1. SCIAMACHY – The Need for Atmospheric Research from Space

The recognition, that significant changes in the composition of the Earth's atmosphere are occurring on both short and long timescales and thereby modifying our environment and climate, has resulted in scientific debate as well as public concern, and emphasises the need for global measurements of atmospheric constituents at representative spatial and temporal sampling. Established examples, where change has been identified, are:

- the precipitous loss of Antarctic and Arctic stratospheric ozone (O_3) resulting from the tropospheric emission of chlorofluorocarbon compounds (CFCs, halones and HFCs) (*WMO 2003*),
- the global increase of tropospheric O_3 (*WMO 1995*) and its impact on air quality,
- the trans-boundary transport and transformation of pollution resulting for example in acidic deposition and impacting air quality far from pollution sources (*WMO-IGACO 2004*),
- global dimming attributed to changes in aerosol and clouds (*Wild et al. 2005*),
- the observed increase of tropospheric greenhouse gases such as CO_2, CH_4, N_2O and O_3 and its impact on climate change (*IPCC 2001*), and
- the coupling between stratospheric ozone loss and increased greenhouse gas concentrations (*Shindell et al. 1998*).

In order to assess the significance of such changes a detailed understanding of the physical and chemical processes controlling the global atmosphere is required. The accurate assessment of the impact of current and future anthropogenic activity or natural phenomena on the behaviour of the system, comprising the atmosphere and the Earth's surface, requires quantitative knowledge about the temporal and spatial behaviour of several atmospheric trace constituents (gases, aerosol, clouds) from the local to global scales in the troposphere, stratosphere and mesosphere. These data sets are also needed to test the predictive ability of the theories currently used to model the atmosphere. The SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY, 'SCIAMACHY' is a Greek expression, which means *chasing or hunting shadows* and is equivalent to do the impossible task) as part of the atmospheric chemistry payload on-board the Environmental Satellite (ENVISAT) of the European Space Agency ESA was conceived to make a significant contribution to the required data sets and the understanding of climate change.

1.1 How can we study the Earth's Atmosphere from Space?

Prior to the advent of space flight, measurements of atmospheric composition were limited in geographical coverage. The development of satellite platforms in low-Earth and geostationary orbit over the last three decades has provided the opportunity to observe the Earth and its atmosphere in novel viewing geometries. The potential to make near simultaneous observations at the global scale for the first time has facilitated the emergence of *Earth System Science*. In particular the atmospheric sciences have gained from satellite observations. This is because remote regions of the atmosphere over the land and oceans, where ground-based stations or ship-borne measurements are usually rare, can now be probed regularly from space and variations of geophysical parameters on small and large scales, both spatially and temporally, can be studied.

Passive atmospheric sounding from space can be achieved in two ways – either by analysing *absorption* or *emission* spectra, both requiring accurate measurement of radiation leaving the top of the atmosphere. Absorption and emission processes in the atmosphere produce spectra, which are characteristic for the emitting or absorbing atom or molecule.

Emission spectra consist of the signals from atmospheric constituents which radiate mainly in the infrared and microwave spectral range according to their characteristic thermal excitation. They can be regarded as the thermal 'fingerprint' of the atmosphere. From the emission line properties trace gas concentrations are derived.

Measuring *solar absorption spectra* at the top of the atmosphere is the approach utilised in SCIAMACHY. Atoms, molecules and particles absorb, emit and scatter the incoming solar electromagnetic radiation. The incoming solar radiation is described to a good approximation by the emission from a black body having a temperature of about 5800 K, modulated by atomic absorption lines, the solar Fraunhofer lines. The upwelling radiation at the top of the atmosphere from the Ultraviolet (UV) to Short-Wave Infrared (SWIR) comprises – after travelling through the atmosphere – the solar output, modified by scatter-

ing, absorption and emission processes along its light path through the atmosphere and reflected as well as scattered at the Earth's surface (details see chapter 7).

The SCIAMACHY project has from its outset the aim to utilise all the information contained in the radiation upwelling from the atmosphere to space in order to derive the amounts and distributions of atmospheric constituents, parameters and selected surface phenomena. This task requires – beside high quality measurements – an accurate understanding and knowledge of the absorption spectroscopy and the scattering of electromagnetic radiation in the atmosphere and at the Earth's surface.

1.2 The Road to SCIAMACHY

Recognising the need for global observations of the Earth system, the scientific community has proposed for research and monitoring purposes global observing systems. Over the past three decades pioneering efforts have been made by the scientific community to establish networks of ground based instruments and satellite projects. The overall objectives are

- to improve our understanding of the physical and chemical processes determining the behaviour of the atmosphere,
- to demonstrate and assess the capability and applicability of remote sensing from space for Earth System and Atmospheric Science, and
- to move towards a global observing system adequate to meet the needs of Earth System Science and to provide the global data needed for policymakers.

The first measurements of atmospheric ozone from space were made by the Soviet space program in the middle of the 1960's. In the early 1970's NASA initiated its efforts to make global measurements of atmospheric ozone with the Backscattered Ultra Violet (BUV) instrument aboard the NASA Nimbus 4 satellite. This instrument was significantly enhanced and extended to both the Solar Backscatter Ultraviolet (SBUV) and Total Ozone Mapping Spectrometer (TOMS), which flew on NASA's Nimbus 7 satellite. Subsequently NOAA was responsible for a series of SBUV-2 instruments on its operational meteorological platforms while NASA operated several TOMS instruments on a variety of satellites (see figure 1-1). Useful solar occultation measurements began in 1978 with the launch of SAM-II (Stratospheric Aerosol Measurement) which was followed by the Stratospheric Aerosol and Gas Experiment (SAGE-I, SAGE-II) and the Russian occultation spectrophotometer SFM-2. The research mission SME (Solar Mesospheric Explorer), launched in 1983, made limb scanning measurements of solar backscattered radiation to determine ozone and nitrogen dioxide. Another milestone in the exploration of the atmosphere from space is the Upper Atmosphere Research Satellite (UARS), which carried instruments to sound the upper atmosphere like the Microwave Limb Sounder (MLS) and the Halogen Occultation Experiment (HALOE). UARS was launched in 1991 and the measurements of HALOE were extended into 2005.

The European participation in remote sounding of atmospheric constituents and parameters was focused initially on the development of the geostationary METEOSAT programme. Initiated by ESA and finally transferred to EUMETSAT, it provided measurements of meteorological parameters. While the first polar orbiting European Research Satellite (ERS-1), primarily a platform for microwave and radar sensors, did not address the needs of the atmospheric chemistry community, the second European Remote Sensing satellite (ERS-2), carrying the Global Ozone Monitoring Experiment (GOME), took Europe a large step forward towards ozone and atmospheric composition measurements. GOME on ERS-2 is a smaller scale version of SCIAMACHY derived from the original SCIAMACHY concept, measuring in nadir viewing geometry the upwelling radiation at the top of the atmosphere between 240 and 793 nm. ERS-2 was launched on April 20th, 1995 into a sun-synchronous orbit with an equator crossing time in descending node of 10:30 a.m. The feasibility of the SCIAMACHY instrument and retrieval concepts could be successfully demonstrated for nadir observations with GOME. The absorptions of the trace gases O_3, NO_2, BrO, OClO, H_2O, SO_2, and HCHO could be observed as predicted and the retrieval of total and tropospheric column information from GOME measurements was achieved (*Burrows et al. 1999* and references therein). In addition, similarly to SBUV, O_3 profiles including some information on tropospheric ozone, were retrieved from GOME observations *(Munro et al. 1998)*.

Recently, several new missions were launched and contribute significantly to research in the fields of atmospheric chemistry and physics: NASA's Earth Observing System (EOS) satellites TERRA, AQUA and AURA, the Japanese Advanced Earth Observing System (ADEOS1/2), the Canadian/Swedish ODIN mission and ESA's ENVISAT.

SCIAMACHY is part of the atmospheric chemistry payload on-board ENVISAT. As described in more detail in chapter 1.4, following the call for Earth

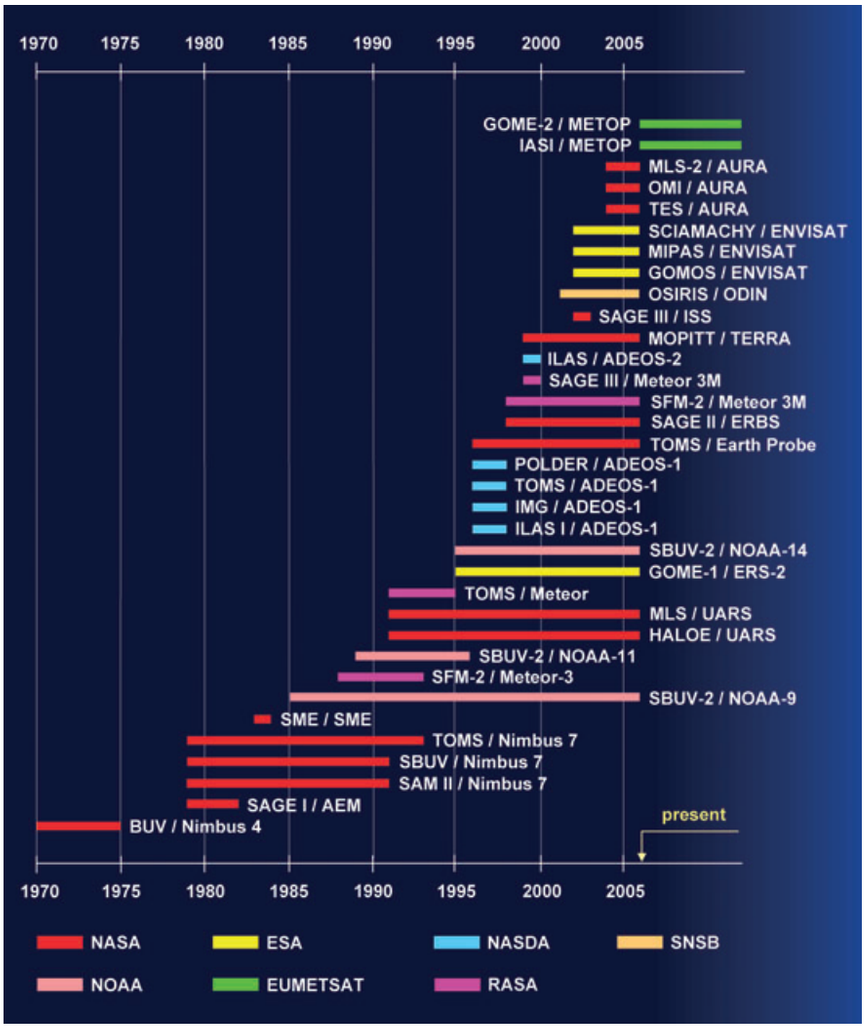

Fig. 1-1: Atmospheric science space-borne instruments and missions since 1970 with relevance for SCIAMACHY. The list of missions is not intended to be complete but to illustrate the progress in space borne instrumentation for atmospheric composition monitoring. (graphics: DLR-IMF)

Observation instrumentation in the Announcement of Opportunity for the Polar Platform issued by ESA, the SCIAMACHY proposal was – after peer review – selected as part of the payload for the satellite now known as ENVISAT, which was launched in March 2002.

The heritage of the SCIAMACHY instrument lies in both, the ground based measurements using Differential Optical Absorption Spectroscopy (DOAS) and previous satellite atmospheric remote sensing missions like SBUV, TOMS, SME and SAGE. SCIAMACHY combines and extends the measurement principles and observational modes of the nadir scattered sunlight recording instruments SBUV and TOMS, the solar occultation instrument SAGE and the limb scattered sunlight measuring instrument SME within one instrument. SCIAMACHY observes in the wavelength range from 214-2386 nm

- the scattered and reflected spectral radiance in nadir and limb geometry,
- the spectral radiance transmitted through the atmosphere in solar and lunar occultation geometry,
- the extraterrestrial solar irradiance and the lunar radiance.

Limb, nadir and occultation measurements are made during every orbit. Trace gases, aerosols, clouds and the surface of the Earth modify the light observed by SCIAMACHY via absorption, emission and scattering processes. Inversion of the radiance and irradiance measurements allows retrieval of the amounts and distributions of a significant number of constituents from their spectral signatures.

1.3 Determining Impacts on the Earth's Atmosphere

SCIAMACHY's Goals

The main objectives of the SCIAMACHY mission are to improve our knowledge of global atmospheric composition, its change in response to both natural and anthropogenic activity and the processes associated to it as well as the related global issues of importance to the chemistry and physics of our atmosphere such as:

- the impact of anthropogenic activity and natural processes on tropospheric ozone, air quality and global warming,
- exchange processes between the stratosphere and troposphere,
- the interaction of stratospheric chemistry and dynamics,
- natural modulations of atmospheric composition resulting from volcanic eruptions, lightning, solar output variations (e.g. solar cycle), or solar proton events.

Instrument	*Name*	*Measurement Height*[1]			*Target Species*	*Observation Geometry*[2]				
		TR	ST	ME		N	L	SO	LO	STO
BUV	Backscatter Ultraviolet Ozone Experiment		X		O_3	X				
GOME-1	Global Ozone Monitoring Experiment	X	X		O_3, NO_2, H_2O, BrO, OClO, SO_2, HCHO; clouds and aerosol	X				
GOME-2	Global Ozone Monitoring Experiment	X	X		O_3, NO_2, H_2O, BrO, OClO, SO_2, HCHO; clouds and aerosol	X				
GOMOS	Global Ozone Monitoring by Occultation of Stars	X[3]	X	X	O_3, NO_2, H_2O, NO_3; aerosol, T					X
HALOE	Halogen Occultation Experiment		X		CO_2, H_2O, O_3, NO_2, HF, HCl, CH_4, NO			X		
IASI	Infrared Atmospheric Sounding Interferometer	X[3]	X		O_3, H_2O, CO, CH_4, N_2O; T	X				
ILAS I, II	Improved Limb Atmospheric Spectrometer		X		O_3, NO_2, N_2O, H_2O, CFC11, CH_4; aerosol			X		
IMG	Interferometric Monitor for Greenhouse Gases	X	X		O_3, N_2O, H_2O, CH_4, CO, CO_2	X				
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding		X	X	O_3, NO_x, N_2O_5, $ClONO_2$, CH_4, CFCs, HNO_3, etc.; T and P		X			
MLS	Microwave Limb Sounder		X	X	ClO, O_3, H_2O, HNO_3; T and P		X			
MLS-2	Microwave Limb Sounder		X	X	CO, HCl, ClO, O_3, H_2O, BrO, N_2O, SO_2, HCN, CH_3CN		X			
MOPITT	Measurement of Pollution in the Troposphere	X			CO, CH_4	X				
OMI	Ozone Monitoring Instrument	X	X		O_3, SO_2, NO_2, HCHO; aerosol	X				
OSIRIS	Optical Spectrograph and Infra-red Imager System		X	X	NO, OClO, O_3, NO_2; aerosol		X			
POLDER	Polarisation and Directionality of the Earth's Radiance	X			H_2O; polarisation, aerosol, clouds	X				
SAGE I	Stratospheric Aerosol and Gas Experiment		X		O_3, NO_2; aerosol			X		
SAGE II	Stratospheric Aerosol and Gas Experiment		X		O_3, NO_2, H_2O; aerosol			X		
SAGE III	Stratospheric Aerosol and Gas Experiment		X		O_3, OClO, H_2O, BrO, NO_2, NO_3; aerosol			X	X	
SAM II	Stratospheric Aerosol Measurement		X		aerosol			X		
SBUV	Solar Backscatter Ultraviolet Ozone Experiment	X	X		O_3	X				
SBUV-2	Solar Backscatter Ultraviolet Ozone Experiment	X	X		O_3	X				
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography	X	X	X	O_3, O_2, $O_2(^1\Delta)$, O_4, NO, NO_2, N_2O, BrO, OClO, CO, H_2O, SO_2, HCHO, CO, CO_2, CH_4; cloud, aerosol	X	X	X	X	
SFM-2	Spectrophotometer		X		O_3; aerosol			X		
SME	Solar Mesospheric Explorer		X	X	O_3, $O_2(^1\Delta)$, NO_2		X			
TES	Tropospheric Emission Spectrometer	X	X		HNO_3, O_3, NO, H_2O, CH_4, CO, SO_2	X	X			
TOMS	Total Ozone Monitoring Spectrometer	X	X		O_3, SO_2; aerosol	X				

[1]ME = mesosphere, ST = stratosphere, TR = troposphere / [2]N = nadir, L = limb, SO = solar occultation, LO = lunar occultation, STO = stellar occultation / [3]upper troposphere

Table 1-1: The different passive satellite instruments designed to determine trace gas distributions in the atmosphere, coverage of their measurements, species measured and the satellite platform. The list of sensors refers to fig. 1-1.

Subject	*Parameter from SCIAMACHY Data*	*Application Areas*
Surface	spectral surface albedo, UV A/B, chlorophyll content	– Earth radiative budget – ocean biology – spectral surface characteristics
Troposphere (*incl. Boundary Layer*[1])	columns of O_3, NO_2, BrO, SO_2, HCHO, CHOCHO, H_2O, CO, CO_2, CH_4, clouds, aerosol, actinic flux	– transport and transformation of pollutants including air quality – tropospheric ozone and oxidation potential – carbon budget – quantification of emissions – climate-chemistry interaction
Tropopause Region	concentrations of O_3, NO_2, H_2O, CO, CH_4 Clouds, thermodynamic phase of clouds	– transport processes in the tropopause region – water budget, including ice clouds – impact of aviation on climate – climate-chemistry interaction
Stratosphere	profiles of O_3, NO_2, BrO, OClO, H_2O, aerosol, Polar Stratospheric Clouds	– development of the ozone layer – climate-chemistry interactions – solar-terrestrial interactions
Mesosphere	profiles of O_3, NO, OH, metal ions, temperature, Polar Mesospheric Clouds	– climate-chemistry interactions – solar-terrestrial interactions
Top of the Atmosphere	Earth spectral reflectance	– Earth radiative budget
Sun	spectral solar irradiance, Mg-Index (solar activity)	– Earth radiative budget – solar-terrestrial interactions – solar physics

[1]sensitivity to boundary layer dependent on surface albedo, cloudiness and aerosol loading

Table 1-2: Summary of parameters to be derived from SCIAMACHY and the relevant application areas.

To achieve these goals, SCIAMACHY was proposed to deliver a multitude of parameters characterising the system *Earth-Atmosphere-Sun*, especially key trace gases and parameters in the troposphere and stratosphere. The following gases were targeted for measurement: O_2, O_3, O_4, NO, NO_2, NO_3, CO, CO_2, HCHO, CH_4, H_2O, N_2O, SO_2, BrO, OClO. The combined use of nadir and limb observations yields tropospheric amounts of the constituents down to the ground or cloud top depending on cloud cover. In addition to the trace gases, information on clouds (cloud top height, cloud optical thickness, ice-water cloud discrimination) and aerosol can be deduced from the SCIAMACHY measurements. Particularly interesting, among these, are Polar Stratospheric Clouds (PSC) and Noctilucent Clouds (NLC), also referred to as Polar Mesospheric Clouds (PMC).

Table 1-2 summarises the parameters to be derived from SCIAMACHY measurements and their application areas while the succeeding chapters provide detailed descriptions of the associated scientific problems. It is expected that the data sets obtained by SCIAMACHY can significantly contribute to the quantification of the complex interactions between natural and human activities, climate, atmospheric composition, and the relevant chemical and physical processes.

The Atmospheric Layers

The Earth's atmosphere is a complex system comprising a set of layers, which differ in their temperature gradient with respect to altitude. Figure 1-2 shows typical temperature and pressure profiles for mid-lat-

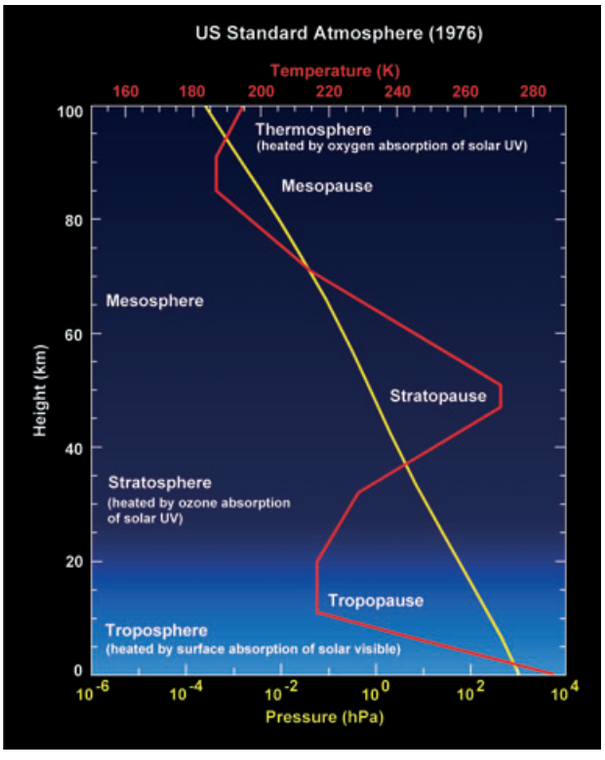

Fig. 1-2: Atmospheric pressure and temperature profiles for mid latitudes (US Standard Atmosphere).

itudes. The rate of temperature change in the atmosphere as a function of height can be used to define regions of positive and negative gradient or lapse rate. Starting at the Earth's surface, the temperature decreases up to the region known as the tropopause. The latter separates the troposphere, which is vertically well mixed, from the stratosphere, which is characterised by slow vertical mixing. In the stratosphere the temperature increases from the tropopause to the stratopause, which separates the stratosphere from the mesosphere. In the thermosphere, above the mesosphere, the temperature increases again.

The increase in temperature in the stratosphere results mainly from the absorption of solar radiation between 200-300 nm by the stratospheric ozone layer. In the thermosphere a different but related mechanism results in a temperature increase, caused by the absorption of short wavelength solar radiation typically below 200 nm by molecules, atoms and ions. The temperature of the thermosphere is modulated significantly by the solar cycle.

The pressure of the atmosphere is highest at the Earth's surface and decreases with height according to the barometric formula. The height of the tropopause varies between about 8 km at the poles and 16 km in the tropics. The stratopause occurs at typically about 45-50 km and the mesopause typically at 85-90 km. Between 80 and 90% of the atmospheric mass are contained within the troposphere. The troposphere and stratosphere contain over 95% of the mass of the atmosphere.

Anthropogenic Impact on the Earth-Atmosphere System

The composition of the Earth's atmosphere is different from that of neighbouring planets such as Mars and Venus, which are apparently lifeless. Fossil records indicate that the atmosphere evolved to its present composition as a result of life. The atmospheric increase of the concentration of molecular oxygen since several billion years indicates that it resulted from photosynthesis after the appearance of life (e.g. *Wayne 1992*). With the formation of a sufficiently thick ozone layer harmful short wave radiation became attenuated so that life could spread over the Earth's surface, initially in the oceans still requiring the protecting environment of water, later also on land. According to the *Gaia hypothesis* the biosphere has played an important role in determining the composition of the atmosphere since life on Earth began (*Lovelock 1979*). This hypothesis also suggests that the biosphere maintains favourable conditions for life on Earth. On geological timescales the impact of anthropogenic activities on the atmosphere has been of minor significance. However, since the onset of the industrial revolution at the end of the 18th century land use, energy and food requirements for the increasing human population have risen dramatically with the consequence of severe impacts on the Earth environment, especially to the Earth's atmosphere. Examples relating to significant modifications of the Earth's atmosphere include (after *Crutzen and Stoermer 2000*):

- Within a few generations fossil fuels that were generated over several hundred million years have been exhausted. The release of SO_2, globally about 160 Tg/year into the atmosphere by coal and oil burning, is at least two times higher than the sum of all natural emissions, occurring mainly as marine dimethyl-sulfide from the oceans.
- 30-50% of the land surface has been transformed by human activities; more nitrogen is now fixed synthetically and applied as fertilizer in agriculture than is fixed naturally in all the terrestrial ecosystems.
- The escape into the atmosphere of CO and NO_x from fossil fuel and biomass combustion likewise is larger than the natural inputs, giving rise to photochemical ozone (smog) formation and degraded air quality in large regions of the Earth.

- Several climatically important greenhouse gases have substantially increased in the atmosphere: CO_2 by more than 30% and CH_4 by even more than 100%, accelerating the radiative forcing. CO_2 and CH_4 are now regulated via the Kyoto Protocol.
- Mankind releases many new and not naturally produced substances into the environment. Some of them, the chlorofluorocarbon gases, have led to the Antarctic *ozone hole* and would have destroyed much of the ozone layer if no international regulatory (Montreal Protocol) measures to end their production had been initiated.

Considering the major and still growing impacts of human activities on the Earth and the atmosphere on global scales, Crutzen and Stoermer proposed to use the term *Anthropocene* for the current geological epoch (*Crutzen and Stoermer 2000*).

The behavior and composition of troposphere, stratosphere and mesosphere are coupled through dynamic, radiative and chemical processes as indicated in figure 1-3. Overall, the conditions experienced by the biosphere at the Earth's surface are determined in a complex manner by the physical and chemical processes occurring in all these regions.

Tropospheric Chemistry

Most gases, like greenhouse gases (CO_2, CH_4, etc.) or pollutants (NO_2, CO, etc.) from natural processes and human activities are emitted into the troposphere. The main source of pollutants in the northern hemisphere are fossil fuel combustion (energy for traffic, industry and domestic heating) coupled with some biomass burning. In the southern hemisphere biomass burning is the dominating source of pollutants. Pollutants are emitted within urban and near-urban areas where they are dispersed over the surrounding countryside and, depending on the atmospheric life-

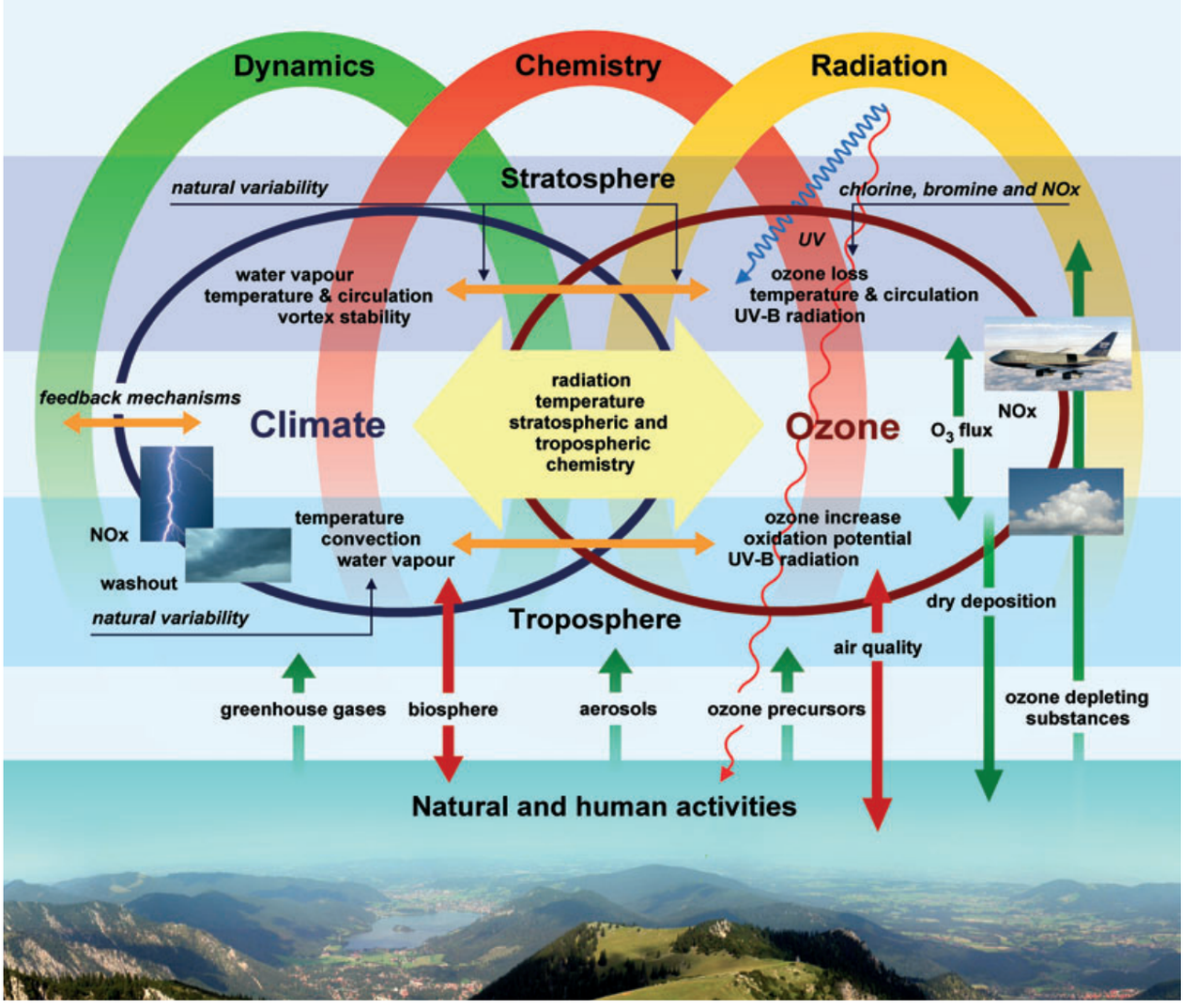

Fig. 1-3: Interactions between human activity, atmospheric composition, chemical and physical processes and climate. (graphics: DLR-IMF, after WMO-IGACO 2004)

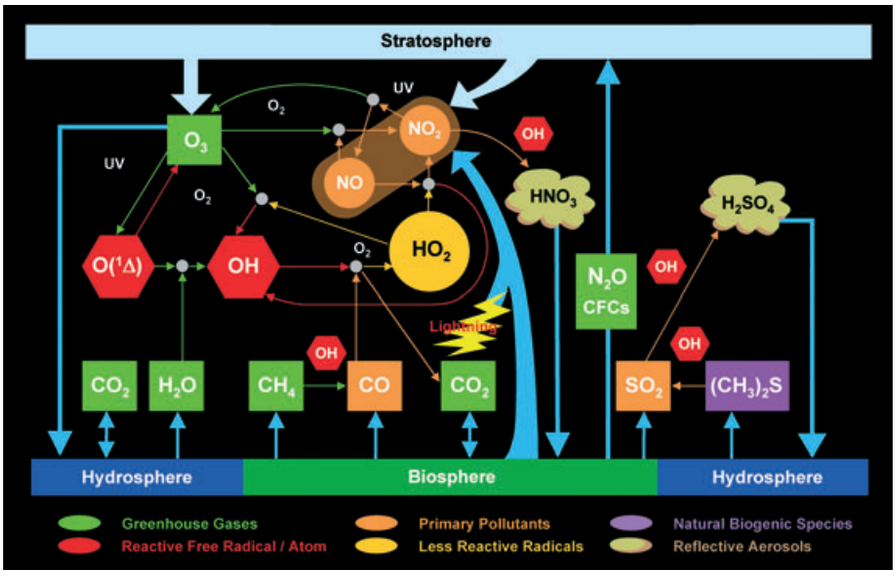

Fig. 1-4: The dominant physical and chemical processes determining the composition of the troposphere. (graphics: WMO-IGACO 2004)

time of the pollutant or its secondary reaction product(s), are transported around the globe.

Tropospheric processes as sketched in fig. 1-4 are well known to exhibit strong variability influenced by meteorology, diurnal variations in the sources of the emissions and solar illumination. Photolysis of O_3 initiates the production of OH that determines, to a large extent, the oxidative (or cleansing) capacity of the troposphere. The role of the halogen oxides in the boundary layer as oxidants is currently a research matter. Many of the tropospheric trace gases are transformed into acids and other soluble products which are removed from the atmosphere by precipitation or by uptake on aerosols and subsequent dry deposition on surfaces. The atmospheric oxidation efficiency is vital in the control of radiatively and chemically active pollutants. Therefore, any change in the atmospheric oxidation efficiency directly affects the air quality, atmospheric chemical and radiative budgets and global biogeochemical cycles.

The lack of information on the temporal and spatial distributions of the relevant species, as well as the source strengths of CO, CH_4 and NO_x (NO and NO_2), severely limits the quantitative understanding of the processes involved in tropospheric ozone production and destruction. This is also a prerequisite for quantitative estimates of the hydroxyl radical distribution and thus of the cleansing power of the atmosphere which is expected to be changing as a result of increasing emissions and resulting concentrations of O_3, CH_4, NO_x and CO. One of the major challenges facing atmospheric science is to assess, understand and quantify the impact on air quality of a changing climate and atmospheric composition.

SCIAMACHY is the atmospheric chemistry sensor on ENVISAT designed to determine the amounts of trace gases and aerosol in the lower troposphere, including the planetary boundary layer. From SCIAMACHY nadir and limb measurements tropospheric columns of O_3, CO, NO_2, BrO, CH_4, H_2O, SO_2 and HCHO are retrieved. In cloud free regions, the tropospheric measurements of SCIAMACHY include the planetary boundary layer. In addition, surface spectral reflectance, aerosol and cloud parameters – cover and cloud top height – and the tropospheric radiative flux from 280-2380 nm will be retrieved. These data are required for studies of the oxidising capacity of the troposphere, photochemical O_3 production and destruction, tropospheric pollution (biomass burning, industrial activities, aircraft), long range transport of pollutants as well as quantification of natural and human emissions.

The Tropopause Region

Exchange of gases and particles between the stratosphere and the troposphere is of importance for the chemical composition of both regions and the atmospheric energy budget in the case of water vapour *(Holton et al. 1995)*. For example downward transport of stratospheric ozone is a source of tropospheric ozone which, as a precursor of OH radicals, to a large extent determines the oxidising power of the troposphere. In the opposite direction upward transport of the precursor molecules (e.g. H_2O, CH_4, CFCs) originating from the planetary boundary layer provides the feedstock for ozone-destroying HO_x, NO_x, BrO_x and ClO_x radicals. For example CH_4 is emitted into the planetary boundary layer. Due to their long tropospheric lifetime molecules are transported to the stratosphere, where they are the dominant source of the ozone-destroying HO_x radicals. An adequate knowledge of the processes that determine stratosphere-troposphere exchange and the distribution of trace gases, especially in the lower stratosphere, is required. Photo-chemically stable gases in the troposphere are useful as tracers for transport of tropospheric air into the stratosphere and for stratospheric dynamics, e.g. CH_4 and H_2O. Similarly,

gases which have relatively high stratospheric but low tropospheric abundances such as O_3, can be used as tracers for downward transport from the stratosphere.

For the investigation of stratosphere-troposphere exchange, SCIAMACHY measurements of the height resolved profiles of O_3, H_2O, CH_4, BrO and NO_2 as well as aerosol will be of primary significance. In addition, SCIAMACHY will deliver information on the thermodynamical phase of clouds, which are important for the water and energy budget especially in the tropical tropopause region. With these measurements investigations of the downward transport of stratospheric O_3 and upward transport of important species (e.g. aerosol, CH_4, H_2O) become possible. In the neighbourhood of the tropopause the different measurement modes of SCIAMACHY will have different vertical and horizontal resolutions. The solar and lunar occultation mode yields measurements with a vertical resolution of 2.5 km and a horizontal resolution of 30 km across track and extending roughly 400 km along track. For the limb measurements the spatial resolution is approximately 3 km vertically and typically 240 km horizontally across track and extending roughly 400 km along track. Therefore studies of relatively small scale features such as tropopause folding at mid-latitudes requiring a high spatial resolution are unlikely to be unambiguously observed by SCIAMACHY. However larger scale stratosphere-troposphere exchange will be readily observed.

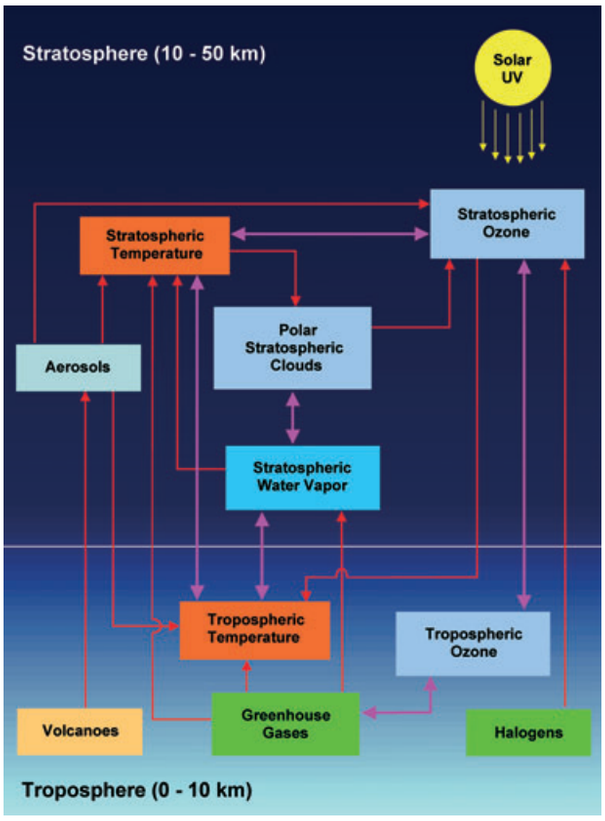

Fig. 1-5: Schematic sketch of the interactions between stratospheric ozone and other atmospheric constituents and processes. Anthropogenic emissions are shown in green while other factors affecting the climate system (e.g., volcanoes) are shown in beige. Red arrows indicate where one species or process affects another. Feedbacks are shown with bold purple lines. For example, decreasing polar stratospheric temperatures increase ozone depletion. Reduced ozone then causes stratospheric cooling, creating a positive feedback. (graphics after: NIWA)

Stratospheric Chemistry and Dynamics

No part of the global environment has been disturbed by human activity as significantly as the stratosphere. In the upper stratosphere and lower mesosphere ozone is removed by catalytic cylces involving halogen oxides. In addition, a very substantial depletion of stratospheric ozone over Antarctica has been observed during springtime since the end of the 1970's. This depletion is largely due to the emission of industrial chlorofluorocarbon gases (*WMO 2003* and references therein). Also over the Arctic a major depletion of stratospheric ozone by about 100 DU (Dobson Units) has become obvious during springtime in the past decade. Surface reactions on liquid aerosols, nitric acid trihydrate (NAT) particles and ice particles are believed – via the activation of chlorine – to be primarily responsible for these changes. International regulatory measures, in the form of e.g. the Montreal Protocol having now been taken to eliminate the production of chlorofluorocarbons by the end of the 20th century *(WMO 1995)*. However the amount of stratospheric chlorine will reach its maximum at the beginning of the 21st century. A first recovery of the ozone layer is expected around 2010 *(WMO 2003)*. The loss of ozone in the stratosphere is also affected, in a synergistic manner, by tropospheric emission of greenhouse gases (see figure 1-5). For example, the anthropogenic tropospheric concentrations of nitrous oxide and methane are increasing, leading to additional formation of stratospheric NO_x and water vapour (H_2O) and potentially enhancing the probability for formation of PSCs. Reactions on these clouds lead to the activation of chlorine radicals that are responsible for the formation of the 'ozone hole'. Thus, even though the stratospheric chlorine content is expected to decline at the beginning of the 21st century, ozone depletion in the lower stratosphere at higher latitudes may not.

Future stratospheric aircraft and spacecraft could emit water vapour and nitric oxide into the stratosphere and, as a result of the introduction of advanced supersonic and hypersonic aircraft, environmental issues may ensue. For example the emissions of addi-

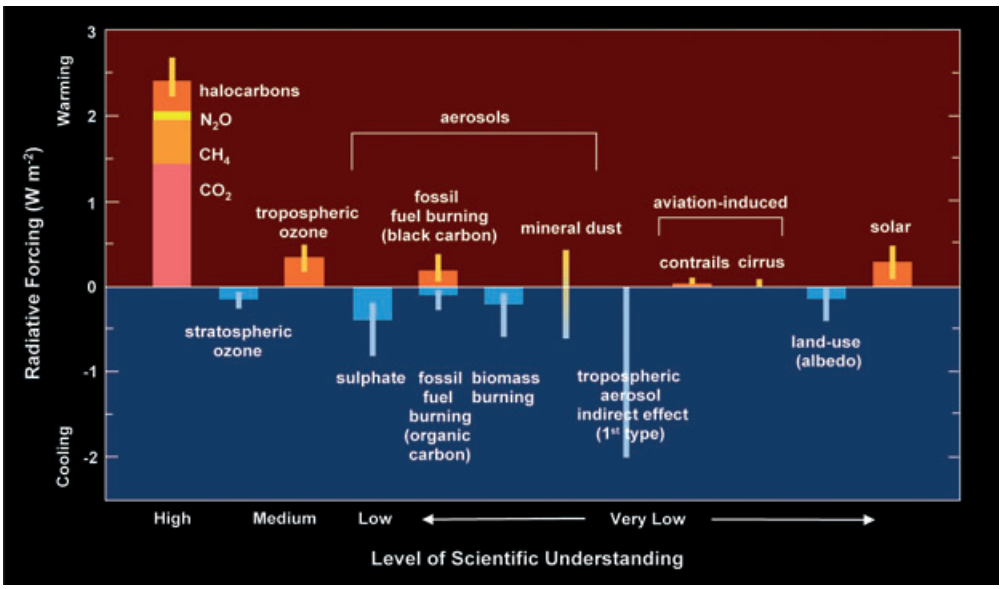

Fig. 1-6: Global, annual mean radiative forcings (Wm^{-2}) due to a number of agents for the period from pre-industrial (1750) to present (late 1990s; about 2000). The height of each box denotes a central or best estimate value while its absence indicates that no best estimate is possible. The vertical bars visualise an estimate of the uncertainty range, for the most part guided by the spread in the published values of the forcing. The uncertainty range specified here has no statistical basis and therefore differs from the use of the term elsewhere in this document. A 'level of scientific understanding' index is associated to each forcing, with high, medium, low and very low levels, respectively. (IPCC 2001)

tional H_2O and NO_x may strongly enhance PSC formation. Improved understanding of stratospheric chemical processes and distributions of trace constituents, including aerosol and PSCs, is essential for environmental assessments of future space and aviation activities.

SCIAMACHY's studies of the stratospheric chemistry and dynamics will utilise the simultaneous retrieval of total columns from nadir measurements and vertical stratospheric profiles from limb and occultation measurements of O_3, NO_2, BrO, H_2O, OClO (under ozone hole conditions), as well as aerosol and stratospheric cloud information. SCIAMACHY is intended to make measurements when halogen loading of the stratosphere maximises at the beginning of the 21st century. In general, SCIAMACHY observations will yield detailed information about the development of stratospheric O_3 above the Arctic and Antarctica, the global stratospheric active halogen species (BrO, OClO), and the global O_3 budget as a function of the height in the atmosphere. Thus the SCIAMACHY data set may allow testing of the accuracy of current stratospheric models and their predictive capabilities.

Mesospheric Chemistry and Dynamics

The mesosphere extends from the temperature maximum at the stratopause around 50 km altitude to the atmospheric temperature minimum at the mesopause around 85 km. There has been much discussion of upper stratospheric and mesospheric chemistry in the context of the *Ozone Deficit Problem* (*Crutzen at al. 1995, Summers et al. 1997*). It has also been suggested that monitoring of H_2O in the lower mesosphere may offer an opportunity for the early detection of climate change *(Chandra et al. 1997)*. Satellites have provided some data about mesospheric temperatures and the temporal and spatial distributions of O_3. In this context, little is known about the global dynamics and chemistry. It is expected that the growth in atmospheric CH_4 will lead to an increase in mesospheric H_2O concentrations which might also result in enhanced PMC formation around 85 km.

In the upper stratosphere and lower mesosphere, SCIAMACHY measurements yield profiles of temperature, O_3, NO, and $O_2(^1\Delta)$ as well as data on PMCs. These measurements can be used to study the distribution of O_3 and the global circulation. The O_3 destruction by mesospheric and upper stratospheric NO will be investigated. In contrast to the retrieval of the majority of trace gases from SCIAMACHY data, NO and $O_2(^1\Delta)$ profiles are to be determined from their emission features rather than their absorptions. The combination of height resolved O_3, $O_2(^1\Delta)$, and UV radiance products from SCIAMACHY provides detailed information about the photolysis of O_3 in the upper stratosphere and mesosphere. This will serve as an excellent opportunity to test our current photochemical knowledge of the mesosphere.

Global Warming and Climate Change

Although already discussed over a century ago by Arrhenius in 1896 *(Arrhenius 1896)*, the issue of global warming caused by the injection of the so-called *greenhouse gases* such as CO_2 and CH_4 into the atmosphere has become prominent in recent years. This is because of the rapid increase in atmospheric CO_2 associated with the combustion of fossil fuels in the second half of the 20th century. The recognition that other species can behave in a similar manner but often more effectively than CO_2 has resulted in the definition of the *global warming potential* of trace gases. The list of greenhouse gases now comprises many species including H_2O, CO_2, CH_4, nitrous oxide, CFCs and tropospheric ozone. Governments of many nations, concerned with the potential harmful consequences of global warming, have mandated to make evaluations aiming to provide national and international policymakers with an accurate assessment of our current understanding of climate change *(IPCC 2001)*. The increasing evidence that current global warming is to a large extent man-made was documented in the 3rd assessment report of the Intergovernmental Panel of Climate Change (IPCC) in 2002. Fig. 1-6 summarises the global annual mean radiative forcing of relevant agents contributing to global warming.

As the concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities, global warming and its impact on the Earth-atmosphere system will further increase. One of the future challenges is to quantify the complex feedback cycles (see fig. 1-3) between climate, atmospheric composition, natural and human activity which are driven by global warming. For example global warming is expected to result in more frequent dry, hot summer periods in Europe – like the summer of 2003 – with degraded air quality in wide parts of Europe.

For use in climate research, SCIAMACHY measurements will provide the distributions of several important greenhouse gases (CH_4, CO_2, tropospheric O_3), aerosol and cloud data, surface spectral reflectance (280-2386 nm), the incoming solar spectral irradiance and the outgoing spectral radiance (214-2386 nm). The observation of the greenhouse gases CH_4 and CO_2 will help to better quantify natural emissions globally, thereby improving the scientific basis of the Kyoto Protocol, which was put into force in spring 2005.

As it is intended that SCIAMACHY observations are to be made for many years, this long-term data set will also deliver much unique information useful for the study of the solar-terrestrial interactions and variations of the solar output including its impact on climate change. To maintain continuity with other spectrometers measuring solar spectral irradiance such as SBUV or GOME, SCIAMACHY was calibrated using standard methods which had also been applied to the GOME or SBUV calibration.

1.4 SCIAMACHY's Past and Beyond its Future

The Initial Phases

A first attempt to perform DOAS from space, MAP (Measurement of Atmospheric Pollution) was made by J.P. Burrows, D. Perner and P.J. Crutzen at the Max Planck Institut für Chemie in early 1985, in response to an ESA call for research instruments to fly on EURECA, a free-flying platform to be released from the Space Shuttle for making measurements over several months. During the period from 1985 to 1988 the concepts for remote sounding of atmospheric chemical constituents and parameters was refined and developed further. Additional scientists joined a growing scientific team. The concept of SCIAMACHY resulted from these endeavors.

The SCIAMACHY proposal *(Burrows et al. 1988a)* was submitted in July 1988 by the SCIAMACHY Science Team – and supported by the German Space Agency DARA GmbH (now DLR) – in response to ESA's call for experiments to fly on-board the Polar Platform, an element of the Columbus Programme. This mission, the Polar Orbiting Earth Observation Mission (POEM-1), finally evolved into the mission now better known as ENVISAT.

In February 1989 a peer review selected SCIAMACHY to be part of the payload of ENVISAT and a phase A feasibility study was initiated in summer 1989. During Phase A the Dutch Space Agency (NIVR) supported Dutch industry to join the SCIAMACHY consortium. Later in Phase B, the Belgian Federal Science Policy Office decided to also participate in the SCIAMACHY programme by cooperating with the Dutch partner.

In April 1989, SCIAMACHY was also identified to become part of the payload of the German research program ATMOS of the German Ministry of Science and Technology (BMFT). The aim of ATMOS was to investigate the use of instrumentation on a dedicated small satellite platform for Earth System Science. After the decision was made to support ESA's Polar Platform with a full complement of Earth observation instruments, the ATMOS program focused on the development of SCIAMACHY in Germany and providing some additional support to aspects of the ESA developed instruments MIPAS (Michelson Interfero-

meter for Passive Atmospheric Sounding) and MERIS (Medium Resolution Imaging Spectrometer).

After phase A, lasting from 1989 to 1990, SCIAMACHY was selected for flight by ESA as a national contribution to the ENVISAT project. The ESA conference at ministerial level approved the ENVISAT mission in November 1992 and around this time also the German and Dutch governments initiated the development of the SCIAMACHY instrument hardware. These early decisions triggered the development of one of the major national space projects in Germany and The Netherlands in the past decade. Starting in the next chapter, the reader is invited to learn about the SCIAMACHY mission, its on-ground and in-orbit life. Of particular interest may be chapter 3 where the story of the development of the instrument is continued with a description of the phase C/D 'making' of SCIAMACHY until its launch in 2002.

It is interesting to note that under the impression of the observation of the precipitous loss of ozone in austral spring mid of the 1980's, ESA was recommended at the *ESA User Consultation* meeting in Paris, during November 1988, to start measurements of relevance to atmospheric composition earlier than the launch of ENVISAT. In this context ESA announced a call for experiments to measure atmospheric constituents from ERS-2, which was under construction at that time. As a result, J.P. Burrows and P. Crutzen proposed the SCIA-mini experiment (*Burrows et al. 1988b*), being derived from the SCIAMACHY instrument concept. This proposal was selected but subsequently recommended for simplification. After this exercise, including for example descoping of the limb measurement mode, the renamed instrument GOME was accepted for flight on ERS-2. Based on the original SCIAMACHY concept and benefiting from its scientific and industrial development work, it was 'fast tracked' ahead of its much more challenging successor. GOME fitted into redundant platform resources, known to be available aboard ERS-2 and was successfully designed, constructed and made ready for launch in 1995 within only four years. The instrument is currently flying on the ERS-2 satellite. Its success has demonstrated the feasibility and capabilities of this new instrument concept. Much of the experience gained with GOME can be used directly for SCIAMACHY.

Outlook towards 2020

GOME's in-orbit performance and scientific results triggered the selection of GOME-2 for the METOP satellites of the EUMETSAT Polar System (EPS) by the councils of ESA and EUMETSAT. These operational platforms will fly from 2006 till approximately 2020 making a unique contribution to meteorology and climate research. SCIAMACHY together with the data from GOME on ERS-2 (1995-2003) and the GOME-2 series on METOP (2006-2020), will therefore deliver a data set about atmospheric composition over more than 25 years.

Following the successful demonstration of the measurements of trace gases in the troposphere from space, the core SCIAMACHY scientific team has continued its development work. One spin-off of the initial SCIAMACHY activities is the Ozone Monitoring Instrument (OMI) on EOS AURA. Conceptually OMI is building on the GOME concept (nadir observations in the UV to Visible – VIS), but improving in spatial resolution and coverage by using for the first time two-dimensional detector arrays for space-based DOAS applications.

In addition, stimulated by the SCIAMACHY concept US colleagues proposed and built instruments and missions with elements of SCIAMACHY heritage. These are the Orbiting Carbon Observatory (OCO, 2008 – 2010), a mission to quantify natural CO_2 emissions by performing SWIR nadir measurements similar to SCIAMACHY, but with higher spatial and spectral resolution, and the Ozone Monitoring and Profiling Suite (OMPS) flying from 2009 – 2020 on NPP/NPOESS, a combined limb (UV-VIS) and nadir (UV) backscatter spectrometer using one spectrometer for nadir and one for limb, as in the original SCIAMACHY concept.

In a step beyond the low-Earth orbit, it was further proposed to perform atmospheric constituent measurements from geostationary orbit. Within this context the Geostationary Scanning Imaging Absorption Spectrometer (GeoSCIA) was proposed in 1998 and GeoTROPE, the Geostationary Tropospheric Explorer missions, which combines GeoSCIA with GeoFIS, a Geostationary Fourier Transform Interferometer followed in 2002. The latter has heritage in the IASI sensor. The objective of these research missions is to make measurements of atmospheric pollution with high temporal (hourly) and spatial (10-20 km) sampling, required to understand their regional behavior in the lower troposphere. These are complementary to the METOP measurements, which have limited spatial and temporal coverage. The missions represent the necessary demonstration for the future METEOSAT Third Generation satellites and planned missions for the European Global Monitoring for Environment and Security (GMES) initiative. These activities are part of a wider approach, the so-called 'Global Earth Observation System of Systems (GEOSS)' within the international Global Earth Observation initiative (GEO).