→ ESA'S LIVING PLANET PROGRAMME: SCIENTIFIC ACHIEVEMENTS AND FUTURE CHALLENGES

Scientific Context of the Earth Observation Science Strategy for ESA

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Preface

In 2006, the European Space Agency (ESA) published *The Changing Earth: New Scientific Challenges for ESA's Living Planet Programme* (ESA, 2006), which addressed the most important challenges in understanding the Earth system at the time, and the ways in which satellite observations could make major contributions to advance knowledge. Along with a set of 25 scientific challenges, the document set out appropriate responses whereby ESA could address these important Earth science questions.

An Earth Observation Science Review meeting in 2011 recommended that the science strategy and the scientific challenges be periodically updated. In response, ESA's Earth Science Advisory Committee (ESAC) prepared a new strategy, *Earth Observation Science Strategy for ESA: A New Era for Scientific Advances and Societal Benefits* (ESA, 2015).

A set of revised scientific challenges was presented to the Programme Board for Earth Observation in November 2013. Subsequently, a more detailed description of the challenges was prepared to support the *Earth Observation Science Strategy for ESA*. This publication:

- reviews the achievements in the various Earth system disciplines with respect to the previous challenges (ESA, 2006); and
- provides a revised set of challenges for ESA's Living Planet Programme and puts them in the context of the new *Earth Observation Science Strategy for ESA*.

This publication was compiled as a result of a concerted effort between ESAC and a team of selected external scientific experts.

Contents

Executive Summary

The new *Earth Observation Science Strategy for ESA: A New Era for Scientific Advances and Societal Benefits* provides key elements and scientific direction for the future progress of ESA's Living Planet Programme. The specific scientific challenges to increase knowledge and capabilities in the five Earth science disciplines – atmosphere, cryosphere, land surface, ocean and solid Earth – are identified in the complementary volume, *ESA's Living Planet Programme: Scientific Achievements and Future Challenges – Scientific Context for the Earth Observation Science Strategy for ESA* (ESA, 2015). This volume describes the tremendous scientific effort and progress towards a better understanding of the Earth system that could still be obtained through satellite observations from past decades. It provides a link between the previous scientific challenges identified in *The Changing Earth* (ESA, 2006) and the new Living Planet Scientific Challenges. Furthermore, it provides a current picture of past and ongoing ESA activities and projects, as well as national and international activities.

ESA's new Earth observation Science Strategy aims to cover all areas of science to which Earth observation missions can make a vital contribution. The overarching goal is to challenge ESA and the scientific community to strive for major advances in knowledge along with the technological capabilities that will be needed to respond to ever-increasing societal needs associated with risks and opportunities in our changing global environment. The Science Strategy identifies the following key elements:

- Ground-breaking exploratory missions integrated into flexible observing systems for Earth system science.

- Sustained observations to understand and attribute trends beyond the expected variability.

- International cooperation to provide an integrated, optimised Earth observing system that can fill gaps in observational needs and build new capabilities in a cost-effective way.

- Translational science to synthesise and adapt the data streams from individual instruments and satellites into knowledge.

- Wide communication and dialogue with individuals beyond the scientific sector to help explain the value, opportunities and inspiration provided by Earth observation from space.

The most important Earth science questions to be addressed in the years to come are outlined in the updated scientific challenges summarised below. Measurements provided by satellites are critical in providing access to many of the key elements of the Earth system. Progress in meeting these scientific challenges will provide the foundation for the multidisciplinary science that is needed to secure societal benefits from scientific progress.

ESA must continue to fulfil its critically important role as a knowledgeable agency to provide the essential infrastructure and to nurture the Earth observation scientific community. This role must be undertaken in close partnership with national and international agencies, and with funding bodies, to deliver the crucial benefits of Earth observation from space for science and society.

The updated scientific challenges (shown in blue, to distinguish them from the 2006 challenges in black) are to improve understanding and quantification of various elements in each of the five Earth science disciplines:

Atmosphere

- *Challenge A1:* Water vapour, cloud, aerosol and radiation processes and the consequences of their effects on the radiation budget and the hydrological cycle.

- *Challenge A2:* Interactions between the atmosphere and Earth's surface involving natural and anthropogenic feedback processes for water, energy and atmospheric composition.

- *Challenge A3:* Changes in atmospheric composition and air quality, including interactions with climate.

- *Challenge A4:* Interactions between changes in large-scale atmospheric circulation and regional weather and climate.

- *Challenge A5:* Impact of transient solar events on Earth's atmosphere.

Cryosphere

- *Challenge C1:* Regional and seasonal distribution of sea-ice mass and the coupling between sea ice, climate, marine ecosystems and biogeochemical cycling in the ocean.

- *Challenge C2:* Mass balance of grounded ice sheets, ice caps and glaciers, their relative contributions to global sea-level change, their current stability and their sensitivity to climate change.

- *Challenge C3:* Seasonal snow, lake/river ice and land ice, their effects on the climate system, water resources, energy and carbon cycles; the representation of the terrestrial cryosphere in land surface, atmosphere and climate models.

- *Challenge C4:* Effects of changes in the cryosphere on the global oceanic and atmospheric circulation.

- *Challenge C5:* Changes taking place in permafrost and frozen-ground regimes, their feedback to climate system and terrestrial ecosystems (e.g. carbon dioxide and methane fluxes).

Land Surface

- *Challenge L1:* Natural processes and human activities and their interactions on the land surface.

- *Challenge L2:* Interactions and feedbacks between global change drivers and biogeochemical cycles, water cycles, including rivers and lakes, biodiversity and productivity.

- *Challenge L3:* Structural and functional characteristics of land use systems to manage sustainably food, water and energy supplies.

- *Challenge L4:* Land resource utilisation and resource conflicts between urbanisation, food and energy production and ecosystem services.

- *Challenge L5:* How limiting factors (e.g. freshwater availability) affect processes on the land surface and how this can adequately be represented in prediction models.

Ocean

- *Challenge O1:* Evolution of coastal ocean systems including the interactions with land in response to natural and human-induced environmental perturbations.

- *Challenge O2:* Mesoscale and submesoscale circulation and the role of the vertical ocean pump and its impact on energy transport and biogeochemical cycles.

- *Challenge O3:* Response of the marine ecosystem and associated ecosystem services to natural and anthropogenic changes.

- *Challenge O4:* Physical and biogeochemical air–sea interaction processes on different spatiotemporal scales and their fundamental role in weather and climate.

- *Challenge O5:* Sea level changes from global to coastal scales and from days (e.g. storm surges) to centuries (e.g. climate change).

Solid Earth

- *Challenge G1:* Physical processes associated with volcanoes, earthquakes, tsunamis and landslides in order to better assess natural hazards.

- *Challenge G2:* Individual sources of mass transport in the Earth system at various spatiotemporal scales.

- *Challenge G3:* Physical properties of the Earth crust and its relation with natural resources.

- *Challenge G4:* Physical properties in the deep interior, and their relationship to deep and shallow geodynamic processes.

- *Challenge G5:* Different components of the Earth magnetic field and their relation to the dynamics of the charged particles in the outer atmosphere and ionosphere for space weather research.

→ ESA'S LIVING PLANET PROGRAMME: SCIENTIFIC ACHIEVEMENTS AND FUTURE CHALLENGES

1. Introduction

This volume complements the *Earth Observation Science Strategy for ESA: A New Era for Scientific Advances and Societal Benefits* (ESA, 2015). It highlights specific scientific challenges to increase knowledge and capabilities in the Earth science disciplines. These discipline-based challenges are indicative of the scientific advances that will be needed to tackle the serious global environmental issues we now face. In the context of these new scientific challenges, this volume also summarises the achievements of ESA's Living Planet Programme with respect to the challenges set out in July 2006 in *The Changing Earth: New Scientific Challenges for ESA's Living Planet Programme* (ESA, 2006).

1.1 Changes in the Context of the Living Planet Programme

Advances in Earth system science, in remote sensing and in the information obtained from ESA's Earth Explorer satellites in recent years have had significant impacts on ESA's Earth observation programmes, suggesting the need to review and update the Living Planet Scientific Challenges (LPSCs) formulated in 2006 in *The Changing Earth*.

1.1.1 Four Earth Explorers

Since March 2009, four Earth Explorer missions (Fig. 1.1) have been launched following on from the wealth of scientific achievements brought about by Envisat, which operated between 2002 and 2012, and ERS-1/ERS-2, which operated between 1991 and 2011.

The first Earth Explorer, the Gravity field and Steady-state Ocean Circulation Explorer (GOCE), was launched in March 2009. GOCE's highly sensitive gravity gradiometer has detected gravity field anomalies with unprecedented accuracy and resolution. GOCE has provided the most accurate model of the geoid ever produced, with applications in ocean dynamic topography and circulation and also geodesy, solid Earth and glaciology.

Figure 1.1. Four Earth Explorers: GOCE, SMOS, CryoSat and Swarm. (ESA/ATG Medialab)

The Soil Moisture and Ocean Salinity (SMOS) satellite, launched in November 2009, measures microwave radiation emitted from Earth's surface using an interferometric radiometer. The principal goal of SMOS is to measure and monitor soil moisture and ocean salinity.

The third Earth Explorer, CryoSat-2, launched in April 2010, carries a sophisticated radar altimeter to acquire accurate measurements of the thickness of floating sea ice so that annual variations can be detected, and to survey the surfaces of ice sheets accurately enough to detect small changes. CryoSat-2 has also made important contributions to ocean altimetry.

Swarm – a three-satellite mission – was launched in November 2013. Swarm measures the geomagnetic field by identifying and measuring magnetic signals from Earth's core, mantle, crust, oceans, ionosphere and magnetosphere.

These missions have achieved, or are about to achieve, their main objectives and have addressed a number of LPSCs. They have enabled interdisciplinary science, leading to a number of significant discoveries and a diverse range of potential applications.

1.1.2 Future Earth Explorer Missions

Three further Earth Explorer missions are under preparation and are scheduled to be launched between 2015 and 2020:

- The Atmospheric Dynamics Mission (ADM-Aeolus; Fig. 1.2) will provide direct global measurements of 3D wind fields, which will lead to improvements in numerical weather predictions and climate models.

- The Earth, Clouds, Aerosols and Radiation Explorer (EarthCARE; Fig. 1.3) will quantify cloud–aerosol–radiation interactions, improving their representation in climate and numerical weather prediction models.

- Biomass, selected as the seventh Earth Explorer in 2013, will determine the distribution of above-ground biomass in tropical forests and annual changes in this carbon stock.

Figure 1.2. ADM-Aeolus. (ESA/ATG Medialab)

Figure 1.3. EarthCARE. (ESA – P. Carril, 2013)

1.1.3 Operational Observation Capabilities under Development

ESA is developing a series of six new missions, called the Sentinels, specifically for the operational needs of Europe's Copernicus programme. The first Sentinel satellite, Sentinel-1A, was launched in April 2014.

The Sentinels carry a range of technologies such as radar (Fig. 1.4) and multispectral imaging instruments to monitor the land, ocean and atmosphere. This accurate, timely and easily accessible information will improve the understanding of the environment, help to understand and mitigate the effects of climate change and also help ensure civil security.

The Sentinels will ensure continuity, building on ESA's heritage ERS-1/ERS-2 and Envisat missions. The new Sentinel missions will benefit science by providing uninterrupted data for about two decades. This makes the missions valuable in contributing to deeper insights into the processes and interactions that make up the Earth system, how they are changing as a result of human activities, and how these changes are affecting humans and life on Earth.

Figure 1.4. One of the first radar images from Sentinel-1. (Copernicus data/ESA 2014)

Figure 1.5. MetOp Second Generation. (ESA – P. Carril)

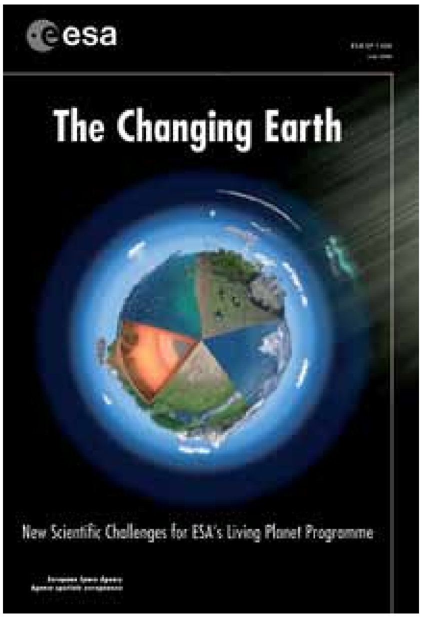
ESA is also developing the geostationary Meteosat Third Generation (MTG) series, which will provide significant observational improvements over the current Meteosat satellites, and will take weather forecasting to the next level.

The Eumetsat Polar System is providing precise observations to improve weather and climate forecasts through MetOp-A, launched in 2006, and MetOp-B, launched in 2012. MetOp-C will follow in 2016. This series of satellites guarantees the continuous delivery of high-quality data from polar orbit for short-, medium- and extended-range weather forecasting and climate monitoring until at least 2020. The second generation of MetOp satellites (MetOp-SG; Fig. 1.5), currently under development, will take over after 2020 with enhanced capabilities for climatology and atmospheric science.

A key role of ESA's Living Planet Programme is to drive and deliver advances in technological innovation and scientific capabilities into a sustained, internationally integrated 'Earth observing system' both for science and for downstream applications.

At the programmatic review of the Earth Observation Envelope Programme in 2011, the Science Review Panel recommended that the Living Planet Scientific Challenges set out in *The Changing Earth* (Fig. 1.6) be reviewed and updated periodically to ensure that their priorities and context remain valid. This recommendation recognised that processes related to global change, climate and environment – and their associated social impacts – are complex and evolving.

Figure 1.6. *The Changing Earth: New Scientific Challenges for ESA's Living Planet Programme.* (ESA, 2006)



1.2 Reviewing the 2006 Strategy

To ensure that the review of the 25 Living Planet Scientific Challenges was carried out in a sustained manner with broad scientific community support, ESA's Earth Science Advisory Committee (ESAC) proceeded in three steps.

1.2.1 Consultations with Scientists to Review the Living Planet Scientific Challenges

In May–June 2013, ESA consulted over 50 scientists from various fields to review and assess the 2006 challenges. They provided valuable inputs, including records (journal articles, books, relevant new products, etc.) and assessments of the progress made since 2006. Many scientists suggested that the 25 LPSCs needed to be updated, and stressed the increasing importance of addressing the value of future missions for the benefit of society. They also identified gaps in observational needs. None of the LPSCs set out in 2006 were considered to have been fully met or to be completely obsolete.

1.2.2 Updating the Living Planet Scientific Challenges

ESAC carefully reviewed and analysed the scientists' comments. The committee noted the positive comments made by several scientists about the success of the Living Planet Programme, and in particular the progress made in addressing the LPSCs. The original challenges have guided the development of Earth science missions for over a decade and have contributed to today's improved understanding of the Earth system. ESAC also noted the scientists' advice to include cross-cutting elements that would describe the interactions and interdependencies between Earth science disciplines, and would respond directly to societal and economic challenges and needs.

1.2.3 Discussions at the 2013 Living Planet Symposium

ESAC presented the LPSCs for discussion with the scientific community at the Living Planet Symposium, held in Edinburgh, UK, on 9–13 September 2013 (Fig. 1.7). At the symposium, which was attended by more than 300 scientists, two sessions were dedicated to discussing the LPSCs.

During these open discussions, the scientists made wide-ranging comments, emphasising the increasing need to connect ESA's science activities and technological advances to global societal issues. Many pointed to the strong multidisciplinary connections among the challenges and the increasing need for international collaboration to respond to them.

In addition, all Living Planet symposium participants were asked to provide additional comments and suggestions by email after the meeting. The various communities provided feedback and support for the newly defined challenges.

This report summarises the updated LPSCs, formulated by ESAC in consultation with the scientific community, through which ESA will address the most important Earth-science related questions in the years to come.

Figure 1.7. ESA's 2013 Living Planet Symposium. (ESA/M. Cochrane)

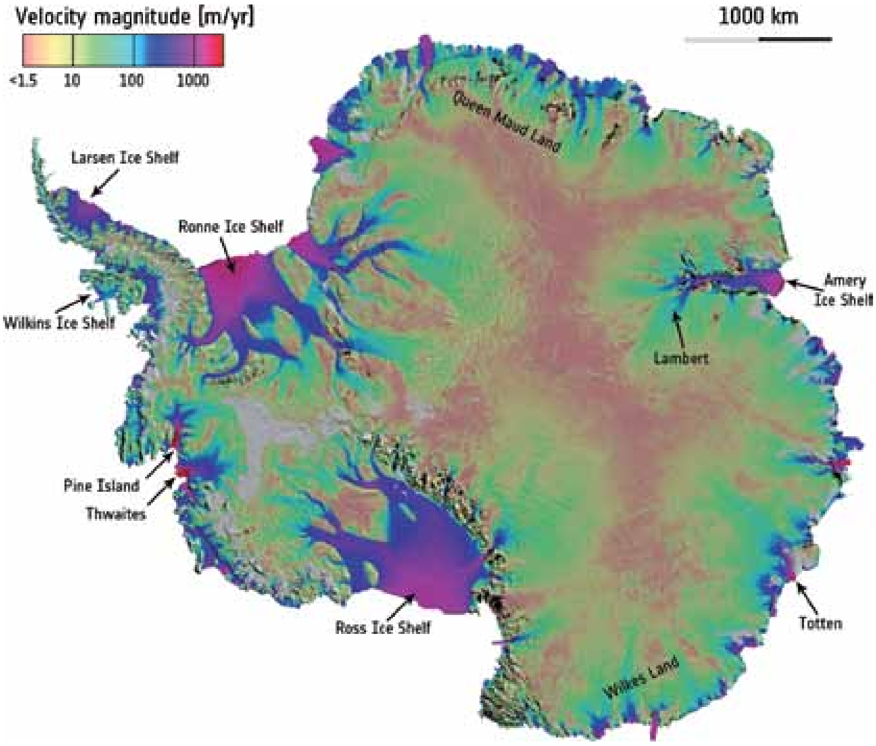


Figure 1.8. The first map of ice velocity in Antarctica. (Rignot et al., 2011)

1.2.4 Earth Observation Missions and the Benefits for Society

Over the past decades, ESA's Earth observation satellites have been monitoring our home planet, providing scientists with unique insights into how the oceans, ice, atmosphere, land and Earth's interior operate as parts of an interconnected system. At the same time, satellite observations have revealed dramatic global environmental changes induced by human activities. ESA's missions have provided insights into a number of societal and economic impacts of these changes; for example:

- The melting of polar ice will have dramatic impacts on the Arctic, leading to increased oil and gas exploration, transport and tourism (Pew, 2010).

- The melting or collapse of ice sheets (see Fig. 1.8) and the resulting sea-level rise could eventually threaten areas that are currently home to one in 20 of the world's population (Stern Report, 2008).

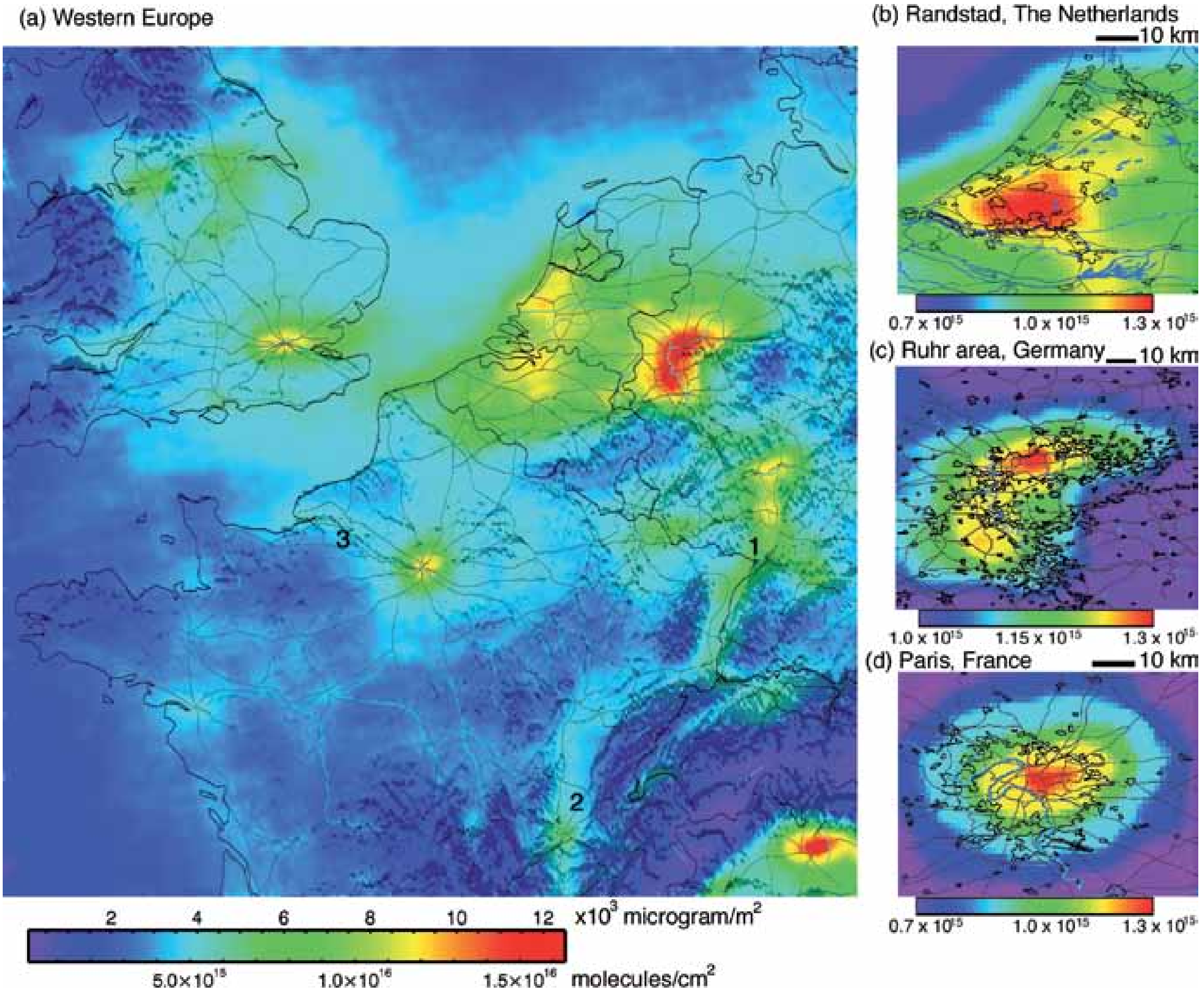
- The global economic costs associated with rapid deforestation and the resulting impacts of climate change could rise to around €800 billion per year by 2100. The total cost of forest loss could be as high as €9000 billion in net present value terms (Eliasch, 2010). New mechanisms such as the UN's Reducing Emissions from Deforestation and Forest Degradation (REDD+) programme are now being put in place to protect forests, particularly in tropical regions and developing countries. It is estimated that in excess of €16 billion per year will need to be transferred from developed to developing countries (EC, 2008). Forest monitoring from space will play a key role in the implementation of REDD+ (e.g. the Group on Earth Observations' Global Forest Observation Initiative; *www.gfoi.org*).

- Growing numbers of people are experiencing water stress. If present trends continue, an estimated 1.8 billion people will be living in countries or regions suffering water scarcity by 2025, and two-thirds of the world's population could be subject to water stress (CEOS/ESA, 2012), with dramatic consequences for coastal ecosystems and agriculture.

- The costs of responding to the impacts of natural and anthropogenic hazards are growing. Examples include the Japanese earthquake and tsunami in 2011, where losses were estimated at about €168 billion (Munich Re, 2012); the Icelandic volcanic eruption in 2010, where the estimated losses for airlines alone amounted to about €1.7 billion (IATA, 2010); and the Deepwater Horizon oil spill in 2010, which released about 4.9 million barrels of crude oil into the environment (OSHA, 2011), requiring the oil company BP to set up a compensation fund of €16 billion (BP website).

- Air quality is deteriorating. It is estimated that the 10 000 largest polluting facilities in Europe cost citizens between €102 billion and €169 billion in 2009 in terms of adverse health and environmental impacts. (EEA, 2011; Fig. 1.9).

Figure 1.9. Concentrations of tropospheric nitrogen dioxide over Europe as measured by the Ozone Monitoring Instrument from December 2004 to November 2005. (Pepijn Veefkind, KNMI)



1.3 Living Planet Challenges

The accompanying volume *Earth Observation Science Strategy for ESA* (ESA, 2015) describes how ESA is addressing all areas of science where their missions can make vital contributions. While it is important to note that the discipline-based challenges described here should be regarded as indicative of the scientific advances that will be needed in a rapidly changing world, they can also:

- provide the basis and direction for future work in each of the five themes – atmosphere, cryosphere, land surface, ocean and solid Earth – in terms of scientific studies, technological developments and campaigns;
- provide information about gaps in observations in the five themes and the coupling of these themes;
- be used to guide the calls for and selection of future ESA missions;
- form the basis for the development of new Earth observation applications; and
- contribute to educating the public, policy makers and scientists with respect to the benefits of the use of Earth observation data.

2. The Scientific Challenges in a Changing World – Updated Living Planet Challenges and Achievements in Context

This chapter describes the scientific context of the updated Living Planet Scientific Challenges and reviews the achievements in responding to the previous challenges (ESA, 2006) in each of the five Earth system disciplines – atmosphere, cryosphere, land surface, ocean and solid Earth. These achievements provide a snapshot in time, as new achievements are continuously being made at national and international levels.

2.1 Atmosphere

2.1.1 Scientific Context of the Updated Challenges

The updated challenges related to Earth's atmosphere are to improve understanding and quantification of:

- *Challenge A1:* Water vapour, cloud, aerosol and radiation processes and the consequences of their effects on the radiation budget and the hydrological cycle.
- *Challenge A2:* Interactions between the atmosphere and Earth's surface involving natural and anthropogenic feedback processes for water, energy and atmospheric composition.
- *Challenge A3:* Changes in atmospheric composition and air quality, including interactions with climate.
- *Challenge A4:* Interactions between changes in large-scale atmospheric circulation and regional weather and climate.
- *Challenge A5:* Impacts of transient solar events on Earth's atmosphere.

The atmosphere separates Earth from space and plays a vital role in protecting life from harmful radiation and maintaining stable thermal conditions. Atmospheric processes associated with motion, heat, radiation, water and other constituents act on shorter temporal and spatial scales than those in other spheres; however, the spheres are linked through important feedback mechanisms so that all scales matter.

Global warming induced by enhanced greenhouse gas concentrations, absorbing aerosol and the depletion of stratospheric ozone are features that relate primarily to the atmosphere, but affect the entire Earth system. This understanding has been reflected in the new challenges by reducing the distinction between climate, atmospheric composition and weather science and moving towards a more integrated concept of the atmosphere that emphasises its role as one of several Earth system components. This consequently changes the formulation of observation and modelling requirements.

Interactions between the atmosphere and the surface – land, ocean and ice – are crucial drivers of atmospheric composition and circulation and, thus, for predicting changes. Local and global atmospheric processes are strongly affected by the surface so that the atmosphere is a natural point for observing surface variability. The challenges related to the atmosphere cannot be addressed without accounting for the surface.

Challenge A1 addresses energy and water cycle components in the atmosphere and at Earth's surface that are crucial for characterising climate variability and the contributions from anthropogenic activities. Observations from the CERES and GERB instruments have provided integrated measurements of outgoing radiation at both short and long wavelengths, but distinguishing between the contributions to Earth's radiation budget of clouds, aerosols and greenhouse gases, including water vapour (Fig. 2.1), is a priority challenge for future observations.

In its fifth Assessment Report, the Intergovernmental Panel on Climate Change confirmed the conclusions reached in previous reports, stating that 'clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of Earth's changing energy budget' (IPCC, 2013).

Global warming induced by greenhouse gases is modulated by aerosol effects, which represent one of the dominant uncertainties in radiative forcing (Fig. 2.2). While this is partly because aerosols show a very high spatiotemporal variability, understanding the role of aerosols in cloud formation and in generating precipitation will be of critical importance in future research.

A better understanding of the role of clouds in the climate system, including cloud–radiation feedback, require accurate descriptions of the properties of clouds and the distribution of water and ice in the atmosphere. An example from ESA's Climate Change Initiative (CCI) Cloud project is the development of long time series of cloud properties for climate research from the ATSR-2 and AATSR instruments (Fig. 2.3).

Precipitation and evaporation are important indicators of changes in the hydrological cycle induced by climate variability, particularly at regional levels. Their links to water vapour, clouds and aerosols for a better characterisation of moisture processes and trends are still poorly understood. In the future, the microwave imager on MetOp-SG will continue the microwave heritage and the Earth Explorer EarthCARE mission will complement existing observations.

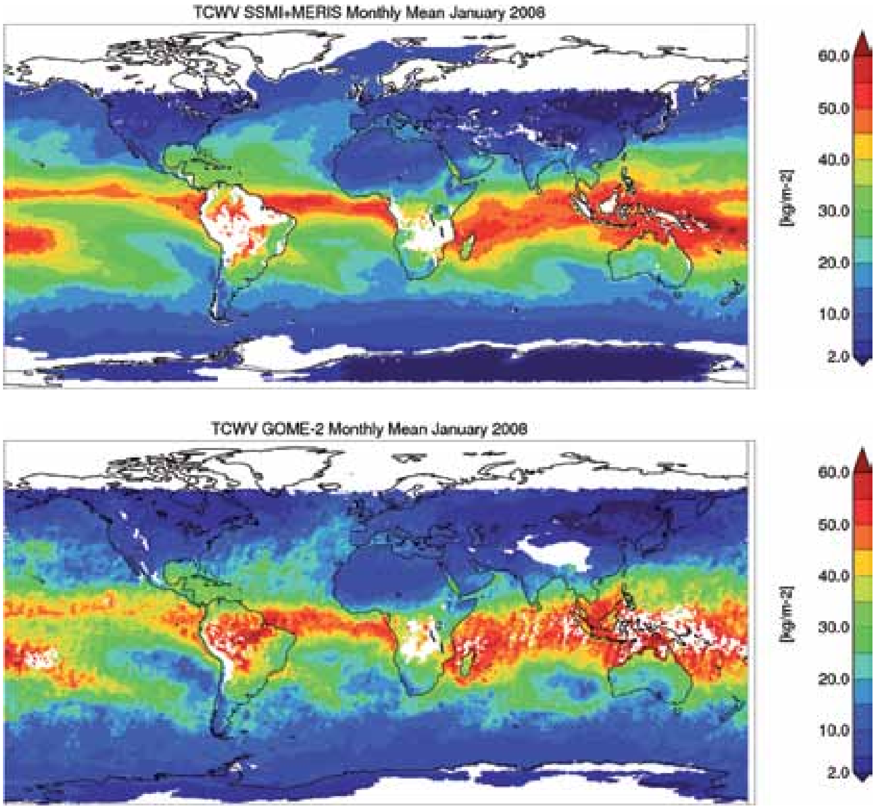


Figure 2.1. Global total column water vapour for January 2008 derived from combined data products from the SSM/I and MERIS sensors for 2003–08 (*upper panel*) and from GOME, GOME-2 and SCIAMACHY sensors for 1996–2008 (*lower panel*). (ESA DUE GlobVapour project/DWD/FUB/DLR/Met Office/ Brockmann Consult/DMI/MPI/NOAA/ESA)

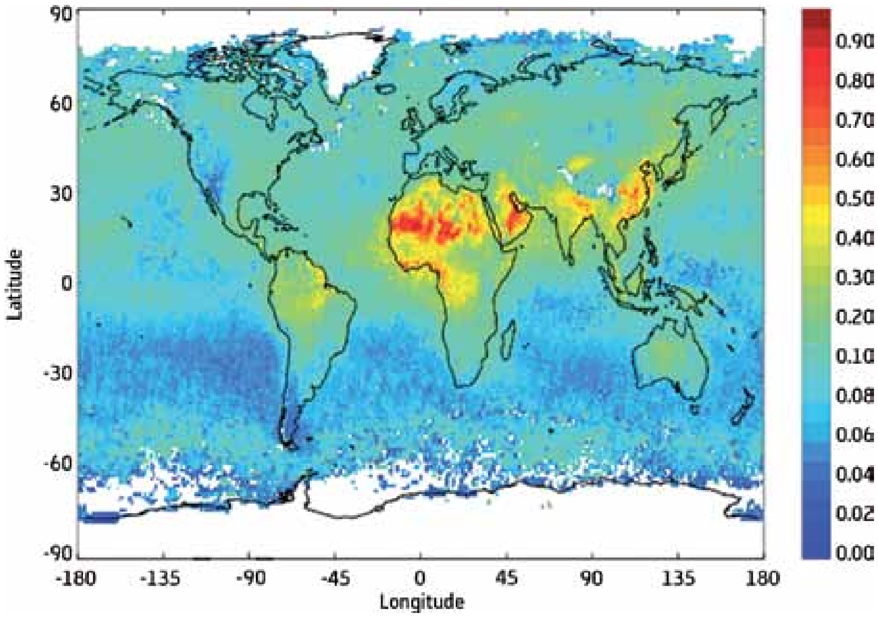
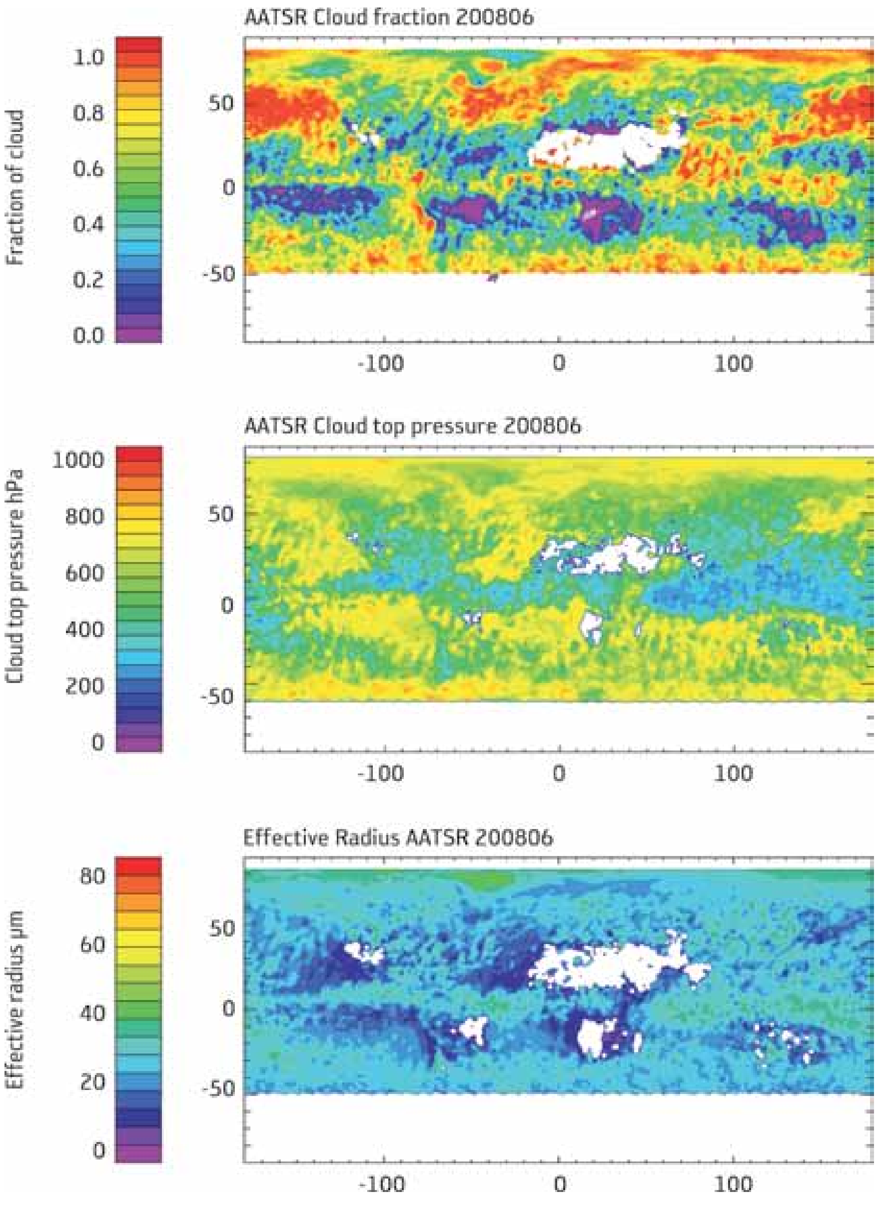


Figure 2.2. AATSR aerosol optical depth (no units). (Swansea University/Aerocom)


AATSR Cloud fraction 200806

AATSR Cloud top pressure 200806

Effective Radius AATSR 200806

Figure 2.3. Envisat AATSR cloud fractional coverage, cloud-top pressure and cloud droplet effective radius. (Rutherford Appleton Laboratory and University of Oxford, UK)

The most urgent observational requirement from Challenge A1 is long-term accurate and stable measurements of short- and long-wave radiation at the top of the atmosphere to assess the contributions of clouds and aerosols, greenhouse gases, in particular water vapour, and surface optical properties to the radiation budget.

Challenge A2 addresses the interactions and feedback processes between the atmosphere and the surface, which are particularly relevant since the characterisation of sources and sinks of carbon and nitrogen, for example, is key to understanding and predicting anthropogenic contributions to environmental change. Emissions of carbon dioxide, methane and nitrous oxide are increasing and the concentrations of these three greenhouse gases in the atmosphere are currently 40%, 150% and 20% higher, respectively, than before industrialisation.

Knowledge of today's carbon sources and sinks, their spatial distribution and their variability over time is one of the essential ingredients for predicting their concentrations in the atmosphere and, in turn, the radiative forcing of climate change by greenhouse gases. With dense spatial and temporal sampling, satellite measurements of the distribution of global atmospheric greenhouse gas concentrations could improve our knowledge of both natural and anthropogenic surface fluxes. The required precision is nonetheless very high since the trends, as well as the diurnal, synoptic, seasonal and inter-annual variations, are two orders of magnitude lower than the background levels.

First estimates of sources and sinks of carbon dioxide and methane have been obtained from SCIAMACHY, GOSAT, IASI and AIRS observations (see Fig. 2.4 for CO_2 measurements). Dedicated missions are planned for the near future, with either passive (OCO-2, Sentinel-4, Sentinel-5 and Sentinel-5P) or active (Merlin) instruments. CarbonSat is a candidate Earth Explorer 8 mission. However, only thermal infrared sounders (IASI, IASI-NG and CRIS), which are mostly sensitive to the mid-troposphere, will provide long time series of measurements as part of the MetOp/MetOp-SG and Joint Polar Satellite System programmes. For methane, there is continuity also in SWIR measurements until 2040, with the exception of the gap between SCIAMACHY and Sentinel-5P. Carbon cycle studies will also benefit from spaceborne measurements of forest biomass (Biomass, Earth Explorer 7) and terrestrial carbon stocks and fluxes (FLEX, the second candidate Earth Explorer 8 mission).

Ensuring the continuity between passive measurements in the SWIR and developing active technologies, such as lidar, will be needed to monitor greenhouse gases over the long term with good enough accuracy for answering the political and societal questions associated with growing emissions and climate responses.

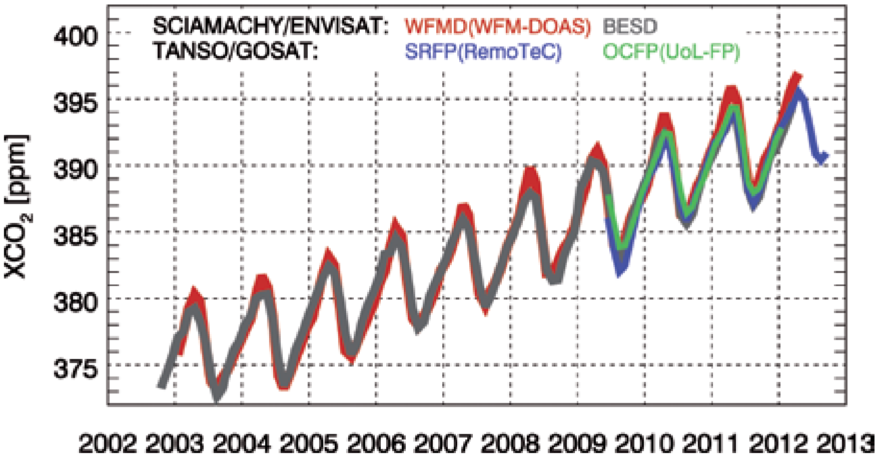


Figure 2.4. Time series of atmospheric CO_2 concentrations over the northern hemisphere (0–60° N) from SCIAMACHY on Envisat and TANSO on Japan's GOSAT, 2002–12. While CO_2 increased over the 10-year period, there are annual fluctuations caused by the absorption and release of the gas through the processes of photosynthesis and respiration. The various colours represent different methods of extracting CO_2 measurements from the measured spectra of reflected solar radiation. (University of Bremen, IUP/IFE)

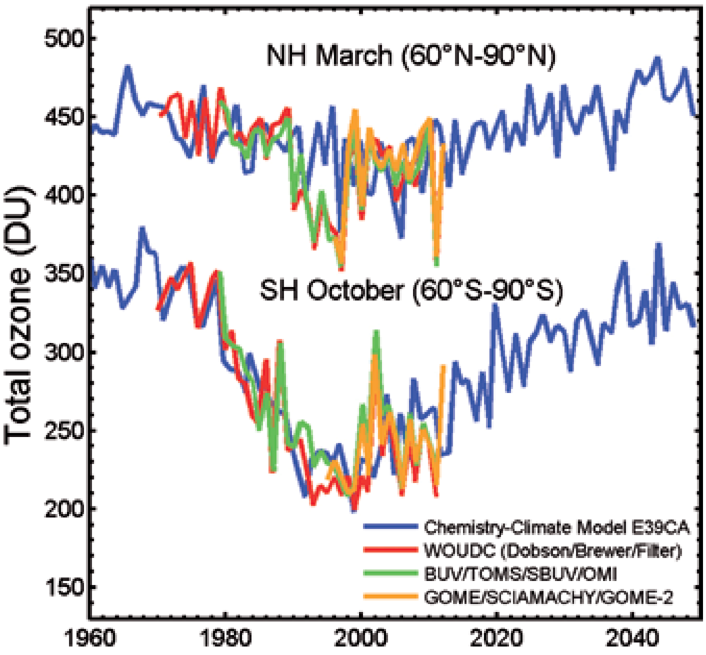


Figure 2.5. Total polar ozone in the northern and southern hemispheres as measured by various instruments, including GOME, SCIAMACHY and GOME-2 on ERS-2, Envisat and MetOp, respectively (orange lines). The blue lines depict projections based on the Chemistry Climate Model E39CA. Total ozone reached its lowest levels in both hemispheres in the late 1990s, but these levels are expected to increase in the coming years. (ESA/DLR/Eumetsat/NASA/WMO/GAW)

Challenge A3 focuses on both the radiative and chemical properties of atmospheric constituents that are relevant for the energy budget and air quality, respectively.

The composition of the atmosphere is now reasonably well understood. Most minor constituents, including species that are present in concentrations of only a few parts per billion, have been measured. Their distributions as a function of altitude and geographical location have been determined from the ground up to the high stratosphere using combined observations from nadir-sounding instruments (e.g. GOME, SCIAMACHY, OMI, IASI) and limb-sounding instruments (e.g. GOMOS, MIPAS, SCIAMACHY, MLS, ACE). Despite satellite observations for monitoring air, the challenge remains to provide reliable information on particulate matter (PM2.5) (e.g. MODIS, MISR, AATSR, CALIOP), ozone and nitrogen dioxide (OMI) at ground level.

Ozone remains particularly important since it is the main absorber of ultraviolet radiation in the stratosphere, although it is a potent pollutant in the lower troposphere. Ozone and ozone-depleting species such as chlorofluorocarbons have been monitored for several decades using several ground-based and spaceborne observations (TOMS, SBUV, GOME, GOME-2, SCIAMACHY, OMI, and to be continued by the Sentinels). Over the past 20 years, the concentration of chlorofluorocarbons has decreased in the troposphere and recently also in the stratosphere, as observed by ACE and MIPAS. The onset of ozone recovery has been identified despite the general large interannual ozone variability. This recovery is occurring later than expected, and is thought to be due to the cooling of the stratosphere caused by tropospheric warming with climate change. For ozone, the quality of the concentration measurements is better than for any other species, but the consistency of the products is still not as good as expected (at least for vertical profiles). The main inconsistency in total ozone, as shown in Fig. 2.5, is between the models and measurements, and not among the measurements themselves.

Reactive gases have strong implications for the environment and human health at regional scales. They require global observations and modelling because of flow dispersion and slow sedimentation and reaction rates. Several satellite instruments (e.g. GOME, MIPAS, GOMOS, SCIAMACHY, GOME-2, IASI, OMI, OMPS-1) have provided global observations of pollutants with increased spatial resolution in recent years.

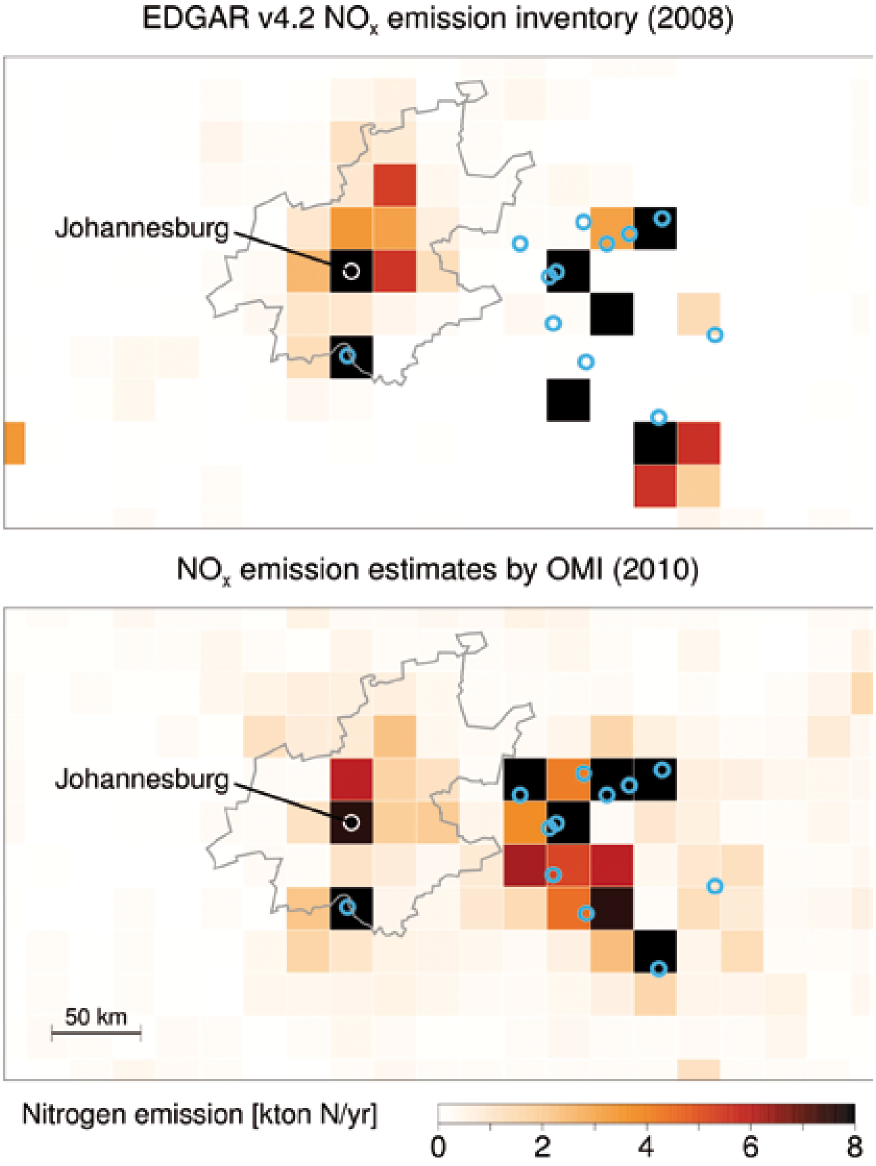


Figure 2.6. Nitrogen oxide emissions over the Highveld region of South Africa. The area outlined in grey indicates the densely populated Gauteng province, containing the cities of Johannesburg and Pretoria. Blue circles indicate the locations of coal-fired power stations, which are important hotspots of NOx emissions. Upper panel: Model-based emissions inventory, based on 2008 data. Lower panel: Emission estimates from the OMI instrument for 2009–10. The use of satellite data can help identify emission hotspots and measure their intensity. (KNMI)

Emissions of pollutants to the ambient environment are at the origin of atmospheric pollution issues. Emission inventories provide important information on the magnitude, type of activity, time evolution and spatial coverage of the estimated emissions. These inventories are being developed for use in scientific applications as inputs to urban, regional, continental or global scale models, as well as by policy makers to evaluate progress in reaching emission abatement targets, and to decide on future strategies. Emission estimates can now also be developed from satellite observations of air constituents, offering advantages such as their spatial consistency, high temporal resolution and rapid availability to users (Fig. 2.6).

Satellite air quality observations can now be operationally assimilated into models, bringing together weather and composition analyses and predictions (e.g. from the Copernicus Atmosphere Monitoring Service) of reactive gases (carbon monoxide, ozone, nitrogen oxides), aerosols including volcanic sulphate, and greenhouse gases (such as methane) at global and regional scales (Fig. 2.7). Building the capability to monitor and forecast the transport of volcanic ash and sulphur dioxide (see Fig. 2.8) will require products that are available even faster than in near-real time (e.g. based on direct broadcasts).

In the future, progress is expected in several areas, such as improved temporal sampling, spatial and vertical resolution (especially in the lower troposphere) and

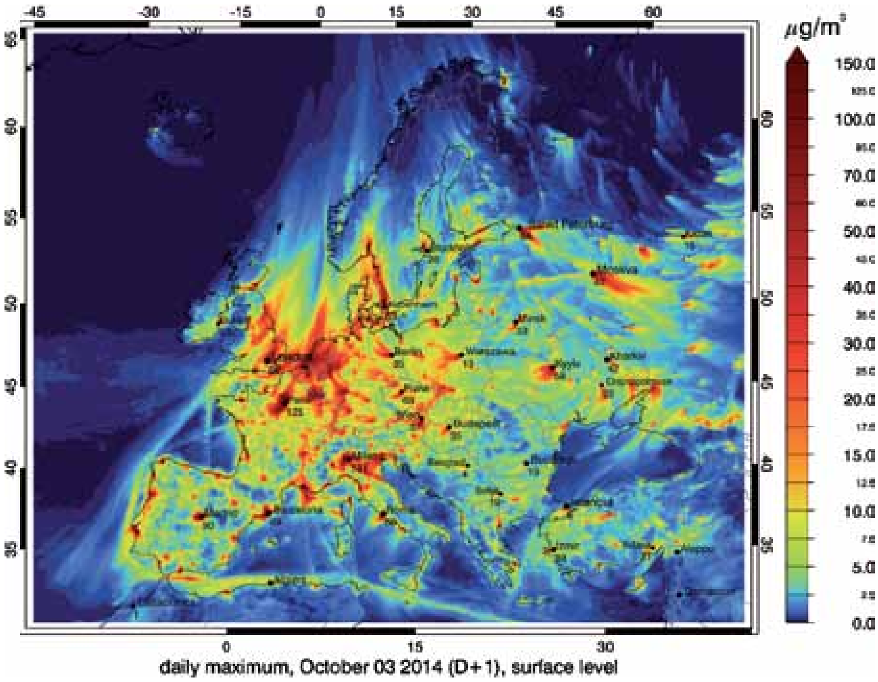


Figure 2.7. GOME-2 and OMI nitrogen dioxide measurements assimilated into the EURAD air quality forecasting model. (University of Cologne)

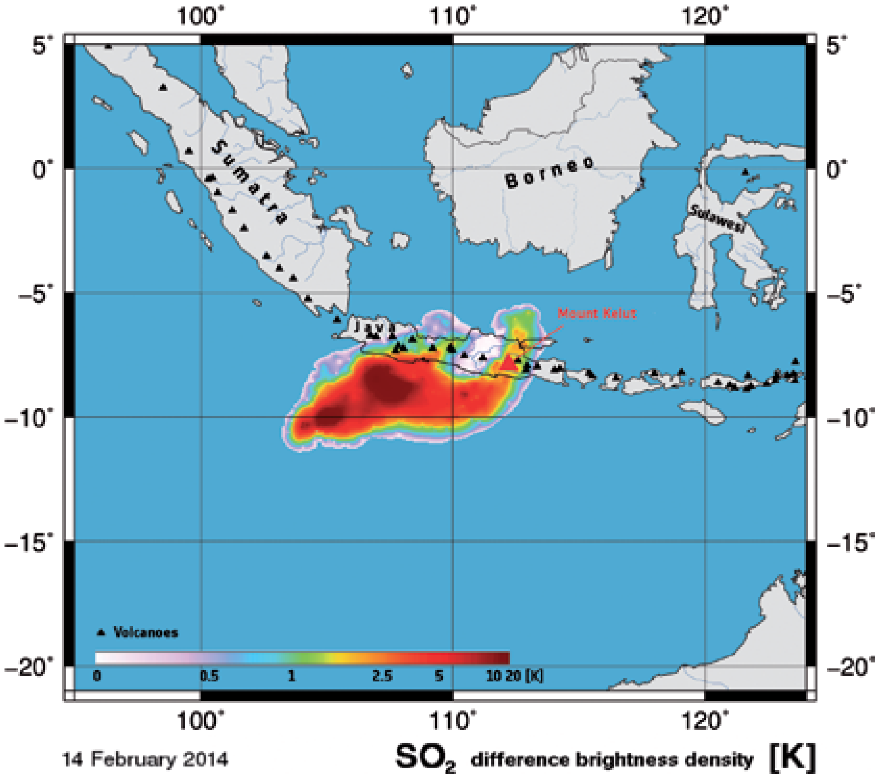


Figure 2.8. Sulphur dioxide concentrations over the Indonesian island of Java on 14 February 2014 following the eruption of the volcano Kelut. Image based on data from the Infrared Atmospheric Sounding Interferometer on MetOp. (ESA/DLR/BIRA-IASB/Eumetsat, 2014)

in quantifying other relevant species, such as formic acid, nitric acid, ammonia and methanol, which can now be detected in IASI measurements. These advances are expected from Sentinel-4, which together with TEMPO and GEMS will form part of a global constellation of geostationary satellites, and Sentinel-5 and Sentinel-5P in conjunction with IRS on MTG and IASI NG on MetOp-SG.

Challenge A4 focuses on the links between weather and climate at global and regional scales. The dynamic and physical processes are represented in similar ways in weather and climate prediction models and will evolve further towards

Earth system prediction models with full coupling to ocean, land and sea ice, and atmospheric composition. Regional downscaling is possible through high-resolution local area modelling using lateral boundary conditions from global models and the assimilation of additional, locally relevant observations.

The most important satellite observations are vertically well-resolved temperature profiles from infrared (MIPAS, IASI, AIRS, CrIS) and microwave (AMSU-A, ATMS) instruments, as well as GOMOS (using its photometers), and radio occultation (GRAS, COSMIC) soundings to constrain large-scale atmospheric dynamics. GOMOS (GOMOS temperature profile data extend from altitudes of about 20 km to 40 km) and MIPAS provide excellent vertical resolution in dynamically active areas such as the upper troposphere–lower stratosphere. Moisture and cloud observations from microwave imagers – SSMI/S, AMSR-2, GMI and MWI – also drive the shorter-term prediction capabilities of clouds and precipitation. Accurate wind observations from ADM-Aeolus are expected to be of particular benefit for tropical regions, but are considered highly advantageous at a global scale. As for Challenge A1, EarthCARE observations of clouds and aerosols will help constrain cloud–aerosol–radiation interactions in weather forecasting models and thus, among others, improve surface weather predictions.

The breakdown of hydrological budgets derived from observations and reanalyses shows that large uncertainties are associated with horizontal moisture transport between land and ocean, which is only accessible from combined modelling and observation capabilities. The link between budgets relevant at climate scales and the accurate representation of the general circulation and physical processes in models is an important area of interaction between weather and climate communities, and thus connects Challenges A1 and A4.

Volcanic aerosols also need to be represented in climate model energy budgets, while for weather prediction, plume tracking data from GOME, SEVIRI, OMI, AIRS and IASI, for example, have produced ash forecasts that will increase air traffic safety. Finally, greenhouse gas observations are as important to climate and weather as they are to atmospheric composition owing to the contribution they make to heating.

Much better observational capabilities are required in regions of strong temperature and moisture gradients, namely, the boundary layer and the upper troposphere–lower stratosphere, which are important for describing momentum and moisture fluxes in the vertical. For the latter, limb observations from MIPAS

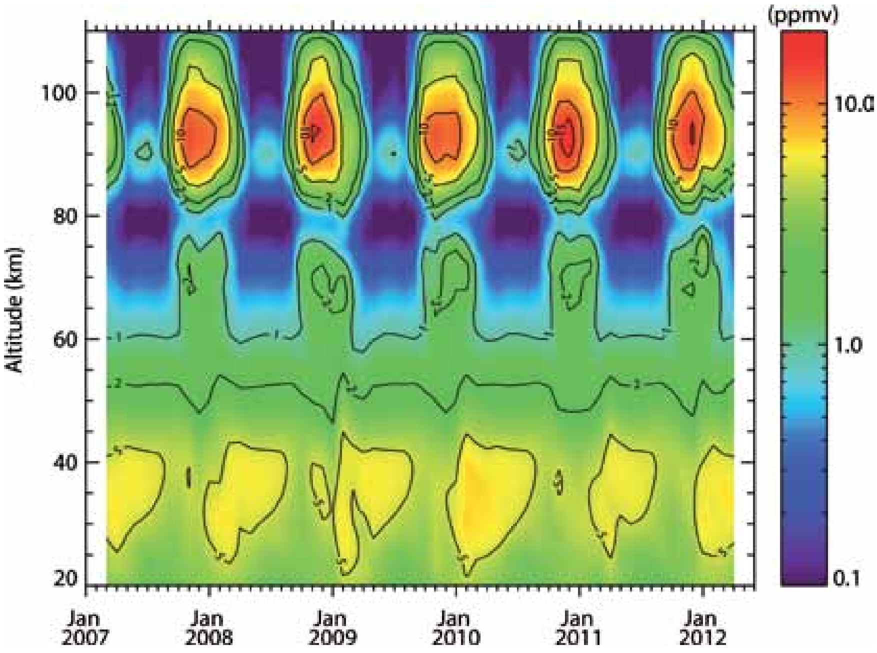


Figure 2.9. Ozone distribution in the stratosphere and mesosphere over the North Pole as measured by the MIPAS instrument. (IAA/IMK)

and MLS have proven useful but their vertical resolution is still limited. For boundary layer moisture, lidar observations may produce the required resolution and accuracy.

Challenge A5 relates mainly to the mesosphere and thermosphere where few comprehensive observations are available. These areas are relevant for atmospheric composition and climate change, as well as for telecommunications. A preliminary upper atmospheric trace gas climatology has been established from, e.g. MIPAS (see Fig. 2.9), GOMOS, HALOE, SCIAMACHY and SMILES. There is strong evidence to suggest that solar proton events can cause enhanced ionisation in the high atmosphere, leading to the formation of species that are transported to lower altitudes in polar areas and thus become relevant for ozone depletion and climate forcing.

The new scientific challenges and their holistic view of the Earth system will require more integrated observing systems in the future. In particular:

- The coupled use of satellite and surface network data in conjunction with model simulations will greatly enhance our ability to monitor the global behaviour of the Earth's atmosphere and to advance our understanding of the underlying processes at all spatiotemporal scales. This points to a strong requirement for future satellite observation accuracy, which must provide benchmark observations for constraining future models. A major challenge in our ability to forecast climate change is to gain a better understanding of the links between clouds, atmospheric circulation, precipitation and the radiation budget. Characterising the role of convection, vertical and horizontal water vapour transport, cloud–aerosol interactions, greenhouse gas sources and sinks – particularly the interaction with vegetation – stand out as the main challenges. Observations sample many elements, but models can improve the information to produce physically consistent budgets, scale interactions and trends, and to enhance resolution and coverage. Observation simulators play an important role in linking measurements and model outputs.

- Simultaneous observations of variables relevant to key processes support both process understanding and model improvement. For example, the combined use of existing imaging, cloud profiling and radiative flux data has produced unprecedented accuracy in the characterisation of not only surface radiative fluxes but also of the vertical heating profiles. Coupling shortwave infrared observations, which are sensitive to the full atmospheric column, with thermal infrared observations, which are sensitive to the mid-troposphere, can help identify sources of greenhouse gas emissions. A combination of observations in the visible and thermal infrared can help to distinguish fine and coarse modes of aerosols. This concept can be explored by the MetOp-SG/Sentinel/Earth Explorer constellations.

2.1.2 Achievements with Respect to the 2006 Challenges

In 2006, ESA's Living Planet Programme strategy identified the five most important challenges related to the atmosphere that should guide ESA's efforts in providing essential Earth observation information:

- *Challenge A1:* Understand and quantify the natural variability and the human-induced changes in the Earth's climate system.

- *Challenge A2:* Understand, model and forecast atmospheric composition and air quality on adequate temporal and spatial scales, using ground-based and satellite data.

- *Challenge A3:* Better quantification of the physical processes determining the life cycle of aerosols and their interaction with clouds.

- *Challenge A4:* Observe, monitor and understand the chemistry-dynamics coupling of the stratospheric and upper tropospheric circulations, and the apparent changes in these circulations.

- *Challenge A5:* Contribute to sustainable development through interdisciplinary research on climate circulation patterns and extreme events.

The accomplishments in recent years demonstrate the significant impacts of ESA's Earth observation data, and the associated support programmes, in advancing atmospheric science.

The Envisat observatory can be regarded as a role model in fulfilling comprehensive and complementary observation requirements targeting the atmospheric component of environmental change. These have included, among others, the monitoring of surface, cloud and aerosol properties (AATSR and MERIS), the profiling of atmospheric composition and temperature (GOMOS, MIPAS and SCIAMACHY) and the detailed mapping of land and sea-surface state (RA-2 and ASAR). Envisat continued several datasets that were founded with ERS, and the Sentinel satellites will extend key missions into the Copernicus programme in the future.

ESA's Climate Change Initiative aims to produce consistent long time series of Essential Climate Variables for greenhouse gases and ozone, clouds and aerosols, but also of surface variables of direct relevance to atmospheric processes such as sea-surface temperatures, sea-ice properties, soil moisture, land cover and fire. ESA's Data User Element (DUE) user consultations and project series (e.g. GlobVapour, GlobAlbedo, GlobCloud, GLobEmission) have helped to bridge the gap between research projects and the sustained provision of Earth observation climate data products at an information level that fully responds to the operational needs of user communities.

The establishment of services based on the (re)analysis and prediction of weather and composition has had major impacts on the climate and atmospheric composition communities throughout Europe. The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis projects ERA-Interim as well as PROMOTE, GEMS and MACC II/ III have laid the foundations for the future Copernicus Climate Change Service (CCCS) and Copernicus Atmospheric Monitoring Service (CAMS). ERA and MACC rely heavily on ESA's Earth observation data and associated data reprocessing efforts. In particular, the impact of Envisat data on the quality of analyses and forecasts has set a benchmark for the future.

The achievements with respect to the 2006 challenges related to the atmosphere are summarised in following. Table 2.1 lists the relevant missions and instruments (past, present and future), while Table 2.2 gives an overview of a number of innovative algorithms and products developed in recent years, and the challenges they have addressed either directly or indirectly. The legacy datasets developed – products that are recognised long-term data series – are shown in Table 2.3.

Table 2.1. Relevant missions and instruments.

Missions/instruments	
ERS-1/ERS-2	GOME, SCATT, ATSR, ATSR-2
Envisat	SCIAMACHY, GOMOS, MIPAS, MERIS, AATSR
Earth Explorers	EarthCARE, ADM-Aeolus, CarbonSat (candidate EE-8)
MetOp	GOME-2, IASI, ASCAT, GRAS
Sentinels	S-5P, S-4, S-5, S-3
Third-party missions	GOSAT, Odin, SciSat

Table 2.2. Innovative algorithms and products, and the challenges they have addressed.

Algorithms and products	Challenges				
	A1	A2	A3	A4	A5
New techniques for producing radiatively consistent aerosol and cloud products (e.g. AERGOM, GlobAerosol, CCI Aerosol, CCI Clouds, STSE ICAROHS, Aeolus L2a product, PROMOTE, Cloud retrieval algorithm development from MIPAS) and better discrimination of aerosol types (e.g. dust, sea salt)	×	×	×	×	
Improved ozone algorithms to fulfil GCOS requirements (TEMIS, PROMOTE, CCI Ozone, GHG, Aerosol & Cloud projects, STSE SPIN project) and linking European and non-European datasets to generate long-term ECVs to be used for ozone assessments	×	×			
Improved algorithms to retrieve better volcanic emission satellite data products to support Volcanic Ash Advisory Centers (GSP projects SMASH & SACS 2; STRIN project VAST)		×	×		×
Improved volcanic ash forecasting using satellite measurements (STRIN project VAST, SMASH, SACS)		×	×		×
New algorithm and integrated modelling approach to compute greenhouse gas fluxes at the ocean–atmosphere interface (e.g. STSE ESA-SOLAS OceanFlux) and the land–atmosphere interface (e.g. STSE CarbonFlux)		×			
Development of innovative sensor and mission concept studies to better quantify carbon fluxes in the boundary layer (e.g. CCI GHG, ADVANSE, inverse modelling studies for Sentinel-4/-5 and CarbonSat)		×			
Advances in retrieving products for ozone, CO_2 and CH_4 (GHGs), CO, nitrous oxides, iodine and other chemical species relevant for air quality and climate research (e.g. ADVANSE, GOME O_3 total ozone and profiling algorithm, development projects, pollution hotspot monitoring project, CCI GHG, STSE CarbonGases, STSE TIBAGS)		×			
New ensemble simulation for GHG retrieval based on Envisat and GOSAT data (e.g. CCI GHG)		×			
Development of new-generation lidar techniques, combination of lidar, radar and imagers, high-spectral-resolution lidar algorithms for wind and aerosol/cloud products, and algorithms for differential absorption (e.g. ADM-Aeolus (L2a and L2b algorithms), EarthCARE, STSE IRDAS and IRDAS EXP)		×	×		
Atmospheric aerosol and cloud database for improving aerosol models, sizing of new missions (LIVAS)	×		×		
Improvements in aerosol models (VRAME, LIVAS)			×		
Surface reflectance databases for improving radiative transfer modelling and retrieval of atmospheric species (GlobAlbedo, ADAM)	×	×			
Advances in treating surface anisotropy for geostationary monitoring the diurnal cycle of atmospheric composition		×			
Improved satellite measurements of emissions and generation of new emission inventories (DUE project GlobEmission)		×	×		
Mesospheric climatologies based on GOMOS, MIPAS and SCIAMACHY data (STSE MesosphEO)		×			
Improved atmospheric spectroscopy (SEOM project)		×			
Measurements of changes in mesospheric and stratospheric composition caused by solar proton events (STSE MesosphEO)	×			×	
Development of new data fusion techniques between atmospheric profiles obtained by instruments operating with different observation geometries (MIPAS and IASI, GOME 2/IASI ozone)		×		×	
Development, using MIPAS observations, of algorithms for the two-dimensional retrieval of atmospheric composition for improved horizontal resolution in future upper troposphere–lower stratosphere missions				×	
Development of an extensive climatology of non-LTE effects in Earth's atmosphere and an algorithm for their modelling.		×		×	
Development of algorithms for the estimation of high-resolution temperature, pressure and density profiles from GOMOS	×				

Table 2.3. Legacy datasets and the challenges they have addressed.

Datasets	Challenges				
	A1	A2	A3	A4	A5
Global time series of ozone, GHGs, aerosol and cloud information with quantification of errors			×		
Development of climatologies of a variety of trace gases (among which ozone, its depleting species and their sources and reservoirs) and water vapour (e.g. DUE, CCI, GlobVapour, STSE SPIN)	×	×			
Global time series of aerosols (e.g. GlobAerosol, CCI Aerosol)			×		
Advances in the development of long-term datasets merging ESA and third-party mission variables (ozone, GHGs, temperature, water vapour and ozone, CCI SPIN) with US datasets	×	×			×

Earth Observation in the Context of Models

- Advances in the assimilation of Earth observation atmospheric data into land surface and carbon models (e.g. STSE CarbonFlux, ALANIS Methane, ALANIS Smoke Plumes, LOGOFLUX, GSP ISOTROP).
- Advances in lidar data assimilation (ADM-Aeolus for wind and aerosol/cloud products, EarthCARE for aerosol and cloud products) for numerical weather prediction models (STSE EarthCARE assimilation).
- Advances in constraining volcanic emission transport models using Earth observation data (combination of chemical, imager, infrared sounder and lidar observations, e.g. STRIN project VAST).
- Post-volcanic eruption aerosol and sulphur dioxide tracking and forecasting with Earth observation and models (e.g. SACS, GSP project SMASH, STRIN project VAST).
- Top-of-the-atmosphere radiative balance through the integration of multiple Earth observation datasets (e.g. from Meteosat) into models.
- New ways to integrate Earth observation-based methane products into land and atmospheric models (e.g. STSE ALANIS, LOGOFLUX).
- Atmospheric composition and air quality analyses and forecasts using Earth observation and models from global to regional scales (e.g. MACC II and MACC III, PROMOTE, TEMIS, Pasodoble, ESA/SOLAS OceanFlux – Sea Spray Aerosols).
- Long time series of global atmospheric reanalyses using Earth observation data and state-of-the art numerical weather prediction models (ERA-Interim, ERA Clim, ERA Clim2, MACC II and MACC III).

Relevant International Research Initiatives/Programmes

- WCRP, WWRP, IGAC, SPARC, GCOS, ACCENT

New Earth System Insights

- Improved quantification of the sources and sinks of emissions, including nitrogen oxides, methane and carbon dioxide (e.g. STSE ALANIS), and their origins (distinguishing between natural and human-induced) (e.g. CarbonSat scientific studies).

- Inputs to the IPCC's fourth Assessment Report (IPCC, 2007, chapters 2 and 7) including examples.

Moving Science to Services

- MACC-II and III, ERA-Interim, TEMIS, PROMOTE, GlobAerosol, SAVAA, SACS, VAST, GlobEmission, GlobVapour, GlobCloud, atmospheric CCI projects on ozone, greenhouse gases, aerosols and clouds.

2.2 Cryosphere

2.2.1 Scientific Context of the Updated Challenges

The updated challenges related to the cryosphere are to improve understanding and quantification of:

- *Challenge C1:* Regional and seasonal distribution of sea-ice mass and the coupling between sea ice, climate, marine ecosystems and biogeochemical cycling in the ocean.

- *Challenge C2:* Mass balance of grounded ice sheets, ice caps and glaciers, their relative contributions to global sea-level change, their current stability and their sensitivity to climate change.

- *Challenge C3:* Seasonal snow, lake/river ice and land ice, their effects on the climate system, water resources, energy and carbon cycles; the representation of the terrestrial cryosphere in land surface, atmosphere and climate models.

- *Challenge C4:* Effects of changes in the cryosphere on the global oceanic and atmospheric circulation.

- *Challenge C5:* Changes taking place in permafrost and frozen ground regimes, their feedback to climate system and terrestrial ecosystems (e.g. carbon dioxide and methane fluxes)

The overarching objectives of cryosphere observations and research are to better quantify, model and predict processes and interactions between cryospheric elements and the Earth system in order to advance the understanding and prediction of climate change and its impacts on the environment and society. The importance of the cryosphere for advancing Earth system modelling and prediction has been recognised by the World Climate Research Programme (WCRP) in its recently formulated six 'Grand Science Challenges', which identify key areas for scientific research, modelling, analysis and observations in the next decade.[1] Five of the six Grand Challenges have important cryosphere components, particularly 'Changes in Cryosphere', which focuses specifically on ice-covered regions; but also the four challenges 'Climate Extremes', 'Regional Climate Information', 'Regional Sea-Level Rise' and 'Water Availability' cannot be addressed comprehensively without accounting for snow and ice.

Several urgent questions of great societal importance led to the formulation of the priority research goals for the 'Changes in Cryosphere' challenge. These include the evolution towards an ice-free Arctic Ocean, as well as the role of ice dynamics – especially those triggered by ocean interactions – in amplifying the contribution of ice sheets to sea-level rise. On land, the declining seasonal

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[1] *www.wcrp-climate.org/index.php/grand-challenges*

Figure 2.10. Envisat ASAR images of the calving of several large icebergs from the Sulzberger ice shelf in Antarctica as a result of the March 2011 tsunami half a world away in Japan. Scientists have long speculated that ocean waves could cause an ice shelf to flex and break, but this was the first observation of a tsunami having this effect. (Brunt et al., 2011)

snow cover and retreating mountain glaciers are very important issues as the seasonal snow and glacier melt provide freshwater for hundreds of millions of people worldwide. In addition, thawing permafrost and declining seasonal frost are strengthening the positive feedbacks between the warming climate and natural emissions of greenhouse gases.

These processes, in which components of the cryosphere play a key role, are major sources of uncertainty in Earth system modelling and in projections of the future impacts of climate change. Several specific research topics have been identified by the international research community and by the WCRP's Climate and Cryosphere (CliC) programme, which aims to provide new insights within the next 5–10 years (WCRP, 2013).

The five strategic challenges related to the cryosphere listed above target the following urgent research questions.

Challenge C1. The information on sea-ice mass needs to be improved in order to quantify feedbacks between sea ice and the climate system, and to improve the understanding of processes coupling sea ice with marine ecosystems and biogeochemical cycling in the oceans. Sea ice in the two hemispheres is behaving in quite different ways: the trend is towards ice retreat in the Arctic, while there is no obvious overall trend in the Antarctic, although there are considerable regional variations (Fig. 2.10). Although sea-ice retreat in the Arctic represents one of the most striking indicators of a warming climate, there are still large uncertainties about how these changes interact with the regional and global climate system and how they affect marine ecosystems.

The regional and seasonal distribution of sea-ice mass and the coupling between sea ice, climate, marine ecosystems and biogeochemical cycling in the ocean becomes Challenge C1.

Challenge C2. Better, spatially detailed data on the mass balance of ice sheets, ice caps and glaciers are needed to improve our knowledge and models of the forcing and interactions with atmosphere and ocean. Moreover, key processes such as ice–ocean–atmosphere interactions in marine-terminating glaciers, ice-shelf/ice-sheet feedbacks and glacier hydraulics are insufficiently known to make reliable assessments of the stability of the ice masses or to predict their response to climate warming (see Figs 2.11 & 2.12).

The mass balance of grounded ice sheets, ice caps and glaciers, their relative contributions to global sea-level change, their current stability and their sensitivity to climate change becomes Challenge C2.

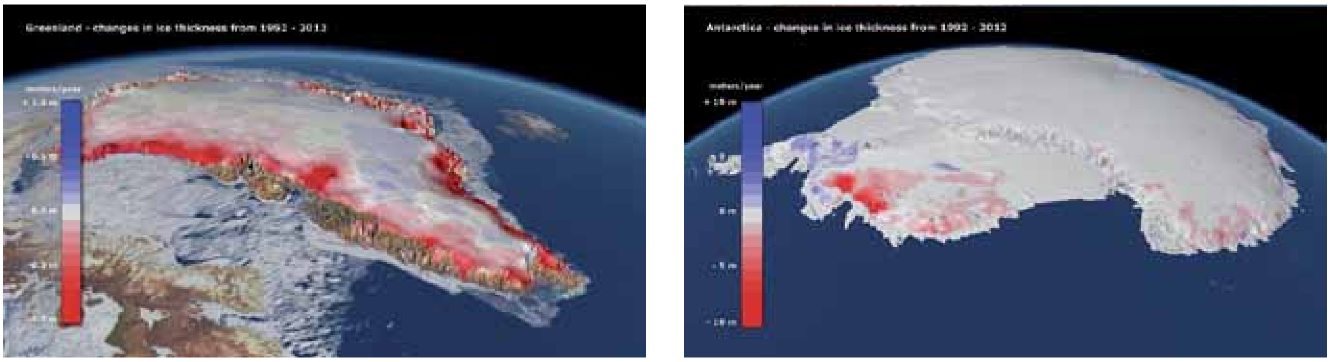

Figure 2.11. Changes in the thickness of the Greenland and Antarctic ice sheets since 1992. (IMBIE/ESA/Planetary Visions)

Challenge C3. The amounts of freshwater stored in seasonal snow and mountain glaciers need to be better quantified. The mass of snow deposited on the ground and its temporal variability are poorly known at all spatial scales. This information is of great societal importance, as about one-sixth of the world's population depends on rivers fed by the melting of seasonal snowpacks and glaciers. In particular, communities in arid and semi-arid environments that rely on these freshwater resources are especially vulnerable should glaciers and snow cover retreat. Changes in seasonal snow have great impacts on energy and carbon cycles from local to global scales. For the optimum utilisation of satellite-based information on snow and land ice, advances in data assimilation into cryospheric process models, hydrological models and land-surface parameterisations of atmospheric circulation models are needed.

Seasonal snow, lake/river ice and land ice, their effects on the climate system, water resources, energy and carbon cycles, and the representation of the terrestrial cryosphere in land surface, atmosphere and climate models, become Challenge C3.

Challenge C4. The representation of the cryosphere in climate simulation and prediction models needs to be improved. The models are moving from global circulation models towards fully coupled models, including processes and interactions between the atmosphere, ocean, cryosphere and biosphere. However, there are still major deficits in the parameterisation and integration of cryospheric processes in these models. Satellite observations are indispensable for improving the reliability and performance of the models, and for delivering key data for model initialisation and validation.

The effects of changes in the cryosphere on the global oceanic and atmospheric circulation become Challenge C4.

Challenge C5. Changes taking place in seasonally frozen ground and in permafrost regimes, and their feedbacks to the climate system and to terrestrial ecosystems, need to be better quantified. In the Arctic, temperatures are rising about twice as fast as the global mean, causing frozen ground to thaw and releasing organic carbon to the atmosphere that will enhance global warming. The current state of the permafrost carbon reservoir and the related greenhouse gas balance are poorly known. Although permafrost is a subsurface phenomenon that cannot be directly observed by remote sensing methods, many parameters that influence the ground thermal and ecological regimes can be captured with satellite data. In addition, changes in seasonal frost and snow are causing major changes in the carbon exchange of boreal forests. Thus, observations of surface and near-surface parameters are complementary to observations of atmospheric trace gases and fluxes, and are being addressed in the Atmosphere theme of the Living Planet Programme.

The changes taking place in permafrost and frozen-ground regimes, their feedback to climate system and terrestrial ecosystems become Challenge C5.

Satellite observations will deliver key information for meeting these five challenges. Advances in these areas will be of great value for supporting major international research programmes such as the WCRP's CliC, GEWEX and CLIVAR programmes, and the Future Earth Initiative. The data and scientific developments will also be of great relevance for operational weather prediction and runoff forecasting, and will support initiatives to improve preparedness for and to mitigate the impacts of climate change on water supplies, sea-level rise, etc. The new Global Cryosphere Watch of the World Meteorological Organization (WMO)[2], a programme that includes observations, monitoring, assessment, product development, prediction and research for all key cryospheric *in situ* and remote sensing observations, will also benefit from these activities.

2.2.2 Achievements with Respect to the 2006 Challenges

ESA's Earth Observation programme has achieved some of its major scientific objectives in the investigation of and understanding processes of the cryosphere. These have included the implementation and utilisation of new satellites with advanced instrument technology, such as CryoSat-2, SMOS and GOCE. Even though these systems were not primarily designed for cryospheric applications (except for CryoSat-2) they have been shown to provide unique datasets relevant to the retrieval of sea ice, land ice and soil freeze/thaw characteristics. On the other hand, resources have been committed for the exploitation of historical datasets in order to provide long time series of key variables concerning ice sheet dynamics, sea-ice concentration and thickness, global glaciated areas and the evolution of terrestrial snow cover (snow extent and snow water equivalent). These activities have employed observational data from past ESA missions (ERS-1/-2, Envisat), as well as optical and active/passive microwave datasets from the missions of other space agencies. The related CCI, STSE and DUE/Glob series projects also directly facilitate the development and utilisation of applications for the Sentinel satellites for monitoring cold regions.

Increasing the understanding and quantification of cryospheric processes and their impact on the global climate by utilising satellite data, has been a third focus area of programme activities. Advances have included a reconciled assessment of the contributions of ice sheets to global sea-level rise (see Fig. 2.12), an improved characterisation of sea-ice dynamics as well as the development of new methods to observe essential parameters that contribute to the dynamics of permafrost and seasonal frost. In addition, advanced techniques to investigate global snow processes using multifrequency synthetic aperture radar were developed during the Phase-A studies of CoReH$_2$O, a candidate Earth Explorer 7 mission. In these cases, the work carried out has also contributed to the development of applications for the Sentinel satellites, such as synergistic approaches employing multiple spaceborne instruments to retrieve information on terrestrial snow processes.

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[2] WMO Global Cryosphere Watch: *www.globalcryospherewatch.org*

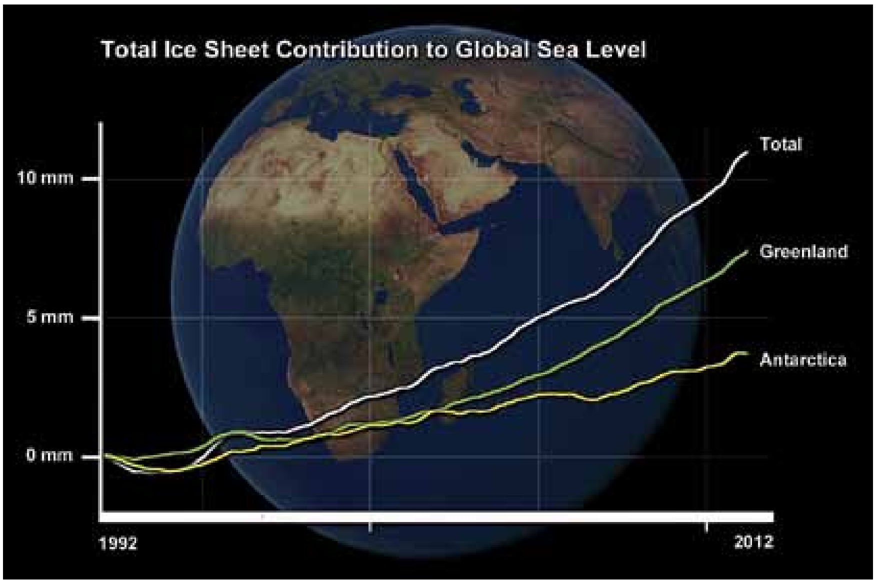

Figure 2.12. Ice-sheet contributions to global sea-level change. (IMBIE/ESA/Planetary Visions)

The 2006 strategy for ESA's Living Planet Programme identified the five most important cryosphere challenges that should guide ESA's efforts to provide essential Earth observation information:

- *Challenge C1:* Quantify the distribution of sea-ice mass and freshwater equivalent, assess the sensitivity of sea ice to climate change, and understand thermodynamic and dynamic feedbacks to the ocean and atmosphere.

- *Challenge C2:* Quantify the mass balance of grounded ice sheets, ice caps and glaciers, partition their relative contributions to global eustatic sea-level change, and understand their future sensitivity to climate change through dynamic processes.

- *Challenge C3:* Understand the role of snow and glaciers in influencing the global water cycle and regional water resources, identify links to the atmosphere, and assess likely future trends.

- *Challenge C4:* Quantify the influence of ice shelves, high-latitude river run-off and land ice melt on global thermohaline circulation, and understand the sensitivity of each of these fresh-water sources to future climate change.

- *Challenge C5:* Quantify current changes taking place in permafrost and frozen-ground regimes, understand their feedback to other components of the climate system, and evaluate their sensitivity to future climate forcing.

The achievements with respect to these challenges are summarised in the following. Table 2.4 lists the relevant missions and instruments (past, present and future), while Table 2.5 gives an overview of a number of innovative algorithms and products developed in recent years, and the challenges that have been addressed either directly or indirectly. The legacy datasets developed – products that are recognised long-term data series – are shown in Table 2.6.

Table 2.4. Relevant missions and instruments.

Missions/instruments	
ERS-1/ERS-2	RA, SAR
Envisat	ASAR, AATSR, MERIS, RA-2
Earth Explorers	CryoSat-2, SMOS, GOCE,
MetOp	ASCAT, AVHRR
Sentinels	S-1, S-3
Third-party missions	GRACE

Table 2.5. Innovative algorithms and products and the challenges they have addressed.

Algorithms and products	Challenges				
	C1	C2	C3	C4	C5
Major advances in the use of InSAR, altimetry and gravimetry for mass balance studies (GRACE, e.g. in Greenland ice and GOCE for enhancing spatial resolution for GRACE in the case of West Antarctica)		×			
Significant advances in ice velocity estimation on glaciers and ice sheets (also 3D velocities) with SAR and optical data (e.g. feature tracking, InSAR)		×			
Advances in detecting grounding line locations using various techniques (InSAR, optical data, CryoSat-2)				×	
New SMOS product for detecting the frozen soil depth and dynamics (SMOS+ Permafrost)					×
New sea-ice thickness measurements from CryoSat-2, with unprecedented accuracy and sampling	×				
Experimental thin sea-ice thickness products (<0.5 m) from SMOS (e.g. SMOS-Ice)	×				
Advances in snow parameter retrieval (e.g. temperature, grain size, fractional cover, production of the first reliable hemispheric long-term time series of snow water equivalents), e.g. STSE SnowRadiance, DUE GlobSnow			×		

Table 2.6. Legacy datasets and the challenges they have addressed.

Legacy datasets	Challenges				
	C1	C2	C3	C4	C5
Coordinated data acquisition and access through various space agencies as a contribution to International Polar Year	×	×		×	×
25 000 glacier area products and a more than 25% increase in the number of glaciers in the GLIMS database (GlobGlacier)			×		
15–30 years of snow cover and snow water equivalent (GlobSnow)			×		
Long-term set of key parameters from the Greenland ice sheet, including its outlet glaciers: changes in surface elevation, ice velocity, grounding line locations and calving front locations (CCI Ice Sheets)		×			
Quality-controlled ice concentration datasets for the Arctic and Antarctic from 1979 to the present, based on passive microwave data (CCI Sea Ice)	×				
Arctic sea-ice thickness datasets based on radar altimeter data from 1993 to the present, and with the best possible validation and error characterisation (CCI Sea Ice)	×				
Arctic-wide estimates of sea-ice motion, deformation and mass flux through selected gateways (data available for various periods from 2004 to 2011) (GlobIce, PolarView, IFREMER ice drift products)	×				
New data on permafrost-related parameters (e.g. land surface temperature, snow extent, snow water equivalent, soil moisture) in the northern hemisphere (e.g. DUE Permafrost)					×
20-year dataset on the dynamics of shallow lakes in Alaska for climate studies (STSE NorthHydrology)				×	

Earth Observation in the Context of Models

- Advances in the assimilation of relevant satellite-observable parameters, including land surface temperatures, snow extent, snow water equivalent, vegetation and soil moisture, into permafrost models (DUE Permafrost).

- Advances in the assimilation of land and atmosphere EO-based products (wetland dynamics, frozen soil dynamics, inundation dynamics, methane total atmospheric column) into coupled land–atmosphere models in order to improve the characterisation of methane emissions from boreal wetlands (ALANIS Methane).

- Advances in the assimilation of lake (lake ice cover and lake surface temperatures) and snow information into hydrological and numerical weather prediction models at high latitudes (NorthHydrology) (Challenge C3).

- Better confrontation of climate models with cryospheric observations (e.g. CCI) to assess the quality of models and data.

- Advances in the assimilation of (simulated) CryoSat-2 ice thickness measurements into a coupled ice–ocean model in order to examine their impacts on Arctic Ocean prediction systems (Challenge C1).

- Improved quantification of the mass loss of ice sheets compensated for solid Earth rebound and its contribution to sea-level change based on altimetry, SAR, GNSS and gravity change (GRACE, GOCE) (Challenges C2, C4, O1, O5, O6).

Relevant International Research Initiatives/Programmes

- CliC, CLIVAR, NEESPI, IPY, IMBIE, GCW, IPI, PEEX, SAON, SIOS

New Earth System Insights

- First quantification of the error in the ice-sheet mass balance (e.g. STSE IMBIE) reconciling error characteristics from different EO techniques (e.g. gravimetry, InSAR, altimetry). Since 1992, the Greenland and Antarctic ice sheets have contributed, on average, 0.59 ± 0.20 mm per year to the rate of global sea-level rise (Challenge C2).

- Better understanding of ocean circulation in polar regions (Challenge C1).

- Advances in attribution issues for sea-ice melting (Challenge C1).

- New CryoSat-2 measurements of trends in Arctic sea-ice thickness (Challenge C1).

- Detection of huge stores of freshwater in the Arctic with ESA altimeter data (Challenge C1).

- New capabilities to quantify the amount and variability of freshwater stored in terrestrial snowpacks and snow accumulation on glaciers (Challenges C1 and C3).

Moving Science to Services

- Operational services for sea-ice monitoring, iceberg tracking, ice-edge mapping, river ice for ice jams, lake ice and snow monitoring services (PolarView).

- GlobIce, GlobGlacier, GlobSnow, DUE Permafrost.

2.3 Land Surface

2.3.1 Scientific Context of the Updated Challenges

The updated Living Planet Scientific Challenges related to the land surface are to improve understanding and quantification of:

- *Challenge L1:* Natural processes and human activities and their interactions on the land surface.
- *Challenge L2:* Interactions and feedbacks between global change drivers and biogeochemical cycles, water cycles, including rivers and lakes, biodiversity, and productivity.
- *Challenge L3:* Structural and functional characteristics of land use systems to manage sustainably food, water and energy supplies.
- *Challenge L4:* Land resource utilisation and resource conflicts between urbanisation, food and energy production and ecosystem services.
- *Challenge L5:* How limiting factors (e.g. freshwater availability) affect processes on the land surface and how this can adequately be represented in prediction models.

Earth's land surface is particularly significant to all societies, since this is where we live and from which we harvest many of the resources for life. It is a complex and heterogeneous environment at many spatial and temporal scales. Humans have probably always adapted the environment to their own uses, but concerns about the recent pace of change and its impacts have grown as our understanding of the interdependencies in the Earth system has increased.

Owing to the complexity of land-surface processes and land–atmosphere interactions, Earth System Models (ESMs) are used to represent our current knowledge of the major processes and their interrelationships. Such computer implementations involve the coupling of models of water, energy, and vegetation and carbon cycle processes at the land surface with those in the atmosphere and oceans. They are used to understand and model land–surface effects and their connections and feedbacks on climate, in particular to simulate (past and) future evolution of the climate. Earth observation aims to provide consistent global monitoring of land-surface variables to drive and test such models and is playing an increasingly important role as the size of satellite archives increases with improved global coverage and better spatial and temporal resolution.

However, the interplay of Earth's ecosystems is far from being fully understood and ESMs do not currently deal well with many anthropogenic effects such as land-cover change (Fig. 2.13). As a result, there are large uncertainties about the roles played by the land surface in carbon dynamics and land–climate interactions. Nutrient cycles are currently not well dealt with in models, or by Earth observation methods and techniques. Biological diversity monitoring from space is currently also rather limited. The detection of extreme events from Earth observation is improving, but controversies over the interpretation of the impacts of drought in the Amazon from observations, for example, serve to emphasise the importance of careful and consistent data processing.

Challenge L1. In the long term, a crucial issue for Earth observation will be to ensure the continuity of consistent measurements of land observations needed to inform and evaluate adaptation strategies for climate change, moving towards a full multisource data assimilation system that integrates multiple spatial and temporal scales and describes land processes coupled

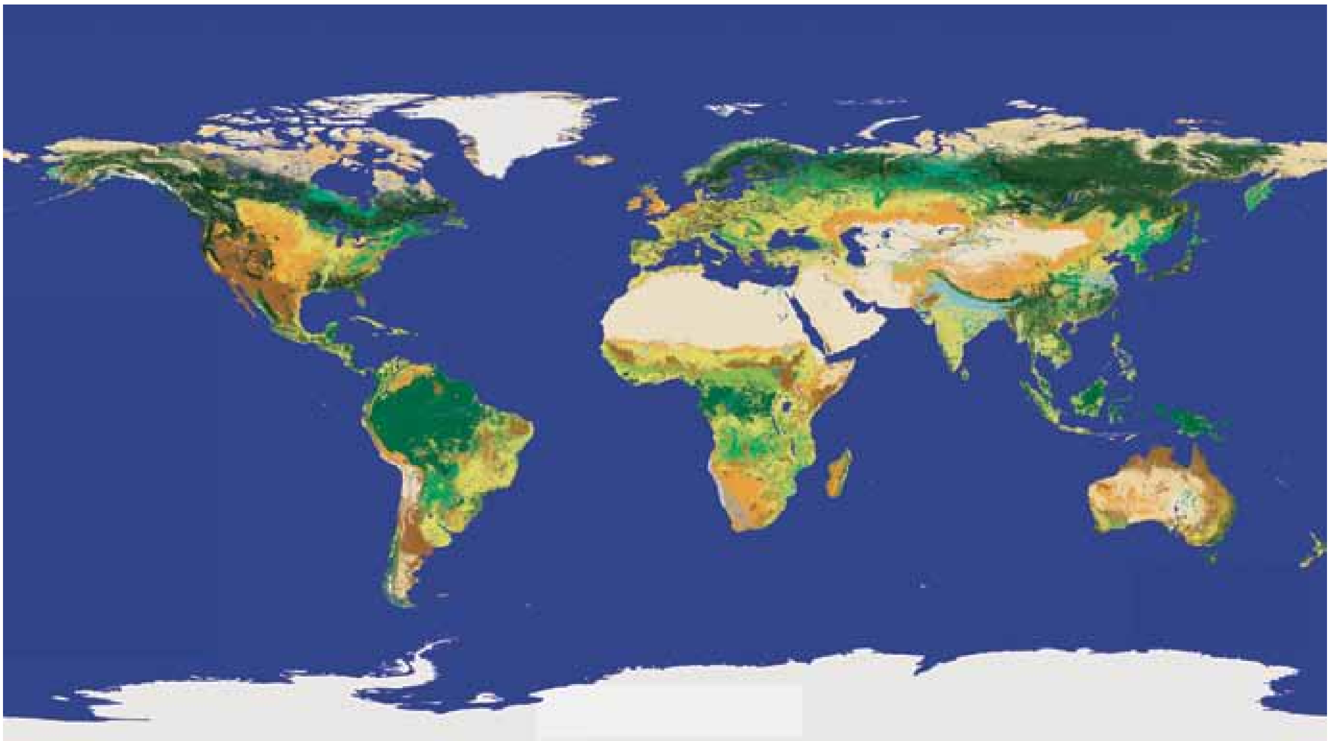

Figure 2.13. Global land cover. (ESA/CCI Land Cover/Université Catholique de Louvain)

to biochemical cycles. The interactions between natural and human components of the Earth system remain poorly understood; in some cases anthropogenic effects (e.g. changes in land use, urbanisation and modification of land structures, contamination, and the exploitation of water and mineral resources) drive the whole land dynamics. In Europe, for instance, the carbon cycle is mostly driven by human interactions rather than by the climate, and this influence is expected to grow as the human population and the demand for food, water and other natural resources increase.

Natural processes and human activities and their interactions on the land surface become Challenge L1.

Challenge L2. Improving scientific understanding of the interactions between terrestrial ecosystems and other components of the Earth system and between water and other biogeochemical cycles, and quantifying their control and feedback mechanisms, are essential for determining future trends through the assimilation of Earth observation data into global dynamic models.

The interactions and feedbacks between global drivers of change and biogeochemical cycles, water cycles, including rivers and lakes, biodiversity and productivity, become Challenge L2.

Challenge L3. Assessing the vulnerability of terrestrial ecosystems and supporting adaptation and mitigation of these vulnerabilities is a crucial goal. Land-use change associated with hydroclimatic effects can affect local and regional climates, for instance, they can result in cooling at the peak of the growing season and warming after harvest, with impacts also on rainfall patterns owing to changes in the transfer of water from land to the atmosphere. The functioning of terrestrial ecosystems, the induced hydroclimatic effects and variable land–atmosphere exchanges associated with modifications in land use must be better understood.

The structural and functional characteristics of land use systems in order to manage sustainable food, water and energy supplies become Challenge L3.

Challenge L4. Some other emerging issues concern the economic and environmental implications of the redistribution of land used for food production (e.g. cropland, pastures and rangeland) or forest for urban development, tourism, mining, growing biofuels, etc. For instance, urbanisation often results in the degradation of ecosystems as a result of air and water pollution, biodiversity loss, large variations in river discharges and temperatures (i.e. urban climatology). On the other hand, urbanisation also provides important economic opportunities and social benefits for farmers and rural populations. It is then necessary to support decisions that balance private gains and social costs.

Land resource utilisation and the conflicts between urbanisation, food and energy production and ecosystem services become Challenge L4.

Challenge L5. New challenges related to the increasing demands of agricultural production in order to ensure global food security are emerging as increasingly important issues in land science associated with global population dynamics. A better scientific understanding of land processes clearly results in direct societal benefit in this area. It is estimated that the demand for food is rising by 1.4% per year and that agricultural production will have to increase by more than 50% over the next four decades to satisfy the demands of the growing world population. Food security will become a critical issue, in particular because the demand for food is rising in parallel with the impacts of climate change on agriculture and environmental conditions. Efforts to improve food production and ensure better usage of water and fertilisers must be made compatible. The application of the scientific understanding of the coupling of water, carbon and nitrogen cycles should better support quantitative yield forecasting driven by global observations and crop/agrometeorological modelling techniques.

How limiting factors affect processes on the land surface, and how they can be adequately represented in prediction models, become Challenge L5.

Land processes are driven not only by physics and chemistry, but also by biology (Fig. 2.14). While physical and chemical processes and feedbacks are often deterministic and predictable, dynamic biological processes, particularly those involving ecophysiology, are rather intricate and feedbacks are difficult to predict. Simple statistical ensemble forecasts are unable to capture the actual spatial and temporal variability of the various phenomena related to vegetation dynamics, including growth, structure and species composition, but also population dynamics, urbanisation, transportation systems, and the use and exploitation of natural resources. One key issue identified is the need to increase the spatial resolution of observations to enhance the capability to resolve different processes. This is true not only for monitoring the land surface, but also for sea ice, atmospheric chemistry and other disciplines, but in the case of land, spatial resolution is key to understanding the variability associated with human impacts and socioeconomic processes. Increased temporal resolution is also desirable to enhance the possibility of resolving diurnal cycles, further exploiting the opportunities offered by geostationary orbital observations, as well as seasonal impacts at higher spatial resolution using constellations of satellites or other configurations of sensors.

The understanding of interactions between dynamic processes and the variability of ecosystems requires long time series of global data at rather high spatial resolution to identify the processes involved. But, good temporal resolution over a long time span is also needed in order to decouple seasonal and interannual natural variability from long-term climatic trends and climate variability. This requires sustained Earth observations, such as those provided by the Sentinel series within the Copernicus programme. Good coordination between the Earth Explorers, Sentinels and other missions (i.e. meteorological satellites) is needed to address specific research and application issues, as no single mission can fully address the complex scientific problems as those

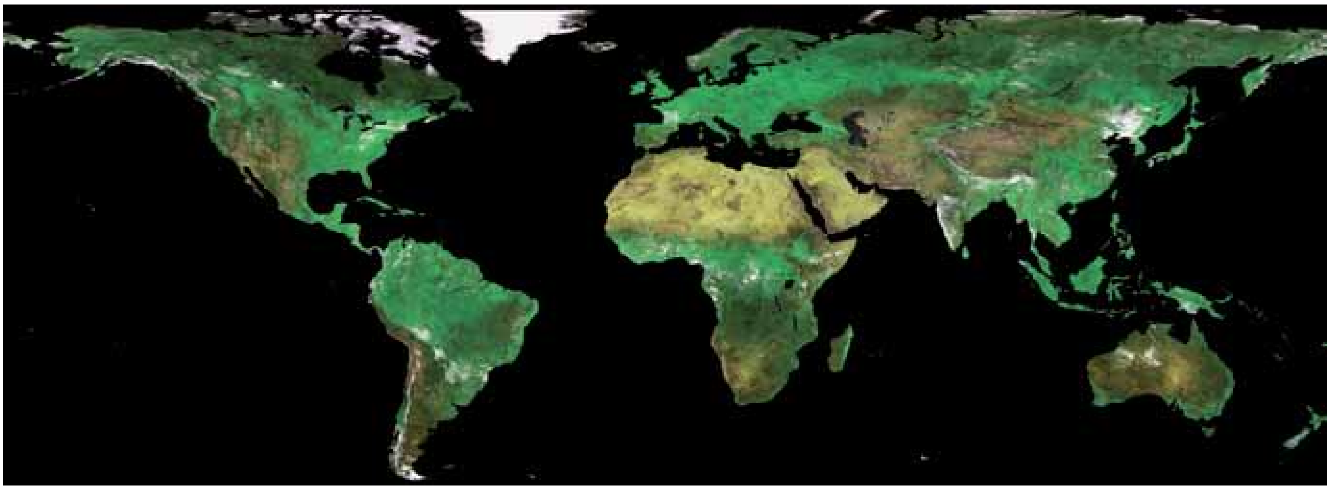

Figure 2.14. Global vegetation map compiled using Proba-V data. (ESA)

identified. Climate services should be developed within the Earth observation programmes for monitoring our ‘Living Planet’ and its health.

The assimilation of Earth observation data into models (via Kalman, particle filters or variational approaches) permits the optimal combination of models and observations. Essential Climate Variables obtained in a comprehensive Earth observation data assimilation framework have the added benefit of internal biophysical consistency, providing effective quality control. Reanalyses offer a well-established technical and scientific framework for integrating the variety of ECV products and for ensuring the internal consistency of Earth observations from various observing platforms and networks. In the near future, handling the huge amounts of data acquired by satellites will represent a challenge, requiring the development of models and data processing infrastructures. This issue is particularly relevant for land, with the new global land-surface observations in high spatial resolution and high temporal repetition, so that models will be needed that are better able to describe spatial heterogeneity and processes, and the feedbacks linked to such heterogeneity, at multiple temporal scales from diurnal cycles to long-term behaviour.

In parallel with the consolidation and continuity of long-term data records based on existing sensors, the description of land-surface processes could benefit considerably from technical developments that would result in the provision of new types of data that are not currently available. Some examples of such data expected in the future include lidar observations of vegetation structures for 3D global vegetation mapping, improved spectral resolution in optical sensors to be able to look at the chemistry of vegetation (pigments, water content, cellulose), enhanced SAR interferometric and tomographic capabilities for global vegetation mapping, or looking at dynamical processes such as photosynthesis variability and the impact on carbon sequestration and global primary productivity using innovative techniques such as vegetation fluorescence. All such new approaches will need to be implemented in a way that complements existing global systematic mapping capabilities (i.e. Copernicus Sentinels) to make possible the transition from current products to the new information available for use in models of land processes. Data assimilation strategies must be formulated to extract the full potential of the combination of all available Earth observation data and the advances in model development taking place within the land community.

2.3.2 Achievements with Respect to the 2006 Challenges

Within ESA's Earth Observation Programme, achievements in recent years have resulted not only in the implementation of new missions, but also in a much better exploitation of archived data through global products (Glob series, CCI-ECVs, STSE results, etc.) and in the derivation of advanced variables used for data assimilation into global land models. The coordination of ESA's efforts and related activities supported by the European Commission and carried out by other European (e.g. Eumetsat) or national entities and space agencies, has been essential for achieving the incremental increase in the understanding of the dynamics of land surface processes.

Over a decade of missions that have delivered essential information to science, ESA's Living Planet Programme has contributed to the improved understanding of Earth and how it functions as a system. Earth observation data have started to allow systematic challenging of and steady improvements in the components of Earth system models and their representation of water, energy, vegetation and carbon cycles. The need to generate long-term, consistent global records of land surface parameters is now widely recognised and improvements have been made in mapping parameters such as fAPAR, land surface temperature, soil moisture, albedo, land cover and fire disturbance through ESA's Climate Change Initiative and the related DUE and STSE projects. Data from the new Sentinel satellites will contribute significantly to continuing and improving such records over the land surface. Projects such as GlobAlbedo are now providing consistent data over the entire archives of a suite of European sensors, with per-pixel associated uncertainty estimation enabled by using a Bayesian framework. In other areas, similar 'data assimilation' methods are starting to improve the ability to generate products from multiple data sources and to merge (and confront) models with products (e.g. STSE EO LDAS, OPTIRAD, STSE 3D Vegetation Lab).

There have been significant advances in using Earth observation to improve the representation of coupled land-surface processes in the energy and water cycles (STSE WACMOS and related projects) and the carbon cycle (STSE ALANIS). GRACE and SMOS (Fig. 2.15) are contributing to improvements in hydrological monitoring, along with much improved mapping of snow cover and properties (STSE SnowRadiance, GlobSnow). An important recent advance has been the capability to measure signals directly related to vegetation photosynthesis from space using chlorophyll fluorescence, which has greatly

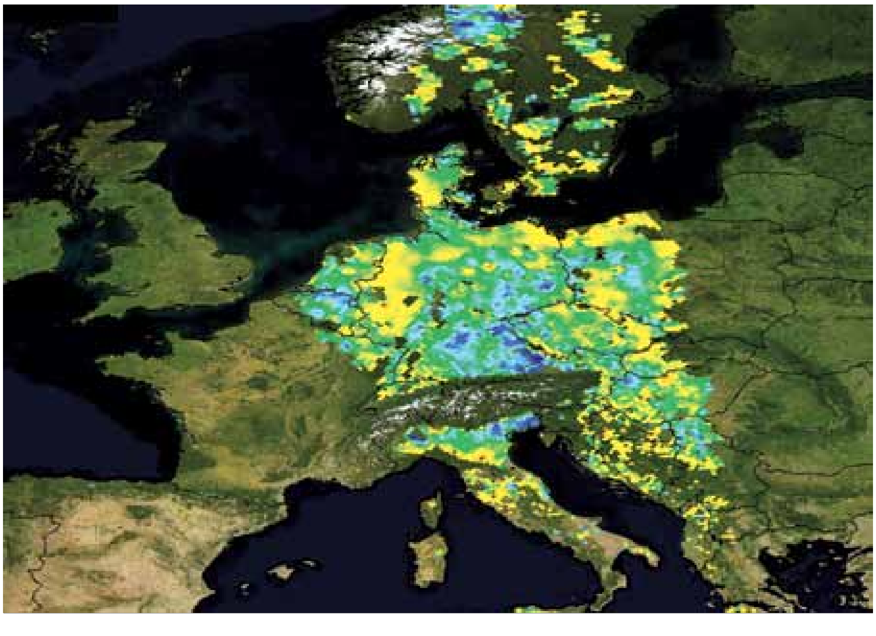

Figure 2.15. SMOS observations of soil moisture in Germany on 31 May 2013. Blue indicates high soil moisture levels, while yellow and orange indicate dryer soils. For example, dark blue corresponds to a value of 0.50, which means that 1 m^3 of soil contains 500 litres of water. (CESBIO/ESA)

assisted the quantification of vegetation primary productivity and has thus improved models of this process. Measurement of process is a significant step forward using satellite observations to constrain vegetation elements of Earth system models. Some advances have been made in quantifying forest biomass using long-term records of ERS SAR (STSE BIOMASAR) and of third-party missions such as ALOS, and exciting new possibilities are emerging from the use of polarimetric SAR as well as from the preparations for the Biomass mission, which will greatly extend the range of biomass that can be measured, and will provide tomographic information on canopy structures.

The strategy for ESA's Living Planet Programme formulated in 2006 identified the four most important land surface challenges that should guide ESA's efforts in providing essential Earth observation information:

- *Challenge L1:* Understand the role of terrestrial ecosystems and their interaction with other components of the Earth System for the exchange of water, carbon and energy, including the quantification of the ecological, atmospheric, chemical and anthropogenic processes that control these biochemical fluxes.

- *Challenge L2:* Understand the interactions between biological diversity, climate variability and key ecosystem characteristics and processes, such as productivity, structure, nutrient cycling, water redistribution and vulnerability.

- *Challenge L3:* Understand the pressure caused by anthropogenic dynamics on land surfaces (use of natural resources, and land-use and land-cover change) and their impact on the functioning of terrestrial ecosystems.

- *Challenge L4:* Understand the effect of land-surface status on the terrestrial carbon cycle and its dynamics by quantifying their control and feedback mechanisms for determining future trends.

These four land challenges have been addressed through dedicated missions (i.e. SMOS) and numerous studies (Glob series, ECV, EO-LDAS, etc.). The achievements with respect to these challenges are summarised in the following. Table 2.7 lists the relevant missions and instruments (past, present and future), while Table 2.8 gives an overview of a number of innovative algorithms and products developed in recent years, and the challenges that have been addressed either directly or indirectly. The legacy datasets developed – products that are recognised long-term data series – are shown in Table 2.9.

Missions/instruments	
ERS-1/ERS-2	SCAT SAR
Envisat	ASAR, AATSR, MERIS (RA-2)
Earth Explorers	SMOS, (CryoSat-2), Biomass, FLEX (candidate EE-8), CarbonSat (candidate EE-8)
MetOp	ASCAT AVHRR
Sentinels	S-1, S-2, S-3, (S-4/-5, S-5P)
Third-party missions	ALOS, PROBA, AQUA/TERRA (MODIS), Landsat, NOAA AVHRR, Radarsat-1 and 2, SPOT, GRACE, Hyperion

Table 2.7. Relevant missions and instruments (past, present and future)

Table 2.8. Innovative algorithms and products, and the challenges they have addressed.

Algorithms and products	Challenges			
	L1	L2	L3	L4
Support of ecosystem science through new radiative transfer schemes and global data such as albedo (GlobAlbedo), snow cover (GlobSnow), land cover maps (GlobCover), biomass (BIOMASAR, GlobForest), soil moisture (WACMOS)	×	×		
Significant advances in the generation of global high-resolution products (land cover, soil moisture, surface temperature, LAI, LUE)			×	
Novel soil moisture data products from the SMOS mission	×			
EO land data assimilation methods (STSE EO-LDAS)				×
Significant advances in the generation of near-realtime global river and lake level products		×		
Development of a methodology for the assimilation of fAPAR, soil moisture and carbon dioxide in models		×		×
Novel biomass products from SAR data			×	×
Surface reflectance databases for improving land surface boundary conditions in atmospheric radiative transfer used to retrieve atmospheric species (GlobAlbedo, ADAM)	×			×
Improved description of surface bidirectional reflectance distribution functions at global scales		×	×	
High-temporal-resolution land products from Meteosat geostationary data (MSG)	×	×		

Table 2.9. Legacy datasets and the challenges they have addressed.

Legacy datasets	Challenges			
	L1	L2	L3	L4
Provision of land cover maps at high spatial resolution (300 m) (GlobCover with data from Envisat/MERIS full resolution)	×		×	
Provision of surface water storage 20-year time series	×		×	
Long-term records of land surface changes from time series of satellite data		×		×
Global maps of vegetation parameters such as LAI, FVC, fAPAR and land surface temperature, soil moisture, albedo, biomass and greenhouse gases		×		×
Global maps of fire disturbance (Fire Atlas)			×	×
Global maps of greenhouse gas emissions				×

Earth Observation in the Context of Models

— Advances in the testing, verification and assimilation of Earth observation data into land surface and carbon models (and also land–atmosphere coupled models) as demonstrated by ALANIS Methane and ALANIS Smoke Plumes. These activities are continuing with the CarbonFlux project with a focus on carbon fluxes.

— Novel approaches to data assimilation (EO-LDAS) (Challenge L1).

— GRACE-based seasonal hydrology estimates (water equivalent) at larger scales integrated with hydrological models.

— GRACE-based large-scale groundwater changes compared with modelling.

— Advances in the assimilation of river level data into catchment basin models.

Relevant International Research Initiatives/Programmes

- AMMA, BALTEX, CCAFS, CEOP, CEOP-HE, CliC, CLIVAR, GCP, GLP, iLEAPS, LOICZ, NEESPI, Diversitas, GEWEX

New Earth System Insights

- Products are increasingly being used to understand biodiversity in support of the UN Convention on Biological Diversity (Challenge L2).

- Significant advances in the use of land cover information for environmental impact assessments (Challenge L3).

- Improved global descriptions of exchange processes between land and the atmosphere (H_2O, CO_2, CH_4, etc.) (Challenge L3).

- Significant advances in the capability to generate long-term records of carbon-related biophysical variables, e.g. vegetation parameters (Albedo, LAI, fAPAR) and disturbances (e.g. fires) (Challenge L4).

- New capabilities to derive biomass information from SAR (Biomass, BIOMASAR) and polarimetric SAR (Pol-inSAR) (Challenge L4).

- Advances in coupling land and atmospheric processes related to the carbon cycle (e.g. ALANIS smoke plumes from land emissions) (Challenge L3).

- Advances in coupling land and atmospheric processes related to the energy and water cycles (e.g. WACMOS, WACMOS-ET) (Challenge L1).

- Improved insights into changes in water cycle components (e.g. WACMOS, WACMOS-ET, Watchful, GlobVapour, CCI Soil Moisture, CCI Cloud) including groundwater from satellite gravimetry (GRACE).

- Advances in the assimilation of multiple datasets into carbon models (STSE CarbonFlux).

Moving Science to Services

- Land cover classification, fire monitoring, forest mapping, soil sealing.

- GlobCover, GlobAlbedo, Diversity II, GlobTemperature, GlobBiomass.

- River & lake near-realtime pilot demonstrations.

- Development of pre-operational services towards exploitation of Copernicus/Sentinel data.

- Operational use of Earth observation data in administrative services already achieved for regional applications.

2.4 Ocean

2.4.1 Scientific Context of the Updated Challenges

The updated Living Planet Scientific Challenges related to the ocean are to improve understanding and quantification of:

- *Challenge O1:* Evolution of coastal ocean systems, including the interactions with land, in response to natural and human-induced environmental perturbations.
- *Challenge O2:* Mesoscale and submesoscale circulation and the role of the vertical ocean pump and its impact on energy transport and biogeochemical cycles.
- *Challenge O3:* Responses of the marine ecosystem and the associated ecosystem services to natural and anthropogenic changes.
- *Challenge O4:* Physical and biogeochemical air–sea interaction processes on different spatiotemporal scales and their fundamental roles in weather and climate.
- *Challenge O5:* Sea-level changes from global to coastal scales and from days (e.g. storm surges) to centuries (e.g. climate change).

The oceans have a fundamental influence on our climate and weather. They store, transport and exchange with the atmosphere large amounts of heat, water and gases. These exchanges regulate world and regional climates on time scales ranging from days (storms and hurricanes), seasons (monsoons), years (El Niño), decades and centuries (climate change). The oceans and marine life also largely control the amount of carbon dioxide in the atmosphere, and they dominate Earth's carbon cycle.

Over the past 50 years, the oceans have absorbed more than 90% of Earth's heating due to the anthropogenic increase in greenhouse gas concentrations, and about 30% of the anthropogenic carbon dioxide emitted since preindustrial times (IPPC, 2013). These buffering services regulate Earth's climate, but have a profound impact on the world's oceans. The warming of the oceans is raising global sea level because water expands when it warms (Fig. 2.16). Combined with melting ice caps and glaciers, the rising sea level threatens natural ecosystems and human structures near coastlines around the world, making them more exposed to increased flood and storm surge risks.

Moreover, levels of dissolved oxygen in the oceans are diminishing owing to increased stratification; together with increasing temperatures, this induces deoxygenation so that the 10% of ocean volume currently characterised by low levels of dissolved oxygen could greatly expand. Absorption of carbon dioxide results in increased acidity, which can reduce the availability of calcium for plankton and shellfish species, threatening their survival. Since many of these organisms serve as the base of much of the marine food chain, acidification could have dramatic impacts on entire ecosystems.

All of these changes are exacerbating existing pressures on the marine environment, such as overfishing, pollution and habitat destruction, and are leading to increased risks to global food security, economic prosperity and the well-being of human populations. Coastal zones and continental shelf seas deserve particular attention. These areas of high biological productivity and biodiversity are exploited for food and other marine resources and provide many valuable ecosystem services.

Addressing these issues of high societal relevance requires a better understanding of the functioning of the oceans and the development of

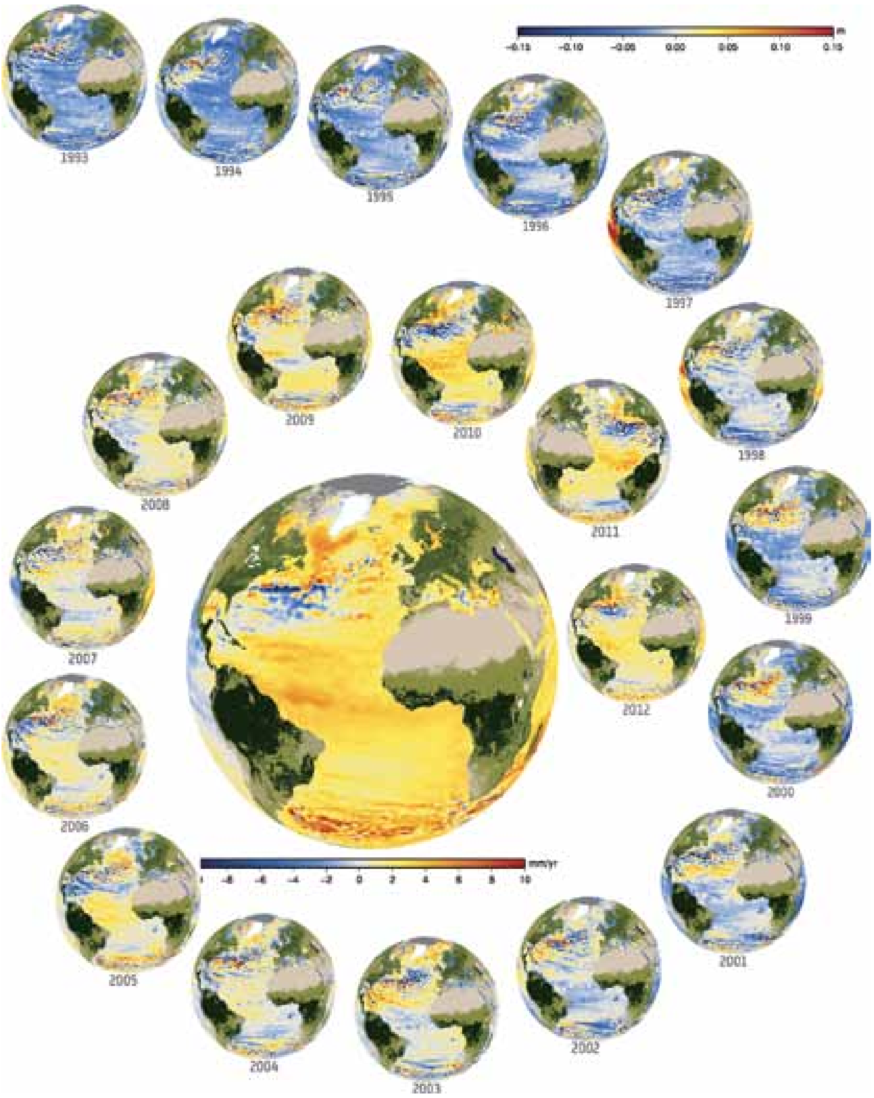

Figure 2.16. Annual mean sea-level anomalies computed from Climate Change Initiative data, 1993–2013. (CCI Sea Level; CLS)

improved ocean (physics and ecosystems) and climate predictions. The five strategic challenges for the ocean, while not exhaustive, target the most important research questions. The ocean is a major component of the ocean–atmosphere–ice and land coupled system and most of the research challenges are related to its interfaces with other Earth system components (Challenges O1, O2, O4 and O5). Within the ocean component, these challenges cover several disciplines, from physics, biogeochemistry to ecosystems and their coupling (Challenges O2, O3). A very-high-resolution description of ocean circulation is required, in particular, to better understand and quantify the major role of mesoscale and submesoscale circulation in heat, energy transport and biogeochemical cycles (Challenge O2). Understanding and forecasting the evolution of marine ecosystems and coastal systems in response to natural and anthropogenic changes are also specific challenges with very high societal relevance (Challenges O1, O3, O5).

These research challenges can only be addressed through long-term, global, high-resolution and high-quality ocean observations. Such observations are also essential for the development of marine (operational oceanography) and climate change services that provide societal benefits and are required to protect the environment.

As a major component of the global ocean observing system, satellite remote sensing plays a fundamental role. The following overarching requirements for satellite observations can be identified:

— *High-resolution observations.* The ocean is a complex engine and its dynamics cover a wide spectrum from low-frequency planetary scales to high-frequency and small scales. One of the lessons of the past decade is the complementarities and interactions between these different scales, implying the requirement to observe the oceans over a broad range of spatial and temporal scales. Many key ocean phenomena are still undersampled and require much higher spatial and temporal resolution. Model resolutions are steadily increasing but our observation capabilities are not. Observing rapid changes in the environment, including the diurnal cycle, is a particular challenge.

— *Integration with* in situ *observations and models.* Satellite observations are now systematically used together with *in situ* observations and models to provide integrated monitoring and prediction of the physical state of the ocean. This has been a strong evolution in oceanography over the past 20 years. Ongoing efforts aim to add the monitoring and prediction of the ecosystem state, by embedding ecosystem models into 3D physical models. Besides the fundamental questions that this evolution raises, in terms of which numerical techniques have to be developed for assimilating satellite ocean colour observations into this new generation of coupled models, the availability of the required parameters at the appropriate spatial and temporal scales are central.

— *Climate datasets and continuity.* The long-term monitoring of the ocean environment still suffers from being fed by observations from inherently short-duration missions of insufficiently qualified consistency. This is a major challenge that future missions must address in order to contribute to building climate-quality data records for the oceans. This is an essential endeavour, to which all missions should contribute whatever their initial goals, i.e. research exploratory missions versus more operational ones. A necessary element is well-resourced post-launch calibration, validation and intersatellite harmonisation programmes as core activities of these missions, rather than ‘nice to have’ programmes that are beyond the responsibility of space agencies. Such activities must also be maintained across missions and linked to efforts to reprocess historical mission data in order to ensure the consistency of datasets and the efficient use of investments. The second element of a strategy towards climate-quality data records is international cooperation in developing and applying rigorous metrological principles to Earth observations. ESA’s strong and reinforced engagement in such activities is essential.

— *Improved technologies.* Recent (and future) questions related to ocean–atmosphere physical and biochemical couplings are (and will be) fully linked to improved measurement capabilities. Indeed, when new high-resolution measurements become more systematically available, these observations will undoubtedly challenge our ability to understand and model small-scale features and dynamics, in terms of both ocean processes and sensor physics. Consequently, the need for an increased spatiotemporal resolution demands not only new instrument designs, but also new opportunities to refine the use of existing observations, better algorithms to interpret the data and new concepts to exploit potential synergies between measurements.

— *Better products.* Besides the challenge of comprehensively covering temporal modes of variability of the ocean, there is a need to improve the interpretation of the different types of observation. This means deriving new products, improving existing products, attaching realistic and defensible uncertainty information to all products and ensuring better internal multivariable consistency. These improvements can be achieved by various means:

improved satellite-borne sensors (e.g. more or new spectral bands, or higher spectral resolution, better sensitivity and dynamic ranges, new observation concepts, etc.); better knowledge of the physical drivers of the measured signals (e.g. through field campaigns), which is needed to improve inversion methods; the application of principles from metrology in tracing uncertainty from raw measurements to products; and the synergistic use of different types of satellite observation (e.g. better atmospheric correction of ocean colour observations thanks to better surface and aerosol characterisation from SAR and atmospheric missions). As far as ocean colour is concerned, a better characterisation of ecosystems, including improved identification of phytoplankton groups, better separation of constituents (phytoplankton and coloured dissolved organic matter), and better characterisation of the phytoplankton carbon stock and its dynamics (productivity) at all temporal scales are needed (Fig. 2.17).

— *Facilitated data usage.* The volume of data available for comprehensive studies of the ocean environment is increasing dramatically as a new era of satellite remote sensing begins, providing more missions, more parameters, increased spatial and temporal frequency of observations, and the increasing demand for synergistic use of different types of observation. This situation calls for a revolution in the ability to use these datasets. Users should be able to process, reprocess and analyse large quantities of data from their desktop, without having to know about data formats, structures and other technical details. Users need to be freed from constraints of the data architecture of orbits, tiles or scenes, because the scientific challenges are at the scale of coastal regions, ocean basins or the global ocean, across many time scales (Fig. 2.18). Intelligent interfaces must be developed that link users to the information content of satellite observations. Data usage must expand beyond institutional users who traditionally have the processing and analysis capabilities: independent research users, small and medium enterprises and citizens can legitimately expect to be empowered by remote sensing observations that are openly accessible. The current situation is not sufficiently open that the full potential of observations for a better understanding and monitoring of the environment is exploited. An open data policy is a prerequisite for these uses to develop, with benefits for knowledge and the knowledge economy.

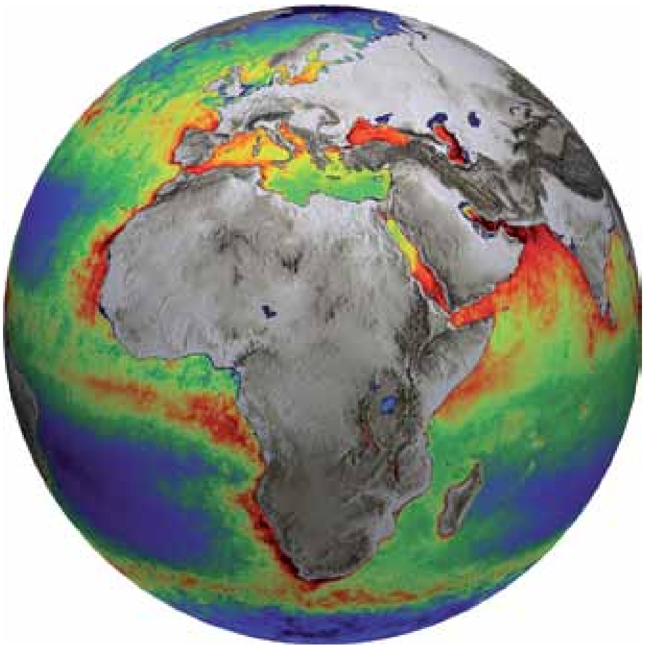

Figure 2.17. Global ocean chlorophyll concentrations from MERIS. (ACRI-ST/CNES/ESA)

Figure 2.18. Global ocean currents from SMOS. (ESA/CNES/CLS)

2.4.2 Achievements with Respect to the 2006 Challenges

The strategy for ESA's Living Planet Programme formulated in 2006 identified the six most important ocean challenges that should guide ESA's efforts in providing essential Earth observation information:

- *Challenge O1:* Quantify the interaction between variability in ocean dynamics, thermohaline circulation, sea level and climate.

- *Challenge O2:* Understand physical and biochemical air–sea interaction processes.

- *Challenge O3:* Understand internal waves and the mesoscale in the ocean, its relevance for heat and energy transport and its influence on primary productivity.

- *Challenge O4:* Quantify marine ecosystem variability, and its natural and anthropogenic physical, biological and geochemical forcing.

- *Challenge O5:* Understand land–ocean interactions in terms of natural and anthropogenic forcing.

- *Challenge O6:* Provide reliable model- and data-based assessments and predictions of the past, present and future state of the ocean.

Thanks to the development of highly successful missions, satellite oceanography is now providing major and unique contributions to ocean and climate research. Satellites provide near-realtime, near-simultaneous global, high spatial and temporal resolution observations of key ocean variables. Over the past 10 years, satellite observations have thus led to major advances in our understanding of this essential role of the oceans, including ocean dynamics from large scale to mesoscale, the coupling between physics and biogeochemistry and air–sea interactions. Significant progress has been achieved in the joint analysis of satellite and *in situ* observations (in particular thanks to the development of the global array of Argo profiling floats) and in the combined use of satellite and *in situ* observations with models. The synergistic use of multiple satellite observations has been significantly developed and has led to new findings on upper ocean dynamics and air–sea interactions. Satellite observations have allowed a much better characterisation of changes in the oceans in response to global warming, such as mean sea level rise (Fig. 2.19), the long-term evolution of the extent and thickness of sea ice, sea-surface temperatures and phytoplankton concentrations.

Satellite altimetry has continued to provide major advances in the understanding of sea level and large-scale ocean circulation and in the monitoring of tropical variability and planetary (Rossby and Kelvin) wave propagation signals, which, for instance, are related to El Niño/La Niña events (Fig 2.20). Global Mean Sea Level (MSL) and its regional variations are now regularly monitored from space. The understanding of variations in MSL has benefited significantly from the complementarity of altimetry with the GRACE and GOCE gravity missions (mass contribution) and the development of the

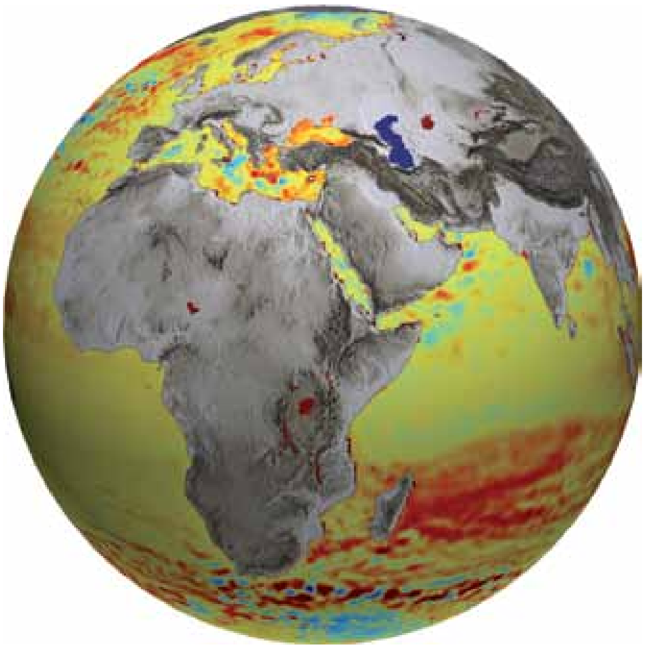

Figure 2.19. Sea-level trends 1993–2010. (ESA's CCI Sea level project)

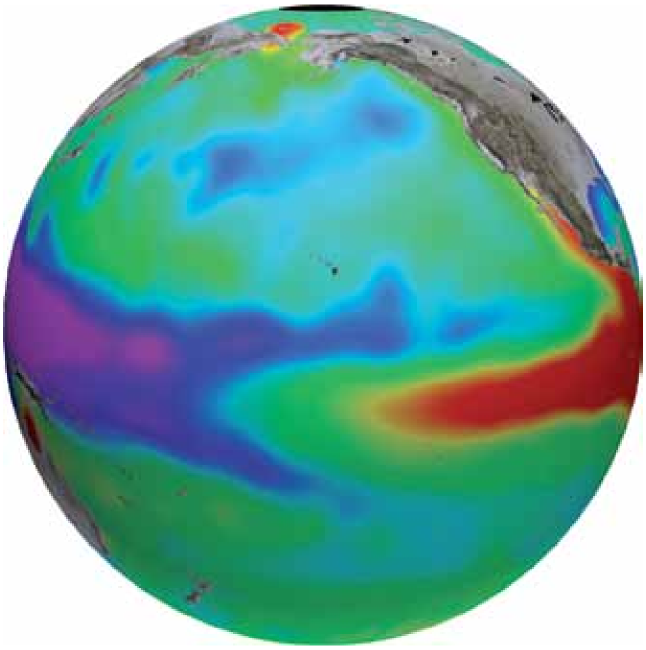

Figure 2.20. Sea-surface temperatures during an El Niño event. (ESA/DEOS/Delft University of Technology)

Argo array of profiling floats (steric contribution). The merging of Envisat and Jason-1/-2 altimeter datasets has allowed the extension of the Topex/Poseidon–ERS-1/-2 time series of sea level and ocean circulation variations at improved resolution. They have allowed the characterisation of mesoscale variability with a level of detail never before achieved at a global scale, and have provided new insights into eddy dynamics and the roles of mesoscale eddies in the ocean circulation, the transport of heat and salt, and the coupling between biology and the atmosphere. This improved description of mesoscale variability has been extensively used to validate eddy-permitting or eddy-resolving models.

Ocean mesoscale and submesoscale processes and dynamics are commonly expressed in high-resolution visible, infrared and radar satellite images. Dynamics within the ocean upper–mixed layer forced by intermittent air–sea fluxes involve very complex physics, and surface mixed layer currents embedded in a mesoscale turbulent field can locally exhibit strong departures from geostrophy and intense frontogenesis. Innovative synergistic approaches combining remote sensing observations (sea-surface heights, sea-surface temperatures, ocean colour, sun glitter, surface roughness and surface winds) are now being developed to ensure the adequate use of the 2D expressions of the mesoscale to submesoscale features revealed in satellite data (Fig. 2.21). These approaches have demonstrated that the sea-surface roughness anomalies derived from the sun glitter imagery compare very well with SAR roughness anomalies, and that the derived roughness anomaly fields are spatially correlated with sharp gradients in the sea-surface temperature field, and are apparently linked to local zones of surface current convergence and divergence. This finding is an important step towards advances in the quantitative interpretation of the upper ocean dynamics from their 2D satellite surface expressions.

The synoptic view and data coverage provided by ocean colour radiometry (OCR) satellite observations make them essential for monitoring marine ecosystems. Over the last 15 years, ocean colour data have made increasingly valuable contributions to investigations of marine ecosystems, coastal and ocean productivity, climate variability, ecosystem assessments and fisheries oceanography. Ocean colour sensors deliver data that can be used to generate a variety of optical and biogeochemical parameters, including chlorophyll and suspended sediment concentrations, dominant phytoplankton groups, phytoplankton carbon, coloured dissolved organic matter (CDOM), diffuse

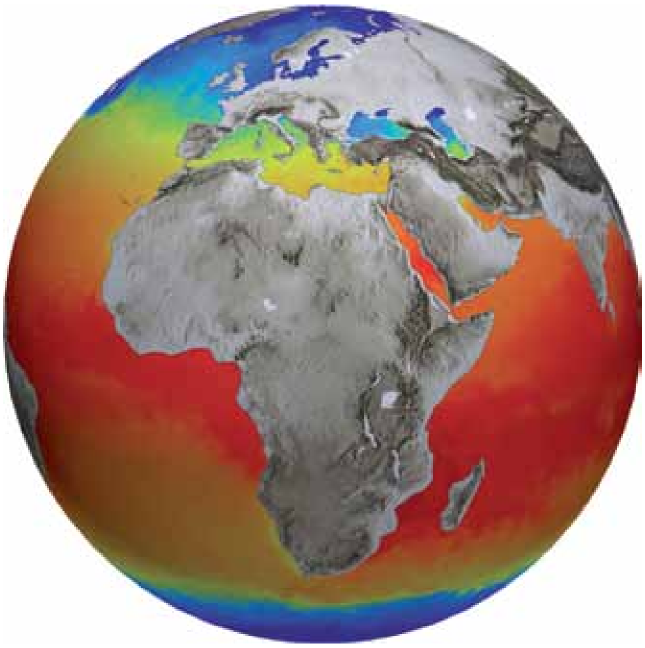

Figure 2.21. Global sea-surface temperatures. (Met Office/OSTIA)

attenuation coefficients, absorption and backscattering coefficients and primary productivity. OCR data are now widely used to validate marine ecosystem models and have recently been shown to be usable in mapping sea-surface salinity in the vicinity of intense freshwater runoff plumes (e.g. in the River Amazon) through the relationship between coloured dissolved organic matter and sea-surface salinity in such environments.

The assimilation of OCR data remains a challenging task and a high-priority research topic. Many of the products mentioned above are also at very early stages of development (e.g. phytoplankton functional types), and significant investment is still needed in field campaigns and theoretical work in order to increase the level of confidence in these new products. Recent studies have also revealed that the role of CDOM is actually often dominant in forming the ocean colour signal, even in open ocean environments where this effect was somewhat overlooked before. In summary, what is needed is a better characterisation of the ecosystem, including improved phytoplankton group identification, a better separation of constituents (phytoplankton and CDOM in particular), and of the phytoplankton carbon stock and its dynamics (productivity) at all temporal scales.

Satellite measurements are quite unique and are often critical for the analysis and short-term forecasting of extreme weather events such as tropical cyclones, mid-latitude storms and polar lows. Thanks to radiometers (e.g. DMSP, WindSat and TRMM) and scatterometers (e.g QuikSCAT and ASCAT) unprecedented synoptic observations of surface winds and atmospheric water content have revealed storm structures in impressive detail. More recently, SMOS observations have been shown to provide unique observations of intense wind regimes associated with hurricanes to complement existing active and passive microwave observation systems.

The combination of different satellite wave measurements (altimeter significant wave heights and the Envisat ASAR Wave Mode measurements) has been used to fully reconstitute the history of the long swell waves propagating over thousands of kilometres across entire ocean basins. Together with available wave forecasts, these results highlight the potential to combine dynamically many different sensor data to derive a more consistent view of storm intensity and its related wave field.

Satellite observations have also enabled rapid progress in the understanding of coupled ocean–atmosphere interactions at the mesoscale. The details of the influence of sea-surface temperatures on surface winds have been thoroughly documented from simultaneous measurements of surface winds (scatterometry) and sea-surface temperature (infrared and microwave) satellite measurements. Discovery of the ubiquity of the co-variability between mesoscale features in the sea-surface temperature field and surface winds in regions of strong sea-surface temperature fronts throughout the world's oceans is, in particular, one of the most significant recent successes of satellite oceanography.

SMOS and Aquarius have provided the first demonstration that sea-surface salinity can be measured from space with an accuracy that is useful for monitoring the global hydrological cycle over the oceans (Fig. 2.22). The ability to measure directly ocean surface currents from space at high resolution has been demonstrated using Envisat/ASAR radar data. The last five last years have also been definitively marked by a major step forward in our knowledge of the geoid and its variations thanks to the GRACE and GOCE space gravity missions. GRACE has provided new insights into climatically important processes such as mass exchange between ice sheets and the oceans, mass redistribution within the oceans, and large-scale variability in precipitation and water availability. GOCE has provided estimates of the geoid and mean ocean circulation at scales of around 100 km with an unprecedented accuracy of about 2 cm. These estimates are a fundamental element of the full exploitation of altimetry for oceanographic applications, and in particular for its assimilation into ocean models.

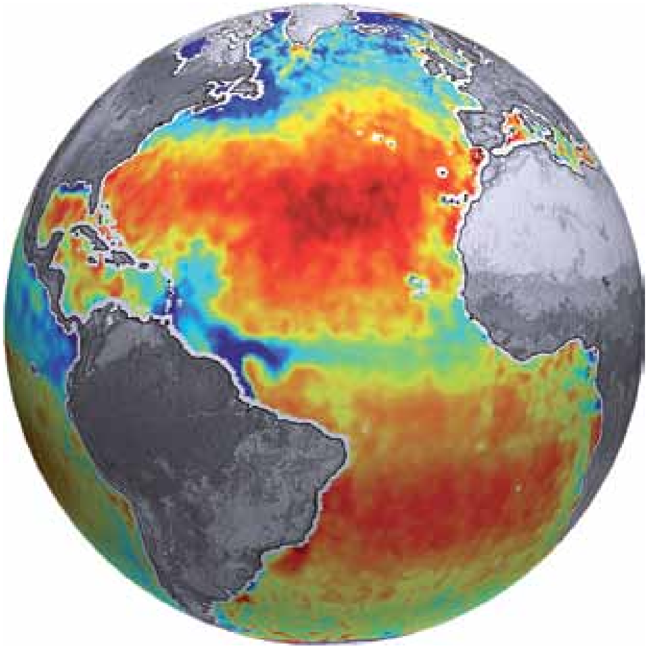

Figure 2.22. Ocean salinity measured by SMOS. (IFREMER/ESA)

Over the past 10 years, there has been significant progress in the development of operational oceanography and associated ocean services, in particular, in the framework of the Copernicus Marine Service. There have been important achievements in ensuring the near-real-time availability of high-quality satellite data including the merging of data from different sensors. Satellite and *in situ* data are now routinely assimilated into global/regional/coastal ocean models to provide in realtime or in delayed mode (reanalyses) integrated descriptions and short-term forecasts of the ocean state and serve a wide range of applications. Downstream services (e.g. oil pollution, water quality and sea-ice monitoring) have also been developed thanks to the exploitation of high-resolution satellite observations.

Also over the last decade, the potential of dual-view thermal radiometry to transform the accuracy of quantification of global sea-surface temperatures (SSTs) has been realised to a significant degree. The exploitation of Along-Track Scanning Radiometer (ATSR) series instruments has matured to a degree that such observations are well established as a reference technology for the constellation of meteorological SST sensors. Climate-quality SST data can now be obtained from satellites without reference to *in situ* observations, giving an independent check on marine climate change. Patterns of variability of SSTs obtained by satellites inform improved historical reconstructions of SSTs over the past ~150 years, which are crucial to the understanding of climate change.

The achievements with respect to the 2006 challenges related to the ocean are summarised in the following. Table 2.10 lists the relevant missions and instruments (past, present and future), while Table 2.11 gives an overview of a number of innovative algorithms and products developed in recent years, and the challenges that have been addressed either directly or indirectly. The legacy datasets developed – products that are recognised long-term data series – are shown in Table 2.12.

Missions/instruments	
ERS-1/ERS-2	RA, AMI, SCATT
Envisat	ASAR, AATSR, MERIS, RA-2
Earth Explorers	GOCE, SMOS, CryoSat-2
MetOp	AVHRR, ASCAT
Sentinels	S-1, S-3, S-2 (coastal), Jason-CS
Third-party missions	Jason-1/-2/-3, GRACE, AQUA/TERRA (MODIS), Aquarius, QuikSCAT, AltiKa

Table 2.10. Relevant missions and instruments (past, present and future).

Table 2.11. Innovative algorithms and products, and the challenges they have addressed.

Algorithms and products	Challenges					
	01	02	03	04	05	06
Significant advances in the use of SAR (e.g. new Doppler centroid-based technique) for line-of-sight components of ocean surface currents	×					
Novel processing methods for high-resolution wind vector retrieval from ASAR image mode		×				
Novel methods for wave spectrum retrieval from ASAR		×				
New high-resolution SAR-based altimeter capabilities from CryoSat-2 transferred to Sentinel-3	×		×			
Improved orbits for satellite altimetry	×					×
New techniques based on SAR for swell tracking	×	×				
Significant advances in coastal altimetry	×					×
Enhanced algorithms for ocean colour in particular for case-2 waters (e.g. STSE WaterRadiance, CoastColour)				×		
Major improvements in geoid models (GOCE, GRACE) to enhance sea-level measurements	×					
Global connection of height systems based upon GOCE for unifying tide gauges and altimetry in the same system; improved coastal sea-level analysis	×				×	×
First attempts to quantify total ocean currents from magnetic field measurements (CHAMP) in preparation for Swarm	×					
Sea floor pressure changes obtained from GRACE mass change analysis	×					×
Advances in the use of SAR for high-resolution sea-state analysis	×	×				
Advances in the use of optical data (e.g. MERIS Sun-glint features) for mesoscale ocean dynamics			×	×		
Advances in the synergistic use of optical and SAR data for mesoscale studies			×	×		
Advances in the systematic production of sea-state variables such as waves and currents	×					
Novel sea-surface salinity data products from the SMOS mission	×					
Novel sea-surface salinity data products inverted from ocean colour-derived dissolved organic matter in intense freshwater runoff	×					
Advances in the synergistic use of optical and microwave data for mesoscale studies			×	×		
Advances in the determination of phytoplankton functional types				×		
Development of SAR altimetry and demonstration of its improved performance (higher resolution, lower noise) thanks to CryoSat-2			×			

Table 2.12. Legacy datasets and the challenges they have addressed.

Legacy datasets	Challenges					
	01	02	03	04	05	06
More than 20 years of merged altimeter products (Topex/Poseidon, ERS-1/-2, Jason-1/-2, Envisat) providing unprecedented global high-resolution descriptions of sea level and ocean circulation	×					
GlobColour has provided 10 years of ocean colour data from MERIS, MODIS and SeaWiFS		×		×		
Ocean Colour CCI – building on GlobColour, advances in the delivery of water-leaving radiance, derived chlorophyll and inherent optical properties using ESA's MERIS and NASA's SeaWiFS, MODIS and possibly CZCS (after careful evaluation) sensor archives				×		
CoastColour has provided advanced coast colour datasets for case 2 waters in coastal areas				×	×	
The Medspiration project has provided near-realtime SST products measured independently by different satellite systems	×	×	×			
Sea-level CCI – advances in providing a long-term sea level ECV of the global oceans and regional maps over the period 1993–2010	×					
Sea-surface temperature CCI – advances in providing SSTs of the global oceans over the period 1991–2010 (phase 1 project)	×					×
Operational multimission SST products through GHRSST (*www.ghrsst.org*)	×	×				
AATSR reference instrument in SST with climate-quality accuracy	×					×

Earth Observation in the Context of Models

- Advances in the use of Earth observation (e.g. ocean colour) data in ocean biological models (e.g. net primary productivity estimates, ecosystem modelling) (Challenges 02, 04, 06).

- The Advanced Synthetic Aperture Radar (ASAR) on Envisat has been used to follow waves in order to refine their propagation paths, locate areas of potentially dangerous crossing seas (waves) and determine their arrival times and intensities.

- First tests to assimilate SMOS sea-surface salinity measurements into ocean models (Challenge 01).

- Exploitation of CryoSat-2 (and then Sentinel-3) data to enhance studies of mesoscale processes (Challenge 03).

- Advances in the development of long-term ocean ECVs (sea level, ocean colour, SSTs, etc.) (Challenge 06).

- Advances in the use of multimission Earth observation data for ocean–atmosphere interaction studies (e.g. CO_2 fluxes, sea spray and aerosols) (Challenges 02, 03, 04).

Relevant International Research Initiatives/Programmes

- CLIVAR, SOLAS, IMBER, GOOS, GCOS, JCOMM, GODAE Ocean View

Advances in Ocean Research and New Earth System Insights

- The availability of global merged altimeter products over long time periods and the development of eddy detection techniques have allowed systematic tracking of individual eddies (Challenge 03).

- Improved understanding of the sea-level wavenumber spectrum in terms of surface quasi-geostrophic dynamics (Challenge O3).

- Improved understanding of the role of internal tides in the sea-level wavenumber spectrum (Challenge O3).

- Discovery of the ubiquitous presence of jet-like structures in the anomalies of geostrophic velocity (striation) from altimeter data (Challenge O3).

- Development of a new theoretical framework to estimate vertical velocities from high-resolution satellite data (Challenges O3, O4).

- Improved understanding of the coupling between physics and biogeochemistry at the mesoscale thanks to the synergistic use of ocean colour, SST and altimeter data (Challenges O3, O4).

- Sea-level trends 1993–2010 measured by radar altimeters (3 mm yr^{-1}) (CCI Sea level) (Challenge O6).

- Time series of ATSR SSTs (1991–2012) have independently quantified ocean surface warming trends between 0.1K and 0.2K per decade (Challenge O6).

- A 10-year (1997–2006) trend in net primary productivity based on SeaWiFS data showing an increase of 1930 teragrams of carbon per year (Tg C yr^{-1}), followed by a prolonged decrease (after 1999) averaging 190 Tg C yr^{-1}.

- A reduction in global ocean primary production by about 6% between the early 1980s and late 1990s was estimated based on a comparison of chlorophyll data from satellites.

- The link between global phytoplankton changes and decadal oscillations in ocean basins (e.g. Pacific decadal oscillations) shown using historical (CZCS) and current (SeaWiFS) ocean colour observations.

- The longstanding argument about the slope of the sea level along the North American coast was settled in favour of a ‘new levelling’ GNSS combined with a recent geoid (GOCE) compared with classic spirit levelling at tide gauges. The tide gauge data are now in close agreement with ocean models just off the coast at a level of several centimetres.

- Numerous inputs to IPCC reports.

Moving Science to Services

- Major advances in the development of operational oceanography in Europe with the Copernicus Marine Service.

- Advances in the development of downstream services focused on marine ecosystem monitoring (dedicated GMES Service Elements and GMES downstream services).

- Operational sea-ice services using SAR observations.

- Operational use of SST and altimetry for seasonal forecasting.

- Use of ocean colour, SST, altimetry and models for fisheries management.

- Oil spill monitoring and forecasting using SAR and models constrained by satellite observations (e.g. Deepwater Horizon).

- Operational use of scatterometer data for wind retrieval, sea-ice extent and sea-ice drift in numerical weather prediction models.

- Operational service demonstration providing ASAR-based winds, swell, currents and roughness. Envisat and Jason radar altimeter data used in models to monitor and forecast Fukushima pollution.

2.5 Solid Earth

2.5.1 Scientific Context of the Updated Challenges

The updated Living Planet Scientific Challenges related to the solid Earth are to improve understanding and quantification of:

- *Challenge G1:* Physical processes associated with volcanoes, earthquakes, tsunamis and landslides in order to better assess the natural hazards.

- *Challenge G2:* Individual sources of mass transport in the Earth system at various spatiotemporal scales.

- *Challenge G3:* Physical properties of the Earth crust and its relation to natural resources.

- *Challenge G4:* Physical properties of the deep interior, and their relationship with natural resources.

- *Challenge G5:* Different components of the Earth magnetic field and their relation to the dynamics of charged particles in the outer atmosphere and ionosphere for Space Weather research.

The solid Earth is a fundamental constituent of the Earth system. It is characterised by processes acting on both very wide timescales (from fractions of a second to billions of years) and very large spatial scales (from molecular to global). The present state of the Earth is a record of its dynamic history from its very origin, including the origin of life. Life would not have developed without Earth's magnetic field that protects against radiation from space, and which originates in the core of the planet. On a human time scale, natural hazards pose major threats, and many resources needed to sustain modern life are rooted in the solid Earth. The solid Earth is part of the fully coupled Earth system and interacts strongly with the surface, the fluid envelopes and the biosphere on human and much longer timescales.

Investigating the solid Earth thus responds to three major societal demands: for better knowledge of Earth and the origin of life, to ensure access to sustainable resources and to live in a safe world.

Specificities of the Solid Earth

Since direct imaging or a direct journey deep inside or to the centre of the planet will remain impossible, indirect approaches will need to be applied by resolving 'inverse problems' constrained by various physical observables measured on the ground or from space, generally complemented by the results of laboratory experiments and modelling.

In recent decades, historical ground-based observation networks have been complemented by multidisciplinary but sparsely distributed ocean bottom observatories and by dense networks of geophysical/geodetic/geochemical sensors in certain target areas. Solid Earth sciences have also benefited from dedicated and commercial space missions – ERS-1/-2 and Envisat SAR – that have provided new global and unprecedented information. The combination of *in situ* and satellite data has become standard in solid Earth sciences such as geology for fault mapping, and has even revolutionised some fields, such as the study of earthquakes through the monitoring of the entire seismic cycle and the discovery of silent earthquakes thanks to space geodesy.

Modelling Earth's inner structure and processes demands both a huge amount of high-quality data, very large computing facilities and, of course, dedicated methodologies for the inversion techniques as well as for handling data. This holds for various scales and also for relatively small features such as volcanoes or areas of mineral or energy resources.

Most of these areas are still either inaccessible or too costly to be instrumented on the ground. This is why there is a need for data with improved accuracy and resolution from space. Due to the extreme time ranges of the processes to be monitored, solid Earth also requires both very long time series of observations in order to establish trends, as well as high temporal resolution in order to identify sudden events, monitor telluric crises and provide early warning for populations at risk. Long time series require compatible and intercalibrated data provided by successive sensors. This, of course, calls for dedicated and specific observation systems in which the space segment is vitally important. In some places such operational systems are already in place, such as earthquake and tsunami warning SMS alert systems.

As is the case with other components of the Earth system, new types of data (such as the gradiometric data that were provided by the Earth Explorer mission GOCE; see Fig. 2.23) call for new methods of interpretation to ensure they are fully exploited. Data analysis must therefore be supported, together with the necessary strong technological support for the development of innovative sensors. As mentioned above, a specific characteristic of the solid Earth is that it cannot be sampled directly and so must be explored using indirect approaches. As a result, most observables reflect a series of processes. Topography, for instance, reflects both deep-seated geodynamic processes and plate tectonics, but also the interactions with fluid outer envelopes and human activities on the surface. In addition, these processes take place at very different time scales.

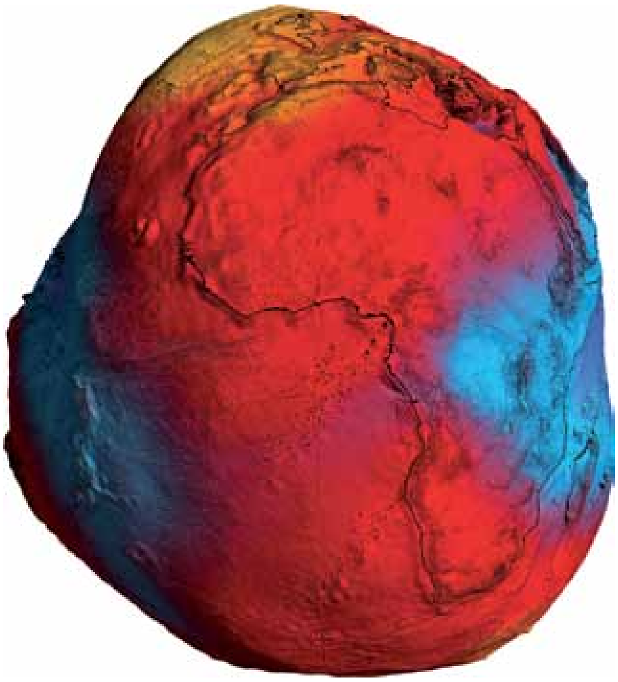

Figure 2.23. Global gravity field model estimated with GOCE data. (ESA/HPF/DLR)

It must be emphasised that obtaining a full picture of the inner structure and processes in the solid Earth requires the combination and joint inversion of different observables. For example, global isostatic adjustment processes and the laterally inhomogeneous viscoelastic response of solid Earth to surface loading could be derived from a combination of temporal gravity field data, altimetric missions such as CryoSat-2 and global positioning information (e.g. STSE CryoSat+ Regina).

Finally, two specific points must be made. First, despite major improvements in recent decades, our knowledge of ocean bathymetry, especially close to the shores, remains poor. Such detailed knowledge is mandatory for a better understanding of Earth dynamics and pelagic resources, among other things. Second, coastal areas are subject to strong anthropogenic pressures as a large proportion of the world's human population lives within 100 km of the coast. Coastal areas are thus evolving rapidly and require specific monitoring systems to characterise mass transfers, for instance.

Challenges for the Solid Earth

The challenges for the solid Earth can be divided into near-term, mid-term and long-term goals. Concerning the processes that are changing the surface of the planet, satellites provide a constant monitoring system that allows the identification of such changes over a given range of time. Efforts must be made to continue the time series and, in parallel, to increase their spatial as well as temporal resolution, ideally to identify surface changes almost immediately, in order to serve as a near-realtime monitoring instrument.

In order to understand the underlying physical processes, satellite observations and global seismological models need to be combined through inverse modelling. For example, large earthquakes most often occur in subduction zones in oceanic areas, and precise measurements of the tiny temporal variations in Earth's gravity field are needed to monitor the associated mass changes, as well as to provide the best possible image of the lithosphere, Earth's solid outer shell, on which plate tectonic forces act (Fig. 2.24). This would allow a better characterisation of the thermal and geochemical properties of the lithosphere, which is essential for validating tectonic models that describe the processes affecting the surface and the presence and distribution of natural resources.

A mid-term goal is to link these models to dynamic processes, first by distinguishing the time dependency in the gravity field associated with mass transport in the deep Earth. This would allow mantle convection and the driving forces of plate tectonics to be monitored over time on a global scale, and to understand and physically model the dynamic processes and tectonic

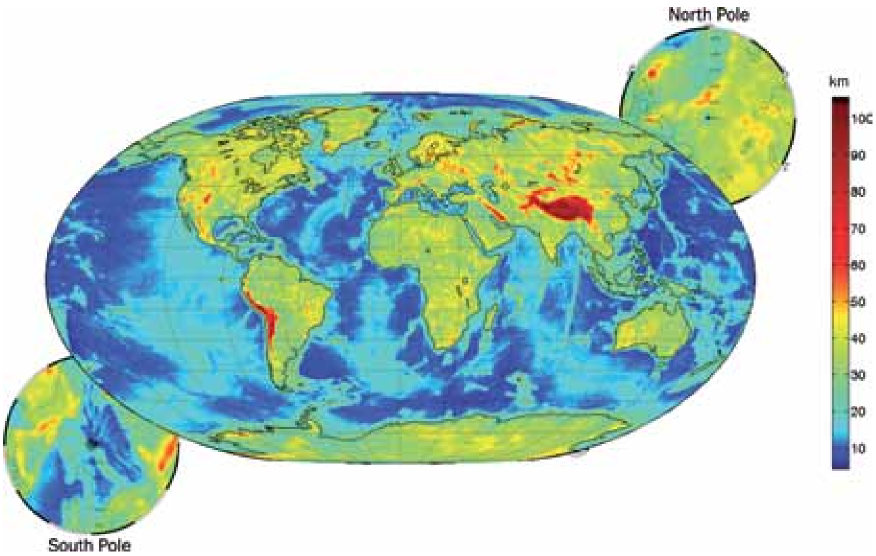

Figure 2.24. Global Moho depth estimated using GOCE data. (Reguzzoni & Sampietro, 2014)

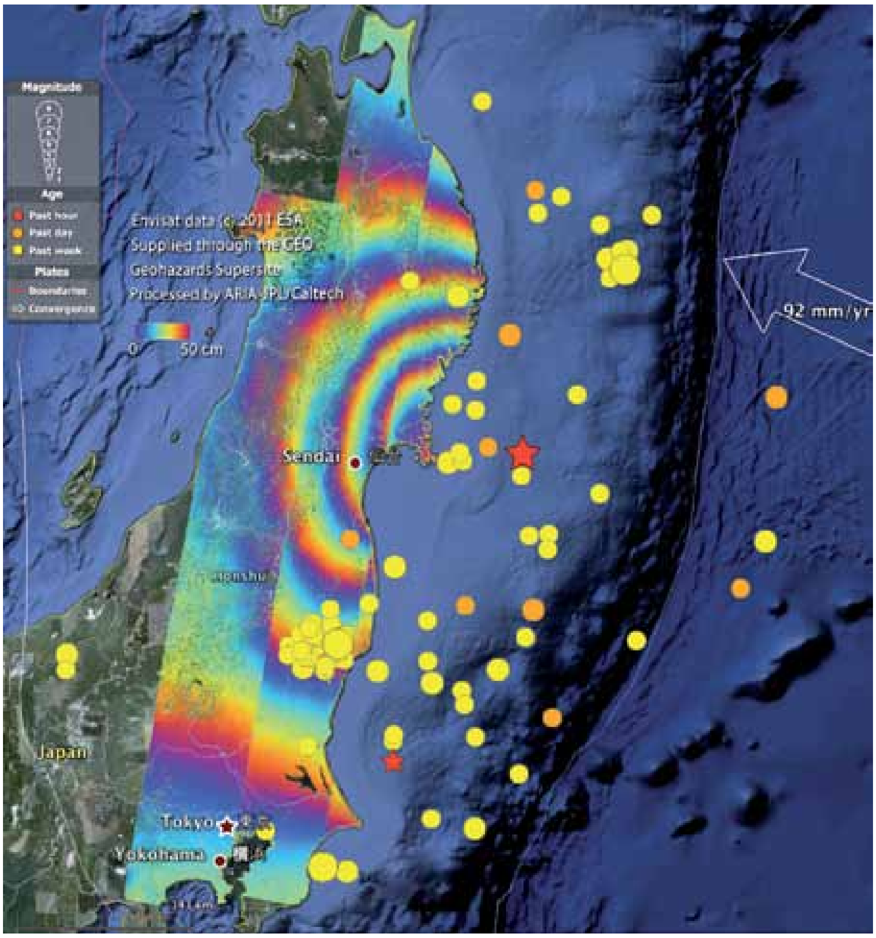

Figure 2.25. Ground displacements in northern Japan following the Tohoku-Oki earthquake in March 2011. (Envisat data, ESA, supplied through the GEO Geohazards Supersite, processed by ARIA-JPL/Caltech; ZENRIN; Geocentre Consulting; Europa Technologies; data MIRC/JHA)

settings in regions at increased risk of natural hazards such as earthquakes or volcanic eruptions (Fig. 2.25). Such models, in turn, will also be important for studying the origin of Earth's magnetic field and its link to plate tectonics, as well the processes leading to its temporary absence and subsequent reversal.

The ultimate goal and long-term perspective is to establish a 4D model of the solid Earth by jointly inverting different types of observation, and also to provide a correct description of the main coupling processes of the inner and outer Earth's system.

2.5.2 Achievements with Respect to the 2006 Challenges

The strategy for ESA's Living Planet Programme formulated in 2006 identified the five most important solid Earth challenges that should guide ESA's efforts in providing essential Earth observation information:

- *Challenge G1:* Identification and quantification of physical signatures associated with volcanic and earthquake processes from terrestrial and space-based observations.

- *Challenge G2:* Improved knowledge of physical properties and geodynamic processes in the deep interior, and their relationship to Earth-surface changes.

- *Challenge G3:* Improved understanding of mass transport and mass distribution in the other Earth system components, which will allow the separation of the individual contributions and a clearer picture of the signal due to solid-Earth processes.

- *Challenge G4:* An extended understanding of core processes based on complementary sources of information and the impact of core processes on Earth system science.

- *Challenge G5:* The role of magnetic-field changes in affecting the distribution of ionised particles in the atmosphere and their possible effects on climate.

As identified by the scientific community, the updated challenges for the solid Earth are not substantially different from those defined in the 2006 strategy. This is because scientists are addressing very challenging issues in a very dynamic Earth system. Some of the many significant advances and achievements made with respect to these challenges over the past 10 years are described in the following.

For instance, geometric satellite techniques providing information on surface displacements such as optical image correlation, GPS and InSAR, the satellite gravimetry missions GRACE and GOCE, and the magnetic field missions Ørsted and CHAMP, have delivered important progress and unprecedented, high-quality global information about the solid Earth.

The physical processes that are changing Earth's surface are associated with changes in stress and strain, and can be resolved by GNSS, INSAR and optical image correlation techniques on an increasingly local scale. These measurements, combined with seismological observations, have helped improve our understanding of the so-called seismic cycle before, during and after earthquakes. They are also being used more routinely for monitoring the deformation of active volcanoes. Our understanding of volcanic processes, which pose major hazards both locally and globally through their indirect effects on climate and pollution of ash plumes and aerosols, has also benefited and will continue to benefit from thermal imaging and various other satellite sensors.

These observations are complemented by measurements of the changes in Earth's gravity field reflecting, for example, co- and post-seismic mass displacements in the lithosphere. Global mapping of these processes is necessary to estimate geohazards such as earthquakes, landslides and volcanic activities. The underlying sources of these processes are linked to the internal structure of the solid Earth. Solid Earth processes – located in the core, at the core–mantle boundary and in the mantle and crust – are studied either indirectly from the signatures of gravity, the magnetic field and topography, or directly from changes in Earth's rotation, surface deformation and changes in the gravity and magnetic fields.

To understand the dynamic processes that drive plate tectonics, a better knowledge of the mass transfers at various scales and the physical properties of the deep interior is needed.

The accurate representation of the lithosphere and deep Earth, from both seismological studies and satellite data, is challenging. To decipher the thermal, compositional and rheological structure of the lithosphere it is essential to distinguish between the lithospheric and sublithospheric signals. Satellite data can help to overcome this limitation. The data now available from satellite missions have an accuracy and resolution that make them well suited for studying the structure of the lithosphere on global and regional scales.

On a regional scale, the high-resolution characteristics of recent satellite missions (e.g. GOCE, Swarm) allows a distinction to be made between the regional setting and local sources, which can be linked to the present-day geological state and even the distribution of natural resources in remote, underexplored regions such as the Arctic, Antarctic or the Sahara.

The ongoing Swarm satellite mission, launched in November 2013, provides an opportunity to distinguish different components of rock magnetisation that reflect the properties of rocks and their tectonic evolution. The magnetic field is also intimately linked to Earth's thermal structure, which in turn is linked to the dynamic processes in the Earth system (Fig. 2.26). With its three-satellite

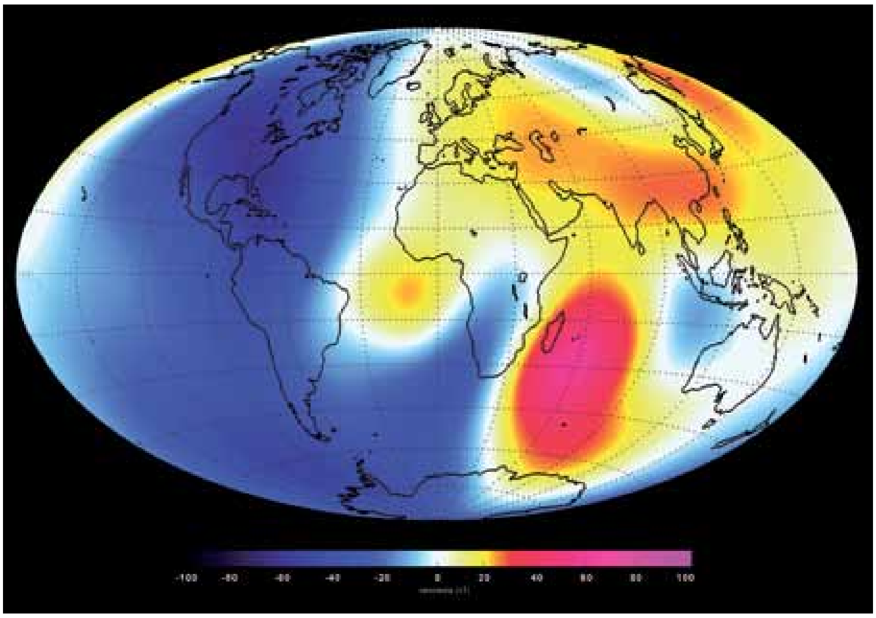

Figure 2.26. Changes in Earth's magnetic field from January to June 2014 as measured by the Swarm constellation of satellites. These changes are based on the magnetic signals that stem from Earth's core. Shades of red represent areas of strengthening, while blues show areas of weakening over the six-month period. (ESA/DTU Space)

configuration, Swarm will provide a resolution down to 200 km at satellite height and improved monitoring of the time-varying geomagnetic field.

A long-term gravity mission is now needed to continue the time series available from GOCE and GRACE (and possibly Swarm), and to continue the observations – with improved accuracy especially at long wavelengths – of the subtle changes in Earth's gravity field associated with the deep-seated processes in the mantle. Until now, neither satellite data nor seismological studies have been able to provide clear evidence of mass transport deep in the Earth system. Since this mass transport occurs on geological timescales, continued long-term monitoring is necessary eventually to image these processes. This will require continuous monitoring of Earth's gravity field from space over decades. Furthermore, dedicated missions will be needed to achieve a better understanding of the underlying processes referred to in Challenges G2, G3 and G4.

The recent Sentinel-1 SAR mission has set new standards in terms of global coverage and revisit times for observing surface motion and crustal deformation at high spatial and temporal resolution and large spatial extent. This will allow the mapping of high-strain regions globally and monitoring of regions at risk of earthquakes, volcanoes and landslides. The observations of very slow movements or dynamics will require a long-term and data-compatible mission plan for successive SAR missions.

The new data being provided by the Earth Explorer missions appear to be an excellent first step towards addressing the updated challenges defined for the solid Earth.

The achievements with respect to the 2006 challenges related to the solid Earth are summarised in the following. Table 2.13 lists the relevant missions

Missions	Instruments
ERS-1/ERS-2	SAR
Envisat	ASAR, AATSR, MERIS
Earth Explorers	GOCE, Swarm, CryoSat-2
MetOp	
Sentinels	S-1, S-2, S-3
Third-party missions	ALOS (PALSAR), SPOT, Landsat, MODIS, GRACE

Table 2.13. Relevant missions and instruments.

Table 2.14. Innovative algorithms and products, and the challenges they have addressed.

Innovative algorithms and products	Challenges				
	G1	G2	G3	G4	G5
Advanced DInSAR (A-DInSAR) techniques (e.g. PSI, SBAS) for ground deformation mapping from SAR data, for various seismo-tectonic applications including pre-, co-, post- and inter-seismic deformation, dome uplift and volcanic monitoring	×				
Wide-area processing from SAR data stacks constrained using GNSS geodetic measurements for regional deformation histories	×				
Wide-swath InSAR and ScanSAR InSAR for large-scale deformation mapping	×				
Precise correlation of optical images and SAR speckle-tracking techniques to derive deformation maps along active faults	×				
Advanced techniques (such as global and local (multiscale) complex, vector and tensor least-squares estimation methods) for GOCE data processing (STSE GOCE+)		×			
Combined GOCE/GRACE full gravity gradient grids at satellite altitude for better constraining regional (exploration) geophysical modelling (STSE GOCE+)	×	×			
Tailored regional combined gravity and magnetic field models from satellite, aerial- and terrestrial data to constrain static and dynamic lithospheric models (STSE GOCE+)	×		×		
Development of dedicated constellation analysis techniques for optimal estimation of core, lithospheric, magnetospheric and ionospheric magnetic fields from Swarm		×		×	
Development of ionospheric conductivity product from the Swarm constellation					×
Development of techniques for deriving for the first time 3D-mantle conductivity from Swarm		×		×	
Novel retrieval of total electron content (TEC) from SMOS					×

Table 2.15. Legacy datasets and the challenges they have addressed.

Legacy datasets	Challenges				
	G1	G2	G3	G4	G5
Long-term deformation series obtained from ERS SAR, Envisat ASAR and ALOS PALSAR archives over active faults, seismic and volcanic areas, complemented by optical datasets (space-based observation data archive of the past 20 years and longer)	×				
Unique GOCE datasets (Level-2 data)	×	×	×		×
Datasets from the Ørsted and CHAMP missions (Earth's magnetic field and its variations)		×		×	
Datasets from CHAMP and GRACE for density and wind modelling in the neutral atmosphere					×
Cluster active archive for complementary magnetic and electric field data further away from Earth					×
TEC products from CHAMP, GRACE, COSMIC and GNSS networks				×	
GOCE/GRACE gravity gradients dataset at satellite and at ground level for geophysicists (STSE GOCE+)	×	×	×		

and instruments (past, present and future), while Table 2.14 gives an overview of a number of innovative algorithms and products developed in recent years, and the challenges that have been addressed either directly or indirectly. The legacy datasets developed – products that are recognised long-term data series – are shown in Table 2.15.

Earth observation in the context of models

— The integration of deformation maps derived from various SAR and optical missions over major faults into 3D fault models, in combination with GNSS and geodetic levelling data, in order to determine slip rate and distribution, as well as crustal strain accumulation along major faults. Integration of similar products into volcanic models in order to improve monitoring and prediction. Similar measurements and techniques, applied over large scales and long intervals, have been assimilated into tectonic models or used for tidal strain monitoring.

- Integration of DInSAR/PSI and optical data for monitoring physical or human-induced subsidence.

- Systematic exploitation of the long-term SAR archives (20 years) in order to derive ground deformation along major rifts zones and to determine the spatiotemporal distribution of magma-driven processes, as well as their implications for rift development and related hazards.

- Combination of surface deformation (GNSS, levelling, SAR) and gravity changes (ground and GRACE, GOCE) for better understanding of postglacial rebound and for improving global isostatic adjustment models (mainly of the mantle) (Challenges G2, G3).

- Combination of GOCE satellite data with terrestrial gravimetric observations for an improved geoid and gravity anomalies (Challenge G3).

- Advances towards the combination of GOCE and GRACE data, terrestrial gravimetric observations and sea-surface topography data for gravity field and mass transport modelling and geodetic applications (Challenges G2, G3).

- Integration of heterogeneous satellite data (such as GOCE gravity gradients combined with other satellite gravity information from GRACE, terrestrial gravity, seismic and magnetic field data), for modelling Earth's interior and its processes (from near-surface to the upper mantle) for various geophysical applications such as improving the Moho model (the crust–mantle discontinuity), to support exploration geophysics (Challenge G2) or to model the deep interior.

- Analysis of pre-, co- and post-seismic gravity fields (GRACE, GOCE) for improving models of offshore earthquakes.

- Joint analysis of the variations in the gravity field over time, measured from space (GRACE, GOCE), and their correlation with large seismic events (combined use of tectonics and gravimetric models) (Challenge G2).

- Integration of high-resolution gravity field data (GOCE) for improved crustal thickness modelling and advances towards the assimilation of GOCE and other gravimetric data in the Moho model, in order to map the crust–mantle discontinuity (Challenge G2).

- Integration of space-geodetic observations and geophysical information in order to better understand and predict geophysical processes (Challenge G2).

- Advances in modelling thermospheric winds and density using accelerometers carried by CHAMP, GRACE, GOCE and Swarm (Challenge G5).

- For the first time, post-seismic waves detected in GOCE thermospheric densities following the 2011 earthquake in Japan (Challenge G5).

- Detection of waves and pulsations and understanding of underlying physical processes as seen by Cluster, CHAMP (and Swarm in the future) and ground data (Challenge G5).

- Improved core models from Swarm will allow better studies of Sun–Earth interactions and the effects of radiation on the near-Earth environment.

Relevant International Research Initiatives/Programmes

- GGOS, Terrafirma, EPOS, Intermagnet, DFG Dynamic Earth programme.

New Earth System Insights

- Improvements in the accuracy of geophysical, geodynamic and geodetic modelling.
- Better understanding of fault parameters and fault ruptures including the identification of blind faults. Improved knowledge of crustal deformation associated with the seismic cycle of several major faults.
- Improved monitoring of inter-seismic strain accumulation; progress toward seismic hazard assessment.
- Improved geoid, with an unprecedented accuracy, in describing Earth's gravity field and its variations over time, with applications in hydrology, ice sheet modelling, oceanography, geophysics and geodesy.
- A better understanding of Earth's interior (focusing on the lower crust/upper mantle) and improved dynamic numerical modelling of stress and strain, with new insights into tectonics.
- Advances in crustal thickness modelling.
- Understanding of long-term dynamic processes as a consequence of postglacial effects.
- Preparation for combining 3D mantle conductivity with seismic and gravity information for understanding the composition of the upper mantle and the consequences for mantle dynamics resulting in near-surface tectonic effects.

Moving Science to Services

- Pre-operational services for ground motion monitoring in relation to different types of geophysical hazards, such as Terrafirma and GlobVolcano, integrating ground deformation measurements from space and *in situ* data.
- Providing the best geoid based on GOCE and local data to perform GNSS-based levelling as a replacement for the labour-intensive classical spirit levelling for large-scale surveys (national agencies and survey companies).
- Total electron content (TEC) products already delivered for space weather prototype services.

3. Concluding Remarks

This volume serves as complement to the *Earth Observation Science Strategy for ESA: A New Era for Scientific Advances and Societal Benefits* (ESA, 2015), which provides the key elements of ESA's Living Planet Science Strategy. ESA's previous Living Planet Science Challenges, formulated in 2006, for global observation, understanding and monitoring Earth as a system have guided Europe's space missions for almost a decade. These missions have provided essential information for science and have improved the understanding of the water, energy and carbon cycles, and have enabled consistent global monitoring of Earth's resources. By reviewing and summarising the achievements with respect to the previous challenges (2015), this volume lays the foundation for the formulation of the new LPSCs. It demonstrates that because the processes involved are inherently dynamic and ever-evolving, so too are the associated challenges. Therefore, none of the previous challenges can be fully closed and areas where further scientific work is needed have been taken into account in the formulation of the updated challenges described in this document.

This publication describes the tremendous scientific effort and progress towards a better understanding of the Earth system that could be gained through satellite observations. It provides a link between the previous and new LPSCs, and provides a current picture of past and ongoing ESA activities and projects, as well as international and national activities. It emphasises that innovation through exploratory satellite missions is the starting point for the delivery of value chains in the future, with key achievements in the various Earth system disciplines – atmosphere, cryosphere, land surface, ocean and solid Earth – through the successful ERS-1/-2, Envisat and the first four Earth Explorer missions:

- ERS/Envisat: more than 2000 peer-reviewed scientific publications, more than 5000 scientific projects; contributions to all five Earth system disciplines.

- GOCE: best global gravity and geoid model; unique view of Earth's inner structure; the first seismometer in orbit.

- SMOS: global maps of soil moisture and ocean salinity; observing and monitoring droughts; tracking major hurricanes and typhoons; measuring thin ice in synergy with CryoSat-2.

- CryoSat-2: tracking sea-ice volume changes in the Arctic; tracking changes in the Antarctic and Greenland glaciers; measuring sea level and ocean currents.

- Swarm: revealing Earth's 'changing magnetism'; agreeing well with models derived from a decade of predecessor missions.

Synergies, cross-cutting science and new applications can be obtained through the interplay of satellite observations with additional information. This synergistic framework for advancing Earth system science will continue as an important feature of the Living Planet Programme's new scientific strategy. The capability to study interactions and interdependencies between the Earth system disciplines has been improved thanks to previous missions – a capability that needs to be considerably enhanced in the future. Examples include:

- Mean dynamic ocean topography for ocean modelling: CryoSat-2 data can be used to generate a high-latitude mean sea surface and, by subtracting the new high-resolution GOCE geoid, to obtain the mean dynamic topography. Data assimilation methods can then be used to minimise the difference between ocean-modelled mean dynamic topography and CryoSat-derived mean dynamic topography to refine high latitude ocean circulation under the ice.

- The contribution of ice sheets to sea-level rise: synthetic aperture radar monitoring of ice-sheet velocities can be used to measure the dynamic component of ice-sheet mass loss. Altimeter monitoring of ice-sheet elevation and topography will allow us to understand the evolution of driving stresses, as well as volume changes over time owing to viscous and elastic responses of the lithosphere/upper mantle to mass unloading. Through a combination of long-term altimetry records, gravity data from GOCE, GRACE and GPS in situ stations to constrain a state-of-the-art model, glacial isostatic uplift corrections can be made to altimeter estimates. This synergistic combination of data from ESA's Earth observation assets provides the unique ability to reduce the uncertainties in the contribution of large ice sheets to sea-level rise.

Further scientific progress through integrated observing systems, national and international collaboration and further exploratory observations will be needed to realise an integrated Earth system science approach as suggested in the *Earth Observation Science Strategy for ESA*. This approach will benefit from the harmonisation of different practices and procedures related to the use of data and data access as well as for assuring data quality. Moreover, sustained observations in critical Earth system science satellite data streams are essential to maintain long-term, consistent observations of key variables. Continued developments across all Earth science disciplines will lead to improvements in the representation of processes in models and in the quantification of resources and biogeochemical fluxes, and will thus allow quantitative responses to societal and economic challenges.

Finally, the synthesis and adaptation of data streams from instruments and satellites into information and knowledge will increase the benefits of the achievements in meeting the scientific challenges and will help raise awareness beyond the scientific user community to the wider public.

→ APPENDICES

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Acronyms

AATSR	Advanced Along Track Scanning Radiometer (Envisat)
ACCENT	Atmospheric Composition Change – The European Network
ACE	Advanced Composition Explorer (NASA)
ADAM	A surface reflectance database for ESA's Earth observation missions
ADM-Aeolus	Atmospheric Dynamics Mission – Aeolus
ADVANSE	Advanced retrieval system for greenhouse gases from SCIAMACHY on Envisat
AERGOM	Aerosol Profile Retrieval Prototype for GOMOS
AIRS	Atmospheric Infrared Sounder (Aqua, NASA)
ALANIS	Atmosphere Land Interaction Study – Wetland Dynamics and CH4 Emissions
ALOS	Advanced Land Observing Satellite (Japan)
AltiKa	Altimeter Ka-band
AMI	Active Microwave Instrument (ERS)
AMMA	African Monsoon Multidisciplinary Analysis
AMSR	Advanced Microwave Scanning Radiometer (Aqua, NASA)
AMSU	Advanced Microwave Sounding Unit
ARIA-JPL	Advanced Rapid Imaging and Analysis Center for Natural Hazards at the Jet Propulsion Laboratory
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer (MetOp)
ATMS	Advanced Technology Microwave Sounder (NOAA)
ATSR	Along Track Scanning Radiometer (Envisat)
AVHRR	Advanced Very High Resolution Radiometer (ERS)
BALTEX	Baltic Sea Experiment
BIOMASAR	Validating a Novel Biomass Retrieval Algorithm Based on Hyper temporal Wide Swath ASAR (STSE, ESA)
BRDF	Bidirectional Reflectance Distribution Function
CALIOP	Cloud–Aerosol Lidar with Orthogonal Polarisation
CAMS	Copernicus Atmospheric Monitoring Service
CCAFS	Climate Change, Agriculture and Food Security programme (CGIAR)
CCCS	Copernicus Climate Change Service
CCI	Climate Change Initiative
CDOM	Coloured Dissolved Organic Matter

CEOP	Coordinated Energy and Water Cycle Observations Project
CEOP-HE	Coordinated Energy and Water Cycle Observations Project – High Elevations
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiant Energy System
CESBIO	Centre d'Etudes Spatiales de la Biosphère (France)
CHAMP	Challenging Minisatellite Payload (Germany)
CliC	Climate and Cryosphere programme (WCRP)
CLIVAR	Climate and Ocean – Variability, Predictability and Change (WCRP)
CLS	Collecte Localisation Satellites (France)
CoReH$_2$O	Cold Regions Hydrology High-Resolution Observatory
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CRIS	Cross-track Infrared Sounder
CZCS	Coastal Zone Color Scanner Experiment (NASA)
DInSAR	Differential Synthetic Aperture Radar Interferometry
Diversitas	International Programme of Biodiversity Science
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMSP	Defense Meteorological Satellite Program (USA)
DTU Space	Danish National Space Institute
DUE	Data User Element
EarthCARE	Earth, Clouds, Aerosols and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EEA	European Environment Agency
Envisat	Environmental Satellite
EO	Earth Observation
EO-LDAS	Earth Observation Land Data Assimilation Scheme
EPOS	European Plate Observing System
EPS	Eumetsat Polar System
EPS-SG	Eumetsat Polar System Second Generation
ERA	European Reanalysis project (ECMWF)
ERS-1/-2	European Remote Sensing Satellites 1/2
ESA	European Space Agency
ESAC	Earth Science Advisory Committee

ESM	Earth System Model
ESTEC	European Space Research and Technology Centre
Eumetsat	European Organisation for the Exploitation of Meteorological Satellites
EURAD	European Air Pollution Dispersion model
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FLEX	Fluorescence Explorer
FVC	Fractional Vegetation Cover
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GCW	Global Cryosphere Watch
GEMS	Global and Regional Earth System (Atmosphere) Monitoring using Satellite and In Situ Data
GERB	Geostationary Earth Radiation Budget
GEWEX	Global Energy and Water Exchanges project
GGOS	Global Geodetic Observing System
GHG	Greenhouse gas
GHRSST	Group for High-Resolution Sea Surface Temperature
GLIMS	Global Land Ice Measurements from Space
GLP	Global Land Project
GMES	Global Monitoring for Environment and Security
GMI	Global Precipitation Measurement (GPM) Microwave Imager
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-state Ocean Circulation Explorer
GODAE	Global Ocean Data Assimilation Experiment
GOME	Global Ozone Monitoring Experiment
GOOS	Global Ocean Observing System
GOSAT	Greenhouse Gases Observing Satellite
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRAS	Global Navigation Satellite System Receiver for Atmospheric Sounding
GSE	GMES Service Element
GSP	General Studies Programme (ESA)
HALOE	Halogen Occultation Experiment (UARS, NASA)
HPF	High-level Processing Facility
Hyperion	Hyperspectral Imager (EO-1)
IAA	Instituto de Astrofísica de Andalucía
IASI	Infrared Atmospheric Sounding Interferometer
IASI-NG	Infrared Atmospheric Sounding Interferometer – New Generation
IATA	International Air Transport Association

ICAROHS	Inter-comparison of Aerosol Retrievals and Observation Requirements for Multi-wavelength High Spectral Resolution Lidar Systems
IFE	Institute of Environmental Physics, University of Bremen (Germany)
IFREMER	French Research Institute for the Exploitation of the Sea
IGAC	International Global Atmospheric Chemistry project
IGBP	International Geosphere–Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
iLEAPS	Integrated Land Ecosystem–Atmosphere Processes Study
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research project
IMBIE	Ice Sheet Mass Balance Intercomparison Exercise (ESA/NASA)
IMK	Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (Germany)
InSAR	Interferometric Synthetic Aperture Radar
Intermagnet	International Realtime Magnetic Observatory Network
IPCC	Intergovernmental Panel on Climate Change
IPI	International Polar Initiative
IPY	International Polar Year
IRDAS	Infrared Differential Absorption Spectroscopy
IRS	Infrared Sounder (MTG)
ISOTROP	Impact of Spaceborne Observations on Tropospheric Composition Analysis and Forecast
IUP	Institute for Environmental Physics, University of Bremen (Germany)
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology (WMO-IOC)
LAI	Leaf Area Index
LTE	Local Thermodynamic Equilibrium
LIVAS	Lidar Climatology of Vertical Aerosol Structure for Space-Based Lidar Simulation
LOGOFLUX	Study of the capabilities of the CarbonSat mission to quantify CO_2 and CH_4 surface fluxes at global, regional and local scales (ESA)
LOICZ	Land–Ocean Interactions in the Coastal Zone (IGBP/IHDP)
LPSC	Living Planet Scientific Challenge

MACC	Monitoring Atmospheric Composition & Climate programme (EU)
MERIS	Medium-Resolution Imaging Spectrometer (Envisat)
MetOp	Meteorological Operational Satellite
MIPAS	Michaelson Interferometer for Passive Atmospheric Sounding (Envisat)
MIRC/JHA	Marine Information Research Center/ Japan Hydrographic Association
MLS	Microwave Limb Sounder (Aura, NASA)
MODIS	Moderate Resolution Imaging Spectroradiometer (Aura & Aqua, NASA)
Moho	Mohorovičić discontinuity
MSG	Meteosat Second Generation
MSL	Mean Sea Level
MTG	Meteosat Third Generation
MWI	Microwave Imager (MSG)
NASA	National Aeronautics and Space Administration
NEESPI	Northern Eurasian Earth Science Partnership Initiative
NOAA	National Oceanic and Atmospheric Administration
OCR	Ocean Colour Radiometry
OMI	Ozone Monitoring Instrument (Aura, NASA)
OMPS	Advanced Ozone Mapping and Profiler Suite
OPTIRAD	Optimisation Environment for Joint Retrieval of Multi-Sensor Radiances
OSHA	Occupational Safety and Health Administration (USA)
PALSAR	Phased Array L-band Synthetic Aperture Radar (ALOS)
PEEX	Pan-Eurasian Experiment
Proba-V	Project for OnBoard Autonomy – Vegetation
PROMOTE	Protocol Monitoring for the Global Monitoring for Environment and Security Service Element: Atmosphere
PSI	Persistent Scatterer Interferometry
QuikSCAT	Quick Scatterometer (ADEOS)
RA-2	Radar Altimeter 2 (Envisat)
RAL	Rutherford Appleton Laboratory (UK)
REDD	Reducing Emissions from Deforestation and Forest Degradation programme (UN)
SACS	Support to Aviation Control Service
SAON	Sustaining Arctic Observing Networks
SAR	Synthetic Aperture Radar
SAVAA	Support to Aviation for Volcanic Ash Avoidance
SBAS	Small Baseline Subset
SBUV	Solar Backscattered Ultraviolet
SCAT	Scatterometer (ERS)
SCIAMACHY	Scanning Imaging Absorption spectrometer for Atmospheric Chartography (Envisat)
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor (SeaStar)
SEOM	Scientific Exploitation of Operational Missions project (ESA)
SEVIRI	Spinning Enhanced Visible and Infrared Imager (MSG)
SIOS	Svalbard Integrated Arctic Earth Observing System
SMASH	Study on an End-to-End System for Volcanic Ash Plume Monitoring and Prediction
SMILES	Superconducting Submillimeter-Wave Limb-Emission Sounder (ISS
SMOS	Soil Moisture and Ocean Salinity
SOLAS	International Surface Ocean–Lower Atmosphere Study
SPARC	Stratosphere–Troposphere Processes and their Role in Climate
SPIN	SPARC Initiative
SPOT	Satellite pour l'Observation de la Terre
SSM/I	Special Sensor Microwave/Imager (USAF)
SST	Sea-Surface Temperature
STRIN	Strategic Initiative
STSE	Support to Science Element (ESA)
SWIR	Short-Wave Infrared
TANSO	Thermal and Near-Infrared Sensor for Carbon Observation (GOSAT)
TEC	Total Electron Content
TEMIS	Tropospheric Emission Monitoring Internet Service
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TIBAGS	Tropospheric Iodine Monoxide and its coupling to Biospheric and Atmospheric Variables: A Global Satellite Study
TOMS	Total Ozone Mapping Spectrometer
TRMM	Tropical Rainfall Measuring Mission
UV	Ultraviolet
VAST	Volcanic Ash Strategic Initiative Team
VRAME	Vertically Resolved Aerosol Model for Europe
WACMOS	Water Cycle Multimission Observation Strategy (STSE, ESA)
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WWRP	World Weather Research Programme

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