Exploitation of the mesosphere (MesosphEO)

Overview: mesospheric variability

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1 Introduction

This overview presents a literature study on variability patterns of chemical composition and thermal structure in the mesosphere and the lower thermosphere (MLT). The MLT region is characterized by very large variability due to photo-chemical and dynamical processes. The MLT region is strongly affected by waves (gravity, tidal, planetary), circulation and oscillation patterns (pole-to-pole circulation, QBO, SAO), as well as solar and geomagnetic influence. Below we overview the influence of the natural processes, which should be taken into account in the combined use the data from different instruments.

2 Photochemical Processes

Processes in the Earth's atmosphere associated with the interaction of atmospheric species with the incident solar light and associated chemical reactions are usually referred to as photochemical processes. The main mechanism involved is the photolysis of O_2, O_3, H_2O, H_2O_2, CO_2 and nitrogen species followed by chemical reactions between the photolysis products. A comprehensive list of the chemical reactions relevant for a modelling of a photochemical steady state in the middle and upper atmosphere is presented among others by e.g. *Allen et al.*[1981] and *Garcia and Solomon* [1983]. While below about 80 km the photochemical equilibrium is mainly controlled by chemistry resulting in a pronounced diurnal variation of the amounts of the photochemically active species, at higher altitudes the transport control starts dominating [*Meriwether*, 1989]. Because of low atmospheric densities at higher altitudes, some of the energy absorbed by the photolyzed species is released at considerable distance from the site of absorption. This phenomenon, is responsible for virtually all the heating at high latitudes in the lower thermosphere during winter [*Garcia and Solomon*, 1983].

Among other species the diurnal variation of ozone is most extensively quantified. As summarized by *Haefele et al.* [2008], odd oxygen (O_x=O+O_3) is produced during the day through photolysis of molecular oxygen. In the middle stratosphere (up to 40-44 km) all odd oxygen is in the form of ozone. As a consequence, ozone volume mixing ratios are enhanced during the day and reach a maximum in the late afternoon. At higher levels the [O]/[O_3] ratio increases owing to its inverse dependence on density. Therefore more and more of the odd oxygen resides as atomic oxygen and ozone shows a strong depletion during the day. After dusk all the O recombines with O_2 to O_3. In addition, odd oxygen is catalytically destroyed during the day by NO_x, ClO_x and HO_x.

As highlighted by *Schanz et al.* [2014], strongest diurnal variation in ozone appears mostly above 3–5 hPa (35 – 40 km). Analyses of the diurnal variations in mesospheric ozone with the ERA-Interim reanalysis data [*Dee et al.*, 2011], Whole Atmosphere Community Climate Model (WACCM) [*Garcia et al.*, 2007; *Marsh et al.*, 2007; *Tilmes et al.*, 2007] and global model and data assimilation system of MACC [*Inness et al.*, 2013] presented by *Schanz et al.* [2014] disagree in details but show a common general dependency with higher diurnal variations at higher latitudes. This finding is confirmed by the results from OZORAM radiometer [*Palm et al.*, 2010] located at Ny-Ålesund, Svalbard (78.9^{o}N, 11.9^{o}E) showing maximum diurnal variation (i.e. the difference between the maximum and minimum value) of ozone at 5 hPa of about 10%. Consistently, significantly lower values of about 2-3% for the maximum diurnal variation of ozone at this pressure level are shown by the microwave radiometer operating at Mauna Loa Observatory (19.5^{o}N, 204.5^{o}E) [*Parrish et al.*, 1992, 2014] and GROund-based Millimeter-wave Ozone Spectrometer (GROMOS) situated at the Bern NDACC site (47^{o}N, 7.5^{o}E) [*Dumitru et al.*, 2006; *Studer et al.*, 2014].

A comprehensive insight into the diurnal variation of ozone in terms of local time sampling and geographical coverage is given by the SMILES instrument providing vertical distributions of ozone in a wide range of local times in the latitude range from 38^{o}S to 65^{o}N (in the nominal mode) [*Sakazaki et al.*, 2013]. In the tropics, SMILES measurements show a diurnal variation of ozone of about $\pm$0.2 ppmv already above 30 km.

Diurnal variations of the mesospheric water vapor are much weaker and much less investigated compared to those of ozone. Comparing measurements from the Middle Atmospheric Water Vapor Radiometer (MIAWARA) [*Deuber et al.*, 2004] and model simulations, *Haefele et al.* [2008] report diurnal variations of the water vapor of about 1% at 3.14 hPa and significantly below 1% at 0.1 hPa. The authors highlight that daily variations of H_2O in the middle atmosphere are expected to be dominated by advection but the effect has not yet been investigated sufficiently. As for ozone, the most comprehensive data set on the diurnal variation of the mesospheric water vapor is provided by the SMILES instrument. As reported by *Kreyling et al.* [2013], the maximum of the H_2O volume mixing ratio is reached at noon. In the upper mesosphere, two maxima are visible, one at noon (0.025 hPa) and one, slightly higher (0.01 hPa) in altitude, at sunset. The nighttime HO_2 maximum appears later for higher altitudes (0.01–0.0025 hPa) before being destroyed at sunrise.

As summarized by *Ogawa and Shimazaki* [1975], the daytime NO profile has a peak around 110 km and a dip around 75 km. This feature is related mainly to the distribution of the NO production rate. The production of NO in the thermosphere occurs mainly through $N(^2D) + O_2 \rightarrow NO + O$ preceded by a photolytic destruction of N_2, whose maximum rates appears around 110 km, and the main sink of NO is the photolytic destruction. There is no appreciable production of NO in the mesosphere. Another source of NO, which occurs through decomposition of N_2O, exists in the upper stratosphere. There is only a weak day-to-night variation of NO in the 75 to 105 km range, whereas it strongly changes diurnally above and below this range. In the daytime mesosphere there is a strong coupling between NO and NO_2 through several interchange reactions and the photolytic destruction of NO_2. The [NO_2/[NO] ratio is established by the condition of photochemical equilibrium. In the nighttime the photochemical equilibrium for NO_2 is no longer valid in the mesosphere. Below ~75 km, NO is almost completely converted into NO_2 during the nighttime.

As pointed out by *Rodrigo et al.* [1991], the mesospheric and thermospheric concentration of CO_x ($CO+CO_2$), is mainly controlled by transport processes and is not very much affected by photochemical processes. CO_2 is transported upwards to altitudes above 100 km where it is photodissociated producing CO. The latter is transported downwards into the mesosphere where it is lost by the oxidation to CO_2. A recent study on the distribution of CO and CO2 has been carried out by *Garcia et al.* [2014] analyzing the ACE and MIPAS CO and CO2 measurements with the 3D WACCM model.

Using model studies, a very strong diurnal cycle of OH has been shown by *Rodrigo et al.* [1991]. Below 80 km, the diurnal variations of H and O control the OH variation, so that it decreases with the H and O concentrations in this altitude range. Below 80 km during evening twilight, there is an initial increase in the concentration of OH followed by a decrease, because at these altitudes and at the beginning of evening twilight, the decrease of the atomic hydrogen concentration H is smaller than the increase of O_3 concentration. Later on, the H decrease controls the OH behavior during the rest of the night. Above 80 km the OH variations are directly correlated with the O_3 evolution.

3 Waves

The dynamics of the mesosphere-lower thermosphere (MLT) (60 to 110 km) is dominated by waves and their effects [*Vincent*, 2015]. The basic structure of the MLT is determined by momentum deposition by small-scale gravity waves, which drives a summer-to-winter pole circulation at the mesopause. Atmospheric tides are also an important component of the dynamics of the MLT. Observations from extended ground-based networks, satellites as well as numerical modelling show that non-migrating tidal modes in the MLT are more important than previously thought, with evidence for directly coupling into the thermosphere/ionosphere. Major disturbances lower in the atmosphere, such as wintertime sudden stratospheric warmings, temporarily disrupt the circulation pattern and thermal structure of the MLT. Below a short overview of the MLT variability caused by waves is presented.

3.1 Planetary waves

3.1.1 Sudden stratospheric warmings and their effects in the MLT

Sudden Stratospheric Warmings (SSWs) are large scale perturbing events in the winter polar regions that affect the structure and circulation of the middle atmosphere. SSWs are caused by dissipation of planetary waves in the upper stratosphere [*Matsuno*, 1971; *Schoeberl*, 1978; *Holton*, 2004]. During a SSW, the zonal mean temperature in polar stratosphere increases by several tens of Kelvins in few days. The warming is accompanied with a weakening of zonal winds and disturbance of the polar vortex. In case of major sudden stratospheric warming, the zonal mean wind is reversed and the polar vortex can break down completely.

It is known since the work of *Matsuno* [1971] that SSWs are accompanied with a cooling in the mesosphere. This was explained in his paper as a result of the mean flow and planetary wave interaction based on mass balance. *Holton* [1983] pointed out that the changes in the mean wind profile alter the conditions for the gravity wave propagation and result in reduced gravity wave momentum flux in the mesosphere, which leads to mesospheric cooling via reducing wave-induced diabatic descent [*Garcia and Boville*, 1994]. In addition, a lower thermospheric warming has been observed [*Funke et al.*, 2010]. The latter is thought to be caused by a secondary downward flow induced by an equatorward mesospheric circulation, which is generated by the net eastward forcing due to gravity wave breaking [*Liu and Roble*, 2002].

It has been recently discovered that some of the sudden stratospheric warmings (as observed in 2004 and then again in 2006, 2009 and 2012) result in unusual subsequent features: dramatic cooling at ~50 km, then the reformation of stratopause near 80 km, following by the enhanced downward transport from the mesosphere and thermosphere into the polar vortex area. Observational evidence of enhanced downward transport of trace species has been reported in several papers [*Funke et al.*, 2005, 2014; *Manney et al.*, 2005, 2008; *Randall et al.*, 2006, 2009; *Hauchecorne et al.*, 2007; *Smith et al.*, 2009; *Sofieva et al.*, 2009; *Renard et al.*, 2009; *Damiani et al.*, 2010; *Pérot et al.*, 2014].

The short-term changes in the chemical composition and temperature structure of the mesosphere in response to SSWs are large, up to a few hundreds of percent, as reported in observational studies using the satellite measurements [*Manney et al.*, 2009; *Damiani et al.*, 2010; *Sofieva et al.*, 2012]. They are caused by changes in both chemistry (the rates of chemical reactions depend on temperature) and dynamics (changes in vertical motion and mixing).

3.1.2 The quasi-two-day wave and its impact on the MLT

The quasi-two-day wave (QTDW) is a primarily westward travelling planetary wave that is of considerable interest because it can be one of the largest features of the MLT [*Vincent*, 2015]. It is a transitory phenomenon appearing after the summer solstice and is primarily a zonal wave number 3 phenomenon in the southern hemisphere but is often a mixture of wave numbers 3 and 4 components in the northern hemisphere.

Studies of radar and airglow emissions from the MLT by *Hecht et al.* [2010] found the airglow intensity response was much larger than what would be expected from the airglow temperature response, suggesting that the QTDW is causing a significant composition change, possibly due to minor constituent transport. Combining temperature measurements made with the MLS and SABER satellite instruments, *Forbes and Moudden* [2012] explored interactions between the QTDW and various tidal modes.

Due to its large amplitude (up to 100 ms^{-1} in zonal wind, more than 10 K in temperature), the QTDW has significant impact on the MLT and its variability.

3.2 Gravity waves

According to the present theory (see review by *Fritts and Alexander* [2003]), the internal gravity waves (GW) are generated in the troposphere above mountains, above convective zones and in the jet streams. They propagate upward with growing amplitude (caused by decreasing air density) until they reach instability conditions and break down. The turbulence, generated by the breaking of GW, leads to effective turbulent mixing of the atmosphere and to dissipation of kinetic energy into heat at the final step of this process.

Gravity waves have broad spectra. The intrinsic periods can range from a few minutes up to a few tens of hours; the vertical wavelength can range from a few meters up to a few kilometers, and the horizontal wavelengths cover the scales from a few hundreds of meters up to a few hundreds of kilometers [*Fritts and Alexander*, 2003; *Alexander and Barnet*, 2007].

In the mesosphere, the GW amplitude is so large that GW become unstable and break down. The rms of temperature perturbations in the mesosphere due to gravity waves usually exceed 5 K (e.g., [*Ern et al.*, 2011]). The atmospheric density and density perturbations induce also corresponding perturbations in trace gases, but a dedicated study on this phenomenon has not been performed so far.

The wave propagation and breaking produces a drag on the background flow. Since it tends to occur continuously and globally, it affects the global circulation and chemical composition of the middle atmosphere. The understanding of the global effects of the relatively small-scale gravity waves is continuously improving. Gravity waves are responsible for the observed reversal of the summer-to-winter temperature gradient in the upper mesosphere. As a relatively recent finding, it was suggested that gravity wave breaking can stimulate the strong downward transport of mesospheric air masses (NO_x rich) to lower altitudes in the polar vortex region [*Hauchecorne et al.*, 2007], which can, in turn, cause ozone depletion in the high-latitude winter stratosphere [*Funke et al.*, 2005; *Randall et al.*, 2006, 2009; *Hauchecorne et al.*, 2007; *Siskind et al.*, 2007, 2010]. The role of gravity waves in shaping the mesospheric response to sudden stratospheric warmings (which dominate the variability of Northern Hemisphere wintertime stratospheric circulation) has been recognized and actively discussed [*Holton*, 1983; *Garcia and Boville*, 1994; *Dowdy et al.*, 2007; *Wang and Alexander*, 2009], but it still remains not sufficiently quantified [*Siskind et al.*, 2010].

While the lapse rate is generally positive in the mesosphere (decreasing temperatures with height), it is common to find there localized regions of negative lapse rate. These are known as mesospheric inversion layers, with the temperature difference in the layer up to 40 K locally and ~10 K in monthly mean. They are caused by the interaction of waves, tides, and the mean flow [e.g., *Meriwether and Gardner*, 2000; *France et al.*, 2015]. Mesospheric inversions were first observed by *Schmidlin* [1976], and since then have been extensively documented using in situ and satellite temperature data. Mesospheric inversion layers are known to be climatological features in the mesosphere-lower thermosphere, persisting for days and spanning thousands of square kilometers [e.g., *Hauchecorne et al.*, 1987; *Leblanc and Hauchecorne*, 1997; *Meriwether and Gardner*, 2000; *Duck and Greene*, 2004; *France et al.*, 2015]. The gravity wave breaking plays an important role in forming the mesosphere inversions.

3.3 Tides

Atmospheric tides (or tidal waves) are large scale oscillations that play an important role for the dynamics in the mesosphere and above where their amplitudes grow to a substantial size. They couple different layers of the atmosphere and their signatures can be observed in many geophysical parameters, starting with winds, temperature and pressure. Correspondingly also trace gases are affected, either through transport or modified chemistry.

3.3.1 Generation, types, propagation

Tides can by excited by a number of ways. The most prominent way is the periodic absorption of solar radiation. The main contributions arise from the absorption of infrared radiation by water vapor in the troposphere, the absorption of ultraviolet radiation by ozone in the stratosphere and through the absorption of ultraviolet and extreme ultraviolet radiation by oxygen molecules and atoms in the mesosphere (and lower thermosphere) [*Chapman and Lindzen*, 1970; *Forbes*, 1995]. Another important excitation mechanism is the large-scale latent heat release from deep convection, particular in the tropics [*Forbes et al.*, 1997; *Hagan and Forbes*, 2002]. Non-linear interactions between different tides or between tides and planetary waves give also rise to this phenomenon [*Teitelbaum and Vial*, 1991; *Hagan and Roble*, 2001]. Other mechanisms involve land-sea differences, longitudinally asymmetric topography as well as the gravitational pull of the sun. Also the gravitational pull of the moon can excite tides, which are referred to as lunar tides (opposite to solar tides, as tides excited by the other mechanisms are often collectively referred to) [*Chapman and Lindzen*, 1970]. The gravitational force is to a lesser extent exerted directly onto the atmosphere but mainly mediated through the Earth's oceans. The dissipation of tides occurs mostly in the thermosphere.

There are two classes of tidal oscillations, i.e. migrating und non-migrating tides, which are related to the excitation mechanisms outlined above. Migrating solar tides are sun-synchronous and move westward with the apparent motion of the sun. They have typically periods that are harmonics of the solar day, most prominently 24 h (diurnal tide) and 12 h (semi-diurnal tide). Observations also exhibit periods of 8 h (ter-diurnal tide) and 6 h (quar-diurnal tide) [e.g., *Smith*, 2000; *Smith et al.*, 2004; *Moudden and Forbes*, 2013]. The seasonal variation is given through the changing sun position and hence the excitation pattern. This can be applied analogously for lunar migrating tides whose periods are harmonics of the lunar day. This refers to the period of two consecutive moonrises at given location on Earth. This period is a bit longer than a solar day, i.e. 24 h 51 min.

Non-migrating tides on the other hand are excited by a longitude-dependent source, such as latent heat release, topography or land-sea contrasts. As such non-migrating tides do not follow the apparent motion of the sun (or moon). They can propagate both east- and westward or be stationary.

As tides propagate through the atmosphere away from their excitation region their amplitudes increase with altitude if no damping occurs, like for gravity waves. In this case, the amplitude increases exponentially with altitude due to decreasing air density and the conservation of kinetic energy. The amplitudes are typically largest for those tides generated by solar heating. Tides have a pronounced latitude and seasonal dependence. The solar diurnal migrating tide shows the largest amplitudes in the tropics and sub-tropics, where it commonly dominates the tidal spectrum in the mesosphere. It typically peaks around equinox [*Burrage et al.*, 1995; *Hagan et al.*, 1997; *McLandress*, 1997]. Diurnal non-migrating tides have a very similar latitude-dependence [*Oberheide et al.*, 2006; *Wu et al.*, 2008]. The solar semi-diurnal migrating tide dominates at mid-latitudes given the annual variation in insolation in this region [*Burrage et al.*, 1995]. Effects of the semi-diurnal non-migrating tide have been noticed at all latitudes [*Hagan and Forbes*, 2003]. In terms of vertical wavelengths tides can exhibit a broad spectrum from about 10 km to infinite wavelengths. In the latter case their phase remains constant with altitude.

Tides are modified by the background atmosphere and also modify the background themselves. The generation of new tides by interactions with other waves is one aspect of this. QBO, ENSO and solar cycle influence on tides have been found by a number of studies [e.g., *McLandress*, 2002; *Gurubaran et al.*, 2005; *Oberheide et al.*, 2009; *Pancheva et al.*, 2014]. For the analysis of long-term changes in many mesospheric parameters diurnal variations by tides (and other processes) and their change need to be accounted for [e.g., *Beig et al.*, 2003; *DeLand et al.*, 2007].

3.3.2 Observations of solar tide effects

Tidal variations can be observed in many atmospheric parameters, e.g., mesospheric temperature, ozone, water vapor. Hereafter, the differences between maximum and minimum values are referred to as the amplitudes of tidal variations.

She et al. [2002] presented lidar observation at Fort Collins (41°N/105°W), which showed clear tidal variations in upper mesospheric temperatures. Yearly averages for the diurnal tide indicated amplitudes of 8 K while the semi-diurnal tide was somewhat stronger with amplitudes up to 12 K. In seasonal averages the tidal amplitudes were found to be significantly larger, peaking at about 20 K for the wintertime semi-diurnal tide in the uppermost mesosphere. *Shepherd and Fricke-Begemann* [2004] combined observations from lidar and the UARS/WINDII (Upper Atmosphere Research Satellite/Wind Imaging Interferometer) instrument to analyze amplitudes of thermal tides at low and mid-latitudes. At 55°N and 89 km, the diurnal, semi-diurnal and ter-diurnal tides showed amplitudes of 10 K, 8K and 5 K, respectively, averaged over boreal winter. At 28°N in November, the diurnal variation was similar, but for the other two components the amplitudes were approximately twice as large as at mid-latitudes. At 86 km in the latitude range between 40°S and 40°N Forbes and Wu [2006] found diurnal migrating tides with amplitudes of 20 K, based on measurements of UARS/MLS (Microwave Limb Sounder). Even towards higher latitudes the amplitude of this tide was about 4 K to 8 K. The semi-diurnal migrating tide exhibited typically an amplitude of 4 K to 8 K at this altitude, peaking with somewhat higher values at low latitudes in February or around 60°N/S during spring. Besides that smaller non-migrating tides were detected. Towards lower altitudes the tidal variation was found to be smaller but not negligible. First observations of thermal tides in the Antarctic during summer season were reported by *Lübken et al.* [2011]. The observed amplitudes were typically of the order of 4 K to 8 K in the altitude range between 84 km and 96 km, for both the diurnal and semi-diurnal tide. Overall these amplitudes were considerably larger than expected from tidal theory. A first-order guidance in terms of tidal signatures in temperature (and wind) is available in form of the GSWM model (Global Scale Wave Model, *Hagan and Forbes*, 2003; *Zhang et al.*, 2010a, 2010b). This is a two-dimensional, linearized, steady-state model focusing on tides and planetary waves up to the thermosphere. However, there is a tendency to underestimate the amplitudes in comparison to the observations as pointed out in the publications above (and others).

Photochemistry dominates the diurnal variation of ozone in the mesosphere. However, there are secondary tidal effects that influence ozone. This considers on one hand tidal variations of temperature that change reaction rates for ozone due to their temperature dependence. On the other hand the ozone distribution is closely linked to atomic oxygen. This constituent has a considerably longer life time, especially in the upper mesosphere and is thus influenced by tidal variations [*Smith et al.*, 2008, 2010]. TIMED/SABER (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics/Sounding of the Atmosphere using Broadband Emission Radiometry) observations exhibited large ozone volume mixing ratios at the equator around 95km during equinox. Based on a simple model, *Smith et al.* [2008] could attribute those to the diurnal migrating tide. Overall these simulations indicated tidal variation of 30 ppmv at these altitudes at equinox. *Pancheva et al.* [2014] analyzed contributions from diurnal and semi-diurnal non-migrating tides in the same region and found peak amplitudes of up to 2 ppmv in October.

Diurnal variations of water vapor are mostly due to tides. So far only a few reports exist, all based on ground-based radiometers. *Haefele et al.* [2008] and *Scheiben et al.* [2013] reported on observations near Berne (47°N/7°E) showing dominating diurnal tides with variations of 0.1 ppmv in the altitude range between 0.1 hPa and 0.01 hPa. *Hallgren and Hartogh* [2012] analyzed measurements at ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research, 69°N/16°E) showing larger variations than at Berne. The diurnal tide dominates over the semi-diurnal tide and peaks with values more than 0.5 ppmv at equinox in the altitude range between 70 km and 75 km.

3.3.3 Observations of lunar tide effects

The moon's gravitational attraction is responsible for tidal oscillations not only of the oceans, but also in the Earth's atmosphere. There exist different tidal contributions associated with the moon's orbit around the Earth [e.g., *Forbes et al.*, 2013], but the lunar semidiurnal tide with a period of 12.421 solar (synodical) hours is the most important one. The lunar semidiurnal atmospheric tide was for the first time successfully identified in surface pressure data in 1832 by *Sabine*, [1847], who analyzed pressure data taken at St. Helena. The first identification of the lunar semidiurnal tide in surface pressure at extra tropical latitudes was carried out by Sidney Chapman [*Chapman*, 1918] and was based on 64 years of hourly surface pressure readings.

The amplitudes of the tidal signatures generally increase as the tides propagate vertically in the atmosphere and reach considerable values in the MLT region. The lunar semidiurnal tide has been identified in MLT winds [*Stening et al.*, 1987, 2003; *Sandford and Mitchell*, 2007] with amplitudes of up to about 5 m/s in the mesopause region. It has also been identified in the MLT temperature field with amplitudes on the order of 0.5 – 1 K at mesopause altitude [*Forbes et al.*, 2013; *von Savigny et al.*, 2015] and about 5 K at 110 km altitude [*Forbes et al.*, 2013].

After the international geophysical year 1957/1958 several studies attempted to identify lunar tidal signatures in airglow emissions. However, most studies failed to convincingly demonstrate the presence of a lunar tidal signature, probably due to the short duration of the data sets [e.g., *Davidson*, 1963; *Huruhata*, 1965; *Forbes and Geller*, 1972]. Lunar tidal signatures in airglow emissions and OH rotational temperatures were reported by, e.g. *Semenov and Shefov* [1997] and *Khomich et al.* [2008]. However, the amplitudes of some of the signatures identified in these studies are surprisingly large, and partly inconsistent with other studies. Recently, *von Savigny et al.* [2015] employed a 10-year data set of OH and O green line nightglow emissions – as well as atomic oxygen and OH(3-1) rotational temperature – retrieved from SCIAMACHY nightglow measurements to identify statistically significant lunar semidiurnal tidal signatures. Apart from the identification of lunar tidal signatures in all parameters studies, a consistent relationship between all reported signatures was found. In addition, the SCIAMACHY observations were in good agreement with model simulations with the Global Scale Wave Model (GSWM).

Several studies were published on lunar tidal signatures in noctilucent clouds (NLC) or polar mesospheric clouds (PMC). The studies by *Kropotkina and Shefov* [1975], *Gadsden* [1985], *Gadsden and Schröder* [1989] and *Dalin et al.* [2006] are all based on visual NLC observations by ground-based observers. Several of these studies report lunar tidal amplitudes in cloud occurrence of 30%, which is surprisingly large. In addition, the identified tidal periods differ significantly between the studies, casting doubt on the validity of the results. *von Savigny et al.* [2016] were the first to employ non-visual NLC observations to search for lunar tidal signatures. They used the 30+ year SBUV(/2) satellite data set and identified highly significant lunar tidal signatures in NLC occurrence frequency and NLC ice water content with a relative amplitude of about 5%. In addition, the lunar phase in NLC parameters was found to be consistent with the phase of the lunar temperature tide at the polar summer mesopause.

4 Circulation and oscillation patterns

The mesosphere-lower thermosphere is dominated by the effects of atmospheric waves. As explained in the previous section, these waves (planetary waves, gravity waves, tides) have a direct effect on the thermal and chemical structure of the MLT. They also have a strong effect on the mesospheric circulation which, in turn, affects even more its thermal structure and chemical composition. The mesosphere is characterized by a large-scale meridional circulation from the summer pole to the winter pole, driven by gravity wave breaking and dissipation [*Brasseur and Solomon*, 2005]. In addition, oscillation patterns or major disturbances in the stratosphere may significantly modify the GW fluxes, and hence lead to significant changes in the wind, thermal and chemical structure of the MLT. This includes the Quasi-biennial-oscillation (QBO) [*Baldwin et al.*, 2001] and the Semi-Annual Oscillation (SAO) [*Garcia et al.*, 1997] in the tropical zonal wind, as well as sudden stratospheric warmings. This section presents a literature review of the mesospheric variability due to these circulation and oscillation patterns.

The pole-to-pole circulation at the mesopause leads to upwelling/downwelling of air over the summer/winter pole, associated with adiabatic cooling/heating, respectively. These vertical motions produce temperatures that are more than 50 K cooler or warmer than would be expected by radiative equilibrium alone. This leads to extremely cold conditions in the summer-time upper mesosphere region at high latitudes, associated with an increase in water vapor volume mixing ratio (VMR), which results in the formation of Polar Mesospheric Clouds (PMC), also called Noctilucent Clouds (NLC). These clouds have been observed by a number of instruments, and their climatology is now well known [e.g., *Thomas et al.*, 1991; *Pérot et al.*, 2010; *Gumbel and Karlsson*, 2011; *García-Comas et al.*, 2016]. PMCs affect in turn the background atmosphere. Areas of depleted water vapor due to ice growth are found above the cloud layer, while regions of enhanced water vapor due to sublimation are found near the bottom of the PMC layer [*Christensen et al.*, 2015; *Hervig et al.*, 2015]. The pole-to-pole circulation also causes significant perturbations of the chemical composition in the winter hemisphere. Species with sources in the MLT can be locally enhanced in the polar region, due to rapid downward motion of air. *Randall et al.* [2007] showed that nitric oxide (NO) produced by energetic particle precipitation (EPP) in the upper mesosphere and lower thermosphere is transported down to the lower mesosphere. This leads to increases in EPP-reactive nitrogen (NO_y) compounds (NO, NO_2, HNO_3, N_2O_5, $ClONO_2$ and HNO_4). The highest concentrations are observed in the winter solstice mesosphere, decreasing continuously with time and towards lower latitudes. The whole mesospheric altitude range, as well as the upper and middle stratosphere is affected by these changes in chemical composition, as springtime peaks in NO_y concentration are found around 25 km [*Funke et al.*, 2014]. Several studies have shown that mesospheric concentrations of other trace species that are more abundant in the thermosphere are also characterized by a peak in winter. Penetration of carbon monoxide (CO) into the polar vortex was observed by MIPAS for example [*Funke et al.*, 2014]. *Smith et al.* [2010] found a wintertime maximum of atomic oxygen around 85 km at high latitudes. *Damiani et al.* [2010] showed that observed OH perturbations in the Northern high latitudes were also due to downward transport. In contrast, trace species that have their sources at lower altitude, like CH_4 and H_2O, are characterized by a decrease in concentration during polar winter, due to descending CH_4- or H_2O-poor mesospheric air [*Orsolini et al.*, 2010; *Funke et al.*, 2014]. WACCM simulations of the mean mesospheric circulation and its impact on the wintertime transport on trace species are presented in *Smith et al.* [2011].

During NH winter, the circulation is often disturbed by SSWs as discussed on Sect 3.1.

The zonal mean zonal wind QBO is observed in the lower tropical stratosphere with a maximum at around 30 km, having an amplitude close to 20m/s [e.g., *Reed*, 1966]. Such oscillations, with opposite phases, have also been inferred for the upper mesosphere based on satellite measurements [*Burrage et al.*, 1996]. In the upper mesosphere, the zonal mean zonal winds of the SAO peak near 80 km with velocities of about 30m/s, westward during equinox and eastward around solstice. These two modes of oscillations of the zonal wind are mainly produced by dynamical processes confined at low latitudes, and lead to variations in mesospheric temperatures. *Huang et al.* [2006] derived these variations based on measurements from the SABER/TIMED instrument. According to this study, the mesospheric thermal QBO is characterized by two separate peaks. The first one is observed near 70 km with amplitudes reaching 3.5 K, and the second one is observed around 85 km with amplitudes of 2.5 K, both with a period between 24 and 29 months. The mesospheric SAO also shows separate peaks of about 7 K near 75 km and 90 km, within about 15° of the Equator. The amplitudes vary from year to year and decrease away from the Equator, but they recover again to reach substantial magnitudes at mid-latitudes. The SAO can also be seen in the mesospheric chemical composition. *Lossow et al.* [2008] have shown that a clear semi-annual variation in the water vapor distribution appeared in the entire mesospheric altitude range in the equatorial area, based on Odin/SMR measurements. It also exhibits a double peak structure, with maxima near the equinoxes at about 75 km and around the solstices at 81 km. The phase reversal occurs in the small layer in between, consistent with the downward propagation of the SAO in zonal wind in this altitude range. Furthermore, in the Northern hemisphere subtropics, higher H_2O VMRs are observed during summer than during winter.

5 Influence of solar and geomagnetic activity

5.1 27-day solar cycle effects

The number of studies dealing with solar-driven 27-day signatures in mesospheric parameters is quite limited. *Hood et al.* [1991] reported on solar-driven 27-day signatures in mesospheric ozone and temperature retrieved from measurements from the SME IR spectrometer and the SAMS instrument on the Nimbus-7 spacecraft, respectively. Both the temperature and the ozone response show a phase relationship to solar forcing that varies with altitude. *Hood et al.* [1991] speculate that a combination of photochemical, thermal and dynamical mechanisms is responsible for the observed phase relationship. Solar 27-day signatures in mesopause temperature were also identified in SCIAMACHY OH(3-1) rotational temperature retrievals at low latitudes by *von Savigny et al.* [2012]. Using a superposed epoch approach the epoch averaged 27-day signature had an amplitude of about 0.3 K and was found to be statistically highly significant. This study also determined the sensitivity (in K/(100 sfu)) of mesopause temperature to solar forcing at the 27-day time scale (sfu stands for solar flux units and corresponds to the unit of the F 10.7 cm radio flux). The obtained sensitivity was 2.46 (± 0.93) K/(100 sfu), which agrees well with most published values of the temperature sensitivity for the 11-year solar cycle [e.g., *Beig et al.*, 2008].

Shapiro et al. [2012] extracted solar 27-day signatures from MLS/Aura observations of OH and H_2O in the upper tropical mesosphere. Around 80 km altitude OH is found to be in phase with solar forcing, whereas H_2O is negatively correlated with a phase lag of about 7 days. The identified 27-day responses in both OH and H_2O are significantly larger for higher solar activity compared to solar minimum condition. The phase lag between solar forcing and H2O is more or less consistent with the photochemical lifetime of H_2O [e.g., *Gruzdev et al.*, 2009], implying a dominantly photochemical driver of the 27-day signature in mesopause H_2O at low latitudes. The MLS/Aura data set was also recently used to extract a solar 27-day signature in mesospheric HO_2 [*Wang et al.*, 2015].

A completely different phase relationship between mesopause H2O and solar forcing is observed at the polar summer mesopause. This mesospheric region is of interest because it hosts noctilucent clouds, also known as polar mesospheric clouds. *Robert et al.* [2010] discovered a solar 27-day signature in NLC observations with SCIAMACHY as well as the SBUV(/2) instrument series using cross correlation and superposed epoch analysis methods. The authors also demonstrated that the immediate cause of the signature is a 27-day signature in polar summer mesopause temperature. However, the underlying mechanism(s) driving the 27-day signature in NLC parameters were unclear.

Temperature at the polar summer mesopause is more or less in phase with solar forcing (with a time lag of a few days at most), and H_2O varies out of phase [*Thomas et al.*, 2015]. This phase relationship between solar forcing and the H_2O response is inconsistent with photochemistry. The fact that the 27-day responses in temperature and H_2O are almost perfectly anti-correlated is strong evidence for a 27-day modulation of the vertical wind, e.g. enhanced upward motion is associated with adiabatic cooling and upward transport of H_2O rich air – and vice versa. Different pieces of evidence that the 27-day signature in NLC is dynamically driven are presented in *Thomas et al.* [2015], *Thomas et al.* [2016], *Thurairajah et al.* [2016] and *von Savigny et al.* [2013].

Recently, a solar-driven 27-day signature has been identified in atomic oxygen in the tropical MLT region by *Lednytskyy et al.* [2016]. This study is based on MLT atomic oxygen retrievals from SCIAMACHY O green line nightglow measurements. The signature has relative amplitude of 1 – 2 %

and a phase of 10 – 12 days, i.e. the maximum in atomic oxygen occurs 10 – 12 days after the maximum in solar activity. This phase lag is inconsistent with a pure photo-chemical mechanism – i.e. enhanced O is produced by enhanced photolysis of molecular oxygen – and may be an indication for downward transport from the lower thermosphere, where most of the atomic oxygen is produced photo-chemically.

In summary, solar 27-day signatures have been successfully identified in various mesospheric parameters (temperature, ozone, atomic oxygen, H_2O, OH, HO_2 and noctilucent clouds), but establishing the underlying physico-chemical mechanisms that drive these signatures is challenging. Recent studies suggest that dynamical mechanisms may play a key role for 27-day signatures in the upper mesosphere and may involve planetary waves [*Huang et al.*, 2015], 27-day modulation of solar thermal tides [*Pancheva et al.*, 2003] as well as potential 27-day modulations of the vertical propagation of gravity waves.

5.2 11-year solar cycle effects

11-year solar cycle signatures have been identified in experimental studies in a variety of mesospheric parameters, including temperature, H_2O, ozone, atomic oxygen, hydrogen, OH* emissions, and noctilucent clouds.

Model simulations of the 11-year solar cycle response of the Earth's middle atmosphere were carried out, e.g. using the WACCM [*Marsh et al.*, 2007] and HAMMONIA [*Schmidt et al.*, 2006] models.

11-year solar cycle effects in mesospheric ozone were studied by *Beig et al.* [2012]. This study is based on HALOE satellite observations in combination with HAMMONIA model simulations. In the lower mesosphere an insignificant solar cycle response in ozone is found, but in the upper mesosphere the sensitivity is about 5% / (100 sfu). The recent study by *Huang et al.* [2016] – being based on SABER ozone observations – comes to somewhat different conclusions, because the ozone response to solar forcing is positive between 80 and 100 km, and negative between 50 and 80 km. Between 80 and 100 km the 11-year solar cycle signature in ozone is found to be positively correlated with the corresponding signature temperature. Between 50 and 80 km, the 11-year signatures in the two parameters are negatively correlated.

Beig et al. [2008] provided a comprehensive review of the knowledge of solar effects on mesospheric and lower thermospheric temperature, considering a variety of experimental techniques and different altitude ranges. For the 50 – 80 km altitude range the majority of cited studies report a positive correlation between solar activity and mesospheric temperature with peak-to-peak temperature differences of up to 5 K (see Table 2 in *Beig et al.* [2008]). The experimental methods include satellite observations, rocket sondes, lidars, rocket grenades and falling spheres. For the mesopause region the low and mid-latitude observations typically find temperature sensitivities of 1 – 4 K /(100 sfu) – in good agreement with the 27-day temperature sensitivity reported above. However, two high northern latitude studies find 11-year solar cycle effects that are not significantly different from zero (Fig. 4 in *Beig et al.* [2008]).

Jacobi [1998] reports on an 11-year solar cycle signature in zonal winds in the upper mesosphere for northern mid-latitudes. During the winter months no statistically significant solar cycle effect is observed, but during the summer the zonal wind is negatively correlated to solar activity.

The 11-year solar cycle in NLC/PMC is well documented in the literature. *Thomas et al.* [1991] were the first to identify an 11-year signature in NLC observations with the SBUV satellite instruments. 11-year signatures have been reported in NLC albedo [*DeLand et al.*, 2007] and NLC occurrence frequency [*Shettle et al.*, 2009] – particularly during solar cycles 21 and 22. The 11-year signature in NLC is out of phase in terms of solar forcing, suggesting that polar summer mesopause temperature is more or less in phase with solar activity. This was confirmed, e.g., by *Hervig and Siskind* [2006], who analyzed 13 years of HALOE temperature, H_2O and NLC observations. The temperature difference between solar maximum and minimum was about 5K at the polar summer mesopause in both hemispheres. *Hervig and Siskind* [2006] also report an 11-year solar cycle effect in H_2O at the polar summer mesopause. At 80 km the signature has amplitude of about 1 ppmv and is anti-correlated to solar activity. During the declining phase of solar cycle 23 and the inclining phase of solar cycle 24 the year, however, there is no clear 11-year solar cycle effect in NLC observations. This finding is currently not fully understood.

An 11-year solar cycle signature was found in MLT atomic oxygen retrievals based on SCIAMACHY O green line nightglow measurements at 557.7 nm wavelength [*Kaufmann et al.*, 2014; *Zhu et al.*, 2015; *Lednytskyy et al.*, 2016]. The retrieval methodology allows deriving atomic oxygen from about 88 to 105 km altitude. The studies find a relative variation in O from solar maximum to solar minimum of about 15% near 90 km altitude, increase to about 25% near 100 km, which is in reasonable agreement with model studies based on the WACCM [*Marsh et al.*, 2007] and HAMMONIA [*Schmidt et al.*, 2006] models.

Kaufmann et al. [2013] report on 11-year solar cycle effects in MLT atomic hydrogen (H). The H retrievals are based on SCIAMACHY OH Meinel emission observations in combination with GOMOS MLT ozone retrievals.

The OH Meinel emissions have also been reported to exhibit 11-year solar cycle signatures [*Teiser and von Savigny*, 2016]. An 11-year solar cycle was found in vertically integrated OH(3-1) and OH(6-2) emission rates, as well as in OH(6-2) emission altitude. In OH(3-1) emission altitude, no statistically significant 11-year solar cycle signature was found.

The solar cycle effect has also been observed recently in the CO and CO2 distributions in the upper mesosphere/lower thermosphere [e.g., *Garcia et al.*, 2016].

5.3 Effects of energetic particle precipitation

Energetic particles—protons, electrons, and heavier ions—that precipitate into the atmosphere come from different sources: directly from the Sun in large solar particle events (SPEs), from the radiation belts during geomagnetic storms and substorms, or from outside the solar system [*Sinnhuber et al.*, 2012]. The particles from these various sources have different energy spectra thus affecting different altitudes and geographic regions.

Solar particles come from the solar wind throughout the solar cycle, or from large solar coronal mass ejections. Solar coronal mass ejections are more frequent during the maximum of the 11-year solar cycle. Solar proton events (SPE) are a consequence of coronal mass ejections, when large amounts of protons and heavier ions are emitted from the Sun. Guided by the Earth's magnetic field, the protons precipitate into the polar cap areas [*Patterson et al.*, 2001]. Since the protons can have very high energies, up to hundreds of MeVs, they deposit their energy in the mesosphere and stratosphere, thus providing a direct connection between the Sun and the middle atmosphere.

Precipitation of energetic particles into the atmosphere greatly disturbs the chemical composition from the upper stratosphere to the lower thermosphere. Most important are changes to the budget of atmospheric nitric oxides (NOx = N, NO, NO2) and to atmospheric reactive hydrogen oxides (HOx = H, OH, HO2), which both contribute to ozone loss in the stratosphere and mesosphere. While changes in HOx are short-term – from a few hours to a few days, changes to the NOx budget due to energetic particle precipitation can be quite long-lived during polar winter and can then be transported down into the lower mesosphere and stratosphere, where NOx is one of the main participants in catalytic ozone destruction.

Satellite measurements have allowed detailed analyses of dramatic changes in the middle atmosphere composition caused by SPE during the last decade [e.g., *Seppälä et al.*, 2004, 2006, 2007; *Jackman et al.*, 2005; *López-Puertas et al.*, 2005; *Verronen et al.*, 2006, 2007; *Funke et al.*, 2011, 2014; *Damiani et al.*, 2012]. According to these studies, HOx and NOx abundances in the mesosphere can increase by a several orders of magnitude, and ozone loss can reach 80-90%.

Energetic electron precipitation (EEP) from the Earth's outer radiation belt continuously affects the chemical composition of the polar mesosphere. EEP can contribute to catalytic ozone loss in the mesosphere through ionization and enhanced production of odd hydrogen. Using satellite measurements by GOMOS, MLS and SABER, *Andersson et al.* [2014] have shown that EEP events strongly affect ozone at 60–80 km, leading to extremely large (up to 90%) short-term ozone depletion. This impact is comparable to that of large, but much less frequent, solar proton events. On solar cycle timescales, we find that EEP causes ozone variations of up to 34% at 70–80 km [*Andersson et al.*, 2014].

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