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On the role of solar and geomagnetic activity in long-term trends in the atmosphere–ionosphere system

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Abstract

The long-term continuous increase of greenhouse gas concentration in the atmosphere and other anthropogenic influences represent serious threat for human civilization. Therefore, it is necessary to determine the long-term trends and changes in the atmosphere–ionosphere system. The observed long-term trends in the 20th century might be, however, influenced by contribution of Sun's origin, and the process of determination of anthropogenic trends from observational data may be "spoilt" by the 11-year solar cycle. The role of solar/geomagnetic activity in long-term trends in various regions of the atmosphere/ionosphere system is briefly reviewed for the first time. The ways of avoiding or at least diminishing the effect of solar cycle on trend determination are mentioned. As for the possible solar and geomagnetic activity responsibility for part of the observed long-term trends, the two main conclusions are as follows: (i) The role of solar and geomagnetic activity in the observed long-term trends decreases with decreasing altitude from the F-region ionosphere down to the troposphere. (ii) In the 20th century the role of solar and geomagnetic activity in the observed long-term trends/changes was decreasing from its beginning towards its end.

Keywords: Long-term trends; Atmosphere; Ionosphere; Solar activity; Geomagnetic activity

1. Introduction

The global surface air temperature increased by about 0.6 °C in the 20th century. More pronounced trends have been observed in the middle and upper atmosphere and ionosphere. There is a tendency to attribute these trends solely to the increasing concentration of greenhouse gases in the atmosphere. However, the observed long-term trends in the ionosphere and atmosphere cannot be explained solely by the greenhouse effect. The considerable increase of geomagnetic activity in the 20th century and the increase of solar activity in its first half contribute to trends observed in the 20th century. The existence of the strong 11-year solar cycle can result in the incorrect determination of trends from shorter data series.

Here I present the first brief overview (in no way a full review) of the results on the geomagnetic and solar activity contributions to the observed long-term terms and to their determination in the atmosphere–ionosphere system with particular attention paid to the ionosphere, particularly to the lower ionosphere. The ionosphere, the ionized component, is much more under the solar/geomagnetic control than the neutral component. The geomagnetic control in fact means control by space weather phenomena, which reflect in and have been recorded through the geomagnetic activity that itself does not affect the ionosphere–atmosphere system; it is the only measure of space weather activity available for a long time. The paper is based on the invited review presented at the 3rd IAGA/ICMA Workshop "Solar

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Forcing of the Middle Atmosphere", Prague, September 2003. It also represents a contribution to activities of the IAGA/ICMA working group "Long-term Trends in the Mesosphere, Thermosphere and Ionosphere".

The calculation of trends and estimates of long-term changes of anthropogenic origin may be affected by solar and geomagnetic activity basically in two ways:

1. Inappropriate selection of data and/or missing measures to correct for medium-term solar/geomagnetic activity variations, which makes the calculation of trends vulnerable to a substantial effect of the 11-year solar cycle.
2. Long-term changes of solar and geomagnetic activity, which contribute to long-term trends.

Therefore Section 2 deals with the long-term trends in solar and geomagnetic activity. The following sections are organized in terms of height from the troposphere upwards, and from neutral to ionized component. Section 3 treats the influence of solar and geomagnetic activity on trends in the troposphere, Section 4 in the stratosphere, Section 5 in the mesosphere and lower thermosphere, Section 6 in the lower ionosphere, Section 7 in the thermosphere, and Section 8 in the F-region ionosphere. Brief conclusions in Section 9 close the paper.

2. Long-term trends in solar and geomagnetic activity

Long-term changes of solar activity and/or geomagnetic activity may play an important role in the observed long-term trends, particularly in the ionized component of the atmosphere, in the ionosphere. The geomagnetic activity in terms of the aa-index was increasing throughout the 20th century (e.g., Stamper et al., 1999) and appeared to stabilize near its end. The number of geomagnetic storms per solar cycle had also been increasing until it had reached the level of about 400 events per solar cycle and then it stabilized for the last few cycles (Clilverd et al., 2002). Long-term drifts in the solar open magnetic flux seem to be probably the main driver of these long-term changes of geomagnetic activity (Lockwood, 2003), even though there might be also other drivers (Richardson et al., 2002).

The general solar activity variability and/or variability of solar electromagnetic radiation over long time-scales has usually been studied with the use of sunspot numbers, which are available for several centuries, or with various proxies over longer time spans. The amplitude of sunspot cycles was increasing throughout the first half of the 20th century until the peak in cycle 19 (1957–1958), then dropped a little and basically stagnated until the end of the century. However, sunspot numbers are only a good proxy for long-term changes, not the physical quantity that affects various levels of Earth's atmosphere. The troposphere is affected by variability of the total solar irradiance, the stratosphere by solar ultraviolet radiation, the mesosphere, lower thermosphere and lower ionosphere by solar X-rays and the solar extreme ultraviolet radiation (EUV), and upper levels by the solar EUV variability.

The secular total solar irradiance trend during the last three solar cycles inferred from satellite measurements remains a question of controversy. Various results provide rather weak but different, even opposite trends, and their origin is not clear, it is not necessarily the solar magnetic activity cycle and its variation (e.g., Wilson and Mordvinov, 2003, and references therein).

Long-term changes in the EUV and X-ray emissions are rather difficult to be studied directly due to relatively short series of direct measurements by different satellites and presence of a strong solar cycle effect. Lean et al. (2001) used the EUV satellite measurements and proxies (before 1974 only proxies) and found an increase of the chromospheric EUV emission from 1900 to about 1950 and almost no trend in recent decades, overlapped by a strong solar cycle. Indirect ionospheric evidence yields a general trend of increasing solar EUV and X-ray irradiance for the period 1932–1999, which appears to be supported by SOHO solar data (Davis et al., 2001).

Other features of solar/space weather activity, like the high-energy proton fluence variability, may influence trends only locally, like protons in the lower ionosphere over polar cap, and not much is known about their long-term changes. As for the galactic cosmic ray flux, most of its mild long-term trend near the Earth seems to be explainable by the interplanetary magnetic field variations (Lockwood, 2001).

Thus the main potential solar drivers of long-term atmospheric/ionospheric changes during the 20th century are the geomagnetic activity essentially throughout the century and the general solar activity until about 1960, or in the EUV and X-ray flux may be even in more recent years. The determination/estimation of trends in various solar parameters may be affected by the 11-year solar cycle. Since we deal with trends in atmospheric and ionospheric parameters only in the 20th century, solar irradiance (total or spectral) reconstructions from the Maunder minimum until present or over longer time scales are not mentioned here.

3. Troposphere

A review of solar effects on climate and weather has been provided by Rind (2002). The presence of the solar cycle was identified in the lower tropospheric temperature, surface temperature, and upper ocean temperature (van Loon and Shea, 1999; Lean and Rind, 2001). Coherence with solar activity was found for some features of tropospheric circulation, e.g. latitudinal position of storm tracks (Brown and John, 1979). Some of the effects are pronounced in data stratified by the phase of the QBO: the polar winter stratospheric temperatures (e.g., Labitzke, 1987, 2001), the Northern Hemisphere tropospheric circulation and temperature (Barnston and Livezey, 1989; Venne and Dartt, 1990), and, more specifically, the North Atlantic storm tracks (Tinsley, 1988). Recently, Kodera (2002) found that the North Atlantic Oscillation (NAO) in winter depends on the phase of solar cycle.

Thus there is some impact of long-term solar variability on the troposphere. However, it does not mean automatically an impact on tropospheric trends. In model calculations as well as in analyses of observations, the solar activity was found to be responsible, together with major volcanic eruptions and the greenhouse effect, for global mean temperature variations in the first part of the 20th century, but not for the rapid global warming in the last two-three decades, which is considered to be essentially of anthropogenic origin (e.g., Stott et al., 2001; North and Wu, 2001; Bertrand and van Ypersele, 2002).

The effects of geomagnetic activity on tropospheric circulation have been demonstrated experimentally (Bochníček et al., 1999a, b; Bochníček and Hejda, 2002) as well as theoretically (Arnold and Robinson, 2001), but they remain less understood than the solar ones. Their possible influence on long-term trends has not yet been studied, but it might be responsible for a part of experimentally estimated solar influence on trends due to similar long-term development of solar and geomagnetic activity at least in the first half of the century.

There are some indications of the galactic cosmic ray variability impact on cloudiness and, thus, upon the troposphere on the solar cycle time scale (e.g., Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2003). However, the reality of that effect is under debate (e.g., Sun and Bradley, 2002) and the explanation of observational correlations is possible also through variability of the total solar irradiance (Kristjánsson et al., 2002). This effect may be masked in observational studies of solar influence on trends in the troposphere as a part of the direct solar effect (expressed either through the total solar irradiance or the sunspot numbers).

Thus it may be said that there is some effect of solar origin on the observed long-term trends (e.g., in temperature) at surface and in the troposphere during the first part of the 20th century, but not towards its end. The role of the above space weather parameters in the solar contribution is not clear, but I do not expect it to be dominant.

4. Stratosphere

One of the principal stratospheric parameters is the concentration of ozone. The effect of the 11-year solar cycle in total ozone is small, $\sim 1.5\%$ (e.g., Hood, 1997). Therefore it may be well corrected for and does not affect determination of trends in total ozone, which are affected much more by changes in chemistry, dynamics and other parameters (e.g., Staehelin et al., 2001).

Another important minor component is water vapor. Ground-based, balloon-borne, airborne and satellite data reveal a trend of increasing water vapor concentration in the stratosphere of about 1%/yr since the 1950s (e.g., Nedoluha et al., 1998; Oltmans et al., 2000; Rosenlof et al., 2001), which is not geographically localized. However, its explanation is not clear enough, because methane photolysis mechanism can explain a half of this increase at maximum. About 10% of this increase might be perhaps accounted for by long-term change of the El Niño-Southern Oscillation (Scaife et al., 2003). With respect to the length of the period of available data and their time-development, it is almost certain that the trend in the stratospheric water vapor concentration is not influenced by contributions of solar origin.

There is a measurable but moderate solar cycle effect in temperature and ozone in the upper stratosphere and stratopause region. Labitzke (1987, 2001) and Labitzke and van Loon in a couple of papers (e.g., 1993) found a correlation of temperature and geopotential height with solar activity on the solar cycle time scale. In winter this correlation becomes well pronounced after dividing data according to the phase of the quasi-biennial oscillation (QBO). Quite recently Labitzke (2003) disclosed an important role of the QBO in solar correlations even in summer.

Stratospheric data for trend calculations are available (except for ozone) since the late 1940s, since the International Geophysical Year (IGY, 1957–1958) or from the (late) 1970s (satellite era). However, except for the solar cycle, long-term changes of solar and geomagnetic activity were relatively small since the IGY. The solar cycle effect in stratospheric parameters is not strong, and geomagnetic activity effects appear to be substantial only rarely. Therefore, their effect on trends cannot be significant. The effect of solar cycle can largely be removed by appropriate selection of the analyzed period. Ramaswamy et al. (2001) reviewed trends in stratospheric temperatures for the period from the mid-1960s to mid-1990s and came to the conclusion that for data series of the length of about 30 years (about three solar cycles) the solar activity cannot affect the calculated trends in stratospheric temperatures.

Thus we may conclude that Sun's influence on the observed trends in the stratosphere in the second half of the 20th century is negligible, if any at all.

5. Mesosphere and lower thermosphere

When we go up to the mesosphere, we enter the region where the solar control begins to compete successfully with the ‘‘meteorological’’ control.

Trends in temperature in the mesosphere and mesopause region have most extensively been studied among trends in the mesosphere and lower thermosphere (MLT) region. Beig (2002) and particularly Beig et al. (2003) critically summarized the results. The solar cycle effect at northern middle latitudes seems to be heating by several degrees from the solar cycle minimum to its maximum in the mesosphere and slightly less in the mesopause region, larger in winter than in summer. At high latitudes, there seems to be large heating in the mesosphere and essentially no heating in the mesopause region. There are substantial differences between various authors (e.g., Labitzke and Chanin, 1988; Kokin et al., 1990; Mohankumar, 1995; Keckhut et al., 1995; Lübken, 2001; Beig and Fadnavis, 2001; Espy and Stegman, 2002). The solar cycle effect seems to alternate its sign with height. Nevertheless, the solar cycle effect appears to be larger than the trend-related change over one decade (Beig et al., 2003; Khosravi et al., 2002). Therefore it must be taken into account, when temperature trends are determined. Fortunately, many data series are sufficiently long to allow diminish and/or filter out the solar cycle effect. Geomagnetic activity (storms) probably plays less important role and its effect on temperature has a complex height structure at middle latitudes with a negative effect in the middle mesosphere (Laštovička, 1988).

One must be careful in calculating the trends in the MLT region temperatures in order not to ‘‘spoil’’ the trend with the strong solar cycle effect. On the other hand, the long-term change of solar activity in the last four decades was rather weak, therefore the solar contribution to the observed trends in temperature, if any, has to be small and unimportant.

Another important quantity in the MLT region is wind. There is a worldwide network of observatories to measure the wind in the mesopause region, particularly near 95 km with meteor radars and other instruments. In the prevailing zonal wind neither the trend, nor solar cycle effect is clear (Jacobi et al., 2001, 2003). The prevailing meridional wind appears to weaken (Jacobi et al., 2001) in agreement with model calculation (Jacobi et al., 2003), but the solar cycle effect again is not clear. Anyway, the solar cycle effect in winds does not seem to be strong and does not affect the determination of trends significantly.

The water vapor concentration in the mesosphere exhibits a similar trend to that in the stratosphere, $\sim +1\%/\mathrm{yr}$ (e.g., Nedoluha et al., 1998), even though this statement is based on shorter data series. There is no available indication of a solar cycle influence on the trend. However, the increasing concentration of water vapor resulted in a significant decrease of the mesospheric ozone concentration near sunset (not near sunrise) according to HALOE measurements, probably as a consequence of the production of ozone-destroying hydrogen species via photolysis of water vapor (Marsh et al., 2003). This process may be influenced by variations of solar activity and, therefore, more research into the possible solar activity effect on changes of mesospheric water vapor and ozone is needed. Nevertheless, the basic long-term trends in the concentration of both species seem to be very predominantly of non-solar origin.

No information about long-term trends in the gravity wave activity is available. However, long-term trends in the planetary wave activity have been studied based on the planetary wave activity inferred from long-term, continuous measurements of the radio wave absorption in the lower ionosphere over Europe (e.g., Laštovička et al., 1994; Laštovička, 1997). Some increase of planetary wave activity was found in the 1970s and early 1980s with no change in the 1960s and early 1990s. There was evidently no solar activity effect on those long-term changes. It should be mentioned that in the stratosphere at northern high latitudes (50–90°N) in January–March, a significant decrease of planetary wave activity has been observed since the 1980s (Hu and Tung, 2003).

6. Lower ionosphere

The lower ionosphere is the lowest part of the ionosphere, located below about 100 km. However, for the sake of trend studies we consider the lower ionosphere up to 120 km, i.e. including the maximum of the E region of the ionosphere. The studied region consists of two ionospheric regions, D and E regions, located below and above 85–90 km, respectively. The lower boundary of the lower ionosphere varies between about 40 km (solar proton events at high latitudes) and 75–80 km (night, quiet conditions, middle and low latitudes). For trend studies we understand under the term lower ionosphere only its ionized component, which means practically the electron density, because much more observational data are available for the electron density than for the ion density and ion composition. The lower ionosphere is an extremely variable part of the ionosphere, where both the solar/geomagnetic/high-energy particle effects and the meteorological effects play an important role and compete with each other. In terms of the neutral atmosphere, the lower ionosphere corresponds to the mesosphere and lower thermosphere. The lower ionosphere exhibits a strong solar cycle effect, and particularly the D region at higher latitudes is strongly affected by geomagnetic storms (e.g., Laštovička, 1996), while storm effects on the E region are weaker (e.g., Brown and Wynne, 1977; Buonsanto, 1999). Therefore a substantial influence of solar origin on the trend determination and trends themselves is possible. An overview of trends in the lower ionosphere has quite recently been given by Laštovička and Bremer (2004).

The effect of solar cycle on the calculation of trends may be eliminated or at least diminished by three ways. First, right selection of data (examples are shown in Figs. 1 and 2). Second, to correct data for solar and geomagnetic activity variability and calculate trend from corrected data, as it was done for the indirect LF phase reflection height data (e.g., Bremer and Berger, 2002). Third, to apply a method developed by Danilov (1997) for E-region studies. A multi-parameter regression analysis of experimental data, which takes into account dependencies on the solar zenith angle, local time, latitude, solar activity and geomagnetic activity without any allowance for possible effects of trends, was applied to construct an empirical model of electron densities. The ratio of observed electron density in each particular experiment to the corresponding model density, r_c, was investigated in search for long-term trends.

To study trends in the lower ionosphere, data sets obtained by the following methods were used: A3 radio wave absorption (LF or MF-HF, oblique incidence on the ionosphere, continuous wave, e.g. Laštovička et al., 1993), A2 (cosmic radio noise) riometric absorption (e.g., Ranta et al., 1983), IPHA (Indirect Phase Height Analysis—indirect measurements of the LF phase reflection height, e.g., Lauter et al., 1984), LF radio wave reflection heights, rocket measurements of electron density, and ionosonde (vertical ionospheric sounder) measurements of the maximum electron density in the E region and of its height.

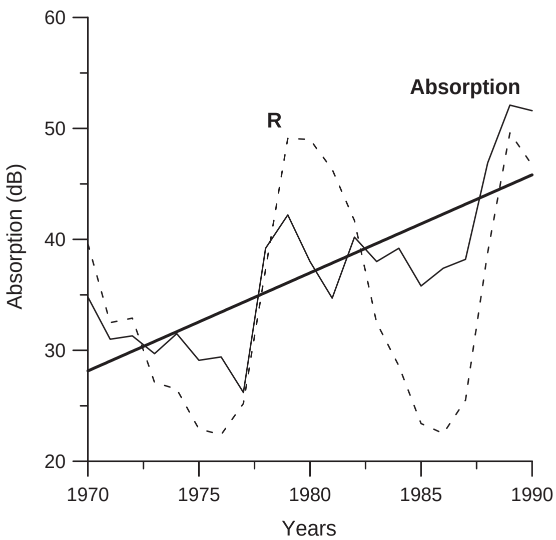

Fig. 1. Trend (thick straight line) in the yearly average raw absorption data (thin line), slope = +0.893 dB/yr, at 1412 kHz, 1970–1990 (adopted from Laštovička and Pancheva, 1999). R—yearly average sunspot numbers (dashed line).

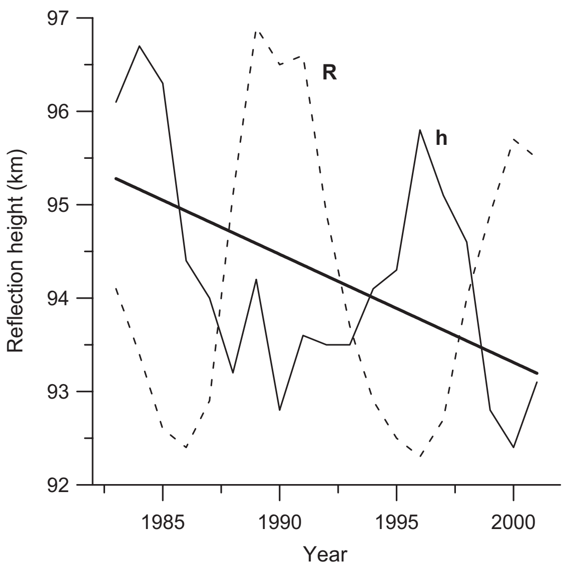

Fig. 2. Trend (thick straight line) in the nighttime LF reflection height (h—thin line), yearly average raw data, over 1983–2001 as measured at Collm on 177 kHz (adopted from Kürschner and Jacobi, 2002). R—yearly average sunspot numbers (dashed line).

Fig. 1 illustrates the case when even a strong solar cycle effect did not affect much the trend. The A3 radio wave absorption data exhibit a strong solar cycle effect. However, the positive long-term trend in Fig. 1 is not affected significantly by the solar cycle due to the right selection of data (from solar cycle maximum to solar cycle maximum; the level of solar activity in 1967–1969 was the same as in 1970) and relatively strong trend.

The A2 riometric absorption did not provide a conclusive result and appears not to be an appropriate tool for studying trends, perhaps because the trends in electron density are height-dependent in the lower ionosphere (Laštovička and Bremer, 2004) and the A2 absorption integrates over a relatively broad range of altitudes.

As stated above, calculation of trends in the IPHA data were made with data corrected for solar and geomagnetic activity (e.g., Bremer and Berger, 2002) and, therefore, no evident solar cycle effect occurs in the data series used and the observed trend may be considered to be very predominantly of anthropogenic origin.

Another situation is with the LF reflection heights, shown in Fig. 2 as an example of a trend strongly affected by solar cycle. These data are by-product of wind measurements at Collm, Germany. Fig. 2 shows that the data series is relatively short, and it begins under lower solar activity conditions (high reflection heights due to lower electron density) and ends under high solar activity conditions (low reflection heights). Therefore the trend line in Fig. 2 is strongly affected by the solar cycle and it does not represent real trend. Laštovička and Bremer (2004) estimated the real trend to be a little bit more than a half of that shown in Fig. 2.

Rocket data on electron density yielded negative trends below about 87–90 km in agreement with ground-based data, but positive trends above (Friedrich and Torkar, 2001) in contradiction with ground-based data (Laštovička and Bremer, 2004). Since the database consists of slightly more than 100 rocket launches over almost 50 years, it is possible that solar and geomagnetic influences contribute to the contradiction. More detailed investigation of this problem is required.

In the E region, trends in foE and the height of E-region maximum, hmE, have been studied. The global network of ionosonde measurements has been utilized for trend examinations. Trends in foE are generally positive while those in hmE are generally negative (e.g. Bremer, 2001; Danilov, 2002a) in qualitative agreement with model expectations, changes in ion composition (foE) and idea of thermal shrinking of the upper atmosphere (hmE). Fortunately the global ionosonde network has been working since the IGY (1957–1958) and a couple of stations even before, therefore there are relatively large amount of data for trend investigations. The positive trend in foE is suggested to be caused by a negative trend in $\varphi^+ = (NO^+/O_2^+)$ near the maximum of E region and, therefore, by a positive trend in the effective recombination coefficient. The negative trend in φ^+ was revealed by analysis of rocket measurements (e.g., Danilov, 2001).

Long-term changes of geomagnetic activity might be also important for trend calculations, particularly in the ionized component at higher latitudes and higher heights. Mikhailov and de la Morena (2003) claim that before about 1970 the long-term changes/trends in foE had been controlled predominantly by geomagnetic activity, whereas since about 1970 they have been controlled predominantly by anthropogenic factors. Their result is based on the change of sign of the relation between foE_{132} and Ap_{132} (132 months, i.e. 11-year smoothed values)—the negative sign corresponds to the sign of effect of geomagnetic storm (activity). Table 1 as an example of possible strong geomagnetic activity impact on long-term changes of foE shows negative signs, i.e. geomagnetic control, before about 1970, and positive signs, i.e. non-geomagnetic, anthropogenic control, after about 1970.

Table 1
Sign of the relation between foE132 and Ap132 (132 month (=11 year) smoothed values) and the period of occurrence of the given sign for five selected midlatitude stations from western Europe (Slough) to eastern Asia (Khabarovsk), adopted from Mikhailov and de la Morena (2003)

Station	Sign	Period	Sign	Period
Slough	+	1968–80	–	1936–67
Rome	+	1972–95	–	1962–71
Tomsk	+	1971–92	–	1950–70
Askhabad	+	1973–81	–	1962–72
Khabarovsk	+	1970–83	–	1965–69

The lower ionosphere is under strong control by solar and geomagnetic activity. Nevertheless, suitable selection of analyzed periods or data corrections make it possible to avoid or at least substantially diminish the effect of solar cycle on the trend determination, the trends being considered to be of basically anthropogenic origin. This anthropogenic origin means primarily the greenhouse effect, but some contribution of anthropogenic non-greenhouse changes of ozone concentration seems to be likely (e.g., Bremer and Berger, 2002). On the other hand, as Mikhailov and de la Morena (2003) claim for foE, trends in older data, but not in the data of the last 2–3 decades of the 20th century, might be to a substantial extent of Sun's origin, particularly of geomagnetic activity change origin.

7. Thermosphere

In the thermosphere, only trends in neutral density have been studied due to availability of data. The trends in thermospheric density around 350 km were derived by Keating et al. (2000) from satellite drag measurements. The observed decrease of thermospheric density was about 5% per decade for solar minimum years. It was interpreted as a consequence of greenhouse cooling. Emmert et al. (2004) analyzed satellite drag measurements, as well. To avoid the strong effect of solar cycle on thermospheric density, data were separated according to the level of solar activity. The average trends of decrease of the thermospheric density ranged at heights of 200–700 km from −2% to −5% per decade; they were largest for solar minimum conditions and they increased with increasing height. The trends were largely independent of geomagnetic activity, local time, latitude and season, which support their anthropogenic origin.

It was possible to find trends in the thermospheric density, which were not affected by solar cycle and agreed at least qualitatively with the expected effect of greenhouse cooling, due to appropriate selection of data, which took into account the phase of solar cycle.

8. F-region ionosphere

The F-region ionosphere is predominantly controlled by solar and particularly geomagnetic activity, or physically more correct by space weather phenomena, which mostly affect the geomagnetic activity. Buonsanto (1999) reviewed the effects of geomagnetic storms on the F region. There is also a modeling activity in this area towards quantitative modeling of the effects of geomagnetic storms (e.g., Fuller-Rowell et al., 2000).

For the sake of trend investigations we have to divide the F region into two parts, the F1 region ($h \sim 160-200$ km) and the F2 region characterized by the maximum critical frequency foF2, which corresponds to the maximum electron density in the ionosphere, and by the height of this maximum, hmF2. Trends and their relation to solar/geomagnetic activity in the F1 and F2 regions differ substantially.

As for trends in the F1 region, they have little been studied. However, investigations with corrections of data for solar (R) and geomagnetic (Ap) activity revealed positive trends in foF1 in reasonable agreement with model predictions (e.g., Bremer, 2001).

There is a lot of controversy about the interpretation of observed trends in foF2 and hmF2, and partly even in their values obtained by different methods (e.g., Ulich and Turunen, 1997; Jarvis et al., 1998; Bremer, 1998, 2001; Mikhailov and Marin, 2000, 2001; Danilov, 2002a and references herein, 2002b, 2003a; Danilov and Mikhailov, 1999). Some studies provide trends of opposite sign in foF2 for different regions (e.g., Bremer, 1998, 2001). A brief critical review of problems with trend determination in the F2 region was done by Ulich et al. (2003). Another problem is with hmF2, which has to be computed from M(3000) for older data. Different methods of that calculation resulted in even opposite trends in hmF2 for some stations like Ottawa (Ulich, priv. comm.).

The trends are interpreted as a consequence of greenhouse cooling (Ulich and Turunen, 1997; Jarvis et al., 1998), or as being controlled by geomagnetic activity (Mikhailov and Marin, 2000, 2001). Danilov (2002b) developed a special method to separate the "non-geomagnetic" trend component. He obtained a decrease of foF2 by -0.12 MHz/decade (Danilov, 2003a). The anthropogenic origin means for most authors the increasing atmospheric concentration of greenhouse gases, but possible role of space debris as anthropogenic pollutant responsible for part of the observed trends cannot be entirely excluded (Danilov, 2003b). A substantial, may be dominant part of long-term trends/changes in foF2 is still likely caused by the respective variations of geomagnetic activity, even though the existence of the anthropogenic contribution to the trends is evident (Danilov, 2003a). The situation remains to a large extent controversial and unclear (even though slightly less than a few years ago), and more research into the problem of determination, and particularly interpretation, of F2 region trends is necessary.

9. Conclusions

Presence of the solar cycle and other long-term variations and changes of ionization rate of solar origin, investigated usually in terms of effects of solar and geomagnetic activity, may affect the trend determination, and in some parameters even to some extent cause the trends. It is possible to suppress or even avoid the effects of Sun's origin, namely of solar cycle, on trend determination with the use of proper selection of analyzed periods, or with the use of data corrected for solar and geomagnetic activity, or with the use of differences from or ratios to an empirical model, which includes the solar and geomagnetic activity, local time, season, latitude and may be some other parameters. The solar and geomagnetic activity may have a crucial impact on the trend determination when data series are relatively short, like LF reflection heights, or when we study trends in the ionized component (ionosphere).

On the other hand, the solar and geomagnetic activity may be responsible for part of the observed long-term trends due to its secular change during the last century, particularly during its first half. To this end, the two main conclusions are as follows:

1. The role of solar and geomagnetic activity in the observed long-term trends decreases with decreasing altitude from the F-region ionosphere (very important) down to the troposphere (negligible at least in the last three decades), and from the ionized component to the neutral component.
2. In the 20th century the role of solar and geomagnetic activity in the observed long-term trends/changes was decreasing from its beginning (some role even in the troposphere) towards its end (important probably only in the F2 region), and the role of the greenhouse effect was increasing towards the end of the century. This was caused both by a continuous increase of concentration of greenhouse gases in the atmosphere and by much weaker trend in the solar and geomagnetic activity towards the end of the 20th century compared to its first half.

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