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Climate and Weather of the Sun-Earth System (CAWSES)

Highlights from a Priority Program

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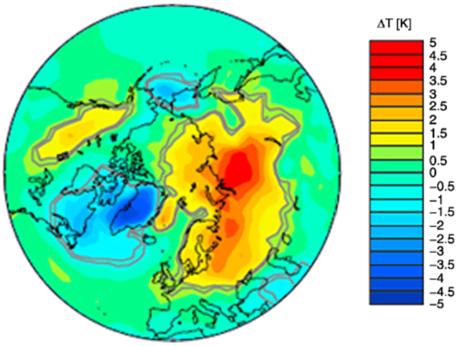
Foreword

The Sun, combined with the Earth's orbit, has always governed the activities of humanity on timescales from the changing seasons to glacial cycles. Changes in climate can be driven by alterations of the total solar irradiance (TSI) but recent evidence from satellites shows only modest changes in TSI which has only a minimal impact on the current changes that are being observed in the climate system. However the solar insolation at ultra-violet and extreme ultra-violet wavelengths changes from ∼7 % to more than 100 % over a solar cycle and hence can result in major changes in the middle and upper atmospheres. For example, weaker westerly winds at the Earth's surface are observed in winters at sunspot minimum, and at sunspot maximum the temperature of the thermosphere is about 400 K greater than at sunspot minimum and the winds are about twice as strong.

Energetic particles from the Sun can change the climate system too. Observations of surface air temperatures, derived from climate re-analysis data, show differences between periods when there are significant space weather events compared to those periods when events are absent [*Seppälä et al.*, 2009]. Differences can be as large as ∼4 K with areas of warming and cooling approximately the same suggesting a redistribution of energy. However, the mechanism by which these changes occur is not known.



As changes in the Earth's atmosphere occur, whether due to changes of solar origin or in response to enhanced green house gas concentrations, the propagation and dissipation of gravity and planetary waves, and tides is altered. Clouds, whether they occur in the troposphere, stratosphere and mesosphere have a marked impact on the atmosphere. Thus, changes can occur on all spatial and temporal scales and both within and between different levels of the atmosphere caused by solar variations.

Addressing the Sun-Earth connections is both an essential and urgent issue. To understand both the natural variability of the climate system and those caused by humanity is essential for the prediction of future climate scenarios that have greater confidence. Therefore it is timely for the international community to have a focused scientific effort to address these critical issues.

Research over previous decades has provided solid explanations of many of the individual processes that are involved in the coupling of the Sun to the Earth environment but to make real progress at these scientific frontiers a system-level approach is now required, and indeed possible for the first time. The necessary science infrastructure has developed to a point where it is possible to address these topics. The worldwide research community now has access to international data sets from every critical region in the space environment, a highly-distributed, ground-based network of sensor, virtual observatories, advanced computational and visualisation facilities, and sophisticated Sun-to-Earth community models.

But the availability of data and models is not enough; an operating framework is also required and this has been provided by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). It was established as an Inter-Union Commission of International Council of Science (ICSU) in 1966 with the aim to promote and organise international interdisciplinary programmes of limited duration in solar-terrestrial physics. In 2004 SCOSTEP began the Climate and Weather of the Sun-Earth System program—CAWSES—with the specific objective to enhance understanding of the space environment and its impact on space weather and the climate. CAWSES made very substantial progress since its inception not only in pushing back the frontiers of knowledge but also in building science capacity in developing countries. It held the first virtual conference which had 270 participants. After five years, it was recognised that there was much still to be achieved and hence SCOSTEP endorsed CAWSES-II to run from 2009–2013.There was re-focusing of the working groups to reflect the evolution of science questions but the fundamental aim remained the same.

CAWSES and CAWSES-II only provide a scientific strategy and framework that gives focus for the development of relevant science activities. For such international initiatives to be successful the engagement of scientists across many disciplines in many countries is essential. It needs passionate scientific leadership, and champions who can persuade funding organisations to support the research. Funding agencies also have to be willing to take initiatives, and sometimes risks. The Deutsche Forschungsgemeinschaft (DFG) German Research Foundation recognised the importance of Sun-Earth connection science and created a German CAWSES Priority Programme. The Programme, very ably led by Prof. Dr. Franz-Josef Lübken, has explored many aspects of Sun-climate links as is amply demonstrated by the comprehensive and illuminating chapters in this book stretching from fundamental solar physics through to the surface of the planet. There is an excellent blend of theory, observation and modelling. The Programme has also been very successful in educational terms giving many opportunities for early career scientists. We commend both the German CAWSES Priority Programme and the book—both are truly excellent exemplars for the research community.

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Chairs of CAWSES

Alan Rodger and Susan Avery

Preface

The Sun is the most important external driver of climate. Although the total solar irradiance (TSI) fluctuates by less than 0.1 % during a solar cycle, the solar impact on the terrestrial atmosphere can be significant, in particular in the upper atmosphere where the highly variable energetic part of the solar spectrum is absorbed. TSI variations on centennial time scales are of similar magnitude. Unfortunately, the scientific understanding of the variation of solar radiation (and its spectral components) and its impact on the atmosphere is rather limited. This concerns the direct modification of composition by solar radiation, but even more so various coupling mechanisms. For example, photochemically active gases are generated in the upper atmosphere, propagate to lower layers where they substantially alter the composition, e.g., the abundance of ozone. Planetary waves, gravity waves, and tides are excited in the atmosphere and propagate over large distances. They transport trace gases, energy, and momentum. Although these waves are most pronounced in the middle atmosphere, they may modify the background circulation in the entire atmosphere, even in the troposphere. As can be seen in various chapters in this book, major progress has been achieved in our understanding of solar radiation, its impact on the atmosphere, and coupling mechanisms within the atmosphere. Still, various uncertainties exist. For example, the observed solar signal in some parts of the middle atmosphere is larger than can be explained by models.

The purpose of this book is to summarise the scientific results related to a major research program of the international SCOSTEP organisation (Scientific Committee on Solar-Terrestrial Physics) called CAWSES (Climate And Weather of the Sun Earth System). The German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) ran a priority program (‘Schwerpunktprogramm’, SPP) from 2005 to 2011 focusing on several important science topics from CAWSES. The aim of the CAWSES SPP is a better understanding of the influence of the Sun on the terrestrial atmosphere and the physical/chemical processes involved in various coupling mechanisms within the atmosphere. The DFG spent approximately 10 Million Euro for a total of 25–30 institutes. Most of the financial support from DFG was used for postdoctoral and PhD student positions. In 31 chapters, this book presents the scientific summaries from 28 projects supported under a total of 93 individual grants. International cooperation was strongly encouraged and supported by funds for travel, etc. At each stage of the proposals, an international team of reviewers assisted the DFG in their selections. Several hundred papers were published in international peer reviewed journals within the priority program.

The book is structured in six parts, namely i) solar radiation, heliosphere, and galactic cosmic rays (Chaps. 2 to 6), ii) solar influence on trace gases (Chaps. 7 to 10), iii) thermosphere, energetic particles, and ionisation (Chaps. 11 to 17), iv) mesospheric ice clouds (Chaps. 18–20), v) gravity waves, planetary waves, and tides (Chaps 21 to 28), and vi) large-scale coupling (Chaps. 29 to 32). The evolution of solar radiation, its effect on galactic cosmic rays (GCR), and their potential impact on cloud droplets in the troposphere are studied in detail. Some chapters concentrate on the direct effect of solar radiation on trace gases, mainly on ozone and water vapour in the stratosphere and mesosphere. Precipitating particles of solar or geomagnetic origin modify the upper atmosphere directly. They also produce photochemically active species which can be transported downward and significantly affect the mesosphere and upper stratosphere. This aspect is studied in several chapters. Results on short and long-term variations of mesospheric ice clouds, as well as related microphysical aspects are presented. Planetary waves, gravity waves, and tides play a key role in distributing and modifying a signal being imposed somewhere in the atmosphere by, for example, the solar cycle. Physical details of this process and implications of wave morphology for the entire atmosphere, from the thermosphere to the troposphere, are presented in several chapters. Finally, results on global aspects of the solar cycle, long-term variations, and comparison with anthropogenic climate change are covered.

This book addresses researchers and students who are interested in actual results on solar cycle and long term variations in the atmosphere. The chapters are written by lead scientists from nearly all major German research institutions where the terrestrial atmosphere is investigated. A brief introduction is provided at the beginning of each chapter to familiarise a broader community with the scientific background. Each chapter was subject to an international peer review process to ensure high quality.

In the name of the German CAWSES community I thank the German Research Foundation for funding the CAWSES priority program. We appreciated the constructive and stimulating support from the reviewers, some of whom accompanied our program for the entire six years. As speaker of this program I would like to express my appreciation for all the activities, excitement, and success being created in various groups. Perhaps most important, many students were involved and contributed to the enthusiasm when working on a wide range of scientific topics of solar-terrestrial physics. I thank Dr. Norbert Engler and Monika Rosenthal for their excellent assistance when compiling this book.

Kühlungsborn Franz-Josef Lübken
February 2012

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Chapter 1
Scientific Summary of the German CAWSES Priority Program

Franz-Josef Lübken

Abstract The German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) launched a 'priority program' (Schwerpunktprogramm, SPP) focusing on science topics related to CAWSES (Climate And Weather of the Sun Earth System) which refers to a program of the international SCOSTEP organization (Scientific Committee on Solar-Terrestrial Physics). The CAWSES-SPP ran from 2005 to 2011. In 31 chapters, this book presents the scientific highlights from 28 projects supported under a total of 93 individual grants. This chapter summarizes some important results from this book and puts them into a CAWSES program perspective. Long-term trends and solar cycle variations in various parameters are studied in basically all chapters. Five chapters cover the evolution of solar radiation, its effect on galactic cosmic rays (GCR), and their potential impact on cloud droplets in the troposphere. Four chapters concentrate on the direct effect of solar radiation on trace gases, mainly on ozone and water vapor in the stratosphere and mesosphere. Precipitating particles of solar or geomagnetic origin modify the upper atmosphere directly. They also produce photochemically active species which can be transported downward and significantly affect the mesosphere and upper stratosphere. This aspect is studied in seven chapters. Microphysical aspects of mesospheric ice clouds, and their short and long-term variation, are studied in three chapters. Planetary waves and gravity waves (including tides) play a key role in distributing and modifying a signal being imposed somewhere in the atmosphere by, for example, the solar cycle. Physical details of this process and implications of wave morphology for the entire atmosphere, from the thermosphere to the troposphere, are presented in eight chapters. Finally, results on global aspects of the solar cycle and long-term variations are presented in four chapters. Basically all chapters involve observations and modeling.

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1.1 Introduction

The purpose of this chapter is to summarize some important scientific results from the remaining 31 chapters in this book. Considering the quantity and quality of scientific results presented in more than 600 pages, it is obvious that such a summary cannot cover all aspects. An important advantage of a concerted scientific action like this priority program of the German Research Foundation is that various groups with different expertise worked together on a common research topic. Indeed, basically all groups involved in the CAWSES-SPP had collaborations with other groups, thus creating substantial synergy effects. Some of the cross-references to other chapters in this book are explicitly mentioned in the text, while others are obvious from the context. Although CAWSES-SPP was primarily a German program, all projects had strong cooperations with several international research institutes.

The aim of CAWSES is a better understanding of the influence of the Sun on the terrestrial atmosphere on time scales from hours to centuries. The focus of the CAWSES-SPP was on scientific problems dealing with important aspects of the solar-terrestrial system. The Sun influences the atmosphere through the absorption of radiation and energetic particles, through the generation and modification of photochemically active trace gases, and through the generation of waves, including tides. The physical and chemical processes involved are coupled through various complicated mechanisms. Although the total solar irradiance fluctuates by less than 0.1 %, the solar impact on the terrestrial atmosphere can be significant, in particular in the upper atmosphere where the highly variable energetic part of the solar spectrum is absorbed. A local disturbance can be distributed over large vertical and horizontal distances through various coupling mechanisms such as transport of trace gases and propagation of waves. Figure 1.1 highlights some of the basic processes and important coupling mechanisms involved.

Medium and long-term variation of solar activity and its influence on the terrestrial atmosphere is also relevant to assess the importance of natural processes in long-term trends in comparison with anthropogenic influences. The following topics were investigated in the scope of this priority program:

- Characterization of the variability of solar forcing by electromagnetic radiation and by impact of energetic particles.
- Analysis of solar forcing on the thermal, dynamical, electro-dynamical, and compositional structure of the atmosphere in the height range from the upper troposphere to the lower thermosphere and on time scales from hours to centuries. This includes investigation of neutral gas, plasma, and aerosols.
- Investigation of the coupling mechanisms in the atmosphere, including transport of trace gases, and generation, propagation and destruction of waves (e.g., planetary waves, gravity waves, tides, turbulence).
- Identification and understanding of solar signals in atmospheric parameters which are not directly influenced by the Sun, including a study of the relevant physical and photochemical processes.
- Comparison of solar induced long-term variations with anthropogenic climate change.

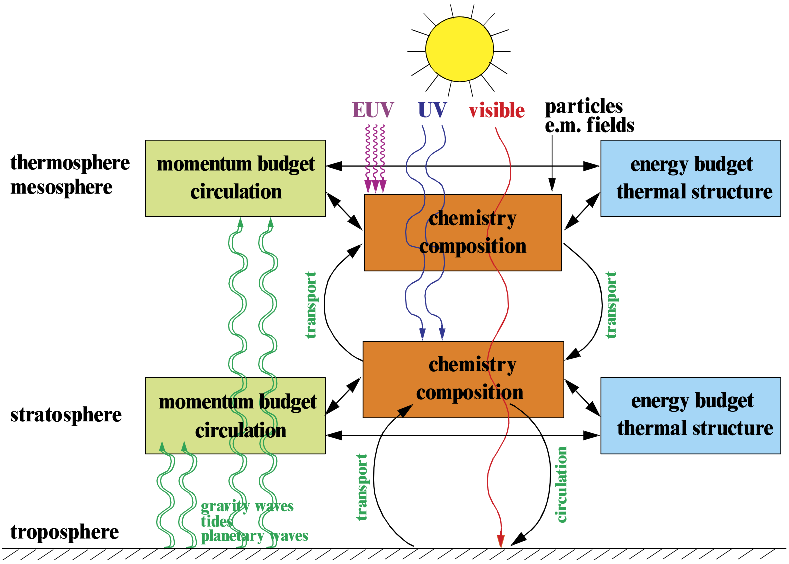


Fig. 1.1 Some fundamental physical/chemical processes of solar activity and coupling mechanisms affecting the Earth's atmosphere. Solar radiation and particles affect the terrestrial atmosphere from the thermosphere to the ground. Various coupling mechanisms exist which can distribute and modify the solar signal over large spatial scales. Several of these processes are studied in the CAWSES priority program. From *Lübken et al., J. Geophys. Res., 2010* (Copyright by American Geophysical Union)

Although space weather was not an explicit topic in the priority program, several results are highly relevant to this issue, for example tropospheric processes creating thermospheric tides which affect satellite orbits. This summary is organized according to the main topics covered in this book, namely

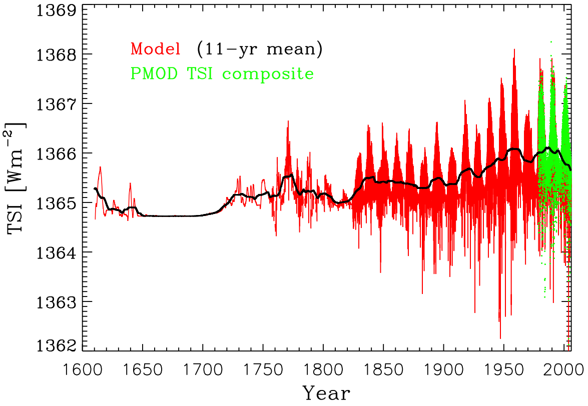
1. Solar radiation, heliosphere, and galactic cosmic rays (Chaps. 2 to 6)
2. Solar influence on trace gases (Chaps. 7, 8, 9, 10)
3. Thermosphere, energetic particles, and ionization (Chaps. 11 to 17)
4. Mesospheric ice clouds (Chaps. 18, 19, 20)
5. Gravity waves, planetary waves, and tides (Chaps. 21 to 28)
6. Large-scale coupling (Chaps. 29, 30, 31, 32)

For practical reasons, citations given in the chapters are not repeated here. Acronyms are listed at the end of the book.

1.2 Solar Radiation, Heliosphere, and Galactic Cosmic Rays

The first five chapters cover solar radiation and the modulation of galactic cosmic ray flux in the heliosphere and its potential impact on the troposphere. Solar variability is the most important external driver of climate. The reconstruction of total

Fig. 1.2 Total solar irradiance since 1610 reconstructed using the SATIRE-T model (*red line*) and the PMOD composite of measurements since 1978 (*green*). The 11-yr smoothed TSI is shown in *black*. From *Krivova et al.* (Chap. 2)



solar irradiance (TSI) and spectral solar irradiance (SSI) is important for a reliable evaluation of the connection between solar variability and Earth's climate. Unfortunately, our information about TSI and SSI is insufficient, increasingly so when going back in time. Satellite measurements are performed only since 1978, and telescope measurements of sunspots are available since 1610. Before that, cosmogenic isotopes such as ^{14}C and ^{10}Be are used as indirect indicators of solar variability. As is shown by *Krivova et al.* (Chap. 2) the physics-based SATIRE model reproduces TSI to an accuracy of a few percent if compared to satellite observations. It is confirmed that TSI has increased by ~1.25 W/m^2 since the Maunder minimum (Fig. 1.2). Surprisingly, the contribution of UV radiation to the solar cycle TSI variation is higher than previously considered. This has potential impact on the effect of solar cycle and long-term solar effects in the atmosphere.

The EUV and UV parts of the solar spectrum are absorbed in the mesosphere/lower thermosphere (MLT) and stratosphere, respectively. Therefore, a comprehensive study of the effect of solar radiation on photochemistry and composition requires measurements (or models) of spectrally resolved solar irradiance.

Weber et al. (Chap. 3) analyze SSI variations during the solar storm in October 2003 ('Halloween storm') and during solar cycles 21 to 23. Amongst others, they use first measurements of daily spectral solar irradiance from the UV to the near infrared from the SCIAMACHY satellite. During the Halloween storm, the irradiances in the near UV (above 300 nm), visible, and near IR are reduced(!) by about 0.4 %, which is in agreement with TSI reduction by the same amount observed by others. This reduction is much larger compared to solar cycle variations of TSI which is only ~0.1 %. The SCIAMACHY observations are compared to the net effect of brightening by faculae and darkening by sunspots, respectively. These features on the solar surface are described by solar proxies, namely Mg-II and sunspots, respectively. It is shown that proxy based models underestimate solar cycle changes in the UV. This challenges the application of solar proxies in chemistry models and highlights the importance of long-term measurements of SSI.

The effect of solar radiation on trace gases is investigated in several chapters. Solar rotation with a period of 27 days leads to variation of UV radiation (here

205 nm) which photolysis O_2 and thereby affects ozone. From observations by SCIAMACHY *Weber et al.* find only a small 27-d signal during solar cycle 23 (0.2 % ozone change for a 1 % change in UV radiation). The effect is not persistent in time.

The Sun modulates galactic cosmic rays (GCR) entering the solar system. GCR create cosmogenic isotopes such as ^{14}C and ^{10}Be. Speculations that GCR could affect climate directly through cloud production are controversially discussed in the literature. *Fichtner et al.* (Chap. 4) investigate in detail the modulation of GCR when entering the heliosphere, magnetosphere, and the terrestrial atmosphere. They show, for example, that the production of ^{10}Be depends on various time-dependent parameters most of which are not known accurately enough. The uncertainties of various cross sections alone result in an uncertainty of the production rate of ^{10}Be by $\sim$25 %. This has potential implications for the retrieval of long-term climate records from cosmogenic isotopes.

Rohs et al. (Chap. 5) try to identify the GCR effect on clouds by studying MIPAS cloud parameters relative to neutron count data indicative for GCR. They concentrate on six events of strong solar eruptions ('coronal mass ejections') where the interaction of solar wind with GCR particles leads to a significant decrease of GCR ('Forbush decreases'). Even for these strong events they found no, or only a weak correlation between GCR and high clouds. Still, considering the entire data set they conclude that a GCR effect on clouds cannot be excluded at this point.

The impact of solar radiation via cosmic rays is believed to be introduced through particle charging affecting cloud formation. Unfortunately, many steps are involved from the charging of nuclei and droplets to cloud formation. Little is known quantitatively about the physical mechanisms involved. *Rzesanke et al.* (Chap. 6) performed laboratory studies to characterize the influence of charges on the microphysics of cloud droplets. They quantify the enhanced scavenging of aerosol particles by charged cloud droplets and measure the size dependent contact freezing probabilities. They also found a substantial decrease of saturation vapor pressure in the vicinity of charged droplets which has so far not been taken into account in cloud modeling. These laboratory results are important not only for tropospheric clouds but also for ice particles in the mesosphere.

1.3 Solar Influence on Trace Gases

Four chapters cover the direct solar effect on trace gases in the middle atmosphere. More contributions to solar modulation of trace gases are described in Sect. 1.4. Ground-based microwave radiometry allows ozone and water vapor in the stratosphere and mesosphere to be measured nearly continuously. Some observations exist for several years which allows study of the impact of solar radiation on these trace gases on time scales from days to solar cycle. *Hartogh et al.* (Chap. 7) present water vapor and ozone measurements at high and middle latitudes (69°N and 52°N). They find an anti-correlation between H_2O and solar activity in the winter mesosphere, which is expected since enhanced photo-dissociation by Ly_α during solar maximum destroys water vapor. This anti-correlation is also present in summer but is much weaker and only in the uppermost part of the height range covered by the instrument (∼70–80 km). Below that altitude the correlation is positive in summer, which is explained by increased up-welling from the 'moist' stratosphere, and/or by additional photochemical sources for H_2O (autocatalytic production). Water vapor shows a general decrease since 1996 in the mesosphere, both in summer and winter. This is surprising since an increase of H_2O is generally expected due to the increase of methane in the troposphere (source for H_2O in the mesosphere).

Palm et al. (Chap. 8) present ground based microwave observations of ozone at Spitsbergen (78°N) on time scales from days to months. As is well known, mesospheric ozone concentration is larger during night since it is destroyed by photolysis during day. The authors perform a detailed analysis by measuring ozone as a function of solar zenith angle. Even in polar summer (when the Sun is above the horizon all day) a diurnal variation is observed which is explained by the wavelength dependent attenuation of UV radiation destroying ozone. The situation is complicated by the fact that UV radiation also produces ozone by generating atomic oxygen through photo-dissociation of O_2 (atomic oxygen is a key substance in the production of ozone). During the solar storm in October/November 2003 ('Halloween storm') they measure details of a strong ozone decrease (by up to 60 %) in the mesosphere and upper stratosphere. In short, ionization by solar protons produces HO_x which destroys ozone (see next section for more details). Since HO_x is short-lived, this effect disappears shortly after the solar storm is over.

Sinnhuber et al. (Chap. 9) construct a new long-term ozone data set using various measurements from satellites and data assimilation. This data set reproduces ozone variability on intra-seasonal time scales much better compared to ECMWF ERA-40 reanalysis. The data set is analyzed, concentrating on winter at high latitudes. Systematic variations ('anomalies') related to changes in the Northern Annular Mode (NAM) are detected. NAM describes a large-scale pressure and circulation pattern in the North Atlantic. Positive NAM index is associated with stronger, colder polar vortex, and reduced ozone, whereas a negative NAM index is associated with a disturbed polar vortex and intrusion of ozone rich air from lower latitudes. Anomalies in the autumn polar vortex and related Arctic ozone variations may persist for several months and may propagate downward from the stratosphere to the troposphere (Fig. 1.3). However, this signal may be distorted by tropospheric events propagating into the stratosphere. It is therefore not surprising that an earlier observation of an unexpected (and unexplained) correlation between ozone in autumn and ozone in spring is not confirmed. The new data set is also used to study long-term and decadal ozone trends, which are of general importance for trends in the middle atmosphere (see, for example, Chap. 18). On global scales total ozone has decreased by roughly 0.1–0.3 %/year in the period 1979–1999 (much stronger at SH polar latitudes), and has increased by up to 0.3 %/year thereafter (2000–2007). Interestingly, this change of trends is not only due to anthropogenic effects in gas-phase chemistry (including ozone destroying trace gases) and polar heterogeneous chemistry, but also due to climatological changes in meteorology (transport and temperatures).

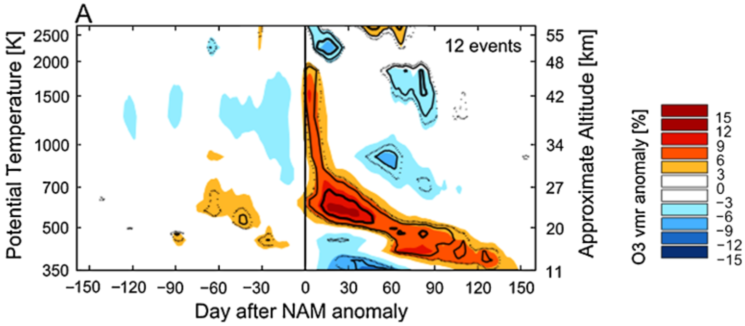


Fig. 1.3 Ozone anomalies (in percent relative to average conditions) north of 65°N relative to the beginning of a weak vortex (day 0). If the vortex is weak (negative NAM) ozone rich air from mid latitudes enters the polar region. The temporal/spatial characteristics of the anomaly is determined by a complex interaction of photochemistry and dynamics. The anomaly propagates from the stratosphere to the upper troposphere and is visible for several months. From *Sinnhuber et al.* (Chap. 9)

Kaufmann et al. (Chap. 10) deduce atomic hydrogen at ∼80–95 km from measurements of hydroxyl (OH) by SCIAMACHY and ozone by GOMOS. They concentrate on equatorial latitudes and find an ∼8 % increase of hydrogen from 2002 to 2008, i.e., in the declining phase of the solar cycle. They confirm that chemical heating rates are on the order of 4–10 K/day which is important for the energy budget at these altitudes. Heating rates have decreased from 2002 to 2008, which needs to be taken into account when studying solar induced long-term temperature variations in the MLT region.

1.4 Thermosphere, Energetic Particles, Ionization, and Impact on Trace Gases

From CHAMP measurements *Lühr and Marker* (Chap. 11) find significant local density enhancements (up to nearly doubling) in the upper thermosphere (∼400 km) at high latitudes. Combining these observations with EISCAT measurements they provide an explanation of these enhancements which involves a chain of processes originating from soft-energy particle precipitation, Joule heating caused by small-scale field-aligned currents, increasing temperatures, and finally an upwelling of 'molecular-rich' air from below. The amplitude of the enhancement increases with solar flux. This demonstrates that solar activity can influence thermospheric background not only by absorption of EUV radiation but also by rather indirect effects.

Satellite observations now allow to study ionospheric effects on planetary scales. *Arras et al.* (Chap. 12) use GPS measurements by CHAMP and other satellites to derive, for the first time, a global and comprehensive coverage of sporadic E-layers (E_s), i.e., an enhancement of ionization at ∼110 km altitude. They find maximum occurrence during daytime at mid latitudes of the summer hemisphere. The current theory of E_s formation is based on vertical convergence of ions and electrons caused by $\mathbf{v} \times \mathbf{B}$-forces originating from horizontal winds and the horizontal component of Earth's magnetic field. The authors support this theory by combining the morphology of E_s with observations of tidal parameters by meteor radars.

As is shown in several chapters, ion chemistry can significantly affect trace gases in the middle atmosphere (see below). It is therefore important for models to have a good representation of ionization. For the first time *Wissing et al.* (Chap. 13) present a 3D ionization model (AIMOS) based on satellite observations of energetic particles. AIMOS considers electrons, protons, and alpha particles. It combines solar and geomagnetic sources over a wide range of energies. The model is tested and improved by using observations from EISCAT. It turns out that ignoring some ionization processes (e.g., particles during the night) may lead to a substantial underestimate of electron densities, which may have severe consequences for ion chemistry modeling.

As has been mentioned above, high-quality radar measurements by EISCAT strongly supported the development of models and the interpretation of satellite observations. *Röttger et al.* (Chap. 14) summarize the operation of EISCAT and present the main scientific highlights where EISCAT contributed. There are several examples where the combination of EISCAT observations and models led to a better understanding of the physical/chemical processes involved.

It is known since several years that photochemically active species, being produced in the lower thermosphere and mesosphere, may be transported into the stratosphere where they significantly alter the concentration of trace gases such as ozone. In Chaps. 15 and 16 by *Reddmann et al.* and *Sinnhuber et al.*, respectively, new measurements from MIPAS and simulations by various models are used to study this important coupling mechanism. Some new and crucial details are identified. It is important to realize that particles with different energies ionize the polar atmosphere at different altitudes. For example, regular low energy electrons leading to auroras are absorbed in the MLT region, whereas high energy protons during solar proton events (SPEs) penetrate into the stratosphere. Both produce ions, which lead to photochemically active gases such as NO_x ($= N + NO + NO_2$) and HO_x ($= OH + H + HO_2$) destroying ozone. The relative importance and the altitude dependence of photochemical effects and their influence on trace gases are studied in these chapters.

Auroral electrons are much more frequent than SPEs but are commonly not considered to be important for stratospheric chemistry because they are absorbed at higher altitudes. However, during polar winter NO_x is transported downward to stratospheric altitudes. The photochemical lifetime of NO_x is large (weeks to months) because sunlight destroying NO_x is absent. In total, NO_x intrusions from the MLT region are likely to be more important for the chemical state of the middle atmosphere than SPEs (Fig. 1.4). NO_x intrusion can add 5 %–10 % of the total global NOy (NOy = all active nitrogen species including NO_x). At high latitudes, ozone is reduced by up to 50 % in the middle atmosphere, and total ozone is reduced by about 20 Dobson units. The effect lasts for several months. More important details are described in these chapters. For example, ion chemistry plays a crucial role

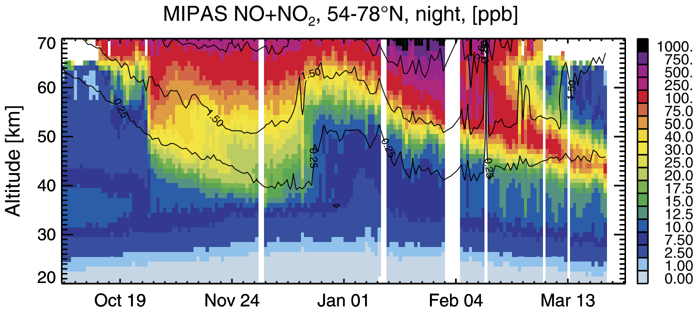


Fig. 1.4 MIPAS observations of NO_x ($NO + NO_2$) in the polar night. The color bar gives NO_x mixing ratios in ppb. The *black lines* are isolines of the CO mixing ratio for 0.25, 1.5 and 5 ppm, indicating transport. A large solar proton event in late October 2003 caused a significant enhancement of NO_x. However, even more NO_x is transported from the thermosphere to the stratosphere in January and February 2004 due to high geomagnetic activity which is not directly related to the SPE

in explaining the conversion of HCl to other chlorine species affecting ozone. Other photochemically active gases, such as HNO_3, are formed during SPEs. For the first time, an enhancement of H_2O_2 during a SPE was observed by MIPAS.

The downward transport of species from the lower thermosphere to the stratosphere depends on the general circulation of the atmosphere and thereby on gravity waves (see Sect. 1.6). This allows use of NO_x observations in the middle atmosphere to validate models which use different parameterizations for gravity waves. This topic was also covered in the HEPPA model comparison initiative. In summary, the transport of photochemically active gases from the thermosphere to the stratosphere is an important coupling process in the atmosphere which, amongst others, depends on dynamical coupling.

Baumgärtner et al. (Chap. 17) applied a whole-atmosphere model (MESSy), including various extensions, to study in detail particle precipitation effects in the entire atmosphere. Surprisingly, they find (in the NH winter) localized effects of geomagnetic activity from the MLT region all the way down to the troposphere(!), both in observations (ERA-40) and in the model. Sensitivity studies were performed to identify the physical mechanism which involves the production of NO_x, ozone destruction, heating of the stratosphere due to the reduction of IR cooling, and finally a modification of the polar vortex related to a stronger NAM index (stronger vortex) at high geomagnetic activity. In the troposphere NAM anomalies are related to weather anomalies. Further studies are required to confirm the effect of geomagnetic activity in the entire atmosphere and to better understand details of the proposed mechanism.

1.5 Mesospheric Ice Clouds

Mesospheric ice clouds are very sensitive to background conditions, in particular to temperatures, and are therefore suitable to improve our understanding of the middle