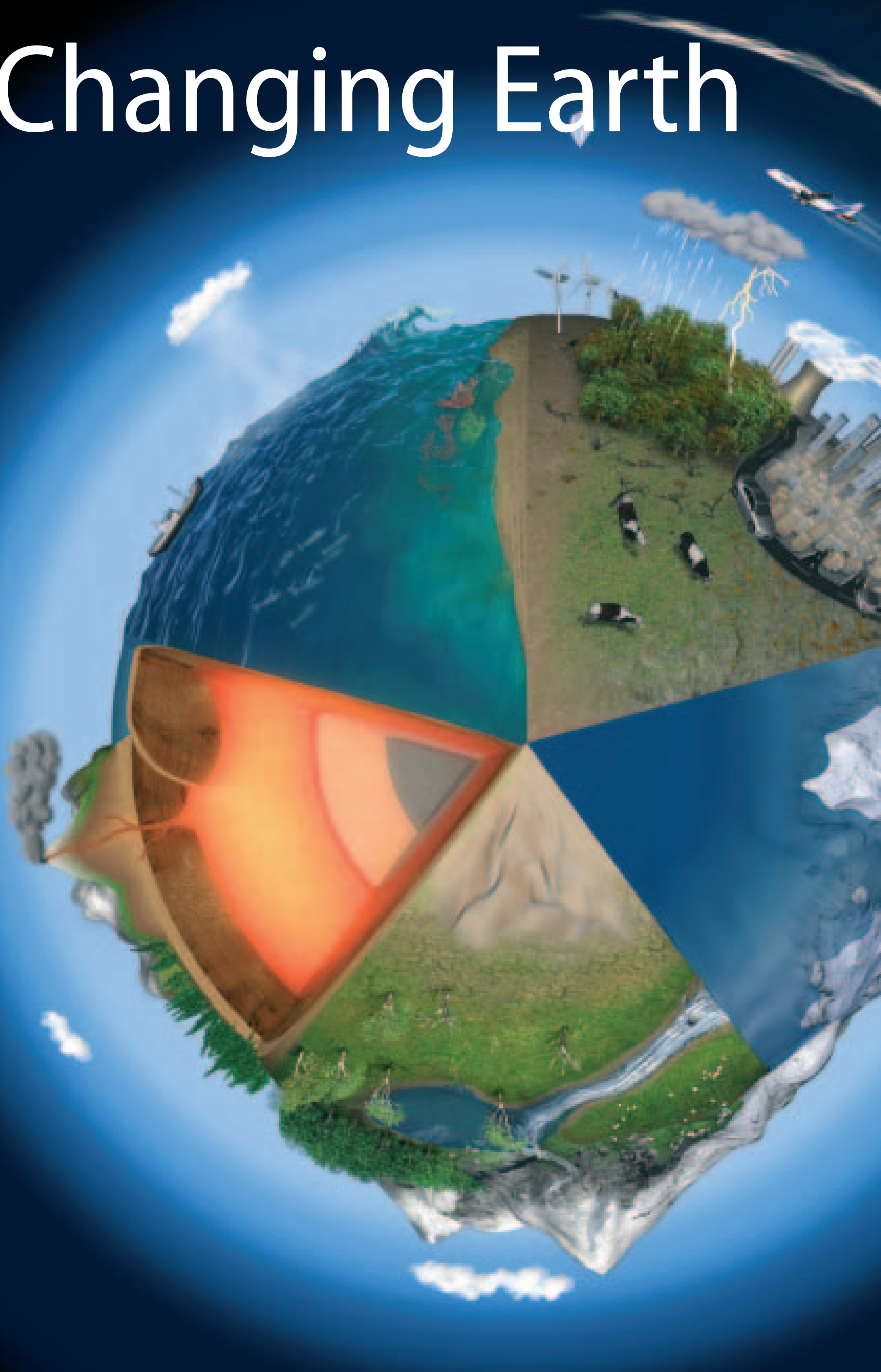
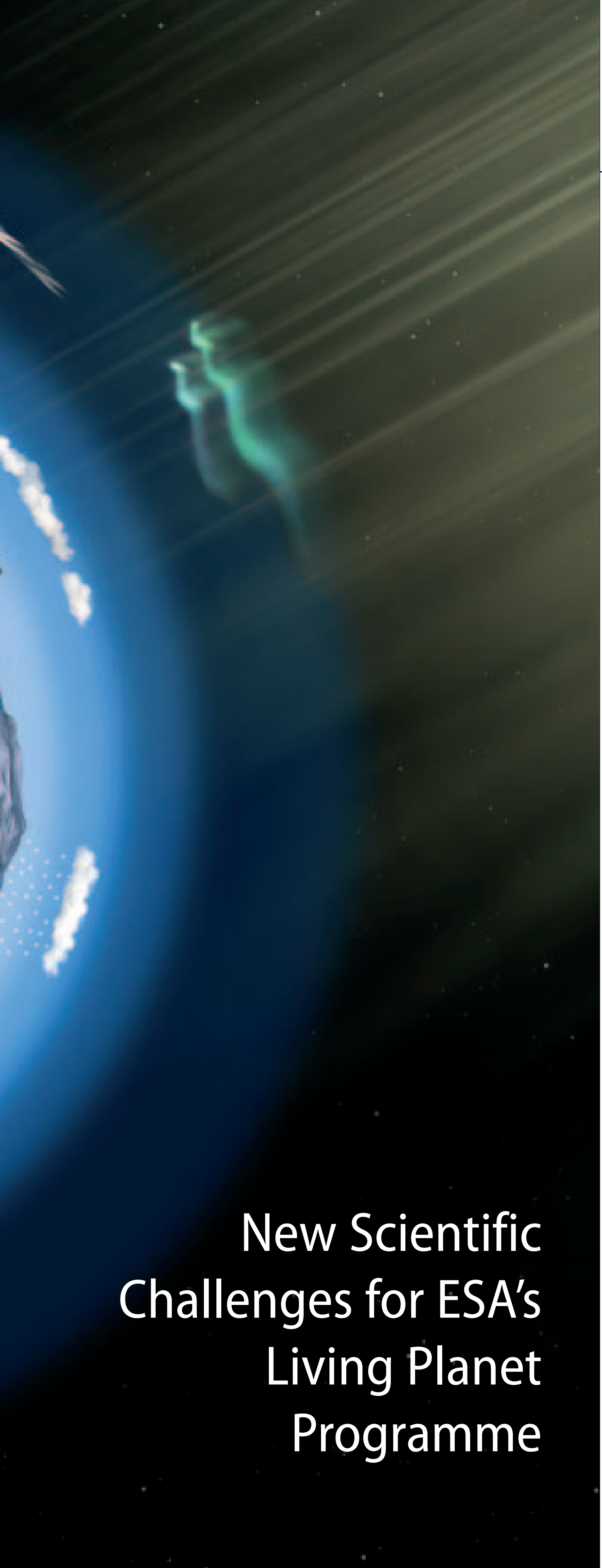
The Changing Earth





New Scientific Challenges for ESA's Living Planet Programme

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Global change is the most fundamental challenge facing humanity today. As we begin to understand more about the Earth as a system, it is clear that human activity is having a profound and negative impact on our environment. For example, our understanding of carbon dioxide as a greenhouse gas and the strong link between atmospheric carbon dioxide concentrations and temperature both point to human activity leading to a warmer world, unlike anything seen over the last million years. A better knowledge of the Earth System and of the effect of increasing human activity is crucially important for managing our environment and our ability to derive sustainable benefit.

Introduction

Since observing the Earth from space became possible more than 40 years ago, satellite missions have become central to monitoring and learning about how the Earth works. When ESA established its Living Planet Programme in the mid-1990s, a new approach to satellite observations for Earth science began, with focused missions defined, developed and operated in close cooperation with the scientific commun-

The strategy report is available as ESA publication SP-1304

In 2005 a committee of six external scientists and six Earth Science Advisory Committee members undertook a thorough review of the scientific value of ESA's Earth Observation Envelope Programme. The review report was overall extremely positive in evaluating the science output of the Programme and contained 11 recommendations to the Agency. These are all being implemented

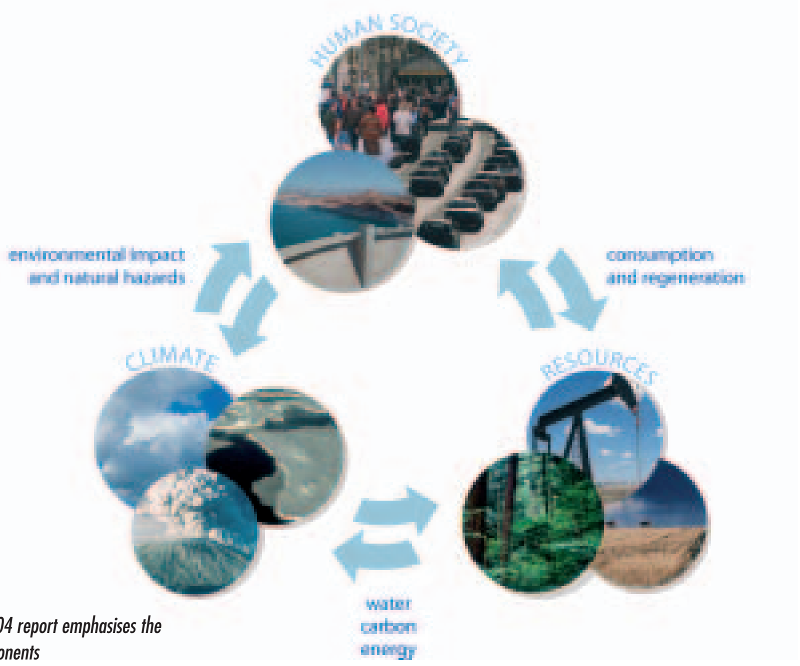
ity. A comprehensive strategy was formulated for implementing the Programme, which has resulted in the selection of six Earth Explorer missions covering a broad range of science issues. Six candidates for the seventh mission have been identified. At the same time, significant advances have been made in Earth science using data products and services from the Agency's ERS and Envisat satellites.

At the Ministerial Council meeting in Berlin in December 2005, ESA Member States reconfirmed their commitment to the concept of the Living Planet Programme by funding the third phase covering the period 2008–2012. In addition, they approved the initiation of the space component of the Global Monitoring for Environment and Security (GMES), in close cooperation with the European Commission. Although this programme is designed to provide data that underpin operational services, it will also contribute significantly to Earth science, in particular through the collection of long time series of observations. In turn, the Earth Explorers will provide new understanding that paves the way for new operational services. In this sense, the Living Planet Programme comprises complementary elements of research and operations. This synergy has long been demonstrated by the development and scientific exploitation of meteorological satellites, which continue to be an important part of the Living Planet Programme.

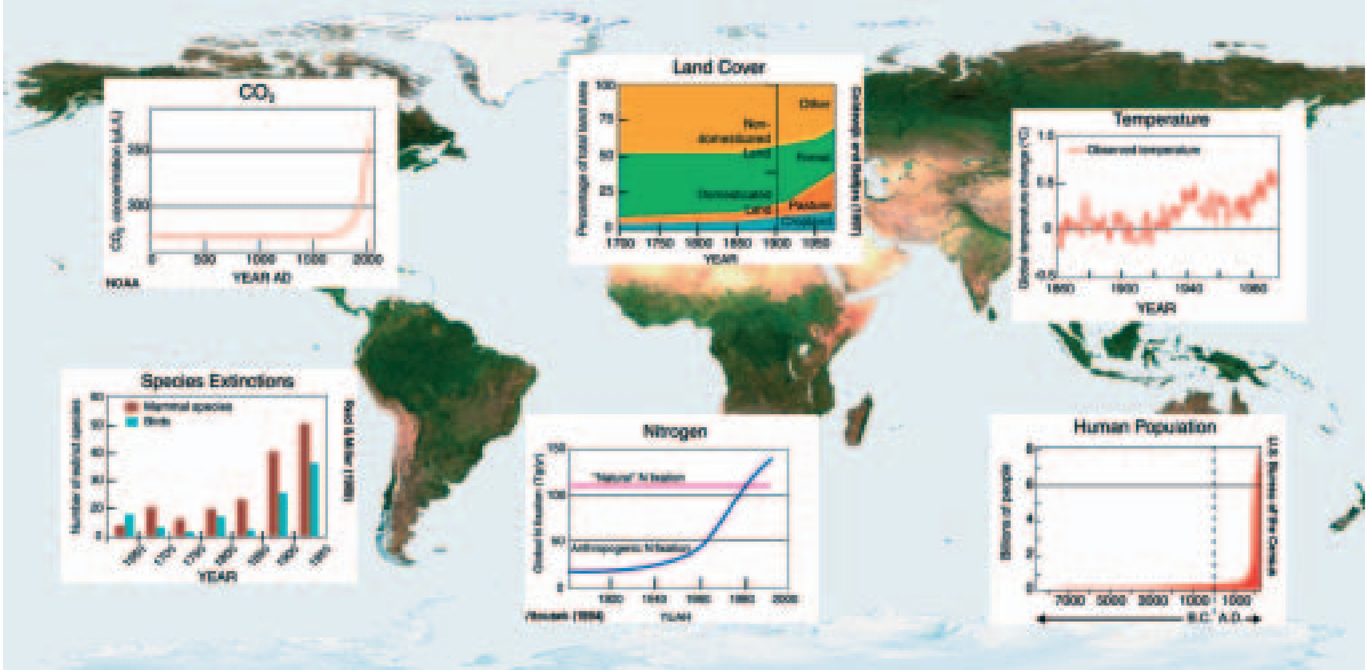
Recent developments and advances already made in the Earth sciences have emphasised the need for an updated science strategy. The recent Stern report (*http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm*) assesses the impact of climate change on the global economy and concludes that while 'business as usual' might have very high costs, preventive measures implemented from today would have a relatively minor impact on the economy. Another recent study, on the socio-economic benefits of GMES, performed by Pricewaterhouse Coopers, concluded that the benefits of GMES are potentially very large, but they require political will in order to be efficiently implemented.

The updating of the strategy was recently undertaken under the guidance of the Agency's Earth Science Advisory Committee and in wide consultation with the scientific community.

Looking to the future, the new strategy aims to assess the most important Earth science questions to be addressed in the years to come. It outlines the observational challenges that these raise, and the contribution that the Agency can make through the programme. These challenges will guide ESA's efforts in providing essential Earth observation information to the



The ESA SP-1304 report emphasises the different components



Selected aspects of global change (atmospheric composition, land cover, temperature, biodiversity, nitrogen fixation and human population) based on information compiled by the International Geosphere-Biosphere Programme

user communities, in close cooperation with our international partners.

Underpinning the new strategy is a set of ambitious objectives, which includes:

- launching a steady flow of missions addressing key issues in Earth science;
- providing an infrastructure to allow satellite data to be quickly and efficiently exploited in areas of research and applications;
- providing a unique contribution to global Earth observation capabilities, complementing satellites operated by other agencies and *in situ* observing systems;
- providing an efficient and cost-effective process for rapidly translating science priorities into space missions, adequately resourced with associated ground support;
- developing innovative approaches to instrumentation.

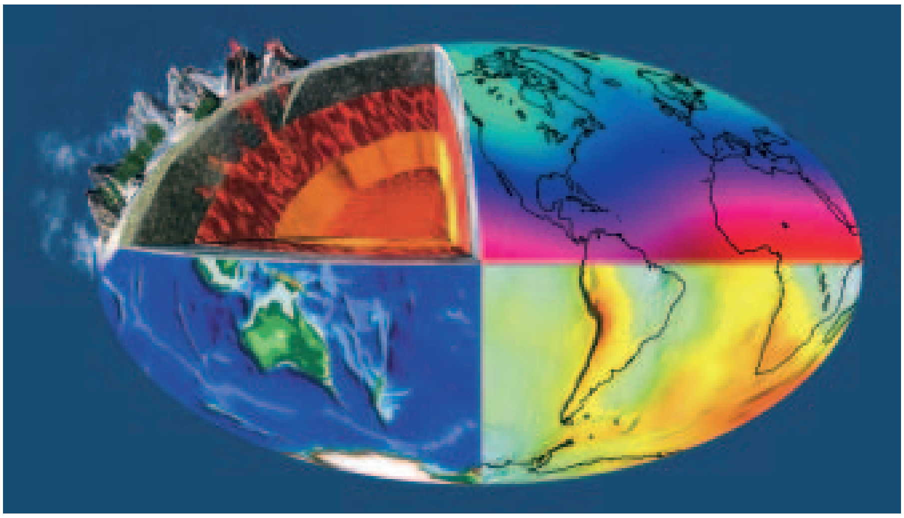
The overall vision for ESA's Earth observation activities is to play a central role in developing the global capability to understand our planet, predict changes and mitigate the negative effects of global change on its population.

The Challenges of a Changing World

Records show that the Earth has always undergone major changes. Change is a natural property of the Earth System, but there is mounting evidence that those imposed on the system during the last 150 years cannot be compared with any previous changes. In the last century, mankind has driven the greenhouse-gas concentrations far beyond the maxima reached during the last million years. It has become responsible for 70% of the nitrogen and 95% of the phosphorus cycle on Earth, and has reduced tropical forest areas by 50%. To determine whether these human-induced recent changes could ultimately destabilise the Earth System, both natural system variability and the consequences of human activities have to be fully understood and quantified. This is the scientific basis required for the sustainable future management of the Earth System as a whole.

While the large-scale processes of global change are increasingly stressing the biosphere, other less wholesale changes may have equally serious consequences for the viability of ecosystems. The loss and fragmentation of habitat, forest degradation and loss of wetlands all remove ecological niches occupied by species. Over-exploitation of the natural world, as by over-fishing and over-grazing, will lead to loss of renewable resources and biodiversity. Still more stress, and even a health hazard, is placed on populations by water and air pollution, either through catastrophic events such as oil-spills and explosions at chemical plants, or more insidious effects from the long-term use of insecticides, run-off of nitrogen-based fertilisers and air pollution in metropolitan areas. In addition to these threats to the natural world, managed systems are also subject to processes such as loss of fertility, desertification, water stress and erosion.

Two issues are at stake here. The first is sustainability. Human life draws heavily on resources provided by the living world: clean air, fresh water, food, clothing and building materials. In the interest of future generations, we have to find ways to guarantee that the functioning of the life-support system and the ability of the ecosystems to deliver goods and services are maintained.



Information that can be acquired from space relevant to Solid Earth and Earth System Science

The second is biodiversity. On our own planet, we are pursuing a course that is reducing the richness of life, and diminishing the world that we will hand on to future generations. The fact that life on Earth has existed continuously for several billion years is due to its diversity. It is very likely that in the course of the present reduction of biodiversity, the Earth System's extraordinary stability in the face of external forcing is also being reduced.

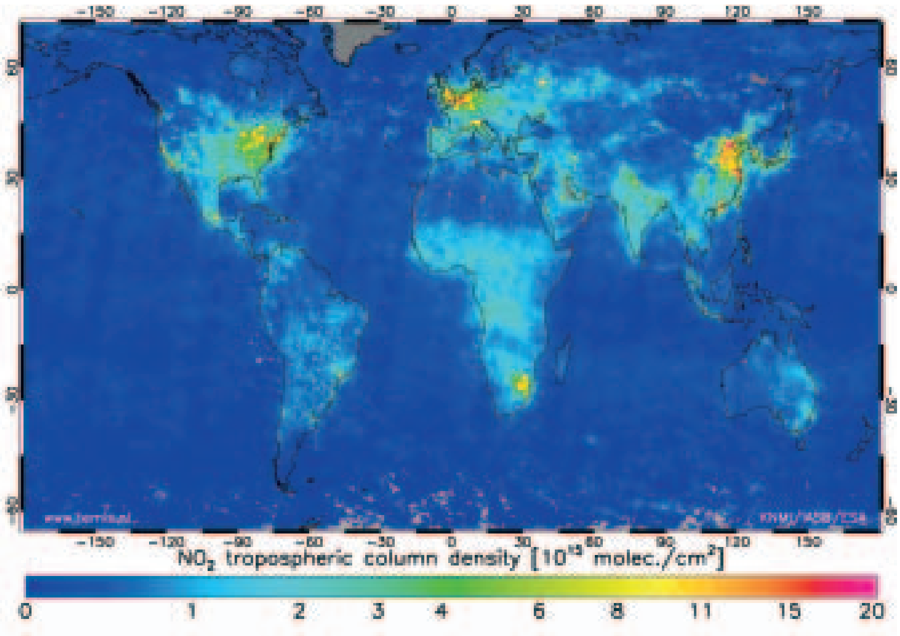
Global variations in the Earth System display very large regional differences. The human inputs to the system also show widely different patterns of change across the globe, be it deforestation, manipulation of hydrological resources, occurrence of fires, fossil-fuel burning or land-use management. What seems clear is that these highly variable local and regional types of environmental management sum together to produce global changes with major influences on the Earth System. We are only just beginning to understand the related feedbacks and consequences for the Earth as a living planet, with humanity as one of its life-forms. Measurements of the Earth's properties provided by satellites are critical in providing access to many of the key elements of the Earth System.

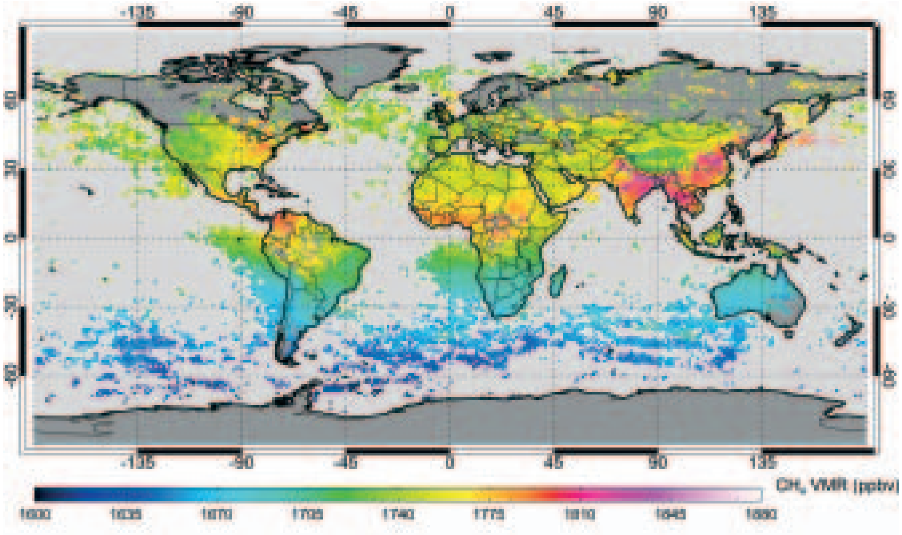
The Rationale of Earth System Science

The latter half of the 20th century saw the full emergence of the concept that the behaviour of planet Earth can only be understood in terms of the coupling between the dynamic processes in the atmosphere, solid Earth, hydrosphere, cryosphere, biosphere and anthroposphere. All of these components are interlinked by a network of forcing and feedback mechanisms that affect the other components. Global-scale effects can arise from regional processes, and global-scale behaviour can have widely different regional manifestations. In addition, processes acting at one time scale can have consequences across a wide range of longer time scales. This paradigm, in which the Earth is seen as a coupled set of dynamical systems, constitutes the scientific discipline known as 'Earth System Science'.

Major progress in many Earth science disciplines has revealed that traditionally separated disciplines, such as oceanography and atmospheric dynamics, are in fact intimately connected on a range of time and spatial scales. For example, the irregular El Niño Southern Oscillation (ENSO) shows strong coupling of atmospheric and oceanic processes, which are in turn strongly connected to the spatial patterns and overall mean of global vegetation productivity. Spectacular new evidence from Antarctic ice cores has shown that, over long time scales driven by orbital fluctuations, the Earth's mean atmospheric temperature is intimately connected to the atmospheric composition, notably the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). It is very striking that over at least six periods of about 100 000 years duration the atmo-

The mean tropospheric nitrogen dioxide content for 2003 as measured by Envisat's SCIAMACHY instrument. Hot spots are the industrialised areas of Europe, China, the USA and South Africa. Many mega-cities elsewhere can also be identified as localised spots with enhanced concentrations. (KNMI/BIRA-IASB/ESA)





Envisat SCIAMACHY measurements of column-averaged methane volume mixing ratio (VMR), in parts per billion, averaged over the period August – November 2003 on a 1 x 1° horizontal grid. At least five (and up to 150) measurements are taken for each grid cell. Only a few observations are available over the ocean, since low ocean reflectivity substantially reduces the retrieval quality. Occasionally, Sun-glint or clouds at low altitudes do allow measurements over the ocean. (University of Heidelberg/ESA)

spheric concentrations of these trace gases lie naturally within well-defined bounds.

A primary lesson learned is that understanding the strongly nonlinear behaviour of the Earth System requires atmospheric, ocean, land, cryospheric and Earth-interior processes all to be considered, in addition to the external solar driver. The Earth needs to be thought of as a system that naturally regulates itself through a complex web of interactions and feedbacks between processes.

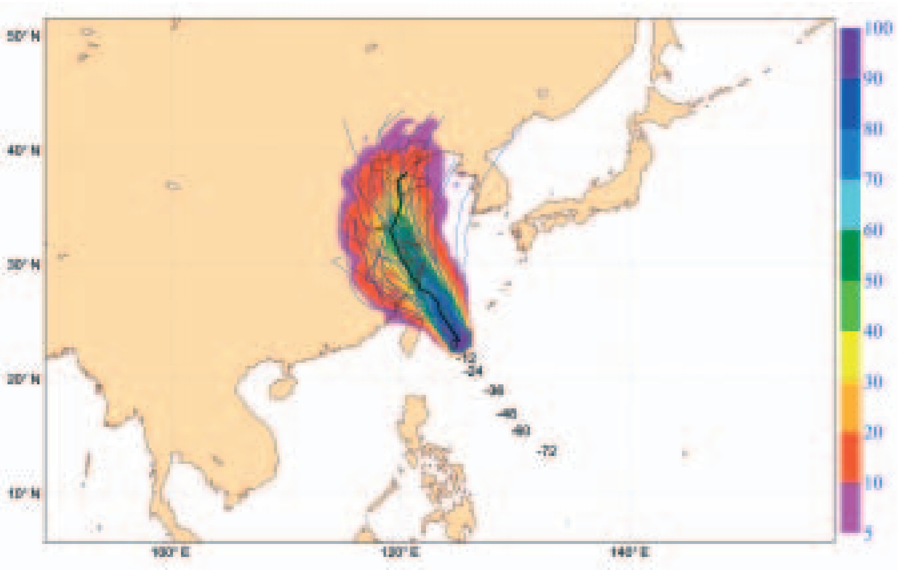
At the same time as we began to understand better the Earth as a system, it became clear that recent human activities are having a profound impact on this system, pushing it into states with unknown consequences for the planet and mankind. An unequivocal indicator of this is the atmospheric CO_2 concentration, which, since the Industrial Revolution and the mass use of fossil fuels, has risen far beyond its natural limits. Our understanding of CO_2 as a greenhouse gas, and the strong link between its concentration and temperature, both point to human activity leading to a warming world, unlike anything seen over at least the last million years.

Our perception of the Earth as a system finds its scientific expression in a modelling spectrum running from the conceptual to the highly computational. These models encapsulate our understanding of the Earth's processes, their dynamic behaviour, their relations and their feedbacks. Quantitative models, by their very nature, consist of equations whose solution requires input data, and evaluating the models also requires data. Hence our total knowledge about the system is contained in our models, our measurements and how we put them together. Improved understanding of how to represent the dynamics of the Earth processes, together with the explosion in computing power, has allowed the construction of ever more powerful computer codes capable of solving the coupled equations that make up an Earth System model with a spatial resolution as high as about 10 km. An equally influential development has been the explosion in the size of databases, both from models and satellite data, and the interconnectivity of computer systems and databases. Pinning these together has led to enormous advances in the methods of model-data fusion and data assimilation. These have been driven primarily by the needs of Numerical Weather Prediction, but the methods are cascading down to encompass all aspects of the Earth System.

The Wider Context

From the outset, ESA's Living Planet Programme had the ambition to facilitate international cooperation and use existing facilities and competences within the ESA Member States and

Strike probability of Typhoon Matsa, starting from the European Centre for Medium-range Weather Forecasts ECMWF) analysis of 4 August 2005 00:00 UT. The ECMWF operates an 'Ensemble Plotting System' in which, in addition to the operational high-resolution forecast, alternative forecasts are made at a lower resolution. (ECMWF)



The Major Challenges for Understanding the Earth System – the Scientific Direction for ESA's Living Planet Programme

Key characteristics of satellite measurements

They are global, enabling us to deal meaningfully with the overall properties of the system, while also providing observations of spatial heterogeneity.

They are repetitive and homogeneous, so that time-varying phenomena can be discriminated. In many cases, long time-series are available, so that oscillations and trends can be recognised, and signatures of anthropogenic change can be distinguished from natural fluctuations.

Near-simultaneous observations of many different variables can be made, allowing the state of the whole system to be diagnosed, and interrelations within the system to be identified.

Near-realtime data delivery (within a few hours) can be ensured, which facilitates assimilation of satellite data into complex models of the behaviour of the Earth System.

The Challenges of the Oceans

Challenge 1: quantify the interaction between variability in ocean dynamics, thermohaline circulation, sea level, and climate.

Challenge 2: understand physical and bio-chemical air/sea interaction processes.

Challenge 3: understand internal waves and the mesoscale in the ocean, its relevance for heat and energy transport and its influence on primary productivity.

Challenge 4: quantify marine-ecosystem variability, and its natural and anthropogenic physical, biological and geochemical forcing.

Challenge 5: understand land/ocean interactions in terms of natural and anthropogenic forcing.

Challenge 6: provide reliable model- and data-based assessments and predictions of the past, present and future state of the oceans.

The Challenges of the Atmosphere

Challenge 1: understand and quantify the natural variability and the human-induced changes in the Earth's climate system.

Challenge 2: understand, model and forecast atmospheric composition and air quality on adequate temporal and spatial scales, using ground-based and satellite data.

Challenge 3: better quantification of the physical processes determining the life cycle of aerosols and their interaction with clouds.

Challenge 4: observe, monitor and understand the chemistry-dynamics coupling of the stratospheric and upper tropospheric circulations, and the apparent changes in these circulations.

Challenge 5: contribute to sustainable development through interdisciplinary research on climate circulation patterns and extreme events.

The Challenges of the Cryosphere

Challenge 1: 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 2: 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 3: 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 4: 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 5: 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 Challenges of the Land Surface

Challenge 1: 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 bio-chemical luxes.

Challenge 2: 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 3: 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 4: 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.

The Challenges of the Solid Earth

Challenge 1: identification and quantification of physical signatures associated with volcanic and earthquake processes from terrestrial and space-based observations.

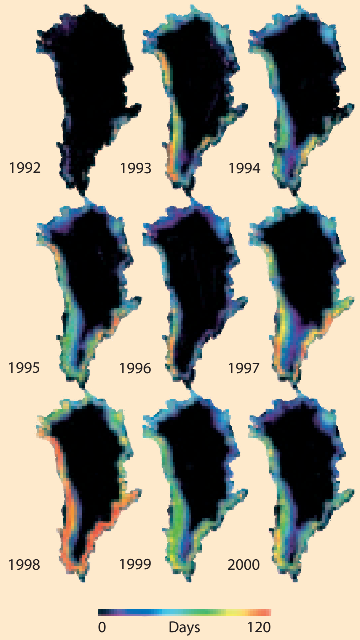
Challenge 2: improved knowledge of physical properties and geodynamic processes in the deep interior, and their relationship to Earth-surface changes.

Challenge 3: 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 4: an extended understanding of core processes based on complementary sources of information and the impact of core processes on Earth System science.

Challenge 5: the role of magnetic-field changes in affecting the distribution of ionised particles in the atmosphere and their possible effects on climate.

Melting duration for the Greenland ice-sheet surface for the years shown, estimated using ERS Scatterometer image data. The conclusion is that melting is increasing. (I. Ashcraft, Brigham Young University)

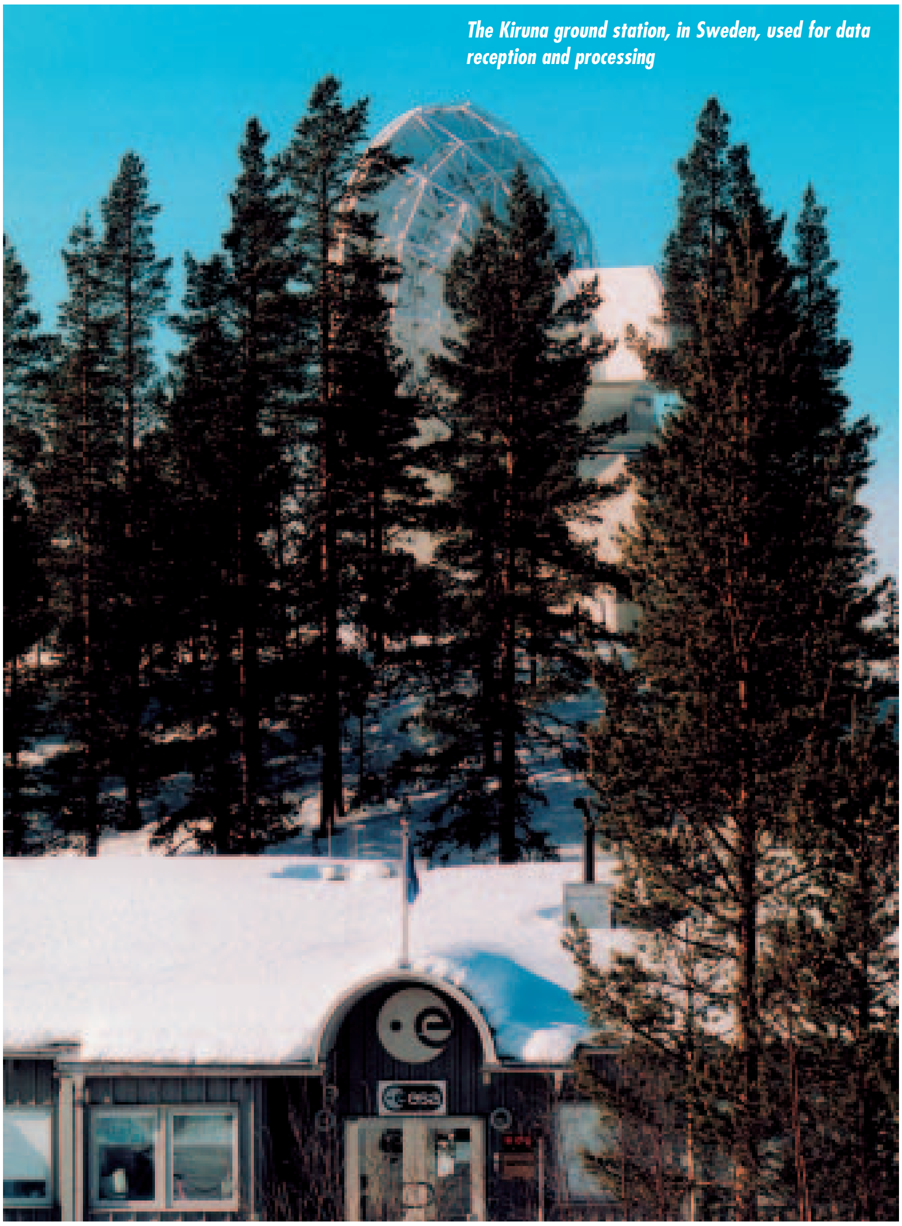


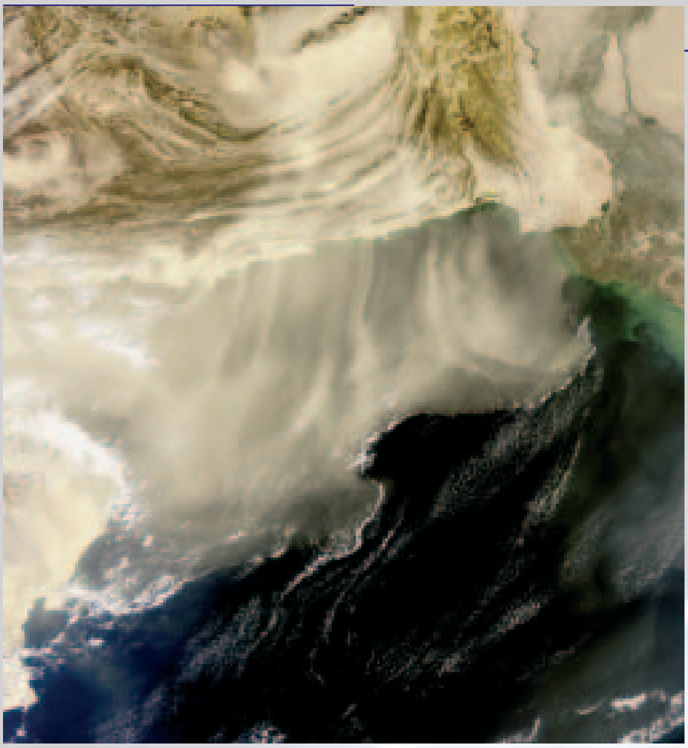
Canada. This cooperation takes several forms, from direct cooperation on the implementation of specific missions, through joint science activities in connection with ESA's and other agencies' missions, to interaction with international scientific research programmes, in order to ensure that ESA's activities have an optimum impact from a global point of view.

Over the years, European countries have developed a strong leadership in Earth System Science. The development of fully coupled Earth System models is well underway at the Hadley Centre and the University Global Atmospheric Modelling Programme (UGAMP; UK), at the Max Planck Institute for Meteorology in Hamburg (D) and at the Institut Pierre Simon Laplace and Meteo-France (F), to cite but a few. Many other European organisations are working in the same direction. Europe also holds a strong position in other key areas of Earth System Science, such as oceanography and glaciology. Furthermore, several European organisations with an interest in Earth System modelling have grouped together within the European Network for Earth System Modelling (ENES).

Earth System models are developed through a complex and systematic process of comparison with observations at the relevant scale. Systematic differences between model simulations and observations, called 'biases', point to the incorrect representation of some process that must be improved in the models, or to systematic observational errors that must be corrected. Once the biases are reduced to a minimum, the remaining random differences between the models and the observations can be exploited to improve further the model's formulation, or to create a set of model variables representing the reality at a specific point in time. The model can then be used for predictions. This whole process is called 'data assimilation' and lies at the heart of Earth System Science. Europe has developed a very strong leadership in pioneering the variational approach to data assimilation. This approach was first successfully developed in meteorology, where the European Centre for Medium-Range Weather Forecasts, together with partner European meteorological centres, has acquired an undisputed lead. Similar data-assimilation techniques are also being developed in the other fields of Earth science.

An important benefit of Earth Science satellite missions and other activities is the well-established potential they provide for developing new Earth observation applications, the development of operational systems for meteorology being a prime example. Other areas are also progressing, and political decisions like international treaties on, for example, ozone and carbon, emphasise and formalise the need for related applications. The link between science and applications works both ways. On the one hand, scientific progress forms the basis for the development of new applications, but operational systems also make important contributions to scientific

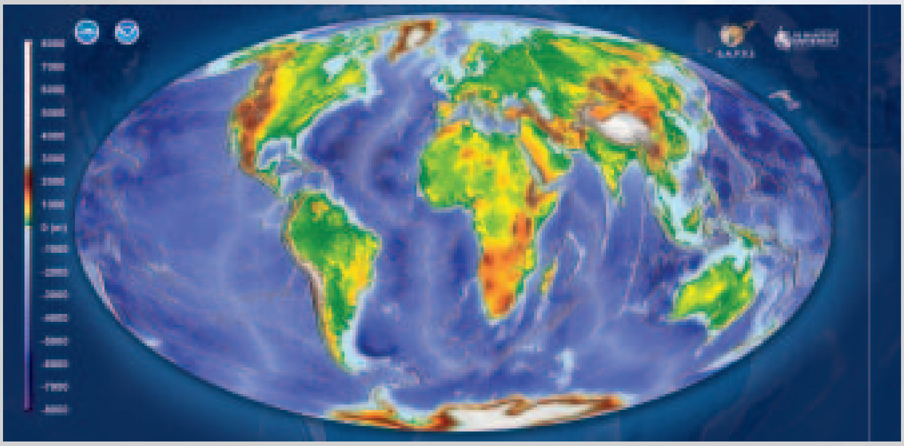

The Kiruna ground station, in Sweden, used for data reception and processing



This Envisat/MERIS image of 13 December 2003 is dominated by a dust and sand storm covering the Gulf of Oman. The scene includes a large part of Baluchistan, a mountainous region with some deserts and barren plains, and parts of southwestern Pakistan and southeastern Iran (top right & top centre). It shows the dust particles (aerosols) of a continental air-mass interacting with a humid marine boundary layer (Somali jet), leading to cloud at the edge of the outbreak. (ESA)

Envisat ASAR image of the Scott Coast, Antarctica, showing the collision of the B15A iceberg with the Drygalski ice tongue in April 2005. (ESA)

Banda Aceh as seen by Spot-5 before (2003; left) and after (30 December 2004) the devastating Indonesian tsunami. The damaged infrastructure and areas still under water are clearly visible. (CNES/SpotImage, 2004; processing SERTIT)



Global topography and bathymetry measured by space-based radar altimetry. (ESA, using bathymetry data courtesy of: W. Smith, NOAA Geosciences Lab., USA, D. Sandwell, Scripps Institute of Oceanography, USA, and altimeter-corrected elevations from P. Berry, DeMontfort Univ., UK) research, particularly by providing long time-series of global data, something that is notoriously difficult to justify in research-oriented space activities. A good example in this respect are the missions of Eumetsat and similar organisations.

During the last decade, the Integrated Global Observing Strategy Partnership (IGOS-P) has formulated global observing needs for a number of themes. Other more recent developments are the GMES intiative by the European Union, ESA and other partners, and the Global Earth Observation System of Systems (GEOSS), to which GMES is Europe's planned contribution. Although these initiatives go well beyond the scientific needs, these are also included and these intiatives therefore provide a natural link between science and applications.

Development of specific collaborations with major science initiatives through, for example, the Earth Systems Science Partnership and with international user organisations such as the United Nations Conventions, have also been a feature of the Programme. In all its aspects, it has also been a major contributor to the development of European industry in the technology-development, manufacturing and service sectors.

Living Planet Contributions

ESA's primary contribution to Earth Science is the provision of data products and associated services from the Agency's Earth observation satellites. In addition to data from its own satellites, ESA also facilitates the provision of data from other organisations' satellites.

Earth observation satellites for Earth science are identified, selected and developed in close cooperation with the scientific community. Identification of candidate missions or mission concepts is regularly conducted via open calls for proposals to the scientific community, where the newly identified challenges guide future calls. New concepts usually require a stepwise approach, where studies and campaigns are undertaken in order to advance the concepts. The Agency undertakes preparatory activities in order to ensure that the concepts finally selected for implementation correspond to the highest priority user needs and have the broadest possible scientific impact.

The goals of the science strategy will be achieved only if the data gathered are validated and exploited thoroughly by all the research communities concerned. To achieve the envisaged scale of impact within the science community and in society at large, a strong European role, innovation and commitment in the area of data exploitation must be maintained. Data exploitation under the Living Planet Programme should, in terms of its prime objectives, maximise advances and achievements in European scientific understanding of the Earth System, develop new applications that can benefit society and contribute to improved quality of life, and demonstrate new techniques and technologies that can strengthen European industry's competitiveness. Specific attention should be given to stimulating and facilitating the use of Earth observation data by research communities that do not specialise in remote sensing.

Manifested in ESA's day-to-day contacts with the science community, the requirements associated with Earth observation mission operations, ground segments, data and information handling can be summarised as:

– easiest possible data access, continuously adapting to the latest technology;
– coherent access to many (ideally all) sources of Earth observation data and even other geo-data;
– fast access, ideally in near-realtime;
– long-term access over many (tens of) years;
– adaptation of mission, acquisition planning and operations strategies to user demand.

Today's users can handle and process, and therefore request, substantially higher volumes of Earth observation data than ever before. This trend is increasing exponentially. Payload ground segments must anticipate such an exponential increase in the demand during the design phase, in order to meet the actual demand at the start of mission operations. Modelling and long-term trend monitoring have led to a large increase in the demand for time-series and historical data, including regular reprocessing.

The evolution in the scientific requirements, where the science projects represent large investments both financially and in terms of manpower, means that operations and ground segments for scientific missions now have to:

– offer the same level of reliability and operability as former 'operational' missions;
– additionally provide a higher degree of flexibility in adjusting and tuning the operations schemes to new projects and technologies, and offer a much closer and intelligent dialogue with the user community.

Science today relies on a multitude of Earth observation data sources, which can no longer be characterised as science-only missions. Data from public, operational or commercial missions, as well as non-space data, are often indispensable inputs to science projects. A technically simple and coherent (and financially affordable) access mechanism needs to be established.

It is essential for the success of the science strategy that the technology developments, scientific investigations and applications developments carried out under the Programme are accompanied by a systematic and concerted effort to communicate the achievements to a much wider audience, both within Europe and beyond. This effort should address the general public, political decision-makers, schools and universities, all of whom need to be made aware of, kept regularly informed about and kept interested in Europe's achievements in Earth observation. They must be convinced of the tangible benefits of investing public funds in this effort.