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Trends in the Neutral and Ionized Upper Atmosphere

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Abstract This article reviews our knowledge of long-term changes and trends in the upper atmosphere and ionosphere. These changes are part of complex and comprehensive pattern of long-term trends in the Earth's atmosphere. They also have practical impact. For example, decreasing thermospheric density causes the lifetime of orbiting space debris to increase, which is becoming a significant threat to important satellite technologies. Since the first paper on upper atmosphere trends was published in 1989, our knowledge has progressed considerably. Anthropogenic emissions of greenhouse gases affect the whole atmosphere, not only the troposphere. They cause warming in the troposphere but cooling in the upper atmosphere. Greenhouse gases such as carbon dioxide are not the only driver of long-term changes and trends in the upper atmosphere and ionosphere. Anthropogenic changes of stratospheric ozone, long-term changes of geomagnetic and solar activity, and other drivers play a role as well, although greenhouse gases appear to be the main driver of long-term trends. This makes the pattern of trends more complex and variable. A consistent, although incomplete, scenario of trends in the upper atmosphere and ionosphere is presented. Trends in F2-region ionosphere parameters, in mesosphere-lower thermosphere dynamics, and in noctilucent or polar mesospheric clouds, are discussed in more detail. Advances in observational and theoretical analysis have explained some previous discrepancies in this global trend scenario. An important role in trend investigations is played by model simulations, which facilitate understanding of the mechanisms behind the observed trends.

Keywords Global change · Long-term trends · Ionosphere · Upper atmosphere

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1 Introduction

The anthropogenic emissions of greenhouse gases influence the troposphere, weather, and climate. They appear to be the primary driver of a significant increase of surface temperature in recent decades, thus affecting directly our life. Another anthropogenic pollution of the atmosphere, ozone depleting substances, is responsible for depletion of the Earth's stratospheric ozone layer, particularly in Antarctica, in the form of the spring ozone hole. Both greenhouse gases and ozone depleting substances thus affect the environment, and can adversely influence human health. However, these polluting substances affect not only the troposphere and stratosphere, their effect is observed to penetrate throughout the upper atmosphere, including the mesosphere (∼50–90 km), the thermosphere (∼90–1000 km), and the ionosphere, which is embedded in the upper atmosphere (e.g., Rishbeth and Roble 1992; Laštovička et al. 2006a). The thermosphere is the operating environment of many satellites**,** including the International Space Station, and thousands of pieces of space debris, the orbital lifetime of which depends on long-term changes of thermospheric density. Propagation of Global Positioning System (GPS) signals and radio communications are affected by the ionosphere, so anthropogenic changes of these high-altitude regions can affect also satellite-based technologies which are increasingly important to modern life. As with global change near the Earth's surface, the challenge facing upper atmosphere climate scientists is to detect long-term trends and understand their primary causes, so that society can mitigate against potential harmful changes.

The 0.6°C increase in global surface air temperature during the twentieth century (e.g., IPCC 2007) has been attributed predominantly to the increasing atmospheric concentration of greenhouse gases. However, the greenhouse gas increase has an opposite, cooling effect in the upper atmosphere. Greenhouse gases in the troposphere are optically thick to outgoing longwave (infrared) radiation, which they both absorb and reemit back to the surface to produce the heating effect. In contrast, greenhouse gases in the much lower density upper atmosphere are optically thin to outgoing infrared radiation. In-situ collisional excitation results in atmospheric thermal energy readily lost to space via outgoing infrared radiation, while the absorption of radiation emanating from the lower atmosphere plays only a secondary role in the energy balance. The net result is that the radiatively active greenhouse gases act as cooling agents, and their increasing concentrations enhance the cooling effect in the upper atmosphere. This effect of greenhouse gases may be called "greenhouse cooling" (Cicerone 1990).

The global atmosphere is close to a hydrostatic equilibrium, which means that the height of a given pressure surface is determined by the average atmospheric temperature below. The cooling is expected to result in thermal contraction of the upper atmosphere and we may expect a significant decline in thermospheric density at fixed heights, which was observed in long-term satellite drag data (e.g., Emmert et al. 2008). Downward displacement of ionospheric layers should accompany this contraction. The cooling will also affect chemical reaction rates and, thus, the chemistry of minor constituents, resulting in further changes to the ionosphere.

The combination of the lower atmosphere heating and the upper atmosphere cooling is supported by a much stronger greenhouse effect that is observed on Venus where the 96% concentration of carbon dioxide in the atmosphere and a more dense atmosphere result in a troposphere that is more than twice as warm as the Earth's troposphere and a thermosphere that is 4–5 times colder than the Earth's thermosphere (e.g., Bougher and Roble 1991). While the Earth's troposphere is much colder than the thermosphere, the Venusian troposphere is substantially warmer than the thermosphere

Long-term changes in the upper atmosphere and ionosphere have been of interest since pioneering study of Roble and Dickinson (1989). They suggested that global cooling will occur in the upper atmosphere in conjunction with global warming in the troposphere due to long-term increase of greenhouse gas concentrations, particularly carbon dioxide (CO_2). Modeling studies by Rishbeth (1990) and Rishbeth and Roble (1992) broadened these results to the thermosphere-ionosphere system. Investigation of long-term changes in the upper atmosphere has become a significant topic in global change investigation, and many results have been published in the last twenty years (e.g., Aikin et al. 1991; Akmaev 2003; Akmaev and Fomichev 2000; Akmaev et al. 2006; Alfonsi et al. 2002, 2008; Beig 2000, 2006; Beig et al. 2003; Bencze 2009; Bremer 1998, 2001, 2005, 2008; Bremer et al. 2004, 2006, 2009a; Bremer and Berger 2002; Bremer and Peters 2008; Cannon et al. 2004; Chandra et al. 1997; Clemesha et al. 1992; Clilverd et al. 2003; Cnossen and Richmond 2008; Danilov 1997, 2002, 2005, 2008a, 2008b, 2009; DeLand et al. 2006, 2007; Elias 2009; Emmert et al. 2004, 2008; Fomichev et al. 2007; Foppiano et al. 1999; Garcia et al. 2007; Gavrilov et al. 2002; Golitsyn et al. 2000; Gruzdev and Brasseur 2005; Hall et al. 2007a, 2007b; Holt and Zhang 2008; Keating et al. 2000; Jacobi et al. 2005, 2006, 2008, 2009; Jarvis 2006; Jarvis et al. 1998, 2002; Keuer et al. 2007; Kirkwood et al. 2008; Kubicky et al. 2008; Laštovička 2002, 2005, 2009; Laštovička et al. 1994, 2006a, 2006b, 2008a, 2008b; Laštovička and Bremer 2004; Laštovička and Pancheva 1991; Lübken 2000, 2001; Marcos et al. 2005; Marsh et al. 2003; Merzlyakov et al. 2009; Mikhailov 2002, 2006a, 2006b, 2008; Mikhailov and de la Morena 2003; Mikhailov and Marin 2000, 2001; Nedoluha et al. 2003; Offermann et al. 2004; Ortiz de Adler et al. 2002; Portnyagin et al. 2006; Qian et al. 2006, 2008, 2009; Remsberg 2007; Rishbeth 1997; Schmidt et al. 2006; Semenov et al. 2002; Sharma et al. 1999; Shettle et al. 2009; Smirnova et al. 2010; Sridharan et al. 2010; Ulich et al. 2003, 2007; Ulich and Turunen 1997; Xu et al. 2004; Yue et al. 2006, 2008).

In the early period of long-term trend studies in the upper atmosphere, results of individual studies were often inconsistent and sometimes controversial. However, with the increasing amount of observational and model results and findings, a global pattern of trend behavior began to emerge, and, in 2006, the first global scenario of trends in the upper atmosphere and ionosphere was constructed (Laštovička et al. 2006a, 2008a). However, at that time results concerning some variables were not consistent with the global scenario. Moreover, in recent years it became increasingly clear that other drivers play an important role in long-term trends in the upper atmosphere and ionosphere, in addition to the increasing atmospheric concentration of greenhouse gases, which is the dominant driver of upper atmosphere trends.

This paper provides contemporary information, reviews recent developments and suggests some directions of future research in the field of the long-term trends in the upper atmosphere and ionosphere. We focus primarily on the ionosphere and thermosphere, but long-term trends in the mesosphere are also treated. Observational and modeling results are mixed together; the structure of the paper is topical rather than methodological. Section 2 discusses the term “long-term trend” in order to clarify the topic of investigation. Section 3 describes difficulties and problems in trend investigations. Section 4 deals with other drivers of trends. Section 5 presents the global scenario of trends in the upper atmosphere and ionosphere and some results supporting this scenario. Sections 6–8 describe recent developments in three areas which were initially inconsistent with the global scenario of trends, namely the F2-region ionosphere, middle atmospheric dynamics, and noctilucent or polar mesospheric clouds. Section 9 treats aspects of the recent development of modeling of trends in the upper atmosphere and ionosphere, including current problems to be overcome by future development. Section 10 contains a brief discussion of possible or desirable future development of trend investigations. Section 11 closes the paper with a summary and conclusions.

2 What Does the Term "Long-Term Trend" Mean?

Most authors understand the term "trend" as a "long-term trend", i.e. as a long-term tendency of essentially monotonic or quasi-linear change, either an increase or decrease of the values of a particular variable with time. If the long-term behavior is substantially unstable on medium time-scales, or oscillatory, the term "long-term change" is usually used. Strictly speaking, trends are often not linear. However, in most cases the linear trend approximation is sufficient, and in other cases we use the linear approximation to facilitate comparison with trends in other parameters. Ideally, a trend continues to infinity. In reality, a period of quasi-stable trends begins and ends in concrete years/periods. An example would be the Antarctic ozone hole, which appeared in the late 1970s, has recently stabilized, and it is expected to disappear in the second half of this century. Since the mutual role of some trend drivers in the upper atmosphere and ionosphere, and in some cases even the sign of their effect, change with time (e.g. ozone), an overall linear trend cannot be stable in time, and in reality a quasi-stable trend should begin and end within a certain period. Such behavior may be characterized by a sophisticated mathematical curve, but may often be approximated by the so-called piecewise contiguous linear trend model (Weatherhead et al. 2000; Reinsel et al. 2005), wherein substantially different linear trends are fit to the data within different time intervals, the latter also being model parameters. Upper atmosphere and Ionosphere linear trends should be understood in such a way, even though for some parameters the period of quasi-stable trend may be identical with the period of available data for trend studies, i.e. such trends might appear to be monotonic.

It is also possible to use a slightly different and more mathematical approach. A truly linear trend in a time series, by definition, corresponds to the lowest frequencies that are not taken into account in a spectral decomposition. More precisely, quoting Kendall (1973) "The essential idea of the trend is that it shall be smooth", which is equivalent to a continuous slowly varying change in a time series over long time scales (Graigmile et al. 2004). Assuming the trend is not a small temporal part of a major very long period cycle or due to some temporally-coincident stochastic change, then it is possible to temporally and spectrally decompose the time series to separate the oscillatory and true trend elements using, for instance, the wavelet transform technique. However, practical application of such an approach has to be made with care, as the trend has a non-infinite period limited by the length of the dataset or by the limited length of the stable trend interval. This is probably the reason why the attempt of a Chilean team to use such an approach in foF2 trend analysis (Laštovička et al. 2006b) was unsuccessful (Laštovička et al. 2008b).

3 Difficulties and Problems—Methodology, Data Uncertainties, Natural Variability

Important points to be discussed in relation to long-term trend studies include various uncertainties in data, the long-term consistency of measurements, and effects of applications of different methods of trend determination. These issues are particularly important for detecting weak trends in noisy time series, for instance trends in foF2. Different methods have been developed for extracting long-term trends from particular data sets. These methods often include either averaging or interpolation procedures, and thus it is very difficult to compare trend estimates obtained by different authors. Ulich et al. (2003) discussed some practical problems of determining long-term change.

Long time series of measurements need to be consistent. Instrumental changes and malfunctions need to be well documented and corrected for, and subsequent instruments must be well inter-calibrated with previous ones, which is of particular importance for satellite-based data. Before attempting to compute any trend, one has to verify whether or not the time series in question includes instrumental effects. Inhomogeneous data series are one of the reasons of differences of results of different authors. Furthermore, historic time series usually contain data gaps, which have to be treated with care. Some methods of analysis require continuous data sets with constant sampling frequency, but interpolation can introduce incorrect data points, which might skew the results of the analysis.

In the F2-region of the ionosphere, studies of the F2-layer peak height, hmF2, suffer from an additional complication. The height cannot be directly scaled from ionograms; for historical data it was computed from the critical frequencies of the E and F2 layers as well as the propagation parameter M(3000)F2 using empirical formulae. These formulae were derived in the 1970s based on various regional data sets and to be simple and straightforward enough to be used by the computers of those times, but these formulae are by no means globally valid, and their use results in different trends. It is necessary to carefully verify which one is applicable to the area in question.

Atmospheric time series usually vary on diurnal and seasonal time scales. In order to see beyond this variability, cyclic influences on the measurements need to be properly removed and/or considered in interpretation of results. This is usually done by fitting multi-parameter models to the data. Care must be taken that these cyclic parameters are adequately removed and/or considered, especially if the diurnal and seasonal sampling is not uniform.

Solar activity can have a crucial impact on trend determination when data series are relatively short, or when trends in the ionosphere or thermosphere are estimated. However, the effect of the 11-year solar cycle can often be suppressed or minimized with proper selection of the analyzed period, with application of corrections for solar activity, or by studying the residuals from empirical models based upon solar (and geomagnetic) inputs, season, latitude and time. However, for variables with very strong solar cycle effects and weak trends, such as foF2, even relatively small “remnants” of solar cycle effects may influence determination of long-term trends and, thus, different methods of removal/suppression of the solar cycle effect may contribute to differences between various reported trends. Solar activity changes are usually represented by the F10.7 and E10.7 indices, or by sunspot numbers. Estimated trends can be sensitive to the choice of solar activity proxy; for example, the use of sunspot numbers instead of F10.7 or E10.7 produces less reliable trends for F2-layer parameters (Laštovička et al. 2006b).

The temporal extent necessary to obtain reliable trend estimates from a data set is not easy to determine (Weatherhead et al. 2002). For a time series beginning and ending at different phases of the solar cycle, even if it covers several solar cycles, residual solar cycle effects affect the estimated trend. If the trend estimate is plotted as a function of the length of the time series it is derived from, a damped oscillation results, the decay rate of which can be used to estimate the number of years of data required to produce a reliable trend (Jarvis et al. 2002; Clilverd et al. 2003).

One relatively little known factor, which affects the magnitude of determined trends, is data smoothing, e.g., in the form of running averages, which may artificially improve the statistical significance of results if the reduction in the number of degrees of freedom is not accounted for properly. This also tends to reduce the magnitude of trends, as illustrated by the behavior of trends in foF2 (Laštovička et al. 2006b).

Comparison of the results of different methods of trend determination applied to the same data set of foF2 values showed good agreement among some methods, but substantially different results were obtained by other methods (Laštovička et al. 2006b). This is the case for trends that are much weaker than overlapping natural variations. On the other hand, strong trends, as expected, appear to be essentially method-independent, as documented by Križan and Laštovička (2005) for laminae in ozone profiles.

Long-term changes of solar activity and/or an increase of geomagnetic activity throughout the twentieth century might play an important role in the observed long-term trends. This is treated in the next section about other drivers of trends.

4 Drivers of Long-Term Trends

Which agents are responsible for the observed long-term trends? The main reason for the observed long-term trends is considered to be the increasing concentration of greenhouse gases (predominantly CO_2) in the atmosphere, which affects the whole atmosphere from the surface up to heights of several hundred kilometers, both in the neutral and ionized component. However, there are also other drivers of long-term changes and trends in the upper atmosphere, which cannot be neglected (e.g., Laštovička 2009).

In the thermosphere and ionosphere, several drivers can play a role in long-term trends. Solar activity appears to have decreased during in the second half of the 20th century, and particularly in the beginning of the 21st century, which is a tendency opposite to what is required to explain the observed ionospheric trends in the E and F1 regions. Moreover, the effect of solar activity, on solar cycle time scales, can be reduced when long-term trends are computed both in the ionosphere and thermosphere. Different corrections to solar activity is one of the sources of differences between different trend results in F2-region parameters, foF2 and hmF2. Thus, solar activity itself has little or no direct effect on observed ionospheric trends.

However, it is necessary to mention that trends may be quantitatively different under solar activity maximum and minimum conditions, which is the case for thermospheric density (e.g., Emmert et al. 2008). For thermospheric density the reason is much larger relative role of the CO_2 radiative cooling compared to the NO radiative cooling under solar minimum conditions (Qian et al. 2006). The NO radiative power decreased by almost an order of magnitude from 2002 to 2009, whereas the CO_2 radiative power decreased only by $\sim$35% according to SABER/TIMED measurements (Mlynczak et al. 2010). This effect may be considered as an indirect effect of solar activity on trends in the thermosphere and ionosphere.

Another potentially important driver of trends is geomagnetic activity and its long-term changes, an increase of geomagnetic activity throughout the twentieth century (Clilverd et al. 1998; Stamper et al. 1999; Mursula and Martini 2006), even though due to some calibration/instrumental problems in the 1950s the increase is probably smaller than thought earlier (e.g., Martini and Mursula 2008). Geomagnetic activity might be even dominant in trends in foF2. Laštovička (2005) found that in the 20th century the role of geomagnetic activity in the observed long-term trends/changes in the atmosphere-ionosphere system was decreasing from its beginning towards its end. Mikhailov and de la Morena (2003) found that trends in foE were controlled by geomagnetic activity before about 1970, but not in more recent years. Bremer et al. (2009a, 2009b) found that the change of dependency of trends on long-term change of geomagnetic activity occurred around 1970 in the E region, in mid 1990s in the F1 region, and around 2000 in the F2 region. Quite recently, the geomagnetic

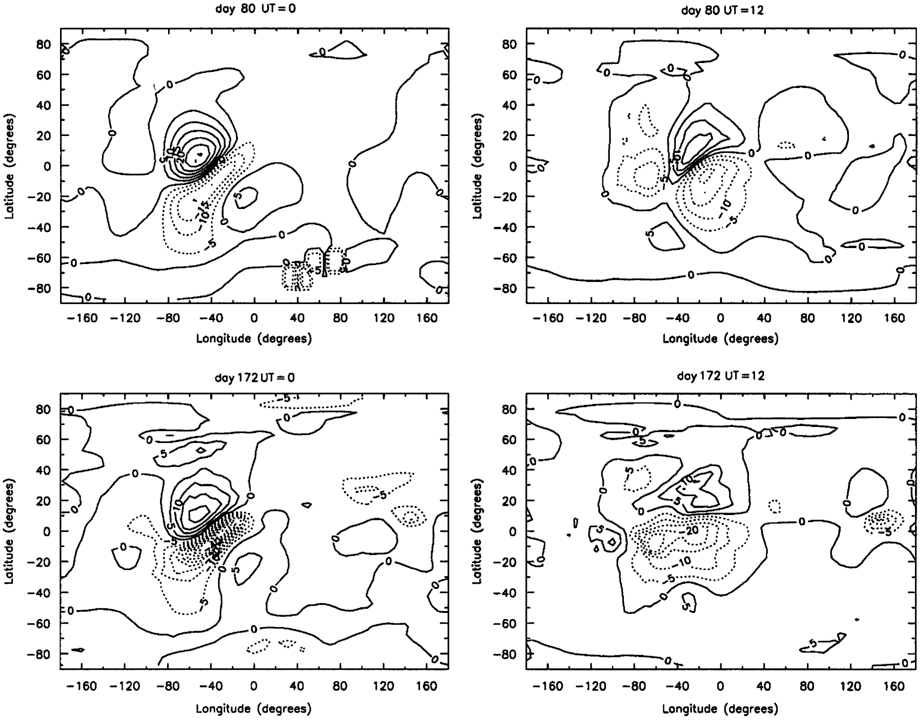


Fig. 1 TIE-GCM model simulation of effect of changes of the Earth's magnetic field in hmF2 (difference between 1997 and 1957 in km) at day 80 (*top*) and day 172 (*bottom*), 00 UT (*left*) and 12 UT (*right*). After Cnossen and Richmond (2008)

activity control of trends was lost even in the F2 region, as it will be discussed in more detail in Sect. 7. Thus it seems that currently the long-term changes in geomagnetic activity are not the main driver of trends in any variable, contrary to past years, when it probably controlled ionospheric trends.

A regionally important driver is the secular change of the main magnetic field of the Earth, which forces the International Association of Geomagnetism and Aeronomy (IAGA) to issue every five years a new reference map of the surface magnetic field (IGRF—International Geomagnetic Reference Field). Figure 1 shows the results of model computations using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) of the impact of long-term (secular) changes of the Earth's magnetic field on hmF2, the height of maximum of the ionosphere (fof2 and/or maximum electron density provide a very similar pattern). This effect is insignificant in most regions, but in the equatorial to mid-latitude Atlantic Ocean and in the South America it seems to play a substantial role in trends in hmF2 and foF2 (from Cnossen and Richmond 2008; c.f., Yue et al. 2008). Physical analysis by Elias and Ortiz de Adler (2006) demonstrates the important role of secular changes of the Earth's magnetic field in long-term trends in the F2 region parameters in the South America. This effect is dominated by changes of inclination and to some extent also declination of the Earth's magnetic field, but changes of field strength cannot be neglected, as well. Cnossen and Richmond (2008) found that most of the modeled changes in hmF2 and foF2 were due to plasma transport driven by neutral winds, which are mainly caused by changes in the inclination of the magnetic field.

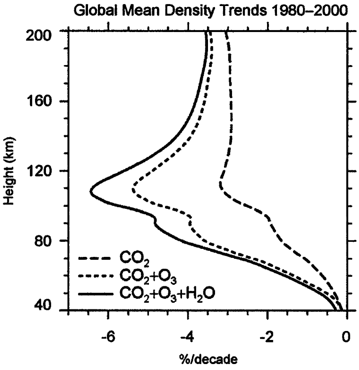


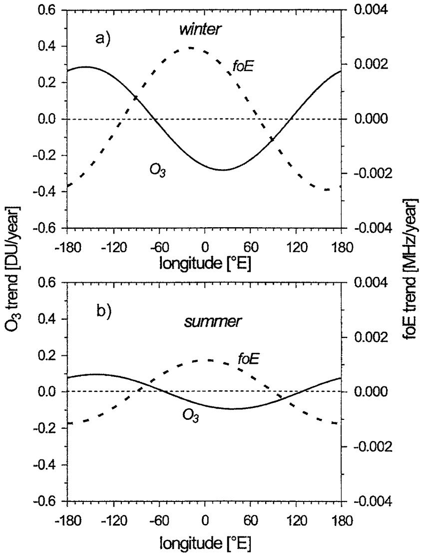
Fig. 2 Trends in global-mean atmospheric density at 40–200 km caused by changes of CO_2, ozone and water vapor concentrations over 1980–2000 according to model calculations by Akmaev et al. (2006)

In the mesosphere and lower thermosphere the most important additional driver seems to be the stratospheric ozone depletion, with an important but unclear role played by changes of the MLT region dynamics, including atmospheric wave activity, and possibly also by mesospheric water vapor concentration. Figure 2 shows the results of model calculations (Akmaev et al. 2006) of the impact of ozone and water vapor trends on trends in atmospheric density. The maximum temperature effect of stratospheric ozone depletion, which amplifies greenhouse thermal contraction of the upper atmosphere, occurs 110 km, i.e. in the lower thermosphere, and it seems to be detectable well into the thermosphere. Water vapor also seems to enhance the contraction of the atmosphere, but its role is less important. This model probably somewhat overestimates trends in atmospheric density (see Fig. 8), but the existence of some influence of these two drivers is indisputable. Unfortunately, there is limited observational information about trends in ozone concentration in the mesosphere and mesopause region, which could affect other trends in the MLT region. Analysis of ozone data from UARS/HALOE satellite observations, finds no detectable trend for sunrise ozone but a strong negative trend for sunset ozone in a narrow region near 80 km, in anti-correlation with water vapor trends (Marsh et al. 2003). However, due to the length of the analyzed interval and uncertainty in the present-day water vapor trend, the mesospheric ozone trend remains uncertain.

Additional support of the role of ozone in long-term trends in the MLT region is provided by ionospheric data analyses. Analysis of long-term variations of the low frequency reflection height near 81 km and the total ozone content from Arosa revealed similarity in trends in the sense that in the period of the midlatitude ozone decrease of 1980–1995 the trend in reflection heights was steeper (Bremer and Peters 2008). Figure 3 shows longitudinal variation of deviations of foE trends and total ozone trends from zonal mean trends (ionosondes and ERA-40 in 30–75°N). A clear anti-correlation between foE trend deviations and total ozone is evident both for winter and summer with slight phase shift, with more pronounced effect in winter. On the other hand, at F1 region heights in foF1 no such relation between trends in foF1 and total ozone has been observed (Bremer 2008).

The role of stratospheric ozone in long-term trends in the mesosphere, lower thermosphere and E-region ionosphere is crucial. Stratospheric O_3 concentration has been decreasing since about 1979, with a turnaround of the trend near 1995 at northern middle latitudes (e.g., Harris et al. 2008) at northern middle latitudes and later also in other regions. Thus now ozone changes affect trends in a way opposite to that in the 1980s. This should result in some modification of trends e.g. in mesospheric temperatures and as observations document, this is the case (see Sect. 5).

Fig. 3 Longitudinal variation of deviations of foE trends from the average trend in foE (ionosondes between 30–75°N) and of deviations of total ozone trends from the average trend (ERA40, 30–75°N); *top panel*—winter, *bottom panel*—summer. After Bremer and Peters (2008)



Another important factor is long-term trends in atmospheric dynamics and atmospheric wave activity. They are treated in more detail in Sect. 7. Here we only mention that these trends also seem to be non-stable and changing (Laštovička 2009). Trends in mesospheric water vapor are little known (see Sect. 8) but with respect to recent drops in the stratospheric water vapor concentration in 2001 and 2008 (e.g., Solomon et al. 2010a) we expect also rather non-stable trends in the mesospheric water vapor concentration.

Greenhouse gas concentration is steadily and more or less homogeneously increasing. However, other drivers change their behavior both in time and space. Stratospheric ozone concentration after a period of depletion reversed trend and began to recover; its changes are large at high latitudes but almost negligible at low latitudes. Geomagnetic activity is no more increasing and its effect is more important at high than at low latitudes. Secular changes of the main magnetic field of the Earth are very regional phenomenon introducing in various regions even opposite effects on trends. The mesospheric water vapor is uncertain but probably non-stable. Possible trends in atmospheric wave activity are very probably also non-stable. *Therefore we can hardly expect stable, non-changing trends and stable role of various factors responsible for trends—they will be changing both with time and space* (*location*). This phenomenon complicates trend investigations in the upper atmosphere and ionosphere, but on the other hand it contributes to or even explains substantial part of differences between various results of different authors, mainly observational results.

Recent model calculations illustrate the role of other trend drivers (see also Figs. 1 and 2). Figure 4 shows TIME-GCM simulated changes of temperature and neutral density due to estimated changes of trace gases other than CO_2 (Qian et al. 2011). Forcing from these trace gases caused additional cooling in the mesosphere, slight cooling in the upper thermosphere, but some warming in the altitude region around 100–120 km (in fixed height coordinates); it caused neutral density decrease in the mesosphere and thermosphere with maximum density reduction around 110 km. The results on atmospheric density changes are qualitatively consistent with the results by Akmaev et al. (2006) (Fig. 2).

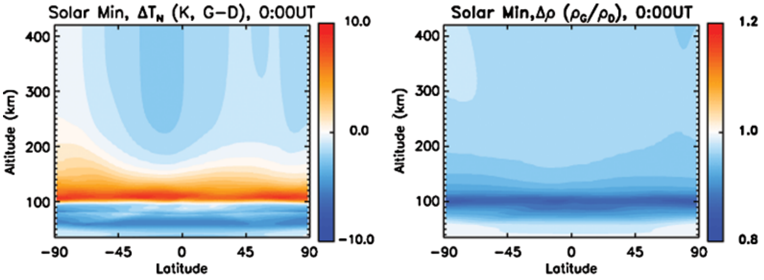
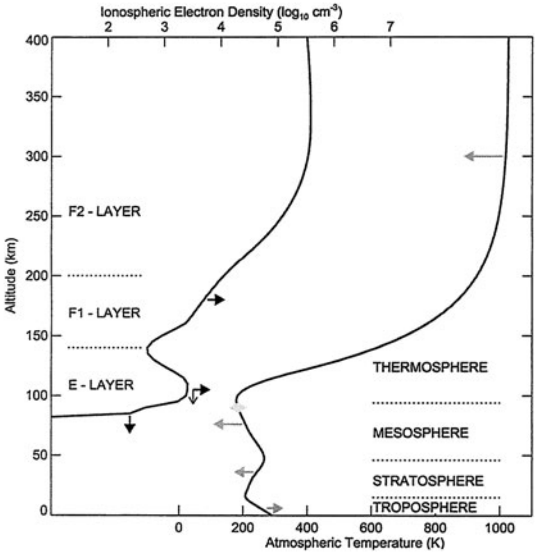


Fig. 4 Changes of neutral temperature and neutral density due to trace gases other than CO_2, such as O_3 depletion (*halved*), H_2O increase (*doubled*), and CH_4 increase (*doubled*), under solar minimum and geomagnetic quiet conditions, at 0:00UT, simulated by the NCAR TIME-GCM model. The difference between the simulation case with doubling of CO_2 only and the simulation case with doubling of CO_2 plus changes of concentrations of other gases is shown. After Qian et al. (2011)

Fig. 5 The first scenario of global change in the atmosphere and ionosphere. Adopted from Laštovička et al. (2008a). Arrows indicate the direction of change. Temperature profile—*left* cooling, *right* heating, no change of temperature in the mesopause; electron density profile—changes in electron density (*horizontal*) and heights of ionospheric layers (*vertical*)



5 Global Scenario of Trends in the Upper Atmosphere and Ionosphere

Early observational results on long-term trends in the upper atmosphere and ionosphere were rather chaotic, partly contradictory and they did not provide a scenario of trends. However, with increasing number of observational and model results a systematic pattern of trends began to emerge. Then in 2006 the first global scenario of long-term trends in the upper atmosphere and ionosphere has been constructed (Laštovička et al. 2006a, 2008a) as it is shown in Fig. 5. The scenario is created by trends in mesospheric temperature (mesospheric cooling and no trend in mesopause region), electron concentration in the lower ionosphere below 100 km (increase at fixed heights), maximum electron concentration (slight increase) and height of this maximum (statistically rather insignificant decrease due to coarse resolution of height measurements by ionosondes) in the E region, electron concentration in the F1-region maximum (slight increase), thermospheric neutral density (moderate decrease) and F2-region ion temperature (some decrease—preliminary result). All these trends are qualitatively mutually consistent and qualitatively agree with model simulations of consequences of the enhanced greenhouse effect, and with the hypothesis of global cooling and contracting of the upper atmosphere. Changes in temperature influenced chemistry of minor constituents, which is probably the main reason of observed changes in the E and F1 region ionosphere.

As regards trends in mesospheric temperatures, the 2006 scenario was based on an extensive analysis by Beig et al. (2003) updated by Beig (2006). New results since 2006 essentially confirm previous results, i.e. a cooling by 2–3 K/decade for middle latitudes and maybe a little bit less at low latitudes for heights of about 50–80 km and essentially no trend in the mesopause region, and partly remove some discrepancies and/or "outlier" results. Remsberg (2007) re-analyzed temperature trends from HALOE measurements at latitudes 40°N–40°S and found a more pronounced cooling at midlatitudes compared to low latitudes. Kubicky et al. (2008) re-analyzed long-term trends in middle atmospheric temperature at northern polar latitudes from historical rocket measurements at Heiss Island. Cooling peaks with about -6 K/decade at 65 km both in winter and summer; however, in summer at 75 km a statistically insignificant heating is observed. Previous high estimates of trends are considerably reduced. Perminov and Semenov (2007) analyzed results of Russian rocket soundings over 1964–1994. Above 55 km (top height of measurements was 75 km) they found large seasonal variation of trends and their remarkable latitudinal dependence; trends were substantially (2–3 times) stronger in winter than in summer. Inclusion of recent data on low frequency phase reflection heights near 81 km confirmed previous results on mesospheric cooling based on older data (Bremer and Peters 2008).

The absence of temperature trends in the mesopause region appears surprising at first glance. However, Fig. 6 shows that all observational data provide for the Northern Hemisphere no statistically significant trend except for the results of Semenov et al. (2002). This data series is the longest, but with several two-year data gaps, which, makes reliability of the trend result quite questionable. Re-analyzed OH temperatures ($\sim$87 km, mesopause region) above Wuppertal (Germany, 51°N) give no detectable trend in annual average values over 1994–2004, but the annual amplitude shows a moderate increase before 2001 and substantial decline after 2001 (Offermann et al. 2006), which reflects seasonality in trends. In a longer data series of 1988–2008, a slight but statistically significant overall cooling trend was found, with substantially different trends in individual months, and systematic changes in the shape of seasonal variation of temperature (Offermann et al. 2010). Also, recent model simulations reveal a lack of any significant temperature trend near the mesopause (Schmidt et al. 2006; Garcia et al. 2007; Fomichev et al. 2007). Similarly predominantly no statistically significant trends were reported for the Southern Hemisphere (Beig et al. 2003; Beig 2006).

Changes in the stratospheric ozone concentration have some influence on mesospheric temperatures (e.g., Bremer and Peters 2008; see also Sect. 4) and as the ozone trend reversed in the mid-1990 or in the second half of the 1990s, an impact of this ozone trend reversal should be expected. Observational data confirm this. In the mesosphere, HALOE trends are weaker than older rocket and lidar-based trends, because the ozone effect over the period of HALOE observations was close to none (Remsberg 2009). In the mesopause region the turnaround of ozone trends resulted in a change from no trend to a mild negative trend, at least at low latitudes (e.g., Venkat Ratnam et al. 2010). Temperature trends in the mesopause region in general changed from no trend to a slight negative trend (Beig 2010). This all means that the global scenario of trends remains qualitatively the same but it is somewhat changed quantitatively. Further monitoring of trends in mesosphere and mesopause temperatures is needed.

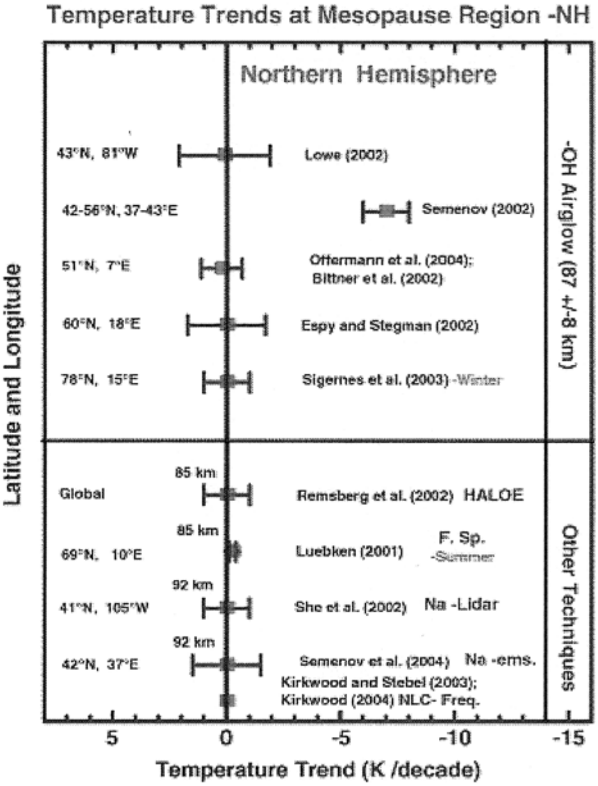


Fig. 6 Summary of trends in the northern hemisphere mesopause region temperatures. After Beig (2006)

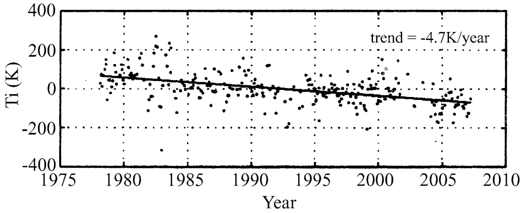


Fig. 7 Long-term trend in ion temperature, Ti, 1978–2007, noon, 350–450 km, Millstone Hill (Holt and Zhang 2008)

Above the mesopause region there are no observational data which would make it possible to calculate temperature trends, only model simulations, which indicate slight heating at fixed altitude just above 100 km, which is replaced by cooling at higher altitudes (e.g., Qian et al. 2011). However, there is some observational information about trends in ion temperature in the upper thermosphere, which is based on long-term measurements of the incoherent scatter radar at Millstone Hill (46.2°N, 288.5°E). The first paper on long-term trends in ion temperatures has been published by Holt and Zhang (2008). Figure 7 displays long-term trends in ion temperatures at 350–450 km. The trend is quite large, a cooling by 47 K/decade, even though it is substantially less than the solar cycle effect. Scatter of data is quite large but the cooling trend is strong enough to make cooling itself reliable. Quite recent results (Zhang et al. 2011) reveal that this trend depends strongly on height, as shown in Table 1. Trends are negative but they are strong and peak near 400 km, are still relatively strong and statistically significant in the exosphere, but they are weak and statistically insignificant below 250 km. The negative trend in the thermospheric ion temperatures together

Table 1 Dependence of the Millstone Hill ion temperature trends on height. After Zhang et al. (2011). Bold—statistically significant trends

Heights (km)	Trend (K/year)
200–250	−0.4
250–300	**−2.6**
300–350	**−4.1**
350–400	**−4.9**
Exosphere	**−2–3**

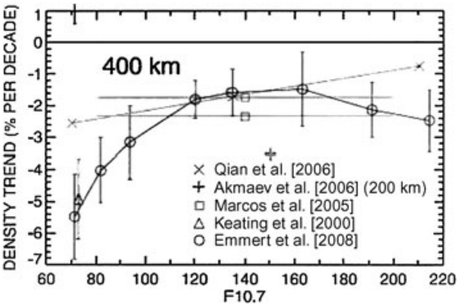


Fig. 8 Summary of various observational (Keating et al. 2000); (Marcos et al. 2005; Emmert et al. 2008) and model (Akmaev et al. 2006; Qian et al. 2006) results on long-term trends in the thermospheric neutral density (adapted from Emmert et al. 2008)

with a negative trend in the thermospheric neutral density indicates a negative trend in the thermospheric neutral temperature, as well. However, it is necessary to mention that model trends in ion temperatures display quite different height dependence and much weaker; the origin of this discrepancy is not known (Qian et al. 2011).

Trends in thermospheric neutral density are very important. They affect the ionosphere but moreover they influence orbital lifetime of low orbiting satellites and space debris. Figure 8 summarizes various modeling and observational thermospheric density trend results. The curve by Emmert et al. (2008) is based on thermospheric densities derived from an analysis of drag of about 5,000 space objects. Observational and model results display a general agreement. These results essentially confirm previous results with only slight quantitative corrections. Figure 8 reveals a clear negative trend for 400 km, typically a decrease by about 2%/decade for high and medium solar activity, which becomes much stronger for low solar activity, more than 5%/decade at solar minimum. Thermospheric density trends at 200–600 km are similar; they become somewhat stronger with increasing height. These trends not only support the idea of thermospheric cooling, they have also important practical impact. A decrease of neutral density results in longer orbital lifetime of space objects including space debris, which means larger than expected future concentration of dangerous space debris at satellite orbits.

Trends in the ionized component are substantial part of the global scenario of trends. Figure 9 shows a global trend in foE and a histogram of trends at 71 individual ionosonde stations (Bremer 2008). Positive trends dominate, but number of stations providing negative trends is larger than negligible. The average trend is $+0.013 \pm 0.005$ MHz/decade. Trends slightly weaken with increasing latitude; their longitudinal dependence seems to be affected, if not determined, by longitudinal dependence of ozone (Fig. 3). Model simulated trends of greenhouse origin are weaker than the observed trends; however, first, part of the difference is very probably attributable to ozone contribution to trends in foE (Sect. 4) and, second, both observational trends and particularly model trends of Rishbeth and Roble (1992) have some degree of uncertainty. Positive trends in foE are supported also by model calculations

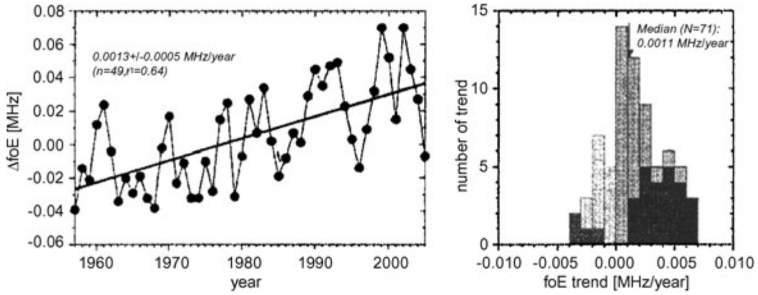


Fig. 9 Global mean foE trend (*left*) and histogram of individual foE trends at 71 ionosonde stations (*right—black* is statistically significant, *grey* insignificant) after Bremer (2008)

of Qian et al. (2008). Differences in trends obtained from data of individual stations displayed by histogram, may be partly of regional origin but mostly they do not seem to be a systematic function of any parameter, therefore they are of unclear origin. However, it is probable that data quality and/or long-term data homogeneity issues play a role in such differences, particularly for relatively close stations. Bremer (1998, 2008) made a similar trend study for hmE. The global trend is negative, -0.29 ± 0.20 km/decade, as expected consequence of mesospheric cooling and, thus, of thermal shrinking. Also histogram shows rather large scatter of trends obtained from data of individual stations. This all makes this trend rather insignificant and/or questionable, mainly due to data problems. First, historical hmE data have coarse height resolution of 5 km. To reach 5 km decrease of hmE, the trend should continue for 170 years. Second, evidently there are some data problems. The longest data series of h'E from Tromso (northern Norway, 1948–2006) reveals an evident decrease after 1975–1980 and no detectable trend before (Hall et al. 2007a).

Bremer (1998, 2008) analyzed foF1 in the same way as foE and obtained from global ionosonde network a weak positive trend, which is only slightly stronger than that for foE and reaches a value of 0.019 ± 0.011 MHz/year. However, there is one significant difference between trends in foE and foF1—no influence of ozone depletion on trends in foF1 was found contrary to that in foE trends.

Cooling and contraction of the upper atmosphere is changing the neutral and ion composition. The ionosphere in the E and F1 regions is approximately under photochemical equilibrium. Therefore, electron density in the E and F1 regions are determined by neutral and ion composition, and solar irradiance reaching to these regions. Cooling and contraction of the upper atmosphere has the effect of increasing ionization rate due to reduced absorption above these regions, enhancing O/N2, and reducing the ratio of NO^+ and O_2^+, the major ions in the E region (Qian et al. 2008). The net effect is an increase of electron density in the E and F1 regions.

Three main areas of discrepancies or unclear trends of the 2006 scenario have been established by Laštovička et al. (2008a). Their key words are: (1) F2-region ionosphere, (2) MLT (mesosphere/lower thermosphere) dynamics, (3) water vapor. These three topics are treated in Sects. 6–8. Item (1) includes contradiction among various results on trends in foF2 and hmF2 and their drivers. Item (2) consists of unstable and/or non-linear trends in MLT winds and largely unknown and/or uncertain trends in atmospheric wave activity in MLT. Item (3) means changes in behavior of water vapor concentration in the last ten years and discrepancies in ground-based observations of noctilucent clouds and satellite-based observations of polar mesospheric clouds. In Sect. 8 we shall deal only with noctilucent cloud trends, as the situation with mesospheric water vapor is not clear due to shortage of observational data. Moreover, we are missing observational information about trends in two important minor constituents of the MLT region, nitric oxide and ozone, except for analysis of insufficiently long ozone data series from limb measurements of HALOE (Marsh et al. 2003); more observations are needed.

6 F2 Region Ionosphere

The F2 region ionosphere main variables, critical frequency foF2 (equivalent to maximum electron density) and height of the F2 region peak, hmF2, did not fit the 2006 scenario of trends due to two problems: (1) Contradictions in magnitude and even sign/sense of trends. (2) Unclear origin of trends—dominantly anthropogenic or dominantly geomagnetic. Here we shall deal with progress since 2006.

In literature there are large discrepancies and controversies between the results of different authors and different methods as for trends in the F2 region parameters foF2 and hmF2. A trial to remove and/or explain some discrepancies between the results of six different groups on trends in foF2 was performed by Laštovička et al. (2006b) via comparison of the results of their different methods applied to a high-quality test data set (1976–1996, two comparable solar cycles) from Juliusruh (northern Germany). The necessity of a very careful correction for the solar cycle effect was pointed out. The correction for the solar cycle effect with F10.7 or E10.7 was evidently better than that with R or R12. Various regression-based methods used by five teams provided comparable weak negative trends in foF2. A Chilean team analyzed the data with regression-based and wavelet-based methods and got quite different results of opposite sign. As shown by Laštovička et al. (2008b), there was however an error in their approach. Also, a neural network-based method (Yue et al. 2006) gave results comparable with regression-based results (Laštovička et al. 2008b). Only the foF2 trends derived by Mikhailov's method, which uses 131-month smoothed values and a special way of eliminating geomagnetic activity effects, are substantially different from other results. However, the explanation has been made that without a special elimination of geomagnetic activity effects, these results are consistent with the others (A.V. Mikhailov, private communication, 2008). Thus, application of different methods can explain only a relatively small part of differences between the results of various authors

The main sources of majority of discrepancies in trend results among various authors seem to be different data sets, quality of data, different analyzed periods, and different way of eliminating the effect of solar and geomagnetic activity. These influences can explain a substantial part of discrepancies among trends obtained by various authors. Since long-term trends in foF2 are by almost two orders of magnitude weaker than the solar cycle change over a decade, the resulting trends are sensitive to selection of analyzed period with respect to solar cycle and to the method of solar cycle effect removal and/or suppression. Ulich et al. (2007) analyzed a 48-years long series of foF2 measurements from Sodankylä (northern Finland). They found that trends depended on the selection of data smoothing. Models based on monthly averages and 13-month running means yielded identical trend of -14 ± 4 kHz/year, while that based on 131-month running means provides weaker trend of -10 ± 4 kHz/year. It is consequence of known effects in statistics; too much smoothing of data to some extent reduces trends (E.C. Weatherhead, private communication, 2005). With trends in hmF2 there is one more problem with calculating hmF2 from M(3000)F2 (direct measurements by incoherent scatters or deduced from digisonde electron density profiles do not provide sufficiently long or continuous data sets), because various formulas used for re-calculating are applicable only under some conditions, and under specific conditions different formulas are the best (McNamara 2008).

Another controversy concerns origin of trends in foF2 and hmF2. The two main candidates are increasing concentration of greenhouse gases and long-term changes of geomagnetic activity (the role of secular changes of the Earth's magnetic field has been discussed in Sect. 4). Based on analyses of foF2 and hmF2 long-term variations of Eurasian ionosonde stations, the so-called geomagnetic control concept has been developed by Mikhailov (2002). Initially formulated for ionospheric F2-layer parameters, later it was extended for the foE (Mikhailov and de la Morena 2003; Mikhailov 2006b) and foF1 (Mikhailov 2008) long-term variations. According to this concept the observed long-term variations of electron concentration in the ionosphere are dominantly controlled by the geomagnetic activity long-term variations (11-year running means Ap indices Ap_{132} are used).

However, this geomagnetic activity control was fully valid only in the past; it is no more the case at present. In the E region the geomagnetic control broke down around 1970 (Mikhailov and de la Morena 2003). Figure 10 reveals years 1972 for Slough and 1967 for Rome. Figure 10 also shows continuous loss of geomagnetic control of foF1 in the 1990s, where the dominant geomagnetic control appears to be lost in the first half of the 1990s. Figure 10 also indicates for both stations possible beginning of the loss of the predominant geomagnetic activity control in foF2 around 2000. Two more data points available now confirm this tendency, so we may say that even in foF2 the predominant geomagnetic activity control of trends was lost at about 2000 and that at present long-term changes in the ionosphere are no more predominantly controlled by long-term changes of geomagnetic activity; the increasing concentration of greenhouse gases seem to be the main controlling factor. This all coincides with Laštovička's (2005) finding that the greenhouse gas control of long-term changes in the atmosphere-ionosphere system was increasing throughout the 20th century, while the solar and geomagnetic control was decreasing.

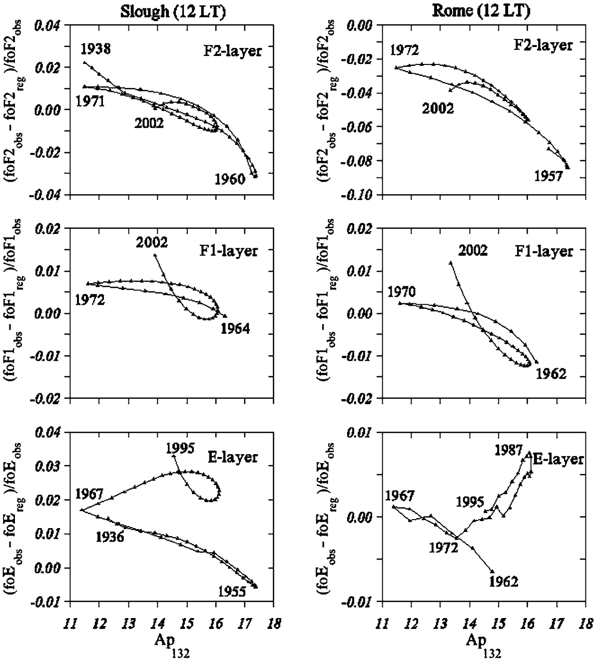
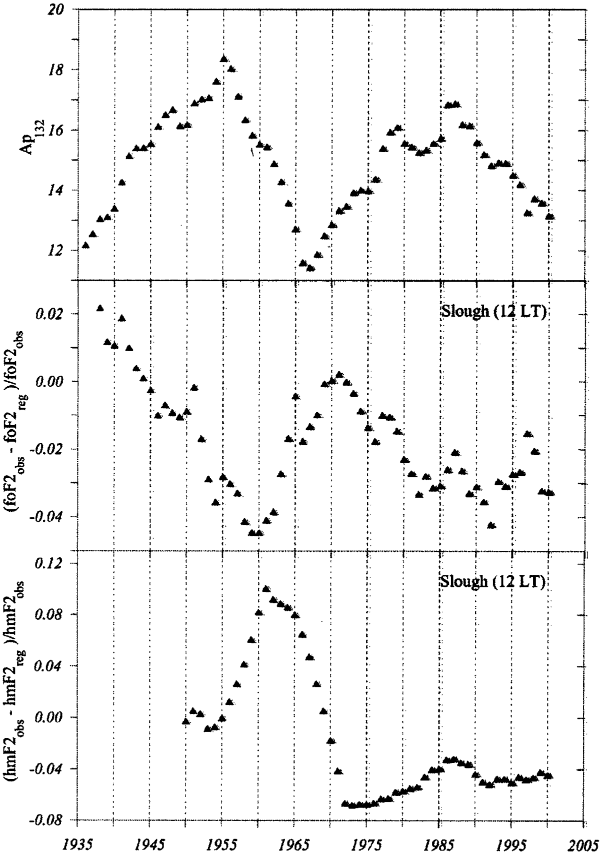


Fig. 10 Relationships between δfoF2 (*top panels*), δfoF1 (*middle panels*) and δfoE (*bottom panels*), and Ap_{132} variations for Slough (*left panels*) and Rome (*right panels*). The change in the type of the dependences appeared earlier in the E region, later in the F1 region, and eventually it began to appear in F2 region. After Bremer et al. (2009a)

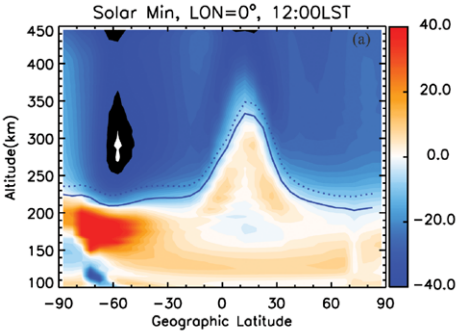
Fig. 11 11-year running means (132 months): Ap132 (*top panel*); ΔfoF2132 (*middle panel*) and ΔhmF2132 (*bottom panel*) long-term variations at noon for Slough (U.K.). After Mikhailov (2006a)



How is it with hmF2? Figure 11 illustrates development of foF2 and hmF2 in dependence on smoothed geomagnetic activity for Slough. Until 1972, foF2 is anti-correlated and hmF2 correlated (with time delay of about 4–5 years) with geomagnetic activity. However, since about 1973 the hmF2 response to geomagnetic activity becomes much smaller (almost negligible) and in the early 1990s hmF2 looses any relation to geomagnetic activity, i.e. we can assume the dominant greenhouse gas control to govern long-term changes of hmF2 at present.

Model calculations of the effect of CO_2 doubling on the ionosphere by Qian et al. (2008) qualitatively explain how such a different behavior of foF2 and hmF2 is possible. Figure 12 show that these calculations confirm observational findings of increasing electron densities at fixed heights in the lower ionosphere, increasing foE and foF1. In the F2 region, plasma transport becomes increasingly important. The combined effect of changes in photochemical and plasma transport processes together with thermal shrinking of the upper atmosphere result in an evident decrease of hmF2 (by more than 20 km), while decrease of foF2 is small, because the cross point between increasing and decreasing electron densities is only a little below the height of maximum electron density in the F2 region; hmF2 for doubled CO_2 concentration is located almost at line of no change in electron density. The electron density trend above the peak of the F2 region is negative. In addition, the interplay of photochemical and plasma transport processes causes complex regional, diurnal, seasonal, and solar cycle

Fig. 12 Model simulation of trends in foF2 and hmF2 at noon, longitude 0°, as a difference between the basic state and the state with doubled CO_2 concentration. *Dashed curve*—hmF2 for basic state; *solid curve*—hmF2 for doubled CO_2. After Qian et al. (2008)



variations of trends in the upper ionosphere (Qian et al. 2009); e.g. the nighttime pattern is significantly different from the daytime pattern.

Thus *trends in the F2-region are at present already predominantly controlled by greenhouse gas increases and, thus, consistent with the presented scenario of trends in the ionosphere and upper atmosphere.* Now we also essentially understand the large scatter and even contradictions of the past reported observational trends in foF2. Factors responsible for this are as follows: small greenhouse gas effect (see Fig. 12), changing role of trend drivers (particularly geomagnetic activity) with time, regional influences of secular change of the geomagnetic field, difficulty in removing of solar cycle influence, local-time dependence of trends, and possibly other factors.

Bencze (2009) claims that the geographical distribution of trends in hmF2 can be explained in terms of the inclination and declination of geomagnetic field and nonmigrating tides. However, observational results supporting this statement are not very conclusive, and this hypothesis is preliminary, pending further research and clarification.

7 Atmospheric Dynamics and Trends

Changes in the temperature field should affect winds. Routine wind measurements in the MLT region at heights 80–100 km have been carried out for several decades, particularly at several stations at northern higher middle latitudes. The most prominent components of the mid-latitude MLT winds are the prevailing (mean) and tidal winds. Long-term trends of prevailing wind and semidiurnal tides have been examined and detected using long-term wind measurements at mid-high latitude stations in the northern hemisphere (e.g., Portnyagin et al. 2006).

Figure 13 shows time series of annual mean zonal and meridional prevailing winds over Obninsk (55°N, 37°E) and Collm (52°N, 15°E). In spite of differences in the measurement techniques and strong year-to-year wind variations, the general tendencies in the climatic MLT wind variations at both stations are similar. Before about 1990, both the annual prevailing zonal and meridional wind weakened, while after about 1990, zonal wind strengthened and the negative trend in meridional wind leveled off. It should be mentioned that lower stratospheric winds at 52.5°N change their trend also around 1990 (Laštovička et al. 2010). However, if look on Fig. 13 in more detail, we see some differences between Collm and Obninsk winds even for annual means. Other stations in the same latitudinal belt, especially Saskatoon in Canada, provide partly different results. Figure 14 gives an explanation why the observational trend results at different longitudes partly differ, even though these model calculations are made for somewhat lower latitude (41.25°N). This simulation is calculated

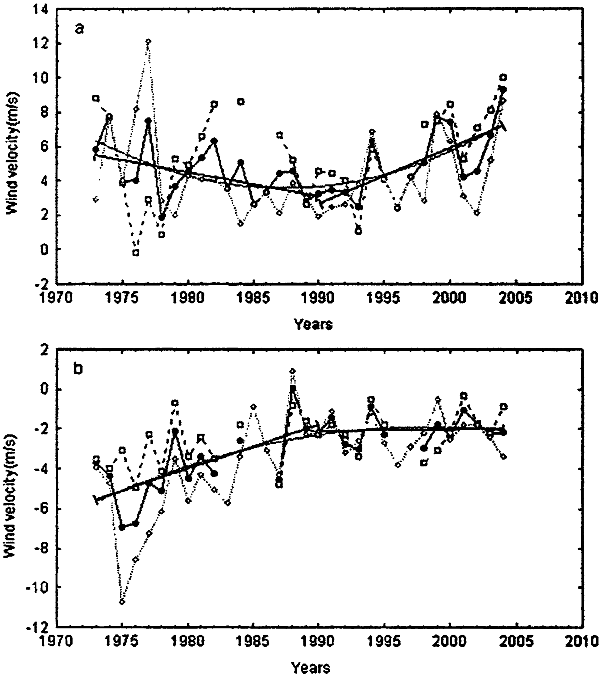


Fig. 13 MLT annual mean prevailing winds over Obninsk (55° N, 37° E) and Collm (52° N, 15° E), *dotted line*—Obninsk, *dashed line*—Collm, *full line*—mean values; *top panel*—zonal component, *bottom panel*—meridional component. From Laštovička et al. (2008a)

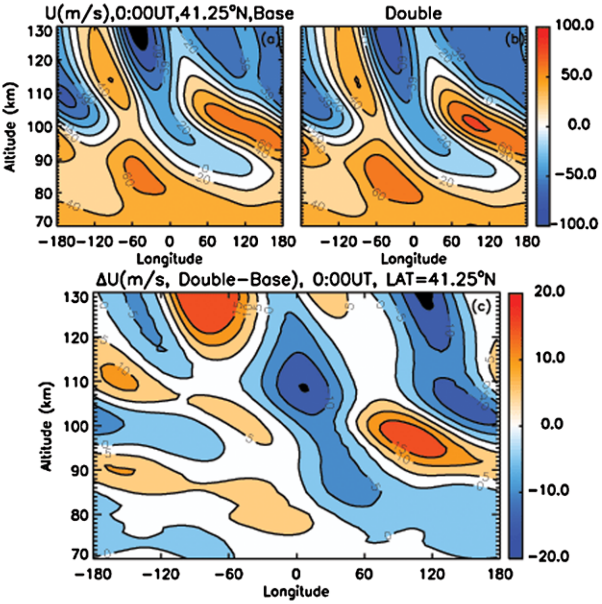


Fig. 14 Zonal wind and change (double CO_2–base CO_2) of the zonal wind at 41.25°N, under solar minimum and geomagnetic quiet conditions, at 0:00UT, simulated by the NCAR TIME-GCM. (**a**) Zonal wind for the base case; (**b**) zonal wind for the double CO_2 case; (**c**) change of the zonal wind between the two cases

for 00 UT, so a part of apparent longitudinal difference of trends is an effect of different day- and night-time trends but even for well daytime or well nighttime intervals the trends are somewhat different, i.e. they reveal some real longitudinal difference which is reflected in the observation-based trends. Another problem is that trends in prevailing wind are height dependent even as to their sign/sense; this is shown by Fig. 14 for simulations and confirmed also by observations (e.g., Keuer et al. 2007). However, simulations shown in Fig. 14 include only changes in the greenhouse gas concentration while ozone and water vapor effects are omitted therefore they illustrate only the greenhouse gas effect, not complete change. More global data coverage is also required in order to get more reliable information about trends in prevailing wind in the MLT region.

Atmospheric waves, namely planetary, tidal and gravity waves coming from below appear to be the main agent responsible for coupling of the lower atmosphere to the upper atmosphere. Very little is known about their long-term changes and trends. Their trends may partly be caused by changes in the source region, i.e. in the troposphere and, therefore, they may differ from the trends in other upper atmosphere variables. There are some indications of possible trends in gravity wave activity (e.g., Jacobi et al. 2006), tides (e.g., Portnyagin et al. 2006), and planetary waves (e.g., Jacobi et al. 2008). However, information on trends in atmospheric waves in the mesosphere and also in the thermosphere is very limited and not quite consistent. Infrasonic waves with periods of seconds to a few minutes (e.g., Blanc 1983; Krasnov et al. 2006) are very probably less important and no information is available about possible trends due to lack of measurements.

Information on trends in planetary wave activity as summarized by Laštovička et al. (2008a) does not provide clear pattern. Planetary wave activity in the MLT region appears to have increased, even though this increase seems to be intermittent. As for recent results, analysis of NCEP/NCAR reanalyses over the period 1960–2000 reveals some increase of the stationary planetary wave of the zonal wave numbers 1 and 2 activity in the stratosphere but a reduction of traveling stratospheric wave activity at typical periods $\sim$5, $\sim$10 and $\sim$16 days (Pogorelcev et al. 2009). Jacobi et al. (2008) analyzed MLT wind measurements at Collm. They report trends in planetary wave activity, which are highly variable with period range and season, being generally positive in zonal wind and weaker and negative in meridional wind, and in total wind being in average slightly positive. The trends are more pronounced for short periods ($T < 7$ days) and for summer, whereas at longer periods and in other seasons they are very predominantly relatively small and statistically insignificant. Overall we can say that there is probably a tendency to strengthening planetary wave activity in the MLT region but more data are needed. Long-term changes in tropospheric/stratospheric stationary planetary waves could affect the occurrence frequency of (major) sudden stratospheric warming. Indeed, the occurrence rate of the major stratospheric warming in the 1990s was low, while in the 2000s it was high. The strong major warming affect the ionosphere at all latitudes down to equator in such a way that morning values of NmF2, hmF2 and ITEC considerably increase whereas their afternoon values considerably decrease (e.g., Yue et al. 2010). Thus long-term changes in the occurrence rate of major stratospheric warming may affect long-term trends of ionospheric parameters at fixed times, which is another potential way of influence of atmospheric wave activity on long-term trends in the ionosphere-upper atmosphere system.

Diurnal and semidiurnal tides are the most important tidal modes. In the mid- and high-latitude MLT region, the semidiurnal tide is dominant. The negative trend in semidiurnal tidal winds seems to cease after the mid 1980s or 1990 (e.g., Portnyagin et al. 2006), or may even reverse. Observations at Scott Base, Antarctica reveal a positive trend since the late 1980s (Baumgaertner et al. 2005). Portnyagin et al. (2006) and Merzlyakov et al. (2009) showed that the prevailing wind and semidiurnal tide in the mesopause region on the Northern Hemisphere as well as in Antarctica changed the trend (mostly to opposite one) near 1990. The most recent results from Collm, however, indicate an overall negative trend (weakening) of the semidiurnal tide (with large seasonal variation of trend) over 1979–2007.

Thus observational data do not provide a consistent pattern of trends in tidal activity in the MLT region. More observations are required.

There are very few studies of long-term trends in the MLT region gravity wave activity. Results of gravity wave analyses from ground-based systems can be strongly dependent on system characteristics. The wave periods seen in wind data measured by MF radars (>10 min), meteor radars (>1 h), and LF drifts (0.7–3 h) are very different and results are not easily comparable. Indirect evidence was rather in favor of some trends in gravity wave activity, but wind measurements themselves did not reveal a trend, as summarized by Laštovička et al. (2008a). There are some indirect indications of possible trends in gravity wave activity (e.g., Jacobi et al. 2006); direct investigation of gravity wave activity in MLT winds at Shigaraki (southern Japan) did not reveal any significant trend (Gavrilov et al. 2002); Hoffmann et al. (2010) found for Juliusruh (northernmost Germany) a weak positive trend at 80–90 km and they mention that some stations display trends, some not. Some mechanisms of trends in GW activity, like changes of storm tracks at midlatitudes, may result in regionally/locally different trends in GW activity even as to sign/sense, thus caution is necessary. Again, more information is very required.

A phenomenon closely related to dissipation of gravity waves is turbulence. Hall et al. (2007b) reported MLT turbulence measurement analysis for Tromso (70°N, 19°E), 1999–2006. Even though this data series is too short to provide reliable trend information, it gives a hint. Steadily positive trend was observed in the upper mesosphere and lower thermosphere and negative trend in the middle mesosphere with average transition height 80–81 km (varying with season). Solar and geomagnetic activities are unable to explain the observed changes therefore strong candidate is anthropogenic forcing. Kalgin (1998) also reported a positive trend in turbulence in the lower thermosphere.

There is no direct information about trends in atmospheric winds and waves in the middle and upper thermosphere. However, Danilov (2008b, 2009) and Danilov and Vanina-Dart (2010) proposed a new method how to estimate trend in horizontal winds based on analysis of foF2 and hmF2, namely foF2(night)/foF2(day) ratio, correlation between foF2(night) and foF2 (day) and scatter of hmF2 values. All these parameters indicate a change in trends in thermospheric winds in about 1980 from a no trend regime to a trend regime. The trend was different for different stations in dependence on station magnetic inclination and declination (Danilov and Vanina-Dart 2010). The trend was better pronounced in spring than in other seasons.

Summarizing, it may be said that there was some but limited progress in the area of long-term trends in the upper atmosphere dynamics and atmospheric wave activity in recent period and main open questions remain unanswered. The trends in atmospheric wave activity represent the key problem of trend investigations as they are capable to affect trends in majority of upper atmospheric and ionospheric variables.

8 Noctilucent Clouds Versus Polar Mesospheric Clouds

The highest atmospheric clouds, noctilucent clouds (NLC) observed by ground-based instruments, appear in extremely cold summer polar mesopause region at heights of about 82–85 km. The same phenomenon, observed from above by satellites, is called polar mesospheric clouds (PMC). Their appearance is controlled by temperature and water vapor content. Long-term trends in the occurrence frequency and brightness of NLCs observed from the ground, at latitudes below about 65°N in Europe do not display a detectable trend in the NLCs according to Kirkwood et al. (2008). Satellite observations cover a larger geographical

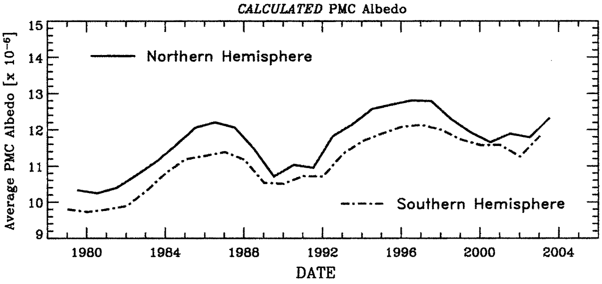


Fig. 15 Average PMC albedo calculated from a fit to the combined SBUV and SBUV/2 data: *Solid line*—Northern Hemisphere, *dot-dash line*—Southern Hemisphere. After DeLand et al. (2006)

Table 2 Latitudinal dependence of trends in the occurrence frequency of polar mesospheric clouds separately for individual latitudinal bands. The relative occurrence frequency in latitudinal bands is as follows: 54–64 : 64–74 : 74–82 = 1 : 2 : 4. Adopted from Shettle et al. (2009)

Latitudes (°N)	Trend coefficient t	Trend %/decade	95% confidence per decade	Statistical significance
54–64	0.017 ± 0.014	9.9	12.4	Insignificant
64–74	0.022 ± 0.018	6.7	9.2	Insignificant
74–82	$\mathbf{0.134 \pm 0.031}$	**19.7**	**9.1**	**Significant**
54–82	$\mathbf{0.069 \pm 0.021}$	**15.6**	**9.3**	**Significant**

area and the highest occurrence frequency of PMCs is around 80°N. The satellite observations indicate an increase in the PMC occurrence frequency and brightness, as illustrated by Fig. 15 for the PMC albedo. Thus NLC-based and PMC-based trends are quite different, which is evident contradiction as NLC and PMC is the same physical phenomenon, only seen from below and from above.

In order to solve this discrepancy, Shettle et al. (2009) analyzed 28 years of satellite PMC observations for latitudinal bands 50°N–64°N (NLC observation latitudes), 64°N–74°N, and 74°N–82°N (Table 2). They observed statistically significant increase only in 74°N–82°N, whereas in 50°N–64°N, it was half in magnitude and statistically insignificant. At NLC observational latitudes, the PMC trend of Shettle et al. (2009) is +9.9%/decade, the NLC trend of Kirkwood et al. (2008) is +4.4%/decade for moderate and bright NLCs, and ∼14%/decade for all NLCs; all trends being statistically insignificant. This means that the PMC and NLC trends are comparable and do not differ within accuracy of their determination in spite of partly different analyzed periods. Relatively large differences between older results were strengthened by the fact that the occurrence frequency of PMC in the latitudinal band with the largest trend is four times as high as in the NLC latitudinal band (Table 2).

Simulations with the LIMA/ice model (Lübken et al. 2009) show that all three factors, temperature, water vapor and Lyman-α solar radiation are important and none of them is dominant in PMC/NLC behavior. Thus, the origin of trends in PMC/NLC remains to be discovered. However, Lübken et al. (2010) found that the occurrence frequency of NLC is determined mainly by water vapor concentration, whereas the NLC layer height is affected dominantly by temperature. The observed trends in PMC (no change of height but increasing occurrence frequency) would then indicate little change in temperature, in line with other mesopause region temperature trend estimates, (Sect. 5, Fig. 6) but increasing water vapor concentration.

Polar mesospheric summer echoes (PMSE), the anomalous radar echoes found between 80–90 km from May through early August in the Arctic, and from November to February in the Antarctic, is a phenomenon closely related to PMC. Bremer et al. (2009b) found a positive but insignificant trend in PMSE occurrence frequency and length of season for Andenes (69°N) over 1994–2008, whereas Smirnova et al. (2010) found insignificant negative and positive trends, respectively, for Kiruna (68°N) over 1997–2008. Longer data series are needed to get more reliable trend results.

9 Modeling of Trends—Recent Developments, Current Problems and Challenges

Since the original finding of Roble and Dickinson (1989) using a global mean model, advances in model development have gained considerable insight into the causes and expected nature of upper atmospheric trends. Ionospheric effects (Rishbeth and Roble 1992; Rishbeth 1997; Qian et al. 2008, 2009) have been modeled, and mesosphere and lower thermosphere responses to multiple trace-gas changes have been studied (Akmaev and Fomichev 2000; Akmaev et al. 2006; Gruzdev and Brasseur 2005). Recent advances in three-dimensional whole-atmosphere models that include both the tropospheric heating and upper-atmosphere cooling response to anthropogenic forcing, such as the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA) (Schmidt et al. 2006), the NCAR Whole Atmosphere Community Climate Model (WACCM) (Garcia et al. 2007) and the Canadian Middle Atmosphere Model (CMAM) (Fomichev et al. 2007) have enabled detailed examination of the stratosphere/mesosphere response to solar and anthropogenic forcing. Development of the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) has also continued, including its three-dimensional and global mean versions, and has been employed to understand the interaction of the solar cycle with thermosphere and ionosphere trends (Roble and Ridley 1994; Qian et al. 2006, 2011). Recent studies employing the TIME-GCM quantify the role CO_2 compared to other anthropogenic gases, as shown above in Fig. 4 (Qian et al. 2011).

Model simulations have enabled a better understanding of some of the specific aspects of the trend scenario described in Sect. 5 and illustrated by Fig. 5. The whole atmosphere models agree that transition from heating to cooling occurs above the tropopause, near 15 to 20 km, and that ozone changes dominate stratospheric cooling; Garcia et al. (2007) obtained reasonable agreement with observed stratospheric trends. In the mesosphere, the dominant cooling mechanism becomes CO_2 radiation, with ozone and water vapor playing additional roles (Akmaev et al. 2006) as shown in Fig. 2. The effects of stratospheric ozone depletion, causing cooling and contraction of the stratosphere, propagate even into the thermosphere.

All the large-scale models also agree that there should be little or no temperature trend near the mesopause. This appears to be in agreement with most of the observations. However, there is not yet any comprehensive explanation of what mechanism is responsible for this apparent paradox, since CO_2 cooling is large near the mesopause. Schmidt et al. (2006) speculate that since the mesopause region is dominated by dynamics, the models are insensitive to radiative changes. McLandress and Fomichev (2006) found amplification in tidal forcing using the CMAM, and proposed a secular increase in the amplitude of the migrating diurnal tide in the upper mesosphere. Garcia et al. (2007) and Fomichev et al. (2007) also found no significant temperature change near the mesopause. TIME-GCM simulations (Qian et al. 2011) show a small negative temperature trend at 90 km, but zero trend at 100 km, when analyzed in altitude coordinates, primarily due to the effect of the positive temperature gradient above the mesopause. Thus, there is a need for further analysis of model processes in order to understand the operative mechanisms in this region, since the results of modern fully-coupled three-dimensional models can be as difficult to understand as the atmosphere itself. Progress in modeling another important mesopause-region phenomenon, PMC/NLC, is described in Sect. 8 above. Lübken et al. (2010) found that the occurrence frequency of NLC is determined mainly by water vapor concentration, while temperature determines the layer height. Thus, anthropogenic changes to the mesospheric hydrogen budget, caused largely by methane increases, may be implicated in possible trends.

Returning to the thermosphere, where the clearest detection of upper atmosphere trends has been established through long-term satellite drag measurements (e.g., Keating et al. 2000; Emmert et al. 2004, 2008; Marcos et al. 2005), significant progress has been made in understanding the solar cycle dependence of temperature and density trends (see Fig. 8). Qian et al. (2006, 2011) showed that cooling trends should be larger at solar minimum, due to the larger relative role of CO_2 radiative cooling compared to the nitric oxide (NO) radiative cooling. This is confirmed by SABER measurements showing that global integrated NO radiative power decreased by almost an order of magnitude from 2002 to 2009, while CO_2 radiative power decreased only by $\sim 35\%$ (Mlynczak et al. 2010). This may explain why early results by Keating et al. (2000) were higher than model estimates at that time, and subsequent analyses by Marcos et al. (2005). Keating et al. compared successive solar minima in order to eliminate the large confounding effect of the solar cycle, obtaining an estimate of 5%/decade decrease in density at 400 km. Emmert et al. (2004, 2008) also found solar minimum variation near $5\%/\text{decade}$, decreasing to about $2\%/\text{decade}$ at higher solar activity. This is in reasonable agreement with models for moderate solar activity, but still larger than model simulations at solar minimum.

Modeling of ionospheric effects, starting with Rishbeth and Roble 1992, have been extended by Qian et al. (2008, 2009). The basic predictions, as described in Sections 5 and 6, are that the E and F1 regions should experience a small increase in density, due to ionization rate and composition changes, as the thermosphere cools and contracts, while the F2 region above the peak should decrease in density (see Fig. 12). The height of all layers is expected to decrease, due to thermospheric contraction. The net result is a very small decrease in foF2. Simulations of the effect of geomagnetic field evolution (Cnossen and Richmond 2008) show that the complicating effect of trends caused by these different effects, and their complex diurnal and spatial structure, may make F-region density trends very difficult to observe. F-region heights should be less ambiguous, but these are more difficult to measure.

Challenges for future model studies include resolving the remaining discrepancies with solar minimum trends in the thermosphere, understanding the reasons for the apparent lack of trends near the mesopause, and explicating the role of changes in atmospheric dynamics, especially tidal and wave forcing, expected from the combined effects of tropospheric heating and stratospheric cooling. For the thermosphere, there is still considerable uncertainty in a fundamental chemical kinetic parameter, the rate of CO_2 collisional activation-deactivation by atomic oxygen, as discussed by Akmaev (2003). Employing a higher rate in model calculations would increase the efficiency of CO_2 radiative cooling above the mesopause, which could increase model trend estimates, particularly at solar minimum. However, Akmaev found that the strong temperature dependence of the radiative forcing and molecular conduction offset changes to the collision rate, resulting in surprisingly low model sensitivity to this parameter. Additionally, atomic oxygen densities themselves are highly variable and not well known. Improved model quantification of lower thermosphere processes will be needed to resolve these issues.

An additional complexity has also been introduced by measurements during the recent minimum between solar cycles 23 and 24. In addition to the inter-cycle period being unusually long, the Sun was unusually quiet, certainly with respect to magnetic activity, and possibly also photon emissions (e.g., Russell et al., 2010). Emmert et al. (2010) found that the thermosphere reached record-low density levels during 2007–2009, 30% lower than the previous solar minimum, which has been explained by a combination of lower solar extreme-ultraviolet radiation, lower geomagnetic forcing, and increased CO_2 cooling (Solomon et al. 2010b, 2011). However, the solar extreme-ultraviolet decrease was the dominant effect. Thus, the simple method employed by Keating et al. (2000), comparing successive solar minima to make the first clear detection of upper atmosphere cooling, can not be considered reliable in the future, as we confront a new dimension in solar variability and upper atmosphere response.

10 Future Trend Investigations

Future investigations of trends in the upper atmosphere and ionosphere should proceed in four general directions, each of which includes both observational and modeling activities:

1. Investigations of trends in atmospheric wave activity (planetary, tidal and gravity waves). This is currently the key open problem of trend investigations in general. The origin of long-term changes is probably of dual nature, variability in the predominant tropospheric source of waves and variability in their filtering by middle (and upper) atmosphere. Both observation-based and model simulation results indicate that trends may vary regionally. Historical data mining could broaden the limited observational basis for trend investigations.
2. Investigations toward making the current global scenario of trends more complete and more quantified, as it is now essentially qualitative. Information about trends in variables not yet included into the scenario is desirable. Longer data series and more sophisticated and accurate models could help to quantify more accurately trends in various atmospheric and ionospheric variables.
3. Investigations of the impact of the changing roles of various trend drivers such as ozone and geomagnetic activity on trends in the upper atmosphere and ionosphere. This is a relatively new but important area in trend research particularly for predicting future trends in the upper atmosphere and ionosphere.
4. Investigations liking the trend scenario for the upper atmosphere and ionosphere with trends in the stratosphere. The impact of stratospheric trends on trends in the upper atmosphere and ionosphere, through changes in stratospheric ozone concentration, temperature, and possibly atmospheric waves and water vapor, is an important subject linking different aspects of global change.

11 Conclusions

The steady increase of greenhouse gas concentrations, primarily CO_2, has caused global warming in the troposphere, but global cooling in the upper atmosphere and ionosphere. In the mesosphere, the cooling trend is in the order of -2–3 K/decade from 50 km to 80 km; whereas no significant cooling in the mesopause region from 80 km to 100 km. In the upper thermosphere, the decreasing trend of neutral density at 400 km is in the order of ~ -1.7–-3.0%/decade for the past 3–4 decades. The cooling of the upper atmosphere causes contraction of the upper atmosphere, which lowers the altitude of the ionosphere, with a global average trend in the order of -0.29 ± 0.20 km/decade at E region peak.

In addition, a long-term global increase of electron density has been detected in these regions, in the order of $+0.013 \pm 0.005$ MHz/decade for foE and 0.019 ± 0.011 MHz/year for foF1. The dominant driver of these trends has been attributed to the increasing greenhouse gas forcing. Various model simulations on long-term trends of the upper atmosphere and ionosphere under greenhouse gas forcing at least qualitatively, sometimes quantitatively, agrees with these detected results. Other forcing mechanisms such as changes in other radiatively active trace gases (e.g., O_3 and H_2O), long-term change in geomagnetic activity, and long-term change in the Earth's magnetic field, also contributed to the observed trends. The combined effect of these drivers, and their changing roles, can cause complicated patterns of trends; this is particularly true for trends in the F2 region.

The internally consistent global pattern of trends in the upper atmosphere and ionosphere, formed by the above trends and trends in several other variables, emerged in 2006 from a chaos of individual trend results for individual variables. This pattern/scenario is formed by trends in mesospheric temperature (mesospheric cooling and no trend in mesopause region), electron concentration in the lower ionosphere below 100 km (increase at fixed heights), maximum electron concentration (slight increase) and height of this maximum (statistically rather insignificant decrease due to coarse resolution of height measurements) in the E region, electron concentration in the F1-region maximum (slight increase), thermospheric neutral density (moderate but statistically significant decrease) and F2-region ion temperature (cooling). All these trends are qualitatively mutually consistent and qualitatively agree with model simulations of consequences of the enhanced greenhouse effect. These trends are caused primarily by greenhouse cooling and thermal contraction of the atmosphere with related changes in minor constituents responsible for ionospheric changes.

Trends for the F2 region ionosphere, MLT dynamics and waves, and water vapor and water vapor related phenomena, are the three main areas that have had controversies or limited knowledge, consequently they were not included in the 2006 trend scenario. Progress has been made in the past four years in these areas. For the F2 region ionosphere, model simulations demonstrated that under greenhouse gas forcing, trend of electron density changes from being positive in the E and F1 regions to being negative in the F2 region; the F2 peak is slightly above this transitional altitude, consequently, the trend of NmF2 is small and negative on a global average basis; the trend of hmF2 is negative on global average basis, due to cooling and contraction; trends of both hmF2 and NmF2 show strong latitudinal, longitudinal, diurnal, and solar cycle variability; cooling and contraction of the upper atmosphere causes changes in neutral dynamics and electrodynamics, which in turn can cause regional positive trends of hmF2 and NmF2 at night time. Model simulations also showed that secular change of the Earth's magnetic field can cause significant regional trends of hmF2 and NmF2 in the equatorial to mid-latitude Atlantic Ocean and in the South American; the sign of the trends can be positive and negative depending on region; and these trends show diurnal and seasonal variations. Furthermore, the role of long-term changes of geomagnetic activity in the observed long-term trends was decreasing. While it was probably dominant in ionospheric trends in the past, since about 2000 trends in foF2 appear to be controlled predominantly by increasing concentration of greenhouse gases. The combined effects of these three drivers and the changing role of geomagnetic activity, as well as difficulty in removing solar cycle influence in trend analysis, have likely contributed to controversies and discrepancies on earlier reported the trends of hmF2 and foF2. In addition, progress has been made on trend of ion temperature in the F2 region. A negative trend of ion temperature was found in the incoherent scatter radar measurements. However, model simulations show a negative trend at lower altitude but positive trend at higher altitude (>350 km), and the simulated negative trend is much smaller than the detected negative trend. More investigations are needed.

There have been discrepancies between trends of NLC and PMC, even though the two are same phenomenon, excepting that NLC are observed from the ground and PMC are observed from space. It has been reported that there were no detectable trend in NLC, but satellite observations indicated an increase in PMC occurrence frequency and brightness over the past several decades. More recent studies found that PMC trends are only significant in the latitude band from 74°N to 82°N, but at NLC observational latitudes ($\sim$ 54°N–64°N), both PMC and NLC trends are statistically insignificant. These findings may explain and reconcile the discrepancies between PMC and NLC trends.

Waves dominate MLT dynamics and also affect the thermosphere. They perform vertical coupling between the lower and upper atmosphere, and are able to influence trends in the upper atmosphere and ionosphere. Limited observational studies indicate possible trends in wave activity, but understanding of this phenomenon is still very limited. Causes and effects of trends in wave activity, are key open questions regarding trends in the upper atmosphere.

An important finding of trend investigations in the last four years is realization of the importance of other trend drivers, and partial specification of their relative role. These drivers include anthropogenic changes of ozone, secular changes in geomagnetic activity and Earth's magnetic field, changes in atmospheric wave activity, and possibly changes of mesospheric water vapor and thermospheric atomic oxygen concentration. Changes of ozone concentration play a role in the mesosphere and lower thermosphere, while long-term changes of geomagnetic activity play a role in the ionosphere, mainly in its F region. Trends in both of these parameters are variable, which results in modification of overall long-term trends in the upper atmosphere and ionosphere, and even more in the relative role of various trend drivers.

The path to developing a comprehensive scenario of trends in the atmosphere-ionosphere system appears to be arduous, but part of it is accomplished. With continued advances in observational analysis and model simulation, a full understanding of the causes and consequences of global change throughout the Earth's atmosphere will be obtained.

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