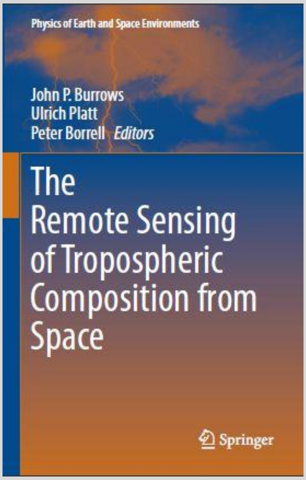
The Remote Sensing of Tropospheric Composition from Space



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Chapter 10

Conclusions and Perspectives

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10.1 Introduction: The Need for Satellite Observations

As will have been appreciated from the earlier chapters, key aspects of the Earth's atmosphere and environment are best monitored with instruments mounted on satellites orbiting the Earth in space. The progress towards this aim during the last twenty years has been remarkable. The objectives of the present chapter are to indicate likely future changes and improvements in instruments and techniques, to describe what the scientific community is suggesting and how the national and international space agencies are proposing to meet the challenges in the foreseeable future.

The need for monitoring the atmosphere and environment is well appreciated: the near exponential growth in the Earth's population and the general improvement in standard of living that has brought many societal benefits has been almost literally fuelled by the inexpensive energy made available from the exploitation of fossil fuels. The growth of emissions into the atmosphere has changed pollution from being a matter of local concern to one having a global impact, and thus the Holocene period has been transformed to the Anthropocene, a period characterised by a growing influence of human activities on the global environment. Today, the development of an acceptable strategy to provide a sustainable development and future for the Earth system with an increasing human population, having its traditional aspirations for growth and standard of living, is currently one of the greatest challenges for society.

The changes in atmospheric composition, and other critical parameters determining the nature and behaviour of the Earth system, have been recognised by the

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majority of the active scientific community, and the impact of anthropogenic activity assessed: the state of knowledge and their conclusions have been summarized in a number of international assessments (UNECE LTRAP HTAP 2007; WMO 2007; IPCC 2007; WMO 2010). One successful outcome was the Vienna Convention on Ozone Depleting Substances and its subsequent amendments (UNEP 2009), which instituted a policy to restrict damage to the stratospheric ozone layer. Similarly, in the developed nations, national and international legislation has been successful in improving air quality in cities. However the continuing growth of anthropogenic greenhouse gas emissions, changes in land use, and the release and long range transport and transformation of pollution are now on a scale which challenges the ability of the scientific community to assess their impact and predict the likely consequences.

Although the need for action to maintain the environment, its ecosystem services and biodiversity is generally appreciated, the disappointment at the outcome of the Copenhagen Climate Conference in 2009 and the animated public discussion of the acknowledged minor errors in the IPCC fourth Assessment Report (IPCC 2007), indicate the challenges facing the policymakers in attempting to reach an adequate compromise to control carbon emissions. The impasse re-emphasizes the continuing and growing need for accurate data to assess the Earth's changing environment, if a sustainable future is to be achieved.

A prerequisite for successful global management is a proper knowledge and understanding of the physical, chemical and biological processes and their feedbacks, which determine the conditions of the local, regional and global environment. A positive outcome of the growth of industrial and economic activity has been, over the last 50 years, the birth and growth of space exploration, together with the development of all the techniques and infrastructure required to operate satellite and ground-based systems for monitoring the global and regional atmospheric environment.

International collaboration is essential to achieve global monitoring. The Committee on Earth Observation Satellites, CEOS, coordinates civilian space borne observations of the Earth. It initiated the Integrated Global Observing Strategy, IGOS, which seeks to provide a comprehensive framework to harmonize the common interests of the major space-based and *in situ* systems for global observation of the Earth. The Integrated Global Atmospheric Chemistry Observations theme (IGACO 2004), a component of IGOS, recognised that global measurements of atmospheric trace composition from space-based instrumentation, together with ground-based networks and aircraft, are required to meet the emerging need for accurate data and provide an early warning of deleterious change.

The 2002 World Summit on Sustainable Development and the Group of Eight leading industrialized countries, established the Group on Earth Observations (GEO), which coordinates efforts to build a Global Earth Observation System of Systems (GEOS 2005); it now incorporates the objectives of IGOS. The European Global Monitoring of Environment and Security (GMES) is the European contribution to Group on Earth Observations. While it is clear that some progress is being achieved, the question remains whether the progress will be sufficient to meet the goals: that is delivery of the evidence needed to underpin an international environmental policy to provide sustainable development, before the changes in the Earth system become irreversible.

10.2 Some Scientific Highlights

The principal chapters of this book have documented the revolution in knowledge and the most important aspects of the evolution of the technology of measurement and retrieval theory for the remote sensing of tropospheric constituents from space. The resulting measurements of the tropospheric composition are challenging and revolutionise our understanding of the chemical processing and dynamics within the atmosphere, of exchange at the surface and at the tropopause and of the biogeochemical cycles.

Perhaps the most important highlight is the unique capability to make measurements needed for numerical weather prediction and to measure tropospheric pollution, its transport and transformation.

The observations have resulted in several discoveries of both natural phenomena and the results of anthropogenic activity: large clouds of bromine monoxide, BrO, seen at high latitudes, the global distribution of iodine monoxide, IO, the global observations of ammonia, NH_3, and the increase in nitrogen dioxide, NO_2, ozone, O_3, and sulfur dioxide, SO_2, over Asia, together with the impact of biomass burning. These have led to a new understanding of our atmospheric environment and have revolutionised research in atmospheric chemistry.

The following section picks out some highlights from Chapters 2, 3, 4, 6 and 8.

10.2.1 Observed Compounds

Perhaps the most notable development in the field is the sheer number of species that can now be observed from space (Table 8.3). The prominent pollutants, ozone, O_3, nitrogen dioxide, NO_2, carbon monoxide, CO, and sulfur dioxide, SO_2, are observed and it is now also possible to observe selected volatile organic compounds, VOCs, methane, CH_4, acetylene, C_2H_2, ethane, C_2H_6, and ethene, C_2H_4. Also observable are some of the products from photo-oxidation such as methanol, CH_3OH, formaldehyde, HCHO, formic acid, HCOOH, glyoxal, CHOCHO, acetone, CH_3COCH_3, PAN, peroxy nitric acid (HO_2NO_2), hydrogen cyanide, HCN, nitric acid, HNO_3, hydrogen peroxide, H_2O_2 and carbonyl sulfide, OCS. Another problem compound observed, resulting from intensive agriculture, is ammonia, NH_3.

The greenhouse gases carbon dioxide, CO_2, methane, CH_4, nitrous oxide, N_2O and water vapour, H_2O are observable. Partially deuterated water, HDO, has also been seen. In addition all three phases of H_2O, ice, liquid and vapour can be observed with microwave sensors.

The interest in stratospheric ozone depletion is reflected in observations in the upper troposphere of the chlorofluorocarbons, CFC-11 ($CFCl_3$), CFC-12 ($CFCl_2$), CFC-113 (Cl_2FC-$CClF_2$), HCFC-142b (ClF_2C-CH_3) and HCFC-22 ($CHClF_2$). Some other halogen compounds seen in this region are sulfur hexafluoride (SF_6), methyl chloride, CH_3Cl, and hydrogen chloride, HCl.

The observations of reactive halogen free radicals BrO and IO have demonstrated the global importance of tropospheric halogen chemistry. The sudden explosive spring growth in the concentrations of BrO in the Arctic and Antarctic, together with the measurements of the depletion of O_3 at the surface, have triggered much interest and speculation about unexpected chemical reactions on the surface of the ice sheets.

The observation of cloud and aerosol optical parameters from space based instrumentation has also seen a remarkable development in the last two decades. As each compound or parameter has its own peculiar spectral characteristics and unique sources and sinks, not all the compounds or parameters can be observed under all conditions.

10.2.2 The Multiple Roles of NO_2

NO_2 is a prominent product from industrial and domestic energy production, biomass burning and transport. NO_2 also plays a key role in a number of pollution problems: acidification of terrestrial ecosystems, eutrophication of lakes and the marine environment, formation of tropospheric O_3 and effects on human health and agricultural productivity (Grennfelt et al. 1994). NO_2 is a key photochemical species in the troposphere, which participates as a chain carrier in catalytic cycles, producing and destroying tropospheric O_3. It is perhaps fortunate then that NO_2 can readily be observed from space in the UV/vis region.

The retrieval of tropospheric NO_2 is providing global knowledge of NO_2 columns. During the period of observations a large increase of NO_2 over urban areas in Asia has been observed, as has the simultaneous decrease over Europe, attributed to legislative demands. Weekly cycles of NO_2 in urban areas were discovered as well as changes in NO_2 due to the fertilisation of soils.

Emissions from shipping show the NO_2 ship tracks over the ocean and indicate the growing impact of pollution from shipping on ocean ecosystems. Observations of the formation of NO_2 from lightning have improved the estimation of nitrogen budgets.

10.2.3 Industrial Emissions and Biomass Burning

The observation of the tropospheric columns of CO and the aldehydes, HCHO and CHOCHO, are providing valuable information about the oxidation of VOC of both natural and anthropogenic origin. These help to enlarge our knowledge of fossil fuel combustion, and anthropogenic, biogenic and biomass burning emissions of VOC and CO.

The extensive CO observations have been particularly well exploited as an indicator of industrial pollution and biomass burning; the long range transport in the southern hemisphere being one focus of activity. The recent measurements of HNO_3 and, in particular NH_3, should add to the possibilities and further constrain the complex models. Measurements in the upper atmosphere from limb observations have also shown the global importance of biomass burning and enabled exchange between the troposphere and stratosphere to be studied.

The increase of air pollutants such as NO_2, SO_2 and aerosol parallels the rapid economic development in eastern Asia. The observation of the transport of pollution from Asia to North America, from North America to Europe and from Europe into the Arctic has huge implications for transboundary pollution control.

10.2.4 Ozone, O_3

Appreciable improvements have been made in the retrieval of tropospheric O_3, particularly in the tropics, where stratospheric O_3 is spatially uniform. However as about 90% of the O_3 lies above the tropopause in the stratosphere, TIR radiation must pass once through this layer and solar backscatter twice before detection. Thus accurate knowledge of the stratospheric O_3 is required in order to retrieve the tropospheric O_3, and particularly boundary layer O_3, with any accuracy.

In the sub-tropics the rapid changes in lower stratospheric O_3 and tropopause height, resulting from streamers and the movement of frontal systems, presents a challenge and requires more research to improve our knowledge of global tropospheric O_3. In spite of the progress made in the retrieval of tropospheric O_3, both in the UV/vis and TIR regions, determination of accurate boundary layer O_3 remains a challenging target for tropospheric remote sensing. However the combined simultaneous use of different spectral features of O_3 and different viewing geometries offers potentially a synergetic solution for this issue.

10.2.5 Greenhouse Gases

H_2O is the most important greenhouse gas and a key component of the hydrological cycle, and the measurements of water profiles and columns have made much progress in recent years. The measurement of the dry columns of the greenhouse gases, CO_2, CH_4 from space has now begun in earnest. Nadir sounding TIR instruments are providing mid- and upper-tropospheric columns and solar back scattered instrumentation in the near and short wave infrared spectral regions are yielding the dry columns of these gases. Seasonal maps of CO_2 concentrations confirm the seasonal features in the Mauna Loa records (Keeling et al. 1976; 2003), and there are some excellent animations using the changes in the dry column of CO_2 to show the "breathing" Earth. However measurements of high accuracy are needed here to assess both anthropogenic emission and the response of the biogeochemical carbon cycle to change. Recent studies have demonstrated the feasibility of measuring CO_2 and CH_4 remotely – and these now pose a considerable challenge for the next generation of instrumentation and systems.

10.2.6 Water Vapour, and Other Hydrological and Cloud Parameters

Parameters, which determine the transport within the hydrological cycle, have been a very successful target for remote sensing. Gas phase H_2O is retrieved successfully by instruments from the microwave to the visible regions; the rotational and ro-vibrational spectra of H_2O are being exploited in both emission and absorption. In addition liquid and ice phase parameters are now also retrieved from both IR and microwave spectral regions.

An important focus of the use of wide-swath sounding, passive and active sensors operating at microwave and mm wavelengths, see Chapter 4, has been the retrieval of meteorological parameters. In this context the accurate retrieval of H_2O and temperature profiles have been critical for the development and improvement of numerical weather prediction.

In limb sounding, retrievals using data from some microwave instruments, although primarily aimed at the retrieval of stratospheric parameters, yield O_3, CO and HNO_3, as well as the established water vapour and cloud-ice observations in the upper troposphere.

The retrieval of liquid water and ice from clouds represent significant Earth observation milestones, and the use of radar will be increasingly exploited for precipitation applications in the future.

10.2.7 Aerosol and Cloud Parameters

The growth in the measurement of aerosol parameters has been a feature in the past few years. These have been facilitated by the launch of new dedicated LEO satellite instruments as well as GEO instruments. There is now a long data record of nadir viewing at selected wavelengths, which yield long term changes in aerosol parameters.

Currently instruments using multiple views and observing different polarisations are providing much improved data products, and the pioneering active systems will give reliable profile data (Chapter 6). A major recent enhancement has been the successful deployment in space of lidar for the observation of cloud and aerosol parameters. Building on LITE and GLAS, the combination of CALIOP and the improved passive remote sounding instruments is providing valuable new insights to enhance our understanding of aerosol amount and transport.

A topical example is provided by the recent eruption of the volcano under the Eyjafjallajoekull glacier in Iceland. Eruptions began unexpectedly in March 2010, the first time since 1821. A strong eruption on the 14th April pushed gas and ash into the upper troposphere. The volcanic plume can be seen in Fig. 10.1 (top) as the

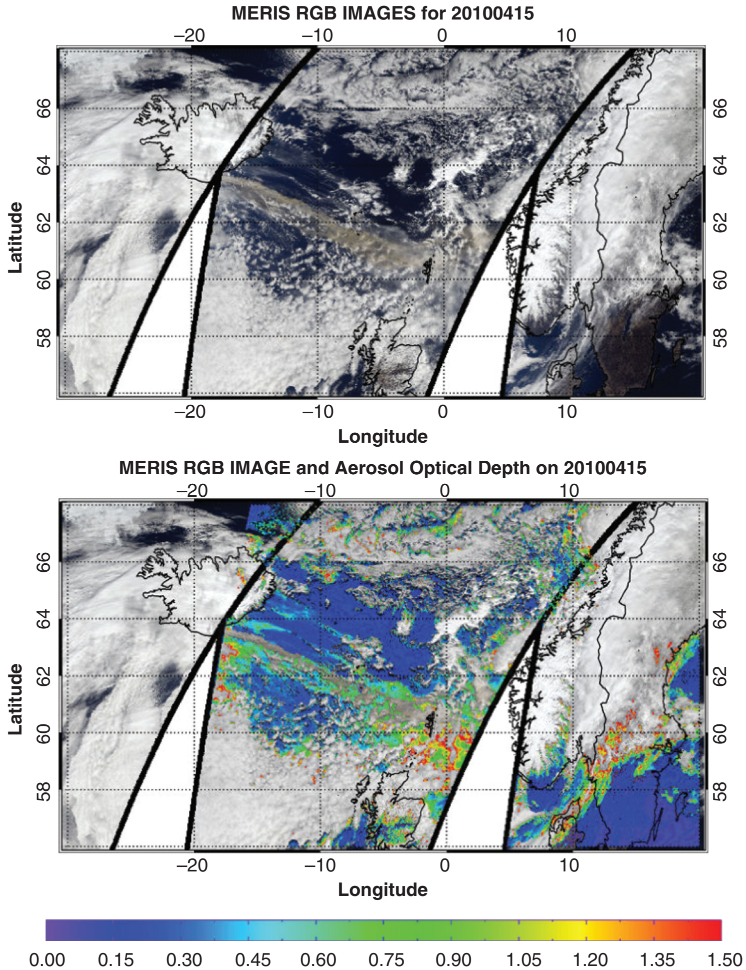

Fig. 10.1 The eruption of the Eyjafjallajoekull volcano: (*top*) the RGB image of three orbit segments (left orbit: 42475, middle orbit: 42476, right orbit: 42477) of MERIS taken close to 10 a.m. local time on the 15th April 2010. In the middle orbit the ash cloud is visible after one day of transport; (*bottom*) as above but with an overlay of the aerosol optical depth; the highest aerosol optical depths are found close to the Shetland Islands with values of about 1.5. AOD derived from the Bremen AErosol Retrieval (BAER). C. Schlundt, W. von Hoyningen Huene, M. Vountas, and J.P. Burrows, Instiute of Environemntal Physics, University of Bremen.

brownish cloud originating from the south of Iceland and transported in an ESE direction while dispersing; it spread the particulate matter over northern Europe leading to closure of air space and the total disruption of air traffic.

An overlay of the optical density of the fine particles has been added in Fig. 10.1 (bottom) and shows the spread of fine particulates over much of the region viewed. The pictures illustrate the assistance that can be gained in practical air traffic management from regular remote sensing measurements with their high spatial and temporal sampling.

Finally for the adequate scientific interpretation of global remote sensing atmospheric data products, results for a number of other parameters are required. Among these are night-time light pollution, vegetation distribution, fire counts and lightning counts; these are illustrated as global maps in Appendix B. They provide practical examples of the synergetic use of multiple data products to improve retrievals and understanding (Section 10.3).

10.2.8 Volcanic Emissions

As shown in Fig 1.11, SO_2 is emitted not only by pollution sources but also, in many cases continuously, by volcanoes. Their releases result in the formation of aerosol and cloud condensation nuclei, which in turn impact on cloud amount and precipitation patterns.

In addition, as Fig. 1.10 shows, volcanic eruptions are a major source of aerosol and particulate matter. This was highlighted in spring 2010 when the inability of aircraft to fly had a large negative impact on sectors of the economy.

10.3 Scientific Needs

The authors of each chapter have provided a future perspective by indicating likely or needed advances in their respective areas. While the chapters should be consulted for the detailed recommendations, a number of common themes emerge.

- Present passive remote sensing instruments in the UV/vis/NIR and the TIR are demonstrating performance close to the achievable limits for the data retrieval, so larger detector areas are needed to improve the signal to noise ratio. Instruments having improved spatial and temporal sampling are required to cope with the accuracy needed to observe the detailed changes in concentrations of long-lived and short lived climatically active gases, and also the concentrations of O_3 and its precursors in the all-important planetary boundary. Better resolution ground coverage is needed in most studies (Sections 2.8.1, 3.5, and 8.4).

- To ensure that measurements are made often enough under cloud free conditions at mid and low latitudes, GEO observations are needed. However the polar regions are not probed by GEO, and combinations of instruments on GEO and LEO satellites with orbits optimised to observe the polar regions are desirable (Sections 2.8.1, 3.5, 6.15, and 10.8).
- More extensive multi viewing, hyperspectral, coupled with polarisation measurements, are needed to improve the determination of aerosol properties and a knowledge of tropospheric radiative transfer (Sections 2.8.1, 6.15, and 10.6.1).
- The determination of tropospheric height-profile information for all atmospheric constituents needs improvement. For selected constituents this might best be provided by the deployment of active systems (Sections 2.8.1, 4.7, and 6.15). The use of simultaneous multiple viewing, passive, remote sensing instruments requires further study for trace gas observations in the lower troposphere.
- While retrievals are under continuous improvement, improved reference input data is needed. For example, absorption cross sections and line parameters are not known adequately well, even for common molecules (Section 2.8.2). Similarly the knowledge of surface spectral reflectivity and emissivity is inadequate.
- Synergistic studies involving instruments mounted on different satellites in different orbits offer the potential to deduce the physical and chemical state of the troposphere including, for example, studying the development of pollution episodes in a more systematic way. However they will require more extensive cross-calibration (Sections 2.8.3, 3.5, 4.8, 8.4, 9.5, and 10.4.2).
- Data assimilation, an essential tool in meteorology for numerical weather prediction, is now being developed for the numerical prediction of chemical composition. However much more development and experience is required in applications such as inverse modelling (Sections 4.8, 9.5, and 10.4.3).
- Although much needed, the production of long term consolidated and consistent data sets of atmospheric parameters is challenging, principally because of the cost. Unfortunately the issue is coupled with the fact that fewer missions designed to study trace species in the troposphere are planned (see the timelines in Appendix D). As a result of the time taken to build and commission space-based instrumentation for Earth observation, there are likely to be problems in the future when more detailed measurements and understanding will be required (Section 3.5, Appendix D). A good example of this recently was the eruption of the volcano under the Eyjafjallajoekull glacier (Section 10.2.7), which resulted in all air traffic over Europe being stopped. The airline industries argue that insufficient data was available and are now asking governments to compensate them for their losses. One solution would be to levy the energy and transport industries to provide the funding needed for an adequate measurement system.
- Improvements in instruments and retrievals are dealt with in more detail in Sections 10.5 and 10.6.

10.4 Further Interpretation of Data from Current Instrumentation

Much of the current generation of space instrumentation was not developed specifically for the determination of tropospheric composition. It was often a by-product of instrumentation designed to observe the stratosphere or to deliver parameters for numerical weather prediction. However much progress has been made in the retrieval of trace constituents and parameters using the current generation of instrumentation, and many more data products have been delivered than expected.

Overall there has been an exceptionally high return on the investment in the hardware and ground segment for research. Operational test services using the new capability have been initiated: for example in Europe, ESA, EUMETSAT and ECMWF have initiated upstream and downstream service elements. To evolve, these will require improved systems, based on the successes of the first generation of instrumentation. However it is also essential to improve instrument performance such as temporal and spatial sampling. Nevertheless the improved evaluation of data from existing sensors in space still holds much promise for better tropospheric data products.

For some chemical species, such as BrO, the maximum information content has been achieved because the optimal spectral window has been used. However for molecules such as NO_2 and O_3 many more spectral features are available. The simultaneous use of such features, often from different spectral regions, has been recognised but its use is still sparse. Similarly the use of multiple measurements for the determination of cloud and aerosol parameters is in its infancy. One important point to note is that improved knowledge of cloud and aerosol will also improve the general accuracy of trace gas retrievals, using data recorded simultaneously.

Limiting factors for the simultaneous use of multiple spectral regions, or combinations of different instruments, are a knowledge of the calibration of the measurements, the accuracy of data bases of the reference spectra and the completeness of the radiative transfer programmes used as forward models in the retrieval process. Further progress using the current and archived set of measurements and data products is likely to come from the following areas.

10.4.1 Retrieval Algorithm Developments

For cloud free scenes in the spectral ranges from the UV to the mid-IR, improved radiation transport modelling has the potential to improve the retrieval of tropospheric trace gases. This could be achieved by:

- having improved simultaneous knowledge of aerosol properties, and
- the explicit inclusion of surface effects, e.g. consideration of (weak) narrow band structures in surface reflectivity and emissivity.

For cloudy and partially cloudy ground scenes, the retrieval of cloud parameters, trace gas and aerosol properties, and also the adequacy of the forward models used in the retrieval algorithms is of central importance.

Presently all operational cloud retrieval algorithms rely on a homogeneous, single-layered cloud model, while real clouds are inhomogeneous objects. Scattered cloud fields, situations with extensive vertical convection or, for thin clouds, both cloud inhomogeneity and the underlying surface bi-directional reflectance function, must all be accounted for. Another issue is the retrievals of ice clouds, which at the moment relies on *a priori* models of crystal shapes mostly based on empirical evidence. The retrievals of mixed phase cloud properties, such as the ice/water fraction, are not yet developed satisfactorily. In general improving the description of the scattering within the atmosphere and at the surface will reduce uncertainty in the retrieved data products.

10.4.2 The Use of Multiple Observations

The retrieval of data products depends on accurate knowledge of the atmospheric conditions. Although the potential is recognised, the synergetic use of simultaneous or near simultaneous observation of trace gas features in the visible, infrared, and microwave regions has not been systematically explored for the retrieval of tropospheric data products. Investigations are necessary to meet this challenge and to show how to benefit from the complementary sensitivities of the different wavelengths to each atmospheric parameter, and thus help to constrain the inversion problems.

Combining data products from different sensors (on the same satellite or on different satellites) potentially yields:

- an increased number of retrieved data products, noting that several trace gases may only be retrieved in selected wavelength ranges, such as IO and BrO in the UV, and NH_3 or CH_3OH in the mid-IR (see Chapters 2 and 3). Combining these data leads to a better characterization and thus to improved constraints of the chemical modelling of a probed air mass;
- improved vertical resolution can be achieved by combining the different sensitivities of trace gas absorption in different spectral regions as a function of altitude, e.g. CO measurements in the short-wave IR and the TIR, or the combination of limb and nadir observation of the same species;
- the combination of simultaneous or near simultaneous knowledge of chemical composition and dynamical parameters.

10.4.3 Data Assimilation

As is well recognised by the operational meteorological community, data assimilation has a special role to play in the improvement of the prediction. The area of environmental and climate prediction is a growing area which meets many of the needs of the policymaking community. Data assimilation combines the knowledge from model and measurement. The method is also valuable in filling in regions where data is sparse, and thus provides an approach for the comparison of retrieved data products which are not measured simultaneously. The resultant hybrid data sets have many scientific uses.

However for the detection of changes and trends, and to ensure unforeseen processes and feedbacks are recognised, it is advisable that there should always be (alternative) data products, which are as free from any modelling information as possible.

10.5 Idealised Requirements for the Evolution of Instrumentation

The type and quality of the data obtained from remote sensing necessarily depend on the scientific problem being tackled. As in all physical experiments the sampling and the signal to noise ratio of the data products must be sufficient to reveal true behaviour of the process being investigated.

However there are different priorities for the data products determining atmospheric composition: numerical weather prediction, numerical environmental prediction, global climate and tropospheric pollution and atmospheric chemistry; all need different temporal and spatial sampling scales. Nevertheless there are common themes which include the following.

(a) The improvement of the vertical resolution for trace gas and aerosol measurements. Three-dimensional fields of trace gas concentrations are desirable at vertical resolutions much better than the atmospheric scale height (7 ± 1 km).
(b) Sufficient horizontal resolution of the measurements, in particular for the retrieval of trace gas column densities and concentrations. In order to resolve structures in biomass burning events, volcanic plumes, and mega cities spatial resolutions better than 4 km are required.
(c) Temporal resolution of the measurements, which is enough to resolve diurnal cycles of trace gas concentrations, aerosol and cloud parameters.
(d) Extension of the number of gaseous species that can be observed from space. Desirable species include speciated VOC, especially alkanes and olefins. Presently only CH_4 and a few oxygenated species are measurable in the boundary layer from space.
(e) Improved measurements of the key species of atmospheric chemistry such as tropospheric O_3, and NO_2. RO_x radicals (OH, HO_2, RO_2 where R is an organic radical) are required to understand the processing on short time scales in air masses.
(f) Improved sensitivity for a series of species to study background levels of NO_x, hydrocarbons, and tropospheric O_3.

For many of these requirements, there is not yet any mature technological solution. This is particularly the case for improved vertical resolution. Improved sensitivity, spatial, and temporal resolution can be achieved using either instruments with a larger aperture (i.e. able to collect more photons in a given period of time), or constellations of instruments (see below). These will provide a challenge for instrument engineering and sampling logistics.

10.6 Perspectives for the Improvement of Instrument Technology

We are in the middle of an ongoing revolution in technology for remote sensing; the progress in the miniaturisation of computer and electronic control systems and in the increase of the rate of data transmission and storage will continue to have a major impact on the development of remote sensing.

For passive remote sensing, the performance is usually determined by the detector system, the limit ideally being determined by the shot noise limit. For active remote sensing, the emitter and receivers would both benefit from technical improvements. However, as a result of the strict quality control used in space hardware and the long development time, the equipment used in space is, in fact, surprisingly old fashioned.

The first generations of satellite instruments capable of probing the troposphere from space necessarily had or have deficiencies and limitations, resulting from technical issues, from the lack of sufficient funding and sometimes from limited vision.

Technical issues, such as the polarization sensitivity of the instruments, narrow band spectral structures of the instrument, spectral under-sampling, spectral structures in the reflectivity of the diffuser plate, degradation and icing of instruments in the space environment, are all examples of known problems. Thus an obvious way to improve future instruments would be to address these issues and to avoid, or minimise, the known deficiencies in future designs.

For instruments relying on solar radiation, improved knowledge of the solar spectrum, the Fraunhofer structure and the small but significant variations, is likely to improve the accuracy of data products in these spectral regions.

In the TIR, sub-mm and microwave spectral regions, improved detector technology will undoubtedly result in improved performance. Similarly improved antennae design and constellations of instruments are likely to meet the evolving needs better.

When considering the likely evolution of technology our vision encompasses the following suggestions.

10.6.1 Polarisation Measurements

Instruments having better defined and calibrated polarization sensitivities are needed. These would provide improved information on the atmospheric radiative transfer and potentially add tropospheric profile information for O_3 (Chapter 2). In addition, the observation of the same ground scene under a variety of viewing angles yields improved discrimination of aerosol scattering and surface reflection.

10.6.2 Measurements for Tomographic Reconstruction

For specific atmospheric conditions having strong gradients, tomographic inversion techniques could be applied to resolve vertical structures in trace gas and aerosol distributions, provided the signal to noise ratio is adequate. Tomography has already been successfully applied to multiple measurements made in the upper atmosphere and in some microwave applications. Multiple observation of the same scene in the troposphere, where chemical lifetimes are often relatively short compared to the upper atmosphere, opens the opportunity for tomographic retrievals.

10.6.3 Multi-Wavelength Hyper-Spectral Measurements

For the optimal vertical resolution for troposphere, many trace gases will be observed by combining passive solar and TIR measurements. This will require both improved data sets of atmospheric absorption cross sections and line parameters, and an adequate, consolidated and consistent radiative transfer model for the different spectral regions.

10.6.4 Multi-Instrument Measurements

Modern micro-optical techniques permit the development of instruments consisting of multiple identical units (e.g. spectrometers or interferometers), each one observing a particular direction or wavelength interval. These would appreciably improve the signal to noise ratio.

10.6.5 Microwave and Sub-mm Spectral Region

One important potential growth area is the new cooled superconductor-insulator-superconductor receivers (SIS) which have the potential to yield measurements with dramatically improved precision and spatial resolution (Chapter 4).

10.6.6 Active Systems

Active remote instruments for trace gas measurements offer the advantage of good vertical resolution (see Section 1.11.2). For aerosol, improved vertical resolution is achieved by evolving the lidar space based systems. DIAL (Differential Absorption lidar) systems are capable of measuring and mapping concentrations and mass emissions of various molecules in the lower atmosphere from the ground upwards. Instruments such as CALIOP need to be extended to multi-wavelength observations. DIAL may also yield tropospheric trace gas observations with unprecedented vertical resolution, albeit with reduced spatial coverage. These techniques for trace constituents are promising for a selected number of gases but probably not generally applicable. Radar systems are being, and will be further, improved to provide better cloud parameters and precipitation measurements. However an adequate constellation of instruments is required to provide global observations for predictive purposes.

10.7 Current and Future Planned Missions

The diagrams in Appendix D give time lines for the various present and accepted future missions to study tropospheric gases and aerosols. The time lines present the information in terms of the tropospheric species being studied, divided into three groups: reactive gases, greenhouse gases and aerosols. Each of these is divided into nadir, occultation and geostationary observations. The diagrams can be used to gauge the likely extent of coverage in the future and highlight the unfortunate gaps that seem likely to develop.

10.7.1 LEO Satellite Instruments

The current generation of NASA low earth orbit research satellites having tropospheric capability comprises the large platforms, such as Terra, Aqua and Aura, coupled with the other smaller missions participating in the A Train. These and the European earth observation satellite, ENVISAT were conceived in the mid-1980s and challenged the engineering experience of the day. Since this time, focussed parts of these missions are being evolved into operational missions by EUMETSAT and NPOESS. The latter system was planned to monitor a wide range of parameters in Earth observation and provide data for long-range weather and climate forecasts. Unfortunately, as a result of cost overruns, a significant fraction the instrumentation aimed at tropospheric remote sounding, has been reduced in scope.

The EUMETSAT ESA MetOp satellite series is the first of the European operational meteorological satellites in low earth orbit. It was initiated with the launch of MetOp A in late 2006 and is planned to measure up to about 2020. MetOp includes the instruments GOME-2, IASI, and AVHRR, which yield concentrations of tropospheric trace constituents. EUMETSAT and ESA are now planning the post-MetOp platforms and payloads to make measurements in the 2020–2030 period. For tropospheric remote sensing of trace constituents, two instruments, UV/vis/NIR sounding mission (UVNS), and the infrared instrument (IRS) are relevant. UVNS builds on the heritage of SCIAMACHY and GOME and has been funded, as the GMES Sentinel 5, through an EU contribution to ESA and EUMETSAT. The IRS builds on the IASI heritage. Instruments for cloud and aerosol parameters such as the visual infrared imager (VII) and multi-channel, multi-viewing, multi-polarisation imager (3MI) are also proposed. VII and 3MI build on the heritage of MERIS and POLDER. ESA has initiated a Sentinel 5 precursor mission, which will have an OMI and an IR instrument focused on CO measurements.

10.7.2 GEO Satellite Instruments

In order to measure air quality, high spatial and temporal measurements are needed, which yield the changing composition of the planetary boundary layer. Geostationary measurements provide high sampling and maximise the number of cloud free scenes for a given spatial resolution.

Sir Arthur C. Clarke's 1945 prediction in the *Wireless World* magazine about the possibility and value of geostationary satellites became reality in 1965 with the launch of INTELSAT I *Early Bird,* the first commercial geostationary communication satellite. The use of GEO orbits for communications and satellite television has blossomed since then. The usefulness of GEO for operational meteorology was recognised in 1974 with the US Synchronous Meteorological Satellite (SMS-1) which became the first operational meteorological geostationary satellite. In 1977 a global system was established with the Japanese Geostationary Meteorological Satellite (GMS-1) and European Meteosat-1. Later EUMETSAT took operational control of the European Meteosat second generation satellites: MSG-1 came into operational service in 2004.

GEO offers a number of possibilities for tropospheric sounding. The fate of most short-lived atmospheric trace constituents and pollutants is regulated by the diurnal cycle of day and night and these crucial variations are lost in single LEO measurements. The smaller signal intensity at the distance of the GEO orbit can be compensated for with larger optics and some signal integration. The principal advantages of GEO instrument platforms are the high temporal coverage and the relatively high probability of observations under cloud free conditions for a given spatial resolution.

A number of proposals to make tropospheric constituent measurements from geostationary orbits have been made by the scientific community.

- Krueger and colleagues (NASA) proposed a geostationary satellite to observe the volcanic ring of fire using a TOMS like instrument aimed at SO_2 and O_3.
- Fishman and colleagues (NASA) proposed the measurement of O_3 and CO in the GeoTropSat initiative in the middle of the 1990s (Little et al. 1997).
- The Geostationary Imaging Fourier Transform Spectrometer (Smith et al. 2006) has been proposed for trace gas measurements primarily aimed at parameters for NWP.

- In Europe the GeoSCIA and GeoTROPE initiatives and proposals were evolved between 1997 and 2004 (Bovensmann et al. 2002; 2004; Burrows et al. 2004). GeoTROPE was planned to combine a SCIAMACHY-like instrument, GeoSCIA, with an IASI-like FTIR instrument, GeoFIS, to make simultaneous measurements from a geostationary orbit.

Although these various proposals clearly indicated the advantages of measuring air quality from a geostationary orbit and provided an impetus for such an initiative, they were not accepted by the agencies at that time.

However ESA and EUMETSAT are now currently preparing the third generation of Meteosat, which comprises two three-axis stabilized platforms, to be launched in between 2015 and 2018. This has been incorporated in the GMES programme (http://www.esa.int/esaLP/SEM3ZT4KXMF_LPgmes_0.html). As a result, the GMES Sentinel 4, which has its heritage in the GeoSCIA concept and the later EUMESAT initiatives to build on this concept, has been selected to fly as part of MTG. Sadly, cost considerations, rather than scientific goals and operational services, seem to be restricting its measurements to Europe rather than Europe and Africa, as proposed for GeoSCIA. This will fly together with an infrared spectrometer, which has some capability for trace gases but is primarily aimed at the provision of parameters for NWP. This combination is approaching the objective of GeoTROPE.

NASA, as part of the NRC Decadal Study, has proposed a GeoCAPE mission (Fishman et al. 2008; NRC 2007). This builds on the GeoTROPSAT and GeoTRACE initiatives and will make measurements similar to GMES Sentinel 4. Recently the JAXA has announced plans for a GEO mission, similar in intention to and building on the GeoSCIA concept. South Korea is also considering a similar mission. The various missions are not aimed at the full Earth disc measurements, principally to minimise cost; this strategy seems likely to be a mistake.

Overall one hopes that the future, envisaged in the IGOS/IGACO strategy (IGACO 2004) and the GeoSCIA initiatives, will be realized with a network of geostationary satellites coupled with similar LEO instruments (Section 10.8). Such a system would provide optimal spatial and temporal sampling for many short lived tropospheric gases (Appendix D).

10.7.3 Greenhouse Gases

A recent achievement is the measurement of the dry columns of the greenhouse gases CO_2 and CH_4 which were shown to be feasible by SCIAMACHY and IASI measurements (Sections 8.2.8 and 8.2.9). The JAXA GOSAT, a dedicated CO_2 and CH_4 platform, was launched in 2009 and data products are now becoming available. A new flight opportunity is available for a second OCO after the failure of launch of the first OCO. However, under current planning, all these experiments will finish around 2015 and, in spite of the recognised need for highly accurate measurements of the two most important long lived greenhouse gases, no follow-on missions have been approved, although CarbonSat mission and CarbonSat constellation have been proposed to meet the need.

An active mission ASCENDS is being considered by NASA, but the proposed active European mission ASCOPE has not been selected. It appears therefore that long lifetime space based laser missions are considered too challenging at the present time. A Franco-German mission MERLIN for the active measurement of CH_4 by DIAL from space is in pre-phase A.

In conclusion, as pointed out by the GMES Working Group 4, there is a clear gap in the measurement of CO_2 and CH_4 after 2014 and there is a need for new and improved measurements of dry columns of greenhouse gases (Appendix D).

10.7.4 Observations from the Lagrange Point

Also being considered by NASA is the resurrection of The Deep Space Climate Observatory (DSCOVR), previously called Triana. DSCOVR was intended to exploit the unique observation opportunities at the Earth's L1 Lagrangian point, at a distance of 1.5 million kilometers, to observe the Earth. At this location a continuous view of the sun-lit side of the Earth yields full diurnal coverage. Although the satellite was constructed nearly 10 years ago, it has been in storage since then. It is now hoped that it will be allocated a launch vehicle in the near future.

10.8 Future Monitoring of the Troposphere from Space

An essential application of trace gas measurements from space will be the continuous monitoring of tropospheric pollution levels by satellite instruments, which, like today's meteorological satellites, would provide maps of the *chemical weather*. To achieve this goal, the frequency of measurements at any point on the Earth has to be increased from once every one to three days, to perhaps a measurement every 1–2 h. Global observation, which would have an adequate temporal resolution of the order of 15–30 min, could be achieved in several ways.

1. The deployment of a number of smaller satellites in polar orbit that pass over any point on the Earth following each other in a determined temporal pattern (see Fig. 10.2).
2. The deployment of an instrument in a GEO orbit (Fig. 10.3) yields the diurnal variation of the atmospheric composition over about one third of the Earth's surface from a single satellite. Three such satellites, positioned appropriately, would be sufficient to observe the entire globe.
3. The large distance of the GEO orbit to the earth of about 36,000 km, compared to ~800 km for LEO, can be compensated for by somewhat larger optics. Also the time for observation is much longer in GEO than in LEO and offers the

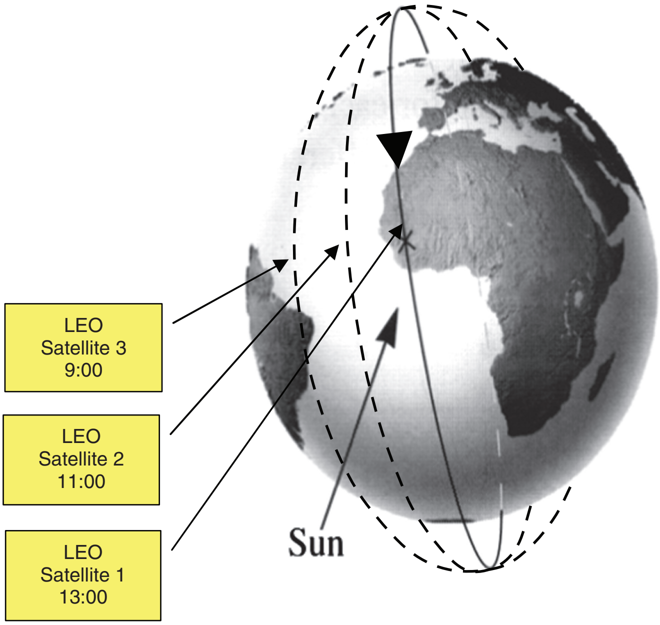

Fig. 10.2 A series of LEO satellites on sun-synchronous (low earth) orbits with suitably staged equator crossing times can provide diurnal profiles and global coverage at the same time. Compared to satellites in geostationary orbits the global coverage of polar regions would be excellent.

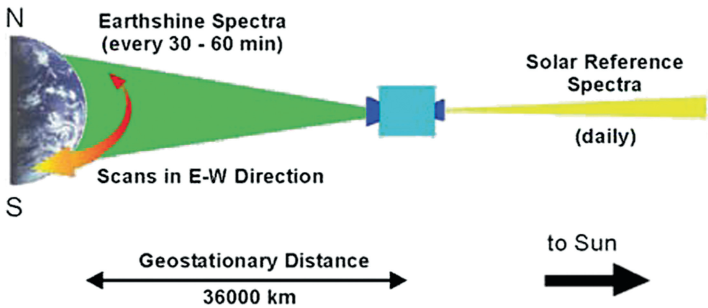

Fig. 10.3 Orbiting the Earth once a day, a GEO satellite maintains a constant position above a point on the Earth's surface. A complete scan of the viewed portion of the Earth's surface would be made every 30 min or so. The GEO altitude (~36,000 km) contrasts with that of the normal LEO satellites at ~800 km above the Earth. Figure: J.P. Burrows and S. Noel, IUP, Bremen.

possibility of time averaging to improve the signal/noise ratio. Several missions are now being considered as described above.

4. Placing a satellite in a halo orbit around the first Lagrange point, L1, about 1.5 million km above the Earth surface, is an interesting possibility. The optical requirements (see point 2, above) are still more demanding than for a geostationary

satellite instrument. DSCOVR, mentioned above, may be the first L1 instrument; however more capability is required that that envisaged in the old design.

In summary, a network of *chemical weather* satellites is needed to measure and monitor our changing environment. The increasing world population will have an increasing thirst for energy, so that an adequate system is required within the next decade. Such a system will be required for the foreseeable future to test our knowledge of the Earth system and its response to anthropogenic activity, the impact of international legislation aimed at achieving sustainable development.

10.9 Conclusions

This book, which has been made possible by the ACCENT project and TROPOSAT scientific community, provides the reader with the information required to understand the remote sensing of tropospheric constituents in the Earth's atmosphere from space. It describes some of the remarkable scientific and technical developments in the emerging scientific area of remote sensing of tropospheric composition that have been achieved in the last three decades.

Less than a generation ago, the global observation of tropospheric trace constituents by remote sensing was considered impossible. Now a set of research instruments and the first operational instruments are demonstrating the benefits for Earth science, and are providing the evidence for the development, monitoring, verification and transparency of international environmental policy.

The evolution of global observing capability for the troposphere has required a rapid development of instrument concepts, atmospheric radiative transfer and retrieval theory, by the scientific community. The new data has expanded our understanding of the biogeochemical processing of the Earth system, and the new capabilities provide the evidence needed to identify and assess the impact of natural processes and anthropogenic activity.

One challenge for the future of tropospheric remote sensing is the logistics of coordinating multiple simultaneous remote sensing and *in situ* measurements to provide useful data products. Such information has strategic importance as the Anthropocene develops.

The operational meteorological agencies, which established the need for NWP, provide a valuable model. A similar approach and commitment is needed to address the needs of environmental remote sensing, which focuses on the identification and quantification of environmental and climate change. This investment has been lacking up to now.

The variety of international initiatives including IGOS and GEO, have been developed to stimulate the satellite missions needed and there is general agreement that more missions are needed. However the rate of generation of new and focussed missions does not meet the need, as the timelines in Appendix D show. NPOESS has aspirations with respect to providing the space segment of instrumentation for both

NWP and numerical environmental prediction. Similarly EUMETSAT includes both NWP and climate. However, in practice, budgets for these organisations are limited and NWP currently dominates the priorities for missions. More resources are needed for the scientific and technological aspects in order to achieve a focussed global measurement strategy that is fit for purpose, such as the GMES space segment for MACC (Monitoring Atmospheric Composition and Climate).

The space agencies and industry are successful but they are expensive: their mandates, given by national governments, often focus on support for improving the national technological infrastructure rather than on clear scientific or policy objectives. In addition the creation of the necessary administrative structure has an appreciable financial overhead.

Scientific understanding and exploitation is the key to the overall development and use of Earth observation but, unfortunately, it is still the poor relative in the overall space programme, despite the undoubted nature of the deleterious effects of the changing atmosphere. Overall governments are to be congratulated on their investments in Earth observation, but only time will tell whether the provision of data will be adequate to meet the future challenges in the detection, attribution and adaptation to global climate change.

The provision of Earth observation, of which the remote sensing of tropospheric composition is a part, is a facet of the greening of the industrial base of key strategic importance and of the knowledge and information revolution. However there is a need for a faster evolution of missions and systems to provide the proper monitoring of the atmospheric environment so that environmental change can be recognised soon enough to take any necessary action. New missions would yield data products which monitor both the health of the environment and its ecosystems as well as the pollution. They would further enhance our understanding of the Earth system and improve the predictive capability of our models. The data products from such missions would provide the evidence needed for the monitoring, reporting, verification and transparency of international environmental agreements.

The scientific community has shown the leadership by initiating the evolution of Earth observation instrumentation in the field of tropospheric composition. This would not have been possible without massive public investment in the infrastructure. We are convinced that the scientific community will continue to propose missions, which not only challenge our understanding of the atmospheric composition but also provide the evidence that the Earth is being managed successfully. Hopefully the space agencies supported by government will continue to facilitate these visions and improve our knowledge of environmental change, thereby supporting sustainable economic development.

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