1. SCIAMACHY – The Need for Atmospheric Research from Space

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Abstract: The Earth's atmosphere is part of a complex system comprising the Sun and the Earth. Throughout the Earth's history, this system responded to natural and anthropogenic phenomena. To assess the significance of changes induced by natural and anthropogenic activities, a detailed understanding of the physical and chemical processes controlling the composition of the global atmosphere is required. Space-based remote sensing instruments can contribute many of the required geophysical parameters on various spatial and temporal scales. The scientific goals of the imaging absorption spectrometer SCIAMACHY, flying on the European ENVISAT platform, are wide ranging and encompassing the need to improve our understanding of biogeochemical cycling and assess the impact of man on the Earth system. SCIAMACHY is an absorption spectrometer sensing simultaneously electromagnetic radiation in the range from the UV to SWIR. It observes the scattered and reflected spectral radiance in nadir and limb geometry, the spectral radiance transmitted through the atmosphere in solar and lunar occultation geometry, and both the extraterrestrial solar irradiance and lunar radiance. Research using SCIAMACHY data includes the following topics: tropospheric ozone, air quality, the transport and transformation of pollution, global climate change, the exchange between the stratosphere and troposphere, stratospheric chemistry and dynamics, mesospheric and thermospheric composition, and solar variability. SCIAMACHY was proposed in the 1980's and is now part of the current fleet of atmospheric remote sensing missions. Due to its success, several missions with SCIAMACHY heritage will extend the important data sets far into the 21st century.

Keywords: Earth's atmosphere – Spaceborne remote sensing – Anthropogenic changes – Pollution – Greenhouse effect – Ozone depletion – Atmospheric chemistry

It is widely recognised that the Earth's atmosphere is part of a complex system comprising the Sun and the Earth, and conditions within it are maintained by a biogeochemical equilibrium. The state of the system has responded throughout the Earth's history to natural and anthropogenic phenomena. Changes in the composition of the Earth's atmosphere and at the Earth's surface are occurring on both short and long timescales and thereby modifying the environment, its ecosystem, the biodiversity of the planet and ultimately the climate. Since the industrial revolution and driven by the supply of energy from fossil fuel combustion, the Earth's population has increased nearly exponentially. This has been accompanied by an increasing standard of living. The recognition that the impacts of the resultant pollution and land use change on the Earth's system from the local to the global scale has reached critical levels has led to public concern, political debate and the evolving of national and international policy which are designed to minimise negative impact on the environment, biodiversity and climate. Established examples, where significant change to the Earth system, resulting from anthropogenic activity, has been identified by the scientific community, are:

- the *ozone hole*, i.e. the rapid loss of stratospheric ozone (O_3) above Antarctica and the Arctic in spring, resulting from the tropospheric release of chlorofluorocarbon compounds, (CFC, halones and hydrogenated chlorofluorcarbon compounds, HCFC – WMO 2003)
- the decline of ozone over extra polar regions, 60°S-60°N, which has slowed down as a result of the implementation of the Montreal Protocol and its amendments (WMO 2007)
- the global increase of tropospheric ozone (WMO 1995) and its adverse impact on air quality
- the trans-boundary transport and transformation of pollution resulting for example in acidic deposition and affecting air quality far from pollution sources (WMO 2004, UNECE 2007)
- global dimming attributed to increases in aerosol and clouds (Wild et al. 2005)

- the observed increase of tropospheric greenhouse gases CO_2, CH_4, N_2O and O_3 and their impact on climate (IPCC 2007)
- the coupling between increased greenhouse gas concentrations and stratospheric ozone loss (Shindell et al. 1998, WMO 2007)

The overarching objective is to achieve sustainable development and to protect the Earth's environment and its biodiversity. This requires an adequate understanding of the complex system comprising the Sun, the atmosphere and the Earth's surface, and the physical chemical and biological processes which determine and maintain the conditions within the biosphere. Improving our understanding of the Earth system calls on the one hand for theoretical models that describe the atmospheric dynamics, chemistry and biogeochemical cycling in the atmosphere. On the other hand there is a clear need for accurate strategies to provide the observational evidence base by means of measurements of the atmospheric composition in the troposphere, stratosphere and mesosphere ranging from local to global scale. Models are validated by such measurements, which also independently provide evidence of the observed changes in the atmosphere. In order to test our understanding and improve the predictive capability of models of environmental and climate change, global measurements of key parameters are needed.

Remote sounding instrumentation on-board space-based platforms have the potential to deliver a unique part of the required geophysical parameters on global scales. During the last decades, substantial progress has been made in sounding even the lowest layer of the atmosphere, the troposphere (Burrows et al. 2011) and SCIAMACHY acted as pathfinder in that field. The SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) project (Burrows et al. 1988a; Bovensmann et al. 1999), being Greek for *chasing or hunting shadows*, has delivered an instrument which flies on-board ENVISAT (Environmental Satellite) of the European Space Agency ESA. It is designed to yield quantitative data about the temporal and spatial properties of atmospheric trace constituents including gases, aerosol and clouds. In addition, it provides information on surface optical properties for ocean colour and land cover studies complementary to other instrumentation. The SCIAMACHY project was designed to address the scientific curiosity and to demonstrate that the measurements needed to regulate sustainable development are feasible from space.

1.1 How to study the Earth's Atmosphere from Space?

Prior to the advent of space flight, measurements of atmospheric composition were limited in geographical coverage and the sampling was skewed to the developed world. In particular, the regions over the oceans and the southern hemisphere were undersampled. During the last three decades, the development of satellite platforms in low-Earth and geostationary orbit has provided the opportunity to observe the Earth and its atmosphere by utilising the novel viewing geometries afforded from space. The potential to make near-simultaneous observations at the global scale for the first time has facilitated the emergence of *Earth System Science*. This approach treats the Earth as an interdependent system which comprises the atmosphere, oceans and land and whose energy is provided by the Sun.

In particular, the atmospheric and meteorological sciences have exploited satellite observations. Remote regions of the atmosphere over the land and oceans, where ground-based stations or shipborne 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 measures the radiation leaving the top of the atmosphere. It may be subdivided into the categories measuring *absorption* or *emission* of atmospheric molecules and atoms. The absorption and emission processes in the atmosphere produce spectra, which are characteristic for the emitting or absorbing atom or molecule. *Emission spectra* consist mainly of the thermal emission from the Earth and the atmospheric constituents, which radiate mainly in the infrared and microwave spectral range according to their characteristic rotational and vibrational excitation. They can be regarded as the thermal 'fingerprint' of the atmosphere. From the emission spectra, trace gas concentrations are derived.

Measuring *absorption spectra* of molecules in the UV, visible (VIS), near (NIR) and short-wave infrared (SWIR) part of the atmospheric spectrum yields information about the electronic properties of atoms and molecules. Concentration is derived from the absorption, i.e. the reduction in the intensity

of electromagnetic radiation, which is integrated along the path travelled by solar photons through the atmosphere. This is the approach utilised by 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 in the solar photosphere, chromospheres and corona, known as the solar Fraunhofer lines. In the Earth system, the incoming solar radiation is further modified by scattering, absorption and emission processes in the atmosphere and by reflection and scattering at the Earth's surface. When leaving the Earth again at the top of the atmosphere, the upwelling radiation carries with it the signature of the atmospheric constituents. The air mass traversed by the solar photons needs to be modelled precisely in order to infer concentration distributions from the integrated air column sampled (see chapter 7). This task requires a quantitative knowledge and understanding of the scattering of electromagnetic radiation in the atmosphere, as well as highly accurate absorption spectroscopy data.

1.2 The Road to SCIAMACHY

The scientific community has long recognised the need for global observations of the Earth system and has proposed global observing systems for research to meet the needs of international legislation monitoring (IGACO 2004). Such systems aim to establish integrated networks that have complementary instrumentation from ground-based, airborne or shipborne platforms, as well as satellite sensors. 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,
- to move towards a sustained global observing system capable of meeting the needs of Earth System Science and the demands for global international treaty verification, monitoring and forecast.

The first measurements of atmospheric ozone and aerosols from space were made by the Soviet space programme in the middle of the 1960's from manned spacecraft. 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 build 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 Fig. 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, performed 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 (Reber et al. 1993), which carried instruments to sound the upper atmosphere like the Microwave Limb Sounder (MLS) and the Halogen Occultation Experiment (HALOE). HALOE measurements were continued until 2005.

The European participation in remote sounding of atmospheric constituents and parameters by autonomous satellites was focused initially on the development of the geostationary METEOSAT programme being established in the late seventies. Initiated by ESA and finally transferred to EUMETSAT, it provided measurements of meteorological parameters since the early eighties. The first ESA payload to carry significant instruments for atmospheric trace gas sounding was SPACELAB-1 which was among the shuttle payload in 1983. One of these instruments, the GRILLE spectrometer, performed observations in solar occultation of most of the nitrogen and carbon families, HF and HCl. It flew once again in 1992 in the NASA SPACELAB ATLAS-1 mission with the JPL ATMOS solar occultation interferometer. This convinced ESA of the possibility of an atmospheric observatory in orbit.

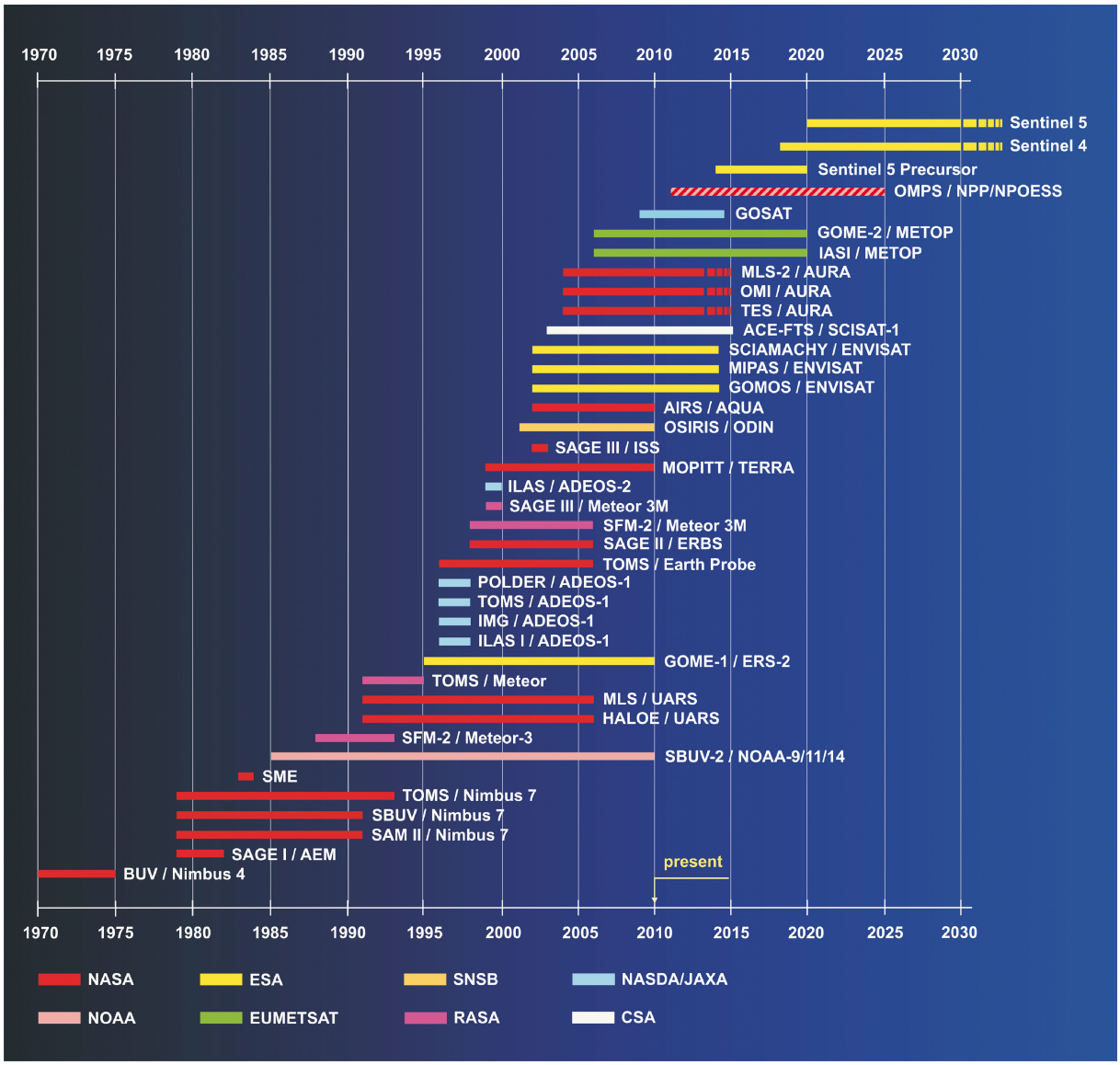

Fig. 1-1: Atmospheric science spaceborne instruments and missions since 1970 with relevance for SCIAMACHY. The list of missions is not intended to be complete but to illustrate the progress in spaceborne instrumentation for atmospheric composition monitoring. (Courtesy: DLR-IMF)

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 20 April 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 were 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).

The interest and the need for global observations of atmospheric constituents is reflected in the number of new missions which have been launched since the start of ERS-2 and contribute significantly to Earth system 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) and GOSAT, the Canadian/Swedish/French ODIN mission and the Canadian SCISAT mission. ESA's ENVISAT, which was launched in 2002, includes SCIAMACHY as part of its atmospheric payload. Together with EUMETSAT's series of METOP platforms, which began in late 2006, it extends the European data record started with ERS-2 to 2020 and beyond. The past three decades can be regarded as the pioneering golden age of Earth Observation with their research missions generally having been very much more successful than originally expected (Table 1-1).

The heritage of the SCIAMACHY instrument derives from 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 detects in the UV-VIS-NIR-SWIR 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,
- the exchange processes between the stratosphere and troposphere,
- the interaction of stratospheric chemistry and dynamics,
- the natural modulations of atmospheric composition resulting from volcanic eruptions, lightning, solar output variations, e.g. solar cycle, or solar proton events.

To achieve these goals, SCIAMACHY was proposed to deliver a multitude of parameters characterising the system *Earth-Atmosphere-Sun*, especially key trace gases and other parameters in the troposphere and stratosphere. The following gases were targeted for measurement: molecular oxygen (O_2), ozone $(O)_3$, the oxygen dimer (O_4), nitrogen monoxide (NO), nitrogen dioxide (NO_2), the nitrate radical (NO_3), carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde (HCHO), methane (CH_4), water vapour (H_2O), nitrous oxide (N_2O), sulphur dioxide (SO_2), bromine monoxide (BrO), and chlorine dioxide (OClO). The combined use of nadir and limb observations yields tropospheric amounts of the relevant 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 SCIAMACHY measurements. Particularly interesting, among these, are Polar Stratospheric Clouds (PSC) and Noctilucent Clouds (NLC), also referred to as Polar Mesospheric Clouds (PMC). It was recognised at the outset that whilst the spatial resolution of SCIAMACHY was low, its measurements would also provide some unique information about ocean colour and land cover parameters.

Instrument	Name	Measurement Altitude[a]			Target Species	Observation Geometry[b]				
		TR	ST	ME		N	L	SO	LO	STO
ACE-FTS	Atmospheric Chemistry Experiment		X		O_3, H_2O, CO, CFCs, HNO_3, NO, and more			X		
AIRS	Atmospheric Infrared Sounder	X[c]			O_3, H_2O, CO_2, CH_4	X				
BUV	Backscatter Ultraviolet Ozone Experiment		X		O_3	X				
GOME	Global Ozone Monitoring Experiment	X	X		O_3, NO_2, H_2O, BrO, OClO, SO_2, HCHO, CHOCHO, IO, clouds and aerosols	X				
GOME-2	Global Ozone Monitoring Experiment	X	X		O_3, NO_2, H_2O BrO, OClO, SO_2, HCHO, CHOCHO, IO, clouds and aerosols	X				
GOMOS	Global Ozone Monitoring by Occultation of Stars	X[c]	X	X	O_3, NO_2, H_2O, NO_3, aerosols, T					X
GOSAT	Greenhouse Gas Observing Satellite	X			CO_2, H_2O, CH_4	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[c]	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, aerosols			X		
IMG	Interferometric Monitor for Greenhouse Gases	X[c]	X		O_3, N_2O, H_2O, CH_4, CO, CO_2	X				
MIPAS	Michelson Inferometer for Passive Atmospheric Sounding		X	X	O_3, NO_x, N_2O_5 $ClONO_2$, CH_4, CFCs, HNO_3, and more, 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				
MTG IRS	Infrared Sounder	X[c]	X		O_3, H_2O, CO, T and P	X[d]				
OMI	Ozone Monitoring Instrument	X	X		O_3, SO_2, NO_2, BrO, CHOCHO, HCHO, aerosols	X				
OMPS	Ozone Monitoring and Profiling Suite	X	X	X	O_3, SO_2, aerosols	X	X			
OSIRIS	Optical Spectrograph and Infrared Imaging System		X	X	NO, OClO, O_3, NO_2, aerosols		X			

Instrument	Name	Measurement Altitude[a]			Target Species	Observation Geometry[b]				
		TR	ST	ME		N	L	SO	LO	STO
POLDER	Polarization and Directionality of the Earth's Radiance	X			polarisation, aerosols, clouds	X				
SAGE I	Stratospheric Aerosol and Gas Experiment I		X		O_3, NO_2, aerosols			X		
SAGE II	Stratospheric Aerosol and Gas Experiment II		X		O_3, NO_2, H_2O, aerosols			X		
SAGE III	Stratospheric Aerosol and Gas Experiment III		X		O_3, OClO, H_2O, BrO, NO_2, NO_3, aerosols			X	X	
SAM II	Stratospheric Aerosol Measurement II		X		aerosols			X		
SBUV	Solar Backscatter Ultraviolet Ozone Experiment	X	X		O_3, SO_2	X				
SBUV-2	Solar Backscatter Ultraviolet Ozone Experiment 2	X	X		O_3, SO_2	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, H_2O, HDO/H_2O, SO_2, HCHO, CHOCHO, IO, CO, CO_2, CH_4, cloud, aerosols	X	X	X	X	
SENTINEL 4 UVN	Ultraviolet-Visible-Near Infrared	X	X		O_3, NO_2, SO_2, HCHO, CHOCHO, cloud, aerosols	X[d]				
SENTINEL 5 Precursor UVNS	Ultraviolet-Visible-Near Infrared-Shortwave Infrared	X	X		O_3, NO_2, BrO, SO_2, HCHO, CHOCHO, H_2O, HDO/H_2O, CO, CH_4, cloud, aerosols	X				
SENTINEL 5 UVNS	Ultraviolet-Visible-Near Infrared-Shortwave Infrared	X	X		O_3, NO_2, BrO, SO_2, HCHO, CHOCHO, H_2O, HDO/H_2O, CO, CO_2, CH_4, cloud, aerosols	X				
SFM-2	Spectrophotometer		X		O_3, aerosols			X		
SME	Solar Mesospheric Experiment		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, aerosols	X				

a) TR = troposphere, ST = stratosphere, ME = mesosphere
b) N = nadir, L = limb, SO = solar occultation, LO = lunar occultation, STO = stellar occultation
c) Mid/Upper troposphere
d) Geostationary orbit

Table 1-1: 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.

In addition to these originally targeted parameters, it became evident from the analysis of the high quality data delivered by SCIAMACHY over the last years that several new parameters could be derived, including tropospheric glyoxal (CHOCHO), tropospheric iodine oxide (IO), mesospheric metal ions, phytoplankton information, and the ratio of HDO to H_2O. Recently, SCIAMACHY was also used to observe the solar backscattered radiation coming from Venus.

Table 1-2 summarises the parameters derived from SCIAMACHY measurements and their application areas while the successive chapters provide descriptions of the associated scientific problems. The data sets obtained by SCIAMACHY significantly contribute to the quantification of the complex interactions between natural and human activities, climate, atmospheric composition, and the relevant chemical and physical processes. For an illustrative summary of SCIAMACHY's achievements, the reader is referred to chapter 10.

Subject	**Parameter from SCIAMACHY Data**	**Application Areas**
Surface	spectral surface albedo, UV A/B, chlorophyll content of plants and phytoplankton	– Earth radiative budget – ocean biology – plant biology – spectral surface characteristics
Troposphere (incl. boundary layer[1])	columns of O_3, NO_2, BrO, SO_2, HCHO, CHOCHO, IO, H_2O, HDO/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 – hydrological cycle
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, PSC	– development of the ozone layer – climate-chemistry interactions – solar-terrestrial interactions
Mesosphere	profiles of O_3, NO, OH, metal ions, temperature, NLC	– 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 derived from SCIAMACHY and the relevant application areas.

The Atmospheric Layers

The Earth's atmosphere is a complex system comprising a set of layers, characterised by their temperature as a function of altitude. Figure 1-2 shows typical temperature and pressure profiles at mid-latitudes. 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.

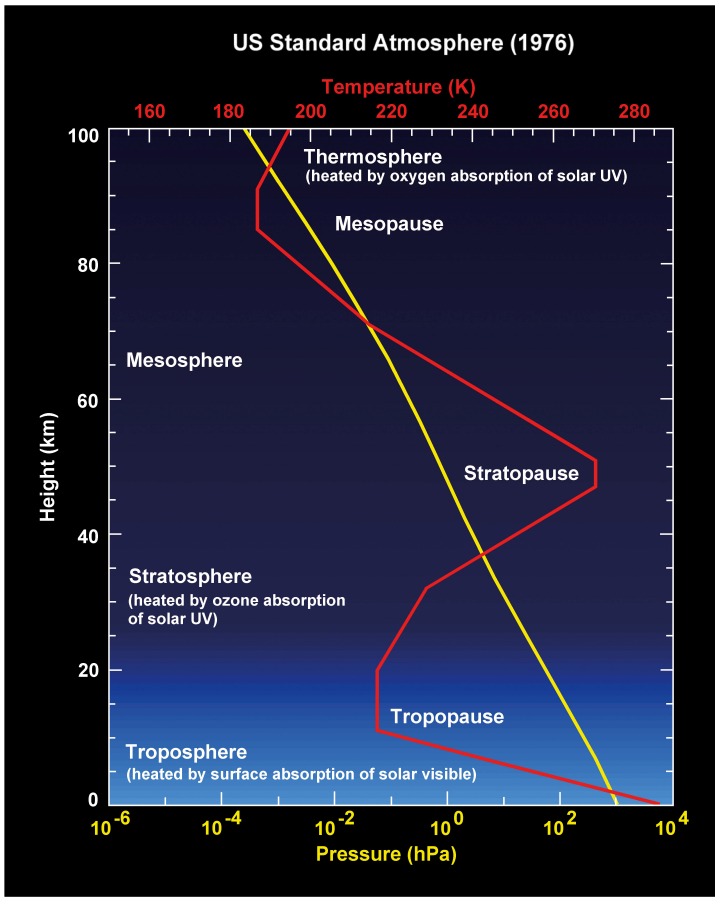

Fig. 1-2: Atmospheric pressure and temperature profiles for mid latitudes. (US Standard Atmosphere)

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 exponentially 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 dictated by the ideal gas law and solar irradiation. The stratopause is located typically at 45-50 km and the mesopause typically at 85-90 km. Around 80-90% of the atmospheric mass are contained within the troposphere.

The behaviour and composition of troposphere, stratosphere and mesosphere are coupled through dynamic, radiative and chemical processes as indicated in Fig. 1-3. The conditions experienced in the biosphere, the layer around the Earth's surface where life resides, are determined in a complex manner by the physical and chemical processes occurring in all these atmospheric layers.

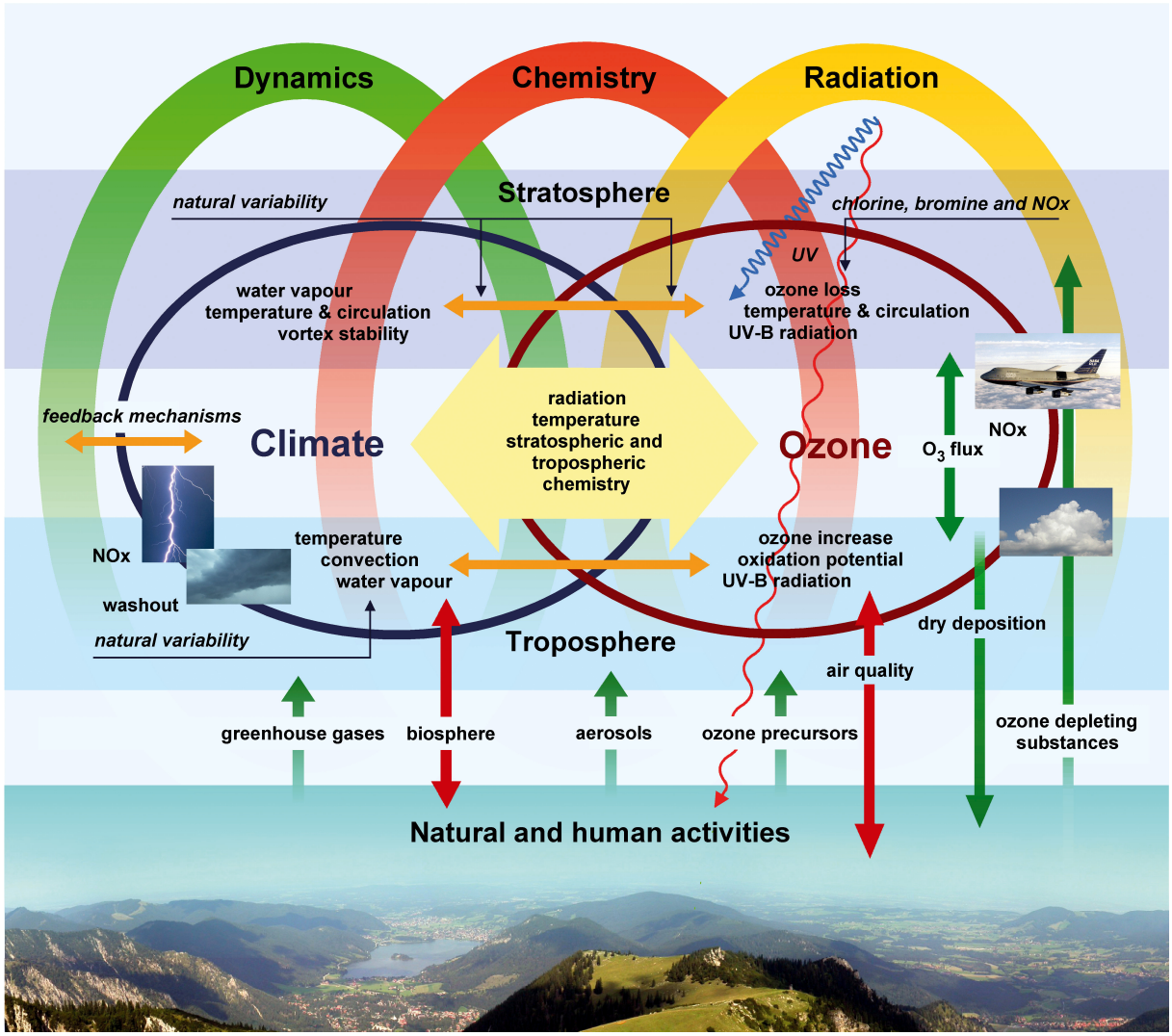

Fig. 1-3: Interactions between human activity, atmospheric composition, chemical and physical processes and climate. (Courtesy: DLR-IMF, after IGACO 2004)

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 for several billion years indicates that it resulted from photosynthesis after the appearance of life (e.g. Wayne 1992, Holloway and Wayne 2010). 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 suggested 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, accommodating a constantly growing human population has dramatically increased the need for land use, energy and food supplies 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):

- Fossil fuels, generated over several hundred million years, burnt and exhausted into the atmosphere within a few generations.
- The release of SO_2, globally about 160 Tg/year, by coal and oil burning, over twice the sum of all natural emissions, mainly marine dimethyl-sulfide from the oceans.
- Human activity transformed 30-50% of the land surface. More nitrogen is now fixed synthetically and applied as fertilizer in agriculture than is fixed naturally in all the terrestrial ecosystems.
- The discharge of CO and NO_x (NO and NO_2) into the atmosphere by fossil fuel and biomass combustion, much larger than natural inputs, giving rise to photochemical ozone (smog) formation and degraded air quality in many regions of the world.
- The substantially increased concentration of atmospheric greenhouse gases: CO_2 by more than 30% and CH_4 by more than 100%, enhancing radiative forcing and causing changing climate. CO_2 and CH_4 are currently regulated by the Kyoto Protocol until 2012.
- New and not naturally existing substances released into the environment. Some of these substances, the chlorofluorocarbons, have caused the Antarctic *ozone hole* to open up and would have destroyed much of the ozone layer if no international regulatory measures, the Montreal Protocol, had been enforced to end their production.

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

Tropospheric Chemistry

Most atmospheric gases, such as greenhouse gases (CO_2, CH_4, etc.) or the pollutants (NO_2, CO, SO_2, etc.) are emitted into the troposphere by natural processes and human activities. The oceans, the cryosphere and land surfaces act as sink to some of these gases. The main sources of pollutants in the northern hemisphere are fossil fuel combustion (energy production, traffic, industry and domestic heating) coupled with some biomass burning; in the southern hemisphere biomass burning is dominating. However, modern agricultural intensive practise is also becoming a significant source of emissions. Pollutants are emitted within urban and near-urban areas where they are dispersed over the surrounding countryside and, depending on the atmospheric lifetime of the pollutant or its secondary reaction product(s), are transported around the globe. The pollutants from North America can e.g. be responsible for a significant fraction of tropospheric O_3 in the European summer due to complex transport and transformation mechanisms.

Tropospheric processes as sketched in Fig. 1-4 are well known to exhibit strong variability influenced by meteorology, diurnal, as well as seasonal 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 power is of vital importance to the control of radiatively and chemically active pollutants. Therefore, any change in the atmospheric oxidation efficiency directly affects air quality.

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, severely limits the quantitative understanding of the processes involved in tropospheric O_3 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, CO, and non-methane hydrocarbons. One of the major challenges facing atmospheric science is to assess, understand and quantify the impact of a changing climate, which has feedbacks with atmospheric composition and air pollution.

SCIAMACHY is designed to determine the amounts of trace gases and aerosol in the lower troposphere, including the planetary boundary layer under cloud-free cnditions. From SCIAMACHY nadir and limb measurements, tropospheric columns of O_3, CO, NO_2, BrO, CH_4, H_2O, SO_2, HCHO, CHOCHO, and IO are retrieved. In addition, surface spectral reflectance, aerosol and cloud parameters

– cloud cover and cloud top height – can be obtained. 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.

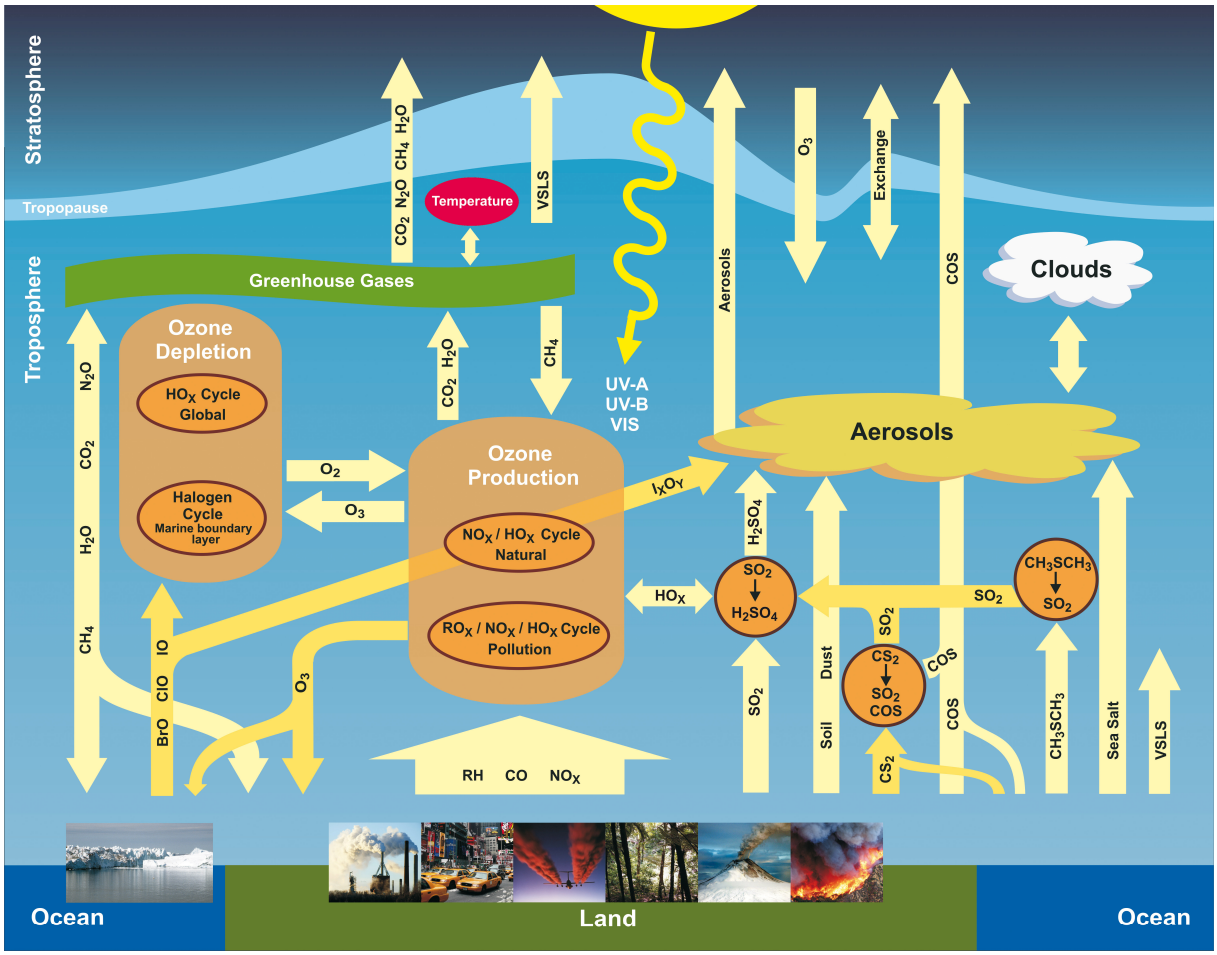

Fig. 1-4: The dominant physical and chemical processes determining the composition of the troposphere. (Courtesy: IUP-IFE, University of Bremen)

Greenhouse Gases: Global Warming and Climate Change

Back in 1896, Arrhenius published his account *On the influence of carbonic acid in the air upon the temperature on the ground*, identifying carbon dioxide and water vapour as important greenhouse gases that change climate (Arrhenius 1896). He calculated, with the help of Langley lunar plots measuring the infrared absorption of the atmosphere, that doubling the atmospheric CO_2 content by burning fossil fuel would lead to an average global temperature rise of 5-6° C, not far from the current IPCC estimates of 2-4.2° C. At the present rate of rise, doubling CO_2 would occur in the last quarter of this century. The list of greenhouse gases now comprises many species including H_2O, CO_2, CH_4, nitrous oxide, CFCs and tropospheric ozone. In addition, clouds and aerosols play an important, yet highly uncertain, role in global warming and cooling. Fig. 1-5 summarises their global annual mean radiative forcing contributions. In order to compare greenhouse gases, taking into account their different infrared absorption and atmospheric lifetime, the concept of *global warming potential* over a 100 year time period has proved useful. For example, N_2O has a global warming potential of 296, i.e. causing a global warming contribution 296 times that of the same mass of CO_2.

In 1989, governments of many nations concerned with the potential harmful consequences of global warming have mandated the Intergovernmental Panel of Climate Change (IPCC) to make evaluations aiming to provide policymakers with an assessment of our current understanding of

climate change. The increasing evidence that current global warming is, to a large extent, man-made was documented in the 4th assessment report of the IPCC in 2007. 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 is predicted to 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. Climate change 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. Stratospheric ozone recovery may be delayed through climate change lowering stratospheric temperatures.

For use in climate research, SCIAMACHY measurements aim to provide the distributions of several important greenhouse gases (CH_4, CO_2, H_2O, 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 better constrain the quantification of emissions globally, thereby improving the scientific basis of the Kyoto Protocol, which was put into force in spring 2005 and currently ends in 2012. As SCIAMACHY has now made 8 years of observations and is capable of making them for many more years, this long-term data set will not only provide unique information about atmospheric composition but, in addition, is also of great value for studying solar-terrestrial interactions, e.g. how solar output variations impact climate change.

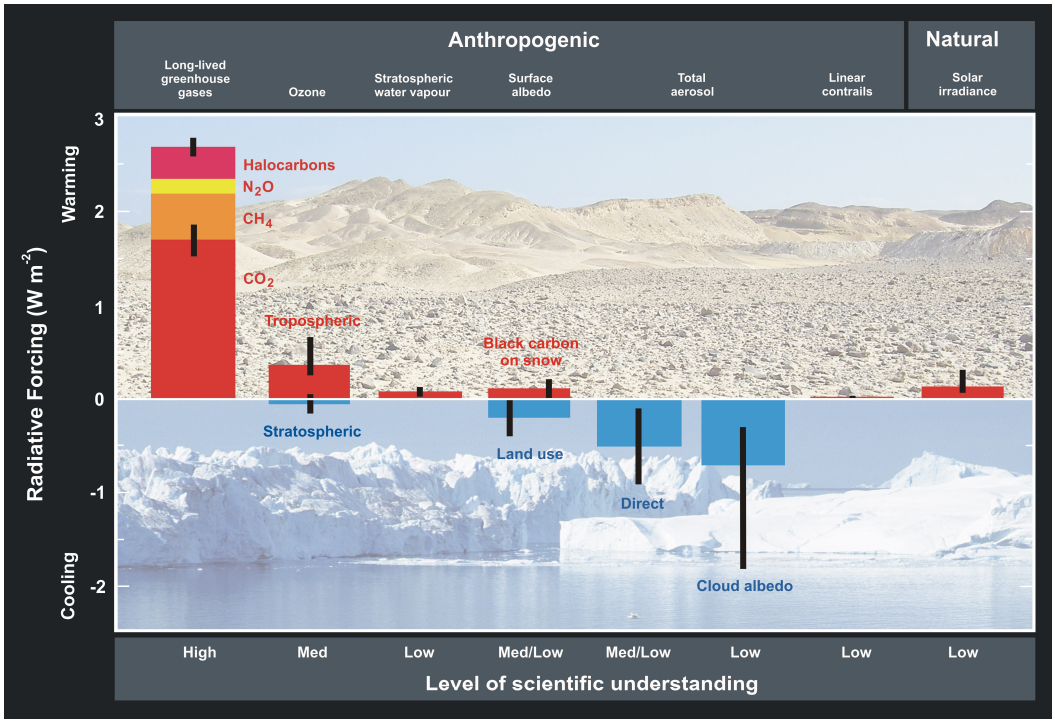

Fig. 1-5: Global, annual mean radiative forcings (W/m^2) due to a number of agents for the period from pre-industrial (1750) to present (2005). The height of each box denotes a central or best estimate value. The vertical bars visualise an estimate of the uncertainty range, for the most part guided by the spread in the published values of the forcing. A 'level of scientific understanding' index is associated to each forcing, with high, medium and low levels, respectively. (Courtesy: adapted from IPCC 2007)

The Tropopause Region

Exchange of gases and particles between the stratosphere and the troposphere is of importance for the chemical composition of both regions, as well as for the atmospheric energy budget (Holton et al. 1995). For example, downward transport of stratospheric ozone is a source of tropospheric ozone which, as a precursor of OH radicals, determines the oxidising power of the troposphere to a large extent. 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 (see Fig. 1.6). Due to the long tropospheric lifetime of the precursor molecules, they are transported to the stratosphere, where they are the dominant source of the ozone-destroying 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. Photochemically 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.

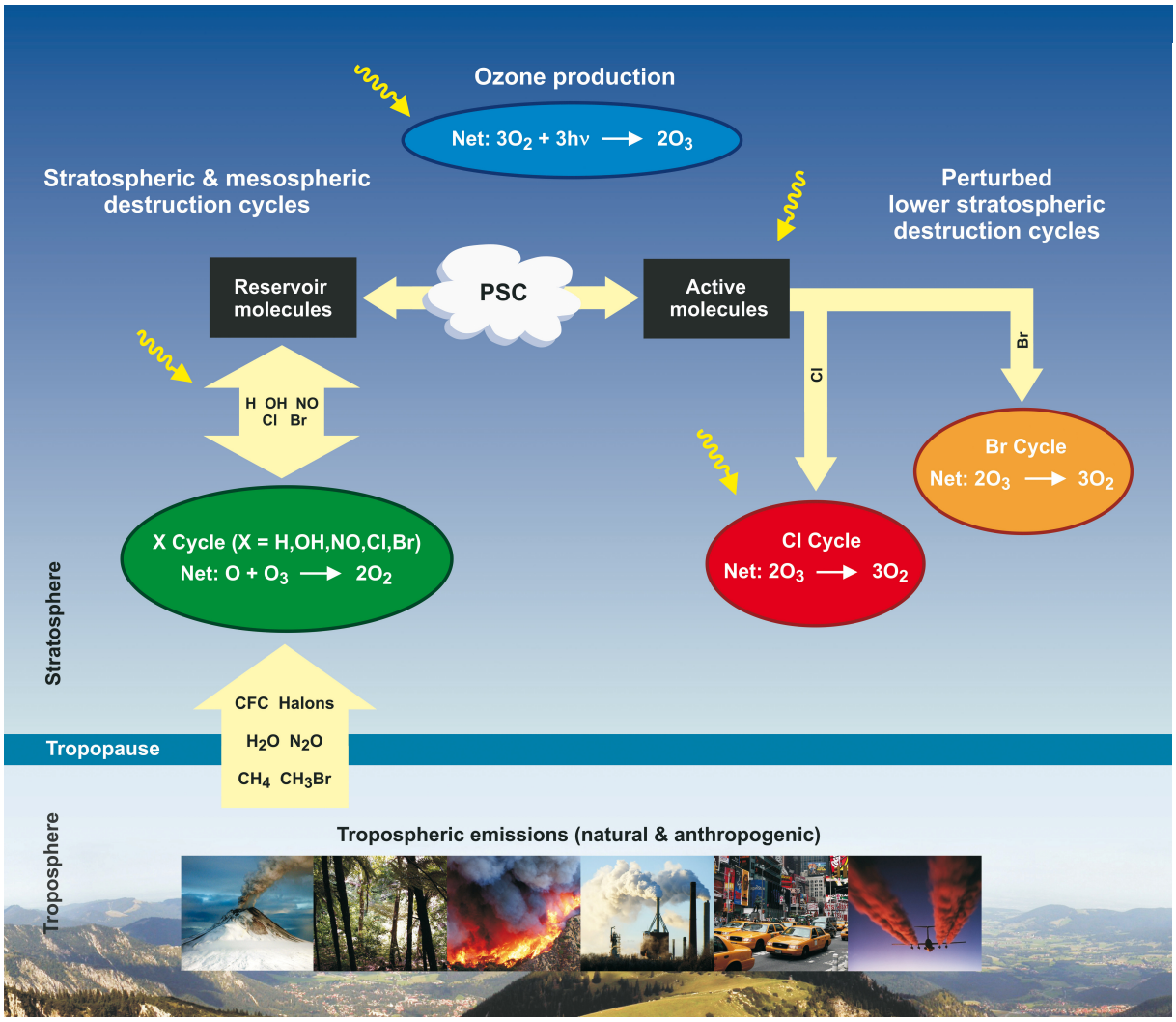

Fig. 1-6: Schematic sketch of the stratospheric ozone chemistry showing production and major destruction cycles. (Courtesy: IUP-IFE, University of Bremen)

SCIAMACHY measurements of the height resolved profiles of O_3, H_2O, CH_4, BrO, and NO_2, as well as aerosol contribute directly to the study of stratosphere-troposphere exchange. In addition, SCIAMACHY is delivering 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 the downward transport of stratospheric O_3 and upward transport of important species (e.g. aerosol, CH_4, H_2O) can be investigated. Across the tropopause, the different measurement modes of SCIAMACHY 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, but the larger scale stratosphere-troposphere exchange and phenomena such as volcanic eruptions will be readily observed.

Stratospheric Chemistry and Dynamics

No part of the global environment has been as significantly disturbed by human activity as the stratosphere. In the upper stratosphere and lower mesosphere, ozone is removed by catalytic cycles involving halogen oxides. In addition, a very substantial depletion of stratospheric ozone over Antarctica – the ozone hole – has been observed during springtime since the beginning of the 1980's. This depletion is largely due to the emission of industrial chlorofluorocarbon gases (WMO 2003, WMO 2007). Likewise 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 Polar Stratospheric Clouds (PSC) containing hydrated droplets of nitric acid and sulphuric acid or consisting of relatively pure water ice crystals are – via the activation of chlorine – responsible for these changes.

International regulatory measures, the Montreal Protocol and subsequent amendments to phase out production of chlorofluorocarbons (WMO 1995), have decreased the chlorine loading of the troposphere. A recovery of the stratospheric ozone layer is expected to set in only after 2010 (WMO 2003). Indications that ozone abundances in the extrapolar regions (60°S-60°N) have stabilised in recent years were observed, in agreement with the observed decline in the abundances of anthropogenic ozone-depleting gases in the atmosphere as a result of the implementation of the Montreal Protocol (WMO 2007). The loss of ozone in the stratosphere is also affected by tropospheric emission of greenhouse gases (see Fig. 1-6). 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 PSC. 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. Therefore, continued monitoring of O_3, the sources of catalysts and the catalysts themselves remains mandatory in future.

SCIAMACHY's observations of the stratospheric chemistry 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 making measurements when the halogen loading of the stratosphere maximised at the beginning of the 21st century and SCIAMACHY observations yield detailed information about the development of stratospheric O_3 above the Arctic and Antarctica, the global stratospheric active halogen species (BrO, OClO), nitrogen species (NO_2), which participate in the catalytic destruction of O_3, and the global O_3 budget as a function of the height in the atmosphere. Thus the SCIAMACHY data provide a unique opportunity to test 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 Noctilucent Cloud (NLC) formation at 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 NLC. 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 can 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 knowledge of the photochemistry of the mesosphere and the interaction of the mesosphere with solar radiation.

1.4 SCIAMACHY's Past and Beyond its Future

The Initial Phases

A first attempt to perform DOAS measurements from space named MAP (Measurement of Atmospheric Pollution) dates back to 1985. It was submitted by J.P. Burrows, D. Perner, P.J. Crutzen, (MPI for Chemistry, Mainz) in response to an ESA call for research instruments to fly on EURECA, a free-flying European platform carried into space by the Space Shuttle allowing measurements for a period of several months. This proposal was not selected at that time but it was further developed, whilst international scientists joined a growing team. The concept of SCIAMACHY resulted from these endeavours. 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 in which Dutch space research scientists and engineers, supported by the Dutch Space Agency NIVR (now NSO), joined the SCIAMACHY consortium. Later, during phase B (1991-1992), the Belgian Federal Science Policy Office entered into the SCIAMACHY project by cooperating with NIVR.

In parallel, SCIAMACHY became part of the payload of the German environmental research satellite 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 programme focused on the development of SCIAMACHY in Germany and providing some additional support to aspects of the ESA developed instruments MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) and MERIS (Medium Resolution Imaging Spectrometer).

After the conclusion of phase A, which lasted 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 in November 1992 approved the ENVISAT mission and around this time, the German and Dutch governments approved and initiated the development of the SCIAMACHY instrument hardware by industry. These early decisions triggered the development of one of the major national space projects in Germany and The Netherlands in the 1990's. Starting with the next chapter, the reader is invited to learn about the SCIAMACHY mission, its on-ground and in-orbit life. Chapter 3 is of particular interest as 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.

Following the recognition of the observation of the precipitous loss of ozone in austral spring during the mid 1980's, the *ESA User Consultation* meeting in Paris of November 1988 recommended for Europe to develop early independent ozone monitoring capability, rather than awaiting the launch of ENVISAT. ESA therefore announced a call for experiments to measure atmospheric constituents from ERS-2, which was under construction at that time. In response, J.P. Burrows and P. Crutzen proposed the SCIA-mini experiment (Burrows et al. 1988b), a scaled-down version of the original SCIAMACHY instrument concept. This proposal was selected for flight on ERS-2, after being further descoped to fit into the available platform resources, to include nadir observation only and was re-named GOME (Global Ozone Monitoring Experiment). GOME was 'fast tracked' on ERS-2, benefiting from the scientific and industrial development work already performed on SCIAMACHY. Within four years, GOME was successfully designed, manufactured, calibrated and integrated into ERS-2 on time. ERS-2 was launched on 20 April 1995. Currently, GOME is still flying on the ERS-2 satellite and delivering data, however limited due to degradation of the platform and the instrument. Although originally a spin off from SCIAMACHY, GOME has demonstrated the feasibility and

performance of both the spaceborne instrument hardware and the ground segment data retrieval software, which in turn has benefited the development of SCIAMACHY with respect to its nadir UV-VIS-NIR mission.

The Next Decades

With the impact of environmental and climate change becoming palpable, as documented for example by the scientific results from GOME and SCIAMACHY, the need for sustained global monitoring of ozone, greenhouse gases and air pollutants has turned into a prime requirement for future satellite missions. The councils of ESA and EUMETSAT approved therefore the EUMETSAT Polar System comprising a series of three METOP satellites. GOME-2 was selected as ozone and atmospheric trace gas payload complement. With the first METOP-A launched in 2006, this series of satellites provides continuous monitoring capability up to the year 2020 from polar sun-synchronous low-Earth orbit. SCIAMACHY, together with the data from GOME on ERS-2 (1995-2009) and the GOME-2 series on METOP (2006-2020), will therefore deliver a data set about atmospheric composition that is covering more than 25 years.

In parallel, initiatives emerged to realise a comprehensive global Earth observation system. Global Monitoring for Environment and Security (GMES), a joint initiative of the European Commission and ESA started in 1998, aims at bridging the gap between scientific data produced and the provision of reliable and timely information services to government and data users. This initiative resulted in the definition of a series of five GMES Sentinel satellites. Sentinels 4 and 5 are devoted to monitoring the atmosphere and were subsequently approved by EUMETSAT Council and the ESA ministerial conference in 2008. GMES is the European contribution to a wider approach, the Global Earth Observation System of Systems (GEOSS), within the international Global Earth Observation initiative (GEO). GEOSS couples the various Earth observation networks internationally to improve global coverage, whilst ensuring open access, accuracy and consistency of data of different sources. In addition, under auspices of WMO and in collaboration with ESA, the Integrated Global Atmospheric Chemistry Observation (IGACO) strategy was published in 2004 and aimed at integrating space data with ground-based and airborne measurements. IGACO established a basis for atmospheric chemistry instrument requirements for future satellites both for scientific and operational applications (IGACO 2004). These international initiatives were accompanied by new satellite missions and mission concepts.

Based on SCIAMACHY/GOME heritage, the Ozone Monitoring Instrument (OMI) is now flying on the NASA EOS satellite platform AURA launched in 2004. GOME technology (nadir observations in the UV-VIS) is advanced by employing two-dimensional CCD detector arrays for the first time, improving spatial and temporal resolution in combination with wide global coverage without the need for a mechanical scanning mirror. This concept will be further improved by TROPOMI, as the spectral range will be extended to the NIR and SWIR. TROPOMI is planned for launch in 2014 as the GMES Sentinel-5 Precursor mission, to bridge parts of the data gap between ENVISAT, Sentinel 4 (launch 2019) and Sentinel 5 (launch 2020).

In addition, stimulated by the SCIAMACHY concept, US colleagues proposed and built instruments and missions with elements of SCIAMACHY heritage. The Orbiting Carbon Observatory (OCO) is a mission to quantify natural CO_2 emissions by performing NIR and SWIR nadir measurements similar to SCIAMACHY, but with higher spatial and spectral resolution. Sadly, the OCO launch failed early 2009, but a reflight is envisaged for the timeframe 2013/2014. The Ozone Monitoring and Profiling Suite (OMPS) on NPP and NPOESS, operational from 2012 to 2025, with a combined limb (UV-VIS-NIR) and nadir (UV) backscatter spectrometer using one spectrometer for nadir and one for limb, follows the original SCIAMACHY idea.

Unfortunately and ignoring the needs from European GMES users, there will be no European measurements of the dry column of CO_2 after ENVISAT and prior to Sentinel 5. In order to fill this data gap, the CarbonSat project was initiated in 2009 (Bovensmann et al. 2010). CarbonSat shall allow to determine CO_2 and CH_4 emitted by fossil fuel combustion, biomass burning and natural emissions and CO_2 uptake in the terrestrial and ocean biosphere employing inverse modelling techniques in combination with measured data. In comparison to SCIAMACHY, CarbonSat will have a much higher spatial resolution (2 km × 2 km) with a 3-6 days revisiting time. In comparison to OCO, the mission will measure CO_2 and CH_4. Due to its across-track imaging capability, 500 km swath compared to 10

km swath for OCO, imaging of emission hot spots will become feasible. The data shall support monitoring of strong localised anthropogenic emission hot spots and shall investigate the feasibility of independent (post) Kyoto treaty verification.

The missions discussed so far refer to space platforms in low-Earth sun-synchronous polar orbit, i.e. at approximately 800 km altitude, measuring the Earth's atmosphere under fixed illumination conditions, revisited after 1 day or more. The diurnal variation of photo chemically active gases (NO_2, CO, O_3) cannot be captured. However, air pollution quantification and forecast require measurement of diurnal variability. From geo-stationary orbit, i.e. at approximately 36.000 km altitude, a certain hemisphere of the Earth is permanently in view such that the same scene can be monitored throughout the day at typically hourly temporal and high spatial (< 10 km) resolution. In addition, increased occurrences of cloud-free conditions, required for troposphere and boundary layer observation, become likely. To address these aspects for the first time, the Geostationary Scanning Imaging Absorption Spectrometer (GeoSCIA) was proposed in 1998. The concept of geostationary air pollution observations was later further enhanced by combining solar backscatter observations with thermal infrared observations in the Geostationary Tropospheric Explorer (GeoTROPE) mission concept, which will now be implemented in parts on the next generation of Europe's geostationary meteorological satellite METEOSAT Third Generation (MTG). The GeoSCIA concept has been adopted by EUMETSAT and ESA to form the concept for the Sentinel 4 UVN instrument as the EU-ESA GMES payload contribution to the MTG programme. Sentinel 4 UVN on MTG shall perform daytime observations of solar backscattered spectra to determine the total and tropospheric column amounts, including the boundary layer, of ozone, ozone precursors and pollutants (NO_2, SO_2, HCHO, CHOCHO) as well as the aerosol optical depth (AOD) over Europe and the surrounding regions with temporal and spatial resolutions of 1 hour and better than 10 km × 10 km. On the same MTG platform, EUMETSAT will install the meteorological InfraRed Sounder (IRS), complementary to Sentinel 4 UVN. The IRS sensor will focus on meteorological parameters (H_2O, temperature and pressure) but shall also obtain vertical distributions of O_3 and CO during day and night with temporal and spatial resolutions of about 20-60 min and 4 km × 4 km. The launch of MTG with the Sentinel 4 UVN and IRS payload is planned for 2019. In order to accomplish an operational MTG in-orbit phase of at least 15 years, a second platform carrying the same instrumentation shall be launched a few years later.

In retrospect, several Earth Observation missions for atmospheric remote sensing, extending well into the 21st century, are of SCIAMACHY heritage. This is by far more than the authors of the original SCIAMACHY proposal of 1988 could have expected.

References

Arrhenius, S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine and Journal of Science*, 41, 237.

Bovensmann, H., Burrows, J.P., Buchwitz, M., Frerick, J., Noël, S., Rozanov, V.V., Chance, K.V., Goede, A.P.H. 1999. SCIAMACHY: mission objectives and measurement modes. *J Atmos Sci*, 56, 127–150.

Bovensmann, H., Buchwitz, M., Burrows, J.P., Reuter, M., Krings, T., Gerilowski, K., Schneising, O., Heymann, J., Tretner, A. and Erzinger, J. 2010. A remote sensing technique for global monitoring of power plant CO2 emissions from space and related applications. *Atmos. Meas. Tech.*, 3, 781-811.

Burrows, J.P., Chance, K.V., Crutzen, P.J., van Dop, H., Geary, J.C., Johnson, T.J., Harris, G.W., Isaksen, I.S.A., Moortgat, G.K., Muller, C., Perner, D., Platt, U., Pommereau, J.-P., Rodhe, H., Roeckner, E., Schneider, W., Simon, P., Sundqvist, H. and Vercheval, J. 1988a. SCIAMACHY – A European proposal for atmospheric remote sensing from the ESA Polar Platform. *Technical Document*, Max Planck Institute for Chemistry, Mainz, Germany.

Burrows, J.P., Crutzen, P.J., Chance, K.V., Geary, J.C., Goutail, F., Harris, G.W., Moortgat, G.K., Muller, C., Perner, D., Platt, U., Pommereau, J.-P., Schneider, W. and Simon, P. 1988b. SCIAmini. *Technical Document*, Max Planck Institute for Chemistry, Mainz, Germany.

Burrows, J.P., Weber, M., Buchwitz, M., Rozanov, V.V., Ladstädter-Weissenmayer, A., Richter, A., de Beek, R., Hoogen, R., Bramstedt, K., Eichmann, K.-U., Eisinger, M. and Perner, D. 1999. The Global Ozone Monitoring Experiment (GOME): Mission Concept and First Scientific Results. *J. Atmos. Sci.,* 56, 151-175.

Chandra, S., Jackman, C.H., Fleming, E.L. and Russell III, J.M. 1997. The Seasonal and Long-Term Changes in Mesospheric Water Vapor. *Geophys. Res. Lett.*, 24, 639-642.

Crutzen, P.J., Grooß, J.-U., Brühl, C., Müller, R. and Russell III, J.M. 1995. A reevaluation of the ozone budget with HALOE UARS data: No evidence for the ozone deficit. *Science*, 268, 705.

Crutzen, P.J. and Stoermer, E.F. 2000. The anthropocene. *IGBP Newsletter*, 41, 17-18.

Holloway, A.M. and Wayne R. 2010. Atmospheric Chemistry. *Royal Society of Chemistry Publishing*, Cambridge, UK, ISBN: 978-1-84755-807-7.

Holton, J.R., Haynes, P.H., McIntyre, M.E., Douglass, A.R., Hood, R.B. and Pfister, L. 1995. Stratosphere-troposphere exchange. *Rev. Geophys.*, 33, 403-439.

IGACO. 2004. An Integrated Global Atmospheric Chemistry Observations Theme for the IGOS Partnership, IGOS Atmospheric Chemistry Theme Report. ESA-SP1282, WMO GAW Report No. 159, WMO TD No. 1235

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007 – The physical science basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.
available at http://www.ipcc.ch

Lovelock, J.E. 1979. Gaia: A new look at life on earth. *Oxford University Press*, Oxford.

Munro, R., Siddans, R., Reburn, W.J. and Kerridge, B.J. 1998. Direct measurement of tropospheric ozone distributions from space. *Nature*, 392, 168-171.

Shindell, D.T., Rind, D. and Logan, P. 1998. Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations. *Nature*, 392, 589-592.

Summers, M.E., Conway, R.R., Siskind, D.E., Stevens, M.H., Offermann, D., Riese, M., Preusse, P., Strobel, D.F. and Russell III, J.M. 1997. Implications of satellite OH observations for middle atmospheric H_2O and ozone. *Science*, 277, 1967-1970.

United Nations Economic Commission for Europe. 2007. Hemispheric Transport of Air Pollution 2007. *Air Pollution Studies*, 16, ISBN 978-92-1-116984-3, United Nations, New York and Geneva.

Wayne, R.P. 1992. Chemistry of Atmospheres. *Oxford University Press*, Clarendon Press, Oxford

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C.N., Dutton, E.G., Forgan, B., Kallis, A., Russak, V. and Tsvetkov, A. 2005. From Dimming to Brightening: Decadal Changes in Solar Radiation at Earth's Surface. *Science*, 308, 847-850, 2005

World Meteorological Organization (WMO). 1995. Scientific Assessment of Ozone Depletion 1994. *Global Ozone Research and Monitoring Project Report*, 37, Geneva.

World Meteorological Organization (WMO). 2003. Scientific Assessment of Ozone Depletion 2002. *Global Ozone Research and Monitoring Project Report*, 47, Geneva.

World Meteorological Organization (WMO). 2007. Scientific Assessment of Ozone Depletion 2006. *Global Ozone Research and Monitoring Project Report*, 50, Geneva.