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The Science and Research Elements of ESA's Living Planet Programme

European Space Agency
Agence spatiale européenne

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The Earth Explorers

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Report prepared by:	Earth Science Division, ESA Directorate of Scientific Programmes
Coordinator:	Chris J. Readings
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Contents

Research Using Earth Observation in the 21st Century

In this document we present the plans for the Earth Explorer element of the European Space Agency's new *'Living Planet'* Programme for Earth Observation. Living Planet marks a new era for European Earth Observation based on smaller more focused missions and a programme that will be user-driven. The users envisaged for the Earth Explorer spacecraft are the Earth Science community of Europe, a community that has cut its teeth on the big multi-user spacecraft ERS-1 and -2 and Envisat. It now will be able to look forward to a programme of more frequent but smaller and more focused missions directed at the fundamental problems of Earth system science.

The Earth Explorer Programme (Part A of this document) has been prepared by the ESA Earth Science Advisory Committee (ESAC). I am very grateful to the Committee, particularly, Professor Mégie, its Chairman, and to the supporting members of the Executive, for their sterling efforts over the past year to bring this plan into being. The programme grows out of European scientific heritage in Earth Observation, exemplified by the Meteosat, SPOT and the ERS satellites. All of these, in their different ways, were trail blazers and have established European competence. The tradition continues with the missions currently under construction, Meteosat Second Generation, Metop and Envisat.

The Agency's overall strategy [described in ESA/PB-EO(98)13 rev. 2] for Earth Observation in the coming decade was endorsed by the ESA Council in March 1998. The Living Planet Programme follows on from Envisat, which is to be launched early in 2000. It is a programme to cover the whole spectrum of user interests ranging from scientific research through to applications. The research-driven Earth Explorer missions will be paralleled by applications-driven Earth Watch missions, designed to focus on specific Earth Observation applications and service provision. In the long run, Earth Watches are expected to become free-standing services outside the Agency. The *Living Planet* Programme contains also an exploitation and technological development element whose purpose is to underpin market development and ensure cost-efficient implementation both of Explorer and Watch spacecraft.

As part of the new user-driven approach, the funding of the Explorer mission is through a new operational 'envelope' programme. Gone will be the days where each new mission required new subscriptions from our Member States. Instead the Member States will subscribe to the programme of Earth Explorers on a rolling basis, allowing much more coherent scientific planning and targeting.

The plan described here has been drawn up following extensive consultation with the Earth Observation community in the ESA Member States (as well as Canada, which has long closely cooperated with ESA in Earth Observation). It is intended to reflect not only their ideas and aspirations but also to be a response to concerns about climate change and man's impact on it. Many of the areas identified in this programme directly relate to the work of the Intergovernmental Panel on Climate Change (IPCC) which was established, under the auspices of the United Nations, to advise governments on the state of knowledge of climate change and its implications.

Furthermore, it is important to see the proposed work as underpinning European interests in monitoring the Earth and its environment. This reflects not only Europe's role in defining, monitoring and verifying international conventions made in response to global concerns, but also her role in providing the information needed to better understand and manage the environment at the regional and European level. In this regard the Agency has remained in close touch with both the European Commission (EC) and the European Organisation for Exploitation of Meteorological Satellites (Eumetsat) in all its planning for the new programme.

Europe has a great scientific heritage and European and Canadian Earth Observation scientists have established themselves as leading authorities in many areas. This level of excellence must be maintained and further consolidated in the future. The proposals contained in this report take this fully into account, building on this and the anticipated state of knowledge. The report identifies the problems that need to be addressed while, at the same time, recognising that the situation is not stagnant but continually evolving so there is a clear need for flexibility and speed of response. There must be continual interactions with the user community, the programme must be user driven.

ESA cannot operate in isolation from the rest of the World as many of the problems are global in nature, often necessitating the provision of levels of resources far exceeding those available to any single country or small group of countries. International collaboration, technical as well as scientific, is at the heart of the programme and the management procedures proposed are designed to maximise the possibilities.

Efficiency of implementation is also a central question in obtaining value for money. The programme will challenge both industry and the Agency to look at cost-efficient ways of implementing missions and new ways of working.

I would encourage you to feel able to comment on the ideas in this document. The Earth Explorer Programme itself will proceed through a continual dialogue with the Earth Observation community. In closing, let me thank again all those in the community, the ESAC and its chairman, Professor Mégie, and the Agency staff who have brought this plan into being.

Roger M. Bonnet
Director of Science

Members of the Earth Science Advisory Committee (ESAC)

Dr. E. Augstein
Alfred Wegener Institute of Polar and Marine Research, Bremerhaven, Germany

Prof. F. Becker
International Space University, Illkirch, France [representative of the ESSC]

Dr. B. Carli
IROE/CNR, Florence, Italy

Dr. A. Hollingsworth
European Centre for Medium Range Weather Forecasts, Reading, United Kingdom

Prof. M. Jacob
CERN/Geneva, Switzerland [representative of the SPC]

Prof. O. Johannessen
Nansen Environmental and Remote Sensing Centre, Solheimsviken, Norway

Prof. Dr. G. Konecny
Institute for Photogrammetry and Engineering Surveys, University of Hannover, Germany
[representative of EARSeL]

Dr. J-P. Malingreau
European Commission–Joint Research Centre, Brussels, Belgium

Prof. G. Mégie
Service d'Aéronomie du CNRS, Université Paris IV, France
[Chairman of the ESAC]

Dr. J-F. Minster
INSU, Paris, France

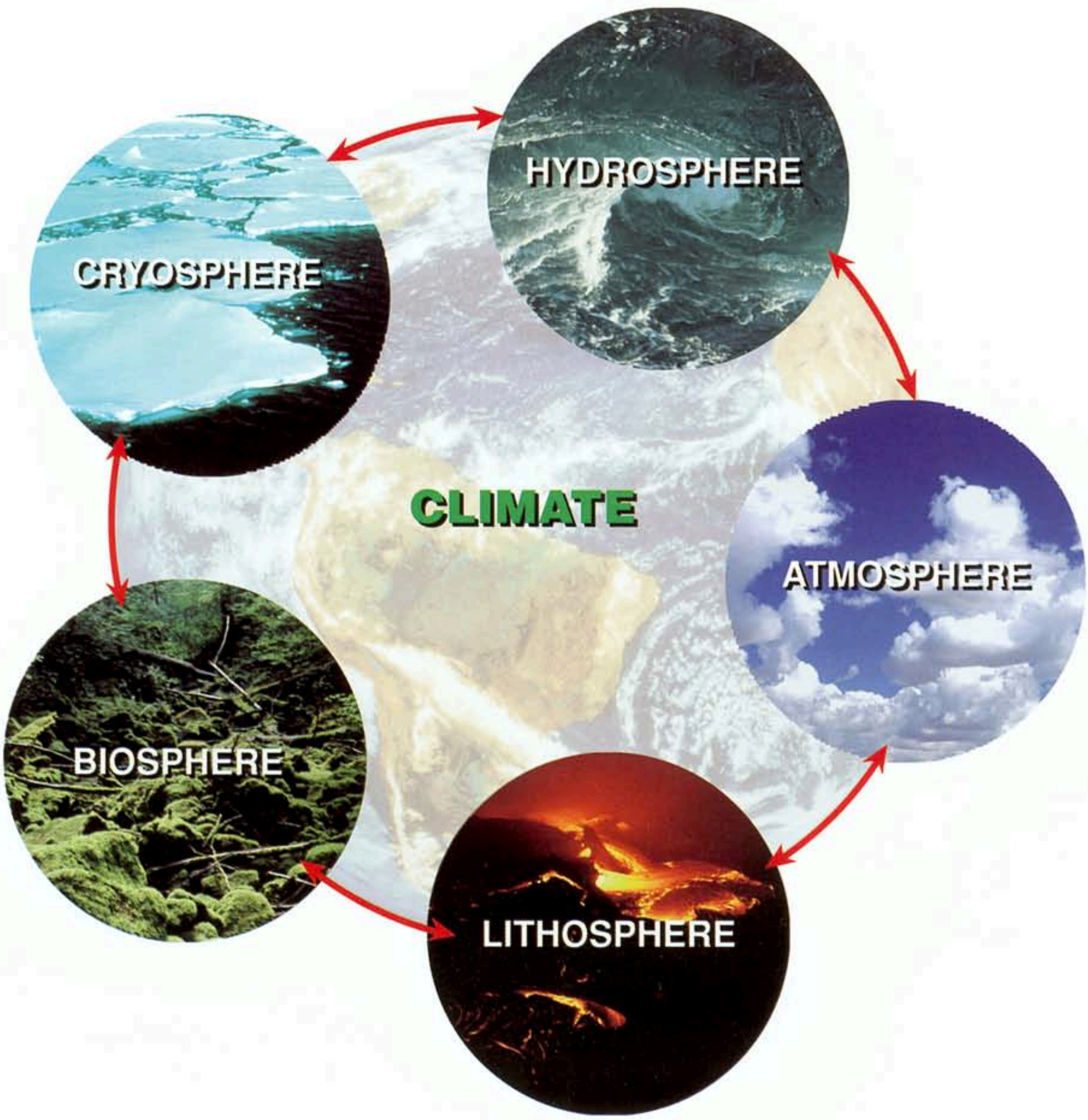
Prof. H. Rott
Institute of Meteorology and Geophysics, University of Innsbruck, Austria

Prof. Dr. Ing. R. Rummel
Technical University of Munich, Germany

Part A

The Objectives and General Context

Elements of the Earth System



1. Introduction

1.1 Background

The past decade has seen increasing public concern about the Earth, its environment and mankind's impact upon it. Global threats such as climate warming, stratospheric ozone depletion, tropospheric pollution and more recent regional events such as the very intense El Niño, the fires in S.E. Asia and the floods in Middle Europe, have left the public more concerned than ever about the need both to monitor and understand what is going on in the Earth's environment. The long term habitability of the planet is at issue and, as one of the richest most technically advanced areas, Europe cannot stand aside. Exploitation, sustainability and political responsibility are all interlinked.

However, there are many aspects of the complex evolving Earth System that we still do not understand. There thus remains a need for a worldwide scientific research effort to improve our understanding of fundamental processes, in which Europe must take its part. Regional as well as global processes, short as well as long term issues, are involved and in most cases all these spatial and temporal scales are strongly interrelated.

To address these issues the provision of data and their integration into appropriate models of the Earth System is of paramount importance. Earth Observation from space is a critical tool in this task as it can provide the global and coherent data sets which are an essential complement to ground, balloon and aircraft based measurements of geophysical systems. European programmes at national or Europe-wide level, such as Meteosat, SPOT, TOPEX/POSEIDON, ERS-1 and ERS-2, have established Europe in a world-ranking position in Earth Observation, both in scientific and industrial capability.

The earliest initiatives, Meteosat and SPOT, have already developed into long term applications programmes integrated into regular operational use. The ERS satellites have made major contributions in areas as diverse as global and regional ocean and atmospheric science, sea ice, glaciological and snow cover investigations, land surface studies and the dynamics of the Earth's crust (seismology and volcanology). In the future Metop and MSG (developed in cooperation with Eumetsat) will continue the development of operational capabilities. Envisat will provide new capabilities to monitor atmospheric composition and chemistry as well as providing continuity and improvement upon the ocean, coastal zone and land cover monitoring capabilities of the ERS satellites. Future Earth Observation programmes in Europe can thus build on this strong European heritage.

1.2 The Context

At the international level, there already exist commitments underwritten by international treaties (see Appendix A) encompassing climate change, stratospheric ozone, atmospheric pollution, forests, water conservation and desertification. Signatories need to undertake further research to ensure the systematic observation of key geophysical parameters. At the highest level the Intergovernmental Panel on Climate Change (IPCC) was established under the auspices of the United Nations to advise governments on climate change and its implications. Mention should also be made of the Panel of the Parties to the Montreal Protocol and the need to fully understand the processes controlling the evolution of the ozone layer. These bodies have highlighted the need for research in many areas, notably the estimation of emissions, bio-chemical cycling and the representation of climate processes in models (Figure 1.1).

Such international initiatives, which take due account of the environmental problems, have their scientific counterparts. These are linked to the need to increase knowledge and understanding of environment processes and climate, as well as to develop a set of models describing the Earth System (from local to regional and global scales) which are capable of properly simulating the impact of man's activities on his environment and the evolution of the Earth's climate. This represents a major challenge as many complex processes are involved and requires a global scientific effort, which is organized under the auspices of international research initiatives, such as the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP). The close links between these initiatives and research on improving our understanding of the Earth's climate and environment further guarantee the coherence of the scientific efforts in addressing environmental problems.

Accepting the importance of these environmental concerns to Europe and of the European heritage, European Ministers, meeting in Toulouse in 1995, endorsed an overall plan for Earth Observation put forward by ESA, the European Commission and the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat). This plan is based on a dual mission scenario for the Agency's Earth Observation Programme which includes two complementary components, namely the Earth Explorer and Earth Watch missions. The former is the specific concern of this document as the Earth Explorer missions have the fundamental aim of contributing to the provision of data essential to the study of the various processes involved and the extension of the existing hierarchy of models of the Earth System. Earth Explorer missions are also intended to help establish the feasibility of new space-based observation techniques of potential application in operational observing systems.

In both cases major technical challenges will have to be addressed, so the role of industry is of fundamental importance. Furthermore, Earth Explorer missions are closely linked to Earth Watch missions, which focus on the long term operational provision of data from space, forming thus a complementary pair which seeks to exploit the unique capability of satellites to provide global, quasi-synoptic, repetitive data sets of homogeneous quality. In some instances these data are not available from other sources, though often they complement those from ground-based systems; both contribute to the establishment of the databases which are required to answer the basic questions to be addressed by Earth System studies.

Figure 1.1 Specific issues within the elements of the Earth system of importance in the context of environment and climate

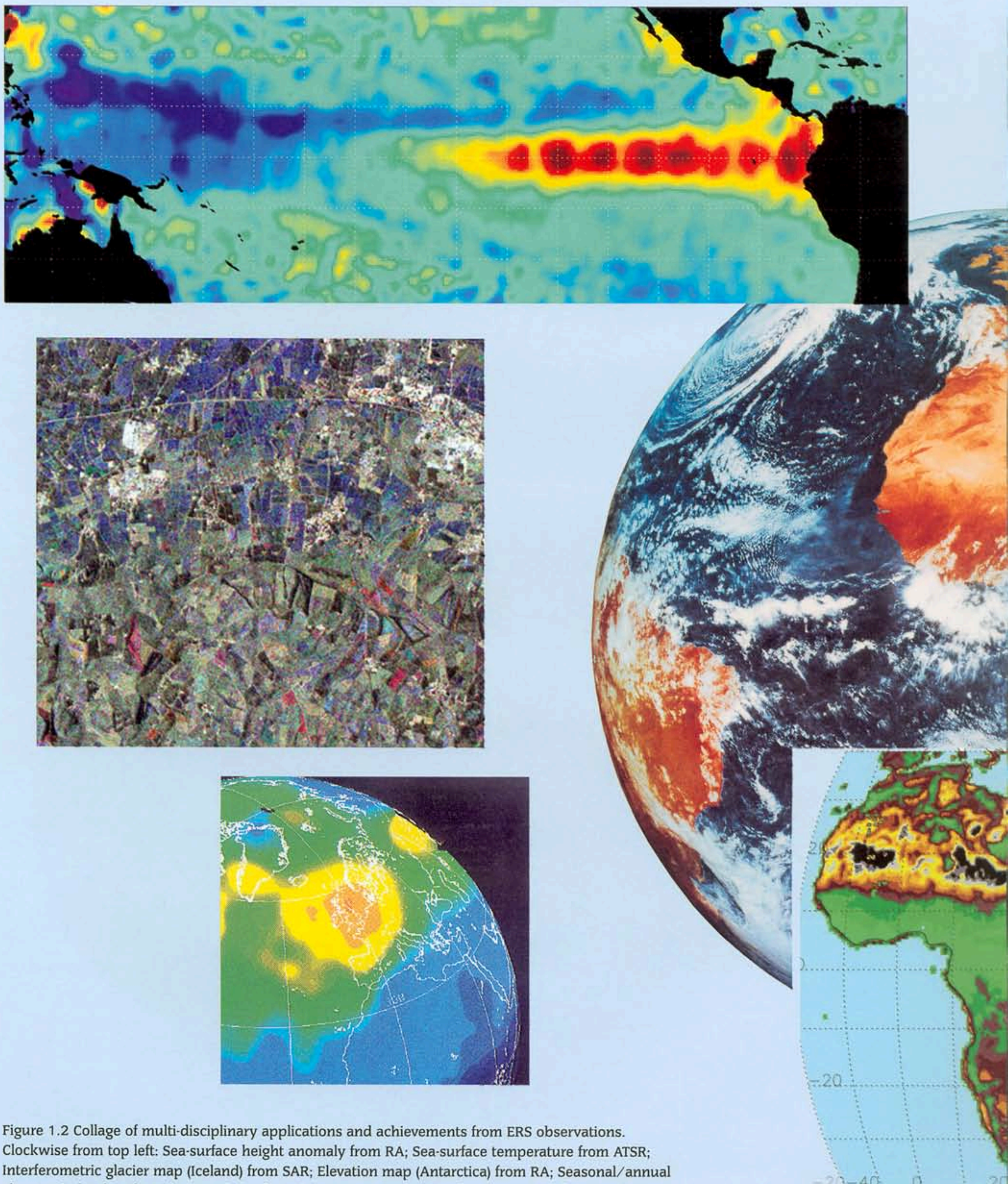
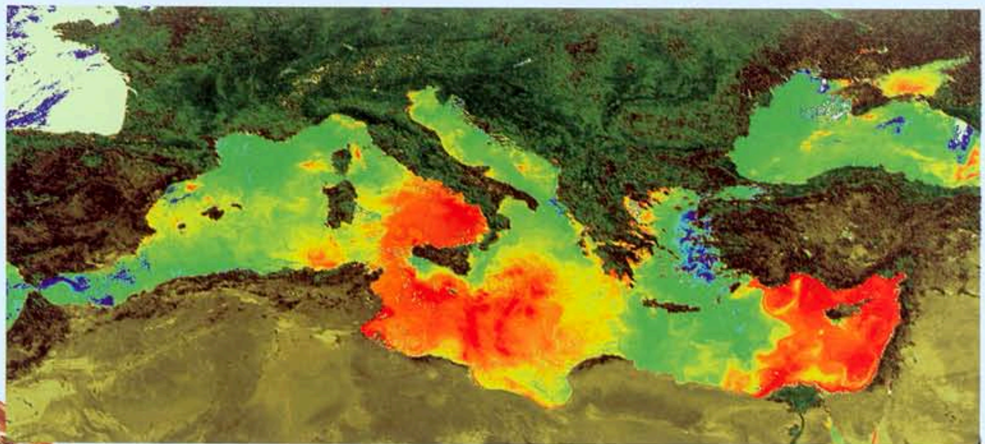
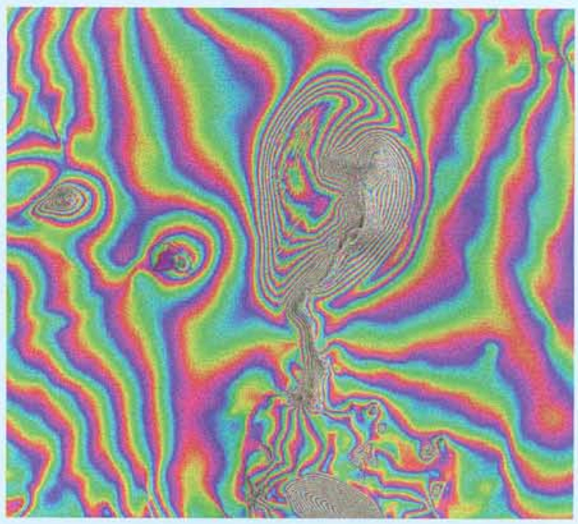
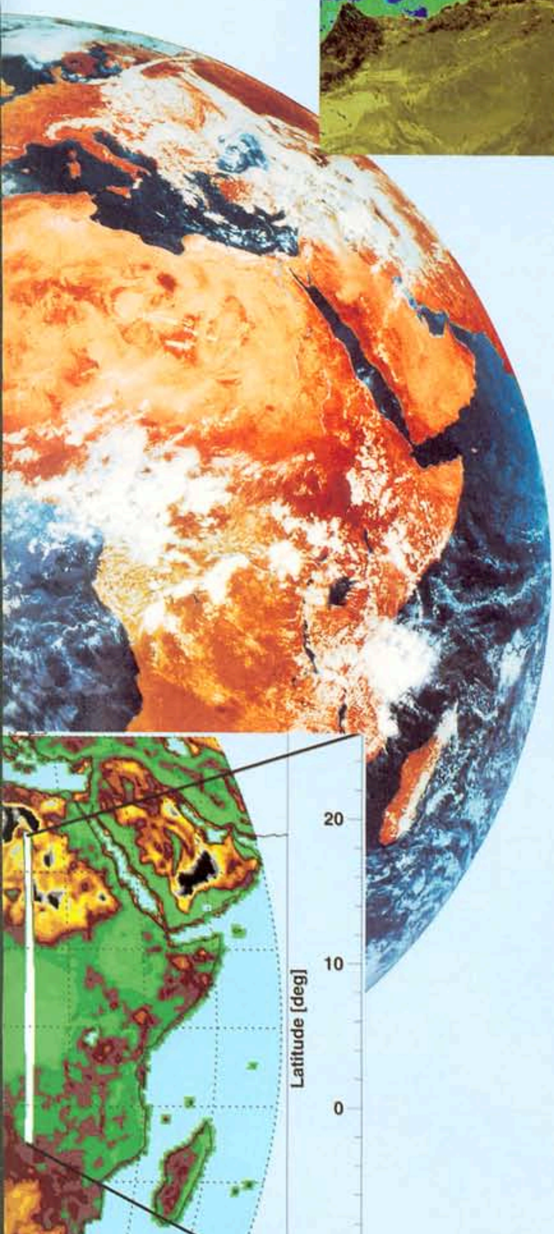


Figure 1.2 Collage of multi-disciplinary applications and achievements from ERS observations. Clockwise from top left: Sea-surface height anomaly from RA; Sea-surface temperature from ATSR; Interferometric glacier map (Iceland) from SAR; Elevation map (Antarctica) from RA; Seasonal/annual changes in land-surface characteristics from Scatterometer; Ozone-column amounts from Ozone Monitor; Land-usage map from SAR



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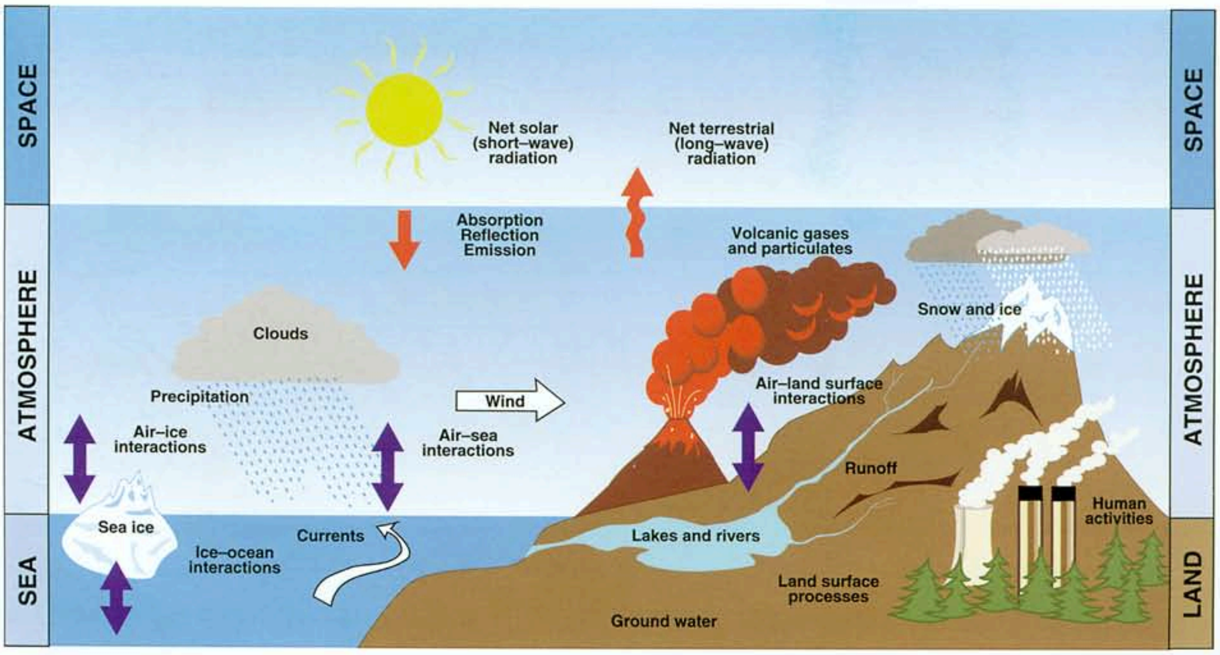
The Earth Explorer component of the Agency's overall Earth Observation or Living Planet Programme will build on the heritage of research missions such as ERS, TOPEX/POSEIDON and Envisat, set in the general forum of Europe's operational missions, namely Meteosat, Metop and SPOT. The scientific achievements listed in Table 1.1 are complemented by the collage of geophysical products from ERS shown in Figure 1.2. Nevertheless, the key problems are global and a worldwide effort is required. Coordination between ESA programmes and national efforts will be essential, but international cooperation will also be a central element. The implementation of the programme must be designed to ensure this occurs at a global level.

1.3 Earth System Models

Ultimately, the manner in which our understanding of the Earth will improve is by the development and elaboration of Earth System models into which data from various sources will be integrated (Figure 1.3). This poses many challenges, including those of data validation, model validation and data assimilation. The first two are essential if models are to be trusted and used for the prediction of human influences, and the latter is essential if optimal use is to be made of the various sources of data likely to be available.

The paradigm for this approach is well illustrated by the achievements in meteorology, of which a good example is the work of the European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF has developed a capability to predict detailed atmospheric behaviour increasingly reliably for periods of up to a week or more and is now producing global seasonal forecasts. ECMWF has led the way in the integration of space data with other data into models which couple ocean and land surface interactions to atmospheric processes. The advances in space oceanographic data gathering capability are encouraging the development of 'ocean forecasting' models of a nature similar to those used by the meteorologists.

Figure 1.3 Schematic of the Climate System



AREA	GLOBAL OCEAN & ATMOSPHERE	REGIONAL OCEAN	SEA ICE	GLACIOLOGY & SNOW	LAND	THE EARTH'S DYNAMIC CRUST
MAPPING & MONITORING	Ocean surface wind field Ocean surface waves Ocean topography Sea surface temperature Atmospheric aerosols Ozone and trace species	Ocean surface wave patterns Surface slicks	Sea ice extent, type, concentration and thickness Sea ice movement Iceberg movement	Ice elevation on major ice sheets Extent of major ice sheets Extent of small ice sheets and temperate glaciers Snow distribution	Global vegetation cover monitoring Crop cover and status Forest cover and status Soil moisture Surface water coverage Wetland vegetation cover Surface lithology Surface landforms Elevation and general land cover	Overall shape of the Earth (geoid) Regional geiod variations Earth's gravity field Land displacements resulting from earthquakes Changing shape of volcanoes during eruptions
PROCESS UNDERSTANDING & TREND DETECTION	Ocean / atmosphere interaction Ocean wave trends Ocean current processes and variations Large scale phenomena (e.g. El Niño, Rossby waves) Sea level change	Regional & small scale atmospheric features, e.g. monsoons, cyclones Ocean dynamics – eddies frontal boundaries	Ice thickness and movement at the edges Understanding structures within sea ice Ocean convective processes through sea ice patterns Ocean / atmosphere fluxes Effects of ocean current and associated temperature changes	Mass balances of major ice sheets – changes in thickness Mechanisms of ice movement within ice sheets Changes in ice sheet elevation patterns	Trends in global vegetation cover Regional soil moisture variation Local soil moisture patterns in relation to river flows	Tectonic structure under the oceans and sea ice Processes governing continental drift Effects of earthquakes on surrounding areas Temporal gravity
MODELLING FOR FORECASTING AND PREDICTION	NWP – better ocean wind and wave fields Tides – better models in polar regions Climate – ocean current patterns, sea surface temperature, aerosol effects	Regional circulation Estuarine processes Coastal sediment transport and erosion Climate – better understanding of thresholds, land / atmosphere interactions, land ocean interactions	Wave modelling – better boundary conditions Climate – effect on thermohaline circulation	Modelling ice sheet dynamics – prediction of possible rapid changes, release of ice to the sea Climate – mass balance Hydrology – changing snow patterns, drainage basins within ice sheets	Climate – land / atmosphere interactions, land ocean interactions Hydrology and agriculture models – early stages of application	Tectonic models of continental and regional development Earthquake models

Table 1.1 A summary of the scientific achievements of ERS

Earth System models take the form of interlinked computer models, which solve a set of mathematical equations describing the evolution of the Earth's fluid environment (atmosphere and ocean) on various time scales, with appropriate boundary conditions particularly at the Earth's surface where the biosphere, vegetation and soils play a key role. Specifically, the equations describe the evolution of the state and composition of the atmosphere, of the physical state of the ocean and cryosphere, of the physical state of the top few metres of soil and dynamical interactions with the Earth's interior, of the physical state of terrestrial vegetation and of the key bio-geochemical cycles which in turn require the representation of terrestrial and ocean biota. This in turn implies a proper description of the properties of the atmosphere, ocean-ice and land surfaces on a horizontal and vertical net of grid-points spanning the whole globe, which define the resolution of the model.

Two factors have limited the realism of numerical models. The first is that there are still many important processes (see Chapter 2) which are poorly or very poorly known. The reliable parameterisation of these processes is essential if the concerns highlighted in the previous section are to be addressed. The satellite data needed to improve model parameterisations will be a key deliverable of the Earth Explorer element of the Agency's Earth Observation Programme. The second limiting factor for developing better numerical models is that the computing cost of solving the equations depends very strongly on the resolution. Thus, for example, halving the spacing between the grid-points in the horizontal increases this cost by a factor of eight. Rapid progress in computer capabilities opens the possibility of realising spatial resolutions of the order of 10-15 km in global models in the first decade of the next century.

To take full advantage of the data to be provided, inter alia, by space observation, a hierarchy of models must be developed which includes :

- high resolution models for the detailed study of climate processes (clouds, radiation, surface-atmosphere interaction,...) and the impact of human activities on these processes

- coarser resolution models, with appropriate processes parameterisation, to be used for impact assessment over extended periods.

The formulation of these models represents a major scientific challenge, all the more so because of the nonlinear nature of the processes involved. This requires simultaneous progress in three different areas :

Area 1 To identify and increase understanding of the various processes involved to the point where they can be represented in models.

Area 2 To extend the existing hierarchy of Earth System models to include these processes.

Area 3 To ensure the provision of the relevant data for use in these models to help address the issues highlighted above.

From its heritage and existing expertise, the European scientific community has the ability to play a key role in defining and implementing such an approach. In this context, the Earth Explorer missions will contribute to all three areas, provided the appropriate modelling tools are developed in a timely fashion to address regional and global concerns.

1.4 The Overall Approach

Considering Earth observation from space, and as part of the Agency's overall strategy, the Earth Explorer component of the programme will concentrate on satisfying research and demonstration requirements. It will take the form of an envelope programme where, within the overall financial provision, missions will be selected according to a series of quite specific criteria. These include relevance to the ESA research objectives for Earth Observation; need, usefulness and excellence; uniqueness and complementarity; degree of innovation and contribution to the advancement of European Earth Observation capabilities; feasibility and level of maturity; timeliness. At all stages the user community will be closely involved to ensure that the programme truly reflects its needs and aspirations.

The present document aims at defining the scientific objectives for Earth Observation focussing on the post-2000 era. Chapter 2 thus identifies the main problems that must be addressed and the associated research requirements for space-based observations of the Earth System. These encompass all components of the Earth System to ensure that the progress, in advancing quantitative knowledge of the various components and their interrelations, is obtained within a time frame compatible with the urgent need for an increase in overall understanding of the Earth System to allow timely political responses.

The Earth System is immensely complex. The atmosphere, oceans, land surface, cryosphere and the Earth's interior all interact. Although on a spatial basis one may divide the Earth system into four basic regimes – Earth Interior, the Land Surface, the Ocean, and the Atmosphere – central research issues now concern the detailed treatment of interactions between the regimes. Moreover, the science required is often interdisciplinary as the Earth System evolves by a complex interlinking of biological, physical and chemical processes. Accordingly, the scientific programme, which is described in this document, is based on four major interdisciplinary themes, each of which may encompass phenomena in several of the regimes. The themes chosen are the Earth interior, the physical climate system, the geosphere-biosphere and the anthropogenic influences on the atmospheric and marine environment. Between them (see Table 2.2) these four Themes span the full Earth System.

To address these science objectives, which are fully in line with the requirements of international science programmes, two types of Earth Explorer mission are envisaged, namely Core Missions and Opportunity Missions. The former will be selected through a mechanism involving extensive collaboration with the user community while the latter will provide the means to respond quickly to flight opportunities or the need for a quick response to a user requirement. In this way the programme will combine stability with flexibility, notably the ability to respond quickly to an evolving situation. Core Missions will generally be selected two by two and will be larger than Opportunity Missions which will be selected individually. Both types of mission can involve international collaboration; both assume that the research community has ready access to data, whether it originates from Earth Explorer missions or from other sources. Chapter 3 outlines an illustrative set of space missions (the outcome of extensive user consultation) which would make a significant contribution to the realisation of the overall objectives of the Earth Explorer Programme.

The scientific problems highlighted in this document represent a global challenge which demands a global solution. International cooperation is therefore a key assumption underlying the Earth Explorer Programme. Europe has much to offer, as it has pioneered and continues to play a leading role in Earth Observation. The Earth Explorer Programme is intended to build on this heritage to the benefit not only of Europe, but also of mankind generally. Chapter 4 sets the objectives of the programme within the international context, as well as demonstrating its relevance in the European context. Chapter 4 also emphasises the fact that the programme has been formulated to ensure the stability and continuity required to fulfil international commitments.

Finally, in the last two chapters (5 and 6) the modus operandi is described and the proposed schedule and financial arrangements outlined. Fundamental to this processes is acceptance of the need for continuing (and extensive) user consultation, coupled with the stability of a long term programme with regular flight opportunities. In this, the Agency will have a pivotal role to play by providing a neutral platform to arbitrate on a European scale between conflicting priorities as well as providing a centre of expertise. The interests of Europe will be of paramount importance and it is essential to view the Earth Explorer Programme within the context of the Agency's role in the overall European strategy for Earth Observation.

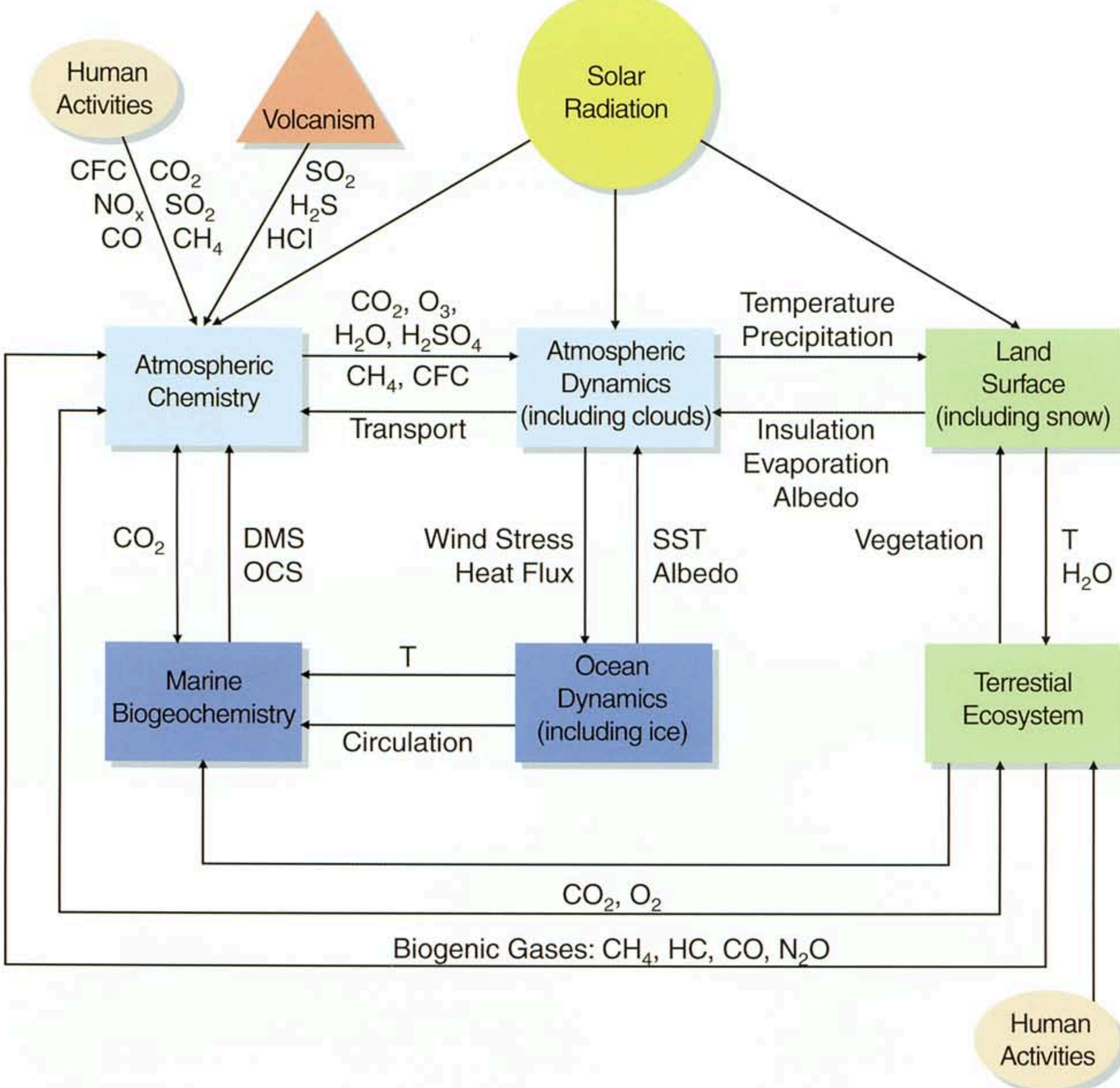


Figure 2.1 Schematic of the various components of the coupled Earth System

2. Earth Explorers: The Research Objectives

2.1 Introduction

Continued growth of population and economic activity imply that anthropogenic perturbations of the Earth System, from local pollution effects to global environmental modifications, are unlikely to abate in the near future. To meet the challenges posed by these developments, there is an increasing need for an accurate description of the current state of the Earth System, and improved estimates of its future evolution, on time scales ranging from days and seasons through decades or centuries, and on local to global spatial scales.

Over the past two decades, the tools to observe, understand and model the Earth System have improved substantially through developments in observational technology, including remote sensing from space, through improvements in numerical simulation and high performance computing, and through new methods for assimilation of time dependent atmospheric, oceanic and chemical data in a hierarchical set of dynamically evolving models of the Earth System. This has deepened our understanding of the complex interactions between the various components of the Earth System (as illustrated by Figure 2.1 on facing page), which together govern the evolution of this system.

Despite these developments, there are still major deficiencies in our ability to describe the current state of the Earth System and its components, and to estimate its future evolutions. These deficiencies arise from a lack of observations (to properly describe the state of the system) and from gaps in our understanding of the many processes involved. Closely allied to these is the need to develop an adequate hierarchical set of models capable of assimilating the data (at the relevant scales) and simulating the state and evolution of the system and its components for impact studies. Also required is the analysis of long term series of data to quantify the natural variability of the Earth System and to detect anthropogenic effects. The development and validation of such models is an essential component of a coherent strategy to understand the main environmental challenges of our time, and to provide the tools and information required to formulate practical applications and responses to those challenges.

The objective of this chapter is to present the main problems to be addressed in the post-2000 era to meet these challenges, together with the associated requirements for space-based observations of the Earth System. It includes consideration of the data requirements of the main components of a hierarchical set of models (see Table 2.1) as well as of data assimilation. The relevant deliverables required from space-based observation are identified. Fuller details are provided in Appendix B.

ATMOSPHERE	Stratosphere	DYNAMICS - RADIATION - CHEMISTRY		
	Troposphere	DYNAMICS - RADIATION - CLOUDS - ENERGY & WATER CYCLE - CARBON CYCLE		
EARTH SURFACE		OCEAN	LAND HYDROSPHERE	LAND GEO-BIOSPHERE
		AIR-SEA INTERACTION, OCEAN CIRCULATION, OCEAN BIOLOGY, COASTAL ZONES, SEA ICE ENERGY TRANSPORT	HYDROLOGY, SOIL MOISTURE	LAND SURFACE PROCESSES, LAND BIOLOGY, ECOSYSTEMS, SNOW & LAND ICE
EARTH INTERIOR		GEOID	GEODESY	GRAVITY & MAGNETIC FIELDS

Table 2.1 The hierarchical set of Earth System models (local-regional-global scale)

To ensure that the progress, in quantitative knowledge of the various components and their interrelations, is obtained within a time frame compatible with the need for an adequate overall understanding of this system, all components of the Earth System are addressed. Furthermore, to emphasise the requirement for an integrated approach, the key questions have been identified with reference to the four Themes introduced in Chapter 1 (i.e. the Earth interior, the physical climate system, the geosphere-biosphere and the anthropogenic influences on atmospheric and marine environment) all of whose complex interactions comprise the main components of the Earth System. Table 2.2 sets them in the context of the hierarchy of Earth System models and illustrates the links between them.

Basic to this work is the provision of data. Both short and long term data sets are required; the former to study specific (short-term) processes and the latter to monitor the state of the Earth System as well as to advance our understanding of longer term phenomena. The generation of reliable, homogeneous, long term series of data sets is of fundamental importance.

A responsive Europe should make a major contribution to the provision of basic space-based observations on which the development of the requisite hierarchical set of Earth System models will depend. The science base needed to develop and validate these models is broad, and will involve many agencies and institutes in extensive and intensive collaboration across a wide range of disciplines. Since these models will synthesize all

THEMES					
COMPONENTS		THEME 1 EARTH INTERIOR	THEME 2 PHYSICAL CLIMATE	THEME 3 GEO-BIOSPHERE	THEME 4 ANTHROPOGENIC IMPACT
ATMOSPHERE	STRATOSPHERE		✓	✓	✓
	TROPOSPHERE		✓	✓	✓
EARTH SURFACE	LAND	✓	✓	✓	✓
	OCEAN	✓	✓	✓	✓
EARTH INTERIOR		✓	✓	✓	

Table 2.2 The main links between the four themes and the elements of the hierarchy of Earth System models

available observations and a- priori information about the dynamics and evolution of the Earth System, the availability of these data will enable Europe to address fundamental issues and to contribute to the development of the hierarchical set of models required to predict future evolutions of this system and to carry out impact studies.

2.2 The Hierarchy of Earth System Models

To illustrate the overall coherence of the research objectives presented in this chapter, they will be set in the global perspective of the development and validation of the hierarchy of Earth System models introduced in Chapter 1, the main elements of which are illustrated schematically in Table 2.1. These comprise the familiar components of a coupled atmospheric and oceanic general circulation model together with interacting elements for, inter-alia: stratospheric and tropospheric chemistry; surface exchanges of energy momentum and gases; ocean surface wave dynamics, ocean biology, sea ice; land surface/soil physical and biological processes, land snow and ice; hydrological processes; land/sea interaction and coastal zone processes; the Earth's interior and geophysical processes; etc..

Within the next year or two, some European institutes will be making regular global runs of many of the most important elements of the hierarchical set of Earth System models at horizontal resolutions of 30-120 km. However, even higher spatial resolutions (typically of order 10 km horizontal resolution) will be required to represent the interactions of fine scale structure (on land and in the ocean) with the other components of the system. These interactions are difficult to describe or aggregate in any other way.

Given the current state of development of numerical algorithms in Europe and the expected evolution of high performance computing, European institutes are well placed to contribute to the development of high spatial resolution versions of these models. The goal would be to develop a series of modules, representing individual elements of the overall system, which can be independently validated for subsequent integration into a global model. Such a programme has a wide range of applications in terms of objectives

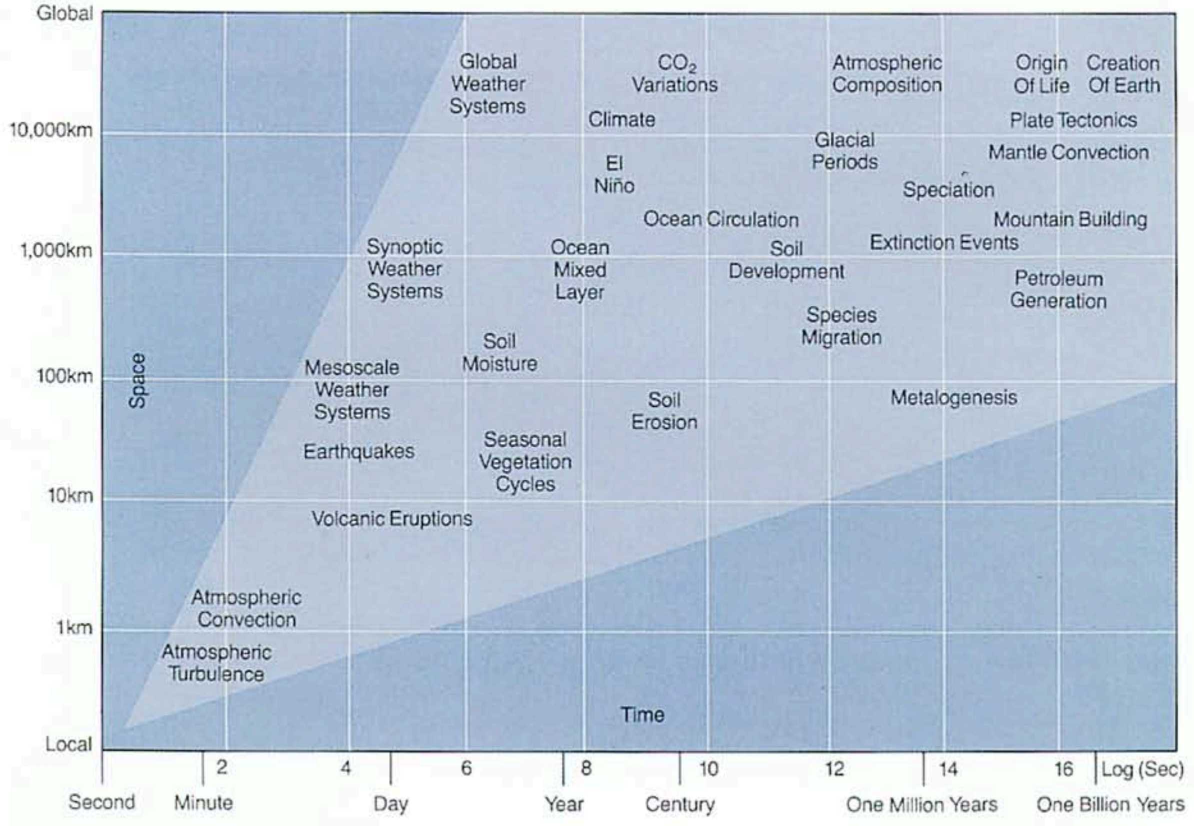


Figure 2.2 Earth System processes: characteristic space and time scales (courtesy of NASA)

and physical phenomena, with temporal scales ranging from hours/days through seasons to decadal and centennial time scales, and with spatial scales ranging from local (10 km) to planetary scales (Figure 2.2). Table 2.3 illustrates some of the applications of such a hierarchical set of Earth System models.

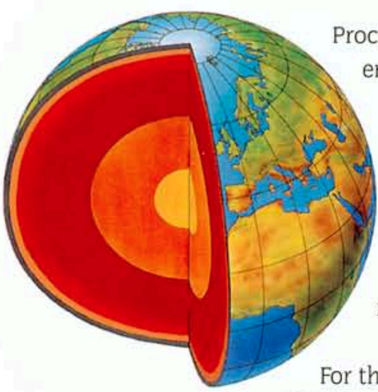
Associated with such a hierarchy of models must be data assimilation schemes capable of ingesting satellite and in-situ observations of the various components of the system into a coherent, internally consistent, quantitative description of its status. This will contribute to climate monitoring, environmental change, climate and biome variability, desertification, climate change, short and medium term weather forecasts, seasonal forecasts, short and medium term ocean forecasts, coastal zone forecasts, and hydrological forecasts. The social and commercial interest of these manifold applications is clear.

The overall framework of models and data assimilation systems will provide the integrating tools necessary to validate a hierarchy of increasingly complex models of sub-systems through detailed comparisons with observational data. As the necessary infrastructure of research networks, models, databases, and telecommunications is developing rapidly in Europe, this clear set of common goals, with defined priorities, will provide an effective focus for European resources on the central issues, helping to ensure the rapid translation of scientific advances into useful applications.

ATMOSPHERE	Stratosphere	OZONE MONITORING UV RADIATION PREDICTION		
	Troposphere	GREENHOUSE EFFECT, POLLUTION, HURRICANES, WATER SUPPLY, WEATHER PREDICTION, AIRCRAFT NAVIGATION & ROUTING		
EARTH SURFACE		OCEAN	LAND HYDROSPHERE	LAND GEO-BIOSPHERE
		SEA LEVEL RISE, SEA STATE, STORM SURGES, TSUNAMIS,SHIP ROUTING & NAVIGATION, FISHERIES,WATER QUALITY, POLLUTION, RESOURCES	WATER SUPPLY, DROUGHT, FLOODING, WATER MANAGEMENT, WATER POLLUTION	FOOD SUPPLY, LAND USE, LAND MANAGEMENT, POLLUTION, DROUGHT, FLOODING, RESOURCES, EROSION, NATURAL RISKS, BIO-DIVERSITY, DESERTIFICATION
EARTH INTERIOR		VOLCANIC ACTIVITIES, EARTHQUAKES, NATURAL RESOURCES, NAVIGATION, CARTOGRAPHY		

Table 2.3 Examples of natural hazards and potential applications (viewed in the context of the Earth System model)

2.3 Theme 1 – Earth Interior



Processes occurring inside the Earth interact strongly with our climate, the Earth's environment and our living sphere on all time scales. This includes volcanic emissions and their interactions with the atmosphere and oceans, environmental changes resulting from earthquakes, tsunamis, soil erosion or land slides, readjustment of the Earth's crust to deglaciation and its effect on sea level, etc. (Figure 2.3). All have profound ecological and economic impacts on mankind. To progress, much better insights are required into the origin, evolution and composition of core, mantle and crust and their roles in Earth interior dynamics.

For this reason, the Earth's gravity and magnetic fields determined uniformly and globally with significant spatial resolution are of fundamental importance. Only by the use of satellites can these general requirements be met.

(a) Marine Geoid and its Impact on Ocean Circulation – Long term variations and the absolute value of the ocean dynamic topography require the determination of the 'hypothetic' ocean at rest, i.e. the marine geoid. This is the basic requirement for modelling ocean circulation and interpreting satellite data. Unfortunately, current insight into geoid uncertainties and their impact on the absolute dynamic topography is limited, particularly at shorter wavelengths less than 1000 km.

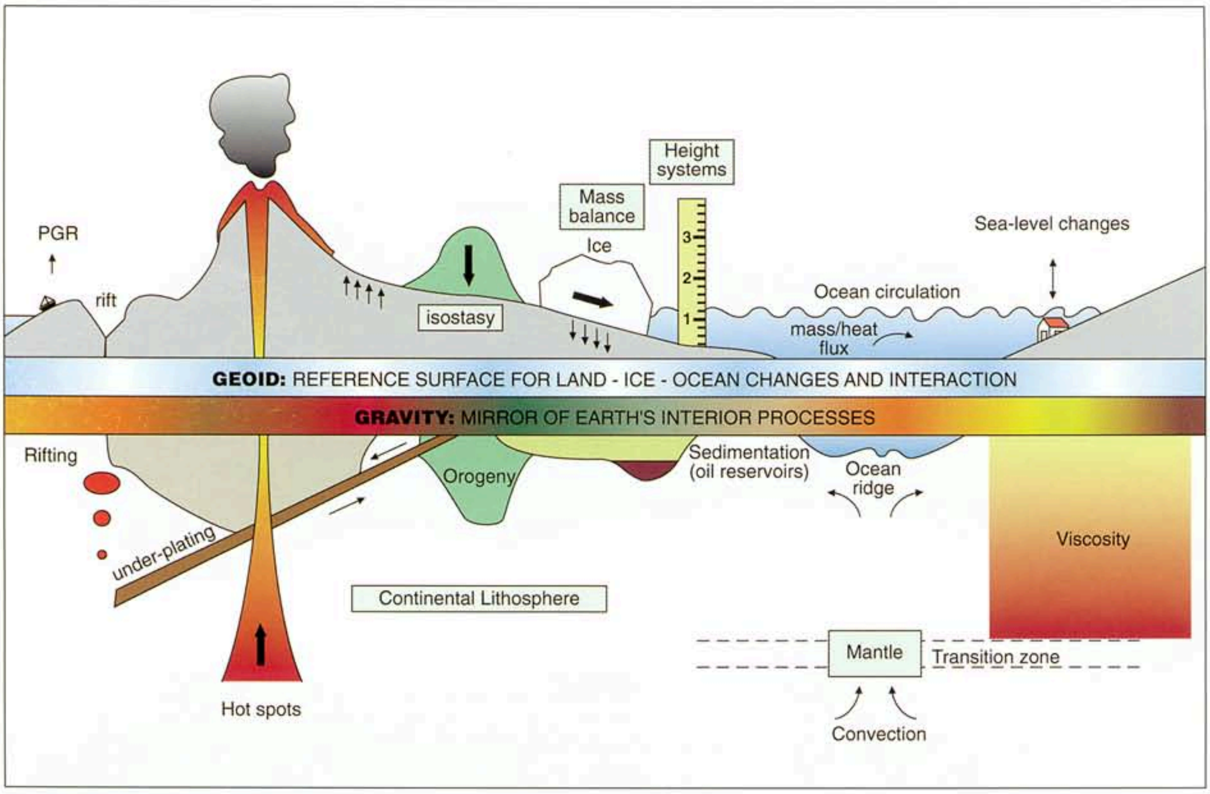


Figure 2.3 Schematic of the Earth as a dynamic system .

Given the continuing need to study and predict climate variation and climate change by the combined use of altimetry, global ocean circulation models, and high-quality global in-situ data, it is thus essential to significantly reduce errors in our knowledge of the Earth's geoid. In particular, at a half wavelength of 100 to 200 km the cumulative geoid errors should be less than 2 cm, leading to errors of less than 0.1 cm at a half wavelength of, for example, 1000-km. This could be achieved once and for all through a single dedicated gravity field mission.

(b) Gravity Field and Earth Interior Processes – Specific issues to be addressed by an accurate and detailed determination of the gravity field includes discrimination between active and passive models of rifting; identification of anomalous mass which may drive basin subsidence; and determination of the deep density structure beneath the continents and of the mechanical strength of the continental lithosphere.

Understanding of mantle processes, in particular convection patterns, and of post-glacial mass readjustment, will greatly benefit from improved and more detailed knowledge of the Earth's gravity field. Moreover, the accurate and detailed determination of the anomalous gravity field plays a key role in advancing understanding of the dynamics of the continental lithosphere. It is also necessary to identify the contribution of post-glacial rebound to sea level change, and the impact of Earth interior processes on the global ocean.

Further progress in the understanding of these processes and improvement in geopotential models requires global determination of the gravity field, without biases and with uniform accuracy to 1-2 mgal (1 mgal = 10^{-5} m s^{-2}) in gravity anomalies with a spatial resolution down to half wavelengths of between 50 and 400 km.

(c) Magnetic Field and Earth Interior Processes – The main magnetic field and its temporal variation is the key source of data for studying core processes, in particular the kinematics of the flow of the bulk of the core and the exact nature of the coupling mechanism between the core and the mantle.

Better global description of the vector magnetic field and the subsequent separation between core motion, secular variation, jerks and low frequency variations in the observed length-of-day, requires that the components of the global magnetic field have to be quantified to an accuracy of better than 1.5 nT.

(d) Geodesy – At present, the different orthometric height systems (datum connection) differ by the order of decimetres between islands and between islands and continents, over distances of a few 100 km. Sea level changes in one part of our planet can therefore not be properly compared with sea level changes in other parts; nor can changes be precisely separated into sea level rise and continental rise respectively.

One of the key objectives in geodesy is therefore to improve and unify the different orthometric height systems to about 0.05 m using high quality gravity field data.

(e) Deliverables for Earth Interior – The main focus of an integrated global observing system, intended to address the objectives detailed above, must be the provision of:

- a gravity anomaly field with a 1-2 mgal precision at 100 to 200 km resolution
- a geoid with a cumulative error of the order of 1-2 cm at a half wavelength of about 100-200 km
- a unified orthometric height system to about 0.05 m
- the global temporal and stationary magnetic field to better than 1.5 nT.

The precise geoid surface serves as a stationary reference for the study of all topographic processes, including dynamic ocean topography (and therefore ocean circulation), the evolution of the ice sheets and land surface topography.

2.4 Theme 2 – Physical Climate

The various components of the climate system (Figure 2.4) show significant internal variability. These involve fluctuations on a wide range of time scales, from the fast (atmospheric) components (hours to weeks), through the medium term components (seasonal to inter-annual variations) to the long term components (decadal to centennial variations and longer). The variability of the climate is also linked to the changing chemical composition of the atmosphere (Themes 3 and 4). Since the components of the climate system interact with each other in different ways, depending on the time scale, it is convenient to consider the scientific issues in terms of the different time scales.

(a) Fast component – The fast components of climate are primarily atmosphere-related (i.e.weather-related). Understanding the fast components of the climate system requires a thorough knowledge of atmospheric dynamics and of the global energy and water cycle, i.e.requires efforts to ensure a proper representation of the important processes and aspects of the hydrological cycle in atmospheric models. In addition, there

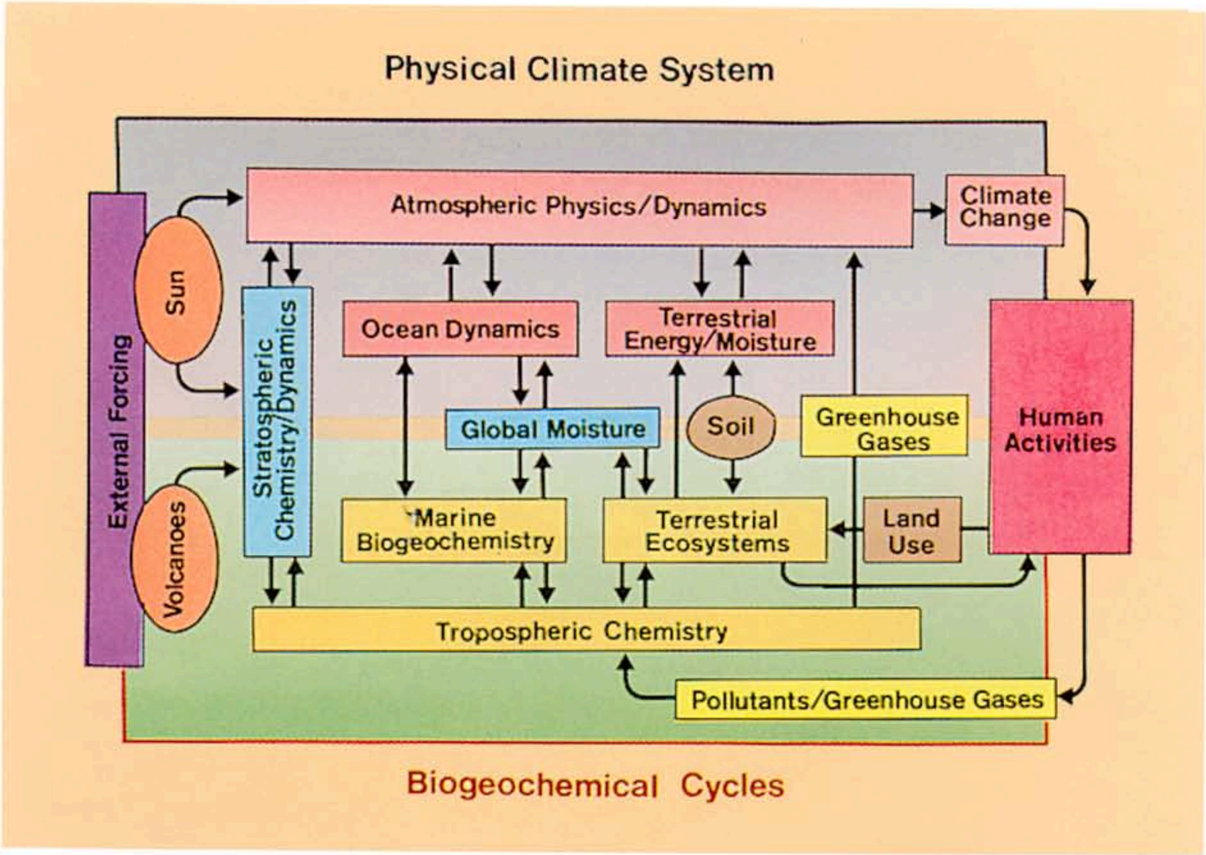


Figure 2.4 Global modelling studies within the IGBP will connect models of the biogeochemical system, the physical climate system, and human impacts, to develop our predictive understanding of the behaviour of the Earth system as a whole

are operational and research requirements for observations of three-dimensional wind, temperature and humidity fields.

(b) Medium term component – Prediction of seasonal to inter-annual climate fluctuations requires the proper description of the atmosphere (the fast component), its interaction with the upper ocean, primarily in the tropics (dynamics and thermodynamics), and its interaction with the cryosphere and the continental biosphere (i.e. sea-ice, snow cover and vegetation – the slower components of the system). In addition to requirements for observation of the atmosphere, these developments will require high-quality long-term ocean observations, including precise sea surface temperature, surface wind measurements, surface dynamic topography, sea-ice and salinity.

Continental-scale variations in soil-moisture and snow-cover are believed to provide system memory which can also be exploited for seasonal forecasting. These climate processes probably have impacts and, potentially, feedbacks at the surface, including temperature and precipitation patterns, vegetation cycles, and, in turn, on snow cover. They are critical to the climate and the economy of temperate and high latitude regions. Measurements of sea-ice extent, age, thickness and advection will all be necessary because they affect ocean-atmosphere heat fluxes, ocean salinity, fresh water transport and ocean-atmosphere dynamics. Environmental changes (c.f. Section 2.6), through changes in atmospheric composition and chemistry, can lead to variations in the optical properties of the atmosphere. In particular, variations in the water content in the atmosphere can affect both the continuum emission in the gas phase, and the contribution of clouds to the overall terrestrial albedo.

(c) Long term component – Long term changes mainly reflect changes in the radiation budget of the Earth System and many processes (including those reflecting human activities and changes in CO_2 levels) contribute to fluctuations in this budget on decadal or longer time scales. Many of the corresponding signals, associated with climate fluctuations, are small and the best possible precision and sampling will be required to observe them unambiguously.

Understanding of convective ocean mixing and of deep and bottom water formation are of particular concern for estimating long-term climatic trends in ocean carbon uptake and its implications for the long-term control of atmospheric carbon dioxide. Accurate representation of the ocean component in global climate models, including information on ocean dynamics and on the carbon and heat cycles is needed.

The terrestrial environment is coupled with the atmosphere through exchange processes involving energy, momentum, moisture, and gases. Changing land-use practices have significant impacts on the hydrological cycle contributing to long term climatic change. However, biophysical and chemical processes involving land surfaces are not adequately represented in climate models, even though they are one of the determining factors for long term climate trends. The same can be said of these types of process in the oceans.

Present climate models predict the largest temperature increases at high latitudes. If correct, this could result in major changes in the mass balance of ice sheets and glaciers over the next few decades. Sea ice and snow cover have much shorter time scales than the ice sheets, but are nevertheless important for climate conditions not only in the short term, but also on decadal and longer time scales. Major changes in the sea ice extent are very likely to have pronounced effects on deep water formation as well as on oceanic uptake of carbon dioxide, two processes that are of significant climate impact.

(d) Deliverables for climate – In summary, it is essential to advance our knowledge of the various processes involved in the climate system. This means:

- *for the fast components of climate* – observation of the three-dimensional wind field; observation of the three-dimensional distribution of clouds and aerosols and their interaction with radiative and dynamic fields

- *for the medium term components of climate* – retrieval of fluxes at the ocean-atmosphere, atmosphere-land/biosphere and ocean-atmosphere-cryosphere interfaces and the assessment of their energy impact

- *for the long-term components of climate* – observation of temporal variability of ocean circulation and the transport of energy and dissolved species; ocean-atmosphere exchange processes for energy and gases; observation of the energy and water cycle of ecosystems and their response to climate; broadband measurements of radiation fluxes at the top of the atmosphere; bio-geochemical processes and their spatial and temporal variability; observation of the current mass balance of the polar ice sheets and its response to climate change; analysis of sea ice dynamics and deep water formation.

2.5 Theme 3 – Geosphere/Biosphere

Within the geosphere/biosphere, major environmental processes and transformations occur which play an important role in the evolution of the climate system and in global environmental changes. This is affected by both natural phenomena and human actions and is of particular relevance to mankind. In particular, impacts such as changes in land cover and use, changes in hydrological conditions, changes in atmospheric composition and changes in sea level need to be understood in order to answer key questions on how climate change affects terrestrial ecosystems and how biological processes and their components through changes in these ecosystems affect renewable and non-renewable resources of the geosphere/biosphere (Figure 2.5).

The international scientific community has devoted considerable effort over the past decade to addressing these questions. However, even if the processes occurring at the interfaces of the biosphere/geosphere system with the atmosphere and the ocean are partially understood and parameterised on the very local scale, extension of that knowledge to regional and global scales has not yet been achieved. The main variables

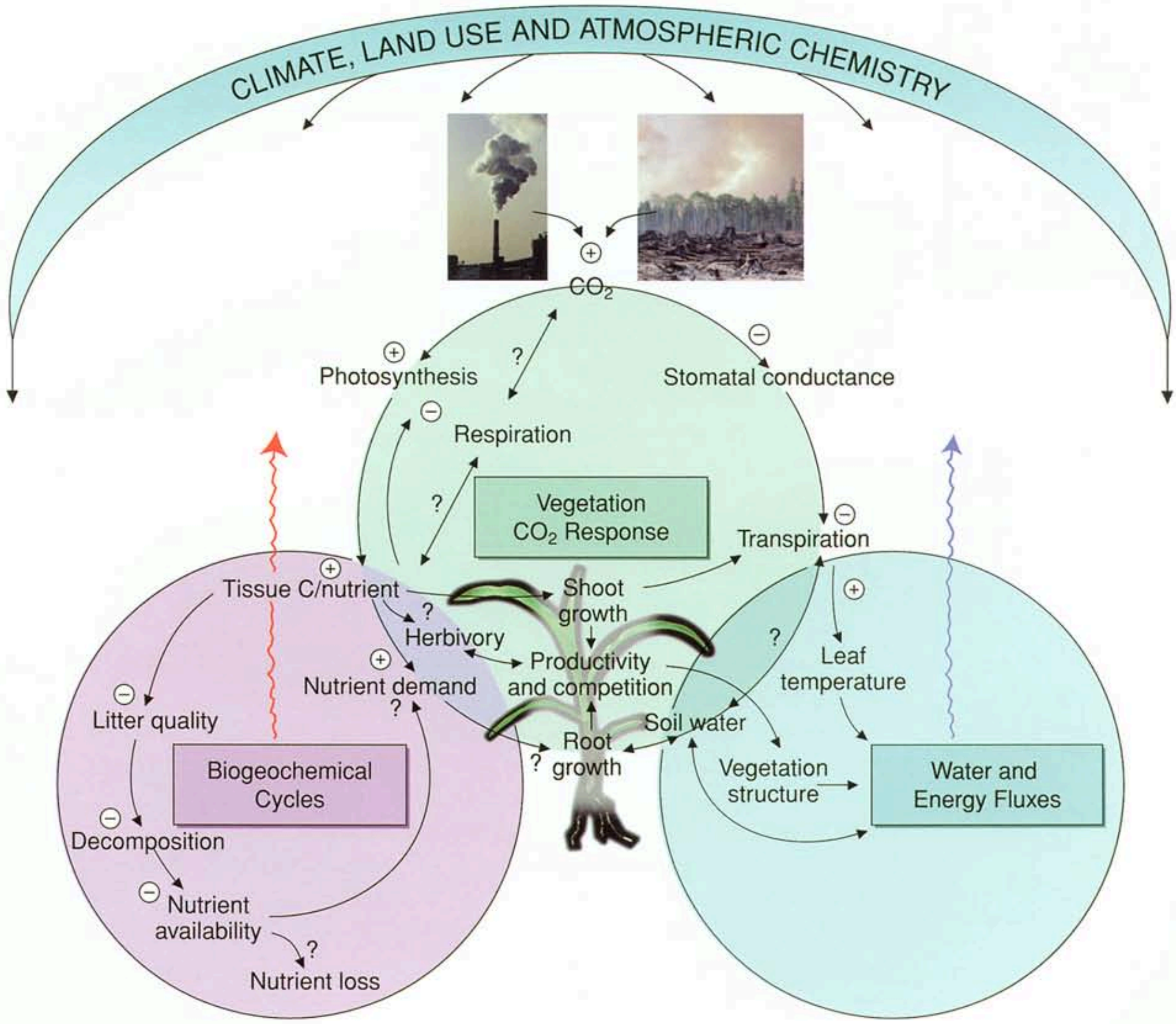


Figure 2.5 Schematic of plant-level surface processes

needed to parameterise the relevant processes are not well known. In turn, the processes that link biospheric phenomena, surface atmosphere interactions, ecosystem processes, etc., are not yet adequately parameterised on all the relevant scales.

Many land surface features and processes of global significance occur at the local scale and must be extrapolated to regional and global scales taking account of significant variations in surface properties. As a consequence, models are not yet reliable enough to determine the impact of human activities on the quality of the environment, the state of the resources, and climate trends. The most important processes to investigate and understand more quantitatively are identified as:

(a) The energy and water cycles – For the energy cycle it will be necessary to measure the incoming and outgoing radiation fluxes which are still not yet known with sufficient accuracy, particularly under cloudy conditions. In addition, the heat fluxes, namely latent and sensible heat, are still very difficult to measure and parameterise with sufficient accuracy. Finally, it is necessary to analyse the soil heat flux, which has a smoothing effect on the annual energy cycle.

In the case of the water cycle, it is clear that knowledge of the spatial and temporal distribution of precipitation, snow cover and water run-off in rivers must be improved, as must that of evapotranspiration, which is directly related to the latent heat flux, and soil moisture. An accurate measurement of soil moisture would substantially improve the predictions of general circulation models, which are very sensitive to this quantity.

(b) The bio-geochemical cycles – The increasing atmospheric concentrations of the greenhouse gases carbon dioxide and methane are of particular concern for climate change and it is important to remember that terrestrial ecosystems are important sources and sinks for these gases.

The main open questions concerning the global carbon cycle relate to lack of knowledge of the exchange processes that link the atmosphere and the terrestrial ecosystems. Thus, to quantify carbon exchange processes, information is required on the spatial distribution of climatological and hydrological parameters, and on the biophysical and biochemical characteristics of vegetation and soil, as well as on its seasonal variability. In addition to the principal greenhouse gases, the photochemically active gases, in particular nitrogen compounds, hydrocarbons, and ozone, play important roles in ecosystem processes.

Strong couplings exist between the energy and water cycles, the carbon cycle and atmospheric chemistry. They come from the radiation process, strongly influenced by the concentrations of greenhouse gases and water vapour, and from the functioning of vegetation. In this respect, the up-scaling of this coupling is of great importance, for the energy, water and carbon dioxide cycles, and for the dynamics of the ecosystems.

(c) The productivity of the different ecosystems – As far as biospheric productivity is concerned, the most important issue is to characterise variables such as the leaf area index, fractional vegetation cover, leaf absorption in the solar spectrum, etc. This information is needed for use in biome or productivity models, which will also require additional information such as the efficiency of the conversion of radiation into organic carbon, etc. This type of information could be derived from an identification of the biome type and the classification of targets at the surface, permitting the documentation of:

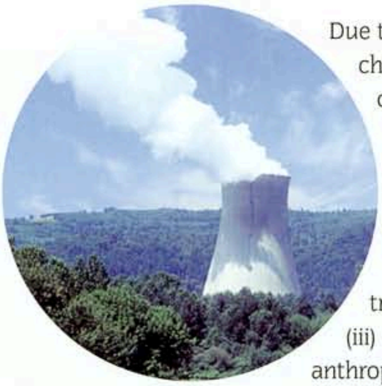
- the state and evolution of the properties of vegetation for a variety of biomes
- the contribution of the biosphere to the carbon cycle
- how perturbations and disturbances in the biosphere affect the global environment
- the productivity of agricultural regions and forests.

(d) Deliverables for geosphere/biosphere – The basic land features and characteristics which must represent the focus of attention in a space observation strategy for the next decade are related to:

- surface characteristics, including geo-biosphysical properties, and changes in these properties such as environmental degradation and pollution
- surface processes such as primary productivity, biochemical and water cycles, energy transfers and interactions with the soil.

Knowledge of the surface/atmospheric exchange processes, together with the exchange processes for energy and water, are determining factors for furthering our understanding and the modelling of ecosystems. In turn, these are linked to improvements in the performances of numerical models and, ultimately, in climate predictions. Spatially distributed information on the physical properties and temporal changes of the terrestrial and marine ecosystems, as provided by satellites, are essential inputs for work in this area.

2.6 Theme 4 – Atmosphere and Marine Environment: Anthropogenic Impact



Due to mankind's activities, the chemical composition of the Earth's environment is changing rapidly, giving rise to many problems (Figure 2.6). These affect all components of the Earth System, i.e. the atmosphere, the ocean, the coastal zones and the soils. The scientific challenges, some of which are complementary to those addressed in Theme 3, are:
(i) to quantify the fluxes of gases and particles between the various components (terrestrial and marine biosphere, atmosphere, oceans, soils),
(ii) to understand the chemical and photochemical transformations and the transport processes, and
(iii) to assess the consequences of the environmental changes produced by anthropogenic variations in these exchanges. Knowledge of the Earth's geoid (Theme 1) is of fundamental importance.

The main environmental changes that are relevant to this scientific strategy can then be subdivided according to the specific components of the Earth's environment and to the temporal and spatial scales involved. Indeed, the variation in the chemical composition of the environment depends on the time scales of sources, sinks and dynamical processes. Shorter time scales are dominant in the boundary layer and the lower troposphere, which are therefore characterised by relatively fast changes (from hours to weeks). Longer time scales are involved in the oceans, upper troposphere and stratosphere, which are characterised by relatively slower changes (from months to decades).

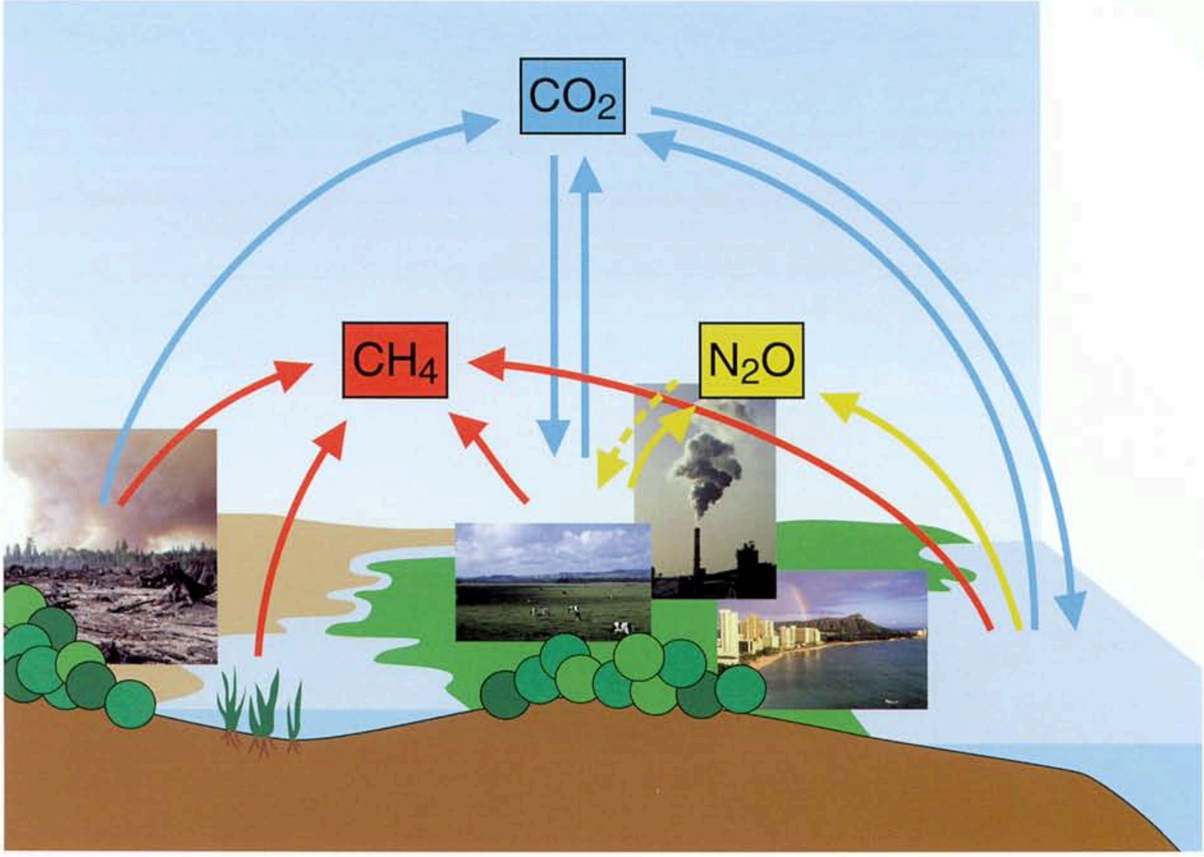


Figure 2.6 Many natural processes and human activities affect the levels of greenhouse gases in the atmosphere. A better understanding of the sources and sinks of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) is urgently needed to improve the reliability of global climate models

(a) Changes in atmospheric composition induced by human activity – The composition of the Earth's atmosphere is changing as the concentrations of a number of radiatively and chemically active trace gases emitted at the surface rapidly increase. These include emissions of methane, nitrogen oxides, hydrocarbons, sulphur compounds and halogen species, which affect the overall distribution of ozone and the hydroxyl radicals in the troposphere, and thus the oxidizing capacity and 'self-cleaning' power of the atmosphere.

Also, the importance of aerosols and clouds, in modifying the chemistry and the climate of both the troposphere and the stratosphere, is only now beginning to be appreciated. There is thus a need to understand and quantify these changes, which affect the tropospheric greenhouse gases and the oxidizing properties of the troposphere, the stratospheric ozone layer, and have quite important consequences for climate change and pollution of the Earth's environment.

(b) Chemical processes in the stratosphere and upper troposphere – The processes occurring in the stratosphere and the upper troposphere determine the chemical composition and their optical and physical properties and thus affect, directly and indirectly, the Earth's climate and the transmission of the ultraviolet radiation. Existing measurements have improved our understanding of the system, leading to the development of comprehensive three dimensional models that can explain most of the observed events. However, the remaining uncertainties, the complexity of the heterogeneous chemistry that occurs on aerosols and in polar stratospheric clouds, and the possible deviations from a steady state, do not allow current models to provide a sufficiently reliable description of the present state of the atmosphere.

This lack of understanding of the lower stratosphere and upper troposphere means that it is not possible to confidently predict the future evolution of atmospheric composition in this region, including the fate of the ozone layer. Indeed, peak stratospheric concentrations of man-made chlorine are anticipated by the turn of the century. Assuming that the provisions of the Montreal Protocol (see Appendix A) are abided by, chlorine levels should fall over the coming decades and should have returned by the middle of the next century to the levels that existed at the time when the Antarctic ozone hole was first observed.

(c) Marine pollution – The presence of man and associated activities, namely the exploration and exploitation of the resources in the marine environment, implies also a risk for pollution of the oceans and the ice-covered seas. In particular, the coastal zones where more than 70% of man's activity takes place are exposed to this risk. Some types of marine pollution have direct short term environmental effects, while others may accumulate in the environment and organisms, posing a long term threat to the use of oceans as a resource. Much remains to be clarified about the impacts of the various types of pollution.

The detection and knowledge of the occurrence and spread of the marine pollution are of increasing interest on scales from the local to the global level. Local, national and international regulations and agreements regulate the limits of acceptable and critical levels of the various pollutants associated with mankind's activities in the marine environment. The key requirement is then to properly monitor marine pollution and its impact, namely water quality in coastal zones, open oceans and ice-covered seas by quantifying sources of pollution and the transport of pollutants.

(d) Deliverables for environmental change – From this discussion clear thrusts appear, namely :

- *for the composition of the atmosphere* – the quantification of the changes in the oxidizing properties of the atmosphere and the relative influence of human activity; the quantification of changes in radiative forcing by greenhouse gases and aerosols
- *for the upper troposphere and lower stratosphere* – the quantification of chemical and photochemical processes; the role of heterogeneous chemistry; the influence of dynamical motions at various spatial scales
- *for marine pollution* – sources of pollution; the transport of pollutants (ocean and coastal currents); coupled physical-biological-chemical processes in the marine environment.

At the same time, complementing these data, the monitoring of key species and key variables (such as sea level) to characterise long term evolutions in the environment, is essential for all aspects of this work. This need for monitoring serves to highlight the links to the Earth Watch programme.

2.7 Towards an Integrated Earth System Model

Although important advances have been made in our quantitative understanding of the Earth System over the past decades, we are still a long way from being able to precisely describe its present state, not to mention our capability to describe its further evolution.

The Earth Observation community is thus facing an enormously important challenge. Its primary objective must be to provide data required to understand basic processes, quantify global budgets and variability, detect evolutions and, thus, ultimately to validate an hierarchy of integrated high resolution models and data assimilation schemes, able to represent the state of the Earth System and to predict its evolution. Only then can a clear understanding of sustainability and consequent political implications be achieved (Figure 2.7).

Expected advances in the necessary tools, including the provision of space-based observations, will allow the wide range of questions presented in this chapter to be addressed in new and innovative ways. They will thus provide the context in which the scientific questions can be sharply formulated and the answers suggested by new observations most thoroughly evaluated.

In this perspective, satellites offer unique capabilities as they provide global, quasi-synoptic and repetitive data sets of homogeneous quality. The number of geophysical variables that can be measured from space is large, and addresses all components of the Earth System. All these characteristics of remote sensing from space are essential as the system itself is continuously changing over a range of space and time scales. Space observations have a key role to play in research on the Earth System as they often provide the only means to acquire the relevant data.

Some of the data requirements should be met by operational space systems, others must look to research space missions, the one complementing the other. This was recognised by European Ministers when they endorsed the dual scenario which consists of two general types of mission, i.e. the Earth Explorer and Earth Watch missions. The Earth Explorer element of the Living Planet Programme, which focusses on process studies and the demonstration of observing techniques, is foreseen as a significant European contribution to fill the gap in current data provisions and in paving the way for advances in operational observing systems.

In addition, a complete and coherent strategy to address the complexity of the scientific issues must exploit the complementarity between in-situ and space-based observations. A framework for this integrated approach is presently offered by the international

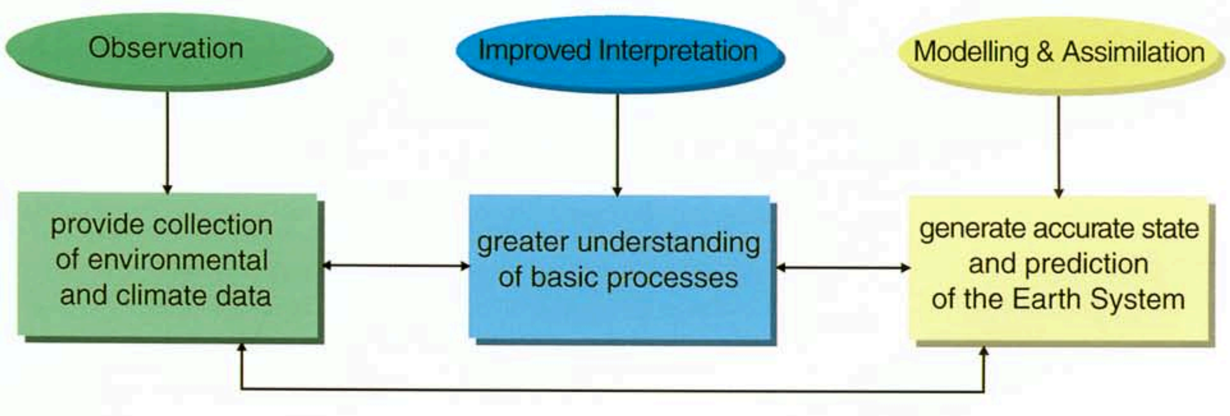


Figure 2.7 Key modules in an integrated Earth System model

scientific programmes such as the World Climate Research Programme (WCRP), and the International Geosphere-Biosphere Programme (IGBP). The scientific priorities established by such programmes foster a maximum scientific return from actions being conducted in the various disciplines. Essential to progress is the provision of facilities capable of assimilating and processing these data to ensure the availability of high quality data sets on a long term basis.

In view of the time lag for implementing new space missions, this is the appropriate moment to formulate an extended plan for the Earth Explorer element of the Living Planet Programme which will provide results in the post-2000 era. This element will contribute, in a complementary way, to all aspects of the Earth System problem and will ensure that advances in our quantitative knowledge are obtained in a time frame compatible with the development of an integrated Earth System model and data assimilation scheme. It is essential to address all components of the system, given the numerous interactions that occur between them. Therefore, the Earth Explorer Programme will cover a succession of space missions encompassing all components of the global Earth System.

3. Earth Explorers: Addressing the Objectives

3.1 Introduction

The worldwide cooperative nature of Earth Sciences has led to a variety of large scale internationally coordinated programmes to tackle interdisciplinary scientific problems on a global scale. Some are coordinated through the United Nations and have a high governmental level involvement; other programmes work through ICSU (the International Council of Scientific Unions) and the WMO (the World Meteorological Organisation). Of the various international initiatives, three in particular must be highlighted, namely the Intergovernmental Panel on Climate Change, the World Climate Research Programme and the International Geosphere-Biosphere Programme. Quite apart from their importance, they encompass or have close links to most of the other international initiatives.

The links between the scientific objectives of the Earth Explorer component of the Living Planet Programme and these international programmes are strong, as illustrated in Table 3.1 which presents an overview of the main international programmes set in the context of the Earth System concept. Comparing this table to Table 2.2 shows that the

Table 3.1 International programmes viewed in the context of the hierarchy of Earth System models

ATMOSPHERE	Stratosphere	WMO/WCRP (GCOS, SPARC) IGBP (IAGC, GAIM)		
ATMOSPHERE	Troposphere	WMO/WCRP (GCOS, GEWEX, CLIVAR, SPARC) IGBP (BAHC, IGAC, GAIM)		
EARTH SURFACE		OCEAN	LAND HYDROSPHERE	LAND GEO-BIOSPHERE
EARTH SURFACE		WCRP (GEWEX, CLIVAR, ACSYS, WOCE, GCOS, GOOS), IGBP (LOICZ, JGOFS, GAIM), IOC (GLOSS, GLOBEC), UNEP (GEMS)	WCRP (GEWEX, CLIVAR, GCOS, CTOS, ACSYS), IGBP (BAHC, GAIM, LOICZ...)	WCRP (GEWEX, CLIVAR,GCOS, GTOS), IGBP (BAHC, LOICZ, LUCC, GCTE, GAIM) UNEP (GEMS)
EARTH INTERIOR		IUGG/IAG (BGI, IGS), ILP		

four Earth Explorer Themes encompass these interests quite well. This is of particular importance as these links between the Earth Explorer component of the overall programme and the international initiatives are essential to ensure that the former addresses the key issues related to the major socio-economic problems facing mankind.

Within this general frame, the Earth Explorer component of the overall programme has to be implemented through carefully designed satellite missions, which will address the scientific objectives identified in Chapter 2. Ideally, all scientific themes related to the Earth System should be studied simultaneously, using space observation complemented by other sources of data to ensure availability of the data sets required for the implementation and validation of Earth System models.

Europe has the ability to design and implement, in a coordinated way, scientific space missions addressing each of the four Earth Explorer Themes. This is reflected in the results of the wide consultation of the scientific community which has led to the ESA meeting in Granada in 1996. During this meeting the interest of European scientists in the Earth Explorer component of the Living Planet Programme was highlighted by the numerous mission concepts put forward on a scientific basis, from which a set of nine missions was identified spanning the objectives of all four of the Themes identified in Chapter 2.

In this chapter these Earth Explorer missions are described to illustrate some potential European contributions. In each case, the proposed mission would provide unique missing information, supplementing and not duplicating data from other sources, whether space-borne or ground-based. Together, these examples demonstrate the feasibility of addressing the objectives listed in Chapter 2.

However, it is obvious that not all of these missions will be selected within the frame of the Earth Explorer element of the Living Planet Programme. Although they constitute a sound basis for addressing the objectives of the programme, due account must be taken of European interests and expertise, of the international situation, as well as of evolving research priorities and last, but not least, financial constraints. Therefore, a mechanism has to be implemented to select specific missions, based on scientific priorities and taking into account these important external constraints as well as potential utility for technology development and evolutions in operational systems.

A key point to note is the continuity of the Earth Explorer element of the Living Planet Programme. This continuity is required because of the complexity of the Earth System itself. Significant progress in furthering our understanding of the Earth's climate and environment, and thus in our ability to predict the future evolution of the system, can only be made through a coherent approach in addressing the objectives of the four Themes. For example, the determination of an accurate gravity field at short spatial scales is a prerequisite to the accurate determination of oceanic circulation, and in turn to the determination of the oceanic component of the carbon cycle and the role of the ocean in the transfer of energy between various areas of the globe. Without knowing precisely the wind pattern in the atmosphere, especially in the tropics, no progress can be made in furthering our understanding of the hydrologic cycle which drives the variability of the climate.

The quantification of precipitation is needed to close the water budget, but this closure relies on the accurate determination of cloud patterns and of their interaction with radiation. The complex nature of the interactions between the stratosphere and the troposphere requires a clear understanding of the chemical, dynamical and radiative processes occurring at their interface, but the quantitative role of the minor atmospheric constituents involved in these processes can only be assessed if one is able to quantify their atmospheric budgets. This in turn requires an understanding of the exchange processes between the atmosphere and the biosphere, and the continental and oceanic surfaces. If one states, as a major objective for Earth sciences over the coming decade, the implementation of high resolution models of the Earth System (as defined in Chapter 1), all the components of the scientific programme should be addressed within that time frame.

This leads to the basic concept of a series of Earth Explorer *Core Missions* with highly focussed objectives that can be implemented so they complement each other. Furthermore, considering that, within the proposed time frame, all aspects of the problem cannot be addressed by Europe alone, synergism with national and international programmes will have to be fully exploited. Here again, the continuity of the programme is an important issue. Only, by defining a long term programme can Europe be in a position to play a key role in the coordination of international activities and in the implementation of fruitful collaboration. Furthermore, within the frame of a well defined and science based Earth Explorer activity, individual European member states will be able to propose appropriate complementary missions which will further reinforce the role of the European scientific community on the international scene.

The requirement for continuity is associated automatically with the need for a long term view of the programme. However, this must be complemented by an appropriate flexibility to take advantage of shorter term opportunities. The possibility, already put forward in Chapter 1, to implement *Opportunity Missions* as well as *Core Missions*, provides the means to define a balanced flexible Earth Explorer element of the overall programme set in an international collaborative frame.

3.2 The European Involvement and Expertise

All of the international initiatives on climate and environment address topics of great political, social and scientific relevance to Europe, many of which are highlighted in Chapter 1, *Earth Explorers: Introduction.* Typical examples include work concerned with improving our ability to predict climate change, stratospheric ozone depletion, acidification of the lower atmosphere and their impact on Europe's climate; or work concerned with improving our ability to predict shorter scale events such as the influence of El Niño and the North Atlantic Oscillation on Europe's weather, the causes of the reductions in rainfall in Southern England and of the 1997 floods in south and central Europe.

The political recognition of the need to observe and monitor the environment is highlighted further in Appendix A, *Environmental Obligations*, which lists the various international conventions to which Europe has wholly or partially subscribed. These are wide ranging, encompassing the atmosphere, forestry, marine pollution, water resources, conservation and desertification. The latter is particularly noteworthy as it indicates the commitment of Europe to a global problem of as yet indirect concern to Europeans. However, to have a commitment is one thing; to be able to meet it is another and here one must consider the European heritage and the current levels of expertise.

As far as the study of the Earth is concerned and the formulation of theories to explain the observations, Europe has a long heritage on which to draw, starting well before the advent of satellites. Many of the pioneers who helped establish the general characteristics of the Earth's system were European, such as the Norwegian and British schools who between them established much of the basis for numerical weather forecasting. Then there is the pioneering work of the German school on continental drift. Many other examples could be quoted of Europeans who have helped lay the foundations of much of our current understanding of the Earth System.

Europe also pioneered the use of remote sensing to study the Earth, and here specific reference could be made to the Dobson spectrophotometer for observing ozone amounts from the surface. This was consolidated by the establishment of an European network of such instruments. Europe has also played a leading role in exploiting radars to study the atmosphere, notably cloud structure and dynamics, the biospheric processes, the ocean circulation and the sea ice processes and extent. In addition, there are a whole series of other instances where European groups have applied remote sensing techniques to the study of the Earth and its atmosphere, including major contributions to the use of satellites in atmospheric chemistry and for atmospheric sounding. The formulation of theories and the development of observational techniques has also been supported by an increasing ability to analyse the data and develop numerical models and assimilation techniques, as highlighted by the worldwide success of the European Centre for Medium Range Weather Forecasts (ECMWF) (Figure 3.1).

Europe has continued to be active in these areas and some more recent examples were listed in Chapter 1, where the heritage and contributions from satellites such as ERS, SPOT, Meteosat, TOPEX/POSEIDON etc. are highlighted. This capability continues into the immediate future with Envisat and various other European initiatives.

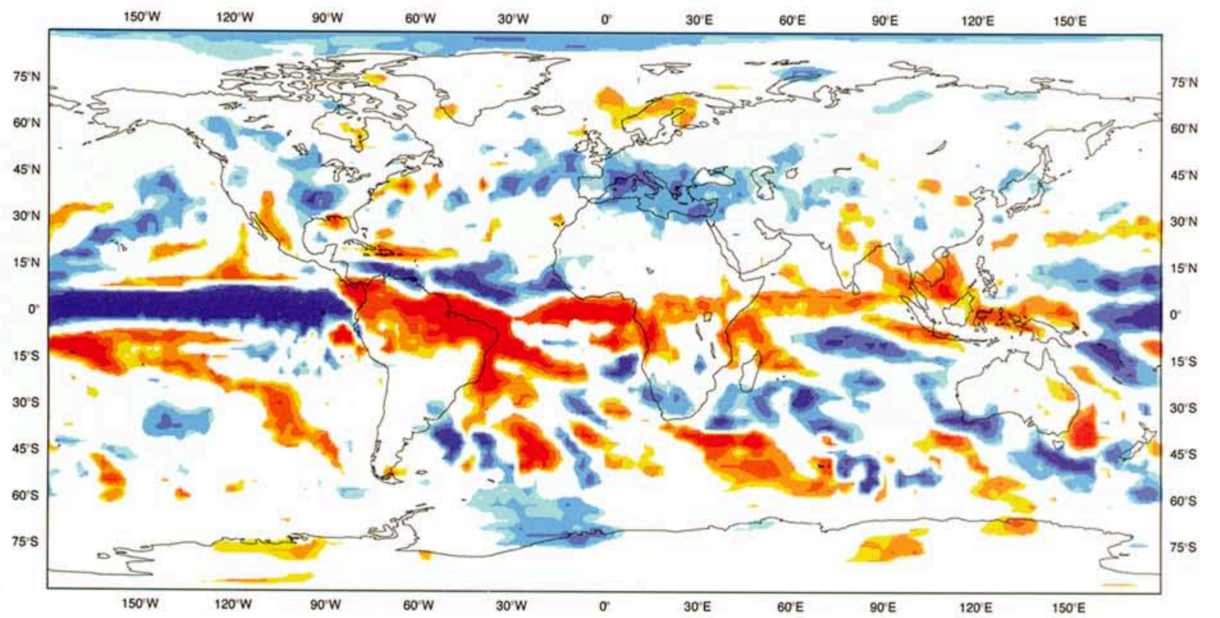


Figure 3.1 Rainfall anomalies for June, July and August 1997 from forecasts initiated in March and April 1997. Only statistically significant (greater than 99%) anomalies are shown. Particularly unusual is the anomaly over south/central Europe. Yellow to red indicates that the ensemble mean rainfall is below normal, blue that it is above. Yellow and light blue indicate that the amplitude of the three-month total rainfall anomaly is in the range 0-50 mm. The other colours in the scale represent anomaly amplitudes of 50-100 mm, 100-200 mm, and greater than 200 mm, respectively.

European scientists are also involved in the development of novel techniques such as those exploiting lidars and microwaves. It is clear that technically Europe has the capability to meet the challenges posed by the Earth Explorer programme.

As far as data analyses are concerned, European scientists are active in areas encompassing the full spread of Earth Observation science. There is no significant area, of the many identified in Chapter 2, where European researchers are not active to some extent or other in helping to establish techniques for deriving the requisite geophysical variables from satellite instruments. Europe plays a major role in atmospheric chemistry, in the use of satellites for meteorology, in the use of both radar and optical techniques to observe the surface of the Earth, etc. The major data assimilation centre in the world is European.

On the theoretical side also, Europe is very strong and well placed to take full advantage of the opportunities afforded by the Earth Explorer component of the Living Planet Programme. Work continues in all the areas identified in Chapter 2 and spans all five 'classical' Earth Observation disciplines i.e. atmosphere, ocean, land, cryosphere and solid Earth. The first ever Nobel prize for Environmental Studies was shared between a European and US scientists. European scientists continue to play a major part in advancing the development of Earth System models.

Together European expertise spans the full range of topics addressed under the four Themes and Europe clearly has the requisite technical and theoretical expertise to exploit the data from the Earth Explorer missions, often collaborating within the context of one of the initiatives described in the previous section. One of the aims of the Earth Explorer element of the Living Planet Programme must be to sustain and exploit these levels of excellence.

3.3 Potential Earth Explorer Missions

3.3.1 Introduction

From an extensive consultation of the European scientific community, a set of nine candidate Earth Explorer space missions has been identified (ESA SP-1196(1)-(9)), which together represent a reasonable attempt to address the scientific objectives put forward in Chapter 2. These build on the European expertise in Earth sciences and on the heritage of previous European Earth Observation Programmes, i.e. ERS, SPOT, TOPEX-POSEIDON, etc.

In the following sections, the scientific objectives underlying each of these nine missions are outlined to illustrate how the needs of the programme might be addressed. However, although such missions constitute a sound basis for an extensive study of the Earth System, they will have to be prioritised and implemented in a coherent way. Indeed, as emphasized in the introduction, combinations of missions have to be formulated to address the objectives of this element of the Living Planet Programme. The relationship between the scientific objectives of these missions and the different elements of the Earth System (as illustrated in Tables 3.2 and 3.3) shows that there is not an unique subset of missions to address the overall objective of the programme. The final definition

<table>
<tr><td rowspan="2">ATMOSPHERE</td><td>Stratosphere</td><td colspan="3">CHEMISTRY MISSION
PROFILING MISSION</td></tr>
<tr><td>Troposphere</td><td colspan="3">RADIATION MISSION
CHEMISTRY MISSION
PRECIPITATION MISSION
DYNAMICS MISSION</td></tr>
<tr><td colspan="2" rowspan="2">EARTH SURFACE</td><td>OCEAN</td><td>LAND HYDROSPHERE</td><td>LAND GEO-BIOSPHERE</td></tr>
<tr><td>GRAVITY MISSION
TOPOGRAPHY MISSION
RADIATION MISSION
PRECIPITATION MISSION</td><td>PRECIPITATION MISSION
TOPOGRAPHY MISSION
LAND MISSION</td><td>LAND MISSION
TOPOGRAPHY MISSION
RADIATION MISSION
PRECIPITATION MISSION</td></tr>
<tr><td colspan="2">EARTH INTERIOR</td><td colspan="3">GRAVITY MISSION
MAGNETOMETRY MISSION</td></tr>
</table>

Table 3.2 Nine illustrative examples of Earth Explorer missions

	THEME 1	THEME 2	THEME 3	THEME 4
	EARTH INTERIOR	PHYSICAL CLIMATE	GEO-BIOSPHERE	ANTHROPOGENIC IMPACT
GRAVITY FIELD	✓	✓		(✓)
MAGNETOMETRY	✓			
DYNAMICS		✓		✓
PRECIPITATION		✓	(✓)	✓
PROFILING		✓	(✓)	✓
TOPOGRAPHY		✓	✓	
LAND SURFACE		✓	✓	✓
RADIATION		✓	(✓)	✓
CHEMISTRY		✓	✓	✓

Table 3.3 The main links between the four themes and the nine illustrative Earth Explorer space missions (brackets indicate weaker links)

of the Earth Explorer Programme will thus be an iterative process based on the selection of specific missions, with due account being taken of the broader context and of the scientific coherence of the long term programme.

It is within this overall context that the nine illustrative Earth Explorer missions are described below. The order of presentation does not reflect any priority at the present time. However, it is based on a classification which serves to illustrate the approaches being taken to address the problem of an interactive and complex system on a scientific basis. Thus, the first six missions are devoted to the determination of global fields of Earth System variables, namely gravity field, magnetic field, wind field, precipitation field, temperature field and ice cover field. One can easily understand the need for knowledge of such fields of variables if one wants to establish global budgets of energy, momentum or constituents between the various components of an interactive system. Furthermore, given the temporal continuity provided over many years by space missions, these data provide information on inter-annual and intra-annual variability, which in turn provides information on the processes which govern the variables and their evolution.

The other three missions concentrate on the interactions between variables or components of the Earth System: cloud-radiation interaction; biosphere-atmosphere interaction, troposphere-stratosphere interaction. This distinction between fields and interactions highlights the main objectives of each mission. However, it does not preclude that, for example, cloud climatology being extracted from the study of cloud-radiation interactions, or that the determination of the gravity field and of the ice cover will further enhance our quantitative knowledge of energy and momentum exchanges between the ocean and the atmosphere. Nevertheless, this complementarity between a climatological approach at various spatial and temporal scales ('the fields') and one focussing on interfaces ('the interactions') ensures the *a priori* coherence of the proposed programme.

3.3.2 The Earth's Gravity Field: The Gravity Field and Steady-State Circulation Mission

This mission (ESA SP-1196(1)) addresses the need for global and regional models of the Earth's gravity field and its geoid (the reference equipotential surface) for use in a wide range of research and application areas, including global ocean circulation, physics of the interior of the Earth, and datum connection.

It would be the first to provide a precise reference surface for the determination of the absolute ocean topography from the data delivered by satellite altimetry – a major deficit in current knowledge which undermines estimates of absolute ocean circulation. The latter is needed to determine the lateral oceanic transport of heat and fresh water and its regional and temporal variations, which are closely coupled to climate variability.

The spacecraft would include two instruments, namely a three axes gradiometer and a GPS/GLONASS receiver known as GRAS (see Section 3.3.6 below). It would exploit the European heritage in altimetry and oceanography as well as in gradiometers. The reference orbit would be dawn-dusk sun-synchronous orbit at an altitude of 250 km.

3.3.3 The Earth's Magnetic Field: The Magnetometry Mission

The fundamental aim of this mission (ESA SP-1196(5)) is to advance our understanding of the structure of the Earth's core and its motion by advancing knowledge of the near-Earth magnetic fields, namely the main field that originates within the Earth's core (and 'secular variations'), and the external field generated by electric currents in the ionosphere and magnetosphere. In addition, it should also be possible to detect the long wavelength part of the lithospheric magnetic anomaly field.

A secondary aim is to help extend our knowledge of the Earth's environment and the effect of the Sun as well as to improve global magnetic field models, which even today form the basis of essential backup navigation systems. Specifically the observations would also be used to improve the International Geomagnetic Reference Field (IGRF).

To achieve these goals, two small satellites would be necessary, namely a relatively high altitude (600 km) satellite to monitor the main field, its secular variations and the external fields (lifetime 5 years) and a low altitude (250 km) satellite measuring the lithospheric anomaly field (lifetime 6 months). The key instruments would be magnetometers, charged-particle detectors and an ion drift meter; plus positioning information. Again the mission would exploit a considerable European heritage in this area, viz. Champ and Øersted.

3.3.4 The Atmospheric Wind Field: The Atmospheric Dynamics Mission

The aim of this mission (ESA SP-1196(4)) is to fill a serious gap in the current (meteorological) operational observing network, by providing observations of three-dimensional wind fields in clear air. Such data would be assimilated into numerical forecasting models such as those developed by ECMWF, where it could be complemented by sea surface wind measurements (from scatterometers) and other auxiliary data. They are a critical element in the further development of predictive capability.

The mission would also support the validation and improvement of climate models and process studies relevant to climate change. This would be achieved by: (a) contributing directly to the study of the Earth's global energy budget by measuring three-dimensional wind fields globally in clear air, and (b) providing the data with which to study the global circulation and features such as precipitation systems and the El Niño.

The intention is to fly a space-borne Doppler wind lidar, capable of measuring winds in clear air plus other variables, on the International Space Station. It would exploit the European heritage in Doppler wind lidars (viz. ALADIN) and numerical modelling including data assimilation.

3.3.5 The Precipitation Field: The Precipitation Mission

This mission (ESA SP-1196(8)) was conceived to measure the distribution of precipitation over the Earth (excluding Polar regions), so that the precipitation processes can be more satisfactorily represented in models used for climate and weather prediction. According to present climate simulations, considerable changes in rainfall patterns are associated with global climate changes.

The top priority of this mission would be to provide accurate rainfall measurements to help improve the representation of precipitation and the hydrological cycle in climate and weather prediction models. Most of the worldwide precipitation falls at latitudes between $\pm 60°$, over two thirds of it in the tropics ($\pm 30°$). The proposed mission would focus on the observation of precipitation at these latitudes.

The core elements of this mission would be a dual frequency rain radar and a microwave radiometer, plus observations made by visible/infrared imagers and vertical atmospheric sounders. It would capitalise on a long standing (ground and aircraft based) European effort devoted to the study of storms and their interpretation. It is also seen as a collaborative effort (Japan and the USA) following on from TRRM.

3.3.6 The Atmospheric Temperature Field: The Atmospheric Profiling Mission

This mission (ESA SP-1196(7)) would provide data for climate research, including climate change detection, as there are indications that tropospheric temperatures are increasing and stratospheric temperatures decreasing. Preliminary studies indicate that these results are consistent with transient numerical climate change experiments, but these results cannot be sufficiently tested since unbiased temperature data at a high enough vertical resolution, particularly in the stratosphere, are not yet available.

Reflecting these needs, the prime objective of this mission is to provide global observations of upper troposphere and lower stratosphere temperatures and humidities in support of climate research as well as operational meteorology. Here the European expertise in data assimilation would be of paramount importance.

The spaced-based system, GRAS, would consist of a set of radio navigation signal receivers (exploiting the GPS and GLONASS systems) flown on a constellation of satellites configured to achieve the requisite geographical coverage and spatial resolution. It would capitalise on the plans to fly such instruments on operational meteorological satellites and European technical expertise (viz. the selection of GRAS by the USA)

3.3.7 The Cryosphere and Ice Cover Field: The Topography Mission

This mission (ESA SP-1196(9)) is intended to measure sea ice surface morphology and freeboard, permitting the determination of sea ice roughness and hence the estimatation of ice thickness which is needed to calculate the ocean/atmosphere energy exchange and freshwater transport in polar regions. It would also provide observations of ice sheet topography.

Precise measurements of the elevation variations of ice sheets, ice shelves and high latitude glaciers are of fundamental importance to the computation of the cryospheric component of the hydrological cycle and for studies of ice/climate interactions. In addition, the measurements of the variability of the ocean topography would provide valuable information on ocean surface currents and ocean dynamics (gyres and eddies). Both are essential inputs to climate models.

Two altimeter concepts could meet the observation requirements, namely a microwave beam-limited altimeter flown on a single satellite and a dual-satellite scenario, with a laser altimeter being used to observe over ice and a conventional pulse-limited altimeter providing data over oceans. It would exploit the extensive European heritage in altimetry and would present a major technical challenge as the ability to derive precise measurements of ice sheet elevation and sea ice thickness are very demanding. In addition, to the core payload, a GNSS receiver and laser retroreflector would be required.

3.3.8 The Biosphere/Atmosphere Interface: The Land Surface Processes and Interactions Mission

The primary focus of this mission (ESA SP-1196(2)) would be land surface processes and their interactions with the atmosphere. It focusses on the measurement of surface characteristics such as albedo, multispectral reflectance, BRDF (bi-directional reflectance distribution function) and surface temperature which are linked to geophysical variables involved in biogenic processes such as productivity, evapotranspiration and nutrient cycles. Such data would foster studies on the effect of increased carbon dioxide, loss of bio-diversity, hydrological cycle, pollution and man-induced pressure on natural resources. The space segment of the mission would proceed in parallel with a measurement programme involving a set of very carefully instrumented ground sites.

A major concern would be the scaling up of local processes to regional and global scales. By advancing the understanding and characterisation of these processes at small to medium scales, the mission would enhance their realistic representation in spatially distributed models at larger scales. This improvement would immediately result in major advances in environmental monitoring and management.

A hyper spectral imager, covering both the visible/near infrared (imaging spectrometer) and the thermal infrared (imaging radiometer), is the core of this mission. It would be configured in a near polar orbit to ensure access to all land areas. The mission would exploit a considerable technical and scientific European heritage in the observation of the land surface and its interpretation.

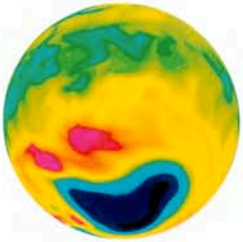
3.3.9 Clouds and Radiation Interaction: The Earth Radiation Mission

The major thrust for this mission (ESA SP-1196(3)) is to advance knowledge of the radiative processes that play a key role in determining the Earth's climate and climate change. Current uncertainties in model predictions of climate change need to be significantly reduced, in particular the role of clouds and aerosols and the radiative response to the observed anthropogenic modifications of atmospheric gases and particle compounds.

The mission would provide key measurements pertaining to clarifying the role of clouds and aerosols and to determining how much global warming is a reflection of anthropogenic emissions and, therefore, a warning of imminent climate change. The extent to which these short term trends reflect natural or anthropogenic variations is still uncertain. A key to the prediction of climate response is a full understanding of the role of radiation in maintaining the present climate and in governing the amplitude and evolution of large-scale climate anomalies.

Two major space-borne instruments are included in this mission, namely a backscatter lidar and a cloud radar which, together, have the ability to observe the characteristics of clouds and aerosols. They would be supported by a broad band radiometer and a cloud imager. The mission would exploit a wide span of European technical and scientific expertise, notably in active instrumentation, viz. ATLID. It is also a strong candidate for international cooperation (Japan and the USA).

3.3.10 The Stratosphere/Troposphere Interface: The Atmospheric Chemistry Mission



Although there are many interesting scientific problems deserving attention in the atmosphere, this mission (ESA SP-1196(6)) recognises the priority of the upper troposphere/lower stratosphere. It focuses on the need to validate our understanding of the chemical processes that occur at these altitudes and to investigate the exchange of trace gases (in particular water vapour and ozone), as well as thermal and kinetic energy, between these two regions.

Current high levels of chlorine and bromine loading in the stratosphere are expected to peak early in the next century and it is extremely important to quantify the anticipated changes in ozone and temperature by making the appropriate quantitative observations. In the troposphere, man-made increases in the concentrations of the precursors of tropospheric ozone and in the greenhouse gases are anticipated. Aerosols, which have both natural and anthropogenic sources, can be expected to play an increasing role in the chemistry of the troposphere.

The satellite would carry a millimetre-wave limb sounder for high resolution profiling of ozone and water vapour in the upper troposphere and chlorine oxide (ClO) in the stratosphere. This would be supported by observations of nitrogen oxides (NO_x) and other key species/parameters. Measurements of the constituents of the HO_x family are also of high priority, but are not included in the present scenario of this mission because OH measurements from space are expected to have insufficient accuracy. The mission would exploit not only the European heritage in the construction of chemistry instruments, but also the extensive experience of the scientific community.

3.4 Concluding Remarks

This chapter has demonstrated the feasibility of pursuing the scientific objectives of the Earth Explorer element of the Living Planet Programme with an appropriate set of focussed missions which would be implemented in a complementary way. Such a set of space missions could be extracted from the nine illustrative missions presented here, as together they span all the Earth Explorer objectives detailed in Chapter 2. Even if all of these missions were not be selected as Earth Explorer missions within the ESA programme, they do constitute an appropriate basis for addressing the major scientific objectives of Earth Sciences in the coming decade.

Therefore, within the framework of international coordination, one should try to ensure the implementation of all of these missions, or missions similar in nature as defined by other partners. Within this overall context, the importance of collaboration is thus clear. Furthermore, in assessing specific proposals, it will be essential to take full account of requirements for data from other sources as well as those provided by specific Earth Explorer missions.

4. Earth Explorers: The Wider Context

4.1 Introduction

Drawing on Chapter 2, Earth Explorers: The Research Objectives, and Chapter 3, Earth Explorers: Addressing the Objectives, this chapter is intended to set the Earth Explorer element of the Living Planet Programme in a more general context. The objective is to ensure that the programme takes proper account of the activities and plans of other entities in order to provide the required complementarity in science missions and data sources. These include not only the international research initiatives already mentioned in Chapter 1, but also the plans of other space agencies such as those in Europe, Japan, the USA, India and China.

The scientific objectives of these various bodies are generally quite closely aligned with those of the Earth Explorer element of the Living Planet Programme ensuring:

- advances in our understanding of climate and environmental processes and hence to the improvement of Earth System models used to predict its evolution
- the provision of data which can be used to further the development and improvement of retrieval algorithms for geophysical and biophysical parameters
- the demonstration of the potential of instrumental techniques that may find operational/commercial application.

The argument for close collaboration is irrefutable and will be fully taken into account in formulating plans for specific Earth Explorer missions. In particular there must be close articulation with national entities in Europe such as the Member States, the European Union and Eumetsat, with full account being taken of the heritage of the Agency's previous and planned missions i.e. ERS, Envisat and Metop.

The Earth Explorer element of the Living Planet Programme must also be viewed within the context of the Agency's overall strategy for Earth Observation, and thus of its Earth Watch component, as together the two types of missions span the interests of the full Earth Observation user community. Within this framework, a key element is the industrial activity required to develop instruments capable of meeting the requirements associated with the objectives of the Earth Explorer element of the Living Planet Programme. This will pose major technological challenges and may necessitate the provision of small technological demonstration/precursor missions, some of these relying on national initiatives. The role of industry in exploiting European expertise to overcome the many technical challenges will be of pivotal importance.

Finally, the collaborative European frame should be further enhanced at the international level by considering the plans of other space agencies, notably NASA and NASDA. Special mention must also be made of the Committee for Earth Observation Satellites (CEOS), which provides a forum for encouraging collaboration between space agencies and between space agencies and the various user entities, thus ensuring an optimum use of data from various sources. This forum will be exploited to the full to ensure that optimum use is made of the resources assigned to the Earth Explorer element of the Living Planet Programme.

4.2 The European Context

To ensure optimum use of resources, the Earth Explorer element of the Living Planet Programme must also be viewed in the context of the various European entities that are interested in the provision of data (including the use of data in numerical models) as well as in the objectives listed in Chapter 2. These include the Agency itself, the ESA Member States, Eumetsat and the European Union.

4.2.1 The European Space Agency

ESA is an essential element in any major European space activity. Many of its advantages fit around three features, namely the economies of scale achieved by working on the European scale, the breadth of coverage offered by a Europe-wide programme, and the possibilities for coordination across Member States (Figure 4.1), with other European entities and with agencies outside Europe. All are essential to the maintenance of European scientific excellence.

The European scale encompassed by the Agency provides a continuity and breadth of activity that cannot be sustained individually in each Member State. The Agency provides a pool of technical, scientific, institutional and management expertise encompassing all aspects of space activities, which is available to all Member States, minimising the need for the costly (and unsustainable) duplication of resources.

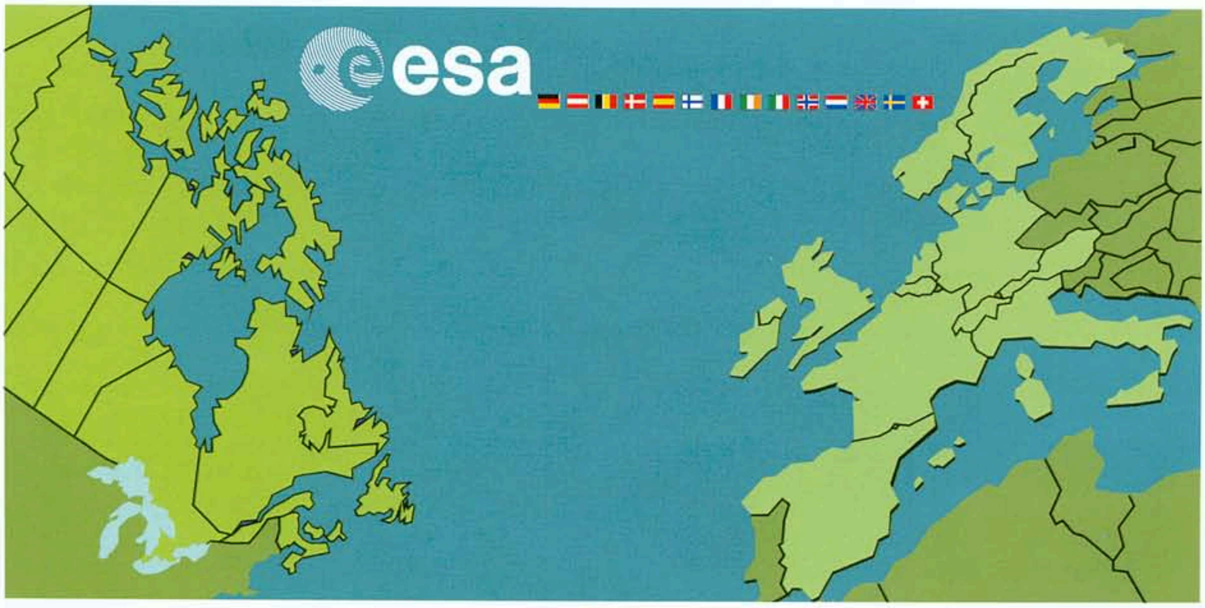


Figure 4.1 Member and Cooperating States of the European Space Agency

The Agency can act as a single point of contact with bodies outside Europe, making it easier to respond to the likely increase in opportunities involving worldwide cooperative programmes. ESA can help highlight opportunities offered through collaborations with other major space-faring nations to all Member States. The existence of the Agency provides a forum and a network of information and contacts, or even support services and facilities, to anyone wishing to set up smaller scale bilateral activities. It also provides the requisite continuity and stability needed to enter into international agreements.

The next programme, in turn, poses new challenges to the Agency. The Earth Explorer missions will in general be smaller and more focused than the ERS and Envisat missions and will need to be implemented appropriately. However, the existence of the programme of phased missions itself will also generate its own efficiency; industry and the Agency will be able to plan against a fairly well-defined timetable and the envelope funding will allow savings made in one area to be straight-forwardly transferred elsewhere as appropriate.

4.2.2 ESA Member States

ESA Member States have their own national Earth Observation programmes, strategic plans and, in some instances, are actually developing space missions (see Table 4.1).

Table 4.1 Examples of national European, NASA and NASDA research missions relevant to the nine illustrative Earth Explorer missions (post-2000)

	NATIONAL/ MULTI-NATIONAL EUROPEAN MISSIONS	NASDA MISSIONS	NASA MISSIONS
EARTH'S GRAVITY FIELD	GRACE		GRACE
EARTH'S MAGNETIC FIELD	ØERSTED, CHAMP		
ATMOSPHERIC WIND FIELD			
PRECIPITATION FIELD		TRMM-FO	TRMM-FO
ATMOSPHERIC TEMPERATURE FIELD	ØERSTED, CHAMP		NPOESS
CRYOSPHERE & ICE COVER FIELD	JASON		JASON, GLASS
BIOSPHERE / ATMOSPHERE INTERFACE	SPOT	ADEOS-2, ALOS	
CLOUDS & RADIATION INTERACTION		ATMOS-1B	CLOUDSAT
STRATOSPHERE / TROPOSPHERE INTERFACE	ODIN	ADEOS-2	EOS CHEM

Many of the objectives of these programmes have much in common with the objectives detailed in Chapter 2 and it is clear that close coordination will be essential if a cost-effective European-level approach is to be ensured. In particular, in addition to scientific collaboration, the following areas should be highlighted:

- cooperation in data processing, algorithm development and in the general provision of support to the research community to ensure the optimum exploitation of space data
- ensuring complementarity between nationally-funded space missions and the Earth Explorer missions
- the possible provision of instrumentation (nationally-funded) for Earth Explorer satellites and vice versa.

These possibilities are, to varying extents, applicable to all ESA's Member States and will be taken fully into account in formulating proposals for each Earth Explorer mission. Similar comments apply to other interested European countries which are not members of ESA.

4.2.3 Eumetsat

The European Organisation for Meteorological Satellites (Eumetsat) was set up to establish, maintain and exploit European systems of meteorological operational satellites. This has recently been extended to include climate monitoring. Eumetsat is working closely with ESA in developing new operational systems, i.e. Meteosat Second Generation and Metop.

The activities of this organisation contribute to a global satellite observing system, coordinated with other space-faring nations, which forms one of the major elements of the World Weather Watch (WWW). In addition, Eumetsat is planning to contribute to the Global Climate Observing System (GCOS). This means that Eumetsat will have a close interest in the Earth Explorer element of the overall ESA Earth Observation Programme as:

(a) Earth Explorer missions can help demonstrate the feasibility of techniques that may find operational application
(b) data from the Earth Explorer element of the Living Planet Programme can help advance knowledge and understanding of processes that are relevant to operational requirements

leading to the development of improved forecasting models and the modification/refinement of operational data requirements.

In addition, there are several other European organisations that can be expected to take a close interest in the Earth Explorer element of the Living Planet Programme. These include the European Centre for Medium Range Weather Forecasts (ECMWF), with its internationally recognised capability and leadership in numerical modelling and data assimilation. Conversely, data generated by Eumetsat satellites will be very useful for addressing some of the problems presented in Chapter 2, namely those which require long term data sets.

4.2.4 The European Union

The European Commission (EC) is taking an increasing interest in fostering the utilisation of data from space-based systems and "will continue to support the development of applications of Earth Observation techniques by carrying out projects for environmental monitoring, including those aimed at increasing the effectiveness of European environmental legislation and international environmental agreements" (EC, COM(96)617). Thus, the Commission could look to the Earth Explorer element of the Living Planet Programme for the demonstration of techniques that could ultimately be exploited on a regular (operational) basis to provide the requisite data.

The Commission can be expected to continue to use its Framework Programmes to support basic methodological research in Earth Observation as well as pilot and demonstration projects of a pre-operational nature. This means that it should be well placed to encourage the enhanced downstream exploitation of data emanating from the Earth Explorer element of the Living Planet Programme, through the support of European researchers. Also of importance is the Centre for Earth Observation (CEO), which is intended to facilitate quicker and easier access to Earth Observation data, including those required to complement data provided by Earth Explorer missions. The relevance of all these various initiatives to scientific research is clear.

Finally, mention must be made of a further pan-European entity, namely the European Environment Agency (EEA) which has the mandate to ensure the provision of information of relevance to the protection and improvement of Europe's environment. Many of the objectives of the Earth Explorer element of the Living Planet Programme will address environmental issues and the provision of data of direct concern to it.

4.3 The Links to the Earth Watch Programme

4.3.1 The Context and the Heritage

In general terms, the Earth Explorer missions may be defined as research/demonstration missions concerned with advancing understanding of the different Earth system processes and/or the demonstration of new observing techniques. This definition may be contrasted with that of the Earth Watch missions, which are pre-operational missions concerned with the operational needs of user communities.

The Earth Explorer missions pave the way for Earth Watch missions by demonstrating the feasibility of new observing techniques (end-to-end system demonstration) and by helping to identify geophysical parameters that should be observed on a regular basis to meet the needs of specific groups of users. They will also provide data sets for operational use, e.g. the reference geoid from the gravity mission.

The Earth Watch missions generally complement Earth Explorer space missions by satisfying some of their data requirements and hence helping to constrain their scope and size. They also provide a means of addressing some of the research requirements for long term data sets, as well as indicating needs for future Earth Explorer missions by highlighting limitations in current operational observing systems. The operational meteorological systems may be viewed in the same light.

In considering the Earth Watch and Earth Explorer missions within the general context of the Agency's overall strategy for Earth Observation, it is also important to take full account of the links between these missions and the current/approved ESA missions, i.e. ERS, Envisat, Metop, MSG, etc. The latter will not only help highlight the need for future Earth Explorer missions, but in addition they provide a source of information on requirements for Earth Watch missions. They also represent a source of expertise on hardware, software, data systems, etc. relevant to both types of mission.

In certain instances the possibility may arise whereby an Earth Explorer mission could actually evolve during its lifetime to become an Earth Watch mission. This is likely to only prove feasible in relatively special circumstances where it becomes clear that the data are highly tuned to the needs of a particular group of operational/commercial users. It presumes that the mission has the requisite lifetime and that the data are of sufficient value to warrant the users agreeing to assume full responsibility for the mission. A prerequisite for such a change would be that the objectives of the original Earth Explorer mission are not compromised and here data access would be a point of particular concern.

4.3.2 Illustrative Examples

Meteosat Second Generation spacecraft at Aerospatiales (F)

There are already some examples of actual missions that have made (or are making) the transition from being a research/demonstration mission (usually via a pre-operational mission) to become an operational mission. The same is true of some observing techniques. In the broadest sense, the Earth Explorer concept includes pre-operational usage as well as research/demonstration; the Earth Watch concept spans the pre-operational/fully operational transition. Examples of missions and instruments include:

(a) *Meteosat* – The first satellite was originally conceived to serve the atmospheric research and meteorological communities on a pre-operational (demonstration) and scientific basis. Over the past decade they have successfully evolved from being ESA funded missions to become fully independent operational meteorological missions funded and now integrated through Eumetsat with the meteorological services. Data from Meteosat satellites finds wide application not only for operational meteorology, but also for research and a wide span of applications (vegetation monitoring, large scale ecosystem dynamics, etc.). The first of a second generation of these satellites is currently under construction.

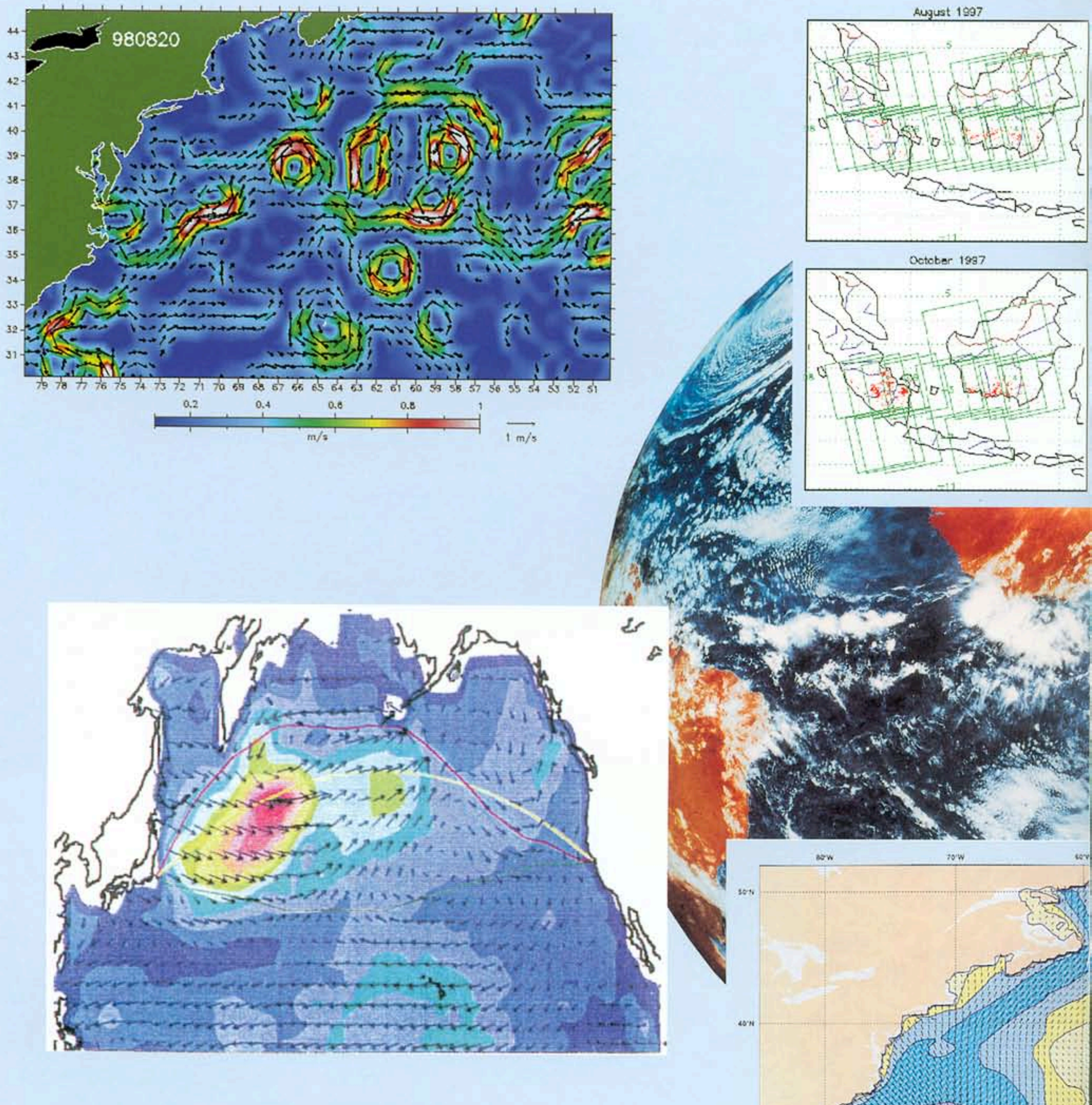
(b) *Landsat* – The first Earth Resources Technology Satellite (ERTS-1) laid the foundations for NASA's Landsat series of surface observation satellites. Initially these satellites were designed to fulfil observational requirements set by the US Geological Survey and the US department of Agriculture. However, they have evolved (via Landsat MSS and Landsat TM) to assume an operational character especially for agricultural applications. In this sense they provide an interesting example of the evolution from an Earth Explorer to an Earth Watch mission though they are still only partially funded by the user community. In many ways this closely parallels the current position of the French SPOT series of satellites.

(c) *Synthetic Aperture Radar (SAR)* – The SAR mode of the C-Band Active Microwave Instrument (AMI) on ERS-1 can be viewed as an evolution of the SAR flown on the US Seasat satellite (launched in 1978). Both were intended for research into ocean and sea-ice phenomena and to provide technical demonstrations of the SAR's multi-user capabilities. On ERS-1 the SAR has successfully demonstrated a wide capability to address operational needs, as well as those of the research community, over land as well as over ocean and ice. The success of the AMI SAR on ERS-1 laid the foundations for the Canadian Radarsat satellite, which is a fully funded operational system. A next step in the technical evolution is the ASAR on Envisat.

(d) *The Wind Scatterometer* – The starting point for this instrument was the wind scatterometer flown on the US Seasat satellite in 1978, which established the link between sea surface roughness and wind speed and direction over the sea. Building on the results of this brief mission, the wind scatterometer mode of the AMI on ERS-1 was designed. Following an initial period of scientific investigation and the validation of models, supported by ECMWF and the European national meteorological services, wind data from the AMI on ERS-2 are now routinely operationally assimilated into NWP (numerical weather prediction) models. This provides a good example of a system that is in the final stages of evolution from research/demonstration to a fully operational mode, as it is planned to fly the Advanced Wind Scatterometer on the operational Metop series of polar orbiting meteorological satellites where, ultimately, they will be fully funded by meteorological services.

(e) *The Radar Altimeter* – The foundations for an operational mission to supply long-term observations of ocean circulation were laid by the radar altimeter on ERS-1. This was followed by an identical instrument on ERS-2 and the radar altimeter on TOPEX/POSEIDON which was a joint CNES/NASA altimeter mission. The success of this latter mission, in routinely providing precise estimates of sea surface topography and corresponding upper layer currents, has paved the way for the follow-on mission, Jason-1, which will be launched in spring 2000. Jason-1 will provide altimetric information on a routine operational basis for use in the forecasting of ocean circulation. To date this is fully supported by public funds.

Although these are all (to varying extents) examples of missions that have evolved to become operational in character, it is pertinent to highlight their continuing relevance to research. Thus, for example, wind scatterometer data are now acquired over land for large scale ecosystem studies and provide, with their coarse spatial resolution (around 50 km), a good reference for GCMs (general circulation models). The SAR is demonstrating an ever expanding research potential with its data finding application over a wide span of research activities including both terrestrial and marine studies. However, even the less novel missions, such as SPOT and Meteosat, are of great relevance to research as they provide a source of long time series of observations essential for the study of long term evolutions in climate. This is further highlighted in the collage of operational products shown in Figure 4.2.



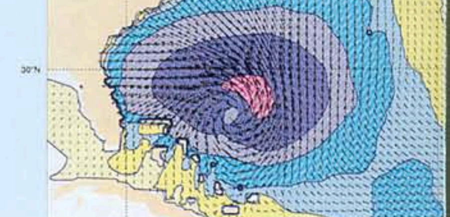
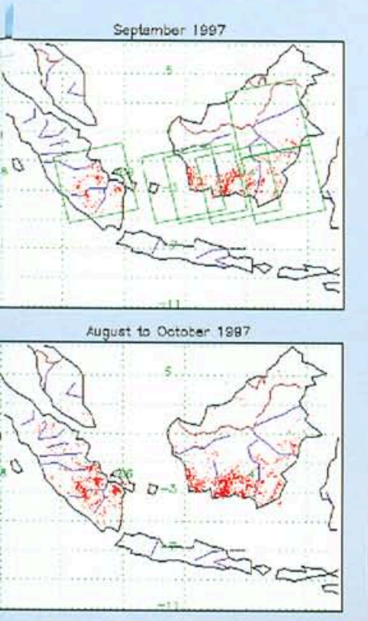


Figure 4.2 A selection of operational products.
Clockwise from top left: North Atlantic surface current derived from combined use of ocean model and radar altimeter; fire detection over the Philippines from ATSR; NO_2 column amounts, showing the impact of the fires in Borneo; Composite image (ERS and Spot) of land usage in Ireland; Hurricane Bonnie depicted in an ECMWF forecast using wind scatterometer and altimeter data; Ship routing (great circle route in yellow, optimal route in red) superimposed on a sea-state map of the Pacific developed using SAR and scatterometer data


September 1997
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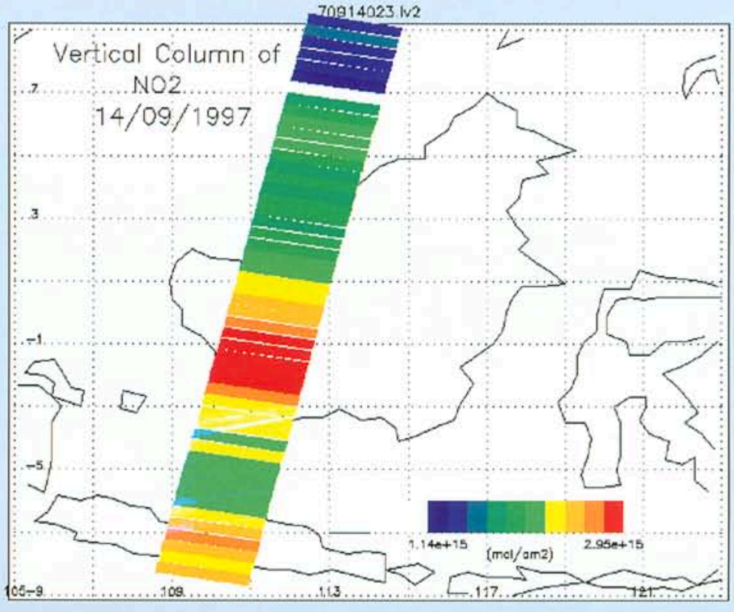
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Vertical Column of
NO2
14/09/1997
1.14e+15
(mol/cm2)
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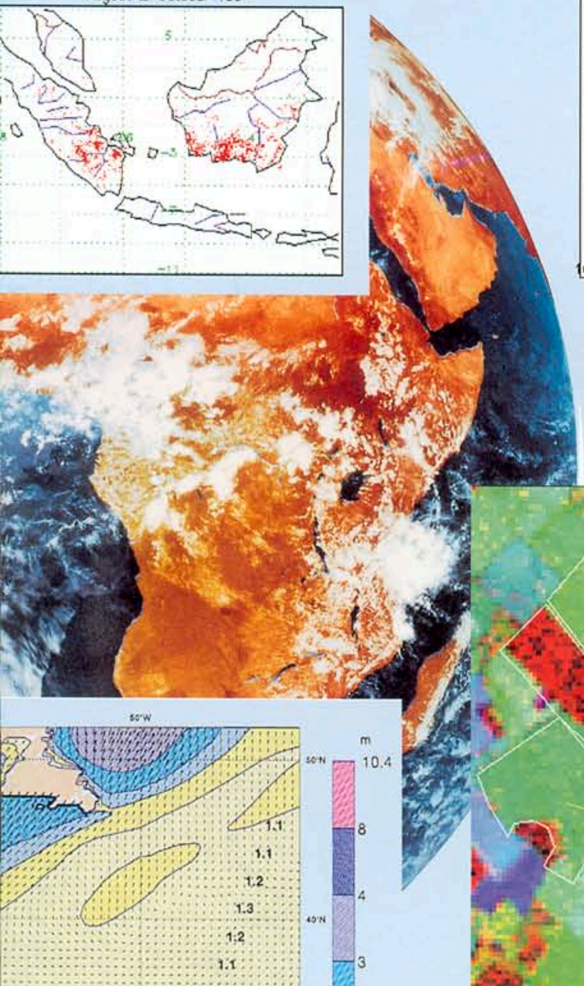
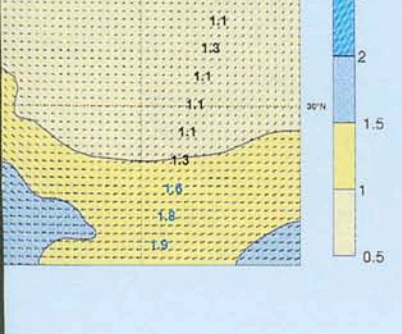



m
10.4
8
4
3
2
1.5
1
0.5


Spring Cereal
Permanent Pasture
Sugar Beet
Winter Cereal
Oilseed Rape
Silage

4.4 The International Context

4.4.1 International Commitments

A point of particular relevance is the link between the nine illustrative missions and European treaty obligations and here specific relevance must be made to Appendix A which lists the main commitments. Almost all the nine missions are relevant to *The Atmospheric Treaties* (Section 2) while for *The Forest Treaties* (Section 3) the Land Mission in particular must be cited. The Chemistry, Precipitation and Radiation Missions are relevant to *The Water Courses Treaties* and the Land Mission to *The Conservation Treaties*. In each case the mission will supply data which either advances knowledge of the relevant geophysical and biophysical processes, or demonstrates the ability of Earth Observation to supply the requisite data. In many cases the missions do both.

A critical requirement of the programmatics (i.e. the manner in which the Earth Explorers will be implemented) will be to ensure that a mechanism is provided within an overall implementation plan for discussions and decision processes to be phased so that effective cooperation can be established.

4.4.2 International Observing Systems

The most well established international forum for coordinating the operational provision of data is without doubt the World Weather Watch (WWW) of the World Meteorological Organisation (WMO). Another prominent, though less established forum is the Global Oceans Observing System (GOOS). These forums address the need for the regular provision of key meteorological and oceanographic data for operational purposes. Complementing these two are the Global Terrestrial Observing System (GTOS), which provides data on land surface characteristics, and the Global Atmospheric Watch (GAW), which provides data on atmospheric composition.

Closely linked to both GTOS and GOOS is the Global Climate Observing System (GCOS), which was established to coordinate the provision of data for climate monitoring, climate change detection and response monitoring, especially in terrestrial systems. These data are intended to find application for national economic development planning as well as contributing to research towards improvements in the understanding, modelling and prediction of the climate system. In the GCOS space plan, seven GCOS 'missions' are identified, namely global radiative properties, ocean characteristics, the ocean/atmosphere boundary, atmospheric dynamics, atmospheric composition, the land/atmosphere boundary and land/biosphere climate response.

Although the number of geophysical variables identified by GCOS is likely to be significantly less than that provided by the conventional operational systems, the GCOS data is generally intended to be of higher quality and have greater consistency/uniformity than operational data sets. This could make them of greater relevance to the data needs associated with some of the objectives of the Earth Explorer element of the overall ESA Earth Observation Programme.

Mention must also be made of the International Association of Geodesy (IAG), which encompasses several operational services. These include the Bureau Gravimétrique

International (BGI), taking care of data collection and distribution, the International Geoid Service (IGeS), preparing optimal regional and global geoid computations, the International GPS Service for Geodynamics (IGS), preparing high accuracy GPS satellite ephemerides on a worldwide scale, and, jointly with the International Astronomical Union, the International Earth Rotation Service (IERS) defining and maintaining inertial and terrestrial reference systems.

4.4.3 An Integrated Global Observing Strategy

In considering the complementarity of ground-based and space-based systems, mention must be made of the Committee on Earth Observation Satellites (CEOS) organisation, which provides a forum for coordinating the activities of the various space agencies and informing users (affiliates) of their plans for future missions. CEOS has quite recently started to consider the formulation of an Integrated Global Observing Strategy (IGOS) combining all sources of data in an optimum fashion to meet data requirements (Figure 4.3 illustrates the concept).

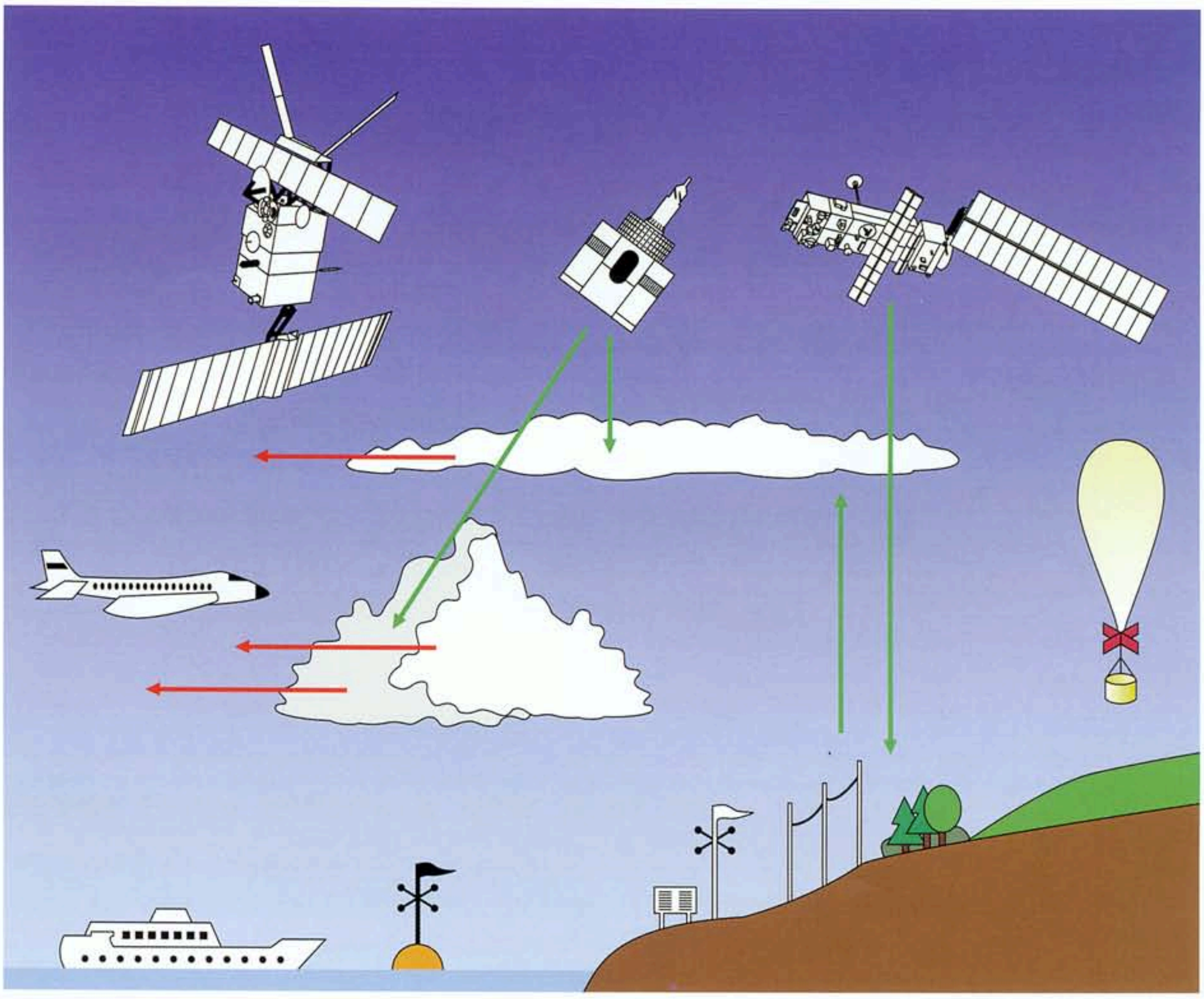


Figure 4.3 Some elements of an integrated global data collection system

As a trial, six initial implementation projects have been identified, namely:

- Ocean Data Assimilation
- Upper Air Network & Tropospheric Winds from Space
- Continuity of Stratospheric Ozone Observations from Space
- Global Observation of Forest Cover
- Long-term Ocean Biology
- Disaster Monitoring and Management Support.

This list is likely to grow with time. The findings emerging from these projects are likely to have a significant bearing on operational programmes. However, this initiative is also of great relevance to the Earth Explorer Programme because the various IGOS initiatives should help ensure provision of the data needed to complement those produced by specific Earth Explorer missions.

4.4.4 Cooperative Mission Implementation

Earth science is naturally both global in scale and internationally cooperative in nature. A central feature of the new programme will be direct cooperation in the implementation of some of the key missions between ESA and other space agencies, such as NASA (USA) and NASDA (Japan). As has been successfully achieved in the ESA Space Science Programme, one envisages missions where ESA will be the leading partner. Such missions are referred to as *Core Missions* within the Earth Explorer Programme.

However, an important element in achieving an overall balanced programme will be smaller ESA commitments to *Opportunity Missions*. One of the critical mechanisms for generating such missions will be through use of flight opportunities offered by partner agencies or through international cooperation where ESA may be the junior partner.

In considering these missions it is important to take into account the plans of other Space Agencies who have carried out similar analyses, in many cases reaching similar conclusions regarding requirements for research missions. Here, in addition to the plans of national European space agencies, one must make special mention of NASA and NASDA who have quite ambitious and wide-ranging plans for the future. Many of the US missions fall within the general scope of a programme called *Earth Science Enterprise* (ESE). Table 4.1 illustrates the current situation by listing some the parallels that exist between these missions and the nine illustrative Earth Explorer missions described earlier in this section. The importance of international collaboration, given the existence of these plans, is clear.

4.5 Concluding Remarks

Providing observations of the processes to enable advances in understanding of the Earth System calls for both enhanced and new measurement techniques. This can be translated into a challenge to develop new and improved space instruments and systems, giving a direct impetus to technological advancement in Europe. The Earth Explorer element of the Agency's overall Earth Observation Programme will provide an ideal vehicle for bringing together in Europe the considerable innovative capabilities of the many and various research institutes and industry, which will be charged and challenged with the system developments.

It is also clear that the interests of many European and international bodies are closely aligned with various of the objectives identified in Chapter 2 for the Earth Explorer element of the Living Planet Programme. This serves to highlight the importance of the issues and the obvious benefits of close cooperation. To avoid duplication and ensure complementarity, it is thus essential to take full note of the plans of other space agencies. International collaboration should lead to significant reductions in the costs (to the Agency) of addressing the objectives of the Earth Explorer element of the Living Planet Programme and there are already several examples of successful joint ventures involving Europe, e.g. TOPEX/POSEIDON and ADEOS. Mention should also be made of the close links between Eumetsat and NOAA. The continuity of the Earth Explorer Programme will ensure that this possibility of cooperation is fully taken into account in assessing candidate Earth Explorer missions, thus leading to an optimal use of resources.

Part B

Implementation and Financial Aspects

5. Implementation of the Earth Explorer Programme

5.1 Introduction and Scope of the Programme

The realisation of the overall objectives of the Earth Explorer Programme requires a serious, sustained commitment by all parties to work in new ways. There must be efficient cooperation between the Member States, the Agency and the various European entities. Furthermore, to be effective, and for the programme to cover the broad front illustrated by the nine candidate Earth Explorer missions, there must be an ordered approach to the implementation. With this known, some certainty will be introduced into the Agency's Earth Observation Programme and the research community will be able to work to an expected time table.

The programme must provide flexibility through choice and quick responses to evolving priorities. This calls for rapid decision processes within the ESA environment. At the same time, in order to be cost efficient and responsive to user requirements, to the interests of Member States and to the necessary international cooperation, the programme must provide continuity and stability. It must also ensure and maintain the scientific excellence of the European and Canadian Earth Observation research communities.

Within the programme, a series of space missions are envisaged which will address evolving research priorities by providing the requisite observational data. Two generic categories of missions are foreseen, namely *Core Missions* and *Opportunity Missions*.

- *Core Missions* will be selected through a mechanism involving extensive consultation with the European and Canadian research communities. Such missions will normally be led by ESA.
- *Opportunity Missions* will involve less extensive consultation and will provide a mechanism for the Agency to respond more rapidly to opportunity. Such missions could well be led by another agency.

The *Opportunity Missions* are intended to correct a serious deficiency in the past Earth Observation programmes, namely inability to react quickly to evolving situations. They could include the provision of instruments to other programmes, small research missions and missions demonstrating new ways of addressing the research objectives. 'Other programme' can mean another international programme, European national programmes or another Agency programme. The implementation of such a mission will be subject to a firm financial ceiling and a fixed (short) time schedule, wherever possible using simplified procedures.

Both types of mission could pave the way for Earth Watch initiatives and other commercial ventures by demonstrating the feasibility of new observational techniques and helping to establish new user communities. However, it is important to remember that the basic motivation underlying the Earth Explorer element of the Living Planet Programme is that of science and that this must not be compromised by other considerations. In particular, it is important to note that to progress scientists require easy access to data. This need is reflected by the data policy for the Earth Explorer Programme which is intended to encourage the use of data from Earth Explorer missions for research. It must also be taken into account in formulating policies for mission management.

5.2 Programme Structure and Efficiency

ESA's Envisat spacecraft

As indicated above, the Earth Explorer element of the Living Planet Programme will consist of a series of *Core* and *Opportunity Missions*. Traditionally, the Earth Observation missions of ESA have been approved on an individual, optional, basis, each governed by its own legal and funding mechanisms. Although this approach has enabled some major achievements (e.g. Meteosat, ERS-1/2), the decision process has generally been slow and inefficient, generating additional costs to Member States and leading to an increasing loss of credibility within the user community and industry.

While it is recognised that a new mandatory programme would not be acceptable to all ESA Member States, a much more efficient system is essential if past and current difficulties are not to be repeated. It must provide a fast and effective decision process together with a long term planning perspective to give a stable framework for both the research community and industry.

The research community needs such an environment to commit effort in support of missions required to address the research objectives of the Earth Explorer Programme (Chapter 2). Industry needs it to optimise the utilisation of resources and hence to achieve higher efficiency, thus achieving enhanced competitiveness on the world scale.

To achieve these objectives, Member States must provide a sustained commitment both towards the research community and, through ESA, to industry. Hence, a programme structure is proposed that takes the form of an optional envelope programme where each Member State can assess its own level of commitment as the programme evolves. After an initial build-up period, it would provide, like the Space Science programme, a stable level of resources. Within this environment new, more efficient, ways of working will be tried out wherever possible exploiting managerial flexibility.

5.3 Interaction with Users

The Earth Explorer element of the Living Planet Programme will be user driven with missions chosen after wide consultation with the community. This means that at each stage it will be necessary to ensure that:

- the process is clear and transparent
- the user community is fully involved
- there is adequate scientific, technical and programmatic preparation.

This has to be achieved strategically, i.e. at the overall programme level, and tactically, i.e. for each individual mission.

Strategically, the Earth Explorer element of the Living Planet Programme will be reviewed at regular intervals (approximately every five years) to assess progress to date and the outlook for the future. During these reviews both the objectives of this part of the programme and its balance will be reviewed. The reviews will be open to the whole European and Canadian research community and will set the scene for Participating States to approve the next phase of this part of the programme.

Tactically, each new cycle of *Core Missions* will be initiated by a *Call for Ideas* to the research community, with candidate missions selected through Peer Review. Successful missions will then go through an assessment phase, guided by a Mission Working Group (MWG). The results will be presented to the community in an open forum before further Peer Review and recommendation for selection for Phase A.

The Peer Review Groups report to the Earth Science Advisory Committee (ESAC) which acts in an advisory capacity to the Agency to safeguard the balance of the Earth Explorer element of the Living Planet Programme and to identify priorities. The recommendations of the ESAC will be put to the Programme Board for Earth Observation (PB-EO), which will make the final decision on which missions go forward to Phase A.

The Phase A studies will, in turn, be guided by Mission Advisory Groups (MAG). On completion of the Phase A studies, the same broad cycle of consultation and assessment will be initiated involving both the ESAC and the Programme Board. The PB-EO makes the final decision on which missions are actually implemented. MAGs will be established to support the implementation of selected missions.

Both the MWGs and MAGs will be composed of leading research experts in the appropriate fields, as will be the ESAC. However, as the ESAC has to cover the full span of Earth Observation, its composition must be more broadly based with all the main disciplines represented.

The users will be further involved in the programme through *Announcements of Opportunity* for data analysis and exploitation. There may also be calls for the flight of nationally provided instruments. The wider research community will also be involved at the programme level through periodic reviews and workshops.

These mechanisms are designed to ensure user involvement in all aspects of the programme from conception to completion. The *Opportunity Missions* will be subject to a similar, but expedited, procedure in which users will be involved at all stages in the process. More information on the actual selection mechanism is given in Section 5.5.

5.4 Importance of Technology Advances

The Earth Explorer Programme will, by its very nature, provide a rich and varied technological environment and will present industry with many opportunities. It will bring industry into contact with a wide range of European research institutes, providing a fruitful environment for the development of new and innovative ideas. Indeed, this has already been very evident during the preparatory activities. Furthermore, the Earth Explorer Programme should help pave the way for future Earth Watch operational programmes in which industry will play a pivotal role.

By offering a clear, long term planning perspective, the Earth Explorer Programme will encourage a far more focused and harmonised technology programme at the European level, enabling industry to plan for the future. The Agency will be much better placed to work with industry to ensure the requisite technology is available at the requisite time and, in particular, the Earth Observation Programme will be better placed to exploit Agency-wide technology development efforts in realising missions.

The Earth Explorer Programme will present many technological challenges, thereby helping to foster innovation in observation techniques and technologies. This is illustrated by the examples presented in Table 5.1, which have emerged from the nine illustrative Earth Explorer missions. It can be seen that each of these calls for the development of new technology and that the total span of technology covered, even for this limited set of missions, is quite wide. The resulting advances will act as a driver for industry and may well seed future Earth Watch programmes. This trend will continue with future *Core Missions*.

The *Opportunity Missions* will provide similar opportunities for the demonstration of new technologies for industry and illustrate capabilities for new instruments or low cost, small satellites. The aim will also be to use the missions as testbeds for developing new ways of working for scientists, engineers and industry. Challenges will be set for everyone involved in European Earth Observation to work quickly and efficiently. In many ways, this will be more attractive to industry as the implementation cycle will be much shorter.

Table 5.1 Examples of technology requirements for Earth Explorer Missions (not exclusive)

Clouds & Radiation Interaction	Laser technology, 94 GHz radar technology, uncooled IR imager
Earth's Gravity Field	Low TC superconducting components, ultra-low-noise cryostat, electric propulsion, proportional gas thrusters, geodetic quality GPS/GLONASS receiver, gas cells, ultrastable structures, control techniques
Atmospheric Wind Field	Laser technologies UV to 10 microns, thermal control, ultra-stable structures
Biosphere / Atmosphere Interface	SWIR and TIR detectors, gas solar cells, manoeuvring satellite, quality reaction wheels, mission and operations management, data handling: analogue and digital processing, data compression and compressors, high speed data links
Stratosphere / Troposphere Interface	Instrument mm, sub-mm and FIR technology, large high frequency antenna manufacturing and testing techniques
Precipitation Field	Rain radar, dual frequency, compact passive microwave radiometer, antenna technology, contactless power and signal transmission systems
Earth's Magnetic Field	Advanced, high performance star sensors
Cryosphere & Ice Cover Field	Laser and microwave altimeters
Atmospheric Temperature Field	First geodetic quality combined GPS/GLONASS receiver, GPS codeless operation techniques, lightweight antenna array

5.5 Programme Decision Processes

5.5.1 Introduction

Two levels of decision will control the Earth Explorer Programme; decisions to control the overall sub-programme and decisions concerned with the selection of the missions within the sub-programme. The decision cycles for mission selection must be repeated at a rate consistent with the timely implementation of the science objectives within the overall financial envelope.

To retain credibility, over a period of about ten years the programme must address the interests of all the main sectors of the user community. Taking into account the wide span of topics to be addressed and the large number of scientists involved, this corresponds to the implementation of a *Core Mission* (see Section 5.5.3) about every two years. With the spread of expertise available in Europe and an estimated Earth Observation user community of many thousands, there will be no difficulty in exploiting the opportunities.

5.5.2 Programme Control Decisions

The Earth Explorer Programme will be initiated as an envelope programme, governed by a Declaration and Implementing Rules, the legal instruments of the optional ESA programmes. It will be a rolling ten year programme subject to review every five years.

The review will ensure that the Earth Explorer Programme:

- adapts to evolving national and international needs and priorities
- encourages efficient implementation, with timely fulfilment of objectives
- meets industrial policy objectives.

The overall review procedure would involve users, the community, the ESAC and Member States through Delegate Bodies. Consultation with industry would be an essential element in the process.

The time scale of five years encompasses the implementation of several missions (see Chapter 6). Furthermore, the period is long enough to guarantee a level of stability for the programme that is essential to ensure efficiency of implementation and in establishing its worth to the community and industry. Five years is short enough for Member States to commit funds whilst retaining financial flexibility on the longer time scale.

5.5.3 Mission Selection Decisions

In this section the steps in the selection process for both *Core* and *Opportunity Missions* are described. Both selection cycles are initiated by a Call, the scope of which will be clearly defined (with the final decision resting with the Programme Board for Earth Observation) taking account of such factors as priorities in European concerns, already approved missions (ESA, national and international), etc.

(a) Core Missions

The *Core Mission* selection cycle will consist of four steps:

1. Call for ideas and/or mission concepts and selection for Step 2
2. Assessment studies and selection for Step 3
3. Phase A studies and selection for Step 4
4. Implementation.

The objective behind Step 1 is to seek the views of the Earth Observation research community on potential Earth Explorer missions. It will be initiated by a *Call for Ideas*. Step 2 is intended to pave the way for Phase A studies and for each of the selected candidate missions a Report for Assessment will be produced. These Reports will form the basis for the consultation with the community as well as for the decision for selection for Phase A study.

Towards the end of Step 3, Phase A *Reports for Assessment* will be produced and the results of the Phase A studies will be presented to the Earth Observation community in a dedicated consultative workshop. The Earth Science Advisory Committee (ESAC) will then evaluate the results with the support of Peer Groups, against the established criteria (see Section 5.5.4), and make recommendations on priorities for implementation for approval by the Programme Board.

The selection cycle is designed to produce a new mission start approximately every two years. At the start of each cycle, up to eight mission proposals would be selected from the responses to the *Call for Ideas* for assessment study. Up to four of these could ultimately be selected for Phase A. For Step 4, the ESAC will recommend an ordered pair of missions for sequential implementation.

The mission selected for the second slot will be kept under review for two years (i.e. up to its implementation) in order to ensure that the Phase A remains current. The linked implementation of two missions at a time reduces unnecessary repetition of studies. An individual selection cycle lasts about three-and-a-half years and cycles repeat every four years.

Recommendations presented to the Programme Board will include programmatic and mission (including cost) information as well as scientific and technical assessments. They will also include consideration of the long-term outlook for the programme.

(b) Opportunity Missions

The selection mechanism procedure established for *Core Missions*, while providing a very solid foundation for choice, inevitably involves a relatively lengthy procedure resulting in a significant time lapse between the initial call for ideas and final selection of a mission for implementation. This can be accepted for major missions, but means that the programme can not easily take advantage of possibilities that may arise for smaller *Opportunity Missions*, for which flexibility and rapid response are essential, especially as these can take several forms (see Section 5.1).

Accordingly, the selection mechanism for this category of mission is an adaption of that for the *Core Missions*, whereby missions are selected via a fast-track procedure involving three steps:

1. Call for proposals and selection for Step 2
2. Feasibility & design studies and selection for Step 3
3. Implementation.

There is no *Assessment Study* phase as it is assumed (given the need for expeditious implementation) that proposals for *Opportunity Missions* will be quite mature and relatively straightforward to implement compared to *Core Missions*. Phases A and B will effectively be merged. The calls will be issued as opportunities present themselves or on a nominal bi-annual basis i.e. at least one call will be issued every two years. They may take the form of a Call for Proposals for small focussed missions addressing specific research objectives or for proposals exploiting flight opportunities by the provision of an instrument.

From the responses to the *Call for Proposals* a limited number of proposals will be selected for Phase A study. Recommendations for selection will be made by the ESAC with the support of Peer Review Groups for Programme Board approval. The evaluation of the proposals will be made against the same selection criteria (see Section 5.5.4) as for *Core Missions*, with due consideration given to the balance of the overall programme and the time scales involved.

Step 3 relies on the Executive confirming an implementation scenario. The final decision on implementation will be made by the Programme Board with the ESAC advising on its scientific merit and technical feasibility. As for the *Core Missions*, recommendations presented to the Programme Board will include programmatic and mission (including cost) information.

Opportunity Missions are planned to be interleaved with *Core Missions* and so a nominal new start rate of one every two years is envisaged. The actual rate will depend on the cost and complexity of individual proposals.

5.5.4 Mission Selection Criteria

Seven individual selection criteria have been established by the Earth Observation Programme Board for the evaluation of any mission selected for the Earth Explorer Programme. They are:

1. Relevance to the research objectives of the Earth Explorer Programme
2. Need, usefulness and excellence
3. Uniqueness and complementarity
4. Degree of innovation and contribution to the advancement of European Earth Observation capabilities
5. Feasibility and level of maturity
6. Timeliness
7. Programmatics.

These will be applied during the evaluation of both *Core Missions* and *Opportunity Missions*. The research objectives (first criteria) are detailed in Chapter 2 and its associated Appendix B. In addition to science, Criteria 2 and 4 will include consideration of the prospects for potential applications and for future Earth Watch missions. Criterion 4 also encompasses assessment of the mission's potential to demonstrate techniques which may find application in Earth Watch missions.

5.6 Cooperation and Optimisation of Resources

This section is specifically concerned with the optimal use of resources through cooperation in the implementation of the Earth Explorer element of the overall Earth Observation Programme. Such cooperation is likely to be essential to maintain *Core Mission* costs within sensible budgetary limits, and its relevance to the list of nine illustrative Earth Explorer missions, described in Chapter 3, *Earth Explorers: Addressing the Objectives*, is demonstrated quite clearly in Table 4.1. It will be equally relevant to *Opportunity Missions*, which in many instances will be direct responses to flight opportunities on other, none ESA, missions.

Cooperation with other National and International Agencies and other entities, including other ESA programmes, is expected to take various forms. Indeed, being user driven, the sub-programme depends on the closest possible cooperation with the research community right from the initial formulation of mission concepts through to the exploitation of data. This in turn implies very close cooperation with Member States and, as appropriate, the European Commission and other European Bodies, to ensure the availability of sufficient resources. The selection mechanism will ensure the initiatives complement other national and international programmes.

The obvious mechanisms for resource optimisation through cooperation are of two types:

- Programme sharing through international cooperation.
- Procurement of instruments through *Announcements of Opportunity* in cooperation with Member States.

Both mechanisms will be pursued throughout Phases A and B of the successive Earth Explorer missions.

5.7 Relationship with the Earth Watch Programme

As indicated earlier, in Chapter 1, *Earth Explorers: Introduction*, the Earth Explorer Programme must be viewed as one facet of the overall Earth Observation Strategy of the Agency. Chapter 4, *Earth Explorers: The Wider Context*, shows how the Earth Watch programme complements the Earth Explorer element of the Agency's overall programme. It is designed to respond to the need for the development of applications and to move techniques from R & D to commercial and operational use. One interesting idea, discussed in Section 4.3.1, is the possibility of an Earth Explorer mission actually evolving during its lifetime to become an Earth Watch mission.

The nature of the links between Earth Explorer and Earth Watch was discussed in Chapter 4, but here it is necessary to extend this discussion by recognising the formal/programmatic links that must exist between the two elements of the Agency's overall Earth Observation Programme. For this it is essential to ensure that:

(a) the observational needs of the applications community are taken fully into account in assessing the *utility* of candidate Earth Explorer missions
(b) proper account is taken of the scientific needs of the European and Canadian research communities when formulating Earth Watch missions.

The latter must not compromise the realisation of a particular Earth Watch initiative by the imposition of additional requirements that undermine its feasibility.

Programmatically, this means that the ESA Earth Explorer and ESA Earth Watch preparation activities should be run within an integrated Earth Observation Programme and that decisions relating to the ESA Earth Explorer element of this programme (detailed above) must take account of the plans and needs of the application community. These must be viewed as a necessary and essential input to the review process, but must not compromise the realisation of the mission or its research objectives. This input must be available during user consultations as well as during Peer Reviews and Programme Board discussions. In this context, the key criteria are those of *utility* and *cost-efficiency*.

6. Financial and Schedule Aspects

For the objectives of the Earth Explorer element of the Living Planet Programme to be achieved efficiently, an envelope programme consisting of a regular series of *Core* and *Opportunity Missions* is essential. Such a programme must have the general characteristics of the Science Programme to provide for the necessary interaction with users and efficient flexibility of management. However, unlike a mandatory programme, an envelope programme recognises that the interests of Member States are not necessarily directly linked to GNP contributions. They may be influenced by other factors linked to industrial capacity, past investments and future applications.

The level of funding is driven mainly by the frequency and cost of missions. The frequency must be high enough to retain credibility with the research community. It must also be high enough to ensure the efficient utilisation of industrial resources. Overall, the timelines of the programme must be such that the interests of all the main Earth Observation disciplines can be addressed over a period of the order of a decade. If significant advances are to be achieved in Europe in Earth Observation science on a broad front (viz. Chapter 2), so that Europe will be in a position to address the political concerns outlined in Chapter 1, an implementation rate of about one *Core Mission* every two years, interspersed by *Opportunity Missions*, is required.

In the future, missions will generally be smaller and more focussed and the envelope mechanism will ensure that they are implemented efficiently. However, individual missions may vary significantly in size and scope and some could still be quite large. Financial control can be exerted by specifying that the ESA contribution to any *Core Mission* must not exceed 400-MECU (in most instances costs should be much smaller than this). As in the Science Programme larger missions would be accommodated by external collaborative arrangements. In a similar way, a financial target of between 50 and 100 MECU would be set for individual *Opportunity Missions*.

The resulting financial and schedule implications are illustrated in Figure 6.1. This is based on current knowledge of the costs of the various types of *Core Missions* and places a cap of 100 MECU on the *Opportunity Missions*. It also assumes a programme build-up over the first four years to arrive at a steady level of resources of 250-MECU per year. After an initial agreement covering the first ten years, the level of funding will be reviewed every five years, to be reconfirmed, or adjusted, for the following ten years. This mechanism provides the flexibility to respond to changing priorities, while at the same time ensuring the stability necessary for the research and industrial communities.

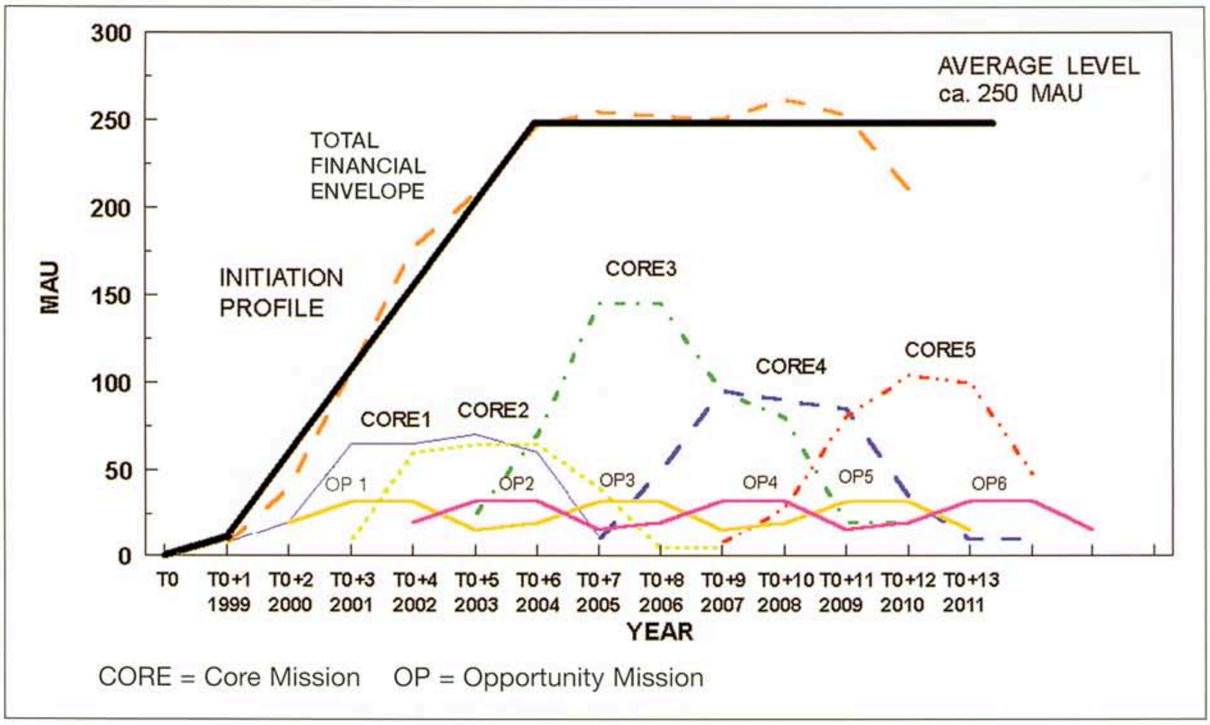


Figure 6.1 Illustration of financial and programmatic implications of implementing the Earth Explorer missions

A level of funding much smaller than this would severely disrupt this element of the Living Planet Programme as a choice would then have to be made between two stark options:

- to significantly reduce the frequency of missions
- to eliminate the Opportunity Missions.

In either case the scope of the sub-programme and many of its advantages would be undermined. The first would mean that the interests of only a small section of the research community could be addressed on reasonable time scales – so reducing the appeal of the this element of the Living Planet Programme to the community as a whole. The second would severely reduce the Earth Explorer Programme's ability to respond to evolving situations – so undermining its ability to redress one of the major weaknesses of the current situation. Both would reduce the opportunities for technological development and the furtherance of Earth Watch concepts. Neither would further the cause of international collaboration or the speed with which some of the major European concerns can be addressed.

Currently the Agency's total Earth Observation Programme runs out at around 600 MECU per annum. Overall, over the next five years, it is intended to bring the annual level of spending down to a mean level of the order of 450 MECU, covering all aspects of Earth Observation. The spending rate of about 250 MECU per annum for the envisaged Earth Explorer Programme is consistent with this target. The level of 450 MECU per annum corresponds to the annual spending of one of the larger ESA Member States, or about a fifth of NASA's annual expenditure, in this area.

Appendices

Appendix A

Environmental Obligations of the European Union and Application of Remote Sensing

Appendix B

The Research Objectives – The Four Themes

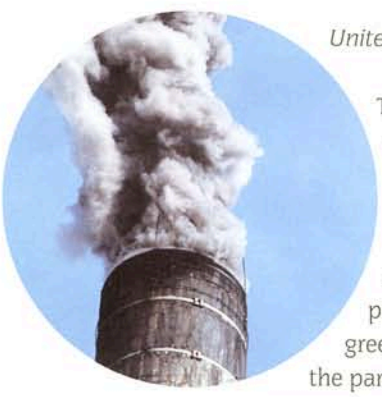
APPENDIX A

Environmental Obligations of the European Union and Application of Remote Sensing

A.1. Introduction

This Appendix contains a compilation of the legal instruments (Ref. 1: Montreal Protocol) under which the European Union is obliged to observe or monitor the environment and which remote sensing may help them address. It is an edited version of an input provided by the Commission extended to indicate the relevance of data from satellites.

A.2. Atmosphere



United Nations Framework Convention on Climate Change of 1992 (FCCC)

The FCCC encompasses scientific and technological research as well as the development of databases. These activities are concerned with improving knowledge of causes and effects, as well as the extents and time scales of the changes of climate.

As a party to the FCCC, the European Union accepts the commitment to adopt policies and take corresponding measures aimed at returning emissions of greenhouse gases to 1990 levels by the year 2000. According to Articles 4 and 5 the parties are obliged to undertake research and the systematic observation of key parameters. In this context it is necessary to determine the concentration of ephemeral trace gases, such as tropospheric ozone, for which satellite data are very useful. European instruments are already available (e.g. GOME on ERS-2) and others will be available in the near future (e.g. Sciamachy on Envisat from 1999).

For the research into the greenhouse effect, additional information is required (e.g. global cloudiness) much of which only can be delivered by satellites such as Meteosat.

Vienna Convention of 1985 on the Protection of the Ozone Layer (Vienna Convention) and the Montreal Protocol of 1987 on Substances that Deplete the Ozone Layer (Montreal Protocol).

According to Articles 2 and 3 of the Vienna Convention of 1995, the parties are obliged to undertake systematic observations, carry out research and exchange information in order to better understand and assess the effects of human activities on the ozone layer and on human health and on the environment arising from the modification of the ozone layer. Research and scientific assessments have to be undertaken with regard to (inter alia):

(a) the physical and chemical processes that may affect the ozone layer
(b) impacts on human health and other biological effects deriving from any modification of the ozone layer
(c) climatic effects deriving from any modifications of the ozone layer.

For the research into the stratospheric ozone layer, satellite remote sensing provides an indispensable contribution to environmental monitoring.

For the moment, continuous monitoring of the density of the ozone layer can be ensured by using the Russian TOM instrument on METEOR and the GOME on ERS-2. In the future other sensors should be available including:

- SCIAMACHY on Envisat
- OMI on Metop.

In terms of cost efficiency and global coverage, the use of satellite remote sensing has a clear advantage over conventional ground-based techniques.

Convention of 1979 on Long-Range Transboundary Air Pollution (LRTAP)

The objective of the LRTAP, to which the European Union is a party, is to reduce and control the transboundary transfer of emissions (Article 2). To achieve this objective, it is *inter alia* necessary to measure the emission and concentration of air pollution. Such measurements can be made by utilising sensors like GOME on ERS-2, SCIAMACHY and MIPAS on Envisat, and eventually OMI on Metop.

A.3. Forest

Council Regulation (EEC) No. 3528/86 of 17 November 1986 on the protection of the Community's Forests against Atmospheric Pollution.

According to this Regulation the Member States of the European Union are obliged to investigate the damage to forests caused by air pollution. The level of damage can be deduced from vegetation indices derived from remote sensing data. The satellites that can provide such data include: TM on LANDSAT, HRV on SPOT, MOMS on PRIRODA, MSU-SK on RESURS and VMI on SPOT-4.

A.4. Marine Pollution

Convention of 1972 on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters (London Convention)

International Convention of 1973 for the Prevention of Pollution from Ships (MARPOL Convention)

Convention of 1974 on the Prevention of Marine Pollution from Land-Based Sources (Paris Convention)

Agreement of 1983 for Cooperation in Dealing with Pollution of the North Sea by Oil and Other Harmful Substances (Bonn Agreement)

Convention of 1974 and 1992 for the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention)

Convention of 1992 for the Protection of the Marine Environment of the North-East Atlantic (Oslo and Paris Conventions)

The European Union is a party to all these treaties except for the London Convention and the MARPOL Convention, which have been signed *inter alia* by France, Germany and The Netherlands. According to the Paris Convention (Article 10), the parties have agreed to establish programmes of scientific and technical research.

The parties to the 1992 Helsinki Convention have undertaken to cooperate in the fields of science, technology and other research, and to exchange data and other scientific information for the purposes of this Convention. Furthermore, the parties are obliged to undertake programmes aimed at developing methods for assessing the nature and extent of pollution and risks in the Baltic Sea area (Article 24). Article 20 of the Helsinki Convention stipulates special obligations of the European Commission *(inter alia)*:

- to keep the implementation of the Convention under continuous observation
- to make recommendations on measures relating to the purposes of the Convention
- to promote scientific and technological research.

The Oslo and Paris Conventions also stipulate (Art. 8) that the parties must establish programmes of scientific or technical research, the results of which have to be transmitted to the other parties.

In general, all parties to the above-mentioned conventions are obliged to acquire data on the state of the sea and to operate a monitoring system to ensure the earliest possible assessment of current levels of marine pollution.

Such monitoring can be achieved by exploiting data derived from satellite observations on water surface temperatures (i.e. AVHRR on NOAA 1-15; ATSR on ERS-1 and ERS-2; AATSR on Envisat), on chlorophyll levels (i.e. SEAWIFS on SEASTAR; MERIS on Envisat) and on oil spills (i.e. instruments on ERS-1, ERS-2 and Envisat; RADARSAT; HRV on SPOT; TM on LANDSAT).

86/85 EEC Council Decision of 6 March 1986 Establishing a Community Information System for the Control and Reduction of Pollution caused by the Spillage of Hydrocarbons and Other Harmful Substances at Sea.

By this decision, the provision of an information system was established to provide competent authorities in the Member States with the data required for the control and reduction of the pollution caused by the spillage of hydrocarbons and other harmful substances at sea. In the case of accidents, the quantity of oil pollution can be assessed using remote sensing satellites (e.g. ERS-l and ERS-2; Envisat; RADARSAT; SPOT; LANDSAT) though this technique is not suitable for monitoring chronic pollution.

A.5. Water Courses

Convention of 1992 on the Protection and Use of Transboundary Water Courses and International Lakes

The objective of this treaty, which the European Union has ratified, is to protect the environment from the adverse effects of human use of transboundary waters. There is a general obligation on the parties to take all appropriate measures to protect, control and reduce any trans-boundary input, which is defined as *"any significant adverse effect on the environment resulting from a change in the conditions of transboundary waters caused by human activity"*.

Convention of 1976 for the Protection of the Rhine against Chemical Pollution

The parties to this convention are France, Germany, Luxembourg, The Netherlands, Switzerland and the European Union. The aim of this convention is to improve the quality of the waters of the Rhine by regulating discharges into it.

The parties are required to monitor all discharges and to inform the other parties if a sudden increase in pollution is detected or an accident occurs which seriously threatens the quality of the Rhine's water (Articles 8, 10 and 11).

Satellite data can help track the transport of pollution across international boundaries.

A.6. Conservation

Convention of 1992 on Biological Diversity (Biodiversity Convention)

The European Commission is a party to this, the most comprehensive international agreement in this area. The convention calls for national action to ensure the conservation and sustainable use of biodiversity (Article 6) and, more specifically, sets out possible measures for conserving ecosystems, habitats and species (Articles 8 and 9).

Within the context of these obligations, there is a requirement to investigate changes in the environment. To a broad extent, satellite data can be used to detect changes.

Convention of 1979 on the Conservation of Migratory Species of Wild Animals (Bonn Convention)

Remote sensing by satellite is for the time being not mature enough (insufficient resolution) for application under this convention.

Convention of 1971 on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention)

Parties of this convention are all Member States of the European Union, but not the European Union itself.

Two principal tasks derive from this Convention:
- Monitoring of wetlands (changes of state resulting from pollution and other interferences).
- Compiling an inventory of important wetlands.

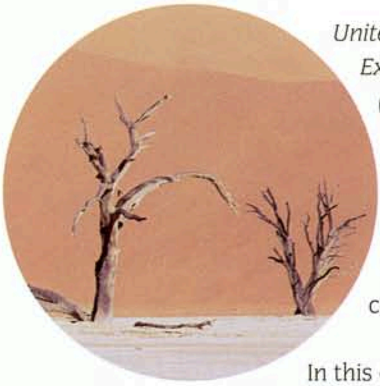
In particular, for compiling the cartography and temporal changes of wetlands, remote sensing by satellites should be considered as an alternative to conventional approaches.

Convention of 1979 on the Conservation of European Wildlife and Natural Habitats (Berne Convention)

Convention of 1980 on the Conservation of Antarctic Marine Living Resources (CCAMLR)

The objectives of these two conventions, to which the European Union is a party, are to conserve wild flora and fauna and their natural habitats (Berne Convention) and Antarctic marine resources (CCAMLR). In both cases, remote sensing data from satellites has a key role to play.

A.7. Desertification



United Nations Convention of 1994 to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa (Desertification Convention).

This convention stipulates the obligations of affected countries (who are party to it) to establish strategies to combat desertification and mitigate the effects of drought. With regard to developed countries (who are parties to it), the convention creates a framework for them to assist developing countries in combating desertification.

In this context, the transfer of Earth observation data and technical expertise from European to developing countries can be an important factor in ensuring the realisation of the objectives of the convention, since satellite sensors can be used for land classification measurements. Moreover, the requirement for wide area monitoring of desertification cannot be effectively implemented without recourse to Earth observation data.

APPENDIX B
The Research Objectives

The Four Themes

B.1 Theme 1 – Earth Interior
B.2 Theme 2 – Physical Climate
B.3 Theme 3 – Geosphere/Biosphere
B.4 Theme 4 – Atmosphere and Marine Environment: Anthropogenic Impact

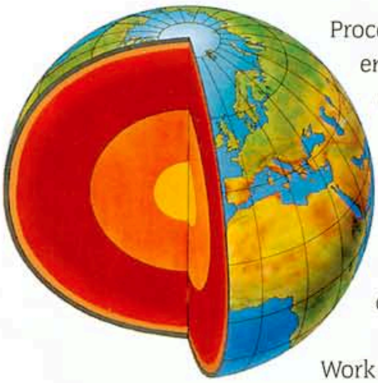
This Appendix contains the reports prepared by the Members of the Earth Science Advisory Committee covering each of the four Themes, i.e. Earth Interior, Physical Climate, the Geosphere/Biosphere, and Atmosphere and Marine Environment: Anthropogenic Impact. In each case these review the current situation, highlight the issues relevant to the post-2000 era and the areas that should be addressed by the Earth Explorer element of the Living Planet Programme.

These reports largely reflect the views expressed during the various user consultation meetings organised by the Agency to determine the views of the Earth Observation Community on the objectives of its Earth Observation Programme. Here specific mention must be made of the meetings held at the Agency's establishment in The Netherlands (i.e.ESTEC, Noordwijk) in May 1991 (ESA, 1991) and October 1994 (ESA, 1994). These attracted wide participation and provided a firm basis for the Committee to start its deliberations.

However, there have been many evolutions since the October 1994 meeting and the Committee has taken full note of these in drafting the four reports reproduced in this Annex.

Appendix B.1
Theme 1 – Earth Interior

B.1.1. Introduction



Processes occurring inside the Earth interact strongly with our climate, the Earth's environment and our living sphere on all time scales. This includes volcanic emissions and their interactions with the atmosphere and oceans, environmental changes resulting from earthquakes, tsunamis, soil erosion or land slides, readjustment of the Earth's crust to deglaciation and its effect on sea level, etc. All have profound ecological and economic impacts on mankind. To progress, much better insights are required into the origin, evolution and composition of core, mantle and crust and their roles in determining the internal the dynamics of the Earth.

Work in this area suffers intrinsically from our inability to measure directly the relevant physical or chemical parameters. Only a few sources of direct information exist about the dynamics of the Earth's interior, the most prominent being the magnetic field, the gravity field and the propagation of seismic waves. In recent years seismic tomography has brought an enormous wealth of new information and holds a lot of promise for the future, but the translation of the retrieved velocity anomaly field to geophysical parameters, like density anomalies, remains problematic. For this reason observation of the Earth's gravity and magnetic fields is of fundamental importance to our progress in the study of the dynamics of the Earth's interior.

Both the observed gravity and magnetic fields are closely related to processes occurring in the Earth's core, its mantle and in the lithosphere. However, the very different nature of their respective sources means that spectral characteristics and variations in time (as well as state of knowledge) differ significantly in the two cases. As a consequence, the scientific objectives underlying the study of the magnetic field are different from those for the gravity field. The latter are also related to further applications in Earth science and ocean circulation linked to a better knowledge of the marine geoid and geodesy. To fulfil these objectives, the gravity and magnetic fields must be determined uniformly and globally to significant spatial resolution within a reasonable time. Only by the use of satellites can these general requirements be met.

B.1.2. Gravity Field and Processes Occurring Inside the Earth

Improved insight into the dynamics of the continental lithosphere is a central issue of studies of the physics of the Earth's interior. This includes its chemical and thermal composition, and processes such as mountain building, underplating and delamination below collision mountain belts, thinning below sedimentary basins and rifts, and thermal processes such as hot spots. Specific issues to be addressed by an accurate and detailed determination of the gravity field are:

- discrimination between active and passive models of rifting
- identification of anomalous mass which may drive basin subsidence
- determination of the deep density structure beneath the continents and of the mechanical strength of the continental lithosphere
- identification of the contribution of post-glacial rebound to sea level change.

In addition, understanding of mantle processes, in particular convection patterns, and of post-glacial mass readjustment, will greatly benefit from improved and more detailed knowledge of the Earth's gravity field.

The impact of processes occurring within the Earth on the global ocean is expressed in a variety of ways and on a wide range of temporal and spatial scales, as illustrated schematically in Figure B.1.1. The most significant impact lies in the longer term (i.e. climate time scales of order 100 years) in which deglaciation and continental rebound (via impact on the marine geoid) influence global sea levels and global ocean circulation. However, the temporal variations in the sea level and ocean currents on short and medium time scales can be directly derived from satellite altimetry.

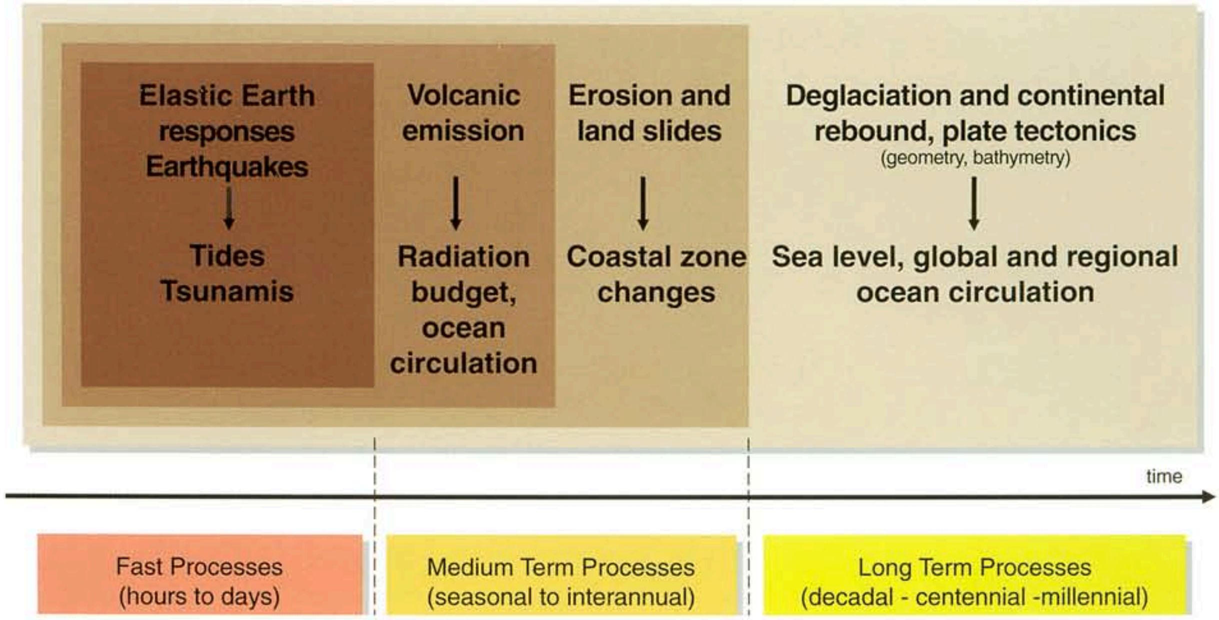


Figure B.1.1 Examples of the impact of processes occurring within the Earth on the Global Ocean

Present day gravity models are based on three data sources:

(a) *Terrestrial (and ship-borne) gravity anomalies determined from gravity (and height) surveys, represented as mean values over equiangular blocks.* Even after more than 50 years of worldwide effort, coverage and accuracy are not satisfactory in certain parts of our planet. In addition, unknown offsets and systematic distortions exist between the various geographical regions, in particular between areas separated by water. This type of data contains medium and high frequency information.

(b) *Gravity obtained from satellite radar altimetry providing global coverage of precise sea surface heights.* Disregarding the topography of the sea surface (i.e. the deviation of the actual ocean surface from the geoid of order ± 1 m), these data provide moderately accurate geoid information. Gravity anomalies derived from it exhibit differences of 1 - 2 mgal (1 mgal = 10^{-5} m s^{-2}) in some areas, but up to 10 mgal when compared with modern ship gravimetry. Altimetry provides information in the medium to high range of frequencies

(c) *Geopotential models determined from the regular analysis of satellite orbits.* This involves the analysis of the orbits of a large number of mostly non-geodetic satellites with a large range of orbit elements and based on a variety of tracking data types. These models take the form of spherical harmonic expansions of the gravity field and provide information on the long wavelength part of the spectrum. One of the best currently available geopotential models, based purely on satellite orbit analysis (no altimetry, no terrestrial surface gravity), is the Joint Gravity Model JGM-1S. It is complete to degree and order of 60, which corresponds to a spatial half wavelength of about 330 km (L = 20000/60 km). However, above degree 36 (or for half wavelengths $L \leq 560$ km) the error estimates approach 100%.

Geopotential models combining all three data sources also exist. The latest and most advanced is EGM96 (degree and order 360 and spatial half wavelength of about 60 km). This model is an optimal transformation of satellite orbit analyses, altimetry and terrestrial gravimetry into one set of spherical harmonic coefficients. However, even this is weak in areas with poor data coverage and distorted by offsets and biases. In ocean areas, the available altimetry corrected for tides and models of ocean topography does not reliably distinguish between the actual ocean surface and the geoid.

Further progress requires global determination of the gravity field, without biases and with uniform accuracy. In terms of gravity anomalies, the required accuracy is 1-2 mgal with a spatial resolution down to half wavelengths of between 50 and 400 km for lithosphere studies. For mantle studies, a spatial resolution of between 100 to 5000 km will suffice.

B.1.3. Magnetic Field and Internal Earth Processes

Improved knowledge of the main magnetic field and its temporal variation is the key to a better understanding of core processes, in particular the kinematics of the flow of the bulk of the core and the exact nature of the coupling mechanism between the core and the mantle. This is needed to explain low frequency variations in the observed length-of-day (l.o.d.).

The lithospheric magnetic anomaly field is produced by spatial variations in rock magnetization in the Earth's upper layers. This magnetization is partly remnant magnetization acquired during the formation of the rock and partly induced by the ambient field. It is therefore proportional to this field and to the magnetic susceptibility of the rock. Observations of the induced field can help to delineate the composition of the old crystalline basement underlying most continental areas, and to investigate the chemical and thermal evolution of the continental lithosphere.

Current models of the main magnetic field using Magsat data provide quite accurate descriptions of the geomagnetic main field in about 1980. However, there has been no comparable satellite geomagnetic survey since then, and so the quality of available main-field information and models has declined over the past fifteen years. Currently, it is necessary to rely very largely on data from a network of magnetic observatories to describe and predict the secular variations. This data set has a notoriously patchy distribution over the surface of the Earth. In regions remote from magnetic observatories, the uncertainties in main-field models are unacceptably high (they can reach 1° or more in the field direction and several hundred nano Teslas (nT) in field strength).

To improve on the currently poor quantitative global description of the vector magnetic field and the subsequent lack of proper separation between core motion, secular variation, jerks and l.o.d., the components of the global magnetic field have to be quantified to an accuracy of better than 1.5 nT.

B.1.4. Marine Geoid and its Impact on Ocean Circulation

Long term variations and the absolute value of the ocean dynamic topography require the determination of the 'hypothetic' ocean at rest, i.e. the marine geoid. Unfortunately, current insight into geoid uncertainties and their impact on the absolute dynamic topography is limited, particularly at shorter wavelengths. These uncertainties result in errors of the order of 10 to 30 cm in amplitude on wavelengths of less than 1000 km which, if interpreted as ocean dynamic topography signals, would correspond to transports of the order of 10 to 30 Sv (10^6 m^3 s^{-1}). This is clearly unacceptable for ocean circulation studies (for comparison the baroclinic transport of the Gulf Stream is about 50-100 Sv).

While in general the magnitude of the ocean dynamic topography signal decreases with horizontal scale, geoid errors increase with resolution. This means that the current absolute dynamic topography deduced from altimetry and geoids is only significant and reliable at scales larger than about 2000 – 3000 km. At shorter wavelengths (< 100km) the ocean signal is dominated by variability, which can be determined with very good precision from altimetry. Thus, in the near future improved eddy-resolving ocean models, adjusted by the assimilation of the altimetry data, should be able to reproduce the mean short-wavelength dynamic topography signal to sufficient accuracy. The difficulty arises at intermediate scales (say 100 – 2000 km half wavelength), where the dynamic topography signature is important in practically all areas of the global ocean.

Thus, given the continuing need to study and predict climate variation and climate change by the combined use of altimetry, global ocean circulation models, and high-quality global in-situ data, it is essential to reduce significantly errors in our knowledge of the Earth's geoid. In particular, at a half wavelength of 100 to 200 km the cumulative geoid errors should be less than 2 cm, leading to errors of less than 0.1 cm at a half wavelength of, for example, 1000 km. This could be achieved once and for all through a single dedicated gravity field mission. In turn, this would significantly upgrade the value of existing and future altimetric sea surface height data. There is no other possibility for measuring the dynamic sea surface height on a global scale with adequate time resolution.

Accurate sea surface heights, referred to a similarly accurate geoid (and ultimately to the temporal changes of the geoid), are also very important to oceanographic and related climate investigations in terms of:

- model verification (identification of errors in ocean models and improved understanding of model physics)
- correction of ocean modelling and the derivation of improved estimates of oceanic fields (mass and heat transports, deep ocean overturning, state of stability of ocean circulation)
- monitoring of changes in sea surface heights on the spatial and time scales associated with natural climate variability or anthropogenic climate changes.

B.1.5. Geodesy

One of the key objectives in geodesy is to improve and unify the different orthometric height systems (datum connection) using high quality gravity field data. At present, these systems differ by the order of decimetres between islands and between islands and continents, over distances of a few 100 km.

One aim of an integrated global geodetic observing system, as suggested in Table B.1.1, should be to reduce these differences to about 0.05 m. Only with this level of accuracy can the physical causes of sea level changes in one part of our planet be compared with sea level changes in other parts. It will also enable 'GPS' heights to be related to the sea levels.

B.1.6. Conclusions

For each of the four sub-themes clear objectives and requirements have been identified, as summarised in Table 2.1. Substantial insights into ice and ocean dynamics and processes occurring inside the Earth could be gained in the near future by the implementation of an integrated global observing system addressing these needs (see Table B.1.1).

This system should be capable of:

- monitoring the kinematics of the surface of the Earth, i.e. all temporal changes of land, ice and ocean surface
- relating the kinematics to the physics of the respective driving mechanisms
- determining the integrated effect of all changes in the Earth's angular momentum
- improving the determination of the oceanic mass and heat transports, as well as estimates of both the land and glacier mass balances (in conjunction with better knowledge of the Earth's gravity field).

To a large extent this integrated observing system is operational already; other parts are under development. It makes use of the International Geodynamics GPS service, the International Earth Rotation Service (IERS), the Permanent Service of Mean Sea Level and other services, of the series of altimeter satellites and, as a new element, of SAR interferometry (INSAR). It is operated by international cooperation under the umbrella of the International Association of Geodesy (IAG). The key element still missing is an

Component	Objective	Observation Techniques
I. Frame	Implementation of global cluster of fiducial points, determined at mm to cm level	VLBI, Global Positioning Systems (GPS), Satellite and lunar laser ranging, Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS), Precise Range and Range Rate Equipment (PRARE)
II.Kinematic observing system	Monitor temporal variations of land/ice/ocean surfaces (plates, intra-plates, volcanos, earthquakes, glaciers, ocean variability, sea level ...)	Altimetry, SAR, Interferometry, Global Positioning Systems (GPS), Tide gauges
III. Earth rotation (polar motion changes in l.o.d., nutation)	Determine integrated effect of changes in angular momentum (mass changes in atmosphere, cryosphere, oceans, core/mantle dynamics; momentum exchange between system components)	Astronomy, VLBI, Global Positioning Systems (GPS), Satellite Laser Ranging (SLR), Laser Retro-Reflector (LRR), DORIS
IV. Global gravity potential (geoid) and its temporal variations	(a) Improve unification of height systems for geodesy and sea level monitoring. (b) Improve quantification of isostasy models, absolute ocean circulation, mass and heat transport and ice flux.	Altimetry and gravity field measurements

Table B.1.1. The link between the objectives of Theme 1 and potential observation techniques

accurate and detailed, globally homogeneous gravity field model which can provide:

- a geoid with a cumulative error of the order of 1 to 2 cm at a half wavelength of about 100–200 km
- a gravity anomaly field with a 1 to 2 mgal precision at 100 to 200 km resolution.

Appendix B.2
Theme 2 - Physical Climate

B.2.1. Introduction

Before the significance of anthropogenic impacts on the climate system can be fully assessed, it is necessary to understand the internal variability of the various components of the climate system and to separate long-term climatic trends from seasonal and inter-annual fluctuations. For this it is essential to advance knowledge of the physical processes and interaction mechanisms involved in the land/ocean/atmosphere system and to study past and present changes in the global environment. Satellite sensors are basic tools for climate monitoring and important data sources for the numerical models used to simulate and understand climate change.

Human activities are causing major changes in the chemistry and radiative properties of the atmosphere. Global climate models predict that a doubling of the carbon dioxide or equivalent greenhouse gas concentration will result in an increase in the global mean tropospheric temperature of 2 to 4 K. However, in addition to the uncertainties regarding global temperature change, the various climate models show large differences in predicted regional warming/cooling patterns and in effects on the hydrological cycle, which are key issues for habitability, water supply, and agriculture in sensitive climatic zones.

To predict possible impacts of human activities on climate, it is first necessary to understand the internal variability of the various components of the climate system. These involve fluctuations of atmospheric and ocean dynamics and composition on a wide range of time scales, from the fast (atmospheric) components (hours to weeks), through the short term components (seasonal to inter-annual variations) to long term components (decadal to centennial variations and longer). Since the components of the climate system interact with each other in different ways, depending on the time scale, it is convenient to consider the scientific issues in terms of the different time scales. Figure B.2.1 summarises the links between the different components of climate, which are distributed over a wide range of time scales.

B.2.2. The Fast Components of Climate – Hours to Weeks

The fast components of climate are primarily atmosphere-related, as all other processes have much longer time scales. An understanding of these components of the climate system requires a thorough knowledge of the global energy and water cycle. This requires a concerted effort by experimenters and modellers alike to calibrate and improve the representation of the hydrological cycle in atmospheric models, including cloud-radiative processes, condensation, evaporation and precipitation processes, turbulent processes in the free atmosphere and in the planetary boundary layer, and the surface aspects of the hydrological cycle.

The success of this effort will depend on the availability of three-dimensional wind fields, temperature and humidity fields, of measurements of planetary and surface albedos, of atmospheric and surface long-wave emission, of optical and microwave backscatter (for cloud and aerosol microphysical properties), of precipitation and of ocean and land-surface characteristics (such as surface temperature, soil moisture, snow and ice cover, etc.). In addition, there are critical operational and research requirements for basic observations of three-dimensional wind, temperature and humidity fields from space.

The deployment of advanced temperature and humidity sounders with much improved vertical resolution on Metop and on American satellites will represent a significant improvement over the inadequate vertical resolution provided by the current generation of instruments. However, current plans for the provision of observations of three dimensional wind fields (through scatterometers and cloud motion vectors) fall far short of operational and research requirements. Since the wind field has a major impact on the hydrological cycle and since many of the relevant features of the wind field (such as jets with very sharp vertical structure) cannot be inferred from measurements of other variables, it is essential to provide the capability for the direct measurement of the wind field from space.

It is generally recognised that the treatment of cloud radiation interaction is the most uncertain aspect of climate modelling. The modelling of clouds requires accurate treatment of:

- cloud source functions such as condensation processes associated with large scale ascent or convective ascent, and processes such as radiative cooling, boundary layer turbulence, and detrainment from convective systems
- sink functions such as conversion to precipitation, radiative heating, large scale descent, cumulus-induced subsidence, dilution through cloud-top entrainment, and turbulent erosion from the sides of clouds.

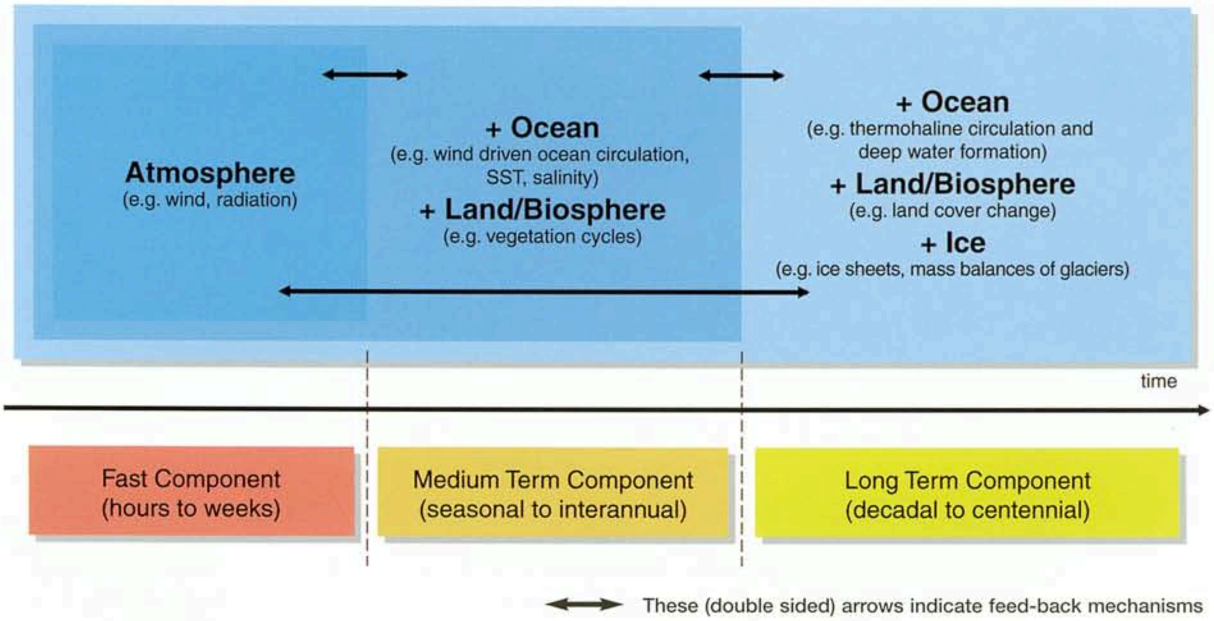


Figure B.2.1 The links between the components of climate

Knowledge of these processes, and of the microphysics of clouds, is essential for modelling the three dimensional distribution of clouds, and their optical and radiative properties. While the 1997 TRMM (Tropical Rainfall Monitoring Mission) and associated field experiments and modelling studies will provide a global three-dimensional view of precipitation processes, TRMM will provide no information about the three dimensional extent of clouds and their optical/radiative properties, which are the key areas of uncertainty. In the time-frame 2004+, when the lessons of TRMM should have been digested, there will be a strong requirement from the climate modelling community for a mission to document the three-dimensional distribution of clouds and their interaction with the radiative and dynamic fields, and for a related set of field experiments and modelling studies to clarify and quantify the mechanisms involved.

The deliverables from these efforts will be substantially improved atmospheric models for application to longer term climate studies and for use in 1–10 day operational forecasting.

B.2.3. Seasonal to Inter-Annual Climate Variations and Processes

Despite the chaotic nature of the atmosphere, there is now clear evidence that slow variations of conditions at the ocean and land surfaces can modify short-term climate variations in a predictable way. Prediction of seasonal to inter-annual climate fluctuations requires the proper description of the atmosphere (the fast component), its interaction with the upper ocean in the tropics (dynamics and thermodynamics) and its interaction with the cryosphere and the continental biosphere (i.e. sea ice, snow cover and vegetation – the slower components of the system). These numerous interactions introduce fluctuations which are specific to the coupled systems and explain much of the climate variability on these time scales.

In addition to requirements for satellite observation of the atmosphere, these developments will require high-quality long-term ocean observations, including precise sea surface temperature (SST), scatterometer surface wind measurements and surface dynamic topography. New techniques, like the measurement of sea surface salinity using low-frequency passive microwave instruments, could make important contributions.

Continental-scale variations in soil-moisture and snow-cover are believed to provide system memory which can also be exploited for seasonal forecasting. Satellites will be necessary to monitor changes on the continents of snow coverage and thickness, vegetation coverage and seasonal cycle, albedo and radiation balance, state of vegetation and its implications for soil moisture. Developments in the modelling of the atmosphere/land/biosphere can therefore be assessed within the same framework, by testing their capability to track and forecast observed variations on these short-term climate time scales. In addition, these climate processes probably have impacts (with potential feedbacks) at the surface, including temperature and precipitation patterns, vegetation cycles, and snow coverage, and so are quite critical to the climate and economy (agriculture, water reservoirs) of temperate and high latitude regions.

Measurements of sea ice extent, age and thickness and the monitoring of the border of ice caps and their discharge will all be necessary because they affect ocean-atmosphere heat fluxes, ocean salinity and ocean-atmosphere dynamics.

The deliverables from these efforts will be coupled atmosphere/ocean data assimilation and forecast systems which should provide useful forecasts on seasonal to inter-annual time scales, and are therefore relevant to studies of decadal and centennial climate variations.

B.2.4. Decadal to Centennial Variations and Processes

Many processes contribute to climate fluctuations on decadal or longer time scales. Unfortunately, however, many of the corresponding signals (changes of SST, dynamic topography, sea level change, sea ice extent, atmospheric winds,...) are small and so the best possible precision and sampling will be required to observe them unambiguously. The strategy needed to document and understand these processes will probably have data from the operational monitoring of the atmosphere as a central component. Oceanographic data requirements from satellites include sea surface temperature, ocean colour, dynamic topography and surface winds, with requirements for high accuracy and optimised sampling.

Scientific understandings of convective ocean mixing and of deep and bottom water formation are of particular concern for estimating long-term climatic trends in ocean carbon uptake and its implications for the long-term control of atmospheric carbon dioxide. Estimation of carbon uptake in the oceans is not very reliable because the exchange of carbon between the ocean and the atmosphere is driven by complex physical and biological processes which vary markedly on both spatial and temporal scales. Detailed process studies, as well as synoptic data sets of ocean parameters, are needed to accurately represent the ocean component in global climate models, including information on ocean dynamics and on the carbon, heat and fresh water cycles.

The terrestrial environment is coupled with the atmosphere through exchange processes involving energy, moisture, and gases. Land cover and its biospheric processes are important factors for long-term climatic change. However, major quantitative questions remain unanswered about the sources and sinks of carbon dioxide and methane, which depend on properties of soil and vegetation and on turbulent exchange processes in the boundary layer. Changing land-use practices have significant impacts on the hydrological cycle, contributing to long-term climatic change, with consequences for various ecosystems. However, biophysical and chemical processes involving land surfaces are not adequately represented in climate models, even though they are one of the determining factors for long-term climate trends.

Climate models predict that the largest temperature increases will occur at high latitudes. If correct, this could result in major changes in the mass balance of ice sheets and glaciers over the next few decades. The sea level rises associated with the melting of ice masses is of urgent concern for coastal communities, including many heavily populated areas around the World. Prediction of sea-level rise depends on the mass balance estimates for ice sheets and glaciers in response to changing climate conditions. The current mass balance of the ice sheets of Antarctica and Greenland is not well known. In fact it is matter of debate whether the total mass of Antarctic ice is presently growing or shrinking. The mass balance of glaciers and ice sheets is also of interest for climate monitoring and studies of past climate conditions, because the ice masses can be considered as time-integrated indicators of climatic change on medium to long time scales.

Knowledge of ice/atmosphere interactions and of the dynamics of the ice sheets is essential for the correct interpretation of these measurements. Sea ice and snow cover have much shorter time scales than the ice sheets, but are nevertheless import for climate conditions not only in the short term, but also on decadal and longer time scales. Major changes in the extents of sea ice and ice shelves will have pronounced effects on deep water formation and on the uptake of carbon dioxide, two processes that have significant climate impacts.

B.2.5. Conclusions

To understand the internal variability of the components of the climate system, it is essential to advance our knowledge of the various processes involved. For the three sub-Themes considered in this Chapter, this means:

- for the fast components of climate:
  - observation of the three-dimensional wind field; observation of the three-dimensional distribution of clouds and aerosols and their interaction with radiative and dynamic fields;
- for the seasonal to inter-annual processes:
  - retrieval of fluxes at the ocean/atmosphere, atmosphere/land/biosphere and ocean/atmosphere-cryosphere interfaces and the assessment of their oceanic energy impact;
- for the decadal to centennial variations and processes:
  - observation of temporal variability of ocean transport of energy and dissolved species; ocean–atmosphere exchange processes for energy and gases; observation of the energy and water cycle of ecosystems and their response to climate; bio-geochemical processes and their spatial and temporal variability; observation of the current mass balance of the polar ice sheets and its response to climate change; analysis of sea ice dynamics and deep water formation.

Table B.2.1 links the objectives and the different observation techniques to be applied for the three sub-Themes.

Table B.2.1 Objectives of Theme 2 and observational techniques proposed

Component	Objective	Observation Techniques
I. Fast - hours to weeks	Three dimensional atmospheric wind fields	Active visible/infrared techniques
	Three dimensional distribution of clouds and aerosols and their interactions with radiative and dynamic fields	Active/passive visible/infrared/microwave techniques
II. Medium Term - seasonal to interannual	Wind driven ocean circulation, SST, salinity	Active/passive microwave techniques
	Changes in vegetation cycles	Visible/infrared radiometry
III. Long Term - decadal to centennial	Thermohaline circulation and deep water formation, ice sheets, mass balances of glaciers, land cover change	Active/passive visible/infrared/microwave techniques

Appendix B.3
Theme 3 – Geosphere/Biosphere

B.3.1. Introduction

Within the geosphere/biosphere, major environmental processes and transformations occur which play an important role in the evolution of the climate system. This is affected by both natural phenomena and human actions and is of particular relevance to mankind, being constantly transformed and adapted to meet basic needs linked to population expansion and economic development. In fact, in the short to medium term, changes in the geosphere/biosphere system due to human activities are likely to be of at least the same magnitude (if not larger) as any natural climate impact. These include the impacts of:

- changes in land, vegetation and cover/land use (forest depletion, agriculture, etc.)
- changes in hydrological conditions to sustain agricultural and grazing activities (overgrazing, lack of water,...)
- changes in atmospheric composition (greenhouse warming, atmospheric deposition,...)
- extreme events (flooding, drought, volcanic activities,...)
- changes in soil degradation, erosion and desertification
- losses of biodiversity
- sea level rise.

In order to understand the cause and impact of such changes some key questions have to be answered :

- How will climate change affect terrestrial ecosystems, including coastal zones, and vice versa?
- What is the role of biological processes in the chemistry of the atmosphere and especially in the production and consumption of carbon dioxide, methane and other trace gases?
- What are the magnitudes of the fluxes to and from the major carbon reservoirs (including CO_2, CH_4,...)? What are the spatial and temporal variations of these fluxes and the corresponding uncertainties?
- What are the roles and influences of vegetation in the water and energy cycles?
- How do changes in the ecosystems, including the soils, affect the renewable and non-renewable resources of the geosphere/biosphere?

The international scientific community has devoted considerable effort over the past decade to addressing these questions. Thus, the World Climate Research Programme (WCRP) and the International Geosphere Biosphere Programme (IGBP) have provided the first sets of data and the first insights into the relevant processes, on local, regional and global scales. However, even if the processes occurring at the interfaces of the biosphere/geosphere system with the atmosphere and the ocean are well understood and parameterised on the very local scale, extending that knowledge to regional and global scales is still difficult. This is because of the strong coupling between these processes and the extreme heterogeneity of the geosphere/biosphere system, which renders the scaling procedures very complicated.

The identities of the main parameters needed to parameterise the relevant processes, particularly those describing the energy, water and carbon dioxide cycles, are not well known. In turn, the processes that link biospheric phenomena, surface atmosphere interactions, ecosystem processes, etc., are not yet adequately parameterised on all the relevant scales. Many land surface features and processes of global significance occur at the local scale and must be extrapolated to regional and global scales taking account of significant variations in surface properties. As a consequence, models are not yet reliable enough to determine the impact of human activities on the quality of the environment, the state of the resources, and climate trends.

Furthermore, due to their heterogeneity, there is much more spatial variability in land surface parameters than is the case for the atmosphere or the oceans, leading to measurement challenges still to be overcome. The large uncertainties in the measurement from space of the components of the biosphere/geosphere processes make the assimilation of remote sensing data into the models still very inaccurate and unstable. Given the importance of scaling, further progress will only be possible by associating space-borne observations with in-situ measurements, modelling and the assimilation of the data into these models at the appropriate scales.

B.3.2. The Processes to Consider

The most important processes to investigate and understand more quantitatively (on different spatial and temporal scales) have been identified as a result of experience gained over the last few decades in modelling the evolution of the geosphere/biosphere system and its links to the climate. These processes involve:

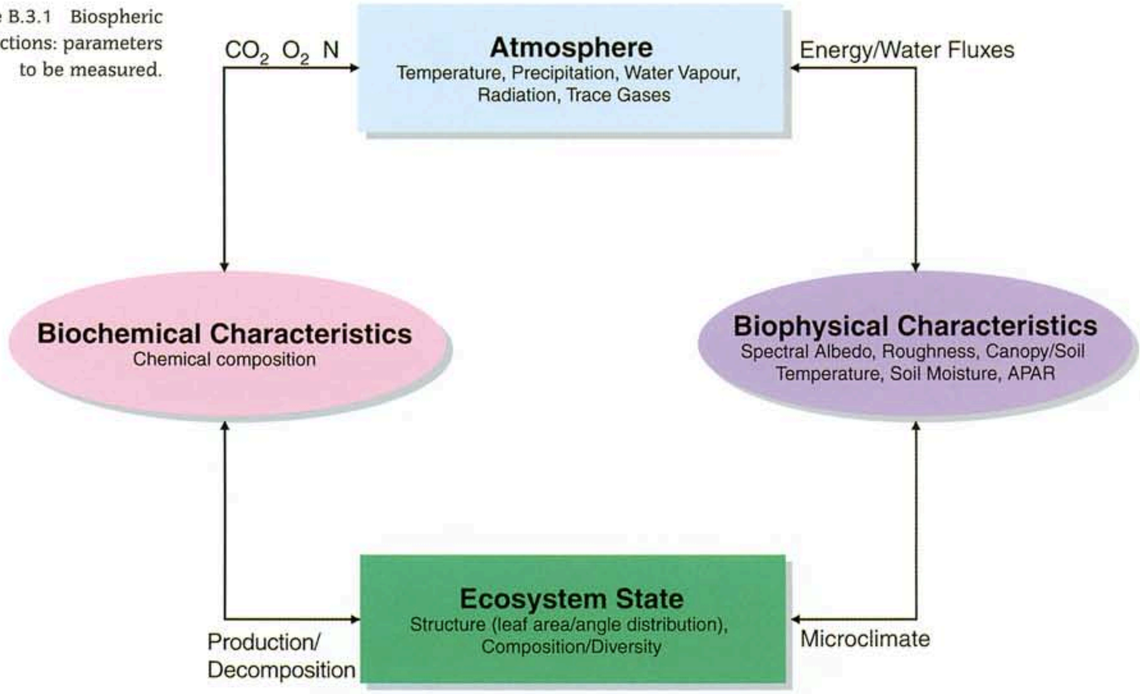
- the energy and water cycles
- interactions with the atmosphere and the carbon dioxide and methane cycles
- the productivity of the different ecosystems, including marine ecosystems
- the state and dynamics of land cover/land use and coastal zones.

The various variables that clearly need to be measured and monitored are summarised in Figure B.3.1

B.3.2.1 The Energy and Water Cycles

For the energy cycle it will be necessary to measure the incoming and outgoing radiation fluxes (at both short and long wavelengths), which are still not yet known with sufficient accuracy, particularly under cloudy conditions. In addition, the heat fluxes, namely latent and sensible heat, are still very difficult to measure and parameterise with sufficient accuracy. This parameterisation, with the most appropriate variables and

Figure B.3.1 Biospheric interactions: parameters to be measured.



parameters at the various scales, has to be improved. Finally, it is necessary to analyse the soil flux which is a determinant of the annual energy budget.

In the case of the water cycles, it is clear that knowledge of the spatial and temporal distribution of precipitation must be improved, as must that of evapotranspiration, which is directly related to the latent heat flux, and soil moisture. An accurate measurement of soil moisture would substantially improve the predictions of general circulation models, which are very sensitive to this quantity. It is also important not to overlook snow cover and water run-off in rivers, which are major components of the water balance. Finally, not only are the absolute values of the incoming radiation and precipitation relevant, but also their phasing with respect to the plant development cycles.

B.3.2.2 Interactions with the Atmosphere

Due to their impact on the Earth's radiation balance, the increasing atmospheric concentrations of the greenhouse gases carbon dioxide and methane are of particular concern for climate change and it is important to remember that terrestrial ecosystems are important sources and sinks for these gases. The exchange processes of methane are not well known, though it is assumed that intense agricultural activities and biomass burning are major sources of excess methane. Oceanic uptake and photosynthesis on land surfaces are considered the main sinks for carbon dioxide, but it is currently not possible to accurately quantify these processes.

This uncertainty is of crucial importance as chemically atmospheric carbon dioxide is relatively inert, and so its concentration is largely controlled by sources and sinks at the Earth's surface. Currently, the rate of carbon dioxide increase in the atmosphere is only about half the rate of the anthropogenic emission. Clearly the excess production is taken up by the oceans and the terrestrial biosphere, both sinks being estimated to be of similar magnitude. However, present estimates of the exchanges and uptakes leave a significant part of anthropogenic carbon unaccounted for, reflecting lack of knowledge on the mechanisms. The significance and geographic distribution of the various carbon sinks is a matter of controversy.

The main open questions concerning the global carbon cycle relate to lack of knowledge of the exchange processes that link the atmosphere and the terrestrial ecosystems. The exchange of carbon dioxide across the air/ocean interface depends on the differences in the partial pressures of carbon dioxide in water and air, and on mixing processes in the atmospheric and oceanic boundary layers. Apart from ocean currents and turbulent exchange processes in the atmosphere and oceans, phytoplankton is an important factor in regulating the partial pressure of carbon dioxide. Thus, to quantify carbon exchange processes, geographically distributed information on climatological and hydrological parameters, and on the biophysical and biochemical characteristics of vegetation and soil, as well as on its seasonal variability, is required. This is needed as input to verify terrestrial ecosystem models and is a prerequisite if our understanding is to advance.

In addition to carbon dioxide and methane (the principal greenhouse gases), the photochemically active gases, in particular nitrogen compounds, hydrocarbons, and ozone, play important roles in ecosystem processes. Increased tropospheric ozone concentrations in northern hemispheric mid-latitudes, resulting from anthropogenic activities, affect the biosphere on regional scales. The main processes for ozone formation include various reactions involving nitrogen oxides (NOx) and volatile organic compounds, which are produced biologically or by the burning of fuel and biomass.

The main drivers for the photodissociation and production of ozone are solar radiation and water vapour. The radiative effects of greenhouse gases are partly compensated by increased aerosol concentrations originating from anthropogenic as well as from natural sources. Improved information is needed to quantify the exchange processes controlling aerosol, including release, global distribution, and deposition. Thus, the key areas in which advances in knowledge are necessary are:

- the carbon cycle (sources and sinks including the terrestrial and oceanic components)
- the role of biospheric processes for the surface/atmosphere exchange of minor atmospheric constituents.

Strong couplings exist between the energy and water cycles, the carbon dioxide cycle and atmospheric chemistry. They come from the radiation process, strongly influenced by the concentrations of greenhouse gases and water vapour in the atmosphere, and from the functioning of the plant stomatae, which influences both the transpiration of vegetation and the absorption of carbon dioxide. In this respect, the understanding of how to scale up this coupling is of great importance, not only for the energy, water and carbon dioxide cycles, but also for the dynamics of the ecosystems.

B.3.2.3 The Productivity of the Different Ecosystems

One of the main goals in geo-biospheric research is study of the productivity of the various terrestrial and aquatic biomes and of the biogeochemical cycling of important elements and processes which determine the state of the biosphere. Specific objectives are to increase our understanding of biochemical processes and dynamics, the biotic contributions to the global energy balance and the change in vegetation state and dynamics.

As far as biospheric productivity is concerned, the most important issue is to characterise variables such as the leaf area index, fractional vegetation cover, leaf absorption in the solar spectrum. This information is needed for use in biome or productivity models, which will also require additional information such as the efficiency of the conversion of radiation in organic carbon. Typically, this type of information could be derived from an identification of the biome type; hence there is a parallel interest in the classification of targets at the surface. This approach would permit the documentation of:

- The state and evolution of the properties of vegetation for a variety of biomes. This is relevant to all applications relating to processes occurring in these ecosystems. It also helps to constrain atmospheric models at the global scale, to address large scale issues involving the water and energy cycles and, at the regional scale, to better control the influence of local conditions.
- The contribution of the biosphere to the carbon cycle, both as a source (respiration) and as a sink (photosynthesis, net primary productivity).
- How major perturbations and disturbances in the biosphere could affect the global environment, for instance through biomass burning and deforestation.
- The productivity of agricultural regions and forests, especially in the context of the current push towards the goal of sustainable development in developed as well as developing regions.

B.3.2.4 Land Cover/Land Use

Improved understanding of processes governing the constantly evolving geosphere, hydrosphere and biosphere is needed to optimise the utilisation of resources, to minimise possible adverse impacts of human activities, and to preserve the quality and diversity of the environment of land surfaces.

For the development and application of diversified models of land processes, spatially distributed information on the properties of the land surface, including vegetation, water, and soil, as well as information on temporal changes of these properties, is required. Key research topics include the development of models of the hydrological cycle (including extent and quality of surface water, water in the soil, land cryosphere), soil transformation (including desertification, erosion,...), biomass productivity, temporal dynamics of vegetation and environmental hazards (floods, landslides, seismic activity).

B.3.3. Conclusions

In summary, without entering into the requirements of all land related applications, it is possible to identify a set of basic land features and characteristics which must represent the focus of attention in a space observation strategy for the next decade. They are related to:

- surface characteristics and conditions (type and condition of land cover, terrain characteristics, soil, surface – and subsurface water, and changes in those conditions, including environmental degradation and pollution)
- surface processes such as primary productivity, biochemical cycles, energy and matter interactions (evapotranspiration, radiation balance, ecosystem processes...).

Both sets of measurement requirements will be necessary for research as well as applications.

Knowledge of the surface/atmospheric exchange processes for trace gases, together with the exchange processes for energy and water, are determining factors for furthering our understanding and the modelling of ecosystems. These in turn are linked to improvements in climate predictions. Spatially distributed information on the physical properties and temporal changes of the terrestrial and marine ecosystems, as provided by satellites, are inputs for work in this area. The links between the geo-biospheric interactions in the time domain are displayed in Figure B.3.2. In addition, Table B.3.1 links the scientific objectives of Theme 3 and the different observation techniques.

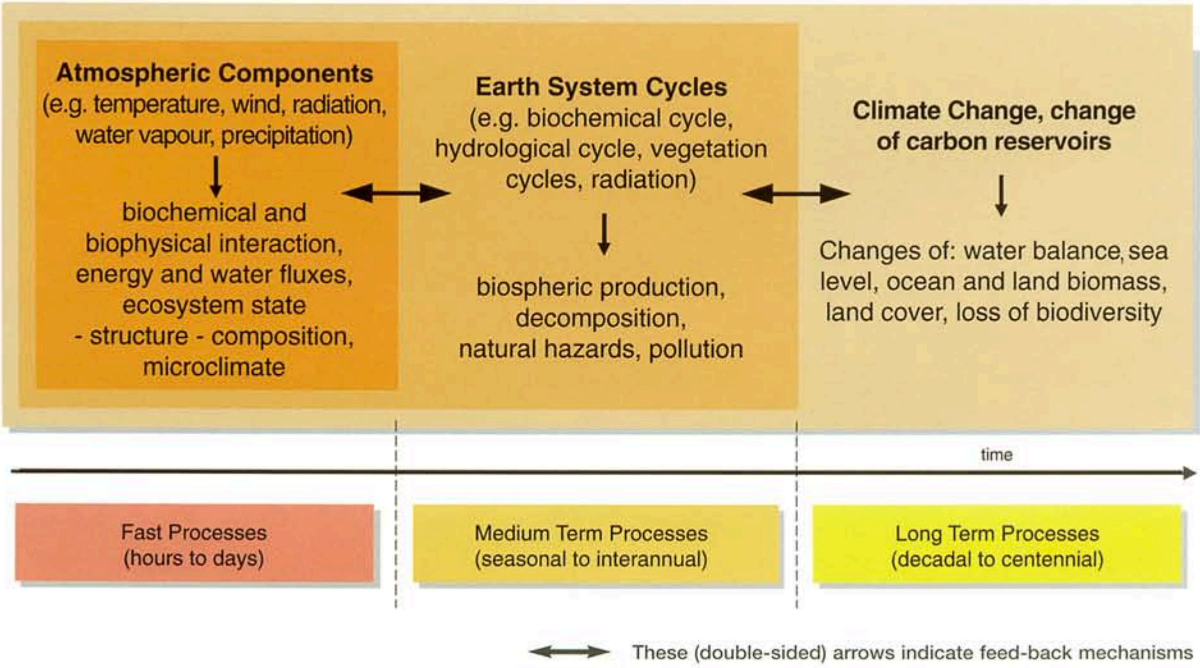


Figure B.3.2. Examples of geo-biospheric interaction: the links between the components

Therefore, two parallel elements should be pursued:

- A scientific programme leading to the derivation of more appropriate and accurate models of geosphere/biosphere processes and surface atmosphere interaction processes, formulated in terms of parameters and variables, which are well identified at each scale and unambiguously related to the quantities measurable from space. Coupled with this must be an improvement in assimilation procedures and processing algorithms.
- The development and provision of instruments capable of ensuring observations of key geo-biophysical parameters characterizing the state of the biosphere/geosphere system and its evolution. These data would be used in the validation and improvement of the corresponding models, as well as in advancing our understanding of scaling from local to global.

Such a programme implies two complementary systems of observation, namely:

- instruments with high spatial and spectral resolution and, if possible, high temporal repetivity, but not necessarily with a global coverage, for studying processes and scaling-up procedures
- instruments with lower spatial and spectral resolution, but suitable for long-term, global observations.

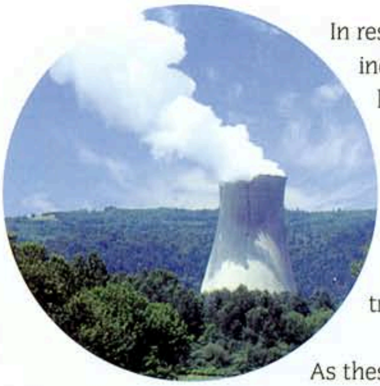
Component	Objective	Observation Techniques
I.Energy and water cycles	Surface temperature energy balance water resource and surface moisture	Thermal infrared radiometry, passive and active microwave observations
II. Chemical interactions with the atmosphere	CO_2, methane, and other greenhouse gas distribution and circulation in the biosphere, sources and sinks of key species	Atmospheric sounding, occultation and absorption spectroscopy
III. State/dynamics of the land cover/ land use and coastal zones	Distribution and circulation of renewable resources, evolution of land use/cover and pressure on resources	Multi-temporal optical spectroscopy and radiometry combined with active microwave observation
IV. Productivity of the different ecosystems including marine ecosystems	Net primary production, temporal evolution of different ecosystems (area, composition, etc.)	Visible/short wave infrared imaging spectroscopy on a regional scale in combination with large spatial scale radiometry/ spectroscopy

Table B.3.1 Objectives of Theme 3 and observational techniques proposed

Appendix B.4

Theme 4 – Atmosphere and Marine Environment: Anthropogenic Impact

B.4.1. Introduction



In response to increasing manmade perturbations linked to continuous growth in industry, agriculture and development of transportation systems, to changes in land use, and to exploration and exploitation of the oceans, the chemical composition of the Earth's environment is changing rapidly. Affecting the atmosphere, the ocean and in particular the coastal zones and the soils, these changes have given rise to many environmental problems ranging from local and regional air pollution, to the global decrease in the stratospheric ozone layer, to changes in the oxidizing and acidifying properties of the troposphere, to marine pollution and lake eutrophication, and to soil acidification.

As these problems cover all scales in space and time, the scientific challenge is to quantify the fluxes of gases and particles between the various components (terrestrial and marine biosphere, atmosphere, oceans, soils), to understand the chemical and photochemical transformations and the transport processes, and to assess the consequences of the environmental changes produced by manmade variations in these exchange fluxes.

Despite the fact that most of the emission and transformation processes involve short scale variations and low concentration trace constituents, space-based observations can play an important role due to their unique ability to provide continuous measurements at the global scale. They give access to the larger scales of spatial and temporal variability and are critical for identifying sources and sinks of primary species. In pursuit of these objectives, future space observations should:

- be developed in a timely manner as long term effects have to be anticipated before prevention becomes impossible, as shown by the unexpected and sudden occurrence of the ozone hole over the Antarctic continent
- be coordinated with measurements provided by ground networks and coordinated airborne and ship-borne campaigns, as the shorter scales involved can only be addressed by such measurements
- exploit new data assimilation techniques linked to the fast development of chemical transport models and coupled ocean–atmosphere models which include chemical and biological processes.

The main environmental changes that are relevant to this scientific strategy can then be subdivided according to the specific component of the Earth's environment of concern and to the temporal and spatial scales involved. Indeed, the variation in the chemical composition of the environment depends on the time scales of sources, sinks and dynamical processes. Shorter time scales are dominant in the boundary layer and the lower troposphere, which are therefore characterised by relatively fast changes (from hours to weeks). Longer time scales are involved in the oceans, upper troposphere and stratosphere, which are characterised by relatively slower changes (from months to decades). Therefore, one must successively study the changes in tropospheric chemical composition induced by human activity in relation to: (a) changes in the oxidizing properties of the atmosphere and climate change, (b) the chemical processes in the lower stratosphere and upper troposphere which determines the future evolution of the ozone layer, and (c) the effects of chemical changes in the ocean which are linked to marine pollution. Figure B.4.1 summarises the links between the various components and the various time scales.

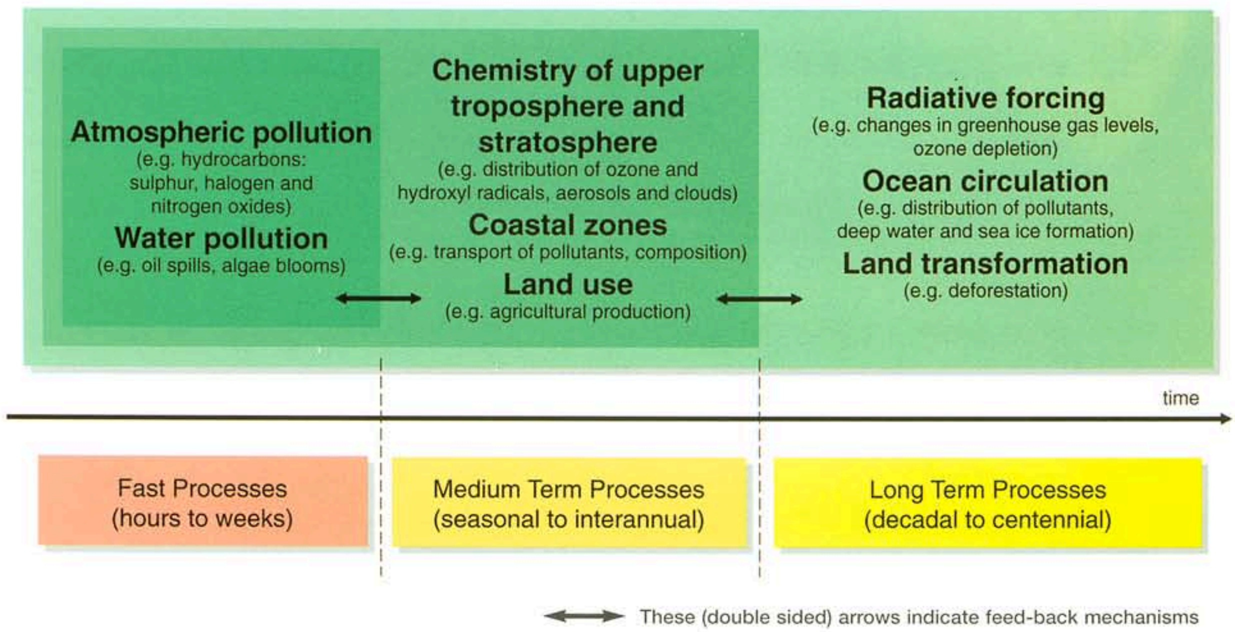


Figure B.4.1 Examples of anthropogenic impact on Atmosphere and Marine Environment

B.4.2. Changes in Atmospheric Composition Induced by Human Activity

The composition of the Earth's atmosphere is changing as the concentrations of a number of radiatively and chemically active trace gases emitted at the surface rapidly increase. The emissions of methane, nitrogen oxides, hydrocarbons, sulphur compounds and halogen species ultimately affect the overall distribution of ozone and the hydroxyl radicals in the troposphere, and thus the oxidizing capacity and 'self-cleaning' power of the atmosphere. Also, the importance of aerosols and clouds, in modifying the chemistry and the climate of both the troposphere and the stratosphere, is only now starting to be fully appreciated. There is thus a need to understand and quantify these changes, which affect the tropospheric greenhouse gases and the oxidizing properties of the troposphere, the stratospheric ozone layer, and have quite important consequences for climate change and pollution of the Earth's environment.

Space observation of changes in atmospheric composition will contribute to two main objectives related to our understanding of processes occurring in the lower troposphere:

- quantification of the changes in the oxidizing properties of the atmosphere and the relative influence of human activity
- quantification of the changes in radiative forcing of greenhouse gases and aerosols.

These objectives can be met, assuming the appropriate complementarity with ground-based, airborne and shipborne measurements, by performing:

- Global measurements of tropospheric ozone with a vertical resolution allowing us to distinguish between the atmospheric boundary layer and the middle and upper free troposphere.
- Global measurements of tropospheric aerosols (optical depth, size distribution, chemical composition). Besides their own interest as part of the global chemistry of the troposphere, such measurements are also of importance for accurately determining the radiation field in the troposphere at various altitudes.
- Global measurements of carbon monoxide and methane, which are the major sinks for tropospheric OH. Carbon monoxide is also a 'negative' tracer of the stratosphere-troposphere exchange processes and a positive tracer of ozone that has originated from anthropogenic precursors, i.e. in the continental boundary layer and from biomass burning.
- Global measurements of water vapour, for investigation of the global field of the OH radical and of the global ozone balance. Furthermore, if the water content in the planetary boundary layer can be distinguished from the upper altitudes, water vapour can be considered as a tracer of boundary layer air.
- Global measurements of NO_x, as precursors of tropospheric ozone, and of reservoir species such as nitric acid and hydrochloric acid. Such measurements can provide an insight into the chemical processes occurring in the free troposphere. They could be coupled with observation of the cloud fields in order to assess qualitatively the global importance of cloud chemistry.

B.4.3. Chemical Processes in the Stratosphere and Upper Troposphere

The processes occurring in the stratosphere and the upper troposphere determine the chemical composition and their optical and physical properties. They thus affect directly and indirectly the Earth's climate and the transmission of the ultraviolet radiation. Existing measurements have improved our understanding of the system, leading to the development of comprehensive three dimensional models that can explain most of the observed events. However, the remaining uncertainties, the complexity of the heterogeneous chemistry that occurs on aerosols and in polar stratospheric clouds, and the possible deviations from a steady state, do not allow current models to provide a sufficiently reliable description of the present state of the atmosphere.

This lack of understanding of the lower stratosphere and upper troposphere means that it is not possible to predict confidently the future evolution of atmospheric composition in this region, including the fate of the ozone layer. Indeed, peak stratospheric concentrations of manmade chlorine are anticipated by the turn of the century.

Assuming that the provisions of the Montreal Protocol are abided by, chlorine levels should fall over the coming decades, and have returned, by the middle of the next century, to the levels that existed at the time when the Antarctic ozone hole was first observed.

In the absence of other influences, a recovery of the ozone layer can then be predicted with some confidence, the details of the recovery (both its timing and its rate) depending on the future levels of both chlorine and bromine compounds. However, the atmosphere in the early decades of the next century will be rather different from the one that existed prior to the depletion of the ozone layer, due to expected temperature and water vapour trends, increased aircraft emissions and increased terrestrial emissions of nitrous oxide. The accurate prediction of its evolution is therefore far beyond our present modelling capacities.

Continuous observation during the coming decade will thus be of paramount importance, and further measurements are necessary for a better validation and implementation of the models, with priority being given to the improvement of understanding in the regions of the lower stratosphere and upper troposphere in which a greater variability is expected and fewer measurements are available. The objectives are then to obtain a better understanding of:

- Ozone depletion in the lower stratosphere, from the tropopause to about 30 km. This understanding is relevant to ultraviolet radiation enhancement at the surface and to the interaction with climate through temperature variations. It requires measurements of temperature, polar stratospheric cloud properties, reservoir and active species of the chlorine, nitrogen, bromine and hydrogen families.
- The distribution of and changes in ozone in the lower stratosphere and upper troposphere, by measuring key compounds of the ozone forming process, notably species of the nitrogen family, together with water vapour, methane and carbon monoxide.
- Stratospheric/tropospheric exchange processes in the vicinity of the tropopause where there is a need to improve modelling of the dynamics of the transition layer between 6 km and 18 km. This requires better knowledege of temperature fields and the observation of long lived species to be used as tracers of dynamical motions.

Vertical profiles, with high vertical resolution and the requisite spatial and temporal (global) coverage, are really required for each variable. However, limited gaps in overall coverage could be acceptable in order to achieve higher spatial resolution and accuracy in specific regions. For instance, the characterization of stratospheric/tropospheric exchanges requires locally high spatial resolution for the characterization of dynamical effects, but a statistical sampling of these effects without full geographical coverage may be sufficient.

B.4.4. Marine Pollution

The presence of man and associated activities, namely the exploration and exploitation of the resources in the marine environment, also implies a risk for pollution of the oceans and the ice-covered seas. In particular, the coastal zones where more than 70% of man's activity takes place are exposed to this risk. Some types of marine pollution have direct short term environmental effects, while others may accumulate in the environment and organisms, posing a long term threat to the use of oceans as a resource. Much remains to be clarified about the impacts of the various types of pollution.

The detection and knowledge of the occurrence and spread of marine pollution are of increasing interest on scales from the local to the global level. Local, national and international regulations and agreements regulate the limits of acceptable and critical levels of the various pollutants associated with mankind's activities in the marine environment. The key requirement is then to properly monitor marine pollution and its impact, namely water quality in coastal zones, open oceans and ice-covered seas by quantifying:

- sources of pollution (oil spills, algae blooms, discolouring pollutants)
- the transport of pollutants (ocean and coastal currents, deep water formation associated with sea ice formation).

This includes the detection and quantification of individual pollution events, the mapping of the accumulated levels of pollution compounds in the water masses, sediments and organisms, as well as the monitoring of transport and dilution of various dissolved pollutants from given source locations. In addition, it is essential to increase understanding of coupled physical–biological–chemical processes in the marine environment.

Traditionally, quantification of pollutant levels requires measurements of actual chemical or biological composition and the concentrations of the various compounds in the water masses. International agreements and national regulations provide the basis for extensive monitoring programmes devoted to long term measurements of various marine pollutants. They also seek to provide guidance on acceptable levels for the various compounds, though lack of understanding must place question marks against their veracity.

B.4.5. Conclusions

When considering each of the sub-Themes identified as part of this Theme (i.e.Environmental Change), clear thrusts appear , namely:

- *For the composition of the atmosphere* – the quantification of the changes in the oxidizing properties of the atmosphere and the relative influence of human activity; the quantification of changes in radiative forcing by greenhouse gases and aerosols.
- *For the upper troposphere and lower stratosphere* – the quantification of chemical and photochemical processes; the role of heterogeneous chemistry; the influence of dynamical motions at various spatial scales.
- *For marine pollution* – sources of pollution; the transport of pollutants (ocean and coastal currents, sea ice transport); coupled physical–biological–chemical processes in the marine environment.

At the same time, monitoring of key species that characterise the long term variations of the environment is required for all aspects of these environmental changes. Table B.4.1 links the objectives and the different observation techniques.

Table B.4.1 Objectives of Theme 4 and proposed observation techniques

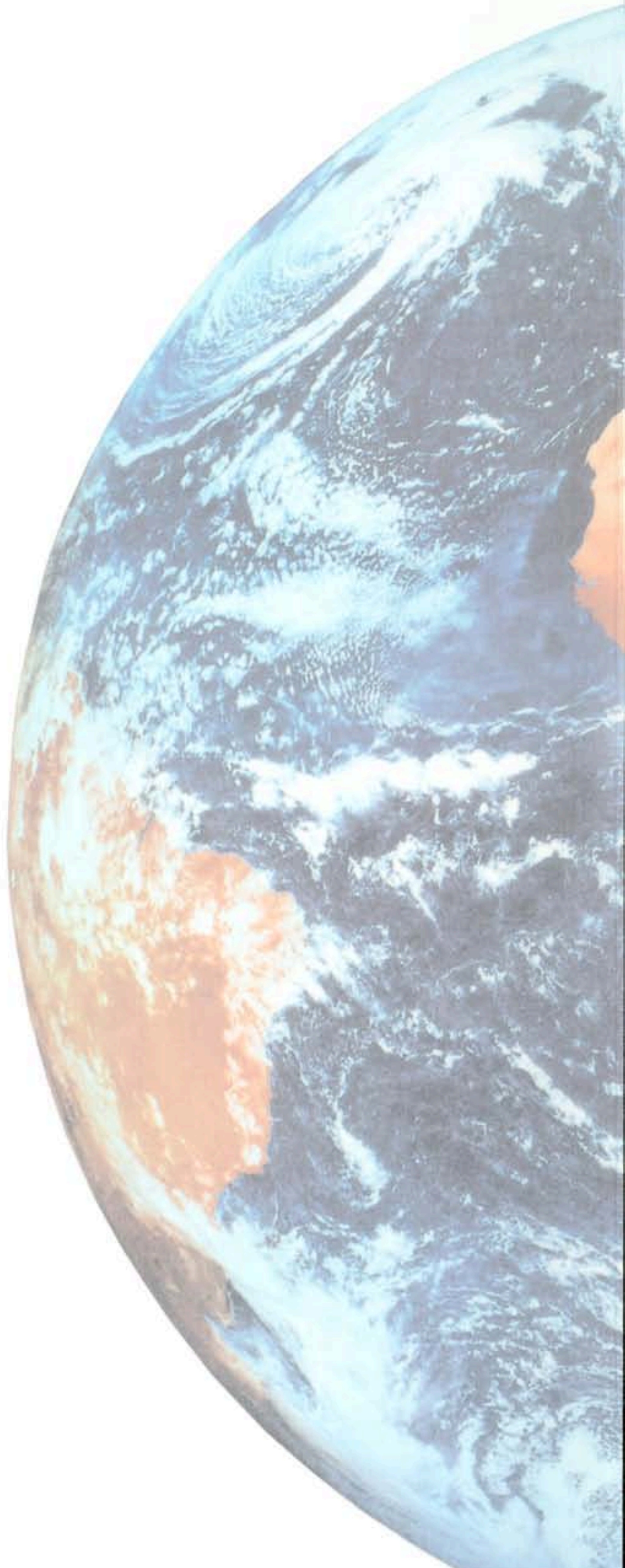
Component	Objective	Observation Techniques
I. Atmospheric composition and environment	Understanding changes induced by human activity in the oxidizing properties of the atmosphere	Nadir sounding spectrometers
	Understanding changes in radiative forcing	
II. Chemistry	Understanding ozone depletion, ozone interaction with climate, and dynamics of tropospheric/stratospheric exchange	Limb sounding spectrometers
III. Carbon cycle	Understanding present global carbon cycle	Imaging spectral radiometers
IV. Marine pollution	Characterisation of sources, transport and processes of marine pollution	Imaging spectrometers, Synthetic aperture radars

Glossary

AATSR	Advanced Along-Track Scanning Radiometer
ACSYS	Arctic Climate System Study
ADEOS	Advanced Earth Observing Satellite
ALADIN	Atmospheric Laser Doppler Instrument
ALOS	Advanced Land Observing Satellite
AO	Announcement of Opportunity
APAR	Absorbed Photosynthetically Active Radiation
ATLID	Atmospheric Lidar
ATMOS	Atmospheric Trace Molecule Spectroscopy Experiment
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle
BGI	Bureau Gravimétrique International
CCAMLR	Convention of 1980 on the Conservation of Antarctic Marine Living Resources
CEO	Centre for Earth Observation
CEOS	Committee for Earth Observation Satellites
CLIVAR	Climate Variability and Predictability
CHAMP	Challenging Mini-satellite Payload for Geophysical Research and Application (GFZ)
CNES	Centre Nationale Etude Spatiale
EC	European Commission
ECMWF	European Centre for Medium Range Weather Forecasts
ECU	European Currency Unit
EEA	European Environment Agency
EECM	Earth Explorer Core Mission
EEOM	Earth Explorer Opportunity Mission
Envisat	Environmental Satellite
EOPP	Earth Observation Preparatory Programme
EOS-CHEM	Earth Observation System – Chemistry Satellite
ERS	European Remote-sensing Satellite
ERTS	Earth Resources Technology Satellite
ESAC	Earth Science Advisory Committee
ESE	Earth Science Enterprise (US)
Eumetsat	European Organisation for Meteorological Satellites
FCCC	United Nations Framework Convention on Climate Change
FIR	Far Infra-Red
GAIM	Task Force on Global Analysis, Interpretation and Modelling
GAW	Global Atmospheric Watch
GCM	General Circulation Model

GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems
GEMS	Global Environment Monitoring System (of UNEP)
GEWEX	Global Energy and Water Cycle Experiment
GLOBEC	Global Ocean Ecosystem Dynamics
GLONASS	Global Navigation Satellite System (Russian concept)
GLOSS	Global Observing System for Sea Level
GNP	Gross National Product
GNSS	Global Navigation Satellite System
GOME	Global Ozone Monitoring Experiment
GOOS	Global Oceans Observing System
GPS	Global Positioning System (US concept)
GRACE	Gravity Recovery and Climate Experiment (NASA)
GRAS	GNSS Receiver for Atmospheric Sounding
GTOS	Global Terrestrial Observing System
HDP	Human Dimensions of Global Change Programme
HRV	High Resolution Visible
IAG	International Association of Geodesy
ICSU	International Council of Scientific Unions
IERS	International Earth Rotation Service
IGAC	International Global Atmospheric Chemistry Project
IGBP	International Geosphere/Biosphere Programme
IGBP-DIS	Data and Information System
IGeS	International Geoid Service
IGOS	Integrated Global Observing Strategy
IGRF	International Geomagnetic Reference Field
IGS	International GPS Service for Geodynamics
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
ISTP	International Solar-Terrestrial Physics programmes
Jason	TOPEX/POSEIDON follow-on
JGOFS	Joint Global Ocean Flux Study
LANDSAT	Land Satellite
LOICZ	Land-Ocean Interactions in the Coastal Zone
LRTAP	Convention of 1979 on Long-Range Transboundary Air Pollution
LUCC	Land Use and Land Cover Change
LWC	Liquid Water Content
MAG	Mission Advisory Group
MECU	Million European Currency Units
MERIS	Medium Resolution Imaging Spectrometer
METEOR	Russian Meteorological Satellite
Meteosat	Meteorological Satellite
Metop	Meteorological Operational Satellite
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding instrument
MOMS	Modular Optoelectronic Multispectral Scanner
MSG	Meteosat Second Generation satellite
MWG	Mission Working Group
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar Orbiting Operational Environmental Satellite System

NWP	Numerical Weather Prediction
ODIN	Swedish-led aeronomy/astronomy satellite (given name)
ØERSTED	Danish-led aeronomy/astronomy satellite (given name)
OMI	Ozone Monitoring Instrument
PAGES	Past Global Changes
PB-EO	Programme Board for Earth Observation
PRIRODA	Russian Launcher
PRISM	Processes Research by an Imaging Space Mission
RADARSAT	Radar Satellite
RESURS	Russian Satellite
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SeaWiFS	Sea Wide Field Sensor
SEASTAR	NASA/GSFC mission with the SeaWiFS sensor
SEDI	Studies of the Earth's Deep Interior
SPARC	Stratospheric Processes and their Role in Climate
SPOT	Système Pour Observation de la Terre
SST	Sea Surface Temperature
START	Global Change System for Analysis, Research and Training
SWIR	Short-Wave Infra-Red
TIR	Thermal Infra-Red
TM	Thematic Mapper
TOA	Top-Of-Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOPEX/POSEIDON	Joint French-US altimeter satellite
TRMM	Tropical Rainfall Monitoring Mission
TRMM-FO	Tropical Rainfall Monitoring Mission – Follow On
UN	United Nations
UNEP	United Nations Environment Programme
VLBI	Very Long Baseline Interferometry
VMI	Vegetation Monitoring Instrument
WCP	World Climate Programme
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment
WWW	World Weather Watch



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Contact: ESA Publications Division
c/o ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
Tel. (31) 71 565 3400 - Fax (31) 71 565 5433