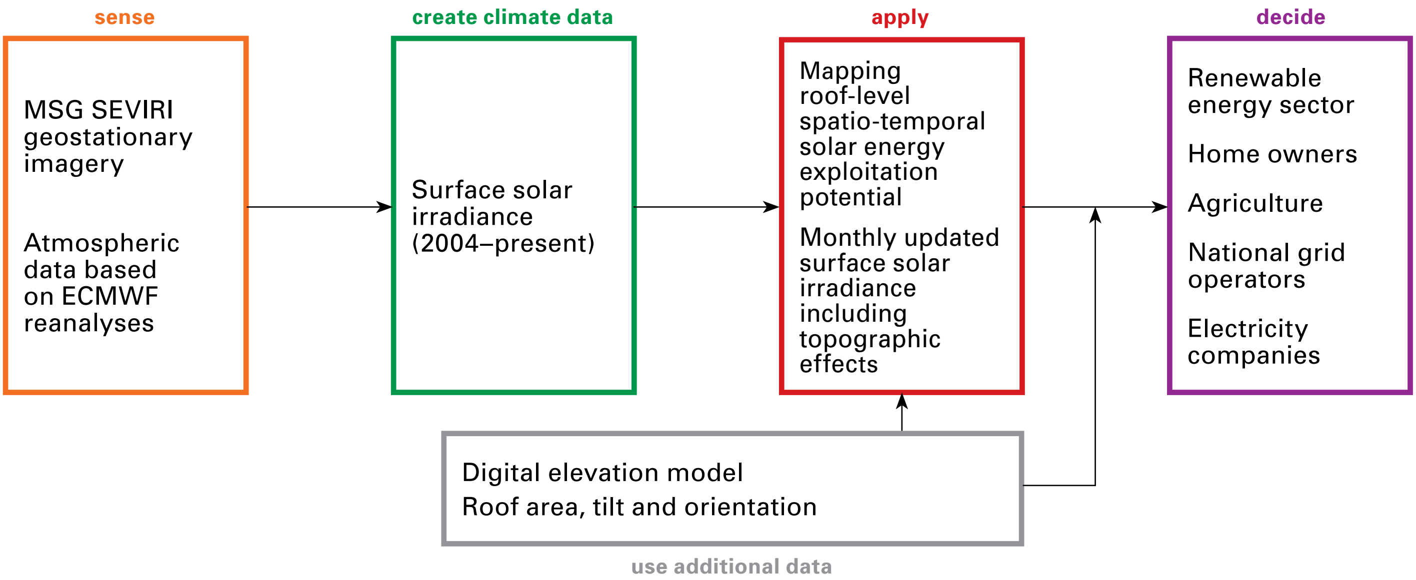
Climate data records used
Ground-based surface solar irradiance measurements of the SwissMetNet national meteorological observation network and the global Baseline Surface Radiation Network (BSRN), for development and validation

Satellite observations used
MSG SEVIRI inter-calibrated radiances from the High Resolution Visible and 0.6, 0.8, 1.6, 10.8, 12.0 µm channels, at 15-minute temporal resolution

Agencies that produce records
- EUMETSAT (MSG SEVIRI) and ECMWF (atmospheric boundary conditions)
- MeteoSwiss (climatological solar energy maps)

Sustainability of service (demonstration or ongoing)
- Operational service: monthly mean and anomaly radiation maps for Switzerland
- Demonstration service: Near real-time direct beam diffuse and direct normal irradiance for customer-defined areas in Europe and Africa

INFORMATION FLOW



DESCRIPTION

Description

Renewable energy sources have started to play an increasing role in the energy infrastructure of our society. However, compared to traditional energy sources, the production, transport and use of renewable energy from solar, wind and hydropower has a higher dependency on meteorological and climatological boundary conditions. Therefore, the precise knowledge of such conditions and their variability through space and time is important in order to optimize decentralized production, to synchronize it to actual usage and to secure the stability of networks which transport energy across national boundaries. Supporting the energy sector with knowledge and tailored information useful for planning and operational purposes is one of the activities of the National Centre for Climate Services (NCCS) of Switzerland, which the Centre implements according to GFCS recommendations.

Geostationary satellite data has complemented sparse station-based Surface Solar Irradiance (SSI) measurements since the early 1980s, particularly for mapping spatio-temporal solar energy potential. Compared to monthly mean station-based SSI measurements, the Heliosat method (Cano et al. 1986) can achieve uncertainty levels of below 5%.

The availability of a scientific method does not, however, guarantee consistent and continuous multi-decadal climate data records. Very few SSI climate data records exist that provide a climatologically homogeneous time series between heritage satellite systems (such as Meteosat First Generation (MFG) Meteosat Visible and InfraRed Imager (MVIRI)) and more recent systems (such as Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI)). Heliosat, like other satellite-based retrieval algorithms, makes the simplified assumption of a plane-parallel dark surface target which offers visual contrast to bright clouds. These basic requirements are not met in complex, snow-covered terrain, such as the Swiss Alps and other high-altitude and high-latitude areas. MeteoSwiss thus engages as a partner of the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) to further develop algorithms and climate data records that satisfy climatological homogeneity criteria and can be used in all terrain. A 28-year SSI climate data record (1983-2010) covering the entire Meteosat disc has been produced (Posselt et al., 2012). MeteoSwiss has also developed the Heliomont method (Stöckli, 2013).

Heliomont derives SSI maps from MSG SEVIRI data, model data of total column water vapour and ozone data from the operational ECMWF forecast and the ERA interim reanalysis. SEVIRI data are used at 15-minute, hourly, daily, monthly and yearly intervals. Special care is taken over snow-cloud separation using infrared channels and topography shading effects at the sub-kilometre spatial scale (Figure 1). Monthly updated visualizations of SSI mean and anomaly data across Switzerland are publicly available (MeteoSwiss, 2015). Monthly updated SSI mean and anomaly data at 2-km resolution for Switzerland are available through the MeteoSwiss data subscription service. Near real-time direct and diffuse normal irradiance at 15-minute intervals, downscaled to 25-m spatial resolution for a customer-defined geographic region within Europe and Africa is currently in demonstration mode and can be provided on request.

The Heliomont climate data records are available for the MSG period since 2004. It features realistic SSI estimates for mountainous regions with the highest SSI levels occurring over snow-covered mountain peaks (Figure 1). The real socioeconomic value of such a satellite-based SSI dataset was demonstrated for two Alpine regions during the EU Interreg project PV ALPS. This project created solar potential maps for regional decisionmakers by merging the Heliomont climate data records with land-use planning and photovoltaic power production estimates. As a consequence, the Heliomont climate data records are now applied in a country-wide solar cadastre showing the roof-level photovoltaic and solar heating potential for the whole of Switzerland (Figure 2). They also support national climate monitoring activities (Figure 3), are used for deriving agricultural suitability maps, and enable the evaluation of the COSMO NWP model.

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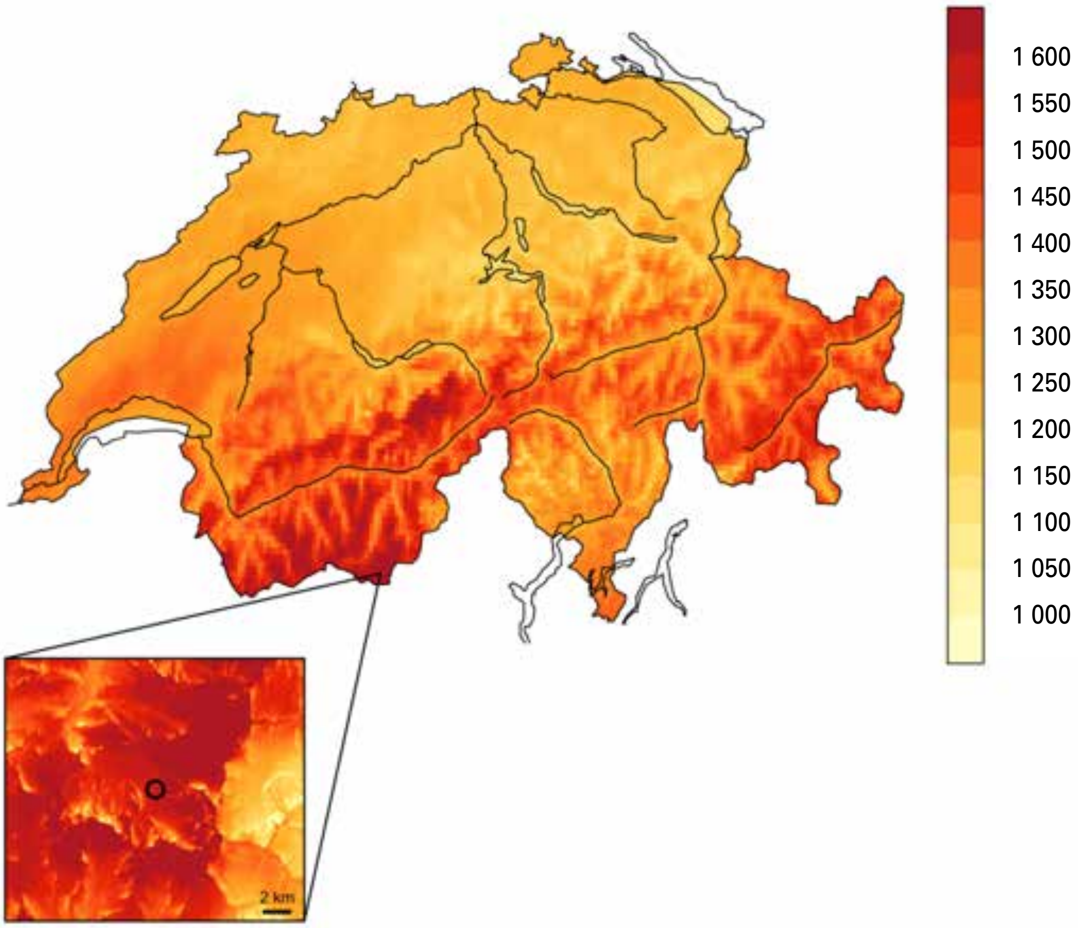


Figure 1. Annual mean surface solar irradiance (kWh m^{-2}) for Switzerland calculated from MSG SEVIRI data using the Heliomont method; cropped area: 25-m resolution downscaled data including the local-scale radiative effects of topography surrounding the Monte Rosa alpine hut (circle)

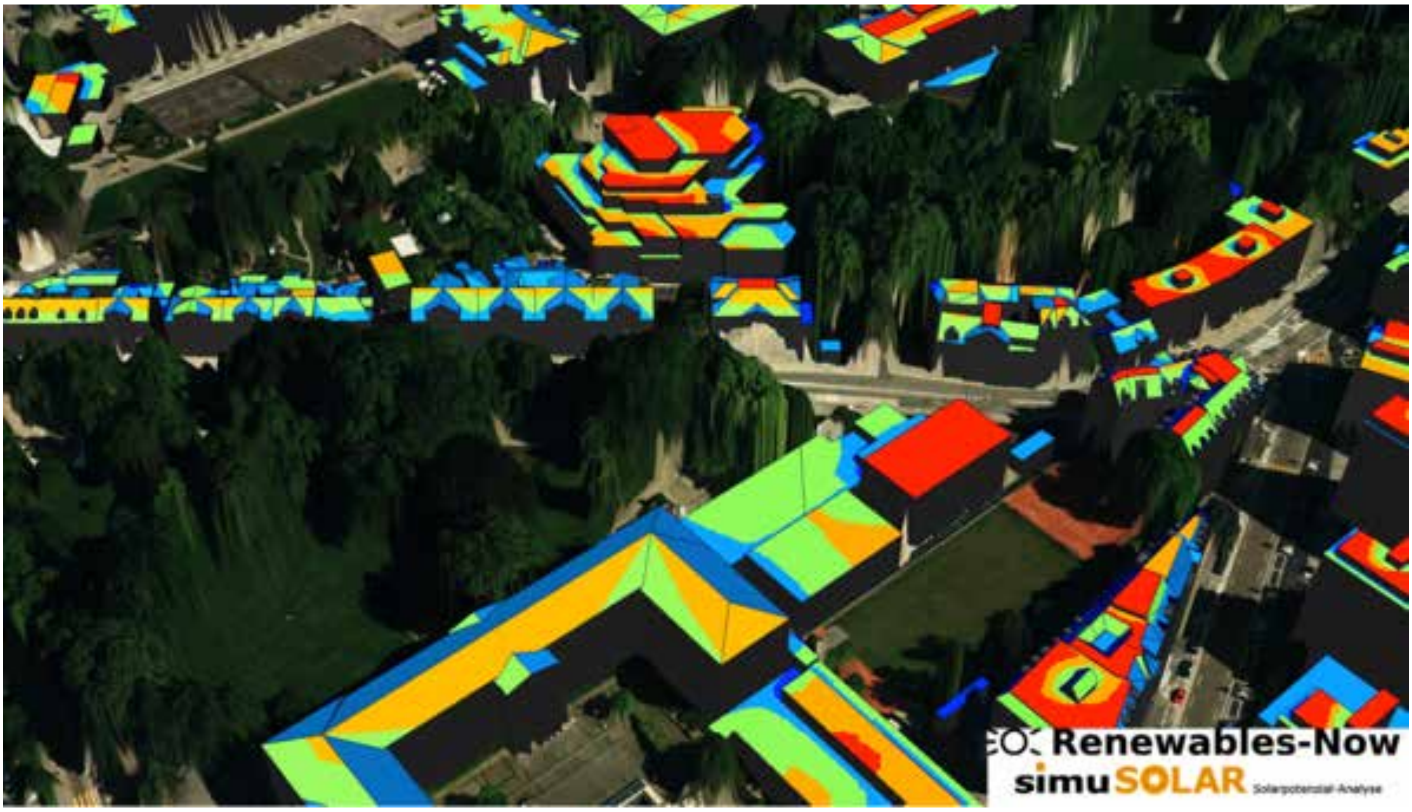


Figure 2. Roof-level suitability map for photovoltaic power production in the city of St Gallen, Switzerland, calculated from MSG SEVIRI data using the Heliomont method (red = highly suitable, orange/yellow = suitable, green = marginally suitable, blue/grey = unsuitable) (Visualization: © simuPlan)

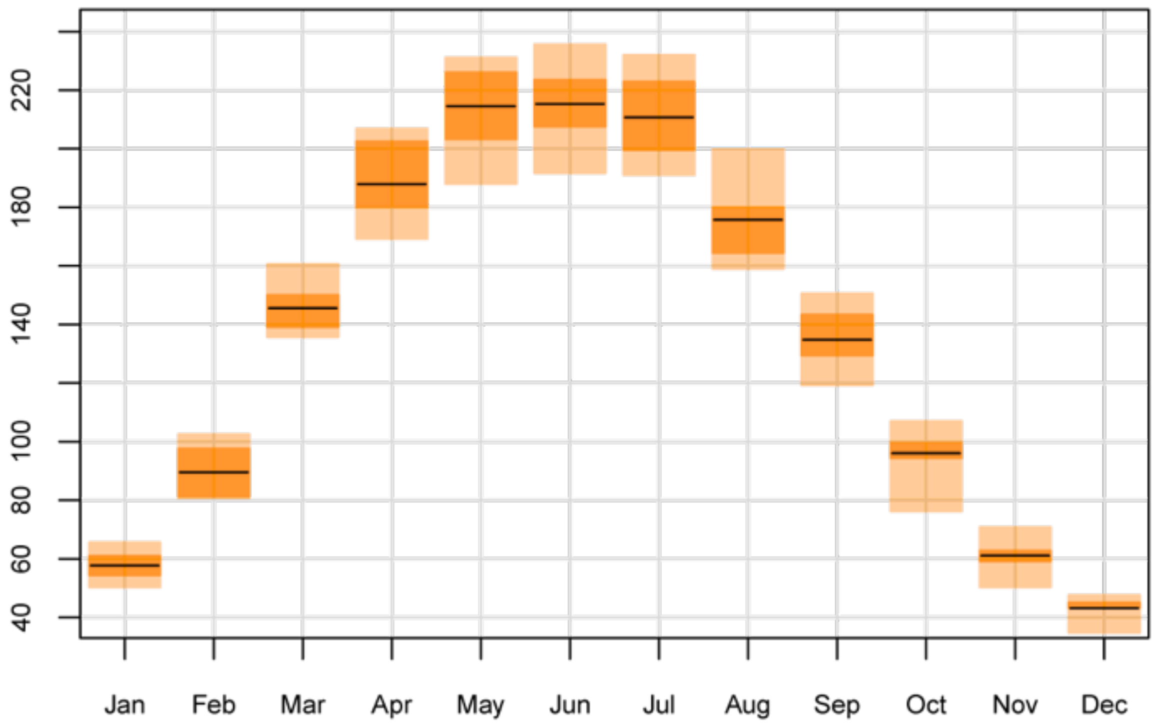


Figure 3. Seasonal course (black lines) and interannual variability (yellow shading) of the monthly surface solar irradiance (kWh m^{-2}) at the Monte Rosa alpine hut (hut location shown in Figure 1)

CASE STUDY 9

PROJECTING NATURAL GAS DEMAND (NORTH-EASTERN UNITED STATES)

SUMMARY

Title
Natural gas production and pricing using Madden-Julian Oscillation (MJO) satellite analyses

Service
2–6 week forecast of natural gas demand in the north-eastern United States of America

End users
Home owners and businesses using natural gas

Intermediate users
Consulting meteorologists

Application(s)
Short-term statistical climate forecasting and climate monitoring

Models used
Statistical model of satellite-derived Madden-Julian Oscillation state and surface temperatures

Climate data records used
Outgoing longwave radiation

Satellite observations used
HIRS (1978–present)

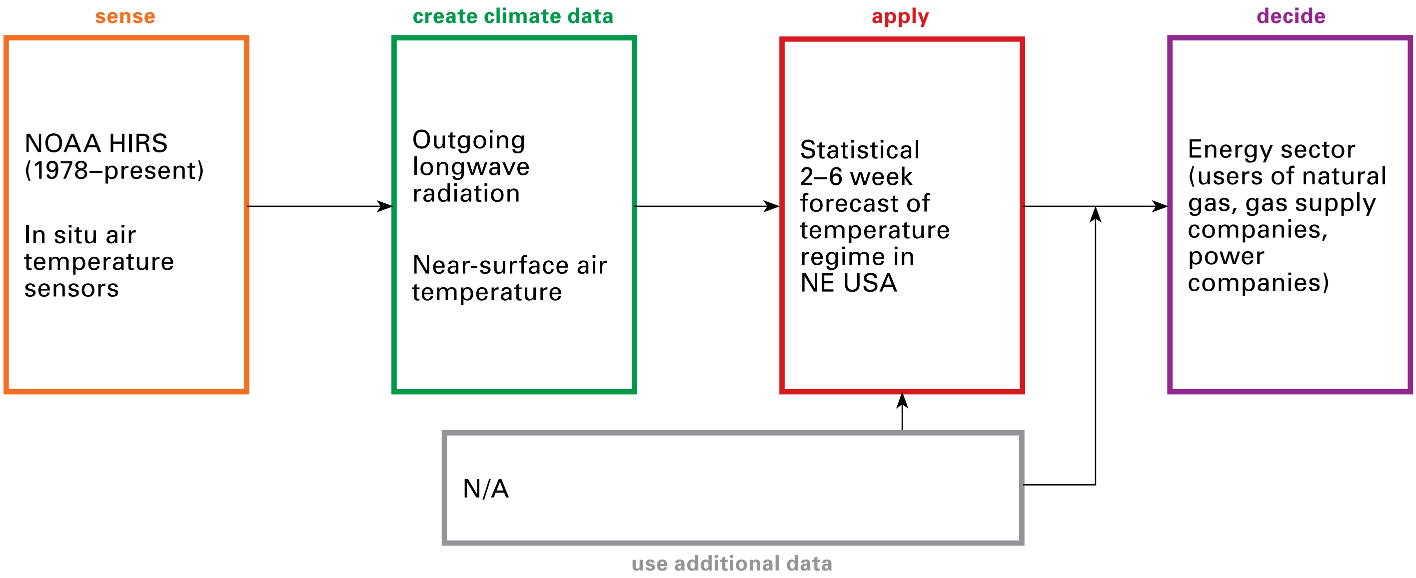
Agencies that produce records
NOAA and Cooperative Institute for Climate and Satellites North Carolina (CICS-NC)

Sustainability of service (demonstration or ongoing)
Ongoing (http://monitor.cicsnc.org/mjo/current)

FLICKR

Natural gas stove

INFORMATION FLOW



DESCRIPTION

It is no surprise that energy demand in the United States of America is driven by changes in temperatures. Forecasting those temperatures as far in advance as possible is a top priority for energy companies. Numerical models are useful for predictions of up to about a week, but their accuracy drops off after that. For longer-term predictions, forecasters in the energy sector often rely on statistical techniques and historical analogues.

Climate data records are ideal inputs into those statistical models. As climate data records have been homogenized, forecasters can be sure that the model will not be affected by data changes through time. Satellite proxies for tropical rainfall, like outgoing longwave radiation, are particularly valuable. They can identify patterns in the tropics that drive a significant part of the global circulation. These patterns also evolve slowly enough to provide higher levels of accuracy for the longer-term predictions that the energy sector needs.

Figure 1 shows an example of how outgoing longwave radiation can be used to anticipate weather patterns over the United States. The Madden–Julian Oscillation is a large area of tropical rainfall that takes about 30 days to move eastward around the globe. In both panels, the rainfall is enhanced near Indonesia and Australia (green shading), although there is a noticeable difference near Hawaii. The lower panel has a large area of enhanced rainfall that is not in the upper panel.

The contours identify changes in the global circulation. The red contours generally correspond to areas that are warmer than usual, while the blue contours are cooler than normal. The patterns in the two panels are practically reversed over North America.

As those differences can be persistent, they have been identified with a newly developed index, the Multivariate Pacific–North American index (MVP) (Schreck et al., 2013), in order to infer temperature anomalies in the continental United States. Satellite observations of outgoing longwave radiation play a key role in this index. By using the MVP and other Madden–Julian Oscillation diagnostics on the website monitor.cicsnc.org/mjo, forecasters in the energy industry will be better prepared to meet the demands of future temperature extremes.

Reference

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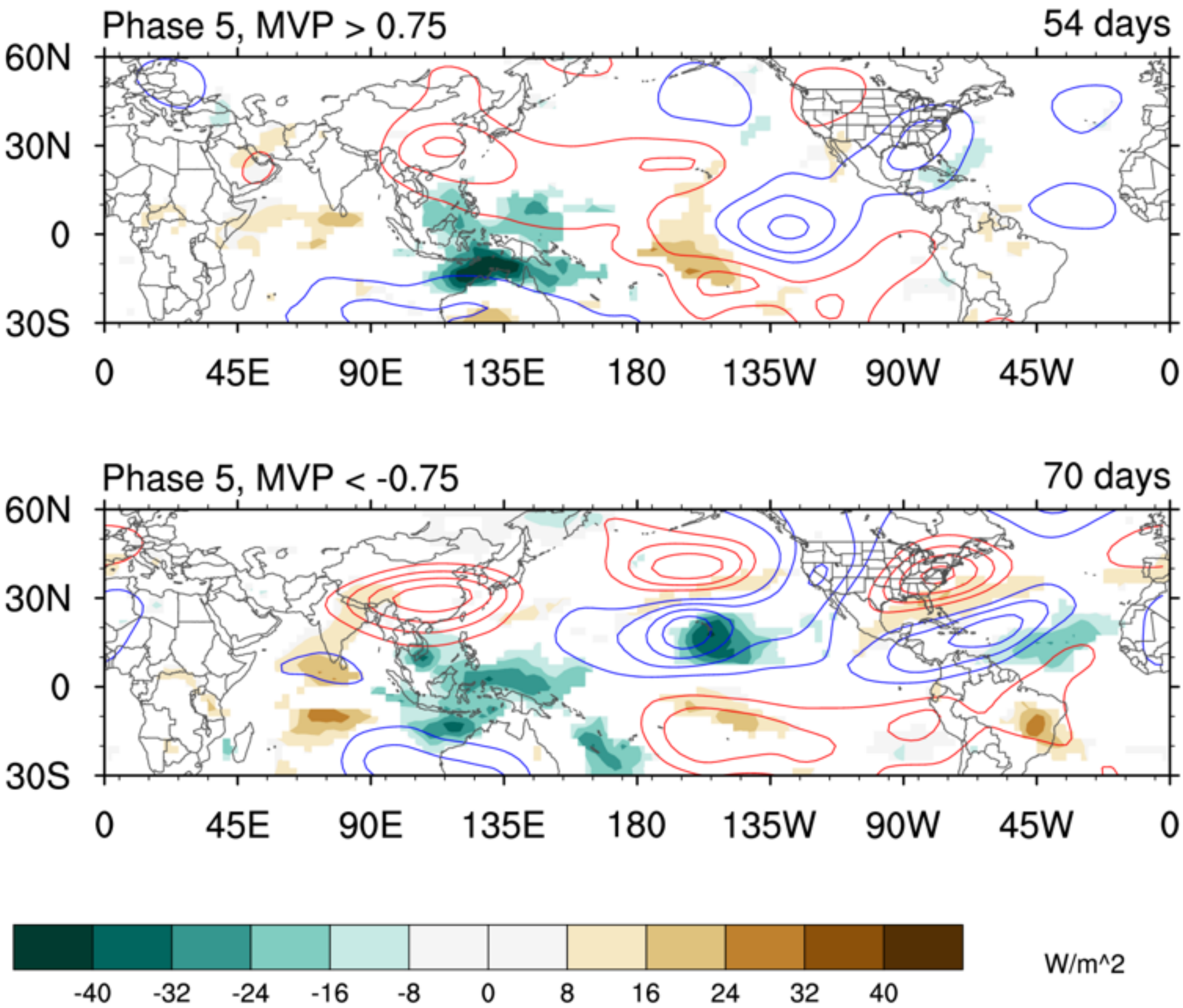


Figure 1. Composite outgoing longwave radiation anomalies (shading) and 200-hPa streamfunction anomalies (red and blue contours every 5x106 m^2s^{-1}) for real-time multivariate Madden–Julian Oscillation phase 5 when MVP >0.75 (top) and MVP <0.75 (bottom). Only outgoing longwave radiation anomalies that are 95% significant are shaded. Red contours (for example, in lower panel over the North-eastern United States) are generally associated with warm surface temperature anomalies. The numbers in the top right denote how many events were used in each composite.

CASE STUDY 10

MONITORING TROPICAL DEFORESTATION IN SUPPORT OF REDD+

SUMMARY

Title
Monitoring global deforestation in support of REDD+

Service
– Maps for forest cover and forest-cover change (on a sample basis (JRC/FAO), or wall-to-wall approach (UMD/Google))
– Global maps of forest cover and deforestation available from Global Forest Watch service of the World Resources Institute (WRI-GFW)

End users
European policy entities (DG CLIMA, DG DEVCO) and development funds providers, national and local authorities in the regions concerned

Intermediate users
World Resources Institute, FAO (Global Forest Resources Assessment program), FAO/UNEP/UNDP (UN-REDD programme), EC–JRC

Application(s)
– Timely and up-to-date information on the location and condition of forest resources, forest change based on multiple snapshots, forest tracks, deforestation analyses
– Climate change mitigation

Models used
Status and trends, derived from remote sensing imagery, forest models, multi-sectoral sources comprising ground networks and partnerships with international bodies, consolidated in information systems

Climate data records used
Global land cover and forest validated distribution for tropical belt

Satellite observations used
– Multi-spectral optical imagery for mapping and monitoring: mainly Landsat satellite imagery (TM/ETM+ sensors at 30m resolution), complemented by similar types of satellite imagery, e.g. SPOT (20–10m resolution), ALOS (AVNIR-2 sensor) and RapidEye (6m resolution). From end of 2015: Sentinel-2 (10 m resolution)
– Multi-spectral optical imagery at very fine resolution for validation (e.g. visual interpretation from GoogleEarth imagery, Rapideye, Quickbird)
– Complementary radar-based forest mosaics at 50–100m resolution (ALOS PALSAR)

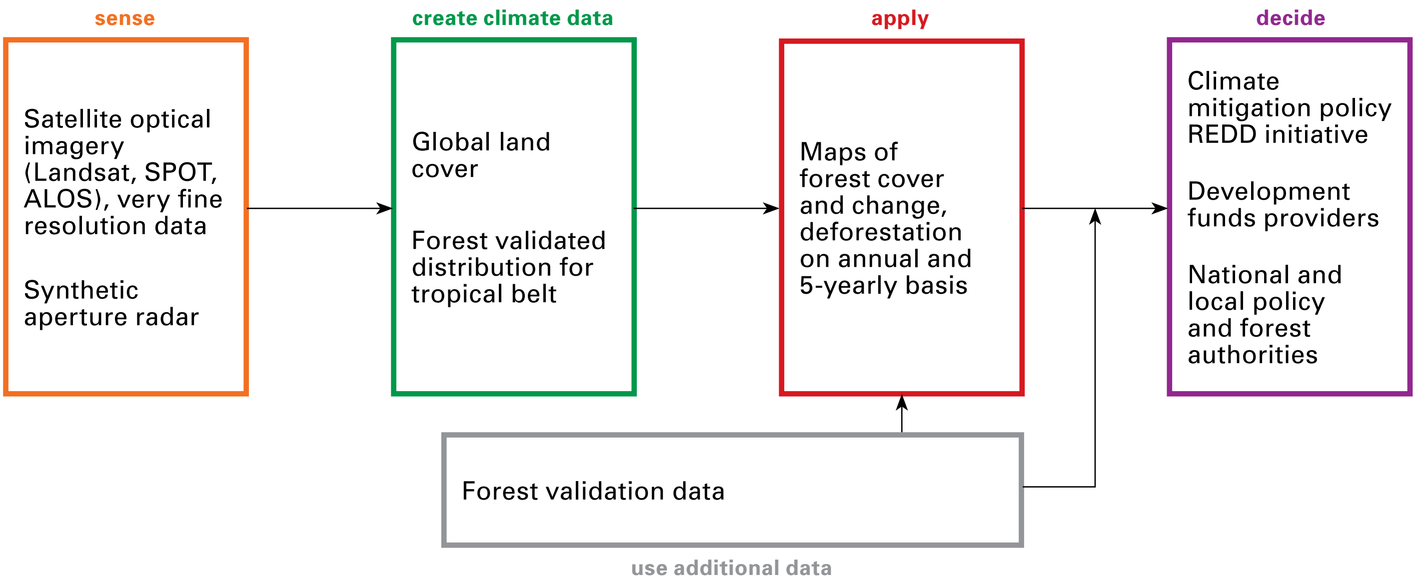
Agencies that produce records
– USGS (Landsat), SPOT-Image (SPOT), JAXA (ALOS), EC/ESA (Sentinel-2), Private operators (Rapideye)
– EC-JRC (crop products)
– University of Maryland (UMD)/Google for WRI-GFW service

Sustainability of service (demonstration or ongoing)
Sustainable operational service providing periodic multi-annual assessments (5-years) or annual assessments

NEIL PALMER (CIAT)

Logging road in East Kalimantan, Indonesian Borneo

INFORMATION FLOW



DESCRIPTION

As global environmental problems affect the security and prosperity of European Union (EU) citizens, the EU is a key player in global efforts towards sustainable development and climate change mitigation. The EU uses its various instruments which facilitate its engagement with third world countries on issues that are of global concern, such as climate change and environmental protection.

The outcome documents of the Rio+20 United Nations Conference on Sustainable Development include a framework for action on forests (UN, 2012). The framework includes three elements. First, it calls for enhanced efforts to achieve sustainable forest management, reforestation, restoration and afforestation. Second, it supports all efforts that slow, halt and reverse deforestation and forest degradation in an effective manner. Third, it notes the importance of ongoing international initiatives such as activities for Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) under the United Nations Framework Convention on Climate Change (UNFCCC).

The service presented here contributes to the assessment of EU and global forest resources. Timely and up-to-date information on the location and condition of forest resources, and internationally-agreed methods for the monitoring, reporting and verification component of REDD+ are needed to properly define, target, implement and evaluate policies related to the UNFCCC and the EU Forest Law Enforcement Governance and Trade scheme (FLEGT).

The information derived provides quantitative measurements of changes in global forest resources with a focus on Eurasia and the tropics. A single system consolidates information on status and trends derived from remote sensing, forest models, multi-sectoral sources comprising ground networks, and partnerships with international bodies. These can be synthesised into data maps such as those in Figure 1. From a technical aspect, the European Commission Joint Research Centre provides tools for the monitoring of forest ecosystems which rely heavily on data from Earth-observing satellites. The system generates regional forest maps, tracks areas of rapid forest change and produces estimates of changes in forest cover for the current and previous decades. Other forest monitoring initiatives using satellite data, such as the DETER and PRODES programmes of the Brazilian National Institute for Space Research (INPE) and the World Resources Institute (using MODIS, CBERS and Landsat data) are complemented by the service.

The service supports the development of the European climate change policy, especially concerning REDD+. Biomass maps and carbon emission estimates will be produced for selected tropical forest ecosystems. The Joint Research Centre products will be made available as input to future climate change impact scenarios in support of the UNFCCC. The products also play a role in developing internationally-agreed methods to estimate greenhouse gas emissions that result from deforestation in developing countries.

The Joint Research Centre's activities, products and services presented here also support the EuropeAid programme of the European Commission Directorate-General for Development and Cooperation (DG DEVCO). The Centre's objectives for EuropeAid are to strengthen the capacity of tropical countries and the tropical region to monitor forest resources (in the framework of REDD+ or FLEGT).

Remote sensing data is essential in monitoring deforestation. Deforestation monitoring is crucial so that countries may benefit from REDD+. Products and services derived from remote sensing data provide vital information that can be used for the National Greenhouse Gas Inventories in the forestry sector and that will contribute to spatially explicit national reporting in line with IPCC guidelines.

To enhance the Global Forest Resource Assessment using satellite data, FAO and the Joint Research Centre produced the Global Remote Sensing Survey (FAO, 2009; 2015). Remote sensing is complementary to Forest Resource Assessments: until 2015 they have mainly been based on national data that countries have provided to FAO in response to a common questionnaire. FAO would then compile and analyse the information and present the current status of the world's forest resources and their changes over time. The assessments have a wide scope and a comprehensive perspective on global forest resources, their management and use.

References

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United Nations, 2012: The future we want. United Nations General Assembly Resolution 66/288, http://sustainabledevelopment.un.org/futurewewant.html.

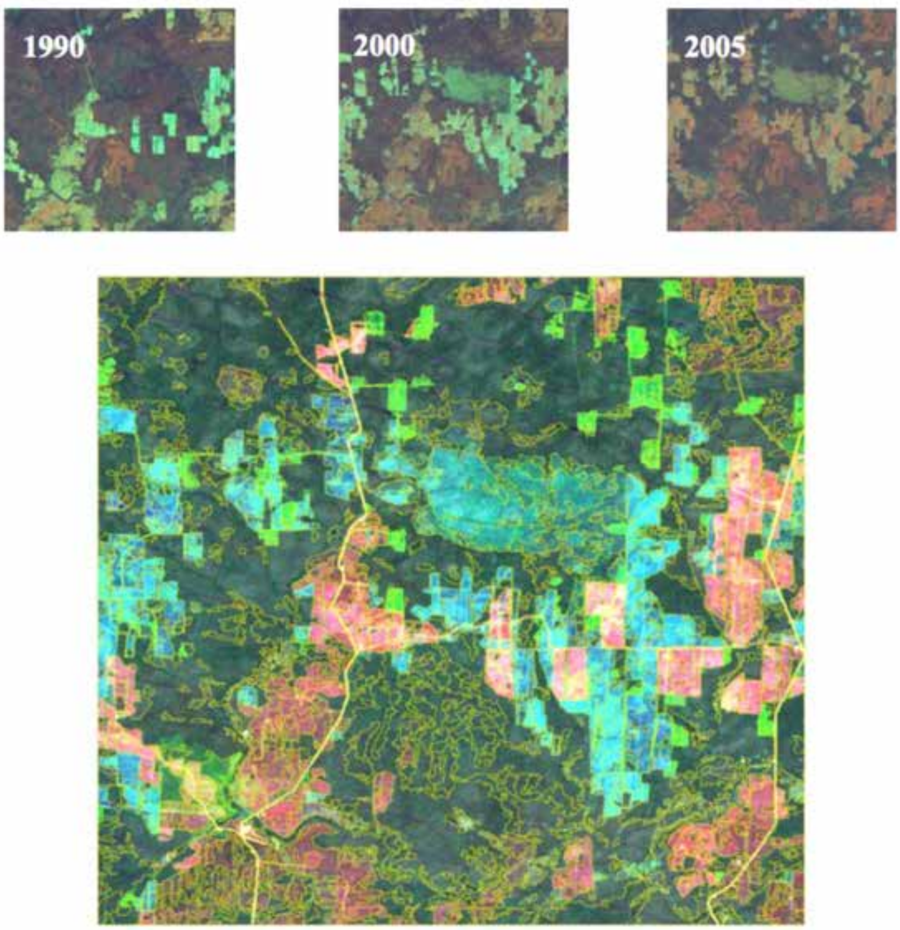


Figure 1. Time 1, 2 and 3 imagery (above) combined into a multi-data image (below) with segmentation polygons overlaid (in yellow). Clearings present in time 1 (1990) appear red, new clearings in time 2 (2000) appear blue, and new clearings in time 3 (2005) appear light green. The single polygon layer from segmentation includes all of this information and will contain classification labels for each time period.

CASE STUDY 11

SEA-ICE EDGE MONITORING FOR POLAR NAVIGATION (CANADA)

SUMMARY

Title
Sea-ice edge monitoring for polar navigation (Arctic Canada)

Service
Assessment of sea-ice conditions in support of Inuit communities' access to safe travel routes and hunting areas

End users
Inuit communities

Intermediate users
- Noetix Research Inc.
- Environment Canada

Application(s)
- Navigation planning
- Fishing and wildlife harvest support
- Climate monitoring, climate change adaptation

Models used
N/A

Climate data records used
30-year average of historical sea-ice edge locations

Satellite observations used
RADARSAT–1/–2, ASAR/Sentinel–1

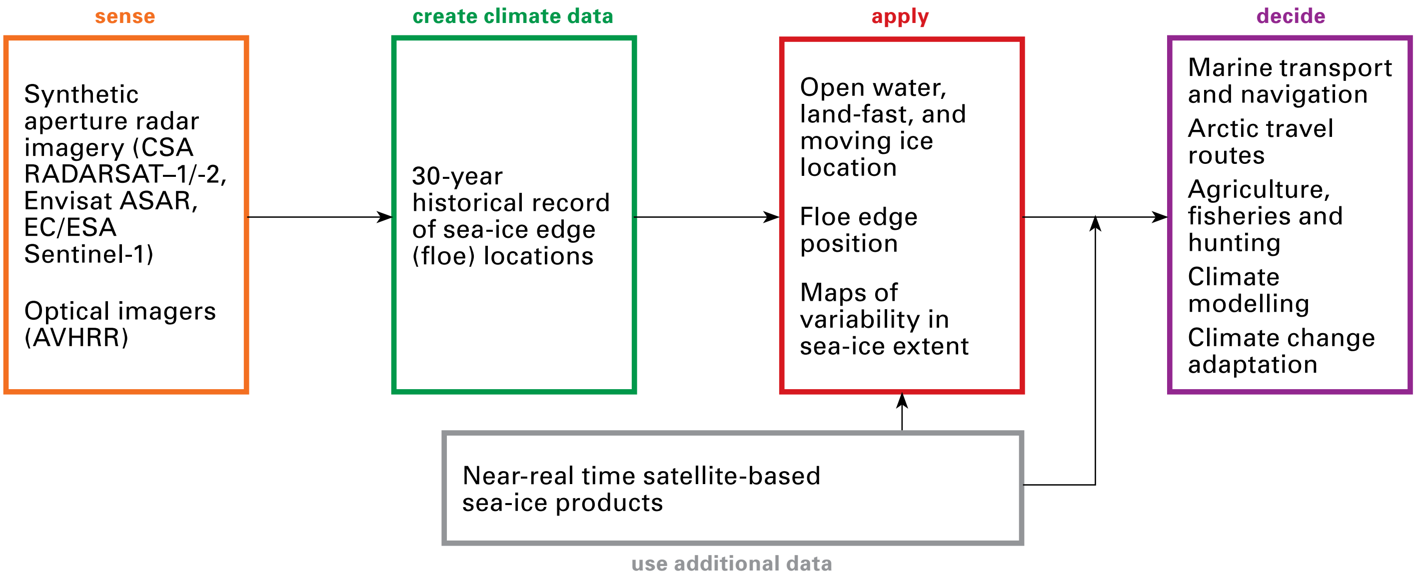
Agencies that produce records
CSA, ESA, MDA Canadian Data Processing Facility (for pre-processing)

Sustainability of service (demonstration or ongoing)
Ongoing service (initiated during International Polar Year 2007–2008)

SHUTTERSTOCK.COM

Polar bear, Spitsbergen, Norway

INFORMATION FLOW



DESCRIPTION

Long-term satellite observations of the Arctic Ocean show trends in reduced sea-ice extent and thickness (Figure 1). However, these trends are not easily transformed into local consequences for sea-ice conditions, which are dependent on geographical contexts. The unpredictability of local sea-ice conditions has raised concerns among Canada's Inuit and other indigenous Arctic communities. Sea ice is critical to the ways in which they travel and hunt. It determines wildlife harvest destinations, travel routes, modes of transport, amounts of fuel needed and travel safety. In Canada, Inuit communities have started to use satellite products to evaluate safe on-ice travel routes.

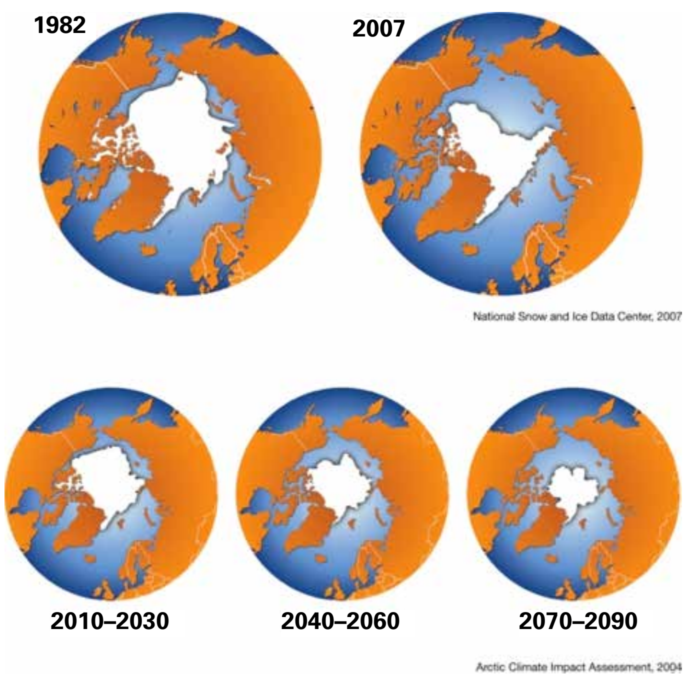


Figure 1. Decrease in minimum sea-ice extent (observed: upper two figures) and climate projections (modelled: bottom three figures)

Source: Hugo Ahlenius, UNEP/GRID-Arendal

Traditionally, weather conditions and geographic reference points were used to determine travel routes. In the past, the latter were used to evaluate sea-ice conditions. That assessment was based on an interpretation of how terrestrial characteristics influence sea-ice formation, stability and decay. However, the nature of the changes in sea-ice conditions is becoming increasingly unpredictable.

The initiative of Canada Ice Services focuses on supplementing traditional Inuit knowledge with Synthetic Aperture Radar data on sea-ice conditions. The final product is accessible to non-technical end users.

Synthetic Aperture Radar is an active microwave satellite sensor that can operate day and night, and is not obstructed by clouds. The underlying physical principles of the sea-ice edge (Floe-Edge) product rely on differences in surface and volume scattering of the radar beam. The contrasts between water, wet first-year ice and multi-year ice are enhanced by the use of both horizontal and vertical polarisation with varying incidence angles.

Data post-processing is undertaken by Noetix Research Inc, which provides the Web-based Floe-Edge service under the auspices of Canadian Ice Service/Environment Canada, a division of the Meteorological Service of Canada.

Periodic satellite data are necessary in order to provide a useful service to the Inuit communities. Product updates may be as frequent as 3–5 times per week across the Northwest Territories, Nunavut and Nunavik (Figure 2; Figure 3 with details of a product).

Jimmie Qaapik from the Inuit community says that climate change is affecting the daily lives of Inuit communities in the high latitudes of Canada, but that they are adapting to these changes with the help of new technology:

> "During the dark season and after storms, radar images are a necessity: they allow us to safely navigate through smooth and rough ice and tell us where the floe edge is. We now know better and faster what happened to the ice. This is important also for fishing, hunting and getting drinking water. This technology keeps us safe." (http://www.bio-medicine.org/biology-news-1/Climate---the-hot-topic-in-Doha-27767-2/)

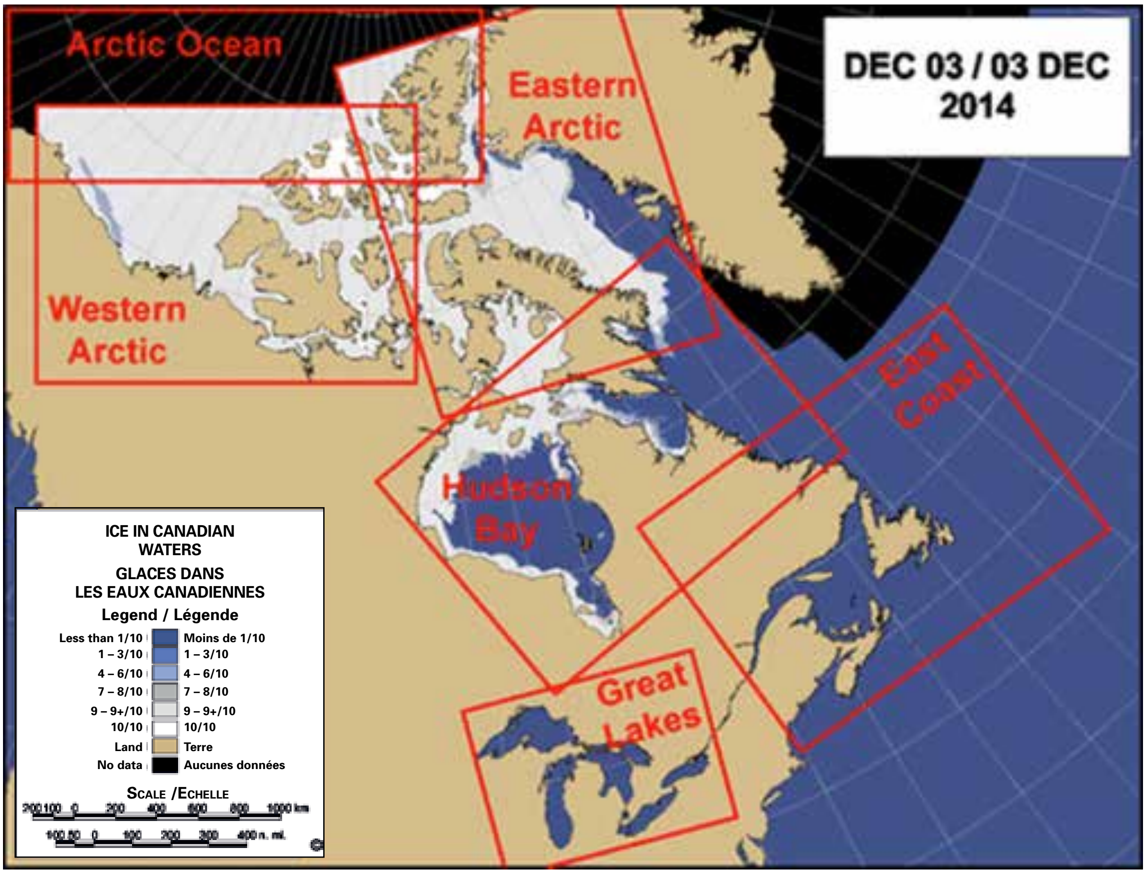


Figure 2. Regions for which Canada Ice Service provides the latest known ice cover information in Canadian waters; Noetix Research Inc analyses data across the Northwest Territories (Western Arctic), Nunavut (Eastern Arctic) and Nunavik, Quebec (Hudson Bay)

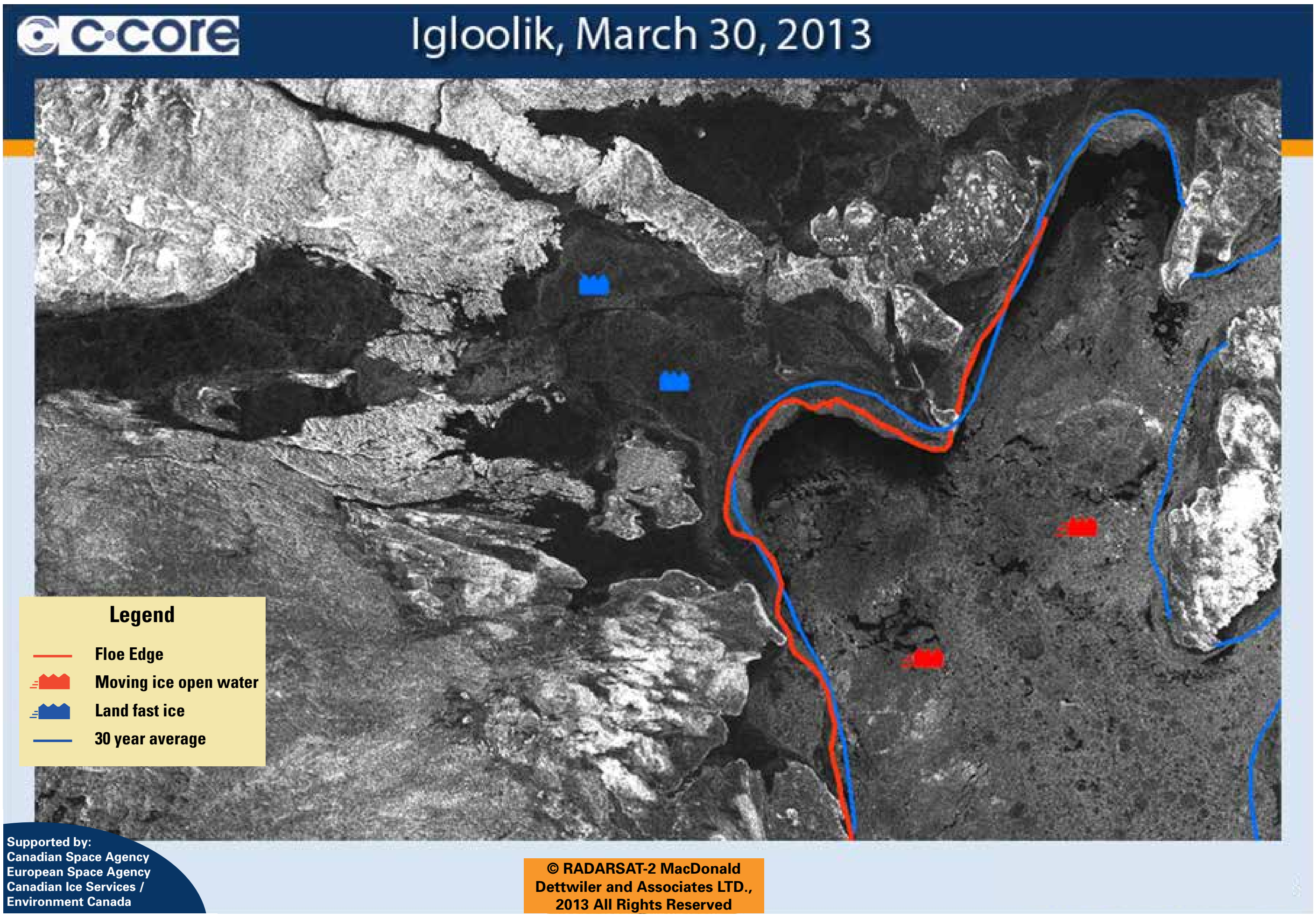


Figure 3. Example of Floe-Edge Service product

CASE STUDY 12

MALARIA EARLY WARNING SYSTEM IN THE SOLOMON ISLANDS USING SEASONAL CLIMATE OUTLOOKS

SUMMARY

Title
Malaria early warning system in the Solomon Islands using seasonal climate outlooks

Service
– Use of relationship between El Niño/Southern Oscillation (ENSO) index and malaria incidence to build a prototype early warning system for public health authorities
– Satellite-derived sea-surface temperature data (a critical component of the ENSO index)

End users
Ministry of health, local public health organizations

Intermediate users
Solomon Islands Meteorological Service

Close-up of a mosquito

Application(s)
– Seasonal climate outlooks and predictions
– Prediction of malaria incidence
– Warnings and advisories to public health authorities

Models used
N/A

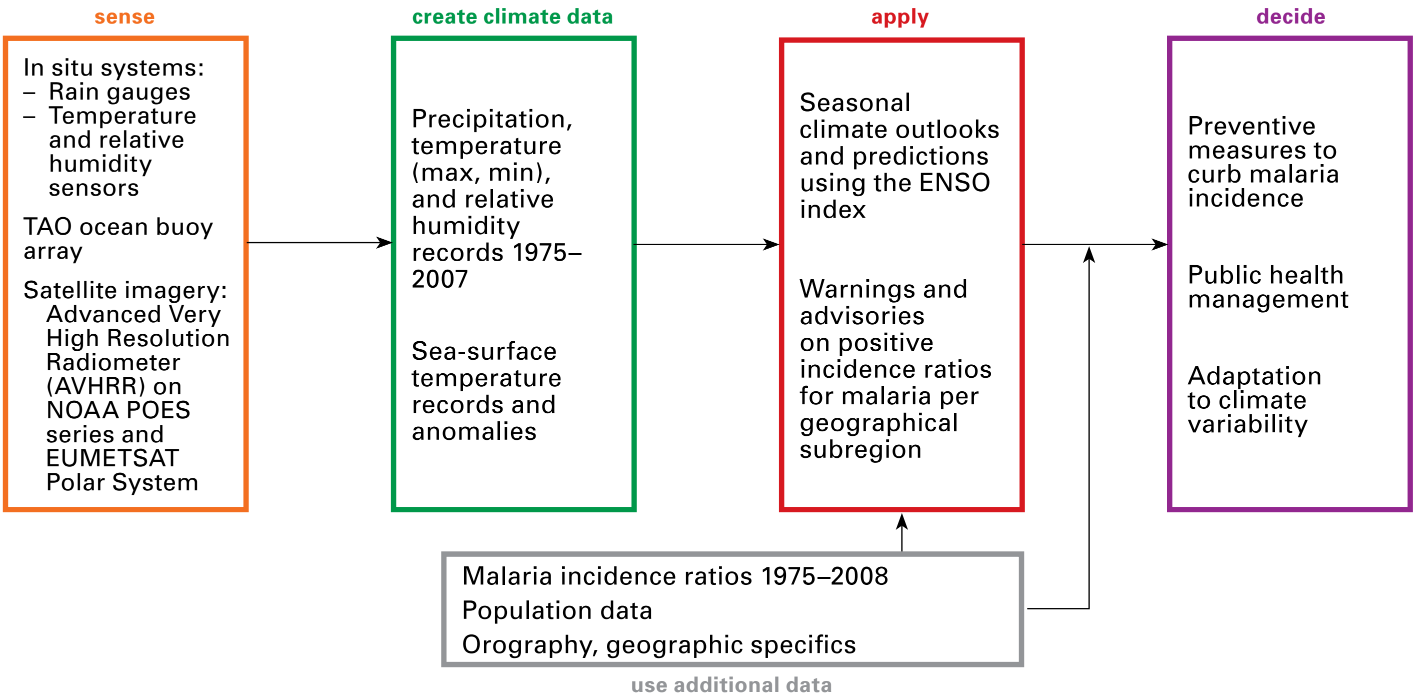
Climate data records used
– Precipitation, temperature (maximum, minimum), relative humidity 1975–2007 (in situ records on Solomon Islands)
– AVHRR-derived SST 1982–present (used in calculating SST anomalies for the ENSO index)
– ICOADS SST

Satellite observations used
AVHRR instrument flown on NOAA POES series and EUMETSAT Polar System

Agencies that produce records
– Solomon Islands Meteorological Service (for in situ CDRs)
– NOAA, EUMETSAT (for AVHRR)

Sustainability of service (demonstration or ongoing)
Pilot project, with prospect for transition into an operational information and warning service

INFORMATION FLOW



DESCRIPTION

Climate variability and malaria incidence

Malaria is a leading cause of death in the Solomon Islands (WMO, 2011). The age-adjusted death rate of approximately 30 per 100 000 of population ranks the tropical western Pacific islands as 33rd in the world. Malaria continues to have high economic and social costs including low productivity at work and absenteeism in schools. The impact of climate change on the health sector is also significant (WMO/WHO, 2012).

Mosquitoes can carry Plasmodium falciparum, a life-threatening form of malaria parasite, which accounts for 60–70% of all confirmed cases in the Solomon Islands. Epidemics tend to occur when environmental conditions such as rainfall, temperature and relative humidity create optimal conditions for mosquito breeding.

The climate of the Solomon Islands is significantly influenced by the El Niño/Southern Oscillation (ENSO) phenomenon. El Niño conditions are generally associated with below-average rainfall and above-average temperatures, while La Niña conditions are generally associated with above-average rainfall and below-average temperatures. The tendency for the ENSO phenomenon to develop and then persist makes it possible to forecast seasonal rainfall and other hydroclimatic variables with some accuracy, employing key climate indices such as the Southern Oscillation Index and patterns of sea-surface temperature anomalies.

The Niño3.4 central equatorial sea-surface temperature anomaly index is an important and commonly accepted indicator of central tropical Pacific El Niño conditions (Reynolds and Smith, 1994; IOC, 2015). The index is used for detecting and predicting the ENSO phenomenon (Figure 1). It is calculated using satellite-derived sea-surface temperatures (mainly from AVHRR data), and in situ observations from the Tropical Atmospheric Ocean project moored buoy array. The sea-surface temperature anomaly is calculated relative to climatological seasonal cycle-based data collected between 1982 and 2005 and using the International Comprehensive Ocean-Atmosphere Dataset (ICOADS; Woodruff et al., 2011). Climate satellite records with higher precision (for example, (A)ATSR) but less geographical and temporal coverage are used to correct biases in the AVHRR record (GHRSST, 2015).

In combining local climate records of temperature and rainfall, malaria incidence data and a standard ENSO sea-surface temperature anomaly, there is potential to forecast elevated risk periods of malaria outbreaks in the Solomon Islands with a sufficient lead time to reduce the potential incidence of the disease through targeted control strategies.

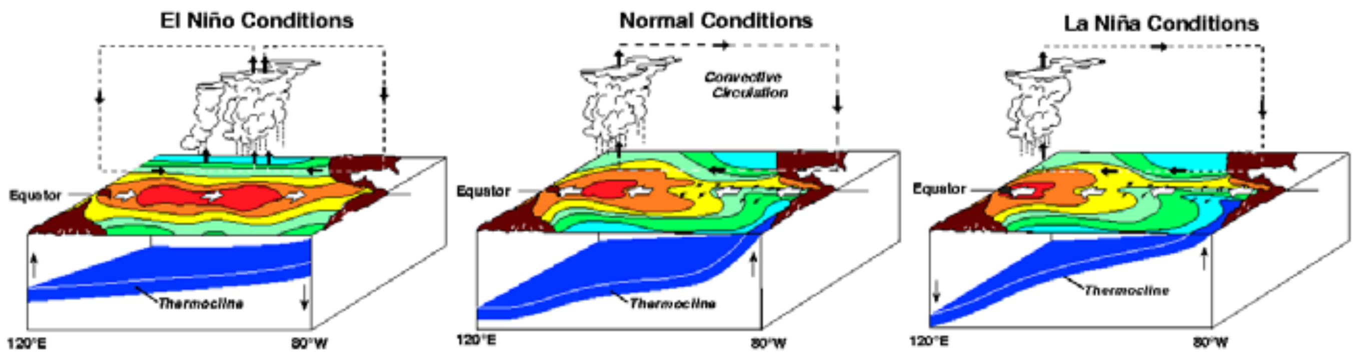


Figure 1. Ocean-temperature (surface and subsurface) and rainfall patterns over the Pacific during El Niño, La Niña and normal conditions (NOAA, 2015). The ENSO phenomenon has a significant impact on weather conditions in the Pacific Ocean and beyond, changing the likelihood of heavy rainfall and droughts in many parts of the world.

A prototype malaria early warning system

The application of seasonal forecasts to the development of a prototype malaria early warning system in the Solomon Islands has been the objective of a project funded by the Australian government. The project was defined and carried out in close collaboration with key users of the system, the Solomon Islands Meteorological Service and the Solomon Islands Medical Training and Research Institute, so that climate information could be effectively integrated into decisionmaking. The project formed part of a larger pilot programme funded by Australia to support Pacific islands' management of and responses to climate variability and change in vulnerable sectors, such as health.

A principal objective of the project was to develop malaria outlooks based on the historical relationship between malaria incidence and the effects of the ENSO phenomenon on rainfall and temperature. The influence of temperature on malaria development appears to be non-linear (IPCC, 2014) and vector-specific (Alonso et al., 2011). Analyses in East Africa show that abundance, distribution and disease transmission are affected in different ways by precipitation and temperature (Kelly-Hope et al., 2009). Determining the precise nature of those relationships in the Solomon Islands was therefore a key component of the project and the subject of lengthy investigation.

Once the relationships were well understood, it became possible to develop a prototype early warning system: the National Meteorological Service could issue bulletins signalling periods in which future climate conditions were likely to favour high malaria incidence; medical services and residents could then take measures to minimise infection. It is also expected that such forecasts would provide sufficient lead time for healthcare services to efficiently incorporate into their planning the need for additional medical resources during these periods.

Lessons from data

In collaboration with the Solomon Islands Medical Training and Research Institute, records of both confirmed and suspected malaria cases for nine provinces were obtained for the period 1975–2007. Corresponding climate data for this period, including rainfall, maximum and minimum temperature and relative humidity data, were prepared by the Solomon Islands Meteorological Service. Records were collected for each of the country's nine provinces and were collated into five regions for the purpose of this study.

Region-specific grouping of data gave significant consideration to geographical location, orographic effects and the availability of malaria outpatients and climate data. Considerable adjustments were made to population data and associated malaria incidence records to take account of the data grouping. Malarial incidence was calculated as a Positive Incidence Ratio, which is defined as the number of positive cases per 1 000 persons.

The numbers of confirmed malaria cases were identified using data from the period 1975–2008 during the peak infection period (December to May). Linear and non-linear regression techniques were used to relate Positive Incidence Ratio to climate factors (such as temperature and rainfall) and non-climate factors (such as population growth). The analyses (Figure 2) show that the incidence of malaria peaks during the wet season (December to April). Somewhat counter-intuitively, however, it was also evident that above-median rainfall during the wet season tends to suppress the number of malaria cases: mosquito breeding sites are likely flushed out by the above-average rainfall in such cases. Below-median rainfall during the wet season tends to increase the incidence of malaria.

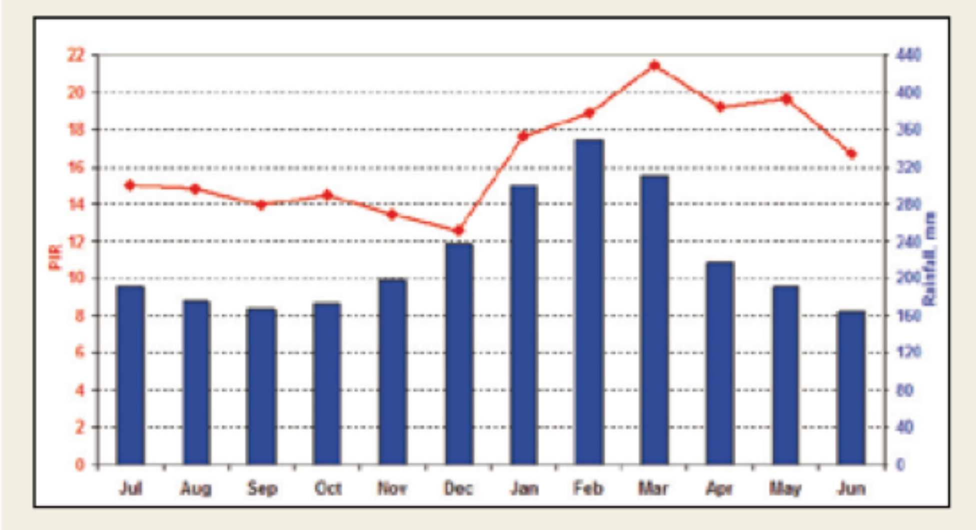


Figure 2. Relationship between Positive Incidence Ratio for malaria on the Solomon Islands and rainfall during the year

Sources: Australian Bureau of Meteorology and WMO, 2012

Those results indicate that malaria tends to be more prevalent during El Niño events and less so during La Niña events. The maximum correlation between rainfall and Positive Incidence Ratio is subject to a significant lag time: the Ratio lags behind rainfall by approximately two months. This makes rainfall a useful parameter for forecasting Positive Incidence Ratio with sufficient lead time to inform planning and management decisions. On the other hand, the influence of temperature on numbers of malaria cases tends to have a shorter lag time. This means that lower than normal rainfall from November to January, followed by higher than normal temperatures in December and January would trigger a high incidence of malaria.

In summary, climate factors (rainfall and temperature) explained up to 70% of variability in the number of malaria cases. An early warning system for malaria based on seasonal climate forecasts for the peak infection period was therefore assessed to be viable for the Solomon Islands.

Towards an operational service

This project has been a pioneering case study of the impact of climate variability and possible climate change on the health of a Pacific community. A prime example of the use of climate information to facilitate improvements in malaria management is the Malaria Early Warning System in sub-Saharan Africa, developed over the last decade by the Roll Back Malaria partners under the auspices of WMO. Now that a robust relationship between ENSO phenomena and malaria incidence in the Solomon Islands has been established, the development of a similar system for the Solomon Islands is considered feasible.

The results of the research described here were presented in a workshop in the capital of the Solomon Islands, Honiara, and received wide coverage in the local media. Following the workshop, Dr Jennifer Mitini, Director of National Health Research and Training, said:

> "The research has answered one of the burning questions we have really tried to answer in the past, but we didn't get results as comprehensive as this [study]. The most important next step is for [the health community] to start working with the Meteorological Services to use the information they collect to help guide us in our control actions, planning and management of malaria cases."

An operational early warning system will require the establishment of a number of protocols and procedures for ensuring the rapid and timely exchange of information between the national meteorological service and relevant health providers, as well as an effective means of informing key government entities and the wider population. The end results will be improved healthcare outcomes for residents of the Solomon Islands and a more appropriate provision of health services during periods of high malaria incidence. Those results will improve the standard of care, the quality of healthcare outcomes, and lead to cost savings due to a more efficient use of resources. In turn, those improvements will likely lead to benefits in the overall well-being of the local population, particularly during periods of high malaria risk and infection potential. There will also be long-term benefits to work and education output (due to a reduction in lost productivity from illness and incapacity), as well as

Figure 3. Climate information helps provide an early warning system for malaria outbreaks in the Solomon Islands, allowing for improved healthcare and a reduction in lost productivity. (WMO, 2012)

improvements to quality of life, subjective life satisfaction and possibly average life expectancy (Figure 3).

Sustained support by satellite operators to an operational health warning system relying on the detection of ENSO is now in place, because of the consistent availability of satellite sensors (such as AVHRR and SLSTR) that enable the derivation of sea-surface temperatures and the calculation of an ENSO index.

Although the study has focused on the Solomon Islands, the methodology could be more widely applied in a number of other Pacific island nations to improve the management of malaria in Papua New Guinea and Vanuatu, dengue fever in Fiji and waterborne pathogens in Kiribati. Contrary to common belief, this study has concluded that if a certain rainfall threshold is exceeded, the incidence of malaria can reduce significantly.

It is not clear whether direct extrapolation of the results of this study to other areas is appropriate, due to factors which can significantly affect the epidemiology of climate-related illness. Those include the substantial differences in the effects of the ENSO cycle on different Pacific island countries and variations in topography and geography across the region.

(Note: The material of this case study is strongly based on text and images published in *Climate ExChange* (WMO, 2012), pp. 100–103.)

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CASE STUDY 13

STRATOSPHERIC OZONE MONITORING AND ASSESSMENT FOR DETERMINING EFFICACY OF THE MONTREAL PROTOCOL

SUMMARY

Title
Stratospheric ozone monitoring and assessment for determining efficacy of the Montreal Protocol

Service
Regular assessment of the state of the ozone layer (including levels of ozone and ozone-depleting substances, many of which are greenhouse gases)

End users
- International bodies (e.g. UNEP, Meeting of the Parties of the Montreal Protocol)
- National governments
- Environmental agencies
- Compliance monitoring agencies
- Health agencies

Intermediate users
- Research scientists
- Policymakers, economists

Application(s)
- Protocol monitoring and compliance verification
- Scientific assessment

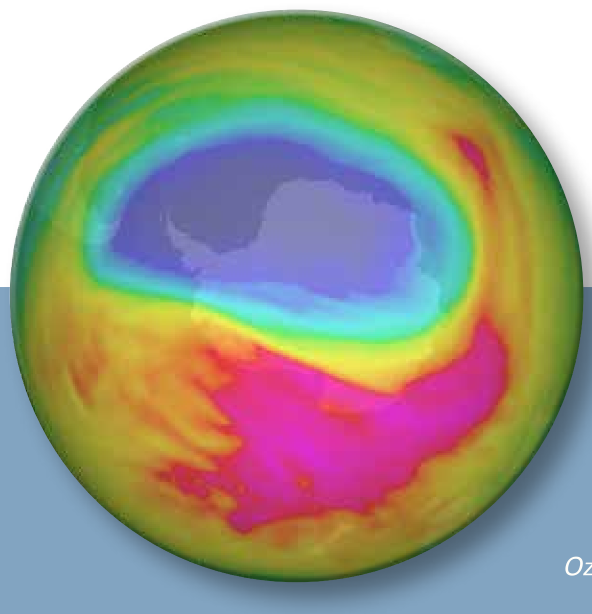
Models used
- Global climate models
- Atmospheric models with coupled chemistry

Climate data records used
- Ozone (total column and vertical profile)
- Long-lived greenhouse gases (e.g. chlorofluorocarbons (CFCs)), other constituents relevant to ozone chemistry (e.g. chlorine and bromine containing gases)
- Methane

Satellite observations used
- Ozone: SBUV, OMI, MLS, GOME-2, Sciamachy, IASI, OMPS-Limb, OSIRIS, SAGE-II, SAGE-III
- Hydrochloric acid: MLS, HALOE
- CFCs: ACE-FTS, TES
- Methane: ACE-FTS, Sciamachy

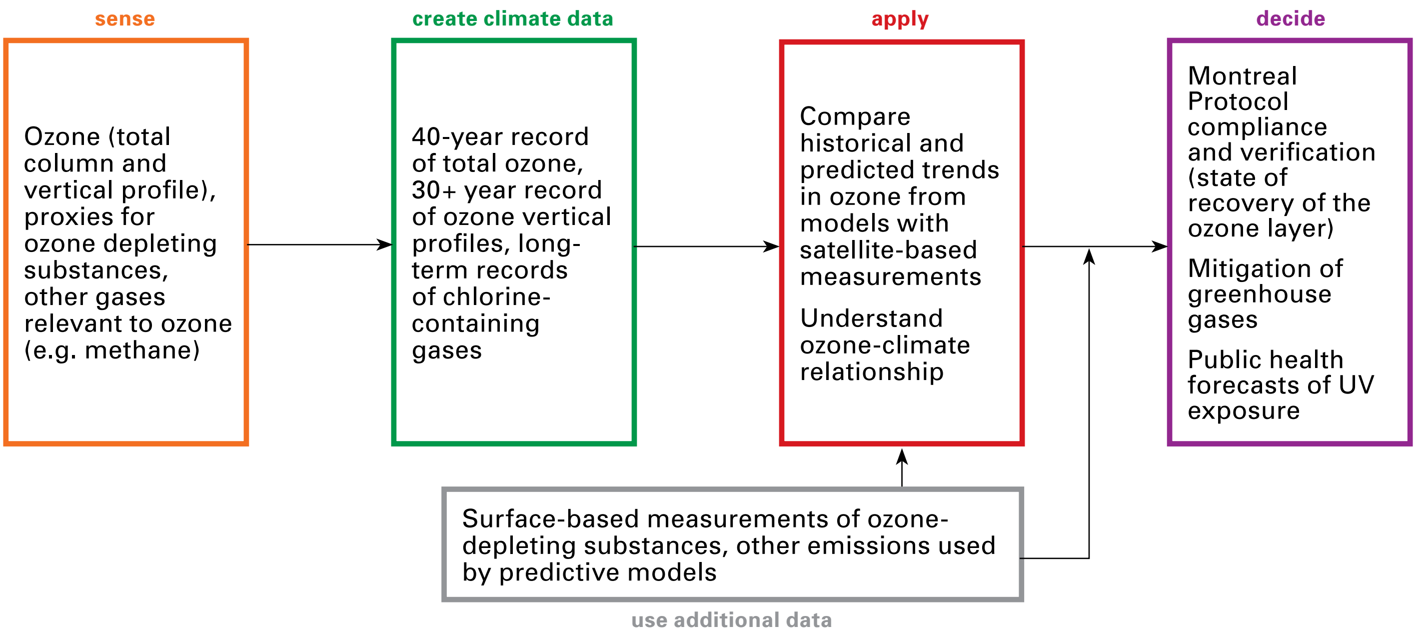
Agencies that produce records
- USA: NASA and NOAA
- Europe: ESA, EUMETSAT

Sustainability of service (demonstration or ongoing)
Satellite measurements of ozone and other constituents relevant to ozone chemistry have been conducted since the 1970s. National space agencies have current and planned missions that will continue the high-quality measurements needed to maintain long-term time series of ozone and shorter records of other important atmospheric constituents needed to improve our understanding of ozone chemistry.



Ozone depletion over Antarctica

INFORMATION FLOW



DESCRIPTION

In 1974, Molina and Rowland first suggested that human-produced CFCs could deplete stratospheric ozone. By the early 1980s, policymakers had taken on the challenge of regulating the production and consumption of these ozone depleting substances and a number of countries had combined their efforts to produce reports on ozone depletion.

In 1985, the atmospheric community was surprised by the published confirmation of a severe downward trend in ozone levels over Antarctica at the British Antarctic Survey's Halley Station (Farman et al., 1985). Figure 1 shows the first image of this depleted Antarctic region (WMO, 1985). This image most likely led to the coining of the term "Antarctic ozone hole." The combination of the strong downward trend of ozone levels over Halley Station and the continental-scale image of this depleted region spawned an immediate scramble by atmospheric scientists to unravel the puzzle of this polar ozone depletion. In the same year, the first major report on ozone depletion "Atmospheric Ozone:

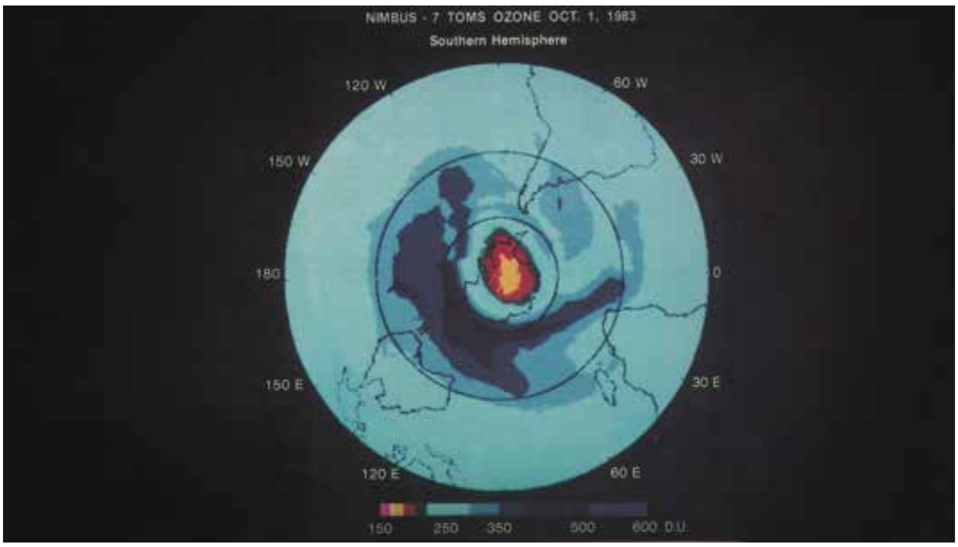


Figure 1. False colour image of total column ozone from the Nimbus-7 satellite's Total Ozone Mapping Spectrometer (TOMS). This is the first image made of the Antarctic ozone hole.

1985" was published under the auspices of the United Nations Environmental Programme and WMO with the assistance of scientists and government science agencies across the world.

The nations of the world responded to the growing body of scientific research by negotiating the Vienna Convention for the Protection of the Ozone Layer. In 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was finalized. In subsequent years, the Montreal Protocol has been strengthened and CFC production and consumption is now banned throughout the world.

The Montreal Protocol is the primary customer for the scientific assessments of ozone depletion. These assessments are mandated under the Protocol every 4 years (the most recent is "The Scientific Assessment of Ozone Depletion: 2014 (WMO, 2014)"). The terms of reference agreed on by the parties to the Protocol ask for information on amounts of ozone depleting substances, on ozone levels and on general stratosphere-related climate issues. While the Montreal Protocol is primarily a treaty that deals with ozone depletion, CFCs and their substitutes also have a powerful impact on the climate. The Montreal Protocol is therefore evolving as climate issues become a major factor in regulating the consumption and production of fluorinated species such as hydrofluorocarbons.

The ozone depletion issue has now entered an "accountability phase". Scientists predicted large ozone losses from ozone depleting substances, governments acted, and levels of such substances have declined since the mid-1990s. Models have projected that the ozone layer will recover by the middle of the century, but these projections must be verified by observations. Current satellite-based observations of total column ozone and ozone profiles (such as the ozone monitoring and profiler suite, OMPS) are the primary measures for validating these projections, and for observing anomalies (such as volcanic forced ozone losses). Ozone observations in the upper stratosphere show hints of recovery, but these results are preliminary (WMO, 2014).

Projections of future ozone levels are thrown off balance by increasing levels of greenhouse gases. In particular, increasing carbon dioxide levels lead to a cooling of the stratosphere. That cooling slows ozone catalytic cycles and should lead to a more rapid increase of ozone over the course of the 21st century. Observations of greenhouse gases, mid-to-upper stratospheric temperature and ozone are key to separating the effects of ozone-depleting substances and greenhouse gases. Figure 2 shows the future projected ozone levels for various greenhouse gas scenarios. While the decline in levels of ozone-depleting substances will cause ozone levels to increase, stratospheric ozone levels will be strongly affected by future greenhouse gas levels.

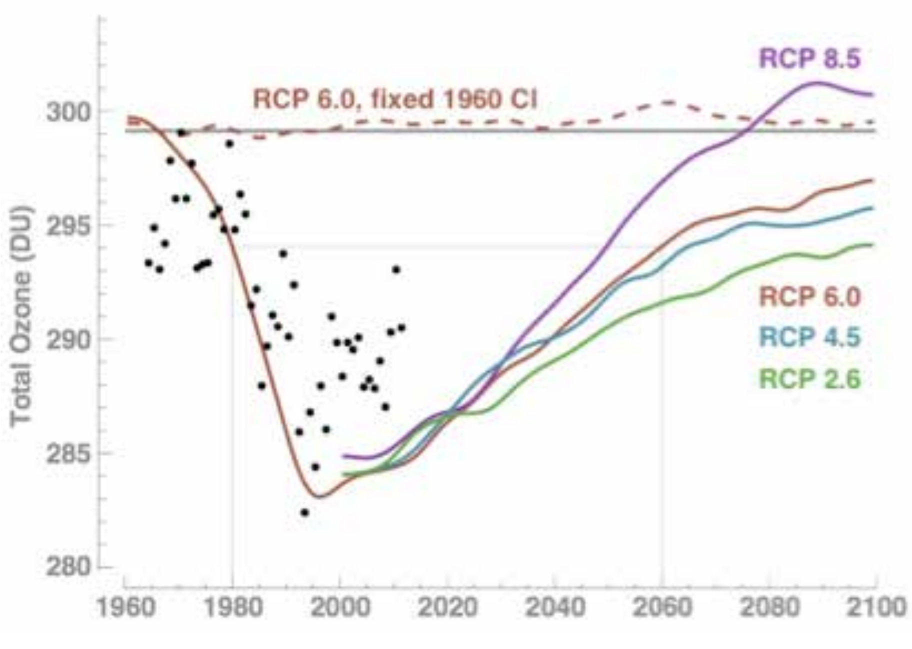


Figure 2. Total column ozone (60°S–60°N). Satellite observations in black, with coupled chemistry climate model simulations in colour. The model is forced with various greenhouse gas scenarios, known as representative concentration pathways (RCPs). A low greenhouse gas level is associated with RCP 2.6, while the highest levels of greenhouse gases are with RCP 8.5. The brown solid line (RCP 6.0) shows the model simulation forced by observed levels of ozone-depleting substances and greenhouse gas levels up to 2013, with a "high" greenhouse gas simulation up to 2100. The brown dashed line shows simulated total column ozone under a RCP 6.0 scenario assuming zero emission of ozone depleting substances.

The Montreal Protocol contributed to limiting greenhouse gas levels, since many ozone-depleting substances that have been phased out under the Protocol are potent greenhouse gases. On the other hand, some replacement substances such as hydrofluorocarbons are strong greenhouse gases and their concentration levels have increased rapidly. It is therefore important that the Montreal Protocol develops in order to estimate future greenhouse gas levels and climate projections.

In addition to ozone and temperature data, satellite observations provide key information to the Montreal Protocol on stratospheric water vapour and aerosol levels (key surface radiative forcings). Satellite observations also allow the tracing of stratospheric chlorine levels by observations of hydrochloric acid in the upper stratosphere. Observations by the Atmospheric Chemistry Experiment (ACE) instrument on SCISAT also provide hydrochloric acid observations and include measurements for CFCs and other gases that can be used to trace the annual cycle of stratospheric species and year-to-year changes of the stratospheric circulation.

Satellite observations are key to ensuring that the international regulation of ozone-depleting substances is working correctly. As levels of ozone in the stratosphere control surface ultraviolet levels, changes in ozone are critical for understanding environmental changes of surface ultraviolet as the stratosphere evolves over the 21st century.

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CONCLUDING FINDINGS AND REMARKS

The 13 case studies show that the main elements of the Architecture for Climate Monitoring from Space (ACMS) are consistent and an effective means of capturing information flow from observations to services.

The case studies cut across different climate domains, spatial scales and geographic areas. They reflect the various levels of decisionmaking in climate-sensitive sectors and show the variety and complexity of contexts in which satellite data can support climate services.

The case studies demonstrate that satellite-based climate data records provide a critical baseline for many climate services. Such records are also very important for climate reanalyses, which in turn underpin a wide range of climate services. In many cases, climate services are generated using a combination of data records from satellites, surface-based observing systems and other sources of information, such as models or socioeconomic data.

In addition to satellite-based climate data records, the importance to climate services of near-real-time satellite data that do not, or only partially, meet climate standards can be seen in several climate service case studies, including on operational drought monitoring, short-term forecasting of renewable energy supply (levels of wind and solar irradiance), or in analysis of anomalies (such as forest cover, sea-ice structure, ozone concentration). Complementary climate data records from surface-based observing systems and other data sources are additionally required for many services.

The case studies reflect the various levels of decision-making in climate-sensitive sectors at global, regional, national, and local scales. However, while an organized information flow from global to national and local scales is in place for weather services, such an information flow does not universally exist for climate services.

The case studies rely on datasets from both research and operational missions. That makes clear that research datasets are an integral part of many operational services, as acknowledged and taken into consideration in the strategy report.[1] While research missions are essential to advance the state-of-the-art, space agencies operating such missions should consider engaging with broader user communities in defining mission requirements for sustained observations.

In a variety of case studies, services heavily depended on climatological products in estimating anomalies for specific geophysical variables. It is recommended that both data providers and users establish better linkages to technical communities working on climatology development. This will ensure that state-of-the-art methods are being adopted by climate service providers, and that climatologies of geophysical parameters beyond meteorology, which are of interest to the users of climate services, are being generated.

In a number of the case studies, classical meteorological variables are used as well as additional geophysical, biophysical and atmospheric composition variables. It is likely that the demand for such a combination of variables will only increase further as the scope of, and demand for, climate services widens. It is important that the operational data providers (such as national meteorological services) become increasingly aware of these additional requirements and datasets, and that these are taken into consideration in the context of their future missions and programmes.

Several case studies highlight the importance of ancillary socioeconomic and demographic information. For example, disaster risk reduction requires data on exposure, population, urban infrastructure, crop information and subsidence due to groundwater extraction. Impacts at a local level are invariably context-dependent: their assessment requires that such contextual data be provided specifically at that level. (Some of these data are also directly or indirectly satellite-derived, such as high-precision digital elevation models, population density estimates from high-resolution imagery or mapping of night-time light sources.)

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1 Dowell et al. (2013), p28: "The climate community has stressed that the overarching goal of observing and monitoring the climate system requires [...] the continued effort of both research and operational agencies. Research agencies have invested in the creation of consistent time-series satellite datasets over decades, both through mission science, team-based and measurement-based climate product processing and reprocessing. Research agencies have also made and will maintain significant investment in calibration laboratories, airborne sensors, processing facilities, and ground networks that support calibration and validation activities for satellite programmes. These contributions to climate science will need to continue to be a vital element of a collaborative climate observation and processing architecture as operational climate services move forward to emerge in operational agencies."

Looking forward, the report shows that:

At the WMO and wider international level, there is currently no process in place to systematically capture climate and GFCS-related service requirements that could be translated into product, observation and instrument requirements. This is a serious issue, since end users of climate services expect effective services from climate information providers in response to their problems and requirements. It is also an issue in many countries, where the systematic identification of climate service requirements and service-driven observation requirements for all climate-sensitive sectors are in their infancy.

Depending on the user's technical expertise, requirements themselves span across the different levels set out in the Architecture (sensing – applying – deciding) and are not limited to any particular level. Those levels, for example, include climate data records (such as a 40-year infrared radiance time series), indicators (an El Niño/Southern Oscillation index, a drought index or a seasonal climate outlook) or synthesized reports (on issues such as annual deforestation rates or crop yield forecasts).

User requirements need to be captured at the different levels of the ACMS, translated into technical deliverables, and addressed through the future development of the Architecture. This should be done through gap analyses and dedicated action to respond to these gaps. Positive contributions could be made by existing WMO programmes (such as the World Climate Services Programme (WCSP)), GCOS, the emerging GFCS User Interface Platform, GEO and the work of the CEOS-CGMS Working Group on Climate.

Several case studies show the use of satellite and in situ data, model output and reanalysis; most are dependent on a range of data sources. Further development of the ACMS should be compatible, as appropriate, with the generic flow of information for a range of data sources (reflected by the modified information flow diagram in Figure 2).

To ensure that climate services are fit for purpose, feedback mechanisms between service users and providers are essential. Several case studies show that climate services are under active development and further improvement is necessary. The ACMS currently reflects a static information flow through the "pillars" of the Architecture. Looking to the future the ACMS also needs to include a feedback loop that assesses the extent to which observing systems and products developed for specific applications are fit for purpose.

One advantage of the Architecture lies in the common structure and terminology it provides. This should facilitate dialogue between data producers and users of climate services across sectors. The Architecture helps producers to improve the way in which they support users' needs as observing systems and derived data products develop. The dialogue should include not only meteorological services, but also the many entities with thematic competencies in relevant sectors such as agriculture, health, forestry, energy and water resource management.

Within the producer–user dialogue, the capacity-building needs of actual and potential climate service users should be systematically identified. The ACMS provides a framework for identifying capacity-building needs at all levels of the information flow, which is consistent with the emerging GFCS User Interface Platform.

An online platform should be established that allows interactive exploration of the region- and country-specific climate service case studies, including key actors, information flows, dependencies, societal benefits and other details.

APPENDIX

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