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GMES - GATO

A European Strategy for Global Atmospheric Monitoring

Directorate-General for Research
Sustainable development, Global change and ecosystems

2004

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FOREWORD

The European Union is committed to monitoring the environment to ensure the quality of life and security of European citizens. The Earth's atmosphere presents one area in which strategic monitoring is essential; scientists, politicians, the media and the public have vested interests in addressing issues such as stratospheric ozone depletion, increasing surface ultraviolet (UV) radiation, global climate change and air quality. GMES is a joint initiative between the European Commission and the European Space Agency to establish, by 2008, a truly European capacity for Global Monitoring for Environment and Security (GMES).

GMES-GATO is an extension of the European research cluster, Global Atmospheric Observations (GATO), which is central to the coordination of stratospheric ozone research and was established in support of the Montreal and Kyoto Protocols. GMES-GATO is one of four GMES thematic projects concerned with the monitoring of the Earth's atmosphere. In this report, the GMES-GATO consortium has defined a strategy for GMES to help develop an integrated global atmospheric observing system by 2008. The preparation of this report has involved a wide range of people from different backgrounds and areas of expertise.

This strategy report assesses what the current European capabilities are and describes how a more rational European monitoring system could be developed. It examines facets such as the observational capability itself, quality assurance and control, data storage and accessibility, and the provision of useful information (often in the form of derived products) to all concerned parties. The recommendations contained herein would help achieve best overall use of data from ground-based and satellite observation systems. This report complements the European Commission's publication, 'A Global Strategy for Atmospheric Interdisciplinary Research in the European Research Area, AIRES in ERA', which describes a balanced research programme to improve our understanding of atmospheric issues.

On behalf of the European Commission, I would like to express my sincere thanks to the authors, reviewers and editors whose commitment and keen interest are reflected in this report. Furthermore I would like to acknowledge the expertise of the European atmospheric community, on which the preparation of this report relied.

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ATMOSPHERIC OBSERVATIONS WITHIN GMES

INTRODUCTION

Global Monitoring for Environment and Security (GMES)

Global Monitoring for Environment and Security (GMES) is a joint initiative between the European Commission and the European Space Agency. The initiative is designed to establish a European capacity to monitor the European and global environments to ensure the security of European citizens. GMES is divided into three periods: Initial Period (2002-03), Implementation Period (2004-08) and Post-2008. The GMES vision is to see the following structural elements of this European capacity in operation by 2008:

- Monitoring and dissemination of information to support European Union policies with respect to the environment and security
- Mechanisms to ensure permanent dialogue between all stakeholders: scientists, policy makers, the media and the European public
- Legal, financial and organisational frameworks to ensure the ongoing operation and development of the European capacity

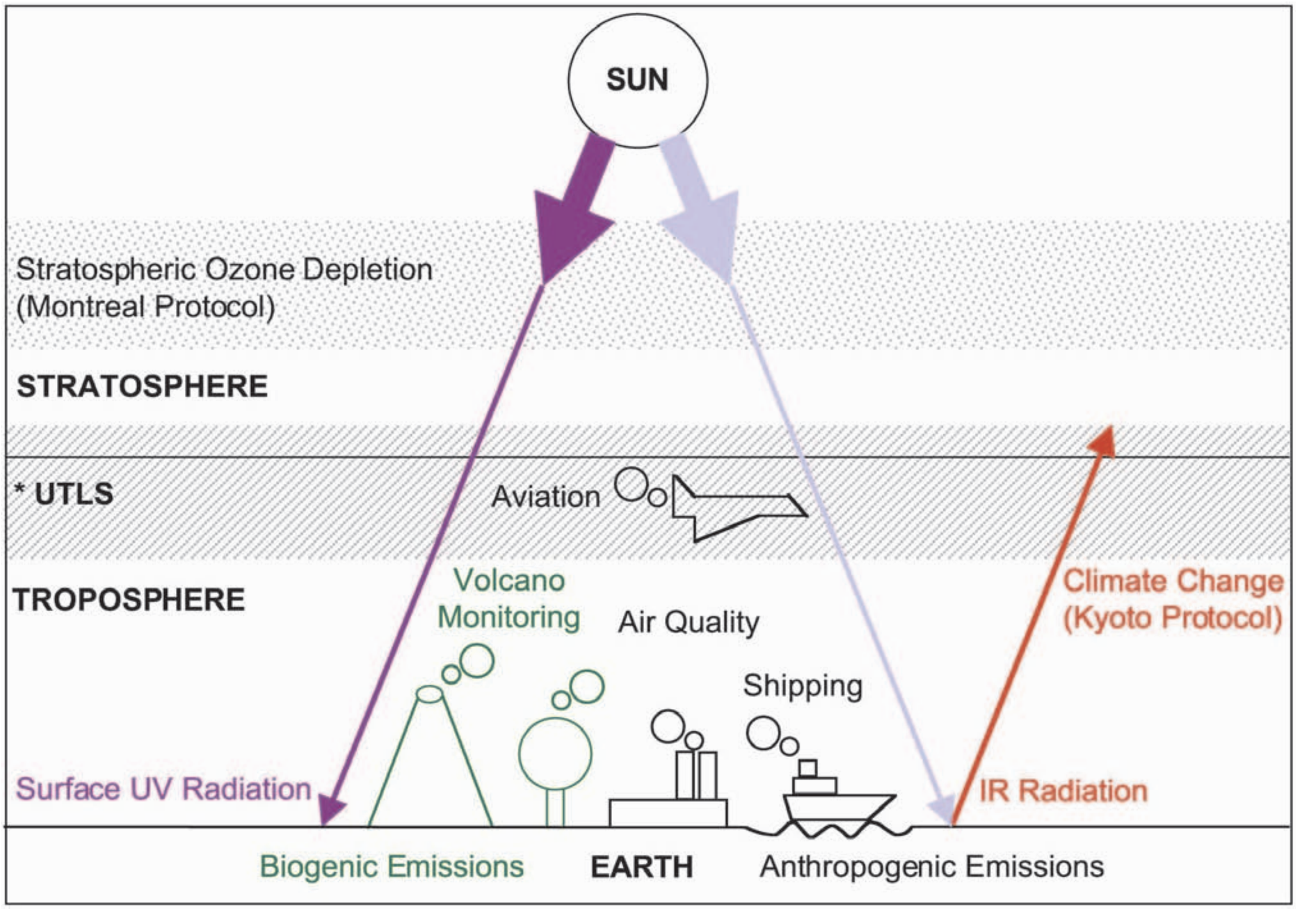
Many of the necessary elements already exist but many of these were conceived and operate independently. GMES aims to add value by establishing a single, coherent strategy to develop the compatibility of existing elements, encourage cooperation between organisations and provide what is currently missing.

Global Atmospheric Observations (GATO) and GMES-GATO

Global Atmospheric Observations (GATO) is an existing European research cluster central to the coordination of atmospheric ozone research. GATO aims to promote the use of data for scientific and public purposes and the integration of observations from a wide variety of sources: ground-based, air / sea-borne and satellite monitoring systems. GMES-GATO is an extension of this research cluster and constitutes one of fifteen GMES thematic projects in the Initial Period. GMES-GATO promotes the use of global atmospheric observations in the current research programme and aids preparation for the integrated atmospheric observing system to be adopted by GMES Post-2008.

GMES-GATO Strategy Report Structure

This report, prepared by the GMES-GATO consortium, defines a strategy for global atmospheric observations to make best coordinated use of existing measurement networks and satellites. Reference is made to the feasibility of multipurpose networks. Chapters 1-4 are structured around the European monitoring capability necessary to support existing environmental protocols in relation to atmospheric concerns (see Figure 1). They cover the Montreal Protocol, which addresses stratospheric ozone depletion and surface ultraviolet (UV) radiation, the Kyoto Protocol in relation to climate change, air-quality protocols and the atmospheric impacts of aviation and shipping. In addition, Chapter 5 addresses the monitoring of volcanic activity with respect to improved public safety and Chapter 6 explores the influence of the atmosphere on Earth surface observations. Chapters 1-6 assess whether or not there exists a rational system to achieve the necessary measurements, monitoring and modelling to meet the requirements of policy, and how such a capacity can be achieved within GMES. This synthesis brings together the ideas developed in the individual chapters and describes the essential elements required to establish a European capacity for global atmospheric monitoring in GMES.



* UTLS = upper troposphere / lower stratosphere.

Figure 1 Major aspects of the Earth's atmosphere considered in the GMES-GATO strategy report.

GMES-GATO OPPORTUNITIES WITHIN GMES

In order to develop a European capacity for atmospheric monitoring by 2008, best coordinated use should be made of existing measurement systems and the identified missing elements, including lack of cohesion, must be established (see Table 1 at the end of this section). The following issues should be considered in relation to all aspects of atmospheric monitoring:

- Verification of compliance with and success of protocols
- Provision of near-real-time information for public and scientific use
- Observation and modelling synergies
- Measurement quality, archiving and access
- Extension of the satellite programme beyond Envisat
- Development of non-satellite monitoring systems for GMES Post-2008
- Provision of funding / rational funding frameworks

Figure 2 schematically illustrates how these issues relate to the atmospheric monitoring process. The potential role of GMES with respect to each of these issues is discussed below. To maintain the emphasis on addressing the needs of end-users, the provision of information with respect to protocols and for near-real-time (NRT) use are discussed first. This top-down approach continues as the elements required for the provision of information are discussed in turn. The fundamental issue of the provision of funding / rational funding frameworks is discussed last. This synthesis is based on recommendations made in Chapters 1-6 which will reduce significant uncertainties surrounding atmospheric concerns and associated policy. More detailed recommendations can be found at the end of each chapter (1-6).

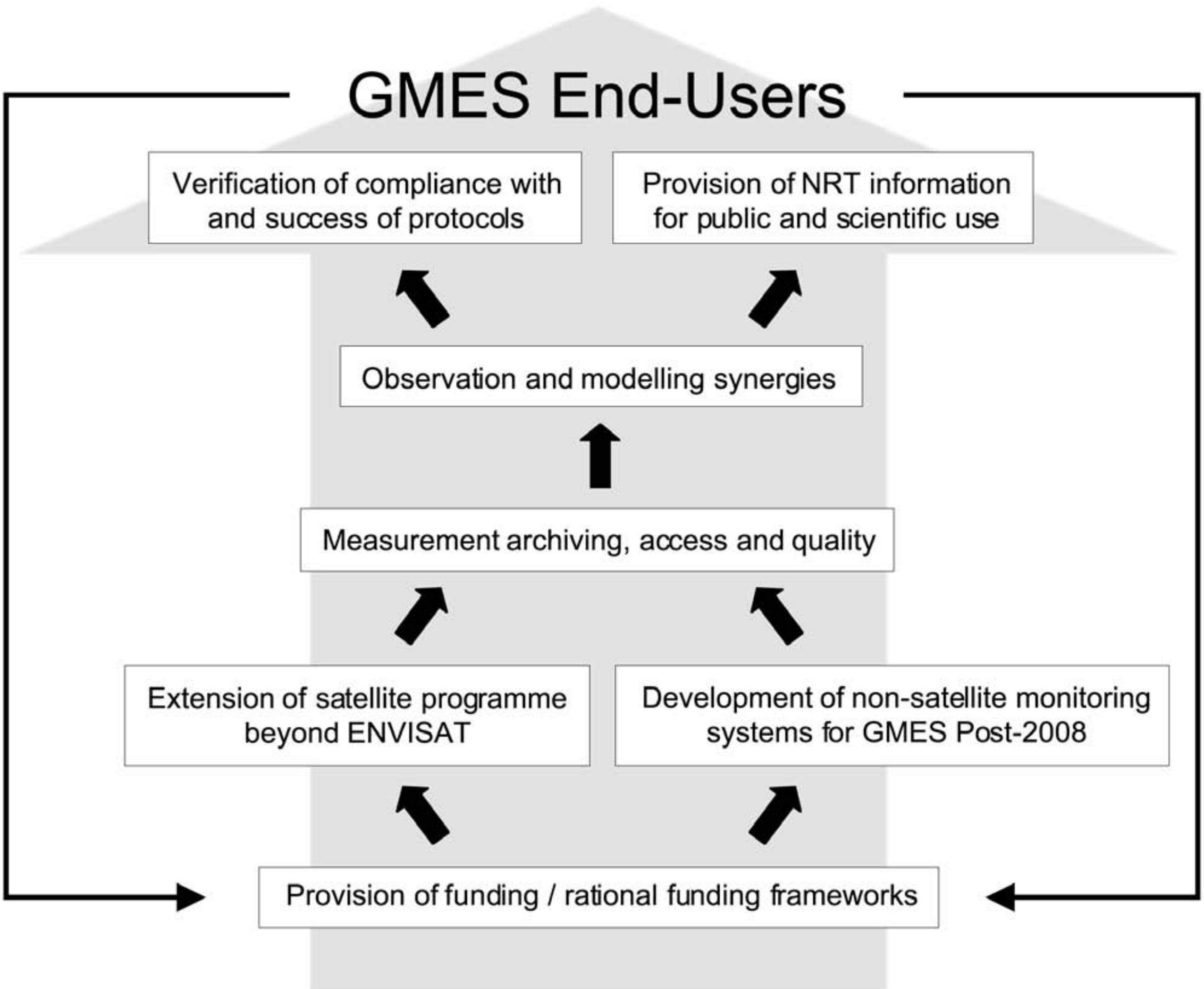


Figure 2 Atmospheric monitoring issues to be addressed in order to establish a European capacity.

Verification of Compliance with and Success of Protocols

The main motive for atmospheric monitoring programmes is to inform the decision-making process. Monitoring is required not only to verify compliance with protocols, such as Montreal, Kyoto and air quality protocols such as the Convention on Long-Range Transboundary Air Pollution (CLRTAP) but also to obtain fundamental information about the state of the Earth's atmosphere, including variability and trends. Improved understanding is required to assess the success of existing protocols, inform the making of future policy and develop existing protocols. It is inherently necessary to monitor many more chemical species than specifically feature in existing protocols. On issues of global impact, such as climate change, Europe's responsibility is to contribute to international knowledge / understanding through international monitoring. Europe bears a responsibility to support programmes which aid developing nations. On issues of local impact, such as UV radiation and air quality, Europe's responsibility is to the European citizen through local and regional monitoring.

The Montreal and Kyoto Protocols, for example, regulate the amount of ozone-depleting substances (ODSs), such as chlorofluorocarbons (CFCs), and green-house gases (GHGs), such as carbon dioxide and methane, emitted into the Earth's atmosphere. It is important to be able to verify compliance with and quantify deviation from such protocols through measurements of atmospheric concentrations. For the Montreal Protocol, ODS emissions can be estimated from observed long-term trends in their concentrations and their atmospheric lifetimes. In addition, concentration measurements of a range of species, which must clearly include ozone, are required to monitor the state of the stratosphere. Measurements and modelling should be combined to differentiate between local anthropogenic sources and background atmospheric composition, and thereby identify regional GHG and pollution precursor emissions. A flux network is required to monitor sub-regional emissions.

Aircraft and ship emissions of carbon dioxide, sulphur dioxide and fine / ultrafine particles are presently unregulated and there is current debate as to whether these emissions should be regulated. If standards are set for ship emissions, analogous to those established by the International Civil Aviation Organization (ICAO) for aircraft emissions of nitrogen oxides, airborne in situ measurements in ship and aircraft exhaust plumes will be required to assess the effectiveness of these standards.

Long-term monitoring records of ozone, ODSs, GHGs and precursors are required to assess the success of compliance with protocols at mitigating detrimental atmospheric change. For example, the question remains, 'Has stratospheric ozone depletion been reduced as a result of current regulation of ODS emissions?'. High quality ground-based and satellite measurements of ozone are essential for accurate monitoring (ca. 1% per decade), required to answer this question. The value of such measurements lies in the extension of existing, established records. Similar commitment to the monitoring of GHGs and precursors is required to assess our ability to reduce climate change and air-quality degradation.

Provision of Near-Real-Time Information for Public and Scientific Use

The second crucial motive for atmospheric monitoring is to provide information of immediate public and scientific value. Successful provision of NRT data requires an efficient system which ensures high-quality measurements are transformed into useful information rapidly. Surface UV radiation and air quality NRT data and forecasts provide excellent examples: UV and air-quality forecasts are commonly included in regular domestic weather forecasts and provide the public with essential health-related information. An example in relation to climate change is the provision of weather forecasts (not discussed further), which include warnings of extreme weather.

A stratospheric ozone and UV radiation database, which accommodates measurements of ozone, should also enable the provision of regional UV index forecasts and timely warnings of extreme ozone events. Several European countries offer public UV warnings, for the purposes of which the UV index has been adopted internationally to quantify the intensity of UV radiation. NRT satellite observations of ozone are required for ozone and UV forecasts. Furthermore, a one-stop facility for the collection and dissemination of UV radiation information should be established to include methods for downscaling global UV data to regional UV index maps.

The extensive ozone loss that takes place in the Arctic during cold winters is a cause of great concern due to its proximity to inhabited areas. Currently available NRT data relevant to Arctic ozone loss are mostly intended for scientific use only. Improved NRT data on the development of the ozone layer are required during periods of severe ozone loss, not only for scientific use but also to inform policy-makers, the media and the public.

For air quality, NRT data and chemical weather forecasts are required on local and regional scales, particularly when human health is at risk, for example during high pollution events, forest fires, Saharan dust outbreaks and following large-scale industrial accidents. The urban and rural effects of such events can be strong and inhomogeneous; the heat-wave through Southern Europe in August 2003 led to urban air pollution and forest fires in rural regions.

A database for volcano monitoring, which accommodates measurements of volcanic gas emissions, should also enable the provision of regional risk assessments of immediate threats to public and aircraft. A network of Volcanic Ash Alert Centers (VAACs) exists, which should be developed to provide timely warnings of eruptions and volcanic ash cloud encounters even in remote flight corridors. Furthermore, following warnings of sustained volcanic eruptions in active regions such as Iceland and Italy, a strategy is required to avoid humanitarian crises.

Observation and Modelling Synergies

The closer coordination of ground-based and satellite observations was recommended by the World Meteorological Organization (WMO) / Committee on Earth Observation Satellites (CEOS). Satellite observations are required to differentiate between dynamical and chemical contributions to atmospheric composition whilst ground-based observations are required to ensure the long-term stability of satellite observation series. Ground-based and satellite platforms can provide comparable and complementary data. For example, ozone measurements from satellites and from stations affiliated with the Global Atmosphere Watch (GAW) network are used for cross-validation and together provide increased temporal and spatial coverage. The combination of complementary ground-based and satellite data aids assessment of the causes of long-term trends and variability.

Crucially, complementary ground-based and satellite observations improve scientific understanding through the provision of different kinds of information. In situ airborne measurements can probe the microphysical properties of clouds and aerosols whilst satellite-based instruments yield information on cloud coverage, for example induced by aircraft and ship emissions. European expertise and experience in regular measurement programmes in the upper troposphere / lower stratosphere (UTLS) using in-service aircraft should be consolidated by extending the range of species measured and increasing coverage of the tropics and Southern Hemisphere. Similar measurement programmes on commercial ships could greatly extend the monitoring capability in the planetary boundary layer (PBL). The UTLS and PBL are difficult to probe from space; high quality and high resolution measurements in these regions are of great value.

Strong synergies exist between observations and modelling. Monitoring and modelling are complementary when studying large scale (including scaling up) or long time scale processes. For example, measurements in the near-field of aircraft and ship exhaust plumes are required to assess the atmospheric impacts of aviation and shipping. The measurements also provide effective emissions for inclusion in large-scale models. The combination of chemistry-transport models and atmospheric observations substantially aids differentiation between local anthropogenic sources of emissions and background atmospheric composition. Monitoring should be combined with inverse modelling to estimate regional emissions of GHGs, ODSs and precursors from atmospheric observations.

Chemical data assimilation will play an increasingly important role. The assimilation procedure provides a true synergy between the knowledge gained from modelled physical processes and the combined observations of atmospheric composition. It provides important feedback on the realism of physical processes described in the assimilation model and the quality of measurements. The assimilation of NRT data is a prerequisite for chemical composition and UV radiation forecasts. Data assimilation is an excellent way to exploit the huge observational data sets produced by satellite instruments and provide rationalised input for protocol assessment. Multi-year reanalysis assimilation runs are important in this respect.

Atmospheric correction is a pre-requisite for all GMES Earth surface monitoring activities. For long time-series analyses of surface products, a strategy is required to ensure the continuity of long-term observations of key atmospheric variables, which include ozone, water vapour and aerosols. Trends in surface properties are invaluable in identifying long-term changes to urban, rural and oceanic environments; trend determination is necessary to monitor the success of climate change mitigation through the Kyoto Protocol. Through the assimilation of these key atmospheric variables, capable centres such as the European Centre for Medium-Range Weather Forecasts (ECMWF) could provide background fields of these variables for atmospheric correction.

Measurement Quality, Archiving and Access

The archiving of measurements is closely related to access, quality assurance (QA) and quality control (QC) procedures. Archiving, QA and QC must operate in parallel such that accessible measurements have been most rigorously quality-checked. Assured quality, effective archiving and efficient access are necessary to provide high-quality information to public and scientists.

QA and QC are required to evaluate the accuracy of measurements and achieve consistent monitoring. A knowledge of the uncertainties surrounding measurements of chemical / physical variables from different platforms is required for validation and intercalibration. Consistent monitoring is a prerequisite for the determination of long-term trends. Data quality objectives and QA procedures must be designed in such a way that agreed standards can be maintained.

Databases should act as repositories for measurements and tools for the dissemination of derived data products. Further integration at the European level is required to achieve effective archiving and efficient access. A one-stop facility is required, from which scientists, policy makers, the media and the public can access information and data. All atmospheric data need not reside in one database but the desired facility should contain links to all atmospheric databases. Databases and processing centres should also be integrated, for example to provide timely data for atmospheric correction.

Raw satellite data must be archived in addition to derived data to enable the derivation of new data products, for example through new / improved satellite retrievals. New data products should be defined by end-users as well as the scientific community. The archiving of raw satellite and non-satellite data is essential to fully exploit existing capabilities.

Extension of the Satellite Programme beyond Envisat

A long-term perspective must be applied to the future of the European satellite programme. With the exception of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) MetOp satellites, no atmospheric composition monitoring satellites are programmed beyond the European environmental research satellite, Envisat. Envisat took approximately ten years to develop and was launched on 1 March 2002 with a planned lifetime of five years. It is hoped that Envisat will remain in operation beyond its planned lifetime, due to end before GMES Post-2008. The long lead time in the development of satellite instruments threatens the long-term continuity of global atmospheric composition monitoring. In the context of CEOS, sufficient satellites are required to ensure the seamless extension of the satellite ozone observation series.

The range of chemical species which can be monitored from space should be increased through the development of new satellite instruments and retrievals from new and old instruments. The monitoring of aerosols and clouds is essential to improve our understanding of their role in climate change and thereby improve predictions of future changes to climate and surface UV radiation. Currently, there exists a knowledge gap in the retrieval of aerosol information from satellite measurements. Improved satellite retrievals are required to characterise areas of special interest, for example in relation to biomass burning, mineral dust, industrial plumes and volcanoes in the context of all-scale air quality. An operational system is required to monitor cirrus clouds based on data from meteorological satellites belonging to the Meteorological Satellite (Meteosat) Second Generation (MSG).

Satellite measurements should be made at a variety of spatial and temporal resolutions tailored to targeted chemical species / physical parameters. Low orbit Earth observing satellites currently provide quasi-synoptic information on regional air quality through a compromise between spatial and temporal coverage. An appropriate instrument on board a satellite in geostationary orbit could provide atmospheric composition information at high spatial and temporal resolutions. Low orbit satellites can provide more detailed vertical information and are better suited to monitor polar regions. The role of geostationary satellites in combination with existing low orbit satellites should be considered in relation to air-quality monitoring.

It is clearly necessary to consider atmospheric correction in the planning of future satellite measurements of surface properties; high-quality ozone, water-vapour and aerosol fields are required to calculate the necessary corrections. Improved fields could be produced through further development of (coincident) measurements, observations from additional satellites / instruments and / or sophisticated data assimilation. Assimilation makes intelligent use of multiple data sources (coincident and non-coincident). Coincident observations could be achieved through a geostationary monitoring system or formation-flying satellites in low Earth orbit.

Development of Non-Satellite Monitoring Systems for GMES Post-2008

At present, the non-satellite atmospheric monitoring system comprises ground-based stations and regular programmes of balloon and airborne measurements. To a large degree networks have developed according to the issues (ozone depletion, climate change, air quality and so on) and are internally coherent, albeit not always at a European level. However, with a few exceptions such as the WMO-GAW programme, less attention has been paid to exploiting the synergies between networks. The development of a non-satellite monitoring system must make best coordinated use of what already exists. A critical part of GMES will be to ensure that the transition is smooth; this transition may not be completed until after 2008.

The rationalisation of existing European networks to form an integral network covering all atmospheric monitoring should include new stations in data sparse locations. The WMO-GAW network would be greatly strengthened through the inclusion of new stations in Southern and Eastern Europe, Russia, the tropics and the Southern Hemisphere. The European atmospheric monitoring community bears a responsibility to operate stations in developing regions, such as

Africa, Asia and South America, which are important with respect to the global atmospheric environment. Such stations should be used to improve the global observations required with respect to ozone depletion, UV radiation, climate change and air quality. Coastal monitoring stations should be developed to verify compliance with marine conventions, including World Health Organization (WHO) standards, and to monitor the impact of ship emissions on land-based air quality. Full advantage should be taken of the plans to develop existing ground networks which have been drawn up by international bodies such as the WMO-GAW and the Network for the Detection of Stratospheric Change (NDSC).

Multipurpose networks could provide a cost-effective means of monitoring on a range of scales. However, care must be taken to ensure the different objectives associated with different monitoring issues are not compromised. For example, progress on air quality issues requires monitoring on local, regional and continental scales. Ground-based measurements are required close to local sources to obtain emission estimates and trends in emissions whilst sites are also required at a distance from those sources to monitor ‘background’ atmospheric composition. Stratospheric measurements are best made at clean sites, away from local air pollution which degrades the quality of these measurements. There is potential for considerable rationalisation of current air quality networks on local, national and European scales. This rationalisation includes the strengthening of many stations. For example, five to ten European Monitoring and Evaluation Programme (EMEP) sites should be upgraded to regional master sites. There is an opportunity for European ground stations to be rationalised in a similar fashion to the Network of European Meteorological Services (EUMETNET), for example to verify emissions and trends in emissions. Further research, particularly modelling, should aid the strategic positioning of ground stations.

The contribution which in-service aircraft make to current atmospheric monitoring must not be overlooked. Europe is the world leader in this area and demonstrates a genuine collaboration between scientists, airlines and aircraft manufacturers. The collaboration between many partners is complex and a secure mechanism is required to ensure in-service aircraft programmes continue in the long term. In-service aircraft provide in situ measurements in the UTLS, which is difficult to probe from space. Analogous monitoring of the PBL from in-service ships is sought.

Many reports have recommended which atmospheric components should be monitored, to what precisions, accuracies and spatial and temporal resolutions. For the most part, this document relies on these reports, particularly the WMO / CEOS Report on a Strategy for Integrating Satellite and Ground-based Observations of Ozone (WMO, 2001a) and the forthcoming Integrated Global Atmospheric Chemistry Observations (IGACO) reports. There is an international consensus and specific recommendations are made in the individual chapters. However it is worth noting that the atmospheric monitoring system must be sufficiently flexible to adapt to new issues. For example, the importance of stratospheric water vapour has become increasingly clear in recent years, with implications for future stratospheric ozone and climate. Similarly, there has been increasing recognition of the health-related importance of small particulate matter (PM10 and smaller). A specific case raised in this report concerns the desirability of a standardised monitoring network for air quality at major air- and seaports to include observations of chemical species and particles. Existing air- and seaport monitoring stations should be integrated into existing air-quality monitoring networks.

The main issue regarding the stability of the current monitoring systems is funding, discussed below. However at the same time as ensuring a stable funding regime, it is important to recognise that budgets are limited and that the European atmospheric monitoring network must be cost-effective and efficient in answering the questions that GMES addresses. There are significant opportunities to improve the cost effectiveness through increased coordination of databases and information systems, in the development of new highly automated instrumentation based on the latest technology as well as in the rationalisation of the observation network itself. In many instances, past funding levels and the desire for stability in the instrument record have led to the use of old technology and labour-intensive approaches in monitoring networks. It is important to ensure that any progress towards newer technologies is not achieved at the expense of data quality.

The cost effectiveness of existing networks has not been previously evaluated. On a project level, the use of local networks may or may not be cost effective. However, it is unlikely that the current use of local and regional networks is cost effective at a European level; research into the current state is required in addition to cost / benefit analyses of new developments. An evaluation requires clear criteria, specific to the issue under consideration. For example, in relation to air quality, the most 'cost-effective' measurements may be those most sensitive to the effects of compliance with policy (National Ceilings Directive and Framework Directive) or those which most reduce current model uncertainties.

Provision of Funding / Rational Funding Frameworks

A coordinated European approach, with greater liaison between funding sources, is essential to streamline funding and thereby provide significantly increased stability for observation programmes, data quality and the use of observations. Current funding is provided through regional, national, governmental, European and private authorities with different interests. In most cases, long-term funding is not available; monitoring activities must rely heavily on the successful renewal of two or three year contracts by individual researchers.

The funding stream for monitoring is in most cases the same as for interest-driven research despite the different nature and aims of the work involved. In recent years, research funding organisations have put an increasing emphasis on 'innovative' and 'wealth creating' science. Atmospheric monitoring does not fall in these categories per se, but rather contributes significantly to policy and public debate through the extension of established, high quality records and increased spatial, temporal and species coverage. GMES offers a great opportunity to acknowledge the value of European monitoring systems through the provision of funding dedicated to monitoring, which is complementary to research and technological development funds.

Summary

GMES provides Europe with a great opportunity to develop a first-class atmospheric monitoring system. The proposed strategy ensures the GMES system will contribute to the solution of global environmental issues, such as stratospheric ozone depletion and climate change in addition to issues of local and regional impact, such as air quality. This system will also address specialised environmental topics such as the impacts of aviation and shipping on the atmosphere and public safety with respect to volcanic activity, including the threat to aircraft.

The proposed strategy requires rationalisation of existing capabilities, strengthening of current weaknesses, development of a cohesive approach to all atmospheric monitoring activities and provision of a rational funding mechanism to ensure quality and continuity. The system will achieve long-term high-quality monitoring through the best coordinated use of existing and proposed satellite and non-satellite monitoring activities. To establish this system, close coordination with on-going research programmes is required at European and national levels.

GMES-GATO opportunities within GMES	Chapters 1-6					
	Montreal Protocol: Stratospheric Ozone Depletion and Surface UV Radiation	Kyoto Protocol: Climate Change	Air Quality Conventions: Local, Regional and Continental Scales	International Conventions on Aviation, Shipping and Coastal Pollution	Volcano Monitoring and Public Safety	Atmospheric Influence on Systems Observing the Earth's Surface
Verification of compliance with and success of protocols	Continuous Atmospheric Monitoring					
	ODS, GHG and precursor emissions and atmospheric concentrations.					
	Long-term, accurate O_3 records.	Flux network for sub-regional emissions.				
		Coastal monitoring to verify marine conventions and monitor impact on land-based air quality.				
Provision of near-real-time information for public and scientific use	Public safety and scientific understanding					
	UV index forecasts.		Chemical weather forecasts e.g. pollution events.		Ash alerts and forecasts for aviation.	
	Low-ozone event warnings including Arctic O_3 loss info.					
Observation and modelling synergies	Data assimilation and modelled forecasts					
		Combine observations and inverse modelling to estimate regional emissions.				O_3, H_2O and aerosols.
	Improved exploitation of measurements from ground-based, air and satellite observing systems					
	Assess causes of long-term trends and variability.					
Measurement quality, archiving and access	Coherent QA/QC, effective archiving and derivation of new data products					
	Improved access to and interoperability of atmospheric databases e.g. through one-stop-facility.					
	Public access to up-to-date atmospheric information.					Integrate databases and processing centres.
Extension of satellite programme beyond ENVISAT	Atmospheric monitoring including continued validation / calibration					
	Improved characterisation of aerosols and clouds.					
		Combined low Earth orbit and geostationary satellites.				Integrate atmospheric knowledge with mission planning.
Development of non-satellite monitoring systems for GMES Post-2008	Consolidate networks of ground-based stations: Integrate existing networks, extend into data sparse regions, strategically position and preserve future flexibility					
	In situ measurements in the UTLS and PBL: consolidate in-service aircraft measurements: start in-service ship measurements.					
			Upgrade 5-10 EMEP sites to regional masters.			
Provision of funding / rational funding frameworks	Secure funding stream for monitoring to ensure long-term continuity					

Table 1 GMES-GATO opportunities within GMES to develop a first-class atmospheric monitoring system; close coordination with on-going international research programmes is required.

THE MONTREAL PROTOCOL: STRATOSPHERIC OZONE DEPLETION AND SURFACE UV RADIATION

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The issues related to stratospheric ozone depletion from chlorofluorocarbons (CFCs) and other halogen-containing substances and the associated enhancement in surface UV radiation are relatively advanced in terms of the scientific understanding and the policy response. Strong, well-founded scientific evidence has resulted in internationally agreed policy measures developed through negotiations under the Montreal Protocol. The investigation of stratospheric ozone depletion is conducted in many countries from a number of different angles. In Europe, a balanced programme of EU research has been developed as described in Atmospheric Interdisciplinary Research (AIRES) in the European Research Area (ERA) (EC, 2001) which includes:

- Atmospheric monitoring
- Field process studies
- Laboratory experiments
- Modelling and theoretical studies
- Development of new instrumentation

In this chapter, we focus on the requirements for the first of these, atmospheric monitoring, noting that the others are essential for success. In the context of GMES, for example, modelling and theoretical studies are needed for the interpretation and exploitation of the raw measurements. In Section 1.1 we briefly describe the scientific issues, old and new, related to stratospheric ozone and UV radiation. The policy and public interest background is presented in Section 1.2. An important theme here is the increasing importance of climate change in relation to future stratospheric ozone and surface UV radiation. The current monitoring system and the outlook for the next 10-15 years is described in Section 1.3. Finally, in Section 1.4, the strengths and weaknesses of the monitoring system which has developed in response to this environmental issue are discussed with respect to the present and the future.

1.1 THE ISSUES

1.1.1 Stratospheric Ozone Depletion

The combination of stratospheric ozone depletion and the associated increase in UV radiation at the Earth's surface has been one of the major environmental issues of the past 30 years. Two of the major landmarks in the development of this field were the publication of the original CFC hypothesis (Molina and Rowland, 1974 inspired by global measurements of CFCs) and the discovery of the Antarctic ozone hole (Farman et al., 1985 based on high quality measurements of total column ozone from 1957 to 1985). More thorough examination of other long-term measurements from ground-based and satellite instruments showed that significant, but smaller decreases have occurred over mid-latitudes in both hemispheres. The following sections, based on the latest World Meteorological Organization (WMO) - United Nations Environment Programme (UNEP) Scientific Assessment of Ozone Depletion (WMO, 2003), describe the scientific issues which require information from atmospheric monitoring for the development of effective public policy.

1.1.1.1 Source Gases

CFCs and other ozone-depleting substances are released by anthropogenic and natural processes, with over 80% of the current day concentration of chlorine-containing substances resulting from human activities. Following the agreement of Montreal Protocol and its subsequent amendments and adjustments, the atmospheric concentrations of the major chlorine-containing compounds, the CFCs, have either stabilised or begun to decrease. These changes are consistent with our understanding of their atmospheric removal processes, their individual lifetimes and their continuing emissions from existing equipment. The concentrations of hydrochlorofluorocarbons (HCFCs) and the bromine-containing Halons are still increasing. Continued monitoring of all the ozone-depleting substances is the best indication of whether or not there is compliance with the Montreal Protocol and a critical test of the effectiveness of the actions taken.

1.1.1.2 Polar Ozone Depletion

On-going observation of ozone loss during successive Arctic winters is important as substantial losses can occur. A striking feature of Arctic ozone loss has been the large interannual variability in ozone loss and its strong temperature dependence. For example, at altitudes around 18 km there were losses of >65% in 1999/2000 and <10% in 1998/1999, with intermediate losses in other winters. Chemical losses in total column ozone in the Arctic vortex have varied between about 5 and 30% since the early 1990s. Overall a decrease in total ozone in the Arctic region has been observed since 1980, although there is considerable year-to-year variation in the observed values related to meteorology and climatic factors such as the North Atlantic Oscillation. This variability in the ozone loss is to be contrasted with the Antarctic where nearly complete ozone loss has taken place at altitudes between about 15 and 20 km in all but one winter since 1990 - the Antarctic ozone hole.

1.1.1.3 Non-Polar Ozone Depletion

Globally, the recent total column ozone for 1997-2001 was approximately 3% below historic values. No significant trends in the total column have been observed in the tropics, whereas ozone is depleted over the mid-latitudes in both hemispheres. In the northern hemisphere, a minimum occurred in 1993 since when there has been a modest increase. Recent values (1997-2001) were 3% lower than historic ones (pre-1980 average values). In the southern hemisphere, total ozone is still decreasing and recent values were 6% lower than historic levels. Major influences here are the different dynamical (meteorological) situations in the two hemispheres and the effect of the eruption of Mt Pinatubo in 1992.

A reduced downward trend in ozone at altitudes around 40 km (where chlorine is clearly playing a dominant role) is the first sign that the measures in the Montreal Protocol are reducing chlorine-catalysed ozone depletion (Newchurch et al., 2003). The main question for the future is whether ozone (and UV radiation) will return to historic levels or not. In particular, how will climate change influence (e.g. through dynamical changes) the anticipated recovery of ozone as halogen levels drop?

1.1.2 Surface UV Radiation

The decline in atmospheric ozone concentrations has led to concerns about increases in surface UV levels at mid- and high latitudes. UV exposure has been linked to health problems in humans and also affects animals and vegetation. UV monitoring is important for the assessment of impacts, e.g. accumulated UV doses on ecosystems, to monitor trends and to investigate processes affecting UV levels.

A number of studies (using satellite and ground-based data) indicate that there has been a long-term increase in surface UV radiation since the early 1980s of 6-14% in the mid- and high latitudes in both hemispheres. These are consistent with the high quality, ground-based UV measurements that have been made since around 1990, and with the observed changes in ozone at the measuring sites. The largest UV increases have been observed in Antarctica during the ozone hole period (September to December each year). A number of other factors also exert a strong influence on UV radiation. In future these factors, especially cloud cover and local albedo, are likely to become increasingly important as the Earth's climate changes. Future changes in ozone, however it recovers, will have a significant influence on future UV radiation.

1.2 WHAT ARE THE POLICY RELATED ISSUES?

There are three main policy issues related to stratospheric ozone depletion and increased surface UV radiation:

- The supply of policy relevant information in support of the Montreal protocol
- The supply of policy relevant information in support of Kyoto protocol
- The supply of information to the public regarding UV radiation

1.2.1 The Montreal Protocol

The international community reacted to the scientific findings on chemical ozone depletion by agreeing the Vienna Convention in 1985 and, subsequently, the Montreal Protocol. A series of international scientific assessments of knowledge about stratospheric ozone were organised by UNEP and the WMO to provide a scientific basis to the Montreal Protocol. Over time this process, in conjunction with similar technological assessments, resulted in the agreement of a number of amendments and adjustments to the original Montreal Protocol. These controlled the emission of ozone depleting substances such as CFCs, methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4), methyl bromide (CH_3Br) and Halons, as well as the emissions of some ‘replacement’ compounds such as HCFCs. Up-to-date information about long-term changes in the atmospheric concentrations of these source gases, ozone and other compounds and in the levels of UV radiation were central to the success of this process in supplying a firm scientific basis for dealing with the global environmental problem of stratospheric ozone depletion and increased surface UV radiation.

The Montreal Protocol has successfully resulted in reduced emissions and atmospheric concentrations of CFCs, methylchloroform and carbon tetrachloride (WMO, 2003). Overall the effective concentration of chlorine in the stratosphere has started to decrease, and it should return to the pre-ozone hole level by about 2050. Atmospheric measurements have thus been used to verify compliance with the Protocol. New policy-related issues are assessed as they arise, e.g. the possible importance of very short-lived compounds containing chlorine and bromine are discussed in the latest WMO assessment (2003). Continued atmospheric monitoring is required to identify the recovery of stratospheric ozone and to ensure the success (or otherwise) of the Montreal Protocol in reducing chemical ozone depletion. In this way, atmospheric measurements will be used to verify the effectiveness of the actions taken.

1.2.2 The Kyoto Protocol

The Kyoto protocol was developed under the Framework Convention on Climate Change (FCCC) as an international response to the rising concentrations of greenhouse gases and their role in climate change. There has been an increasing awareness that the state of the ozone layer over the next decades will depend on climate change in addition to the phasing out of ozone depleting substances such as CFCs and Halons. In other words, the ozone layer will most likely return to a different state, and so the central question of the Montreal process remains 'How and when will ozone and UV radiation recover as CFC concentrations fall?'. It is important to monitor the impact of climate change on stratospheric ozone and on surface UV radiation, and to see, for example, if climate change causes an increase in UV radiation through an increase in the height of the tropopause, i.e. by making the stratosphere smaller, or by a cloud feed-back. The interaction between climate change and stratospheric ozone is a critical factor in determining how stratospheric ozone recovers as the concentrations of ozone-depleting substances fall.

1.2.3 UV Warnings

The public in many European countries is now routinely warned when periods of high surface UV radiation are forecast and informed of the adverse effects of over-exposure to solar UV radiation. This helps to reduce sunburn and, in the longer term, health problems such as skin cancer and cataracts. The UV warnings, which rely on a combination of ground-based and satellite measurements and models, are usually issued by national meteorological agencies. The main period for warnings is in the summer when the sun is high in the sky, there is less cloud cover, and people spend a long time outdoors. In winter, there is a public interest in the timely provision of information when large Arctic losses occur and the ozone-depleted air moves over Europe, as UV radiation can locally greatly increase, especially over reflective surfaces such as snow and ice. Additional information about the size of the ozone loss is required in winter. A procedure for such wintertime warnings is being developed in the GMES-GATO project, which makes use of satellite and ground-based measurements.

1.3 WHAT ARE THE CURRENT CAPABILITIES?

Stratospheric ozone depletion and increased surface UV radiation are global problems which require long-term investigations on a global scale, complemented by more local (in space and time) process studies. ‘Observing’ or ‘monitoring’ is best understood in the wider sense of encompassing observations, numerical modelling efforts and data assimilation activities, and requires many meteorological and atmospheric dynamical parameters for a complete understanding. Accordingly, the component of GMES dealing with this issue has to be seen in a global context and closely integrated with existing global programmes and coordination and assessment activities, particularly those advanced by the WMO and the Integrated Global Observing Strategy (IGOS).

The European component of the global atmospheric monitoring system is made up of a number of facets. In this section we give an overview of the current capabilities and an outlook for the next 10-15 years. In section 1.3.1 the observational capability (instrumentation, platforms and system integration) is described, while in section 1.3.2 issues related to data archiving, use and availability are presented. The exploitation and dissemination of information is discussed in section 1.3.3, and finally, in section 1.3.4, the availability of resources is summarised. For more detail, the reader is referred to the IGOS report prepared on behalf of WMO and Committee on Earth Observation Satellites (CEOS) (WMO, 2001a), the Global Atmosphere Watch (GAW) Strategic Plan (WMO, 2001b) and the Integrated Global Atmospheric Chemistry Observations (IGACO) Theme report (IGACO, 2003). These reports also include information on platforms available for field campaigns (such as research balloons and aircraft) which are not covered in this report.

1.3.1 Observational Capability

1.3.1.1 Ground-based Networks

Atmospheric monitoring is performed by many different institutions using many different instruments and data formats. In order to maximise the use of all this information, international structures have been developed to coordinate the different aspects. For example, WMO operate a global ozone observing network as part of GAW. Participating organisations (principally, but not exclusively, the national meteorological agencies) use standard instruments, procedures and data formats and submit their ozone measurements to a central database, the World Ozone and UV Data Centre (WOUDC) in Toronto. The backbone of the total ozone observing network is the Dobson spectrophotometer which is a well characterised instrument with established quality assurance (QA) and quality control (QC) procedures. The other main instrument measuring total ozone is the Brewer instrument which has QA / QC procedures which are less well established across the network. While both of these instruments can also provide some information about the vertical distribution of ozone, more detailed information about the vertical distribution particularly in the lower stratosphere and troposphere is routinely provided by the ozonesonde network with well established QA / QC procedures. In all cases the success of the current QA / QC procedures (and even the operation of the network itself) is largely limited by the availability of funding for their implementation.

The Network for the Detection of Stratospheric Change (NDSC) is an important component in GAW which has a strong link to research establishments. It comprises a smaller global network of ground-based stations which contains a wide range of high performance instruments (e.g. lidars, microwave radiometers, and Fourier transform infrared (FTIR), UV-Vis and surface UV spectrometers) measuring a suite of stratospheric (and tropospheric) constituents. Again, standard procedures, etc. have been developed by the involved experts. Europe provides major components of these global networks. Quality control procedures which involve tasks such as the periodic instrument comparisons and retrieval algorithm improvements are central features of these networks.

Many ground-based stations have multiple purposes. Most NDSC stations have other instruments which are part of other networks. For example, the tropospheric concentrations of ozone-depleting gases and their replacements are measured within networks such as the Advanced Global Atmospheric Gases Experiment (AGAGE) and the National Oceanic and Atmospheric Administration (NOAA) - Climate Monitoring and Diagnostics Laboratory (CMDL) which contribute to GAW. These networks are discussed in more detail in Chapter 2 as they make measurements of a wide range of greenhouse gases.

No similar global network exists for UV measurements. Instead a number of national and regional / continental networks have developed which tend to have their own standards and procedures. In Europe, most individual countries have their own UV monitoring networks of varying quality. WMO has a Science Advisory Group which coordinates the UV networks, with a view to international standardisation of instrumentation and measurements. However the issue is complicated as there are several classes of instrument, developed with varying aims, which measure different properties of UV radiation with differing levels of accuracy and precision. Europe has played a leading role in this area, and over the last decade a great deal of effort has been expended to provide a backbone of high quality, well-characterised instruments with rigorous quality assurance and quality control procedures. These instruments allow relatively small changes to be measured over long time periods, and also provide a reference into which the national networks in Europe can be linked. A European UV database has been developed, with the aim of including spectral measurements from all appropriate instruments in Europe and applying further, common QA and QC.

An important component of the ground-based monitoring network (i.e. not space-based) is the use of in service commercial aircraft carrying instruments to make atmospheric measurements. Europe is the world leader in this area with a real collaboration between scientists, airlines and aircraft manufacturers. All three European projects (CARIBIC, MOZAIC and NOXAR) have been great successes and have significantly improved our knowledge and understanding of the upper troposphere / lower stratosphere (UTLS). NOXAR made a significant impact with its two year measurement programme due to the scarcity and importance of good measurements of nitrogen oxides (NO and NO_2). In general, however, the value of the existing measurement records has increased dramatically with the length of the record. This can be clearly seen in the rapid increase in the scientific use of MOZAIC data by the international scientific community. For the MOZAIC measurements of ozone and water vapour, much of the value is derived from the sheer quantity of measurements, which have been used to produce climatologies, to compare with models and other measurements, and in process studies, e.g. in conjunction with campaign data. These measurements have been of relatively low cost, with <70€ estimated for each vertical profile of ozone measured. Finally, measurements on commercial aircraft provide an excellent resource for satellite validation in the UTLS where it remains difficult to make good satellite measurements.

These programmes are currently passing through a transitional phase. In late 2002, Lufthansa and the partner research institutes in CARIBIC committed themselves to a further ten years of operations. On the other hand the aircraft carrying the MOZAIC instruments are coming towards the end of their operational lives with the current airlines and there is uncertainty surrounding their future.

1.3.1.2 Satellites

Satellite instruments provide global measurements of many atmospheric constituents and are therefore powerful tools in the armoury of the atmospheric scientist. Satellite instrument development is an important driver for technological advances and benefits greatly from the close links to similar ground-based instruments. In practice the extent of the measurement is constrained by the instrument technique, the technology available when the instrument was designed and the satellite orbit characteristics. In particular the spatial and temporal resolution of the measurements put limits on the scale of processes which can be studied in detail. Further the lifetime of the satellite instrument is very important as the scientific value of these data sets increase dramatically with time, partly due to an increasing amount of data and partly due to greater understanding of the instrument and the derivation of new or improved products. This is an important element in decisions to extend the operations for an instrument such as ERS2-GOME, which is currently in operation beyond its originally planned operational lifetime. For long-term usability, satellite validation efforts should be maintained to address inevitable instrument degradation.

International collaboration is an important element of space-based Earth Observation. Satellites are expensive and budgets are limited, so many research satellites measuring the atmosphere have been international collaborations rather than single country ventures. The Swedish-led small satellite, ODIN was launched in 2002 for a consortium of agencies from Sweden, Canada and France. The National Aeronautics and Space Administration (NASA) satellite, AURA, planned for launch in early 2004, will carry the European instruments HIRDLS (UK) and OMI (Netherlands and Finland). The polar-orbiting satellite, MetOp, dedicated to operational meteorology, represents the European contribution to a new cooperative venture with the USA. Given budgetary limitations, this international collaboration is likely to continue and it is important that the CEOS initiative to provide a global strategy is successful, particularly for high quality total ozone measurements. New technological developments and atmospheric issues will continue to drive this area forward.

The main European satellites making stratospheric measurements are the European Space Agency's (ESA's) ERS-2 (GOME) and Envisat (GOMOS, MIPAS and SCIAMACHY). In future, the

European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) will extend their meteorological satellite series, with the MetOp series (three satellites to be launched sequentially over 14 years starting in 2005) whose payload includes GOME-2 and IASI. While these are not primarily for scientific studies, high quality data on atmospheric variables and constituents will be collected and should be made available for the atmospheric research community. In this regard it is noteworthy that, besides the MetOp series that pursue primarily meteorological objectives, atmospheric research satellites are not programmed in Europe for this decade beyond the Envisat era. Given the long lead times in satellite instrument development, it is likely to prove difficult to achieve continuity in long-term atmospheric monitoring, even when the plans of other space agencies are taken into account. Ensuring the continuity of satellite monitoring of key atmospheric parameters should be among the primary tasks of CEOS.

1.3.1.3 Integration of Observations from Different Sources

The Integrated Global Observing Strategy (IGOS), including satellite and ground-based observations of ozone and other atmospheric constituents, was prepared on behalf of WMO and CEOS (WMO, 2001a), with input from international scientific programmes such as Stratospheric Processes and their Role in Climate (SPARC) and International Global Atmospheric Chemistry (IGAC) as well as research agencies including the EC and space agencies including ESA. It contains a comprehensive description of the available resources for observing the atmosphere. It also makes a number of recommendations which cover most of the issues described in this report. In particular it recommends closer coordination of ground-based and satellite measurements and validation activities to extend over the whole course of each satellite sensor's life. While this falls within the aims of GMES and it is clearly needed from a scientific standpoint, no effective mechanism is yet in place to achieve this.

Such a course of action requires a clear understanding of the roles of satellite and ground-based measurements. A well-run network such as NDSC provides measurements of atmospheric constituents of known quality and, crucially, long-term stability. They can thus be used as a reference for new satellite instruments and the stability of satellite instruments over many years. The global coverage of the satellites can be used in conjunction with the stability, but limited coverage, of the ground-based networks to provide global data sets of proven high quality. For example, the comparison of the GAW ozone measurements with ozone measurements by satellites such as TOMS and, latterly, GOME has proven invaluable in assessing the quality of these measurements in the series of WMO-UNEP assessments over the last 15 years (WMO, 2003 and references therein). Satellite instruments have finite lifetimes limited by technical constraints (and occasionally accidents), whereas from a technical perspective the ground-based networks can continue indefinitely.

The full exploitation of satellite and non-satellite measurements is a major scientific challenge for the coming years which will require innovative approaches towards the combined use of measurement sets with very different characteristics (e.g., temporal and spatial resolution). From a European perspective, the Envisat measurements should play a major role and it is important they are used to the full. EU research on stratospheric ozone and UV radiation is coordinated through research clusters and large pan-European field campaigns. One of the explicit aims of the research clusters is to exploit the available satellite data in the coming years. This explicit aim is necessary as there have been limited European satellite data available in the past and not all research groups consider using it routinely. It is also a principal objective of the EC GMES-GATO project. The satellite measurements should be of value in studies of the tropical stratosphere and upper troposphere, which is a major focus for field measurements in the planned SCOUT-O3 Integrated Project, supported in Framework Programme 6. An important element in achieving the maximum exploitation of satellite data will be improved coordination between national and EC research programmes in Europe, which is the central aim of the ERA. Each country has different research funding structures and it is currently hard to develop effective interfaces and procedures to liase with the various research and space agencies.

1.3.2 Data Products, Use and Archiving

The archiving of and accessibility to data products are critical elements in the exploitation of atmospheric measurements. In this section, we address three aspects of this exploitation: data types, data quality and data archiving / accessibility.

1.3.2.1 Data Types

The following different levels of data products should be distinguished:

- Raw measurement data
- Elementary geophysical data retrieved from the measurements or numerical modelling data
- Derived data, e.g., re-gridded data, assimilated data, homogenised time series and trend data, climatologies, forecast data, etc

It is important that data at *all* levels are archived to enable updating, re-processing and re-archiving.

Various initiatives have been taken to develop user-oriented data products, for example, in the frame of the ESA Data User Programme (DUP). Up to now, four DUP projects have addressed directly or indirectly the ozone depletion issue (DAMS2P, AMASDU, OZONE-FD and TEMIS). Only a few European countries have subscribed to the DUP programme until now (United Kingdom, the Netherlands, Italy and Switzerland). The next phase (Data User Element (DUE)) might include more partner countries.

1.3.2.2 Data Quality

The final value of information derived from atmospheric measurements depends directly on the quality of the measurements. Ensuring that a high measurement quality is achieved is a hard task as it involves defining and implementing QA / QC procedures, as well as refining and improving the original measurements by making full use of advances in understanding the method of measurement and / or the instrument. Quality assessment is an important, time-consuming and continuous issue; for long-term data analysis, it includes the verification of the homogeneity of the time series. This verification often requires the reprocessing of parts of the database. In applications where near-real-time (NRT) data are requested, data quality criteria are generally relaxed to some extent. Fully validated, often re-processed, data are mostly released with larger time delays - at present, these delays are still of the order of 1 year and should be shortened.

The GAW and NDSC networks have well established procedures for QA / QC whose success depends largely on the resources available. For example, regular comparisons with a standard travelling instrument are a costly business in terms of time and manpower, and are being abandoned or replaced by less expensive methods. Such changes in QA / QC procedures must be made in a documented and controlled way to ensure long-term homogeneity and correct use of the data. Most satellite instruments also have clearly defined programmes for QA / QC at the engineering level but not at the scientific data level. Here, one is often limited to ad-hoc validation efforts, instead of a well-organised, long-term validation programme. The use of satellite measurements is also limited by the generally slow pace at which improved versions are produced.

1.3.2.3 Data Archiving / Accessibility

There are many archives of atmospheric data in Europe and the rest of the world (international datasets). Historically these have largely been developed on a national or programmatic basis for data storage, limited by data transfer rates. The rapid increase in data transfer rates has facilitated access to many databases so there is room for some rationalisation of the atmospheric databases in Europe. A likely solution is the development of a virtual database. This is starting (within GMES-GATO for example,) but it will inevitably be an on-going process as the technology develops.

The geophysical interpretation of data mostly requires the inclusion of additional data from other sources in the analyses. Therefore it is important that:

- Data mining can be performed easily over a distributed database system.
- Data are stored in a fully comprehensive way (for experts and non-experts of that particular data product).
- Data formats facilitate the manipulation and integration of data from different sources and archives.

Such a development should be pursued in tandem with the promotion of data for public purposes, e.g. by producing user required information which requires raw data processing, “advertisement” of databases and data products to potential users and the promotion of possible commercial applications.

At present, an effort has been made by various satellite teams, e.g., the Envisat calibration / validation (CAL / VAL) database, and CEOS has initiated some coordination among the satellite agencies. A similar effort concerning non-satellite data has been made within various networks and databases (e.g., the NDSC / GAW and WOUDC databases) but these have not been generally coordinated, either among the various databases or with satellite archives.

For the user there is a lack of clarity as to where data (original and / or updated) are archived and accessible; it is also unclear what the quality is of various datasets of apparently the same geophysical entity in different places. A typical example is GOME / ERS-2 NO_2 data. In many cases, data are subject to data protocols and / or particular access fees, a situation that discourages an integrated exploitation of existing resources.

An increasing problem for data providers is that the effort required to submit their data to different databases is unnecessarily large due to differences in data format, submission procedures, etc., that are used by the various databases. Consequently, data are often not distributed because of practical constraints of time and manpower, even if the data providers are willing to share their data.

1.3.3 Data Interpretation and Dissemination

There are various motivations for the use of atmospheric observations. These include curiosity-driven research into the overall status and workings of the atmosphere, more directed research aimed at providing information for assessments, and the provision of information for public interest and education. While noting that curiosity-driven research has proved to be essential in providing critical information for assessments, the focus here is on monitoring, campaign and numerical modelling activities that provide high quality, consistent data to help address the issues described in Sections 1.1 and 1.2.

1.3.3.1 Scientific Use

An improved understanding of the atmosphere is achieved through a balanced programme of research, as outlined at the start of this chapter (EC, 2001). The main integrating tools are complex numerical models that describe the processes occurring in the atmosphere. To do this they are heavily reliant on detailed information about these processes gained from laboratory studies and field campaigns, and on advances in theoretical understanding. Global atmospheric monitoring provides information about longer time-scales and larger spatial scales than can be studied in other ways. The models are used to study the past behaviour of the atmosphere (e.g. trends in atmospheric composition) and, when coupled to a climate model, the future behaviour. European scientists have developed a large number of numerical models of the atmosphere of varying complexity, with different chemical and transport schemes, and different spatial (mesoscale, global, etc.) and vertical scales. Atmospheric winds and temperatures provided by numerical weather prediction (NWP) models from agencies such as the European Centre for Medium-Range Weather Forecasts (ECMWF) or the UK Meteorological Office (UKMO) are used either, directly, to drive the model dynamics or, indirectly, to assess them.

The quality of the models is best tested by critical comparison with atmospheric observations, either from global monitoring or field campaigns. Past studies have revealed deficiencies in all (dynamical, chemical and radiative) representations of physical processes in models. In order to have real confidence in future model studies, more long-term and global data are needed, along with more critical comparisons.

Data assimilation, an approach which combines the best available information from measurements and models, is an important tool which has been developed in recent years. 4D variational data assimilation analyses provide the most consistent (with observations and theoretical knowledge) global analyses of the chemical composition of the atmosphere. When coupled with NWP models, the data assimilation techniques enable forecasts of stratospheric chemical composition, a few days in advance. The latter can be used to provide forecasts of UV-index on a routine basis (see below).

The EU funded concerted action Data Assimilation in Readiness for Envisat (DARE) brought together a large number of European partners with data assimilation expertise to build a European capacity for assimilation of Envisat data and thereby to improve the quality and cost-effectiveness of Envisat data. DARE recommends close links with NWP agencies and the implementation of a distributed Envisat Satellite Application Facility (SAF) to coordinate assimilation activities.

Particular data services have been developed to provide NRT measurements in the context of campaigns, such as Third European Stratospheric Experiment on Ozone (THESEO) and Validation of International Satellites and Study of Ozone Loss (VINTERSOL), and the COST-713 Action (UV forecasting). For example, such services have been available from GOME for several Arctic winters, and individual ground stations provide similarly quick information about their observations. Daily maps are derived by assimilating real-time GAW and satellite measurements. These services typically consist of a web interface from which data can be retrieved, usually in the form of user-friendly maps or graphs. While they are open to the public, the information is mainly used by scientists to plan their own measurements or to monitor the extent of ozone loss in a particular winter. Reports on the ozone loss in each Arctic winter have been produced since 1997 by the European Ozone Research Coordinating Unit (EORCU), and the WMO coordinates bulletins during the Antarctic Ozone Hole period.

1.3.3.2 Use in Assessments
To make the research useful for policies and environmental bodies, the scientific data must be 'translated' into information usable in the assessments supporting policy development such as the WMO-UNEP and Intergovernmental Panel on Climate Change (IPCC) reports, and similar assessments at national and European levels. The fundamental questions asked by such assessments are: 'What atmospheric changes have occurred in the past?', 'What changes are likely in the future?' and 'How well do we understand the processes leading to such changes?'. Important new questions related to the Montreal Protocol are: 'Are the agreed measures being implemented?' and 'Are the enacted policies having the desired effect?'. In terms of future monitoring

programmes, the central question is 'Are observations currently available or scheduled for the near future which will enable us to assess the effectiveness of the measures taken in compliance with the Montreal Protocol?'.

Atmospheric monitoring plays a critical role in answering most of these questions. Observations of atmospheric constituents and properties are essential in knowing what has happened in the past, and global observations can yield unique information about large-scale atmospheric processes. Continued measurements are needed to judge the effectiveness of the Montreal Protocol (with respect to source gas concentrations and ozone itself) and to assess the interaction between climate change, stratospheric ozone and UV radiation. The system exists to translate observations into useful information for assessments - continued effectiveness in this area depends on continued support.

1.3.3.3 Use for Public Interest

The main areas of public interest are forecasts of UV index, periods of extreme ozone loss and education. It is now common for UV index forecasts to be disseminated to the public via the news media. These forecasts are organised nationally and so there are differences in approach, but they all depend on some sort of modelling and / or data assimilation. Such forecasts are made routinely and are available on the web for public consumption. On some occasions, press releases are issued to inform / motivate the public. Typically these are concerned with particularly severe Arctic ozone loss, the Antarctic Ozone Hole or some other unusual occurrence and require NRT information. At present, press releases are issued on an *ad hoc* basis.

The public interest in environmental issues and ozone depletion in particular provides a natural way to increase the public's understanding of science and its role in society. A wide range of information is available for public consumption and for use in educational programmes, and Earth Observation information, with its graphical display options, plays an important role in this context.

1.3.4 Resources

A significant issue in Europe for global atmospheric monitoring is the way in which it is supported. At present, funding is provided through a large number of different authorities (regional, national and European - governmental and private) with different interests. It is not a cohesive support system, and in practice it relies heavily on individual researchers being successful in raising small amounts of resources from a number of sources. In most instances, mechanisms for long-term funding are non-existent. For example, contributions to international networks like GAW and NDSC are not funded through a European organisation, but on an individual project basis. Stable atmospheric research positions are rare. It is not a stable system, in which a coordinated European approach can be developed, nor a good use of expert time and effort. These comments hold true for all aspects of atmospheric monitoring discussed in this and other chapters, the observations, the databases and the data exploitation, even though most elements of the desired system exist. One reason for this is the tendency in Europe for research councils to concentrate on looking for new innovative projects to support, especially those which may generate wealth. Monitoring is not seen as valuable science, despite its central importance in society's response to environmental issues. Lack of sufficient, consistent resources for monitoring makes the observing system vulnerable (e.g. resulting in discontinuities in records and / or quality more likely) and leads to conditions in which it is hard to develop the required human resources. A true European contribution to the global atmospheric issues requires greater coordination of the available local, national and European resources within the context of the strategies prepared by international agencies.

1.4 IS THIS A RATIONAL SYSTEM?

A rational system for the use of measurements of stratospheric ozone and UV radiation would include components related to the collection of appropriate measurements, data storage and technical processing, and exploitation of data for scientific research, policy development and verification of compliance, and public interest. Stratospheric ozone depletion and enhanced UV radiation is a relatively mature field with respect to the development of a coherent, integrated atmospheric monitoring system. Many of the required pieces exist and significant progress has been made towards integration. Ground-based and satellite measurements have been widely used in the WMO-UNEP and IPCC assessments to assess atmospheric composition changes and to improve the understanding of the processes involved. Public interest in the relevant science, UV forecasts and extreme ozone events is fairly well served through a number of media. The main issues to be resolved are the formation of a stable, integrated system using the existing elements and the continued improvement of individual elements (e.g. more observing stations in the Southern Hemisphere, integration and expansion of existing systems in the former USSR and Eastern European countries, improved user feedback, better quality and reliability of measurements, etc.).

The problem is global and requires a global solution. A number of international programmes exist which address the same issues, and it is important that Europe, as a region with a high level of expertise, continues to contribute to them. A new separate global programme is not needed. Collaboration with international agencies such as WMO and CEOS, with international science programmes such as the World Climate Research Programme (WCRP) / SPARC and the International Geosphere-Biosphere Programme (IGBP) / IGAC, and with research and space agencies in other countries should be maintained and strengthened. IGOS has made a number of recommendations, but as neither WMO nor CEOS have budgets of their own, the European implementation must be performed through GMES. GMES should be integrated with these and similar existing efforts, reinforcing the links between the different initiatives.

Budgets are limited and so it will be important to ensure that the European component to the global observing system is cost effective and efficient in answering the questions that GMES addresses. For example, recent technological advances should enable the development of new, more highly automated instrumentation for ground-based observations to reduce the amount of human labour required to make measurements. Given the importance of measurement stability and continuity in monitoring programmes, such changes need to be introduced gradually. Similar comments hold true regarding databases, many of which have been developed at the national level. Obtaining the resources to achieve better ‘synchronisation’ and effectiveness of databases, and to guarantee long-term archiving and data access, remains a major concern. Finally, coordination of resources at European level will reduce duplication of effort and is an important step in the realisation of the ERA. Studies on how to make the global information system more cost effective are needed to inform GMES.

Ground-based (including in service aircraft) atmospheric monitoring is a subject that should be recognised by research agencies as important in its own right. It is easy to dismiss monitoring as ‘same again’ science without considering that the true value lies in the extension of data records. The operational, application-oriented approach of GMES should help, as long as it is recognised that the main users are the public and governments rather than commercial entities. However, continued monitoring should go hand in hand with continued research to ensure it remains relevant and to maintain the interest of participants. The current funding system is not rational in terms of producing a European component to a global atmospheric monitoring system. A rationalisation of the funding system for ground-based atmospheric monitoring is needed for the success of this element of GMES. The long-term nature of the problem is important.

A longer-term view is also needed in dealing with data from current satellite instruments and in planning for future measurements. Continued effort increases the exploitation of the original raw measurements by increasing the quality / range of the geophysical products (as retrievals are improved) or through the use of the measurements to answer new questions. In this respect it is also important to ensure that the data are made available to a wide community of users and are not heavily restricted through data protocols and so on. With the exception of the meteorological MetOp satellites, satellites measuring atmospheric composition are not programmed in Europe for this decade beyond the Envisat era. Given the long lead times in satellite instrument development, it is likely to prove difficult to achieve continuity in long-term atmospheric monitoring, even when the plans of the other space agencies are taken into account.

Ground-based and satellite data are complementary. Combined use of data results in improvements in the quality of both sets of measurements. Ground-based monitoring networks provide high data quality and continuity over time that cannot be guaranteed by individual satellite instruments, while the satellite instruments provide information about larger spatial scales. Future monitoring programmes will require strong contributions from both classes.

The wider dissemination of the measurements and derived information should be continued and enhanced. More feedback from non-specialist user groups would improve the available information. A programme to involve more students in Earth Observation studies would be beneficial within the wider GMES context to improve awareness of atmospheric environmental science generally and to promote scientific careers. GMES could play a valuable role in promoting dialogue between communities where little contact currently exists.

The relevance of the monitoring programme to on-going research is also important in a wider perspective to ensure that programmes can react to new issues. New areas open up which could benefit from improved global observations. The obvious examples at the moment are the increased emphasis on the upper troposphere and lower stratosphere, with great efforts made to make improved and higher resolution measurements in this region from, for example, Envisat and AURA, and the need for improved long-term measurements of stratospheric water vapour.

It will be important within GMES to maintain and strengthen the link between the meteorological and atmospheric communities: they have common interests and the meteorological satellites can often be exploited for stratospheric research objectives. For example, IASI on MetOp-1 has primary objectives of meteorological interest (pressure, T, O_3 measurements), but will also be exploited for the measurement of stratospheric and tropospheric constituents.

A drive towards new instrumentation for ground-based and satellite instruments and shorter lead times for future satellites would open up technological opportunities for small or medium sized enterprises (SMEs) and other European industries.

Chapter 2

THE KYOTO PROTOCOL: CLIMATE CHANGE

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2.1 THE ISSUES

Greenhouse gases (GHGs) in the Earth's atmosphere absorb energy in the infrared part of the spectrum, which would otherwise be emitted into space. Consequently, anthropogenically emitted GHGs lead to warming of the Earth's surface and the lower troposphere (IPCC, 2001). Likewise, aerosols (small airborne particles) resulting from human activity reflect or absorb solar radiation lead mostly to cooling but in some cases to warming of the lower atmosphere. The warming at the surface is accompanied by a cooling in the upper stratosphere and in the mesosphere, which has an influence on atmospheric circulation and the recovery of the stratospheric ozone layer (Chapter 1).

In recent years, public awareness of climate change and its impact on the environment, the resulting social and economic effects has increased. It has become part of the political agenda as it will be one of the major challenges to face future generations. Potential consequences for European citizens include rising sea levels, migration, changes to patterns of precipitation, melting permafrost in mountain regions and changing ocean currents (IPCC, 2001).

A global plan of action (the Kyoto Protocol) under the auspice of the United Nations Framework Convention on Climate Change (UNFCCC) has been under debate for nearly a decade but still awaits political implementation. By 2012, Europe has committed itself to reduce greenhouse emissions by 8% from the 1990 level.

In order to answer scientific questions related to the political process, the Intergovernmental Panel on Climate Change (IPCC) was founded. The IPCC is responsible for assessing the current state of knowledge of climate change, the present state of the climate and possible future scenarios. Atmospheric monitoring is key to the observation of the evolution of climate change components. Europe has an economic and social responsibility here, both within its own sphere of influence and globally. A short description of each key atmospheric components relevant to climate change is presented below.

2.1.1 Carbon Dioxide

Carbon dioxide (CO_2) is the most important anthropogenic GHG, having increased by about 30% compared to pre-industrial (pre-1750) values. This increase is the result of anthropogenic conversion of fossil fuel to CO_2 for energy production in various industrial- and transport-related processes. Furthermore, albeit to a smaller extent, deforestation has also contributed to the increase in CO_2 concentration. The background trend of CO_2 and its seasonal variation is well documented through global background measurements from ground-based networks (IPCC, 2001).

2.1.2 Methane

Methane (CH_4) is not only a GHG, but is also involved in atmospheric oxidation chemistry and thus presents a chemistry-climate interaction. Furthermore, increasing CH_4 concentrations have also impacted on O_3 photochemistry in the stratosphere (Chapter 1). Its pre-industrial background concentration has increased by nearly 150% due to anthropogenic emissions from sources including gas leaks, landfills and excess biomass burning. Europe constitutes a major source, as does the Russian gas industry that supplies much of Europe's energy.

2.1.3 Nitrous Oxide

Nitrous oxide (N_2O), has increased by about 15% since pre-industrial times as a consequence of the enhanced use of nitrogenated fertilisers and emissions from industrial processes (IPCC, 2001).

2.1.4 Halocarbons

Halocarbons (Hal), like the exclusively anthropogenic chlorofluorocarbons (CFCs), were used for example as propellants and foam blowing agents (Midgley and McCulloch, 1999). As CFCs and related compounds are also responsible for the decline of stratospheric ozone, their usage will be forbidden by 2010 through the Montreal Protocol and its amendments. However, their substitutes (i.e. hydrofluorocarbons (HFCs)), perfluorocarbons (PFCs) and sulphur hexafluoride still contribute to climate change. As emissions of these compounds are still rising, their contribution to climate change will increase, too.

2.1.5 Ozone

Ozone (O_3) is produced by oxidation processes related to fossil fuel and biomass burning. Its short tropospheric lifetime leads to large spatial and temporal variations. In addition to its direct effects, stratospheric ozone has an indirect effect on GHG concentrations as its decline may lead to increased levels of tropospheric OH radicals. The concentration of OH radicals is an important variable that controls the lifetimes of for example, CH_4 and HFCs.

2.1.6 Water Vapour

Water vapour (H_2O) is a very effective GHG in the lower stratosphere. In this atmospheric region, H_2O originates from oxidation of CH_4 and direct emissions from aviation. Its values are increasing in this region of the atmosphere to an extent which cannot be explained by current scientific knowledge (IPCC, 2001). The concentration of H_2O also affects stratospheric ozone (Chapter 1).

2.1.7 Indirect Greenhouse Gases

Indirect greenhouse gases exhibit no direct influence on climate change, but affect levels of GHGs through chemical reactions. Indirect GHGs include the following substances:

- Carbon monoxide (CO) is mainly anthropogenically emitted. It affects the concentration of CH_4 via a reactions with OH, which also produces O_3.
- Volatile organic compounds (VOCs) and nitrogen oxides ($NO_x = NO + NO_2$) are emitted in greater than natural amounts due to human activities. VOCs and NO_x act together in the production of tropospheric ozone.

- Hydrogen (H_2) could be a future energy carrier (the "hydrogen economy") with potentially high emissions due to leakage during distribution and use. H_2 could reduce the OH radical abundance and thus lead to higher lifetimes of greenhouse active substances like CH_4 and HFCs. Furthermore, the most recent studies suggest the abundance of H_2 affects stratospheric water vapour (Tromp et al., 2003).

2.1.8 Aerosols

Aerosols are small solid or liquid particles in the atmosphere. There are several types of aerosols, which can be produced through anthropogenic activity or natural processes. Their role in the climate system is to reflect and absorb solar radiation. Most aerosols reflect more than they absorb and lead to a cooling of the surface and the lowest part of the troposphere. Only a few types of aerosol (mainly soot particles) mostly absorb and contribute to a warming like GHGs.

Aerosols do not last long in the air and so they can be abundant in one place while scarce nearby. Aerosols can also change rapidly from day to day (e.g. after a forest fire or a local pollution event). The cooling or warming due to aerosols thus exhibits large geographical variations, unlike the heating due to GHGs.

The effect of anthropogenic aerosols is largely a cooling of the surface on a global scale. However, the spatial differences in the cooling creates changes in atmospheric circulation, which may lead to changes in climate in certain regions.

In addition to their direct impacts on climate through their interaction with solar radiation, aerosols indirectly impact on climate by altering the formation and precipitation properties of clouds. The indirect effect is not considered in this report, which is restricted to direct climate effects due to the interaction of GHGs and aerosols with radiation in the atmosphere.

Aerosols are either primary or secondary in nature. Primary aerosols are emitted into the atmosphere as particulate matter, whereas secondary aerosols originate from the chemical transformation of gaseous precursors such as SO_2, NO_x and VOCs.

2.2 WHAT ARE THE POLICY RELATED ISSUES?

2.2.1 The Kyoto Protocol

The Kyoto Protocol was negotiated under the supervision of UNFCCC as an international response to the rising concentrations of GHGs and their role in climate change. The Protocol subjects industrialised countries to legally-binding targets in order to limit their GHG emissions. These targets add up to a global reduction of 5% in GHG emissions from 1990 levels, for the five-year period 2008-2012.

The Kyoto Protocol sets limits on the total of emissions of six main GHGs: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. The protocol also establishes three innovative 'mechanisms', known as 'joint implementation', 'emissions trading' and the 'clean development mechanism', which are designed to help parties reduce the costs of meeting their emission targets by achieving or acquiring emission reductions more cheaply in other countries than at home.

The European Community ratified the Kyoto Protocol on 31 May 2002, pursuant to Decision 2002/358/EC. The Kyoto Protocol is legally regulated in the EU by the Council decision 93/389/EEC for a monitoring mechanism of Community CO_2 and other GHG emissions and its amendment (Council Decision 99/296/EC). These decisions have established a mechanism designed to monitor all anthropogenic GHG emissions, which are not controlled under the Montreal Protocol and its Amendments, and evaluate progress made in this field to ensure compliance with the Community's commitments concerning climate change.

In the evaluation report of these decisions (1999/296/EC), the progress towards the aimed reduction is assessed. Projections indicate that existing measures will not be sufficient to continue reducing emissions until 2012. The European Climate Change Programme (ECCP) was initiated to reduce the projected short-comings.

There is a proposal for a new monitoring mechanism Council Decision (COM (2003) 51 final), which should replace the former decisions. It reflects the guidelines of the UNFCCC as recently set out in Bonn and Marrakech (COP 6 and 7), provides further harmonisation of emission forecasts and addresses the requirements in relation to the ratification of the Kyoto Protocol and burden-sharing between the community and its member states.

2.2.2 The Montreal Protocol

The Montreal Protocol, including its Amendments, is an international response to stop the stratospheric ozone decline caused by anthropogenic long-lived chlorine and bromine-containing organic compounds (e.g. CFCs and halons). It sets out specific legal obligations in the form of timetables for the progressive reduction and / or elimination of the production and consumption of certain ozone-depleting substances. As all of these compounds are also GHGs, their world-wide ban in 2010 will also affect climate change. The relevant EU legislation on this subject is the decision on the Montreal Protocol (depletion of the ozone layer) (88/540/EEC).

2.2.3 Other EU-Legislations relevant to Climate Change

In relation to precursors of GHGs, the following legislations are of relevance: the tropospheric ozone pollution directive (92/72/EEC), the directive on volatile organic compounds (99/13/EC), the sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air directive (99/30/EC) and the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants (LRTAP) in Europe (European Monitoring and Evaluation Programme (EMEP)) and its financing (86/277/EEC).

Furthermore, there is the Clean Air for Europe (CAFE) initiative which is centered on air quality issues (Chapter 3), but which also has a strong bearing on climate change.

2.3 WHAT ARE THE CURRENT CAPABILITIES?

2.3.1 Greenhouse Gases

GHGs are measured by different techniques. The most important approaches on a long-term basis are:

- In situ surface concentrations
- Column abundances by Fourier transform infrared spectroscopy (FTIR) from the ground, and via satellites from space.

Measurements of GHGs and related substances have been the subject of many projects within the 5th and the 6th Framework Programmes (FPs) of the EU, which include: AEROCARB, EVERGREEN EARLINET, DAEDALUS, CREATE, Meth-MonitEUr, POET, SOGE, RETRO, FORMAT, CANDIDOZ, UFTIR, ACCENT and SCOUT-O3. With the help of these projects it has been and continues to be possible to build a solid scientific basis in Europe of enormous potential in the implementation of GMES.

On the global scale, a link between GMES and the ongoing Integrated Global Atmospheric Chemistry Observation (IGACO) exercise (within the Integrated Global Observing Strategy (IGOS)) should be established. This activity should run in parallel to efforts to put together a world-wide strategy for continuous monitoring of atmospheric composition.

Combinations of measurement techniques (e.g. in-situ and remote via satellites) have a high potential to examine scientific atmospheric issues but have been employed only on a limited scale to date. Within the EU 5th FP, approaches to link these independent techniques were made within two projects, SOGE and EVERGREEN. In SOGE, *in situ* and FTIR measurements were compared at two background sites, Ny-Ålesund (Spitsbergen) and Jungfraujoch (Switzerland), to determine historic surface concentrations from column abundances. In EVERGREEN, satellite and Fourier transform infrared (FTIR) data are combined, not only to validate the space-based measurements, but also to improve emission estimates of GHGs. In the following sections, the current European capabilities related to the individual measurement techniques are described.

2.3.1.1 Ground-based In Situ Measurements

GHGs are measured at many sites around Europe. However, as most programs are either national or university-supported, no superordinate concept to coordinate efforts is recognisable. For example, intercomparison exercises are normally limited to the duration of a specific project, which makes datasets useless for modelling on a continental scale. Furthermore, many of the sites are at remote locations like mountain sites. These are in principle favoured positions for analysing background atmospheric composition. However, as the focus of research shifts more and more towards regional scales (like verification of regional emissions), stations near to sources are becoming more important. The coverage of stations which perform atmospheric research in Europe is very patchy, both in relation to spatial representativeness and GHGs covered. For the individual groups of GHGs, different networks exist:

- Carbon Dioxide (CO_2)

Within the 5th FP, there exists a cluster of projects, CARBOEUROPE, which is concerned with understanding and quantifying the carbon balance of Europe. Within CARBOEUROPE, the AEROCARB project (http://www.aerocarb.cnrs-gif.fr) provides atmospheric CO_2 and related tracer concentration measurements. Thus the existing twenty monitoring stations at ground level are calibrated and integrated into one coherent ensemble (e.g. Figure 2.1A). The database of ground-based measurements serves as the basis for inverse calculations of CO_2 fluxes.

- Non-CO_2 Greenhouse Gases

The group of non-CO_2 GHGs is composed of CH_4, N_2O and halocarbons. World-wide, there exist two networks for the ground-based measurement of non-CO_2 GHGs; the National Oceanic and Atmospheric Administration (NOAA) / Climate Monitoring and Diagnostics Laboratory (CMDL) (Hall et al., 2002) and the Advanced Global Atmospheric Gases Experiment (AGAGE) (Prinn et al., 2000) (Figure 2.1 B-E). Both networks are mainly funded by US sources and intercompare their independent calibration scales regularly. As all of the sites belonging to these global networks are located in very remote places, only limited information can be obtained for regional emission estimates.

The site at Mace Head (Ireland) belongs to the AGAGE network, but is also a partner in the SOGE project and Meth-MonitEUr projects of the European 5th FP, as well as a flask site for the US NOAA. Within SOGE, European emissions of halogenated GHGs are assessed using a combination of atmospheric models and continuous measurements at four sites (Mace Head, Jungfraujoch, Ny-Ålesund and Monte Cimone). As part of Meth-MonitEUr, a high-precision CH_4 isotope time series is maintained.

With regards to CH_4, the present situation is inadequate. Within GMES, Meth-MonitEUr has recently begun a major intercomparison program to enable modellers to use CH_4 data and combine them with meteorological information. Meth-MonitEUr is also supporting essential concentration and isotope measurements, especially in Russia.

Regarding N_2O, the situation is even less adequate as only few scattered measurement sites with different calibration scales exist in Europe. Moreover, no common European effort is planned in relation to N_2O, although its emissions are far from negligible.

Furthermore, tropospheric ozone is also a non-CO_2 GHG, although it is not included in the Kyoto Protocol as it is not itself emitted. Tropospheric ozone is measured at both very polluted sites and global background locations. The data quality of the measurements is not unified and absolute calibration is hindered by the instability of ozone in standards. At least, at stations within the EMEP network, a standardised quality scheme is in operation. For the background sites within the Global Atmosphere Watch (GAW) network of the World Meteorological Organization (WMO), a calibration scheme exists, which guarantees a minimum quality for data from these locations.

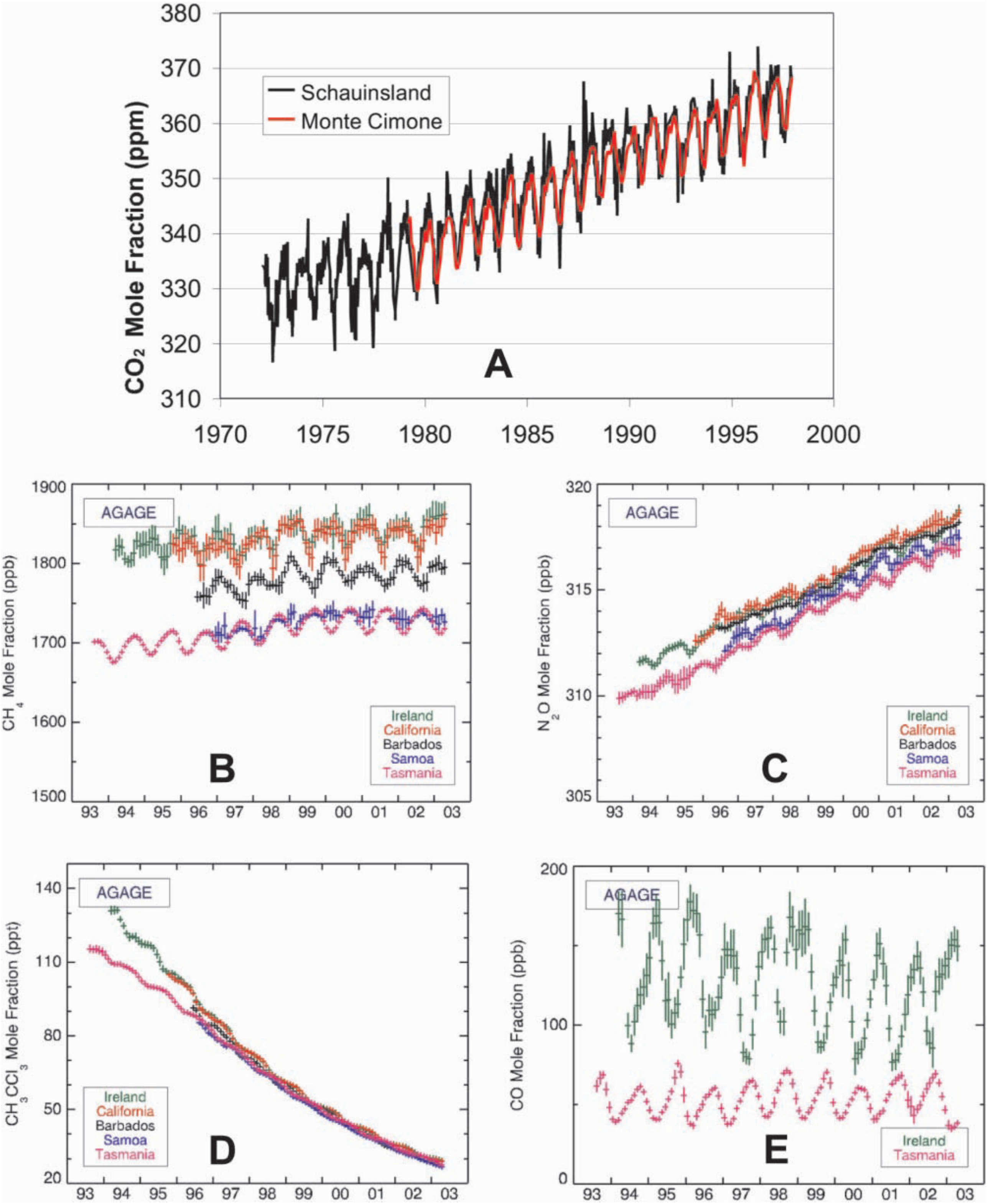

Figure 2.1 Data series of GHGs: A) CO_2 at Schauinsland (Umweltbundesamt Offenbach in cooperation with the Institute for Environmental Physics, University of Heidelberg) and Monte Cimone (Italian Meteorological Organisation). B-E) AGAGE data: B) CH_4, C) N_2O, D) CH_3CCl_3 or 1,1,1-trichloroethane and E) CO.

- Indirect Greenhouse Gases (CO, VOCs, NO_x)

Many measurements of these gases are made close to their anthropogenic sources, becoming sparser in more remote regions For CO measurements, a common quality system exists at GAW stations. However, for NO_x and especially VOC measurements, no common European approach has been taken and only at the sites within the EMEP is a minimum data quality system in operation. Furthermore, only few isotopic studies of CO and VOCs have been performed to date.

2.3.1.2 Ground-based Remote Sensing

With the help of ground-based FTIR spectrometers, solar absorption spectra can be recorded routinely under clear sky conditions. Thus the absorption of IR radiation by trace gases relevant to climate change (e.g. CO_2, CO, CH_4, SF_6, O_3, some CFCs / hydrochlorofluorocarbons (HCFCs) and N_2O) can be measured and converted into column abundances of these gases. Furthermore, SO_2 and aerosols can be measured under certain conditions. The analysis of H_2O is also possible however the uncertainties therein must be reduced.

High-altitude stations are most appropriate because the measurement capabilities for some species, e.g. SF_6, depend on the amount of H_2O vapour above the station and the measurements are less contaminated by local (surface) pollution from the boundary layer. Therefore, the longest quasi-continuous time series in Europe comes from the high-Alpine site of the Jungfraujoch and dates back to 1985.

Most FTIR measurements, performed at nearly twenty sites worldwide, are part of the Network for the Detection of Stratospheric Change (NDSC). Within this network, regular intercomparison exercises (instrumentation and retrieval algorithms) are performed to ensure comparable data. Until recently, only total column abundances have been measured. Some vertical profile information at low vertical resolution can now be retrieved, which means in particular that free tropospheric GHG distributions can be assessed.

At present, efforts are being made to assess the accuracy / precision of tropospheric GHG distributions retrieved from FTIR spectra in order to compare these data with data from state-of-the-art tropospheric models and to derive trends in the free troposphere (e.g. the European project, UFTIR).

2.3.1.3 Space-based Measurements of Greenhouse Gases

Space based measurements of GHGs are relatively new. In particular, total column measurements have only recently become available. Total columns yield information on the emissions from the Earth's surface.

In the early 1990's the National Aeonautics and Space Administration (NASA) UARS satellite with HALOE and CLAES instruments on board pioneered the measurement of CH_4, CO, CO_2, H_2O and other GHGs however this measurement series was restricted to the stratosphere (limb sounding instruments). The measurements were only in part global, covering from the tropics to mid-latitudes in low inclination equatorial drifting orbit. The National Space Development Agency of Japan (NASDA) ADEOS-1 satellite carrying the IMG instrument was first to achieve global coverage of GHG total column measurements, made possible through the combination of a polar orbiting satellite and a nadir-viewing instrument. Due to satellite failure, this measurement series was prematurely aborted (1996-1997). The NASA polar orbiting Earth Observing System (EOS) TERRA (1999-present) carrying the nadir viewing MOPITT instrument allows total column measurements of CO and CH_4. The European Space Agency's (ESA's) environmental monitoring satellite, Envisat (2002-present) carries SCIAMACHY (nadir and limb) and MIPAS (limb), which are capable of measuring a range of GHGs. In Figure 2.2, early retrieval results are shown for CO_2 and CH_4. The NASA EOS AQUA satellite (2002-present) carries the AIRS instrument with GHG measurement capability. Similarly, the NASDA ADEOS-2 (2002-present) carries the ILAS-II instrument with GHG measurement capability.

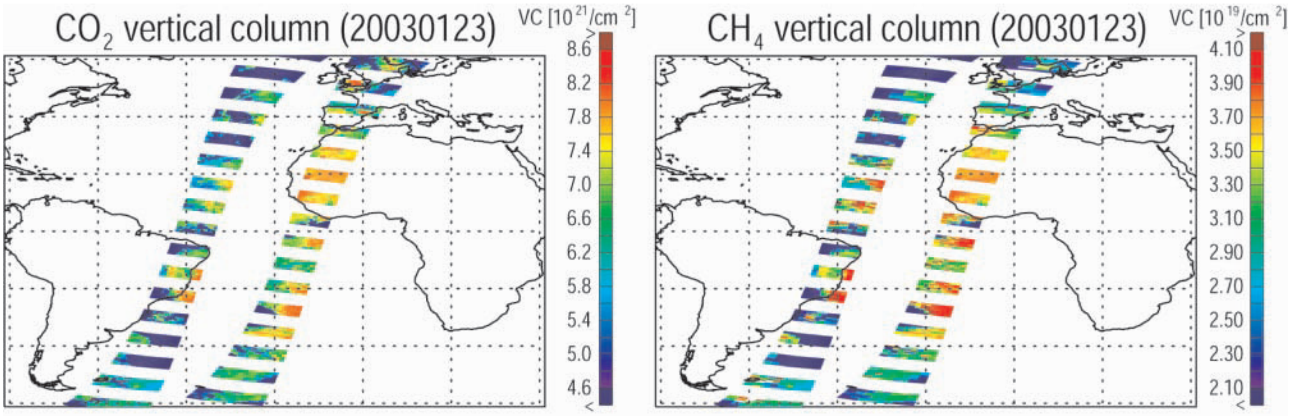

Figure 2.2 Early retrieval results from SCIAMACHY for CO_2 and CH_4 (reference M. Buchwitz University of Bremen).

In the near future, the NASA EOS AURA satellite (2004-2010) will provide new GHG measurement capabilities with the nadir-limb viewing TES instrument on board. Limb viewing HRDLS will provide additional information. Subsequently, the Orbiting Carbon Observatory (OCO) satellite planned in the NASA Earth System Science Pathfinder program (ESSP)-3 will provide a powerful carbon dioxide measurement facility. On the Japanese side, the ADEOS-3 (2007) with ILAS-II on board and GCOM (2007) with a payload yet to be defined will be of interest with respect to GHG measurements. Long-term monitoring of GHGs will be achieved through the European Organisation for the Exploitation of Meteorological Satellites' (EUMETSAT's) MetOp series (2005-2020) with the nadir viewing spectrometer, IASI on board.

The key question asked of all space-based instruments is, 'What spatial and temporal resolutions are achieved and how accurate are the measurements?'. Spectral observations of thermal emission in the IR (FTIR 3-15 μm) represent the more mature remote sensing technology for GHG measurements from ground, balloon (MIPAS-B) and space with a well-established accuracy of measurements. However, due to a lack of contrast near the Earth's surface, total columns cannot be measured accurately from space employing this technique. The near-IR spectral range, pioneered by SCIAMACHY and MOPITT, allows measurement of solar radiation penetrating the atmosphere to the Earth's surface and hence yields a contribution of spectral absorption from the boundary layer. This contribution is important for total column and tropospheric GHG measurements since GHG emissions originate from near the Earth's surface.

In order to pinpoint and follow GHG emissions, high spatial and temporal resolutions will be required. For some GHG precursor gases like CO (precursor to CO_2), NO_2 (precursor to tropospheric O_3) and SO_2 (precursor to aerosol), a temporal resolution of a few hours turns out to be a critical requirement due to the diurnal variation of these gases. This high temporal resolution cannot be achieved by polar orbiting satellites (unless there are ten or more in sequence), but requires satellites in geo-stationary orbit. Measurement accuracies at the percentage level or better must be achieved to provide measurements of value in trend analysis and even more stringent requirements are pertinent to deriving emission data from concentration / distribution measurements.

A further requirement for space-based GHG observations arises because the vertical distribution of GHGs influences the radiative forcing exerted on the atmosphere and hence climate change. For example, ozone is most effective as a GHG in the upper troposphere. Therefore, in addition to total column measurements, the vertical distribution of GHGs must be measured. Limb sounding instruments attached to low earth orbiting satellites can make such measurements but only down to a certain altitude, typically 10-15 km. This is not sufficiently low to probe the free troposphere. Here, a combination of near-IR and thermal IR measurements would help provide additional altitude information due to the different sensitivities total column measurements exhibit with respect to altitude. Such a scheme was proposed by MOPITT but due to malfunction of spectral channels, has not been exploited to date. A combination of near- and thermal IR instrumentation would be particularly appropriate for application on a geo-stationary platform which cannot benefit from good vertical resolution achieved through limb observations in low earth orbit.

2.3.2 Aerosols

The same applies to measurements of aerosols as applies to gaseous air pollutants; a wide variety of capacities and measurement networks exist in Europe. Many of the measurements are concerned with the health aspects of aerosols (particulate matter) and are therefore made close to emission sources. Measurements are financed by individual countries or research projects and the quality of data is incomparable as a result. Moreover different measurement methods are used to quantify aerosol levels in different European countries and in different locations. Therefore a comparison of data is far from straightforward. More precise, harmonised and quality-controlled measurements are needed to obtain a comprehensive picture of the geographical and seasonal characteristics of particulate matter in Europe.

2.3.2.1 Ground-based In Situ Measurements

Ground-based in situ measurements of aerosol chemical and physical properties are made within long-term monitoring networks (e.g. EMEP, Interagency Monitoring of Protected Visual Environments (IMPROVE)) and intensive focused field campaigns (ACE-series, TARFOX, INDOEX, and so on). Long-term networks deliver mostly limited information from point measurements spread over a large geographical area. In contrast, field campaigns achieve very comprehensive physical-chemical-optical characterisation, enabling closure studies between e.g. chemical / size distribution and optical properties, hygroscopic properties, and so on, but offer limited temporal and spatial coverages.

2.3.2.2 Ground-based Remote Sensing

Ground based remote sensing is used to measure column-integrated and vertically resolved aerosol properties. Column integrated aerosol parameters are derived from sun photometer data. Climatologies of aerosol optical depth (AOD), effective size distribution and refractive index are becoming available. The PHOTONS / Aerosol Robotic Network (AERONET) is based on a standardised measurement using a single type of sun photometer. Information on the vertical distribution of aerosols can be obtained from lidar measurements of backscatter profiles. The European Aerosol Research Lidar Network (EARLINET) is an FP5 supported European lidar network.

2.3.2.3 Space-based Measurements

The measurement of aerosol is more complicated than the measurement of gas concentrations in that not only concentration but also size, shape and chemical composition determine the optical properties relevant to the Earth's radiation balance and hence the greenhouse effect. There is also a thin line between aerosol and cloud; (sub-visible) cirrus clouds affect optical depth measurements from space and thereby the retrieved concentrations of both GHGs and aerosols, in addition to themselves influencing the Earth's radiation balance. Similar arguments hold for Polar Stratospheric Clouds (PSCs) and noctilucent clouds.

Current satellite aerosol capability draws heavily on the TOMS (1978), AVHRR (1981), ATSR (ERS 1991-2002, Envisat 2002), MISR (TERRA 1999) and MODIS (TERRA and AQUA 2002) nadir viewing instruments installed on Low-Earth Orbit (LEO) satellite platforms. These instruments, currently in operation, measure aerosol optical depth, which is important but insufficient on its own for climate applications. A more comprehensive aerosol measurement device is the French POLDER instrument on the ADEOS-2 satellite (2002-present) measuring polarisation information needed to determine size and shape factors in the aerosol distribution. A future deployment of POLDER is foreseen on the Parasol platform as part of the NASA EOS A-train. The future planned deployment of the AVHRR-3 instrument on MetOp and of VIIRS on NPOESS will provide long-term data continuity (2005-2020). An example of today's possibilities is shown in Figure 2.3.

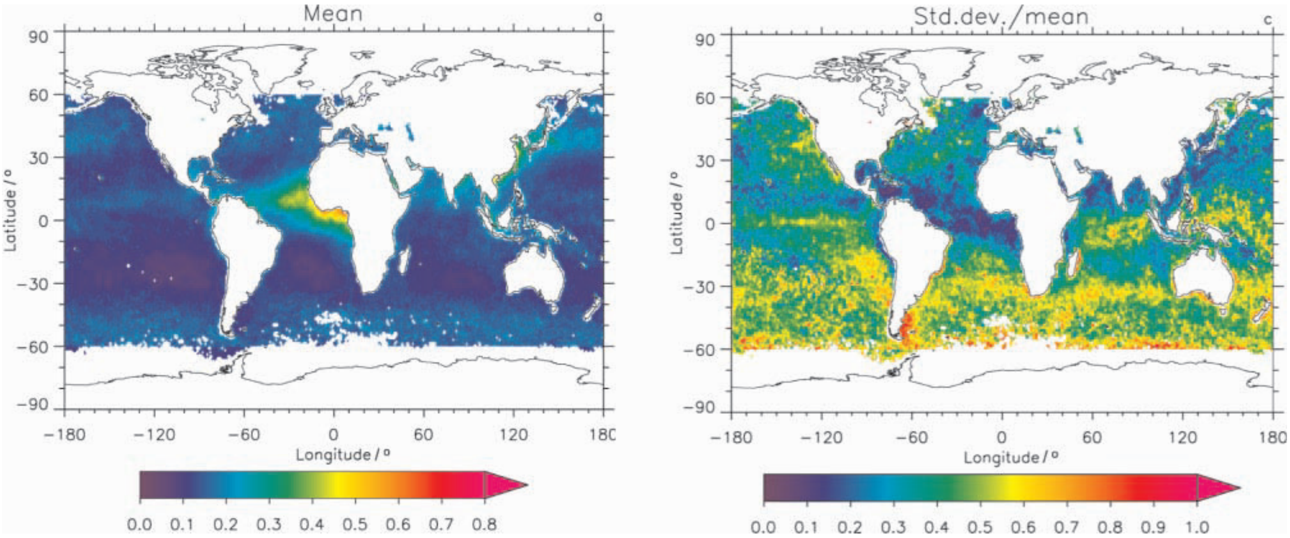

Figure 2.3 AOD at 550 nm derived from the following five different retrievals: AVHRR-1, AVHRR-2, POLDER, OCTS and TOMS. The left panel gives the mean of the five retrievals, the right panel their standard deviation relative to the mean, for an 8 month period in 1996/1997 (from Myhre et al., 2004).

Measurement of stratospheric aerosol is well served by limb viewing occultation instruments, such as SAGE, HALOE and POAM. The SAM / SAGE instrument series has provided a valuable long-term data record from 1978 onward of stratospheric aerosol. From this data record, volcano climatology could be established. Also the limb and occultation viewing modes of SCIAMACHY and MIPAS have demonstrated their potential to identify PSCs and noctilucent clouds.

The high temporal variability of aerosols and the dependence of their reflectance on solar zenith angle, i.e. the time of day, necessitate additional measurement from geo-stationary orbit. The SEVERI instrument on the Meteosat Second Generation (MSG) (2002-2015) will provide basic column properties of aerosols. However, more demanding aerosol measurement requirements cannot be met by presently planned and operational geo-stationary satellites.

2.3.3 Data Centres

Ground-based measurements of GHGs are archived in the World Data Centre of Greenhouse Gases (WDCGG; http://gaw.kishou.go.jp/wdcgg.html).

The FTIR community is part of the NDSC. Total column data are stored centrally in the NDSC / NOAA database (ftp://ndsc.wwb.noaa.gov/pub/). A request will be issued this year to include FTIR vertical profile data in the NDSC database. The UFTIR database, located at the Norwegian Institute for Air Research's (NILU's) Atmospheric Database for Interactive Retrieval (NADIR), will include time series of a number of GHG profiles.

The European Air Quality Monitoring Network (EuroAirnet) provides a structure for the operation of a database (Airbase) from air quality monitoring network stations in more than thirty European countries. Data is aggregated from existing monitoring stations to serve information needs at the European level. Data can be found at the EuroAirnet database (http://www.nilu.no/niluweb/services/euroairnet/).

For some satellites, data is available at the relevant mission's homepage:
(e.g. MOPITT: http://www.eos.ucar.edu/mopitt/data). However access to European satellite data is gained on a more bilateral basis. Aerosol data from many locations can be found via the AERONET project website (http://aeronet.gsfc.nasa.gov). The World Data Centre for Aerosols (WDCA) from the GAW is located at http://rea.ei.jrc.it/netshare/wilson/WDCA/.

2.3.4 Emission Inventories

For GHGs and their precursors, the following emission inventories are relevant:

- EDGAR (http://arch.rivm.nl/env/int/coredata/edgar)
- CORINAIR (CO_2, CH_4, CO and NMVOCs) (http://www.aeat.com/netcen/corinair/94/index.html)
- EMEP (indirect greenhouse gases) (http://webdab.emep.int/)

Furthermore, European countries have to report their estimates of GHG emissions on a yearly basis to the UNFCCC. However these data are of highly variable quality as neither in-depth quality assurance nor independent data validation (e.g. by measurements in combination with models) is required.

2.3.5 Detection of Global Trends

One of the main aims, shared by the different measurement platforms, is the detection of global trends in atmospheric pollutants. This provides an opportunity to check, for example, the development of global GHG emissions and to detect unreported emissions.

In Western Europe, a dense network of ground-based background measurement sites exists. In fact, with stations like Mace Head on the West coast of Ireland, Ny-Ålesund on Spitsbergen and the high-Alpine station of Jungfraujoch, Europe has the most dense network of background sites world-wide. However, blind spots still exist, such as the Mediterranean and Siberia.

However, for some measurements, such as those of CH_4, N_2O and isotopes, the situation as described above is far from ideal and modelers, for example, rather use weekly US NOAA flask data than the more highly-resolved European data of variable quality.

2.3.6 Modelling and Assimilation Techniques related to Climate Change

Until recently only isolated approaches were taken to combine atmospheric models with measurements to assess regional GHG emissions ("inverse modelling"), to assess their effect on climate change and to reduce uncertainties in the estimation of the climatic effects of aerosols. However, lately some promising approaches have been taken, for example in Europe as part of research projects within the 5th and the 6th European FPs (AEROCARB, EVERGREEN, EARLINET, DAEDALUS, CREATE, Meth-MonitEUr, POET, SOGE, RETRO, FORMAT, CANDIDOZ, UFTIR, ACCENT and SCOUT-O3).

GHG and aerosol distributions have traditionally been studied using chemistry transport models (CTMs), with an emphasis on understanding the processes which govern these distributions. Observations have often been used to validate the models. Most GHGs have been studied in this way, including CO_2, CH_4, N_2O, O_3 and a range of halogenated species. Over the last few years, much emphasis has been placed on model studies of a range of aerosols, such as sulphates, soot, organic compounds, biomass-burning and dust aerosols.

In combination with observations, models can be utilised in new ways to yield additional information. One approach is inverse modelling, in which observations of GHG concentrations are used in combination with models to derive the GHG emissions. Using meteorological data, one can determine the histories of air parcels arriving at the measurement sites. There are various techniques to attribute the measured concentrations to the locations which the air parcels visited en route to the measurement sites. A number of GHGs, such as CO_2, CH_4 and several halogenated gases, have been studied using such an approach.

In data assimilation, observations and models are used in parallel to establish distributions of GHGs as well as aerosols. One starting point is a CTM that describes these distributions from the combination of best estimates of emissions, current knowledge of chemical and physical transformations in the atmosphere and transport based on meteorological data. The other source of information is comprised of observations, either surface-based or satellite-based data. These pieces of information, together with estimates of their uncertainties, are used to estimate what is called an assimilated distribution. This can be seen as a way of filling in the gaps between observations with modelled data.

2.4 IS THIS A RATIONAL SYSTEM?

'Various uncoordinated activities throughout Europe at international and national levels should be made mutually reinforcing, with the GMES initiative providing a flexible, efficient framework and a federating force.' P.Busquin, Brussels, March 2002.

As climate change is of high priority in the 6th Environmental Action Programme, Europe is showing leadership in environmental treaties such as the Kyoto Protocol on global climate change. It will be important for the success of these agreements to have access to independent information on an operational basis, to verify and enforce the treaty and to assess the effects of agreed policies. Furthermore, the Kyoto Protocol calls for specific contributions from the different parties to set up global observation systems. This could provide an opportunity for Europe to take a leading role in this process.

To reach these goals a broad range of observations of important atmospheric, oceanic, and terrestrial parameters is required. This information should be used to support future policy-making with evidence of trends, monitor the legal commitments undertaken within the Kyoto Protocol and future treaties, and improve scientific understanding of the underlying processes.

In general a common European approach is urgently needed to address the issues related to climate change.

A state-of-the-art system for atmospheric measurements, with highly capable multifunctional sites combined with sophisticated modelling capacities, should be used to investigate the following important issues related to climate change:

- Verification of greenhouse gas emissions:

- Estimation of global emissions by observation of long-term trends
- Estimation of regional emissions through the combination of in situ / column / satellite measurements and state-of-the-art meteorological models
- Investigation of process-related emissions with a network of flux measurement facilities to check for sub-regional emissions (e.g. melting permafrost soils and the effect of sequestration in the tropics)
- The building of monitoring capacities in developing regions of the world, which are important for climate change (Africa, Asia, South America)
- Improvement of inverse numerical modelling techniques and their applications

- Aerosols and climate (direct aerosol effect):

- Reduction of uncertainties surrounding the aerosol-climate interaction
- The linking of monitoring and modelling capacities
- Improved instrumentation at ground-based background measurement sites with a strong emphasis on vertical and total column information
- Improved satellite instrumentation (e.g. extinction with higher vertical resolution)
- Improved satellite retrievals to characterise areas of special interest (e.g. biomass burning, mineral dust, industrial plumes and volcanoes)
- Improved understanding of processes governing the climatic effect of aerosols in relation to their emissions, physical and chemical transformations and properties

- Water vapor in the stratosphere:

- Reduction of uncertainties surrounding the present increase of stratospheric water vapor
- Explain this increase
- Explore links to stratospheric ozone
- Quantify the effects of greater hydrogen emissions due to the potential future H_2-economy
- Strengthen NDSC stations for long-term H_2O measurements

The following are prerequisites for the investigation of these issues:

- First, a joint effort is required to adequately arrange the different measurement platforms (ground-based *in situ*, ground-based column and satellite-based) according to the scientific and political requirements. The vision is to have a coherent network of interlinked platforms with no under-used or overlapping monitoring infrastructures, which leads to a permanent evaluation of demands and products. Special attention should be paid to regions where few measurements have been made historically, which are crucial from a global point of view (e.g. the Mediterranean, the former Soviet Union and Africa). Atmospheric modelling will play an important role in linking the systems to fill spatial and temporal gaps. Atmospheric modelling depends heavily on highly-precise, intercompared long-term data sets. Therefore the long-term financial support of the sites must be ensured within the GMES process. Until now, European projects have been at a clear disadvantage compared to the USA due to the limited duration of FP projects mainly used for atmospheric composition studies. For example the USA sustains stations in the Mediterranean, the former Soviet Union, Australia and Scotland for CO_2 measurements.
- Second, the information obtained from these platforms has to be combined to obtain the most precise answers to outstanding questions related to the greenhouse effect (e.g. regionally separated emission estimates, the impact of European emissions on climate change).
- Third, access to the different data products must be simplified such that not only researchers can access the data. A simplified means of access must be developed, which should maximise both the data value and the cost-benefit of the investment in observation systems. The final aim is to

have a web-based one-stop facility to house all available data (via quality-checked meta-databases) from the different measurement platforms in a user-friendly format.

2.4.1 Greenhouse Gases

2.4.1.1 Ground-based In Situ Measurements

Ground-based measurement sites are too often isolated and under the responsibility of different authorities. As a result, data lack coherence, its compatibility across countries is mediocre, gaps remain unfilled and its availability over time is not secured. Therefore, the main aim in the near future will be to get the maximum out of existing stations. The following measures are proposed to reach this target:

- Linking the sites into networks with common quality assurance protocols and common standards. Building a network for the continuous *in situ* measurement of all GHG species with a common standardised quality assurance system.
- Optimisation of the spatial resolution of the network according to the species (lifetime) and source region/s.
- Sites which already make a combination of *in situ* and FTIR measurements should better exploit their opportunities to complement / compare with satellite measurements; this exploitation could be an important feature of GMES.
- Stations on the Eurasian landmass should be included in the network, particularly for the purposes of CH_4 measurements, as a result of anthropogenic emissions from gas leaks in NW Siberia and the potentially higher emissions in warmer climates from permafrost regions.
- Flux measurement facilities should be combined to form a network of towers equipped with state-of-the-art flux measurements to analyse emissions and sequestration. This network could also be used as an instrument to monitor the effectiveness of Clean Development Mechanisms (CDMs) such as reforestation in the tropics.
- There is a need to identify the key requirements (e.g. precision and accuracy) for *in situ* measurements to ground-truth satellite measurements.
- A common European monitoring program for CH_4 (including isotopes) and N_2O should be designed to run in parallel with established CO_2 and CFC monitoring which already takes place on a common basis (AEROCARB and SOGE).
- Regarding CO_2, an Integrated Global Carbon Observing (IGCO) initiative is planned within the framework of IGOS. This will provide a chance for GMES to connect activities in this field.
- Regarding CO_2, an optimised operational network of atmospheric *in situ* stations and flask sampling sites with an accuracy of at least 0.1 ppm should be built. The horizontal and vertical coverages of continuous observations must be increased to include continental interiors and poorly sampled regions. This requires the development of cost-effective sensors and the systematic use of platforms of opportunity.
- An optimised operational network of eddy covariance towers should be established to make continuous measurements of CO_2 fluxes, energy and water vapour over land ecosystems.
- For indirect GHGs, such as VOCs, CO and H_2, a common European network of sites close to sources should be established to make continuous measurements of a common standardised quality. Existing remote sites are suitable for background measurement purposes but more sites of a common standard are required close to the sources to validate anthropogenic emissions. In particular, H_2 measurements should be included in the network as anthropogenic emissions of this gas will be potentially enhanced in the future as a result of a "hydrogen economy". This would enable an assessment of future anthropogenic emission changes and their influence on atmospheric chemistry.

2.4.1.2 Ground-based Remote Sensing

Not as many FTIR measurement sites exist as in situ measurement sites. However, as the aim of this technique focuses on the information derived from the atmospheric column, the density of measurements is not of highest priority with respect to improvement. Attention should be paid to the following:

- FTIR measurements are limited to daytime, clear-sky observations. Emission measurements and / or lunar absorption measurements should be performed at night; the combination of day- and nighttime measurements would enable the study of diurnal variability. At present, most FTIR observatories are equipped for daytime measurements only.
- H_2O can be measured but the uncertainties surrounding H_2O measurements must be reduced; at present it has not been proved that stratospheric water vapour can be distinguished from the large tropospheric H_2O burden.
- The measurement of CO_2 is possible in the mid-IR; investigations into the possibilities to make more precise measurements of CO_2 in the near-IR should be intensified.
- It is important to verify the consistencies and possible synergies between satellite data, ground-based FTIR data and ground-based in situ data.
- The combination of satellite data and FTIR-columns should be used to derive and validate global maps of GHG concentrations in the troposphere, as has been achieved for CO (e.g., from IMG / ADEOS or from MOPITT).
- The precision of tropospheric GHG columns retrieved from FTIR spectra should be improved.
- The efforts to derive trends in the free troposphere using FTIR measurements (e.g. the European project, UFTIR) should continue.

2.4.1.3 Space-based Measurements

Space-based measurements will play an increasingly important role in future climate and environmental research as instrument capabilities evolve and the integration of space data into theoretical models progresses. The global nature of climate and environmental issues demand global coverage of observations at appropriate spatial and temporal resolutions and accuracy. The accuracy of space GHG data should be at the percentage level or better for trend analysis, retrieval of emission data and assessment of compliance with air-quality limits. These space-based GHG measurement requirements are hardly if at all met by present and planned satellite missions discussed in Section 2.3.1.3.

The integrated global observation strategy (IGOS)-IGACO initiative is an ambitious initiative to integrate ground-based, in situ and space observations into one atmospheric chemistry transport (ACT) model to obtain the best possible knowledge of the Earth's atmosphere. In this development, the technique of data assimilation plays a central role. Dependent on the meteorological data with which the model is driven, the technique's ability to forecast air quality has currently been developed to a pre-operational stage (Ref. ESA GMES Service Element (GSE)). The technique of data assimilation also enables the construction of long-term data records the integration of data from various source into one model. The IGOS initiative was supported by the recent International Earth Observation Summit in Washington D.C. in July 2003, where all parties called for a 10 year implementation plan to establish a comprehensive, coordinated and sustained global earth observation system as well as activities to improve the use of data (Ref. GMES). The following are considered prerequisites:

- Development of new sensors for integrated global atmospheric composition observation, based on the heritage of current and planned space missions. The primary species, GHGs, to be addressed are CO_2, CH_4, water vapour and tropospheric ozone as well as related gases, CO, NO_2, possibly HCHO, and C_2H_6 measured from LEO satellites.
- High temporal sampling frequency is required in relation to highly variable gases like tropospheric ozone, CO, NO_2, and water vapour. This requirement can only be met with the use of sensors on geo-stationary platforms, which enable sampling times of one hour or less. This

application would require new satellite development work as currently no such system has been developed or is planned.

- Enhanced knowledge of the vertical distribution of gases. This requirement would enable differentiation between the planetary boundary layer, where emissions take place, the free troposphere, where the greenhouse effect is most significant, and the stratosphere, where GHG species are broken down. Here, the combination of spectral channels from the near- and thermal-IR, limb and nadir measurements would enable the retrieval of vertically resolved information. Spectral line shape information at high spectral resolution would provide additional height resolved information. New instrument development will be required here too.
- Satellite observation of column integrated atmospheric CO_2 distribution to an accuracy of at least 1 ppm is required with synoptic global coverage: observations at all latitudes during all seasons. The measurements should be able to detect the global distribution of atmospheric CO_2 and capture atmospheric CO_2 gradients directly above source / sink regions.
- A combination of satellite observations and long-term measurement continuity are required to deliver the global observations of parameters required to estimate surface-atmosphere CO_2 fluxes, where direct *in situ* measurements are scarce. Efforts have already been made by the FTIR community to measure CO_2 from the ground and from space in the near-IR.

2.4.2 Aerosols

Although aerosols exhibit an effect on climate, their anthropogenic emissions are not regulated in the Kyoto Protocol. However scientific interest in aerosols is shifting more and more from human-health aspects to global aspects in reflection of the important aerosol climatic impact. The radiative forcing due to aerosols is dependent on their chemical and physical properties. Consequently it is rather challenging to comprehensively assess the effects of this group of atmospheric constituents. Numerous challenges remain in the scientific understanding and characterisation of tropospheric aerosols at the fundamental and technological levels. The IGOS-IGACO integrated observation system discussed in Section 2.4.1.3 should include aerosols. Here, data assimilation is to play an essential role in the integration of data from ground-based networks and satellite data into one consistent theoretical model.

Scientific gaps in knowledge still exist in relation to vertical aerosol profiles and long range transport. The characterisation of aerosols with respect to chemical composition and size are key to addressing both of these issues. Both a representative ground-based measurement network and remote sensing by satellites are needed. In addition, in situ observations above the ground will be very useful, from balloons and, in particular, dedicated aircraft measurement campaigns. In particular the following outstanding issues must be addressed by future developments:

2.4.2.1 Ground-based In Situ Measurements

- New measurement techniques for the on-line chemical / size characterisation in addition to advanced air quality models are necessary to improve predictions of and diagnose the dynamics of aerosols in the troposphere.
- More precise, harmonised and quality-controlled measurements are needed to obtain a comprehensive picture of the geographical and seasonal characteristics of particulate matter in Europe. These observations will enable differentiation between the regional component of particulate matter and that attributed to long range transport.
- There is a need for measurements of smaller particles such as $PM_{2.5}$ and even smaller. This standardisation would improve our understanding of the anthropogenic influence of particulates and further the implementation of control strategies.
- The aerosol spatial and temporal variabilities have not been investigated thoroughly enough for comprehensive aerosol representation within global models.

- The chemical mass closure and optical properties of aerosols must be investigated, as well as the quantification of aerosol emissions and secondary particle formation.

2.4.2.2 Ground-based Remote Sensing

- Ensure continuation of sun photometer observations of aerosol spectral optical thickness, sky radiance and derived parameters such as particle size distributions, single-scattering albedo, complex refractive indices (PHOTONS / AERONET) and lidar observations to provide vertical information.
- Improve retrieval algorithms to reduce uncertainties in the measurements of sun photometers and lidars.
- Expand the sun photometer network in Europe to regions of poor / no coverage.
- Improve the utilisation of the measurements by integrating the information more closely with observed data from satellites and ground-based in situ stations as well as aerosol model data.

2.4.2.3 Space-based Measurements

- Inclusion of measurements of the vertical distribution of aerosols, relevant to both climate and air quality, as well as additional parameters such as aerosol absorption, refractive index and phase function, size distribution and shape factors. An appropriate but demanding technology is the space-borne lidar following the LITE experiment in the early nineties. New passive instruments would be able to meet the more demanding requirements. Multi-viewing instruments (ATSR, POLDER) and instruments that make use of polarisation information (POLDER, GOME-2) could provide the basis for the future development of new sensors.
- The highly variable regional, continental and global aerosol distributions require satellite sub-hour sampling times that are currently not achieved by LEO satellites but require a satellite in geo-stationary orbit.
- Development of algorithms in an operational context to enable the monitoring of aerosols by meteorological satellites of the next generation (MetOp, NPOESS).
- The measurement of the sulfate aerosol precursor gas, SO_2; the measurement of precursors to organic aerosols in the troposphere would be of additional relevance.

2.4.3 Data Centres

For the different measurement platforms, specific data centres exist. What is needed is a one-stop resource for data obtained by all measurement techniques, quality-checked with reference to a common standard. This resource could be a gateway to different meta-databases with a user-friendly input mask.

2.4.4 Emission Inventories

At present, emission inventories are entirely 'bottom-up' estimates, made from adding together emissions based on self-reported national data sets. Atmospheric studies - "top-down" - are the only independent way to check "bottom-up" emission estimates. The estimates can be checked by several methods including trajectory studies (especially with isotopes).

The aim within GMES should be to establish a database of validated regionalised inventories of all types of relevant GHGs, quality checked with reference to a common standard. To achieve this, the following must be addressed:

- Efforts to organise emission estimates by industry and individual national bodies in a consistent way (e.g. on a 1° x 1° grid) should be supported by a common scheme.

2.4.5 Detection of Global Trends

At present in Western Europe, a very dense network exists for the detection of global trends in GHGs, which needs only punctual improvements. The following topics should be addressed within GMES:

- Improved equipment at stations in regions of Europe, which are not well represented at present (e.g. the northern part of Eastern Europe associated with potentially high emissions of GHGs, such as CH_4 triggered by a warmer climate).
- Globally, there are significant gaps in the coverage of the tropics (e.g. in Africa and South Asia). As these regions of the world significantly affect global atmospheric chemistry related to global change, the EU potentially could build up a monitoring capacity by providing knowledge and measurement equipment.

2.4.6 Modelling and Assimilation Techniques related to Climate Change

Modelling can be used to extract or combine in-situ and remote atmospheric measurements to get the most accurate information required to make decisions related to climate change. For example such a system could be used to test compliance with international treaties down to a regional European level. Inverse modelling will enable the detection of sources and sinks of carbon and other greenhouse active components, which will be very important in the framework of the Kyoto Protocol and the carbon credits for reforestation. Therefore a well-established monitoring system with regards to the carbon (and other constituents) cycle, composed of a state-of-the-art model, assimilation techniques and ground-based and satellite observations, will certainly be extremely valuable in the context of the Kyoto protocol and post-Kyoto negotiations.

This part of GMES will support the ECCP for verification of European-wide emissions of GHGs and their limitation within the first commitment period, 2008-2012. For example the avoidance of 23 million tonnes of carbon dioxide equivalent, envisaged with the proposed new regulation of fluorinated gases (DG Environment, ENV.C2) could be checked by such a system. The following items should be addressed within GMES:

- Optimisation of the spatial resolution of existing air monitoring sites by testing their representativeness. For this an atmospheric modelling study (e.g. using particle models or numerical weather prediction (NWP) models) at different regional and continental background sites will be mandatory.
- The testing of models to aggregate information from in situ and remote measurement platforms in relation to constituents relevant to climate change. First approaches have already been taken within the following European projects: AEROCARB, EVERGREEN, Meth-MonitEUr and SOGE.

Chapter 3

REGIONAL AIR QUALITY: LOCAL, REGIONAL AND CONTINENTAL SCALES

Authors: P. Monks and A. Volz-Thomas

3.1 THE ISSUES

This chapter deals with issues related to air quality (AQ), i.e. gaseous pollutants and particulate matter from the urban and regional scale to the global scale. AQ on these scales has implications for a number of contemporary issues including:

- Human health (e.g. respiratory, cancer, allergies…)
- Eco systems (e.g. crop yields, acidification / eutrophication of natural ecosystems)
- National heritage (e.g. buildings)
- Regional climate (aerosol and ozone exhibit a strong regionality in climate forcing)

For this document the relevant scales are local (urban <100 km) and regional (political units, ecosystems, ca. 1000 km) and the global scale (hemispheric scale transport >1000 km). Gaseous and particulate air pollutants have been the focus of much scientific work and legislation in the realm of regional AQ.

3.1.1 Primary Pollutants

The primary pollutants (e.g. CO, SO_2, NO_2 and volatile organic compounds (VOCs)) are those directly emitted into the atmosphere from a range of anthropogenic sources, such as transportation, industrial processes and agriculture. Some VOCs and NO_x ($NO_x = NO + NO_2$) have concomitant biogenic sources.

3.1.2 Oxidants

Owing to its toxicity for plants, animals and humans, and its importance as a greenhouse gas, strategies were developed in the US and later in Europe to reduce the levels of ozone in the troposphere both during photochemical episodes and in general. These strategies are not as straightforward as for primary pollutants because ozone is not emitted into the atmosphere but is formed *in situ* from a complex mixture of precursor pollutants (CO, VOCs and NO_x) under the action of ultraviolet (UV) radiation from the sun. Therefore ozone abatement strategies must be directed towards lowering the emissions of ozone precursors, NO_x and VOCs. The non-linear influence of NO_x and VOC emissions on ozone formation and destruction, the influence of transport and dispersion processes on the atmospheric distribution of chemical compounds, and the vast differences in their chemical lifetimes require thorough scientific understanding for the design of successful abatement strategies.

3.1.3 Aerosols

Aerosols affect life on earth in several ways. They play an important role in the climate system; the effect of aerosols on the global climate system is one of the major uncertainties of present climate predictions. They play a major role in atmospheric chemistry and hence affect the concentrations of other potentially harmful atmospheric constituents, e.g. ozone. They constitute an important controlling factor for the radiation budget, in particular in the UV-B part of the spectrum. At ground level, they can be harmful, even toxic, to man, animals, and plants. Because of the adverse effects that aerosols can have on human life, it is necessary to achieve an advanced understanding of the processes that generate, redistribute, and remove aerosols within the atmosphere.

3.1.4 Persistent Organic Pollutants and Mercury

Persistent organic pollutants (POPs) and mercury (Hg) are substances that possess toxic characteristics, persist, accumulate in the biosphere, are prone to long-range transport and deposition and are likely to cause significant adverse human health or environmental effects close to and far from their sources.

3.2 WHAT ARE THE POLICY RELATED ISSUES?

European policy on AQ is set out in the Air Quality Framework Directive, and its various daughter directives. These specify limit values and alert thresholds for key air pollutants and lay down requirements for reporting to the EU. Fine particulates, total suspended particulates, sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone, benzene and lead are covered. For the future, daughter directives are planned for poly-aromatic hydrocarbons (PAHs), cadmium, nickel, arsenic and mercury. The main objective of the Directive is to reduce human exposure to, and the environmental impact of, ground-level air pollution. Areas that fail to meet the relevant AQ guidelines are to be identified and early warning of air pollution problems are to be given to the public. Furthermore, the Habitats Directive requires the ability to identify pressures and impacts on important habitats, including those of air pollution.

The United Nations Economic Commission for Europe (UN-ECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) has played a major role in AQ policy formulation and development. It entered into force in 1983 and has been extended by eight specific protocols. In 1988 the Parties to the Convention (now 48, including Canada and the United States of America) adopted the Sofia Protocol, which required the Parties, by the end of 1994, to have limited their emissions of nitrogen oxides or their transboundary fluxes to the level in 1987.

In 1991 the Parties adopted the Geneva Protocol. The member states, in the main, agreed to reduce emissions of VOCs or their transboundary fluxes by at least 30% by 1999, relative to a base year between 1984 and 1989. The stated aim was to reduce episodic peak ozone concentrations, though the extent of the reduction to be achieved was not quantified (UN ECE 1991). Implementation was achieved through a series of directives (Directives 70/220/EEC and 88/77/EEC) developed by the EC.

In 1999, the Gothenburg protocol to abate acidification, eutrophication and ground-level ozone was adopted by the executive body of UN-ECE. The protocol set emission ceilings for 2010 for four pollutants: SO_2, NO_x, VOCs and ammonia. Once the Protocol is fully implemented, Europe's emissions compared to 1990 should be cut by at least 63% for SO_2, 41% for NO_x, 40% for VOCs, and 17% for ammonia.

In relation to these policies there a number of questions:

- Have the currently implemented strategies led to the predicted changes in precursor concentrations, and did they result in the expected ozone and aerosol reductions (peak levels, accumulated dose over a threshold of 40 ppb (AOT 40), average concentrations and fluxes to the biosphere)?

- What is the influence of natural vs. industrial, agricultural, and vehicle (fossil fuel based) emissions on European oxidant and aerosol levels?
- What fraction of European surface ozone (peak values, background) is susceptible to control by local or European measures and what are the most important external sources (flux from the stratosphere and transport from other continents)?
- How does climate change influence abatement strategies?
- How does air pollution influence regional climate?
- What are the major primary and secondary sources of particulate matter and how are health effects related to its chemical composition and size distribution?

The protocols define specific requirements for monitoring. The European Monitoring and Evaluation Programme (EMEP) has the objective to provide the CLRTAP with information on the deposition and concentration of air pollutants and on quantities and source allocation of transboundary fluxes related to acidification, eutrophication, photo-oxidants, particulate matter, heavy metals and POPs.

In the European framework directive on ambient AQ management and the subsequent daughter directives, numerical models are for the first time accepted for the assessment of AQ in EU member countries.

Therefore, an important question is, 'Do the existing tools provide the necessary information to assess the success of implemented or support revisions of the strategies?', concerning:

- The geographical distribution and density of monitoring sites, the suite of parameters, time resolution and quality of measurements, and data evaluation strategies
- The suitability of model results for AQ assessment and planning in terms of the accuracy and precision of the modelled atmospheric concentrations

In order to answer the latter, the model uncertainties must be known, as must the necessary improvement in terms of resolution, accuracy of meteorological fields, boundary conditions, nesting strategies, chemistry (including heterogeneous processes at surfaces, on aerosols and in clouds) and data assimilation.

Different from gaseous pollutants, atmospheric aerosol is characterised by its chemical composition as a function of size. Since the potential health effects depend on both physical and chemical properties, an important question is 'Are the current monitoring criteria for fine particles (mass below a certain threshold, e.g. PM10 and PM2.5) appropriate (with respect to health effects) or do the monitoring strategies need to be revised?'. In many ways the scientific understanding of aerosol science is not at a sufficient level to address many policy-led questions.

3.3 WHAT ARE THE CURRENT CAPABILITIES?

3.3.1 Surface Measurements

Surface measurements are the backbone of regional AQ monitoring. There are a range of local (e.g. urban), regional, national and international measurement networks in place. Measurements at surface sites are essential to monitor ambient concentrations and deposition in the so-called atmospheric boundary layer (ABL) that varies in thickness between approximately 100 and 2000 m, depending on meteorological and topographical conditions, as well as the time of day. Figure 3.1A shows a number of regional AQ measurement sites across Europe. Most of the sites belong to national weather services or national / regional / urban governments / agencies and are implemented in the framework of different atmospheric networks. Compliance with the quite different network protocols often requires the monitoring of only a limited number of chemical substances, leading to a situation where very few stations measure a comprehensive suite of chemical species and atmospheric parameters.

One of the largest trans-national organisations in regional AQ monitoring (103 primary sites) is EMEP (www.emep.int). The EMEP provides the observational underpinning to:

- Establish pollutant concentrations, deposition, emissions and transboundary fluxes on the regional scale, including intercontinental transport and boundary conditions for urban AQ.
- Identify trends in time as well as their sensitivity to European emission reductions.
- Assess the success of international abatement strategies for atmospheric pollutants.
- Improve the understanding of atmospheric chemical and physical processes and provide data for the validation of models.
- Provide data which, in conjunction with models, are the basis for the assessment of environmental problems related to air pollution including comparison with effect thresholds and exposure levels.
- Provide measurements required to assess the effects of atmospheric pollutants.
- Explore the environmental concentrations of new substances and support the development of cost-effective abatement strategies.

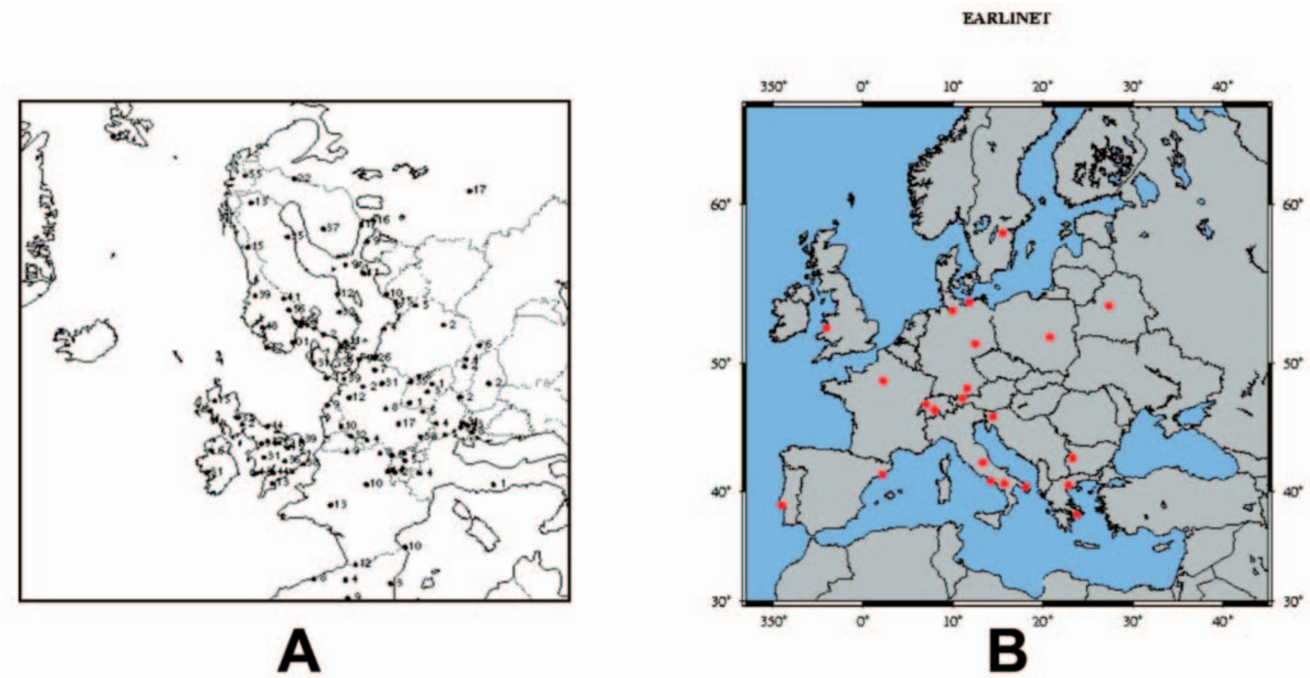

Figure 3.1 A) Regional ozone measurement stations. B) The European Aerosol Research Lidar Network (EARLINET) to establish an aerosol climatology.
(Source: http://lidarb.dkrz.de/earlinet)

Observations at sub-urban locations (e.g. the UK, Germany, the Netherlands and Switzerland) indicate significant downward trends of almost a factor of two over the last decade for the predominantly motor vehicle exhaust species, NO_x and VOCs. It has also been argued that peak ozone levels have decreased over this time period. A policy modelling study (Midgley et al., 2003) strongly suggests that this decrease is in accordance with the decrease of precursors due to the VOC protocol. It is not clear however, how much the apparent decrease in peak ozone levels is the result of meteorological factors. This result is highlighted in Figure 3.2 which demonstrates the excellent correlation between peak ozone levels and monthly hours of sunshine in North-Rhine Westfalia (NRW). In fact, the extreme ozone levels observed in 2003 strongly support this argument. More information is clearly required to unequivocally assign the apparent decrease in peak ozone to the success of current abatement strategies.

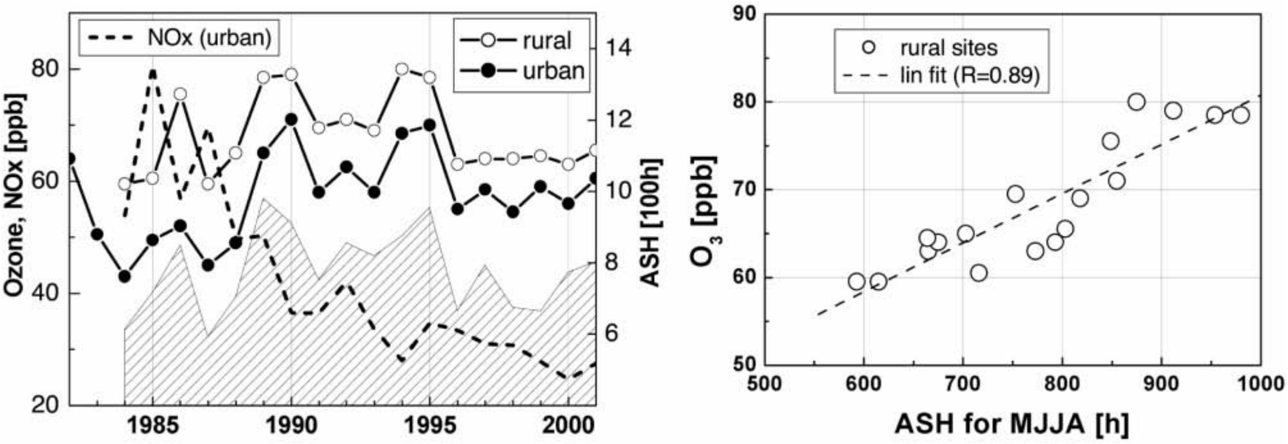

Figure 3.2 Time series of the 98 percentiles of O_3 at rural (open circles) and urban background stations (filled circles) from the TEMES monitoring network in NRW and the number of accumulated sunshine hours (ASHs) at Jülich in summer (May, June, July and August, hatched area). The NO_x trend from urban stations is shown as a dotted line. The right panel shows the correlation between the 98 percentiles of O_3 and the hours of sunshine. (Source: Midgley et al., 2003)

3.3.2 Ground-based Remote Sensing Networks

There are also ground-based networks aimed at establishing a quantitative database of the horizontal, vertical and temporal distributions of aerosols on a continental scale. The EARLINET network comprises 21 stations (see Figure 3.1B) distributed over most of Europe, using laser remote sensing to measure the vertical distribution of aerosols, supported by a suite of conventional observations. The goal of such a network is to provide aerosol data with unbiased sampling, for important selected processes, and air-mass history, together with comprehensive analyses of these data.

Besides the lidar networks, there is a database for sonde information on the troposphere. Routine radio and ozone sondes are released by national meteorological organisations as well as some scientific institutions with long-term records.

3.3.3 Aircraft Measurements

3.3.3.1 Research Aircraft

There is a European fleet of research aircraft (http://www.esf.org/eufar/) of varying size and capability. The aircraft are deployed for *in-situ* research into aerosols, gas-phase composition, cloud microphysics, radiation and meteorology as well as the remote sensing of aerosol, wind and ozone profiles. There is a potential operational role for these aircraft; for example, small aircraft can be used to make measurements in the vicinity of large urban settlements to provide regular information on the distribution and chemical transformation of chemical species. There is the potential to utilise the data sets from this aircraft fleet to generate semi-climatological data, in particular for species that are not (yet) susceptible to general monitoring.

3.3.3.2 In-service aircraft

Instruments have been deployed since 1994 aboard long-range passenger aircraft as part of the EU-project, MOZAIC (http://www.aero.obs-mip.fr/mozaic/), which provide detailed information on the distribution of O_3 and H_2O in the upper troposphere / lower stratosphere (UTLS) and on the vertical profiles over Europe, North America, Asia, and Africa. These profiles are useful in obtaining a better understanding of the climatology of ozone in the Northern Hemisphere and the seasonal variation in the free troposphere (FT) and lower stratosphere. Due to the high measurement frequency (ca. 2500 flights per year), the data are also useful in determining the boundary conditions for regional AQ and climate modelling. Since 2001, instruments for the measurement of CO and NO_y (the sum of NO and its atmospheric oxidation products) have been in operation in MOZAIC and have provided detailed information on the distribution of these important ozone precursors on a quasi hemispheric scale. Similarly, in the former NOXAR project, an instrument for the measurement of NO and NO_2 was deployed for several years on a passenger aircraft. The CARIBIC program has employed a different approach by deploying a fully instrumented container on commercial aircraft with a frequency of 10-20 flights per year. The two approaches are complementary; CARIBIC provides measurements of a larger suite of species but at a much lower frequency than MOZAIC.

Figure 3.3A compares the time series of ozone obtained from surface measurements made at Mace Head in the boundary layer on the western edge of Europe, at Zugspitze (Germany, 3000 m asl) in the lower FT and onboard MOZAIC aircraft in the upper troposphere over Europe and North America. While all time series show a statistically significant increase in ozone within the time period spanned by the data, there are distinct differences in the years in which this increase occurs. The increase is also observed at other background sites, such as the European Sounding Rocket Range (ESRANGE) in Sweden and is mostly confined to the winter season.

Another puzzle is the quite different seasonal variation observed in the marine boundary layer, where ozone reaches a maximum in spring, compared to the FT, where a pronounced maximum is observed in summer (Figure 3.3B).

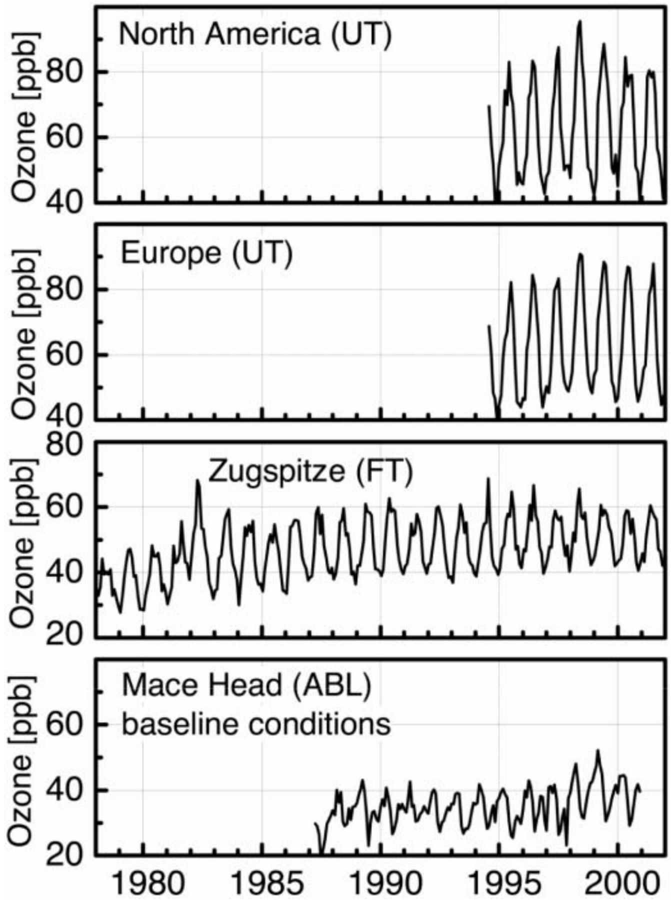

Figure 3.3A Comparison of ozone concentrations from the MOZAIC aircraft data in the upper troposphere (UT) over North America, Europe from Zugspitze, Germany (lower FT) and Mace Head, Ireland (ABL, selected for maritime baseline conditions). (Source: Midgley et al., 2003)

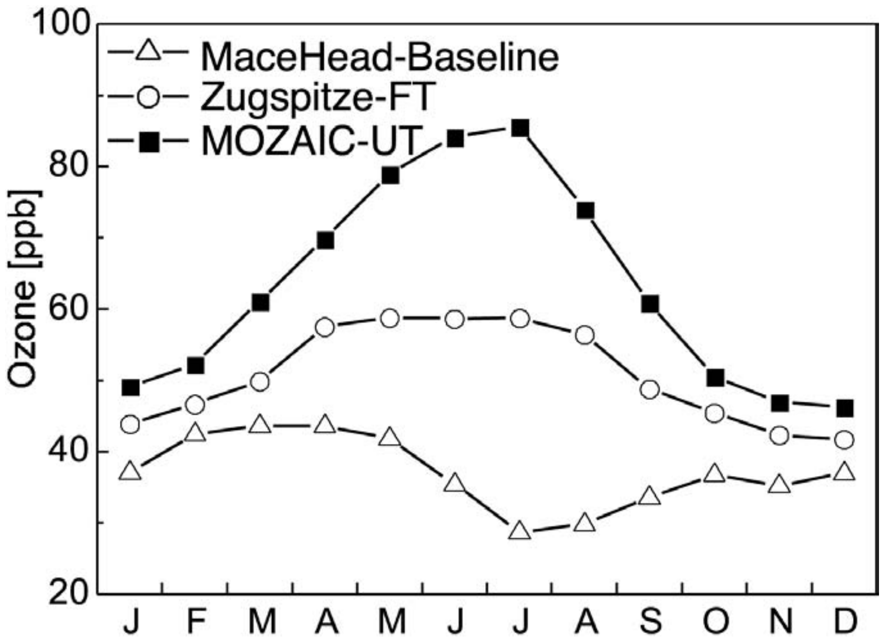

Figure 3.3B Average seasonal cycle of ozone in the marine ABL at Mace Head (triangles), in the lower FT at Zugspitze (circles) and in the UT over Europe (squares) calculated from the MOZAIC data over the period 1994-2001. (Source: Midgley et al., 2003)

3.3.4 Satellite Data

Newly observed global distributions of tropospheric species such as NO_2, SO_2, HCHO and aerosol, obtained through observations from space and the data from missions planned for the near future should enable the study of tropospheric distributions over large areas and in locations which were only accessible to occasional individual observations in the past. For example, analysis of the GOME data produced the first maps of the tropospheric NO_2 distribution over Europe (Figure 3.4A). NO_2 plumes from large agglomerations, such as Milan, London, Paris, and the Ruhr area, can be clearly identified from the data and greatly improve our understanding of the distribution, sources, lifetime, and transboundary transport of NO_2; there exists an important basis for the validation of tropospheric chemistry models and regional emission inventories. GOME data have also proven useful in the identification of NO_x produced by lightning, the most uncertain source of NO_x to the FT, and NO_x produced by biomass burning. GOME data have also been used to follow SO_2 plumes from volcanic eruptions.

The frequency of space observations will be of great help in determining the longer term changes, which are taking place in the troposphere on global and regional scales. An overview of the current availability and applicability of satellite data for tropospheric research can be found at the EUROTRAC-2 Use and Usability of Satellite Data for Tropospheric Research (TROPOSAT) project website - http://crusoe.iup.uni-heidelberg.de/luftchem/troposat/ and in Borrell et al., 2003.

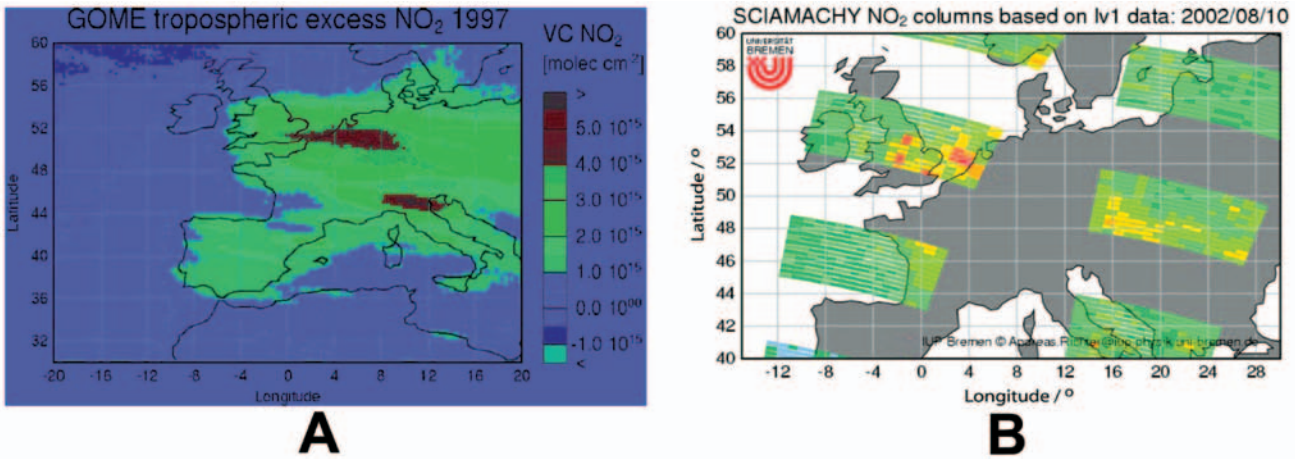

Figure 3.4 A) Annual mean tropospheric NO_2 column in 1997 over Europe under cloud free conditions as derived from GOME measurements (Richter and Burrows, 2002). B) Tropospheric NO_2 columns from SCIAMACHY at a spatial resolution of 60 km x 30 km. (Source: Richter and Burrows, see Borrell et al., 2003)

3.3.5 Laboratory Measurements

Laboratory measurements play a key role in underpinning the interpretation of AQ data and form the basis for chemical models used to predict AQ and formulate mitigation strategies. Europe has three large and a variety of small atmospheric simulation chamber facilities that allow detailed investigations of atmospheric chemistry and aerosol physics under controlled conditions. A range of other special laboratory facilities and computing facilities are also available for detailed studies of chemical reactions in the gas phase, on surfaces and in droplets.

3.4 IS THIS A RATIONAL SYSTEM?

At many monitoring sites in Europe, few parameters besides ozone are measured, not even basic meteorological quantities such as temperature, wind speed and direction, humidity and global radiation. This presents a serious obstacle in the evaluation of the data and their scientific understanding. In many ways there has been a predilection to perpetuate the number of stations in preference to fewer, better equipped stations. In order to evaluate future changes in AQ, monitor the adherence to emission control regulations, and provide high-quality data for the evaluation of forecast and analysis tools for tropospheric pollutants, the European network of AQ monitoring stations must be upgraded considerably. If chemical weather forecasting is to become an important topic in the future, the focus will shift to more complex questions of AQ, including primary pollutants in cities, aerosols and so on, possibly requiring better and different models in addition to the monitoring of different species. From the scientific analyses conducted in the past (e.g. EUROTRAC-2) several key issues have emerged, including the need for:

- More meteorological measurements
- More precursor measurements
- Vertical profiles
- Better homogeneity in terms of spatial coverage of species measured and data quality

Looking to the future, it is necessary to integrate and exploit data.

3.5 WHAT IS THE ROLE FOR GMES?

The best way to summarise the potential role of GMES is to look at the elements of the question, 'Do we have a rational system in place for the measurement, assessment and dissemination of AQ data?'. In an attempt to answer this question, it is clear that at different levels, there are elements in place that can provide the measurements but not in a coherent manner. Furthermore, in some respects, the integrated tools for assessment require development and there is a much clearer need for better integration and dissemination. To fulfil these requirements, GMES must organise a dialogue between the main stake holders involved in the processes of policy formulation and application: the agencies and institutions responsible for monitoring and predicting AQ in Europe, the scientific community concerned with the fundamental understanding of the state of the atmosphere and its variability, the institutions involved in the process of policy formulation and legislation and, last but not least, the public. At a general level:

- The key role of GMES is to provide an integrated data delivery service for users.
- GMES should explore the role of a dedicated satellite mission to deliver AQ information.
- GMES should take sub-national activities and integrate them to achieve a critical mass.
- GMES should develop integrated tools for the delivery of AQ information.

It is clear that, given the complexity of physical and chemical mechanisms involved in the atmospheric cycling of pollutants, a sectorial (i.e. single pollutant) approach to the problem of regional air pollution and its impact on climate change is not well suited to meet the new challenges of sustainable atmospheric composition. In fact, scientific findings over recent decades have clearly highlighted the need for a more comprehensive approach to atmospheric change processes.

A specific recommendation is the revision and upgrade of the present monitoring and modelling capacities in Europe through the formation of a European Integrated Monitoring Network for Atmospheric Change. Such a network should ideally consist of a hierarchy of stations corresponding to different scales.

3.5.1 Background Sites

Existing Global Atmosphere Watch (GAW) sites should be integrated, with a possible expansion into Southern and Eastern Europe and / or Russia. The standard measurement programme should be updated to include O_3, NO_x, NO_y, CO, VOCs, Peroxyacetyl Nitrate (PAN), temperature, wind, humidity, radiation (if possible including photolysis rates), turbulence, ABL height, aerosol composition and total ozone.

3.5.2 Regional Master Sites

At least 5-10 (EMEP) stations should be initially upgraded with extensive measurements to monitor and understand regional-scale ozone and particulate pollution, i.e. O_3, NO_x, NO_y, CO, PAN, peroxides, HNO_3, acid deposition, VOCs, carbonyls, meteorology, radiation, photolysis rates and ABL height. The sites should fulfil high standards in terms of data quality, establish close cooperation with scientific institutions and provide a basis for intensive field campaigns.

3.5.3 Local Monitoring Networks

Existing networks of regional authorities should be integrated. The sites should be equipped with measurements of at least O_3, meteorology, NO_x, CO, aerosols and possibly VOCs (in situ or via a centralised sampling programme).

The regional surface measurements should be augmented by routine observations (preferably weekly-monthly) from small research aircraft equipped with instrumentation for O_3, CO, NO_x, NO_y, PAN, VOCs, radiation, and HCHO. The small aircraft would survey the vertical structure in the vicinity of the station and also serve satellite validation purposes (flight schedules should match satellite overpasses where appropriate). An alternative to climatological surveys would be to characterise the stations in terms of typical meteorological situations, which are subsequently investigated by aircraft flights.

3.5.4 Passenger Aircraft

The station network must be augmented by data from large-scale aircraft monitoring programs (e.g. MOZAIC / CARIBIC), which have demonstrated the feasibility of obtaining reliable in situ measurements at hemispheric scales over long time periods. They are at present the only affordable alternative to probe the free and upper tropospheric region with sufficient spatial resolution, in addition to providing vertical profiles of O_3, CO, and NO_y, which are of great importance for model evaluation and boundary conditions. Thus these European programmes require a long-term perspective.

3.5.5 Satellite Measurements

Currently low earth orbit satellites present a quasi-synoptic view of regional AQ with revisit times between one and six days. It is clear that, given the rate of change of aerosol and oxidant concentrations in the boundary layer, shorter revisit times are required. One strategic option available is the measurement of tropospheric composition from geostationary orbit. An instrument on a satellite in geostationary orbit would have the ability to make high spatial- and temporal-resolution measurements of atmospheric composition. Such options are being considered by the European Space Agency (ESA) and national agencies. The data from satellite must be combined with other sources of data (e.g. aircraft, vertical soundings, and selected ground-based data) that do not require a-priori information from models.

Once the strategy has been developed with respect to the measurements, it will be necessary to develop an integration strategy *viz.*

3.5.6 Assimilation into Urban, Regional, and Global Air Quality Models

Although progress has been made in data assimilation into models, this potentially powerful technique is not yet available at an operational level. The direct assimilation of data, measured from a range of platforms, into the models remains an important task. More model studies are needed to study the transport processes that could explain the structures seen far from source regions (see e.g. Figure 3.4). Data assimilation offers a key method to deliver policy information and thereby clearly adds value to measurements.

3.5.7 Data Quality

High data quality in terms of precision, accuracy, and representativeness is a prerequisite for thorough evaluation of changes in atmospheric composition and the identification of underlying causes. It is also a prerequisite to enable future generations to identify new hazards, just as our generation has analysed data collected more than 100 years ago in order to identify changes in atmospheric composition. Previous work has shown that there is very little value in spending money on the collection of data of poor or unknown quality. Data quality objectives and quality assurance (QA) procedures must be defined in such a way that standards are maintained and QA and quality control (QC) require continuous attention.

3.5.8 Databases

The effective use of data is a critical part of the assessment of AQ and its impacts. There is a requirement for effective databases of AQ measurements and model data. This could be achieved using metadata databases or even through the integration of various data sources. The effectiveness of any database strategy is inherently linked to QA and QC issues (see previous discussions). Databases may not only provide repositories for primary data but should also be used to disseminate results and analyses through appropriate web portals. In many respects, the synthesis, integration and dissemination of relevant findings present weaknesses in the scientific and political AQ communities.

3.5.9 Model Evaluation

Model comparisons have revealed significant differences between models and highlighted the problems that are encountered in such exercises. Detailed evaluation strategies must be defined *a priori*, based upon the model quality objectives, e.g. prediction of peak oxidant / aerosol levels, average concentrations, trends or reduction scenarios. The objectives must be formulated in terms of measurable quantities (bias, variance) by a panel of experts (similar to the Intergovernmental Panel on Climate Change (IPCC) for global models) that defines the tasks and evaluates the outcomes of evaluation. The evaluation strategy should ideally allow an independent evaluation of the different model sub-systems, in particular, transport patterns and chemical fields.

The required experimental data must be selected according to the model quality objectives in terms of the suite of compounds / parameters, required accuracy, precision, spatial and temporal resolutions, and representativeness of the data.

Predictable variations in emissions, such as the weekend effect and particularly summer vacation periods, provide opportunities to perform a powerful test of the performance of models designed to investigate emission reduction strategies. A concerted effort of field measurements, emission inventory assessment based on actual demoscopic data and modelling would provide insights into the extent to which ozone and aerosol concentrations really could be lowered by emission reductions.

The chemical mechanisms used in models must be adapted to the scales of the models and the target quantities. The evaluation of chemical mechanisms should be based upon detailed measurements of the relevant intermediates, including free radicals, and the chemical / physical parameters that control the radical concentrations. Simulation chamber experiments at realistic atmospheric concentrations are best suited to identify and quantify the individual chemical processes and to evaluate chemical mechanisms.

3.5.10 Summary

In order to define the policy-driven user requirements, the questions that require answers must be considered in addition to the products required to assess compliance with, and the success of, policy. The policy framework with respect to gas-phase oxidants and a number of primary pollutants is relatively well developed whereas much less consensus exists in the areas of aerosols and POPs. Table 1 summarises some key actions in relation to specific AQ requirements.

Topic	Requirements for Photooxidants	Requirements for Aerosols	Requirements for POPs
Verification of compliance with protocols	3-D measurement network	3-D measurement network	Surface measurement network
Provision of near-real-time data for public and scientific use	Development of data assimilation tools; Synoptic scale observations	Development of concept	Development of concept
Cost effectiveness of existing networks	Assessment (role of geo) satellites	Assessment	-
Improvement of existing stations for GMES Post-2008	Integrated 3-D observation concept	Development of observation concept	Development of observation concept
Feasibility of multi-purpose networks	Application of observation concept	Application of observatory concept	-
Synergies between observations and modelling	Development of data assimilation	Scientific development	-
Quality assurance, quality control and intercalibration	Harmonisation of concepts; Collaboration with science	Development of concept, role for accreditation	Role for accreditation

Table 3.1 Specific AQ requirements.

In the broader sphere, to achieve the goals of a rational system for the measurement and interpretation of AQ in a cost efficient way and to benefit most from the networks, the following actions should be considered:

- More interaction between monitoring agencies and the scientific community (QC, data analysis, model evaluation)
- Integration of the existing networks (e.g. national weather services, EMEP, GAW, ESA), including standardisation of the monitoring requirements, data formats, and data provision
- Integration of the different existing monitoring systems (ground-based networks, aircraft and satellites)
- Development of integrated tools for the assessment of AQ on a range of scales
- Dissemination of AQ findings and information

Chapter 4

INTERNATIONAL CONVENTIONS ON AVIATION, SHIPPING AND COASTAL POLLUTION

Authors: H. Schlager and J. Pacyna

4.1 THE ISSUES

Air traffic and seagoing ships represent major elements of international transportation and trade. The current global fleets include 18,000 jet and turboprop aircraft and 90,000 large ships (>100 t). Fuel consumption by air traffic as well as ship traffic has increased in the last fifteen years by about 50%. In the coming fifteen years, fuel use by air traffic is expected to increase at the same rate (IPCC, 1999). Fuel use by ships is predicted to increase by 25-50%, depending on the implementation of more efficient ship engines (MARINTEK, 2000).

Aircraft and seagoing ships emit gases and particles into the atmosphere, trigger the formation of contrails and ship track clouds, and may increase cirrus and marine stratus cloudiness respectively. The impact of current air and ship traffic includes changes to atmospheric composition and climate. Locally, aircraft and ship emissions impact on air quality in the vicinity of major airports and seaports.

Besides shipping, the marine environment and in particular coastal regions are affected by emissions related to off-shore activities: the extraction, first treatment and loading of liquid and gaseous fuels, dumping and incineration of waste at sea, as well as atmospheric and riverine transport from land-based sources. These are the main sources for the production of various trace gases in the coastal and open ocean, which are subsequently released into the atmosphere.

4.1.1 Aviation

The principle gaseous emissions from aviation include CO_2, H_2O, NO_x ($NO_x = NO + NO_2$), SO_2, CO, and unburned hydrocarbons (HCs). The annual emissions from air traffic for the year 2000 amount to 130.6 Tg C, 0.71 Tg N, and 0.06 Tg S (IPPC, 1999, and TRADEOFF, 2003). Emissions of CO and HCs are not important on larger and regional scales but may enhance pollution in the vicinity of airports. The aircraft-related shares of total fossil fuel and world transport CO_2 emissions are 2% and 12% respectively. The aerosol emitted from aircraft include primary carbonaceous particles, which form inside the combustor, and volatile particles, which nucleate from gaseous precursors in the cooling exhaust plume.

Aircraft emissions are mainly released in the upper troposphere / lower stratosphere (UTLS) between 8 and 11 km along the main flight corridors, e.g. between Europe and North America. Emissions injected directly into the tropopause region have a larger impact than similar surface emissions due to longer residence times at this altitude. NO_x emissions by air traffic cause an increase in ozone mainly in the upper troposphere of the Northern Hemisphere and a global decrease in CH_4, which lead to a positive and negative radiative forcing (RF) respectively. Accumulation of aircraft emitted H_2O makes only a very small contribution to the total aircraft impact. In ice-supersaturated air masses, persistent contrails are formed by air traffic. Long-lasting contrails have short-wave cooling and long-wave heating effects. The RF due to contrails shows a strong daily cycle and constitutes a net positive RF. There is also growing evidence that aerosols from air traffic or ageing contrails may change the coverage and radiative properties of cirrus clouds.

4.1.2 Shipping

Marine fuels (bunkers) burned by ships are cheap, low grade and sulphur rich residual fuels. The annual emissions of CO_2, NO_x and SO_2 from shipping for the year 2001 amount to 249 Tg C, 6.87 Tg N, and 6.49 Tg S, respectively (Corbett and Koehler, 2003). The CO_2 emissions from ships constitute 3.8% of the total CO_2 emissions from fossil fuel burning and 23% of world transport CO_2 emissions. Emissions of CO and HCs from ships are only important with respect to the local air quality at major seaports. Particles emitted by ship engines have not been characterised in detail so far. A first estimate of particulate matter emissions for the global fleet of seagoing ships amounts to 1.64 Tg PM_{10} per year (Corbett and Koehler, 2003).

Emissions from seagoing ships are released into the marine boundary layer (BL) along the major ocean trade routes where the impact can be significant due to the lack of other pollution. Model studies indicate that ship emissions significantly increase the NO_x and SO_2 concentrations in the marine BL. Elevated NO_x due to shipping leads to enhanced levels of O_3 and OH accompanied by reduced concentrations of CH_4. Increased CO_2 and ozone cause a positive RF whilst reduced CH_4 causes a negative RF. Oxidation of emitted SO_2 to sulphuric acid leads to an increased concentration of sulphate aerosols, which causes a negative RF. Aerosols from ships can also cause an increase in droplet concentration and a decrease in droplet size of existing marine stratocumulus clouds. Consequently, scattering within the clouds and reflectivity increase. Signatures of these effects can be observed in the form of so-called ship tracks. Ship tracks cause a cooling of the atmosphere.

4.1.3 Marine and Coastal Pollution

Coastal regions and the open ocean are sources of various trace gases and particle emissions to the atmosphere. The emissions are produced in the marine environment from precursors, deposited in the sea on particles from the air or transported to the coast by rivers, including organic matter, nitrates, ammonium and sulphates. Sources of these precursors are emissions from shipping, off-shore activities related to the extraction, first treatment and loading of liquid and gaseous fuels, dumping and incineration of waste at sea and transport from land-based sources.

The extraction and first treatment of liquid and gaseous fuels offshore involves a number of activities, each of which represents a potential source of HC emissions. The contribution of emissions from this source to the total national emissions varies considerably between countries due to the specifics of extraction, first treatment and loading of liquid and gaseous fuels. For example, oil and gas production offshore contributed as much as 31% to the total volatile organic compounds (VOCs) and 3% to the total CH_4 emissions in Norway in 1990 (EDGAR, 1990). In the UK, these contributions were 3% and 2%, respectively. The emissions from combined oil and gas facilities may be categorised as direct venting of gas into the atmosphere (often reduced by flaring the gas), fugitive losses, and evaporation from contaminated waste water. Emissions are also generated during loading and transport (including the ballasting of marine vessels), and from gas terminals and pipelines. Details on these sources and emissions are available from the European Monitoring and Evaluation Programme (EMEP) / CORINAIR guidebook (EMEP, 2002).

Less information is available on the emissions of NO_x, CH_4, and fine particles from the incineration of waste at sea although this practice has been prohibited in Europe, unless otherwise agreed in specific annexes to the marine conventions in Europe, described later in this chapter. The contribution of these emissions to total European emissions can be regarded as insignificant.

Atmospheric and riverine transport from land-based sources constitute the main source of nitrate input to the sea and therefore an important source of NO_x released to the atmosphere over the European marginal seas. The amount of nitrate deposition from the air to the sea and the nitrate discharge of river waters are monitored by three major marine conventions: the Oslo and Paris Convention (OSPARCOM), the Helsinki Convention (HELCOM) and the Barcelona Convention.

4.2 WHAT ARE THE POLICY RELATED ISSUES?

4.2.1 Aviation

The International Civil Aviation Organization (ICAO), an agency of the United Nations (UN), has established internationally agreed standards for the control of aircraft noise and emissions in the vicinity of airports. Issues related to emissions and associated ICAO regulations are discussed by ICAO's Committee on Aviation Environmental Protection (CAEP). In 1981, CAEP standards were set in Annex 16, Volume II, for engine emissions of NO_x, CO, and HCs for the landing and take-off (LTO) cycle up to an altitude of 900 m. These standards are manufacturing standards. Emissions during climb and at cruise altitude, where most aviation fuel is burned, are currently not directly regulated.

In 1993 the LTO limits for engine NO_x emissions were further reduced by 20% relative to the 1981 limits. In 1998 a further 16% decrease of NO_x emissions relative to the 1993 limits was proposed for new engines in service from 2003. The percentage reductions relate to the pressure ratio of engines. Since engine pressure ratios have increased over the past 10 years, in order to reduce fuel consumption, the engine NO_x emissions have consequently increased. Overall, this effect opposes the percentage NO_x reductions. The development of the LTO emission standards is described in detail in a report of the EU project, New Emission Parameter covering all flight phases of Aircraft operation (NEPAIR) (Lister and Norman, 2003).

The ICAO standards apply to engines and not to aircraft types. The compliance of new engine types with the standards must be demonstrated by the manufacturers during the certification process with tests on a small number of new engines. The implementation of ICAO standards relies on national regulations.

There is some public pressure for more stringent engine emission standards in aviation including climb and cruise emissions and the sulphur content of aviation fuel. These issues are under active discussion within a CAEP 6 working group on Alternative Emission Technology and the NEPAIR project. There are also discussions as to whether ICAO standards should be better established for aircraft / engine combinations as opposed to engine types alone. The performance of an aircraft, i.e. emission per seat per km, depends on the design of the whole aircraft / engine system.

4.2.2 Shipping

Currently, emissions from seagoing ships are practically unregulated. The Maritime Environmental Protection Committee (MEPC) of the International Maritime Organization (IMO) is responsible for international regulations of pollution from ships. Limits for NO_x emissions have been proposed in 1996 in Annex VI of the Marine Pollution Convention (MARPOL 73/78). They will be enforced if fifteen nations, which represent 50% of the world-wide shipping tonnage, ratify Annex VI. To date, eleven nations have ratified the document representing 54% of the world tonnage. It is therefore expected that Annex VI will be implemented next year. Since NO_x emission limits in Annex VI are not very stringent, a further increase of NO_x emissions from global shipping is expected in the coming years. However, the rate of increase of NO_x emissions has decreased in recent years due to the replacement of old ships by modern ships with engines that incorporate NO_x reduction techniques (Koehler, 2003).

EU legislation does not currently regulate ship emissions. EC has issued a discussion paper "A Community Strategy On Air Pollution From Seagoing Ships" in 2002. The focus on future EU regulations for ship emissions will be on reductions of NO_x, SO_2, CO_2, and HCs. Locally, for seaports in Sweden, Norway and Germany (Hamburg), emission limits are already in force.

The US Environmental Protection Agency (EPA) has proposed ship emission standards for NO_x, CO, and HCs for US ships and ships cruising in US territories to be implemented between 2004 and 2007, depending on the size of the ships. Alaska has already implemented a limitation of the opacity of exhaust plumes from ships cruising off the coast of Alaska.

4.2.3 Marine and Coastal Pollution

There are three major conventions for the protection of European seas:

- OSPARCOM (http://www.ospar.org/eng/html/welcome.html)
- HELCOM (http://www.helcom.fi/convention/conventionframe.html)
- The Barcelona Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) was signed in 1992 and later ratified by fifteen countries. It came into force in March 1998 and replaced the Oslo and Paris Commissions. There are various annexes that regulate the objectives and work within OSPARCOM. The most relevant to climate regulations are: Annex I on the prevention and elimination of pollution from land-based sources, Annex II on the prevention and elimination of pollution by dumping or incineration and Annex III on the prevention and elimination of pollution from offshore sources. All the above annexes deal with the reduction of emissions of nitrates and particles through required reduction of emissions of selected heavy metals. Most of the heavy metals considered under the OSPARCOM are emitted on particles; the exception is mercury. Also some of the persistent organic pollutants (POPs) considered for reduction are emitted on particles. Thus, the reduction of heavy metal emissions would also result in the reduction of particulate emissions.

The Baltic States signed the Convention on the Protection of the Marine Environment of the Baltic Sea Area in 1974. This agreement was revised and the HELCOM Convention was amended in 1992. In the year 2000, the Convention was enforced with the participation of nine countries. As applies to the OSPARCOM Convention, the work of the HELCOM Convention is organised with respect to seven annexes. The most relevant annexes to climate issues are: Annex I on harmful substances, Annex II on the criteria for the use of Best Environmental Practice and Best Available Technology, Annex III on the criteria and measures concerning the prevention of pollution from land-based sources and Annex VI on prevention of pollution from offshore activities. These annexes deal with the reduction of emissions of nitrates and particles through required reduction of emissions of selected heavy metals and POPs. As applies to the OSPARCOM, the reduction of heavy metal emissions would also result in the reduction of particulate emissions. In this way, the HELCOM may be relevant to future climate regulations.

The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean Sea was initially drafted in Barcelona in 1976 and came into force in 1978. Major revisions and amendments were made in 1995. The work of the Barcelona Convention is organised with respect to six protocols. The most relevant protocols with regard to climate issues are: the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources and Activities, the Protocol for the Prevention and Elimination of Pollution of the Mediterranean Sea by Dumping from Ships and Aircraft or Incineration at Sea and the Protocol for the Protection of the Mediterranean Sea against Pollution Resulting from Exploration and Exploitation of the Continental Shelf and the Seabed and its Subsoil. These protocols deal with the reduction of nitrates and pollutants emitted on particles and are hence important with respect to climate regulations.

4.3 WHAT ARE THE CURRENT CAPABILITIES?

4.3.1 Aviation

Aircraft emission inventories have been developed in Europe (EC) and the US (National Aeronautics and Space Administration (NASA)) for the reference years 1990 and 1992, respectively. Both inventories include data on air traffic movements, fuel use and NO_x emissions. The NASA inventory also includes CO and HC emissions. Recently, an update of aircraft emissions for the reference year 2000 has been made in an EU project, TRADEOFF, based on a projection from 1992 aircraft movement data, which accounts for regional growths in air traffic. In the EU project, AERO2K, a more sophisticated inventory is presently under development for the reference year 2002.

Estimates of the aviation impact on the atmosphere were provided by recent assessments (IPCC, 1999, and EU, 2001). An ozone disturbance induced by aircraft NO_x of up to 5% (for the reference year 1992) was estimated for the region of largest impact (9-12 km, 40-65°N), relative to an atmosphere without air traffic. Extensive studies of model performance and reliability in the tropopause region have been performed in the TRADEOFF project. Ozone perturbations by aircraft emissions from 2000 were simulated with five different chemistry-transport models. The estimated maximum ozone increase differs by a factor of two between the models. These differences are mainly attributed to differences in the two-way mixing across the tropopause in the models.

Observations in the tropopause region in areas, where an aviation impact is expected, have been performed with research and in-service aircraft with in situ instrumentation. In addition, information is available from ground-based remote sensing instruments and ozone sondes (see Chapter 2), NO_x and particle perturbations due to aircraft emissions at cruise altitudes have been measured in the North Atlantic region, e.g. in the POLINAT (Schlager et al., 1997, 1999, Schumann et al., 2000), NOXAR (Brunner, 1998) and CARIBIC projects. Aircraft induced ozone changes are difficult to detect due to the relatively small fraction of aircraft-related ozone compared to the variability in ozone at flight altitudes.

Algorithms have been developed to automatically detect contrails using the National Oceanic and Atmospheric Administration (NOAA)-AVHRR infrared satellite data (Mannstein et al., 1999). With this technique the mean coverage by contrails has been determined for specific regions (central Europe and Japan) and seasons. Over central Europe, an average annual contrail cover at noon of up to 1.2% has been determined for the year 1996 in regions with very dense air traffic (Mannstein et al., 1999). Persistent contrails in ice-supersaturated air masses lose their line-shape structure with time and cannot be distinguished from cirrus. Figure 4.1 shows an example of a mixture of fresh and aged contrails observed from space over the English Channel. High resolution observations of cirrus from Meteosat and data on air traffic movements over Europe have been used to estimate the potential influence of aviation on cirrus coverage (due to aged contrails and possibly also due to emitted aerosols from aircraft). About 3% additional cirrus was observed in regions with very dense air traffic (Mannstein et al., 2003 manuscript in preparation). In TRADEOFF, a statistical analysis of satellite and air traffic movement data revealed an increase of cirrus coverage from 14% to 17% in the years 1984 to 1998 in high traffic areas in Europe. Both studies suggest that aviation increases cirrus cover. The inferred enhancements in cirrus coverage from aviation is one order of magnitude larger than the observed contrail coverage over Europe. This highlights the potential importance of this effect.

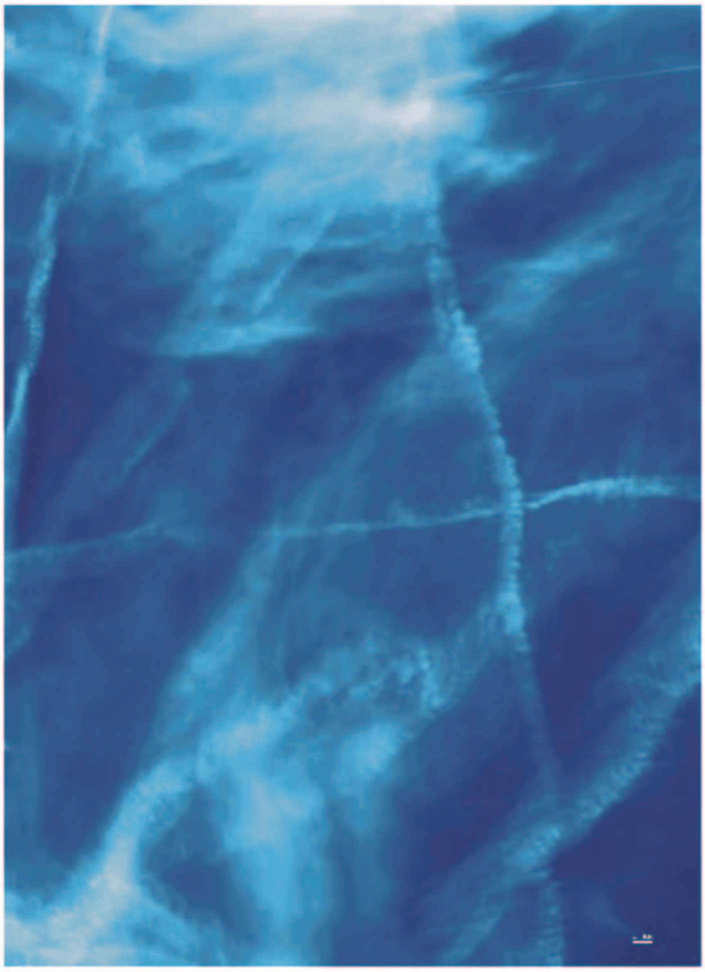

Figure 4.1 Contrails seen from space. The image was taken by the MOMS-2P instrument from the PRIRODA module attached to the MIR space station on May 8 1998, 08:33 UT over the English Channel (49.4°N, 2.9°W). A mix of contrails of different ages can be seen ranging from a very thin fresh contrail (upper right corner of the image) to several km wide contrail cirrus fields (provided by Hermann Mannstein, DLR).

The RF from the different aircraft perturbations have been estimated by IPCC (1999) for the reference year 1992. In the TRADEOFF project, these estimates have been updated for the year 2000. The ranges of RF (mW/m^2) estimated for the most important impacts are 28 (CO_2), 16-32 (O_3), -6 - -12 (CH_4), 5-9 (contrails) and 50-100 (cirrus). The estimates of the overall RF range from 93 to 154 mW/m^2. This is 2-3 times higher than the total RF estimated in IPCC (1999), mainly due to the cirrus impact, of which no estimate had been made in IPCC (1999). It should be noted that the level of confidence in the estimate of the RF by aircraft induced cirrus is considered very poor.

The estimate of RF by contrails is a factor 5 smaller than that in IPPC (1999). This is due to improved parameterisation of contrails for the global scale (Ponater et al., 2002). The geographically resolved distribution of contrail optical depth in the global model, ECHAM, revealed that contrails are in most regions optically thinner than assumed in IPPC (1999).

4.3.2 Shipping

Global inventories of ship emissions have been developed by several groups in Europe and the US (e.g. Corbett et al., 1999, Lawrence and Crutzen, 1999, and Endresen et al., 2003). All these large-scale inventories have relied upon international marine fuel statistics and have distributed the emissions geographically by different methods using data bases of ship movements (e.g. the Comprehensive Ocean Atmosphere Data Set (COADS) and the Automated Mutual Assistance Vessel Rescue (AMVER) system).

Perturbations to the composition of the marine BL due to ship emissions have been calculated using these inventories (Corbett and Fishbeck, 1997, Lawrence and Crutzen, 1999, Kasibathla et al., 2000, and Endresen et al., 2003). In regions with frequent shipping, like the North Atlantic and North Pacific, increases in NO_x mixing ratios of up to 0.5 ppbv have been calculated. A maximum O_3 perturbation of 12 ppbv is obtained during summer conditions. Model simulations of Capaldo et al. (1999) and Davis et al. (2001) suggest that ship emissions account for 60% of the sulphur in the marine BL of the North Atlantic and North Pacific. SO_2 and aerosols from shipping near the European coasts (e.g. in the English Channel) may also have an impact on land-based air quality. However, this has not yet been quantified.

First estimates of the RF due to perturbations as a result of shipping have been made by Endresen et al. (2003). Overall, a positive RF of 20 mW/m^2 was estimated. The negative RF due to ship tracks has not been considered in this study.

Very recently, a bottom-up approach was used to construct a new inventory of ship emissions (Corbett and Koehler, 2003). Data on engine power and the activities of internationally registered ships were used to compute fuel consumption. The computed fuel consumption is more than twice the international fuel use described in the previous inventories. Internationally registered ships apparently burn a significant fraction of fuel which is included in domestic fuel statistics (Corbett and Koehler, 2003). Thus ocean-going ships emit about twice as much as considered in the previously mentioned model studies.

Observations of trace species related to ship emissions in the marine BL are very sparse. Measurements have been mainly performed from research vessels and aircraft during specific campaigns. Available data from the North Pacific do not support the computed NO_x increase in the marine BL due to ship emissions (Davis et al., 2001). A possible explanation for this is inadequate parameterisation of the chemical and physical processes which occur in the sea and air wakes of the ships (Song et al., 2003).

Ship tracks can be observed from space in the visible and infrared. An example of ship tracks observed off the European coast is depicted in Figure 4.2. The modification of the albedo of marine clouds in ship tracks has been studied in detail in a region with dense ship traffic off the coast of California during the Monterey Area Ship Track Experiment (Durkee et al., 2000). An estimate of the global RF due to ship tracks is not possible at present due to a lack of systematic studies on ship track coverage.

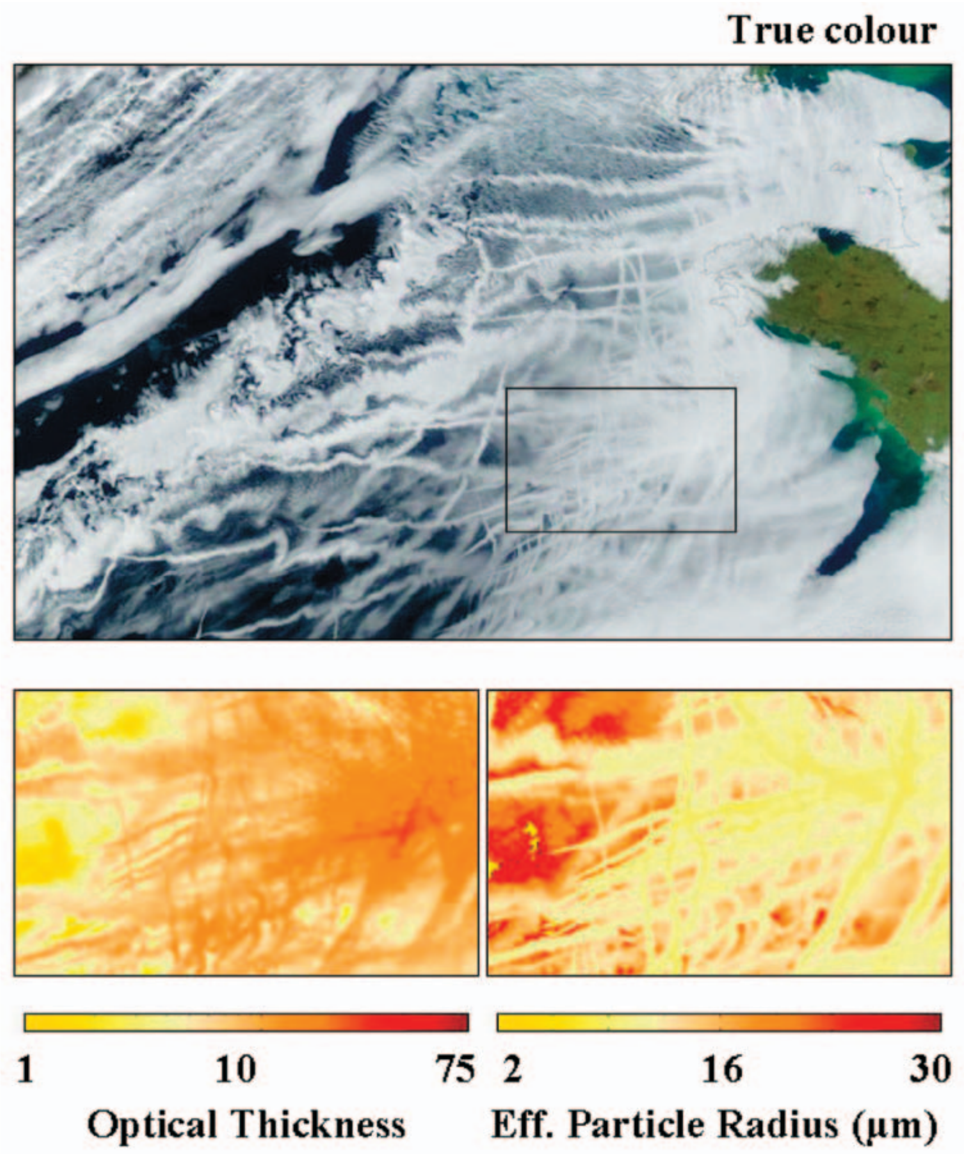

Figure 4.2 Ship tracks in clouds off the coasts of France and Spain. The image was taken by MODIS on the AQUA satellite on 23 January 2003. Lower cut-aways show properties of the clouds in false colours. Ship track clouds contain smaller droplets and are optically thicker (courtesy of J. Descloitres and M. Gray, NASA GSFC).

4.3.3 Marine and Coastal Pollution

Monitoring networks have been established within the above mentioned marine conventions in Europe. During the last two decades, the operation of these networks has been quite successful, resulting in the description of current and past inputs of chemicals, which are regulated by these conventions, to specific seas. In this way the networks serve well their main purpose, which is the examination of implementation of convention agreements to reduce these inputs.

However, the above mentioned monitoring networks are less adequate for monitoring the release of trace gases and fine particles from the sea to the air. The major drawback is that all of these stations are located on the coast, at greater or lesser distances from the sea. The locations of these stations prevent them from measuring the sea-to-air fluxes of trace gases and particles. It should also be mentioned that at present, the OSPARCOM, HELCOM, and the Barcelona Convention for the Protection of the Mediterranean Sea Against Pollution (MEDPOL) stations are not properly equipped with the necessary instruments to monitor these sea-to-air fluxes.

There are other monitoring systems which operate in the European seas to serve different purposes and user groups to those served by OSPARCOM, HELCOM and MEDPOL. The most important is the Intergovernmental Oceanographic Commission (IOC) European Global Ocean Observing System (EuroGOOS) network (EuroGOOS, 1999)). EuroGOOS is the association of European agencies concerned with modelling and forecasting physical oceanic variables. Thus, the necessary parameters for operational meteorology and hydrology are monitored but chemical variables are not measured. It should be added that EuroGOOS is part of the IOC Global Ocean Observing System (GOOS), which also includes networks of organisations in other parts of the globe. For example, other GOOS networks have been in operation in North-East Asia (NEAR-GOOS) and the United States (US GOOS).

The Baltic Operational Oceanographic System (BOOS) serves the marine industry in the Baltic region (BOOS, 2000). The goal of BOOS is to contribute to and improve the efficiency of marine operations, reduce the risk of accidents, improve the assessment of fish stocks and the foundation of public marine management. The BOOS network focuses primarily on measuring physical variables. Due to the different goals and user groups, EuroGOOS and BOOS are not adequate to monitor the sea-to-air fluxes of trace gases and fine particles.

The most important trace gases emitted from the coastal and open oceans include CH_4, N_2O, dimethyl sulphide (DMS) and carbonyl sulphide (COS). The production of these gases in the marine ecosystems and their sea-to-air flux have been studied in a few projects, mostly in Europe (see review by Pacyna and Hov, 2002). Oceanic emissions of CH_4 amount to 5-20 thousand tonnes per year, representing 2% of the global CH_4 budget (Bange et al., 1994, and IPCC, 1996). The oceanic contribution to atmospheric N_2O is estimated to be 20-30% (Khalil and Rasmussen, 1992). However, the study of Bange et al. (1996) concludes that as much as 50% of the total N_2O flux to the atmosphere is from the ocean. The global ocean DMS flux seems to contribute significantly to the global annual emission of gaseous sulphur compounds (IPCC, 1996).

Coastal sea areas are of particular interest (Pacyna and Hov, 2002). The flux rates of CH_4, N_2O, DMS and COS from coastal waters to the air are much higher than those from the open ocean. The contribution coastal areas make to total oceanic N_2O and COS emissions can be as great as 50%.

4.4 IS THIS A RATIONAL SYSTEM?

4.4.1 Aviation

The estimates of total fuel use by current aviation must be consolidated. The aviation fuel use of 200-220 Tg yr^{-1} estimated in the EC 2001 assessment for the reference year 2000 (Schumann and Ström, 2001) is about 30% higher than the corresponding TRADEOFF (2003) estimate. Current emission inventories for aircraft NO_x seem to be sufficiently accurate considering the uncertainties associated with the emission rates of other NO_x sources. Although they are largely based on ground test rig measurements and models to compute emissions at altitude, in-flight measurements have proven that NO_x emission indices adopted for cruise altitudes are correct to within the error limits (Schulte et al., 1997). The knowledge of other NO_x sources to the upper troposphere, in particular lightning, is more likely to limit the reliability of predictions of ozone formation due to aircraft NO_x. The impact of enhanced NO_x on ozone is non-linear, therefore NO_x background levels have to be known at aircraft cruise altitudes in polluted and remote regions. These can be best obtained through regular measurements from commercial aircraft, as demonstrated by the NOXAR, MOZAIC and CARIBIC projects.

Current aircraft emission inventories should be extended to cover particulate emissions in terms of number densities, not only aerosol mass.

Concerning simulations of the chemical and climatic impacts of aircraft emissions, it is necessary to understand the causes of the differences between models. Systematic comparisons are required between the adopted meteorological inputs, chemical mechanisms, lightning parameterisations, vertical discretisation and so on. Important improvements in models are also necessary in relation to transport and mixing processes in the tropopause region and heterogeneous chemistry on sulphate aerosols and ice clouds.

In addition, aerosol-cirrus interactions should be better represented in global models used to assess the impact of aircraft particle emissions on cirrus properties and coverage.

4.4.2 Shipping

There is a need to develop an internationally agreed ship emission inventory. Global ship emissions calculated from current inventories differ by a factor of two depending on the approach. Also particle emissions in terms of mass and number densities should be included in ship emission inventories.

The processes in the wake of ships (dispersion, mixing, chemistry and aerosol / cloud processes) must be studied in more detail using field measurements and supporting modelling to improve parameterisations of these small scale processes in global models.

Focussed observations of ship traffic related trace gases in the marine BL in the vicinity of the main ship corridors are required to validate the predictions of regional and global models. In particular, measurements in major ship corridors near coasts (e.g. in the English Channel) are necessary to assess the impact of unregulated ship emissions on land-based air quality.

In global and regional models, the aerosol modules must be improved. Important issues to be investigated with model studies include the impact of ship emissions on land-based air quality and the transport of ship emissions into regions with strong convective activity. The uplift of ship emissions to the upper troposphere largely enhances their impact due to increased lifetimes.

The mean coverage by ship tracks should be determined using satellite data, in particular in regions with heavy ship traffic, like the eastern North Atlantic. The negative RF caused by ship tracks has to be calculated with global models to get an improved estimate of the overall RF due to shipping.

4.4.3 Marine and Coastal Pollution

Current marine monitoring systems cover mainly meteorological (surface wind, air pressure and temperature, and precipitation) and physical (sea level, bathymetry and geomorphology, water temperature and salinity, surface currents, waves, turbidity and total suspended solids) variables. Much less information is available on chemical and biological variables. Among currently measured chemical core variables, some data are becoming available on dissolved inorganic nitrogen, phosphorus, silicon and dissolved oxygen. Data on other compounds are largely lacking.

The monitoring and modelling of marine ecosystems are complementary activities. Effective models depend on a steady flow of data from monitoring systems. Therefore the priority issue is the combination of observations and models. This issue has been addressed only recently and in very few marine regions; monitoring data have been combined with operational models, such as storm surge models, circulation port models, coupled air-sea forecasting models and coupled drainage basin-estuary models. Air-sea cycling models for some major chemicals are still missing due to a lack of model input information (for model parameterisation) from monitoring systems of the marine ecosystems.

4.5 WHAT IS THE ROLE FOR GMES?

Table 4.1 summarises the main impacts, gaps and requirements related to aircraft, ship and coastal emissions. An important role for GMES should be the support of monitoring of the environments, in which aircraft and ship emissions are released. Regular observations from aircraft in the tropopause region should comprise an important component of an integrated global monitoring system. Measurements from the ground and space in this region are difficult to perform and do not achieve the required spatial resolution for many species of interest. Measurements from research aircraft and the NOXAR, MOZAIC and CARIBIC projects have demonstrated the potential of such an observation system.

The potential for the development of a similar system to make regular measurements (e.g. of NO_x and SO_2) from in-service ocean-going ships should be investigated. At present, NO_2 and SO_2 in the marine BL cannot be measured from space. Emissions of NO_x, SO_2 and particles in major ship corridors near the coast, which are currently unregulated, may have a significant impact on land-based air quality. A funding framework for long-term observations from aircraft and ships is required.

At major international air- and seaports, detailed monitoring of ambient concentrations of emissions and related species is necessary to verify compliance with World Health Organization (WHO) standards. Existing monitoring stations at these sites should be integrated into existing air quality monitoring networks.

Emissions of CO_2 from aviation and shipping are presently not regulated and should be included in the Kyoto protocol.

Monitoring networks have been established within the marine conventions for the protection of European seas to verify the agreed reductions in chemical inputs to the sea off-shore. However, these monitoring stations are not properly equipped with the necessary instruments to monitor sea-to-air fluxes of trace species. Additionally, the number of chemical and biological parameters measured at most of these monitoring stations is currently not sufficient.

Finally, further cirrus cloud and ship track observations from space are required (see Table 4.1).

Issue	Impact	Major Gap	Requirements for Science	Requirements for Policy
Aircraft emissions	RF due to aviation	RF from modified or enhanced cirrus, global aerosol emission inventory	Knowledge of aerosol-cirrus interactions	Regular measurements of trace species in the UTLS region from aircraft, Cirrus observations from space, provision of time resolved air traffic data
	Air quality at airports	Detailed emission inventories for airports	Characterisation of particle and VOC emissions	Improved LTO regulations for particles
	Unregulated CO_2 emissions	-	-	Inclusion of aircraft CO_2 in Kyoto protocol
Ship emissions	RF due to shipping	RF from aerosols and modified clouds; Lifetime of emissions in ship wakes and marine BL	Knowledge of aerosol-cloud interactions and ship plume processes	Regular measurements in ship corridors, ship track observations from space; internationally agreed ship emission inventory
	Land-based air quality	Emission inventories for seaports; quantification of inflow from ship corridors	Characterisation of particles from shipping, knowledge of regional scale dilution of ship emissions	Regulations for ship emissions, monitoring of pollution at seaports
	Unregulated CO_2 emissions	-	-	Inclusion of CO_2 from shipping in Kyoto protocol
Coastal pollution	Land-based air quality	Quantification of sea-to-air fluxes	Coupled air-sea cycling model	Improved marine and coastal monitoring systems

Table 4.1 Summary of the major impacts, gaps and requirements related to emissions from aviation, shipping and coastal pollution.

Chapter 5

VOLCANO MONITORING AND PUBLIC SAFETY

Authors: R. Grainger and H. Graf

5.1 THE ISSUES

5.1.1 Introduction

Around 380 volcanoes were active during the last century, with around 50 volcanoes active per year (Andres and Kasgnoc, 1998). Volcanic activity is not randomly distributed over the Earth, but is linked to the active zones of plate tectonics. Figure 5.1 shows the location of 1509 volcanoes thought to have been active in the last 10,000 years (Holocene). Two thirds of the volcanoes are in the northern hemisphere and only one fifth are located between 10ºS and the South Pole. There is no significant variation in the concentration of volcanoes with longitude, but over 1000 volcanoes (two thirds of those displayed) lie on the Pacific Ocean margin and form the `Ring of Fire'.

Global climatic impacts of volcanic eruptions are caused by the injection of millions of tonnes of sulphur dioxide (SO_2) into the stratosphere: the SO_2 is converted into submicron aerosols that remain in the stratosphere for years and change both the Earth's radiation budget and the circulation of the atmosphere. On average, there is one eruption every ten years that has a global impact, e.g. El Chichón (1982) and Mt. Pinatubo (1991). The Mt. Pinatubo eruption (possibly augmented by El Nino effects) was followed by a severe drought in East Africa which led to the mass emigration of millions of refugees. Very large eruptions take place every hundred years. Previous eruptions of this size (e.g. Tambora, 1816) have led to a dramatic reduction of harvests in Europe and consequent widespread hunger and disease.

In Europe, large cities are at risk where they have developed on the slopes of active volcanoes (e.g. Naples). However the danger to people is not restricted to local hazards; island volcanoes (e.g. Santorini, La Palma) can produce huge tsunamis which have the potential to severely impact on coastal regions. There are world-wide risks to aviation as modern jets are extremely vulnerable to inadvertent encounters with volcanic ash clouds: several severe accidents have been reported in the last two decades.

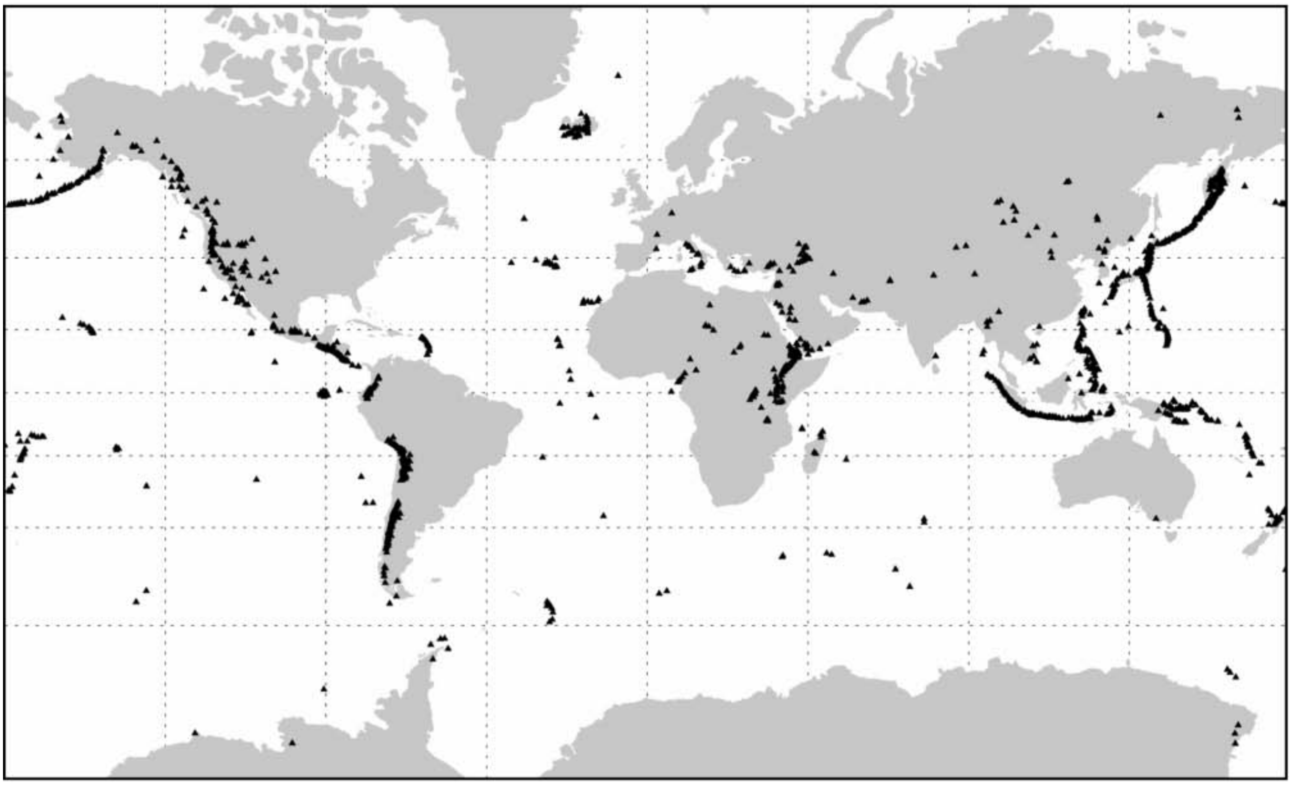

Figure 5.1 Location of volcanoes thought to have been active in the last 10,000 years (Holocene). Volcanic belts cover 0.6% of the Earth's surface. (Source: Smithsonian Institution, Global Volcanism Program)

The impact of a volcano on the atmosphere can be characterised in terms of the erupted magma. Globally, most of the magma mass erupted is of basaltic composition. Basaltic magma is rich in magnesium and iron, and contains comparatively little silica. In general, this magma type is characterised by a low gas content and eruptions are mostly effusive. They consist of a high portion of carbon dioxide (CO_2) and sulphur in the gas fraction. Long-lasting basaltic lava streams can cover large areas (e.g. the Deccan traps in India and the Laki fissure in Iceland). Eruptions of basaltic magma contribute only a small fraction to volcanic sulphur emissions into the atmosphere, and only in rare cases reach the stratosphere.

Felsic magma stems from differentiation processes (i.e. chemical fractionation) in the magma chamber or from the melting of crust material. This highly differentiated magma is rich in silica and alkalis. It contains a higher content of dissolved gases, especially water, and eruptions are generally more explosive but low in sulphur content. Extreme eruptions of felsic magmas include several hundreds to thousands of cubic kilometres of ash emissions in a short time. Bishops Tuff, Fish Canyon Tuff and Toba Tuff are examples of these deposits.

Magmas of intermediate silica content are called andesitic magmas, and are typical of volcanoes at convergent plate boundaries where subduction is the fundamental plate tectonic process. Felsic and andesitic volcanoes erupt less frequently than basaltic volcanoes. They can release large amounts of magma and energy on short time scales, often injecting ashes and gases directly into the stratosphere. In addition, many permanently emit gases during non-explosive phases. As they possess intermediate concentrations of sulphur but are generally explosive, eruptions of subduction zone volcanoes contribute the largest part to the total global volcanic sulphur emission.

5.1.2 Volcanic Emissions

Volcanoes emit gases and particles into the free troposphere, in part because the source height is above the planetary boundary layer, and also because emissions are strongest during eruptions and eruption clouds can reach considerable heights above the crater, ranging from a few hundred metres to some tens of kilometres. Volcanic sulphur emissions to the troposphere make up in the order of 10-20% of total sulphur emissions from manmade and natural sources. However, their long lifetime (they are emitted into the free troposphere where removal processes are less effective) may lead their contribution to equal that of manmade sources with respect to the sulphur burden.

In addition to the release of a number of gases, an explosive eruption blasts molten and solid rock fragments (tephra) into the air. The largest fragments (bombs) fall back to the ground near the vent, usually within 3-5 km. The smallest rock fragments (ash) continue rising into the air, forming an eruption column. Fine volcanic ash injected into the stratosphere is characterised by grain sizes in the micrometer range. In the troposphere these particles are quickly lost through sedimentation and rainout, typically on a timescale of a few days. In the stratosphere, ash is efficiently removed by sedimentation within about a month following an eruption (Pinto et al., 1989).

The composition of volcanic gases at the volcanic vent varies widely, depending on the magma type and the individual volcano's state of activity. Water vapour (H_2O) is the most prevalent volcanic gas, contributing between 50 and 90% by volume; however the contribution to the global H_2O atmospheric concentration is negligible. The second most important volcanic gas is carbon dioxide (CO_2), which comprises 1-40% of the emitted gas by volume. Volcanic emissions contribute less than 1% to the total global CO_2 emission in the long term mean but can provide a substantial contribution in the case of a large scale and sustained basaltic eruption (Cadle, 1980, and Gerlach, 1991).

Typically, sulphur gases contribute 2-35% to volcanic gas emissions by volume. They are the most relevant species to the climatic impact of volcanic events. The dominant sulphur component is sulphur dioxide, with yearly emissions ranging from 1.5-50 Tg. The main halogen component of volcanic emissions is hydrogen chloride (HCl), contributing about 1-10% by volume (Symonds et al., 1988). The upper limit for volcanic emissions of HCl is 0.4-11 Tg per year (Symonds et al., 1988, and Cadle, 1980). This is approximately equal to anthropogenic HCl emissions but HCl emissions from oceans are orders of magnitude higher. HCl is highly soluble and is therefore rapidly washed out of the atmosphere. Hence small eruptions and silent degassing will not be of importance for atmospheric composition with regard to halogens. Volcanoes constitute potentially a very important source of atmospheric bromine. The global volcanic BrO source is between 6,500 and 140,000 tonnes per year and so may exceed anthropogenic CH_3Br (approx. 100,000 tonnes Br per year, Butler and Rodriguez, 1996) as a source of atmospheric bromine. Traces of hydrogen bromide (HBr) are contained in volcanic emissions: typically about 10^{-6} parts per volume. The inclusion of the bromine in HBr and other chemical forms (e.g. HOBr) makes the total volcanic bromine emission higher than the above figure indicates. Hydrogen fluoride (HF) usually comprises less than 1 ppmv in volcanic gas emissions: the annual global emission is 0.06-6 Tg (Symonds et al., 1988). HF is not of importance in general, but during specific events (e.g. Laki 1783, Mt. Hudson 1991), HF emissions may be extreme and lead to severe environmental contamination that is hazardous to plants and livestock.

5.2 WHAT ARE THE POLICY RELATED ISSUES?

5.2.1 Direct Atmospheric Impacts of Volcanic Eruptions

Volcanic eruptions can produce lethally high, local atmospheric concentrations of volcanic ash, acidic gases and secondary particles. The impact of long-lived effusive eruptions can be extended to a regional scale. For example, one of the greatest environmental disasters in history occurred in

1783-4 as a result of the Laki fissure eruption in Iceland. The eruption lasted 9 months, expelled 15 km^3 of lava and ash, and released more than 100 million tonnes of sulphur, chlorine and fluorine gases, and particles into the atmosphere. The eruption affected the climate over the whole of the northern hemisphere and was followed by widespread agricultural crop failures. In addition the volcanic emissions may have caused or aggravated respiratory illnesses. Over 20% of the Icelandic population died during and in the immediate aftermath of the eruption due to climatic effects and contamination of soil induced by the Laki eruption.

Aircraft that encounter ash from explosive volcanic eruptions can experience engine failure and damage to a number of aviation subsystems. Between 1980 and 1994, eighty jet aeroplanes were damaged by unexpected encounters with drifting clouds of volcanic ash in flight corridors and at airports. Ash clouds, which are hazardous to aircraft, exhibit radar reflectivity several orders of magnitude smaller than that of severe weather and consequently do not appear on on-board radar. Visual recognition of a volcanic hazard may be difficult as ash clouds commonly resemble normal weather clouds.

5.2.2 Indirect Effects

Volcanically emitted gases (SO_2, H_2O, H_2S, CO_2 and HCl) can alter the radiative and chemical balance of the atmosphere and so perturb climate and atmospheric circulation. In addition, sulphur containing gases (principally SO_2) are converted to sulphuric acid, which subsequently condenses to form small droplets or aerosols which lead to acid rain.

5.2.2.1 The Troposphere

Volcanic sulphur emissions in the troposphere have a disproportionate effect on the atmosphere: this has been shown by numerical experiments with an atmospheric general circulation model that includes a simplified sulphur cycle (Graf et al., 1997). SO_2 is transformed into H_2SO_4 within days in the troposphere, but with e-folding times of a month in the stratosphere. The fastest transformation occurs in the lower troposphere. Sulphate aerosols in the atmosphere absorb and emit in the longwave, heating the layer, in which they reside and increasing the downward flux of radiation at the surface (for a review see Robock, 2000). In addition, aerosols scatter incoming solar radiation and thereby lead to a net cooling at the surface.

Sulphate aerosols in the troposphere act as cloud condensation nuclei and modify the radiative properties and the lifetime of clouds (Twomey, 1974). The increase in the number of cloud droplets due to an increased number of condensation nuclei leads to an increase in cloud albedo and thus enhances surface cooling. The rate of precipitation or rain suppression in deep convective clouds may also be affected and consequently the spatial and temporal distributions of latent heat release may change. This could have a significant effect on global circulation, as shown for aerosols in general by Nober et al. (2003).

In the tropics, during tropopause folds at mid-latitudes, volcanic sulphate aerosol particles can be transported vertically across the tropopause. Important lidar data show that in more than 50% of observations, the stratospheric aerosol layer has penetrated the tropopause and influenced the formation and maintenance of cirrus clouds in the upper troposphere (Ansmann et al., 1993). Graf et al. (1997) suggested that sulphate aerosol in the upper troposphere is important for cirrus formation. Unusually high cloud particle number concentrations (600 l^{-1}) and extremely supercooled drops at 223-233K were observed in the year following the eruption of Mt. Pinatubo (Sassen, 1992, and Sassen et al., 1995). Song et al. (1996) suggested that the interannual variability of global high level clouds is related to explosive volcanism. The amount and persistence of such clouds increased by as much as 10% following the eruptions of El Chichón and Mt. Pinatubo, mainly at mid-latitudes. These anomalies lasted several years. Thus, violent volcanic eruptions lead to a change in radiative properties of cirrus clouds. Their impact on climate is still not known as this depends on changes in cloud microphysics: the scattering of solar radiation leads to enhanced cooling whilst the absorption of terrestrial radiation leads to warming.

5.2.2.2 The Stratosphere

Emissions of halogen species are significant (e.g. Varekamp et al., 1984, Westrich and Gerlach, 1992 and Bureau et al., 2000) as their direct injection into the stratosphere could lead to catastrophic ozone loss (Prather, 1992). No severe increase of halogens was observed in the stratosphere after the eruption of Mt. Pinatubo (Mankin et al., 1992, Wallace and Livingston, 1992); however, after the eruption of El Chichón in 1982, a clear increase in chlorine concentration was detected (Mankin and Coffey, 1983, and Woods et al., 1985).

Sulphate aerosols in the stratosphere can serve as sites for heterogeneous reactions that convert passive chlorine compounds (HCl, HOCl and $ClNO_3$) into active ones (ClO and Cl) (chlorine activation). After the Mt. Pinatubo eruption, the surface layer of the stratospheric sulphate aerosol was about 300 times higher than usual with peak concentrations of $>3\times10^{-7}$ cm^2/cm^3 (Jäger et al., 1995, and Thomason et al., 1997). The critical value for ozone destruction of 10^{-7} cm^2/cm^3 was reached (Jäger et al., 1995, and Ansmann et al., 1993) for more than one year in northern hemisphere mid-latitudes. Heterogeneous reactions deplete ozone in the presence of halogens like chlorine and bromine (Michelangeli et al., 1989, Hofmann and Solomon, 1989, Granier and Brasseur, 1992, and Solomon et al., 1996). Since the human-induced increase in chlorine concentration in the stratosphere has peaked, the ozone destruction at volcanic aerosol sites will probably decrease over the next few decades.

The radiative effects of stratospheric volcanic aerosols can cause climate perturbations for several years, which include cooling at all latitudes in summer and complex cooling-warming patterns at higher latitudes in winter. Radiation changes also affect the biosphere by changing the ratio of diffuse to direct solar radiation.

5.3 WHAT ARE THE CURRENT CAPABILITIES?

An eruption is the culmination of long-term magmatic evolution beneath a volcano. An accurate understanding of where a given volcano is in its eruptive cycle and how its magma system is evolving requires the collection of a long time-series of high quality data. The character of volcanic activity also varies according to the type of volcano although individual volcanoes are capable of several different kinds of activity and eruption regimes, which depend on the evolution of the magmatic feeding system and the physical state of the volcanic edifice. The types of measures which should be taken by civil defence authorities can vary quite considerably with the type of activity. Science is sufficiently advanced that it is possible to classify volcanoes according to the types of activity that they are likely to produce. However we are not currently in a position to predict with confidence the kind of eruption that will occur when a given volcano shows signs of unrest.

During an eruption, the determination of gas and particle concentrations in a plume is extremely difficult due to the cloud's opacity and the inherent risks of directly observing and sampling the volcanic cloud. Volcanic emissions can be studied remotely by airborne and ground-based instruments and through satellite observations.

5.3.1 Land-based Networks

There is a well-developed network of geophysical observations of the Earth's volcanic activity based on seismometry and the monitoring of individual volcanoes.

Lidars give excellent vertical distributions of aerosols but until recently, could only operate under clear-sky conditions and during the night. The distribution of lidar observatories is uneven, with only one instrument in operation between 19°N and 23°S (it is located at Bandung, Indonesia, which is plagued by bad weather). There are at least three lidar networks world-wide, one in Asia (Uchino and Fujimoto, 1992) and two in Europe (Fiocco et al., 1996, and Bösenberg et al., 1998) but only one of these (EARLINET, Bösenberg et al., 1998) operates using standardised instruments and processing software.

5.3.2 Satellite Observations

In recent years, the launch of new satellites and new developments in remote-sensing techniques have expanded the capability to monitor volcanoes from space (Rose et al., 2000). Satellites have even detected SO_2 from several eruptions that were not known from ground observations. Satellite observations (e.g. by TOMS, AVHRR, GOME and SCIAMACHY) of SO_2 and ash particles are only useful in relation to strong sources (Bluth et al., 1993). SO_2 is the only volcanic gas to be monitored operationally via satellites to date. Since the first TOMS data in 1979, which could only measure the presence of SO_2 from larger eruptions, improved instruments and retrieval algorithms can now detect SO_2 gas from smaller eruptions and the passive degassing of some volcanoes, provided the detection limit of 5-20 Kt SO_2 is exceeded. Of particular importance is the global SO_2 data from HIRS 2 that has been deployed aboard National Oceanic and Atmospheric Administration (NOAA) satellites for the past 25 years. This instrument is sensitive to SO_2 but has yet to be analysed.

Eleven instruments deployed on satellites in the past 30 years have included stratospheric aerosol measurements: SAM II, SAGE, SAGE II, SAGE III, CLAES, HALOE, ILAS, ISAMS, POAM, POAM II and POAM III. The majority of these instruments are limited-time research instruments without a monitoring capacity. In addition, the solar occultation instruments have a very sparse spatial measurement pattern (typically 24 observations per day), being able to measure at satellite sunrise and sunset only.

Recently launched instruments (MODIS, ASTER, AIRS and SEVIRI) offer the potential to provide volcano monitoring. SEVIRI in particular offers advantages for the European region as it is a geostationary satellite with relatively rapid temporal coverage. New spaceborne lidars are about to be launched (CALIPSO) which will be helpful in monitoring aerosols in remote areas. However, the space-time coverage (in the range of ca. 300 km every third day in lower latitudes) will not be sufficient for early warning.

5.4 IS THIS A RATIONAL SYSTEM?

There is a clear operational requirement from the perspectives of cost, accessibility and the uniqueness of measurements for spaceborne sensors to observe the hazardous phenomena of volcanoes. Of the many proposed and operational satellite instruments, many must be discounted with regards to routine volcano monitoring because they:

- Take days or even months to sample volcanic locations and could thus miss a significant volcanic event
- Are not sensitive to SO_2
- Do not have the ability to discriminate between normal water / ice clouds from freshly formed volcanic clouds

Nevertheless there is an opportunity to exploit existing instrumentation; some examples of surveillance techniques and methods to build on are as follows:

- GPS and satellite interferometric methods to observe large-scale deformation patterns and identify areas of strain localisation. The inversion of long term GPS data from a volcanic region can reveal how deformation is localising and where resumed activity is likely.
- Ground and space-based spectrometric techniques to monitor gas and ash emissions.
- Automated observation tools and tele-operated instruments for real-time and all-weather surveillance with standardised data acquisition and processing protocols to enable the linkage of networks and sensors in response to an event.
- Thermal band remote sensing of surface temperature, changes in which are related to renewed activity.
- Detailed simulations of activity, such as the behaviour of an ash plume subject to larger-scale atmospheric circulation, are feasible but must be made more efficient.

Local ground-based networks can provide rapid warning of immediate volcanic danger. However the mechanisms to deal with three major volcanic hazards have not yet been established. These are as follows:

- The threat to aircraft in remote and sparsely populated areas, e.g. the North Asia – North America flight corridor above the Aleutian Islands. The International Civil Aviation Organization (ICAO) has set up a network of Volcanic Ash Alert Centers (VAACs) to provide forecasts of ash cloud dispersion to the civil aviation industry. The European region is covered by two VAACs, run by the UK Meteorological Office (UKMO) and METEO-France in Toulouse. Currently, VAACs provide the best advisory service of remote volcanic clouds to air traffic, but improvements are needed.
- The threat to European countries from a sustained volcanic eruption such as Laki in 1753. For example in the UK, the government response to such an event would involve a number of national agencies (e.g. the UKMO, Department for Environment, Food and Rural Affairs (DEFRA), Department for Health and the Department of Transport) as well as local government civil defence. On a European level there is no strategy in place to deal with the consequences of a sustained eruption that would dramatically impact on human health, transport and food supplies.
- The climate perturbation in the years following a large volcanic eruption has not often been predicted. Prediction requires knowledge of the source strength and location of injected atmospheric trace gases, especially SO_2.
- Volcanic eruptions near inhabited areas threaten lives and result in serious socio-economic impact. Tens of thousands perished last century and the world population at risk from direct volcano hazards now exceeds five hundred million. Existing operational instrumentation has some ability to provide volcano monitoring; considering the potential risk to life and property, the current level of monitoring is inadequate.

Chapter 6

ATMOSPHERIC INFLUENCE ON SYSTEMS OBSERVING THE EARTH'S SURFACE

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6.1 THE ISSUES

Atmospheric monitoring is clearly required as input to assessments of climate change and pollution, which are relevant to a range of political treaties such as Kyoto, Montreal, Convention on Long-Range Transboundary Air Pollution (CLRTAP), and Marine Pollution (MARPOL). It is also the case that measurements of the atmosphere have a very important role to play in the implementation of the overall GMES system for two additional reasons. First of all, satellite-based systems observing the surface of the Earth at almost all wavelengths must intrinsically account for atmospheric effects in deriving surface properties. This provides an imperative for development of an integrated GMES system at a technical level and places a premium on synergistic observations of atmosphere and surface. Secondly, the properties of the atmosphere may themselves determine the properties of the surface, particularly through dependences on local atmospheric composition, local temperature and incoming ultraviolet (UV) radiation. This could be crucial for the delivery of knowledge-based GMES systems, for example in assessments of forest sequestration of carbon dioxide. The second aspect of the atmosphere which affects the properties of the surface and determines knowledge must be examined at the GMES system level by performing a synthesis of inputs and requirements for GMES sub-systems; brief comments are made in Section 6.3.2. This chapter therefore concentrates on the first aspect, namely the atmospheric influence on the derivation of surface products.

It is well known that atmospheric effects must be removed before many surface products can be derived from the observations made by satellites. For example, the derivation of products such as surface imagery, vegetation indices, and surface albedo from visible wavelength data requires knowledge of atmospheric aerosols, ozone and water vapour as well as other trace gases. In addition, surface data must often be corrected for cloud, except those obtained from microwave data for which the effect of rainfall is more significant than that of clouds. Therefore, GMES systems for the derivation of these products require and will benefit significantly from improved *atmospheric correction*. Atmospheric components to GMES are potentially required to contribute to a range of GMES-based knowledge systems with diverse applications such as agriculture and fisheries, SAR interferometry of hazards and the determination of climate change.

The problem of atmospheric correction is complex since it depends on sensor design and wavelength region employed. However, the chief components are atmospheric aerosol, water vapour and ozone. Table 6.1 provides some examples of surface products which require atmospheric correction.

Clearly, good atmospheric correction requires co-located information globally. Arguably, the requirement for ozone is less stringent since the primary contribution is from the stratosphere where horizontal variability of ozone is usually considered to be less than in the troposphere. However, there are occurrences of narrow ozone features in the stratosphere, for example filaments of ozone-rich and ozone-poor air. The requirement for good ozone knowledge is likely to depend on the application and could be quite strong for ocean biology applications.

Parameter	Wavelength Region	Typical Wavelengths	Typical Spatial Resolution	Atmospheric Correction Requirements
Sea / land surface temperature	Infrared	11 µm, 12 µm 3.7 µm (night)	1 km x 1 km	Aerosol, water vapour (T), clouds
Surface reflectance / imagery	Visible	470 nm - 2.2 µm (discrete channels or low spectral resolution)	90 m x 90 m to 1 m x 1 m	Aerosol, water vapour, ozone, O_4, clouds, surface pressure
Vegetation indices (derived from reflectance)	Visible	600 nm - 1 µm	1 km x 1 km	Aerosol, water vapour, ozone, O_4, clouds, surface pressure
Ocean colour (chlorophyll / phytoplankton)	Visible	400 nm -550 nm	1 km x 1 km	Aerosol, water vapour, ozone, O_4, clouds, surface pressure
Sea / land surface height (SH)	Microwave	13.575 GHz, 5.3 GHz, 3.2 GHz	<2 km x <2 km	Water vapour, liquid water
Ocean salinity	Microwave	1.4 GHz	35-50 km x 35-50 km	Water vapour
SAR interferometric processing	Microwave	5.3 GHz	1 km x 1 km	Water vapour, liquid water

* Single frequency altimeters. Dual frequency altimeters are much less sensitive to water vapour.

Table 6.1 Surface parameters with requirements for atmospheric correction.

The MODIS Algorithm Theoretical Basis Document (Vermote and Vermeulen, 1999), provides a useful summary of requirements for atmospheric correction and a similar formulation is presented here based on Table 6.1:

- Tropospheric water vapour, aerosols (ground up to 2-3 km)
- Molecules (Rayleigh scattering - density) up to 8 km
- Clouds at all altitudes in the troposphere
- Stratospheric ozone and aerosols (above 15 / 20 km)
- Carbon dioxide and methane (troposphere - near surface)
- O_4 complex (assumed to be constant relative to O_2)

For many applications, the surface pressure must be known. In addition, where scattering effects occur in the atmosphere or at the surface (principally in the visible), the polarisation of radiation travelling through the atmosphere to the satellite must be known.

A further requirement of these surface measurement systems is that simultaneous atmospheric correction information and surface measurements are required. This places a stringent requirement on temporal and spatial coincidence to be achieved. Therefore, atmospheric information must be obtained from channels on the surface sensing instrument, atmospheric instruments located on the same platform, instruments on other platforms flying in formation with the surface sensing platform, instruments in geostationary orbit or from assimilation models which translate information in time and space from atmospheric observations to the relevant frame of surface measurements. Therefore in future, the overall GMES system should aim towards formation flying in low Earth orbit, enhanced atmospheric systems in geostationary orbit and sophisticated assimilation models.

For surface products which are to be utilised in long time series analyses with respect to climate change, air quality or changes in demography, it is important that the appropriate atmospheric information is also provided on a long term basis with intercalibration of data provision from different sensors and / or versions of the same sensor. Therefore a strategy for the continuity of long term observations of key atmospheric variables is required to meet the requirements of atmospheric monitoring.

This chapter is intimately concerned with the synergy between different GMES system components at system design, technical and data quality levels. At the same time, it offers a route to delivering enhanced measurement systems capable of providing both high quality surface data and enhanced information on atmospheric variability. The potential benefits could be quite large for all relevant communities and knowledge-based systems applicable to related policy issues and GMES services.

6.2 WHAT ARE THE POLICY RELATED ISSUES?

Policy issues in this area arise from two sources:

- Surface data requirements
- Atmospheric data requirements which are relevant to surface measurements

The surface data requirements can be divided into three areas, in which a number of key issues can be identified:

- Environmental hazards
- Environmental monitoring
- Mapping
- Commercial remote sensing

The first three areas are of particular concern for GMES applications and services. Clearly the surface data requirements will cover a large number of policy-related issues which will be best addressed by more specific GMES reports. Some examples are given here to demonstrate the range of issues.

The most obvious examples are taken from the area of land / ocean monitoring and resources, where affected surface products include surface temperature, vegetation and phytoplankton. Areas of policy with significant interest in these products range from economic assessments to local air quality regulation, hazard detection and climate change treaties. The Common Agricultural and Fisheries Policy is one where surface data can be employed to assess land and ocean use through vegetation / phytoplankton mapping and to examine the evolution of the regional environment. More locally, information on land and ocean biological states and productivity is also important for regional / local planning of land / sea use and evolution. Land issues include degradation and marginalisation, fire risk, conservation versus intensive farming and sustainability. The monitoring of land surface hazards such as volcanoes, earthquakes and landslips is desirable for detection and early warning. Ultimately, trends in surface properties will be invaluable in identifying long-term changes to rural, urban and oceanic environments and are pre-requisites for monitoring the mitigation of climate change through the Kyoto protocol.

The atmospheric data relevant to surface measurements is of value in itself as well as providing a necessary component to GMES systems for land applications. The primary data required relate to aerosols, water vapour and ozone although climate gases such as carbon dioxide can be influential. The major applications with regards to policy are:

- Regional air quality and long range transport of pollution
- Climate change and Kyoto protocols

Further information on these requirements can be found in Chapters 3 and 2 of this report respectively.

Finally, it should be noted that there is also a synergy between the exploitation of land and atmosphere observations of the Earth for GMES. Many factors are inter-related, for example, the dependence of phytoplankton on UV radiation is controlled by ozone (principally stratospheric) and clouds. It is clear that trends in surface climate and environmental variables will often require relevant atmospheric information for their interpretation. Atmospheric composition, including carbon dioxide, temperature and cloud / rainfall, is a key variable, as are quantities affected by atmospheric composition, such as UV radiation.

6.3 WHAT ARE THE CURRENT CAPABILITIES?

Most of the surface sensing applications considered in this chapter require high spatial resolution measurements, usually on a scale of less than 2 km x 2 km and often of the order of tens of metres. The exception is the determination of sea surface salinity which is in its infancy. The current capabilities are limited by the variability of the atmosphere relative to this spatial scale and are hence dependent on the major atmospheric contribution. Increasingly, atmospheric information is provided by dedicated channels on surface sensors, which enable the matching of observation scales and truly coincident views of surface and atmosphere. Satellite sensors are therefore discussed first, followed by atmospheric models. Networks of ground-based instruments and balloon-borne / aircraft systems are less important due to the requirement for atmospheric correction over a large number of pixels. However GPS networks provide valuable information for small area applications. Global models could provide some of this information and therefore the role of the European Centre for Medium-Range Weather Forecasts (ECMWF) is considered in a section below.

6.3.1 Surface Satellite Sensors and their Atmospheric Correction

There are a large number of satellite surface sensors recently launched or shortly to be launched. Atmospheric influences on a surface product tend to be dependent on the wavelength region employed by the instrument; aerosol contributions are prevalent in all regions except for the microwave region and water vapour is important in all regions except for the blue end of the visible. Ozone knowledge is most important for the UV and visible regions whilst carbon dioxide and methane become more significant in the near infrared close to 2 μm (potentially also in the thermal infrared).

The most recent passive land instruments have tended to aim towards hyperspectral, multi-angle and dedicated channels for atmospheric correction. Hyperspectral instruments tend to have large numbers of channels (greater than ten and up to a few hundred) covering a range of wavelengths in the visible (from 400 nm) to the near infrared (near 2.5 μm). Both hyperspectral and multi-angle information allow much better discrimination between atmosphere and surface, compared with conventional nadir imagers such as Landsat and AVHRR; bi-directional reflectance effects at the land surface result in complications in this separation.

Excellent examples of recent satellite instruments include CHRIS, MERIS, MODIS and ASTER. Table 6.2 summarises their capabilities.

Instrument	Wavelength Range (nm)	Number of Bands	Spatial Resolution (m)	Across-Track Swath (km)
CHRIS	410-1050	Up to 63	>18 x 18 / 36	13 (steerable)
MERIS	390-1040	15*	300 or 1200	1150
MODIS	405-14385	36	250-1000	2330
ASTER	520-11650	14	15-90	60

* MERIS bands are programmable.

Table 6.2 Characteristics of some passive multi- / hyperspectral sensing instruments

The CHRIS instrument obtains the highest spectral resolutions with spectral sampling ranging from 2-3 nm at the blue end of the spectrum (410 nm) to about 12 nm at 1050 nm. Sampling is about 7 nm near the red edge (ca. 690-740 nm). In comparison, the SCIAMACHY instrument on the European environment satellite, Envisat, which performs atmospheric measurements, achieves spectral resolutions of 0.2 nm for most bands to 1.5 nm. The trade-off lies in spatial resolution as SCIAMACHY achieves a maximum resolution of 26 km x 15 km (more typically 30 km x 60 km) in comparison to the 18 / 16 m achieved by the CHRIS instrument. This trade-off highlights the variability in current capabilities but also the balance between spatial and spectral resolutions. The land surface instruments achieve high spatial resolution but do not achieve high spectral resolution whilst the atmospheric instruments have to aim for high spectral resolution to accurately characterise the atmospheric signal.

Secondly, within the European arena of Earth observation, there is not a great emphasis on coverage of the thermal infrared (CHRIS, MERIS). In the thermal infrared, attention has traditionally been focussed on temperature although there is information on other surface properties. The strongest European programme in thermal infrared temperature measurements is the ATSR series which spans 15 years. The instruments are dual-view, imaging radiometers with spatial resolutions of 1 km x 1 km and swath widths across-track of 512 km; there are seven spectral channels on the latest instruments with two in the thermal infrared, two in the near infrared and three in the visible. The dual-view allows for substantial atmospheric correction over oceans but not over lands where bi-directional surface properties complicate the issue. Even over the oceans, aerosols in the stratosphere from Mt. Pinatubo and high water vapour levels in the atmosphere have clearly demonstrated an influence on results. It is also notable that cloud discrimination can present an additional problem.

Ocean sensing can be as difficult as land sensing despite the homogeneous nature of the sea surface. In the visible, only 10% of the total signal obtained from water–leaving reflectances at some wavelengths is due to surface effects; the remainder is due to the atmosphere (Andre and Morel, 1989). For applications such as chlorophyll determination, knowledge of total ozone and aerosols are therefore significant. It is immediately apparent that good knowledge is required to deduce spatial patterns and determine trends with respect to time in atmospheric contributions. For instruments such as CZCS and SeaWIFS, total ozone from TOMS has been used. The MERIS algorithms employ humidity and ozone from the ECMWF. Since aerosols are more variable, the tendency has been to employ aerosol climatologies or models (typically about ten) updated with instrument observations in aerosol-related channels, for example, when observing dark, dense vegetation.

In terms of required instrumentation, it is most straightforward to tackle the atmospheric correction for total ozone; the spatial variability of total ozone is small on a 1 km x 1 km scale, except where urban air pollution significantly contributes to the total column. Total ozone measurements are described in Chapter 1 of this report but in brief, the SCIAMACHY instrument on Envisat, GOME-2 and IASI on the Meteorological Operational (MetOp) series, and OMI on the Earth Observing System (EOS)-AURA will all provide relevant data, albeit at somewhat lower spatial scales. For surface sensing, total ozone data in the visible region, such as the Chappuis bands between 500 and 715 nm, are strongly required. These may exhibit different sensitivity to the ozone vertical profile compared with total ozone measured in the UV at 300 nm.

Water vapour poses a complex problem due not only to variability in total water vapour but also due to variations in its vertical profile. Furthermore, it can vary strongly in time so coincident measurements constitute a stronger requirement. The MWR on Envisat measures along the satellite track with a footprint of approximately 20 km. The primary purpose is to correct for the interference of water vapour in measurements by the Radar Altimeter on Envisat. Its application to instruments such as MERIS which are wide swath is limited by the horizontal variability. Nonetheless, assimilation schemes could utilise MWR data to improve the global field produced by a model (see ECMWF below). As for ozone, there are issues connected with the water vapour spectral feature of concern and differing sensitivities to the water vapour profile. In this context, the launch of the IASI on MetOp could deliver very helpful information on water vapour, ozone and temperature vertical profiles with a nadir pixel size of 12 km x 12 km and a swath width of 1026 km.

Aerosol data are probably the most complicated to consider due to variations in the vertical profile of composition, concentration and phase. A common approach is to assume that the most significant aerosols are located in the lowest part of the troposphere as a layer with an optical thickness scaling height of approximately 2 km (Santer et al., 2000); relatively inert gases such as carbon dioxide and methane are assumed to follow a simple scaling height dependence also but with a scale height of 7 km (reactive trace gases do not follow this law but are insignificant in relation to the correction of surface data). One aerosol model is usually employed for the whole spectral range. There are capabilities to determine aerosol from atmospheric instruments, e.g. from SCIAMACHY, or else to derive it from surface instruments such as ATSR and MERIS. However, there are problems with spatial resolution and applicability of data over wide spectral regions. In addition, problems occur at times of major volcanic eruptions, such as Mt. Pinatubo, where aerosol is injected into the stratosphere to give a very different vertical profile and spectral characteristic to the aerosol profile. Here the problem is rather different in that a capability is required to measure stratospheric aerosol at times of periodic high volcanic loading but such systems must be in place prior to intense eruptions.

In the future, GMES systems could take further advantage of satellites in geostationary orbit, from where observations can be made throughout the day. Already, data from the meteorological satellite, Meteosat, are of proven value and the Meteosat Second Generation (MSG) will significantly enhance the available data. There are also important possibilities for atmospheric composition missions which would provide relevant datasets from geostationary orbit. Such missions would vastly aid the provision of atmospheric information with the required temporal and spatial coincidences for European monitoring of the surface.

6.3.2 Requirements for Atmospheric Data relevant to Surface Measurements

Structured knowledge of the atmosphere is required to not only accurately derive surface data but also to interpret surface observations. For example, it could be that policy requirements necessitate an interpretation of the drivers of vegetation change. Vegetation change is influenced by changes in atmospheric composition in the vicinity of the vegetation and the atmosphere's influence on available radiation for photosynthesis. The former may require measurements of atmospheric CO_2 concentrations and local air quality whilst the latter may require measurements of stratospheric ozone, tropospheric aerosols and cloudiness. Therefore atmospheric knowledge, which is driven within GMES by the requirements of individual GMES systems, is beyond the scope of this chapter as it must be identified at the system level. Rather in this chapter, the focus is on atmospheric factors which directly affect the quality of satellite measurements of the surface. We therefore recommend that this issue concerning atmospheric data products for the analysis and interpretation of surface data is integrated by a synthesis project for GMES, incorporating inputs from the (land) surface community and the atmospheric community.

6.3.3 Data Assimilation and the European Centre for Medium-Range Weather Forecasts Model

Since the coincidence of atmospheric information with surface information is important, the demand for spatial resolution is high and correction techniques must be global. The only real alternative to direct measurement is the use of model data, for which an assimilation system, such as that at the ECWMF, is ideal as it incorporates many of the available measurements to constrain the model. The advantage of a global model is that the data can be produced in near real-time with horizontal fields and vertical profiles consistent with observed meteorological fields.

Typically, the ECMWF system assimilates approximately 500,000 pieces of data into a model system with 60 vertical levels and operates at close to 0.5º spatial resolution (T511 spherical harmonics; 0.5º is approx. 50 km at the equator and less at higher latitudes). Input data include surface pressure, temperature, wind, humidity from radiosondes, satellite radiances, satellite scatterometer data, satellite cloud wind fields and satellite humidity data. Forecasts / analyses are typically output every six hours.

The current ECMWF model is a recognised and respected operational entity which can be coupled to mesoscale models. With further assimilation of relevant water vapour and ozone data, the model could provide very good background fields of these parameters for atmospheric correction; aerosol is not a model variable. Particularly for ozone, the output could be useful if constrained by total ozone measurements and vertically resolved data in the stratosphere, at the tropopause and in the upper troposphere. The assimilation of water vapour is more difficult.

Further improvements in spatial resolution could be achieved by nesting mesoscale models within standard operational forecasting and analysis models. This development is to be encouraged and could be of great relevance to the high resolution measurements of the land community. Such work has been suggested for the processing of SAR interferograms for work on land surface movement.

Clearly, good access to meteorological forecast / analysis fields of surface pressure, temperature, water vapour and ozone will be of priority for an integrated GMES system. Some GMES systems will require access to the analysis models themselves and to derivatives with nested mesoscale modules for high spatial resolution. In particular, such datasets are required in near real-time.

For stratospheric ozone column / profiles and for total ozone column, the Royal Netherlands Meteorological Institute (KNMI) fast delivery service provides an alternative to the ECMWF model. This system has proved very successful with GOME data and could help provide a very good, fast, assimilation scheme to exploit SCIAMACHY data. Other systems are being developed in a number of countries, to exploit Envisat data in particular.

6.4 IS THIS A RATIONAL SYSTEM?

Present systems within the Envisat operating period provide a basis for a rational system of surface observations with good atmospheric correction. These systems will be based essentially on satellite observations with atmospheric information derived from measurements internal to surface sensing instruments, atmospheric remote sensing instruments and assimilation models such as ECMWF. In order to build an effective rational system, a number of important steps should be taken:

- A network for communication between the surface sensing and atmosphere sensing communities should be established.
- Research studies should be performed into the exploitation of independent atmospheric sensing information within the data processing for surface sensors. The importance of vertical resolution of atmospheric profiles should be quantified and the appropriate wavelengths for measurements of aerosols should be identified. In particular, SCIAMACHY and MWR data should be exploited.
- A strategy should be developed for GMES which specifically accounts for continuity in the observation of key atmospheric variables and intercalibrated datasets, which are required for the derivation of long term trends of surface products.
- The availability of meteorological data from meteorological offices and stations is of considerable concern in relation to the development of improved surface products. Agreements for the exploitation of such data in operational and off-line analyses should be established where gaps still exist.
- The accuracies of ECMWF and fast assimilation schemes should be established for ozone and water vapour relative to surface sensing requirements. Much of this research is on-going but the results need to be quantified and made more accessible to the user communities.
- Research into radiative transfer systems should be encouraged to develop an improved hierarchy of atmospheric models for surface remote sensing. Models should include better representations of horizontal and vertical distributions, and of the differing sensitivities to vertical profiles of gases and aerosols, as a function of wavelength.
- Inter-instrument research into aerosols should be conducted to develop a better understanding of aerosols across the electromagnetic spectrum. This requires research into aerosol information from MERIS, SCIAMACHY and AATSR on Envisat as well as instruments on other platforms.
- Operational data systems should be designed to handle multi-instrument data processing with shared information on atmospheric and surface parameters. In particular, the sharing of data from MetOp and Envisat is desirable.

The elements identified in the list above constitute items that will contribute to an integrated system for GMES to utilise existing and planned mission capabilities. There remain missing capabilities both in surface sensing and the provision of atmospheric information to improve surface sensing:

- Research into the derivation of atmospheric correction information at the high spatial scales of surface sensors. Characterisation of atmospheric variability at these scales.
- Development of synergistic mission system concepts linking surface sensing with high fidelity measurements of the corresponding atmospheric parameters.
- There should be an investigation into formation flying with several European satellites in tandem, in the same orbit.
- The development of assimilation systems providing atmospheric information to surface sensing communities should be underpinned by the operation of relevant atmospheric sensors delivering input data to the assimilation system and tests of the assimilation accuracy.
- Integrated data processing centres (virtual or real) which enable the operational or off-line production of synergic data products to utilise information from different instruments and missions / networks.
- High spatial resolution aerosol mission to investigate aerosol climatology and radiative properties. The prime objective of such a mission may be to target regional air quality.
- A system to adequately measure the profiles of stratospheric aerosol should an eruption result in high volcanic loading of the stratosphere, such as Mt. Pinatubo in 1991.
- High resolution imaging sensors for the thermal infrared with associated atmospheric information systems.
- Continuity of missions will become increasingly important as the synergism between the different instruments and data assimilation is developed.

The most important challenges, which GMES faces with respect to atmospheric correction, surround the development of near real-time capabilities for data accessibility, accessible and linked databases and synergistic data processing centres, effective utilisation of ECMWF and more specific data assimilation systems, the addition of key capabilities in observations of aerosols, water vapour, ozone and infrared imaging tied to the exploitation of satellites in geostationary orbit and formation flying in low Earth orbit.

In the post-Envisat period, there is likely to be a shortfall of information on atmospheric composition and studies should be undertaken to establish what will be missing from the portfolio of required atmospheric information whilst only MetOp is operational. These studies should include examination of the requirements of ECMWF for good vertical profile information to enable accurate global fields of ozone and water vapour.

6.5 RELEVANT WEBSITES

Surface sensing instruments:

- http://envisat.esa.int/instruments/
- http://www.chris-proba.org.uk/
- http://modis.gsfc.nasa.gov
- http://asterweb.jpl.nasa.gov/

Atmosphere instruments:

- http://envisat.esa.int/instruments/
- http://www.esa.int/export/esaME

- http://aura.gsfc.nasa.gov/instruments/omi/links.html
- http://jwocky.gsfc.nasa.gov/

Assimilation models:

- http://www.ecmwf.int
- http://www.knmi.nl/gome_fd/

ACRONYMS

AATSR	Advanced Along Track Scanning Radiometer
ABL	Atmospheric Boundary Layer
ACCENT	Atmospheric Chemistry of Combustion Emissions near the Tropopause
ACE	Aerosol Characterisation Experiment
ACT	Atmospheric Chemistry and Transport
ADEOS	Advanced Earth Observing Satellite
AERO2K	A New Global Inventory of Emissions and Fuel Usage from Aviation
AEROCARB	Airborne European Regional Observations of the Carbon Balance
AERONET	Aerosol Robotic Network
AGAGE	Advanced Global Atmospheric Gases Experiment
AIRES	Atmospheric Interdisciplinary Research
AIRS	Atmospheric Infrared Sounder
AMASDU	Aerosol Mapping Algorithms for Satellite Data Users
AMVER	Automated Mutual Assistance Vessel Rescue
AOD	Aerosol Optical Depth
AOT-x	Accumulated Dose over a Threshold of x ppb
AQ	Air Quality
AQUA	NASA EOS Water Cycle Satellite
ASH	Accumulated Sunshine Hours
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR	Along Track Scanning Radiometer
AURA	NASA EOS Atmospheric Chemistry Satellite
AVHRR	Advanced Very High Resolution Radiometer
BICEPS	Building an Information Capacity for Environmental Protection and Security
BL	Boundary Layer
BOOS	Baltic Operational Oceanographic System
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CAEP	Committee on Aviation Environmental Protection
CAFE	Clean Air for Europe
CAL / VAL	Calibration / Validation
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CANDIDOZ	Chemical and Dynamical Influences on Decadal Ozone Change
CARBOEUROPE	A Cluster of Projects to Understand and Quantify the Carbon Balance of Europe
CARIBIC	Civil Aircraft for Regular Investigation of the Atmosphere based on an Instrument Container
CCA	Cross-Cutting Assessment
CDM	Clean Development Mechanism
CEOS	Committee on Earth Observation Satellites
CFC	Chlorofluorocarbon
CHRIS	Compact High Resolution Imaging Spectrometer
CLAES	Cryogenic Limb Array Etalon Spectrometer
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CMDL	Climate Monitoring and Diagnostics Laboratory

COADS	Comprehensive Ocean-Atmosphere Data Set
CORINAIR	Danish Atmospheric Emissions Inventories
COS	Carbonyl Sulphide
COST-713	European Cooperation in the Field of Scientific and Technical Research - UVB Forecasting
CREATE	Construction, Use and Delivery of a European Aerosol Database
CTM	Chemistry Transport Model
CZCS	Coastal Zone Colour Scanner
DAEDALUS	Delivery of Aerosol Products for Assimilation and Environmental Use
DAMS2P	Development of Global Aerosol Mapping from Satellites Level-2 Products
DARE	Data Assimilation in Readiness for Envisat
DEFRA	Department for Environment, Food and Rural Affairs
DG	Directorate General
DLR	Deutsche Forschungsanstalt für Luft und Raumfahrt
DMS	Dimethyl Sulphide
DUE	Data User Element
DUP	Data User Programme
EARLINET	European Aerosol Research LIDAR Network
EC	European Commission / Community
ECCP	European Climate Change Programme
ECHAM	University of Hamburg Atmospheric General Circulation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emission Database for Global Atmospheric Research
EEC	European Economic Community
EMEP	European Monitoring and Evaluation Programme
Envisat	ESA European Earth Observation Satellite
EORCU	European Ozone Research Coordinating Unit
EOS	Earth Observing System
EPA	Environmental Protection Agency
ERA	European Research Area
ERS	European Research Satellite
ESA	European Space Agency
ESRANGE	European Sounding Rocket Range
ESSP	Earth System Science Pathfinder
EU	European Union
EUMETNET	European Network of Meteorological Services
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EuroAirnet	European Air Quality Monitoring Network
EuroGOOS	European Global Ocean Observing System
EUROTRAC	Transport and Chemical Transformation of Environmentally Relevant Trace Constituents in the Troposphere over Europe
EVERGREEN	Envisat for Environmental Regulation of Greenhouse Gases
FCCC	Framework Convention on Climate Change
FORMAT	Formaldehyde as a Tracer of Photooxidation in the Troposphere
FP	Framework Programme
FT	Free Troposphere
FTIR	Fourier Transform Infrared
GATO	Global Atmospheric Observations
GAW	Global Atmosphere Watch
GCOM	Global Change Observing Mission
GHG	Greenhouse Gas
GMES	Global Monitoring for Environment and Security

GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of Stars
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GSE	GMES Service Element
H_2O	Water
HNO_3	Nitric Acid
HALOE	Halogen Occultation Experiment
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HELCOM	Helsinki Convention
HFC	Hydrofluorocarbon
HIRDLS	High Resolution Dynamics Limb Sounder
HIRS	High Resolution Infrared Radiation Sounder
IASI	Infrared Atmospheric Sounding Interferometer
ICAA	International Civil Airports Association
ICAO	International Civil Aviation Organization
IGAC	International Global Atmospheric Chemistry
IGACO	Integrated Global Atmospheric Chemistry Observations
IGBP	International Geosphere-Biosphere Programme
IGCO	Integrate Global Carbon Observing
IGOS	Integrated Global Observing Strategy
ILAS	Improved Limb Atmospheric Spectrometer
IMG	Interferometric Monitor for Greenhouse Gases
IMO	International Maritime Organization
IMPROVE	Interagency Monitoring of Protected Visual Environments
INDOEX	Indian Ocean Experiment
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
ISAMS	Improved Stratospheric and Mesospheric Sounder
KNMI	Royal Netherlands Meteorological Institute
Landsat	NASA and USGS Land-Surface Sensing Satellite
LEO	Low-Earth Orbit
Lidar	Light Detection and Ranging
LITE	LIDAR in-Space Technology Experiment
LRTAP	Long-Range Transmission of Air Pollutants
LTO	Landing and Take-Off
MARPOL	Marine Pollution Convention
MEDPOL	Mediterranean Pollution Monitoring and Research Programme
MEPC	Maritime Environmental Protection Committee
MERIS	Medium Resolution Imaging Spectrometer
Meteosat	EUMETSAT Meteorological Satellite
Meth-MonitEUr	Methane Monitoring in the European Region
MetOp	ESA Operational Meteorology Satellite
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MIPAS-B	Michelson Interferometer for Passive Atmospheric Sounding - Balloonborne Version
MIR	Montgolfier Infrared
MISR	Multi-Angle Imaging Spectro Radiometer
MODIS	Moderate Resolution Imaging Spectrometer
MOMS-2P	Modular Optoelectronic Multispectral Scanner - 2P
MOPITT	Measurements of Pollutants in the Troposphere

MOZAIC	Measurement of Ozone, Water Vapour, Carbon Monoxide and Nitrogen Oxides by Airbus In-Service Aircraft
MSG	Meteosat Second Generation
MWR	Microwave Radiometer
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NO_x	$NO_x = NO + NO_2$
NADIR	NILU Atmospheric Database for Interactive Retrievals
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NDSC	Network for the Detection of Stratospheric Change
NEAR-GOOS	North-East Asia Global Ocean Observing System
NEPAIR	New Emission Parameter covering all Phases of Aircraft Operation
NILU	Norwegian Institute for Air Research
NOAA	National Oceanic and Atmospheric Administration
NOXAR	Measurements of Nitrogen Oxides and Ozone along Air Routes
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRT	Near-Real-Time
NRW	North-Rhine Westfalia
NWP	Numerical Weather Prediction
O_2	Oxygen
O_3	Ozone
OCO	Orbiting Carbon Observatory
OCTS	Ocean Colour and Temperature Sensor
ODIN	Swedish-led Small Satellite Project for Astronomical and Atmospheric Research
ODS	Ozone Depleting Substance
OMI	Ozone Monitoring Instrument
OSPARCOM	Oslo and Paris Convention
OZONE-FD	GOME Ozone Fast Delivery Value Added Products
PAH	Poly-Aromatic Hydrocarbon
PAN	Peroxyacetyl Nitrate
PBL	Planetary Boundary Layer
PFC	Perfluorocarbon
PHOTONS	Photométrie pour le Traitement Opérationnel de Normalisation Satellitaire
PM x	Particulate Matter Smaller than x μm
POAM	Polar Ozone and Aerosol Monitor
POET	Precursors of Ozone and their Effects in the Troposphere
POLDER	Polarization and Directionality of the Earth's Reflectances
POLINAT	Pollution from Air Traffic Emissions in the North Atlantic Flight Corridor
POP	Persistent Organic Pollutant
PRIRODA	International Earth Remote Sensing Project
PSC	Polar Stratospheric Cloud
QA	Quality Assurance
QC	Quality Control
RETRO	Reanalysis of the Tropospheric Composition over the Past 40 Years
RF	Radiative Forcing
SO_2	Sulphur Dioxide
SAF	Satellite Application Facility
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Stratospheric Aerosol Experiment
SAR	Synthetic Aperture Radar

SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SCOUT-O3	Stratosphere-Climate Links with Emphasis on the UTLS - 03
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SH	Surface Height
SME	Small / Medium Sized Enterprise
SOGE	System for Observation of Halogenated Greenhouse Gases in Europe
SPARC	Stratospheric Processes and their Role in Climate
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
TEMES	Telemetrisches Echtzeit-Mehrkomponenten-Erfassungs-System
TEMIS	Tropospheric Emission Monitoring Internet Service
TERRA	NASA Flagship EOS Satellite
TES	Tropospheric Emission Spectrometer
THESEO	Third European Stratospheric Experiment on Ozone
TOMS	Total Ozone Mapping Spectrometer
TRADEOFF	Aircraft Emissions: Contribution of Different Climate Components to Changes in Radiative Forcing - Tradeoff to Reduce Atmospheric Impact
TROPOSAT	Use and Usability of Satellite Data for Tropospheric Research
UARS	Upper Atmosphere Research Satellite
UK	United Kingdom
UKMO	United Kingdom Meteorological Office
UN	United Nations
UN-ECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
US GOOS	United States Global Ocean Observing System
USGS	United States Geological Survey
USA	United States of America
USSR	Unites Socialist Soviet Republics
UT	Upper Troposphere
UTLS	Upper Troposphere / Lower Stratosphere
UV	Ultraviolet
VAAC	Volcanic Ash Alert Center
VIIRS	Visible / Infrared Imager / Radiometer Suite
VINTERSOL	Validation of International Satellites and Study of Ozone Loss
UV-Vis	UV-Visible
VOC	Volatile Organic Compound
WCRP	World Climate Research Programme
WDCA	World Data Centre for Aerosols
WDCGG	World Data Centre of Greenhouse Gases
WHO	World Health Organization
WMO	World Meteorological Organization
WOUDC	World Ozone and Ultraviolet Radiation Data Centre

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