Long-term trends in the ionosphere and upper atmosphere

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Main driver of long-term trends are greenhouse gases, not the Sun, even though Sun also plays a role in trends.

Therefore the purpose of my talk is not to teach you, it is just to inform you.

Upper atmosphere = mesosphere + thermosphere (+ stratosphere)

Outline

1. Introduction
2. Global scenario of trends
3. Other drivers of trends
4. Role of solar activity in trends
5. Components of global scenario of trends
6. Conclusions

Introduction

Why to study trends in the upper atmosphere?

(1) Anthropogenic emissions of greenhouse gases influence the atmosphere at nearly all altitudes between ground and space, thus affecting not only life on the surface, but also the space-based technological systems on which we increasingly rely.

(2) Life on Earth is more directly affected by climate change near the surface than in the upper atmosphere, but as the story of the Earth's ozone layer illustrates, changes at higher levels of the atmosphere may be important.

(3) Moreover, the mesospheric temperature is more sensitive to increasing greenhouse gas concentration than the tropospheric temperature, the signal/noise ratio being ~20 times larger in the mesosphere.

Therefore it is useful to study long-term changes and trends in the mesosphere, thermosphere and ionosphere.

Greenhouse cooling of the upper atmosphere

- The 0.6ºC 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 long-wave (infrared) radiation, which they both absorb and reemit back to the surface to produce the heating effect. In contrast, greenhouse gases in the much less dense 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”.

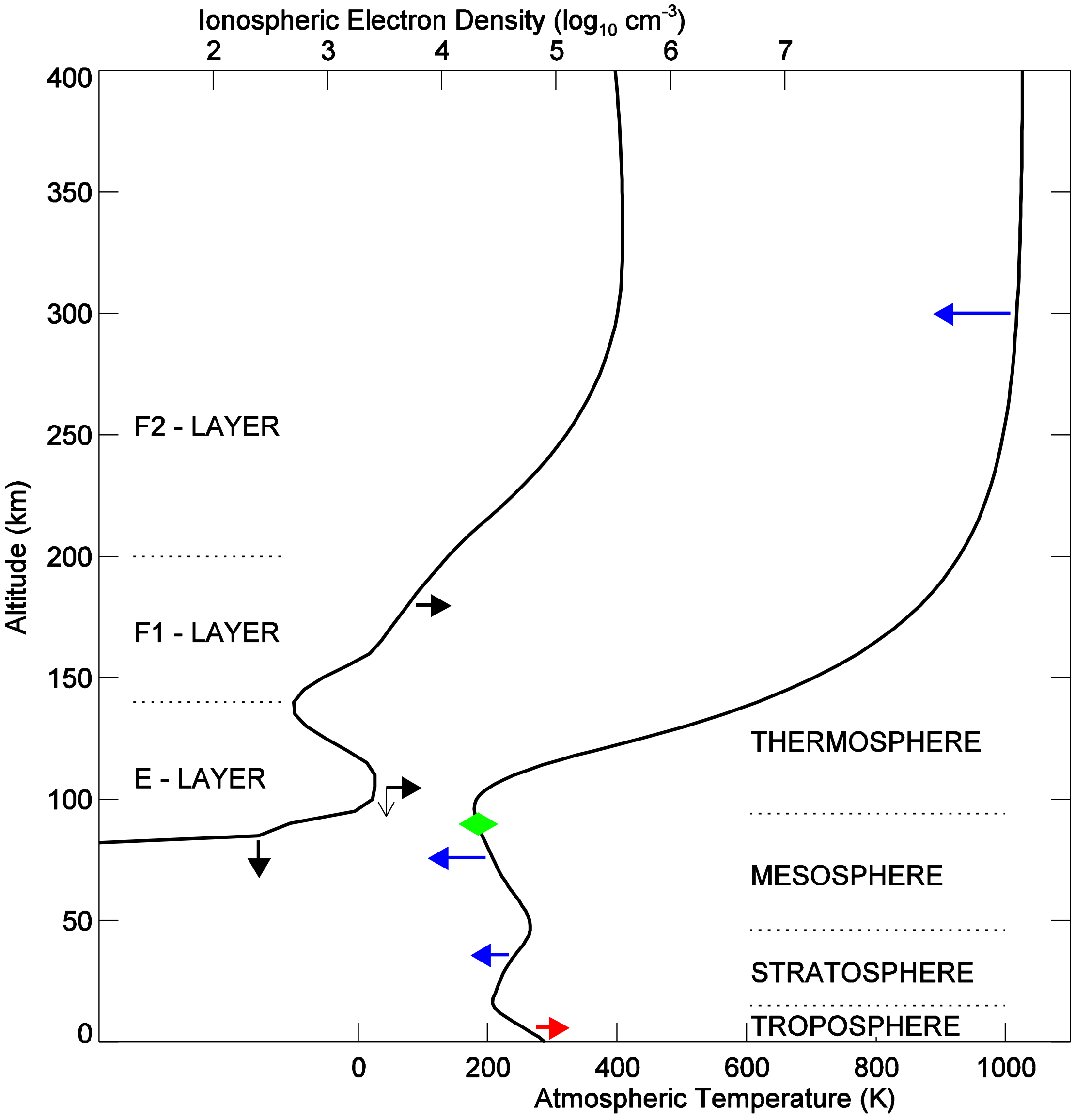
Warming in real garden greenhouse: Light (visible) passes through glass cover, heats the atmosphere inside the greenhouse, heated molecules radiate thermal long-wave radiation, but this **outgoing long-wave radiation** predominantly does not pass through glass and **is trapped in the greenhouse** => **net heating**. Greenhouse gases in the atmosphere act in the same way.

When we **move upwards in the atmosphere**, atmospheric density is becoming lower and lower = **glass cover in the greenhouse is becoming thinner and thinner** and its **ability to trap the outgoing long-wave radiation is becoming lower** and lower until **another effect** of the main greenhouse gas, CO_2, **becomes dominant**. This effect is **infrared emission of CO_2, which means infrared radiative cooling**. Then the **net effect is** what we call **greenhouse cooling**.

The change from greenhouse heating to greenhouse cooling is not a jump-like change with height, it is continuous change with height between the tropopause layer and the lower (lowermost) stratosphere, say at **heights between 10 (warming) and 20 (cooling) km**.

Global scenario of trends

Global trend scenario



Summary of consistent mesospheric, thermospheric and ionospheric trends, which form the global pattern/scenario

Greenhouse effect at Venus versus Earth

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 denser 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 – super-greenhouse effect**.

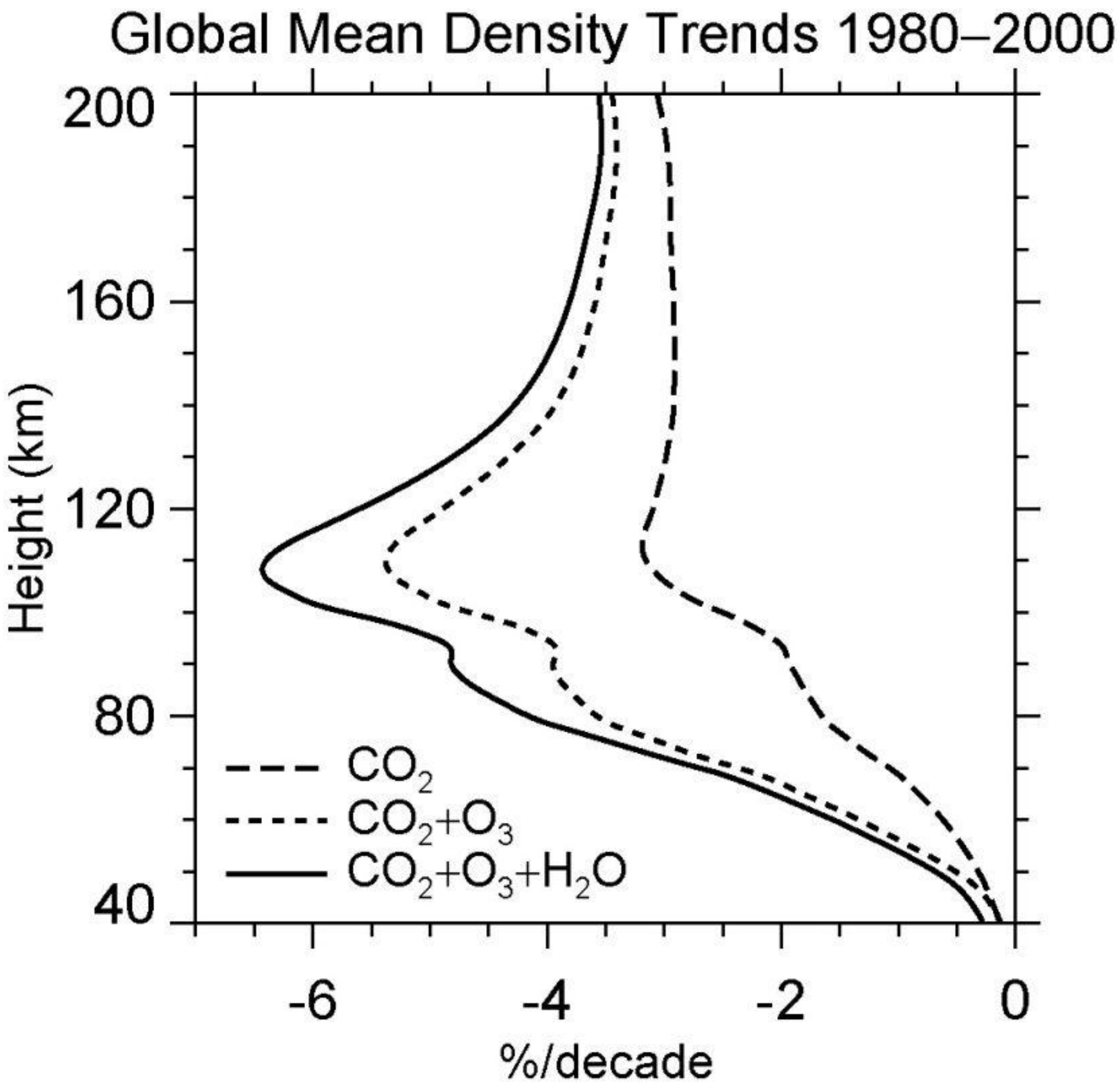
Other drivers of trends

Potential other drivers of trends are long-term changes of:

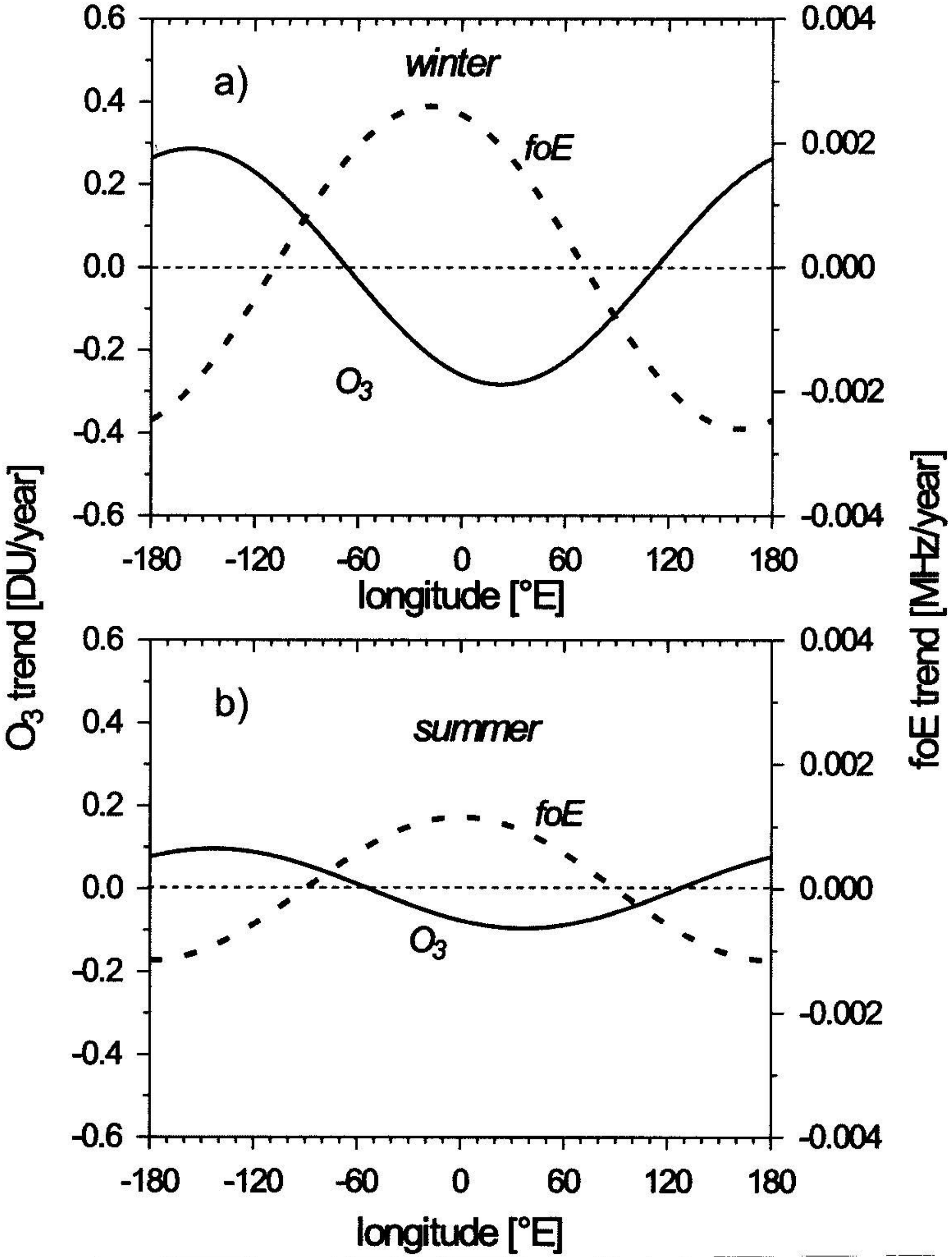
- solar activity
- **geomagnetic activity** (solar wind)
- **Earth’s magnetic field**
- **ozone, namely stratospheric ozone**
- water vapor
- activity of atmospheric waves

=> **Trends cannot be stable, they must change both in time and space**

Role of ozone



Decreasing ozone concentration also contributes to cooling and contraction of the mesosphere. Figure (Akmaev et al., 2006) shows that the largest ozone effect in the neutral atmospheric density occurs in the lower thermosphere around 110 km according to model calculations. **The ozone effect penetrates well into the thermosphere.**

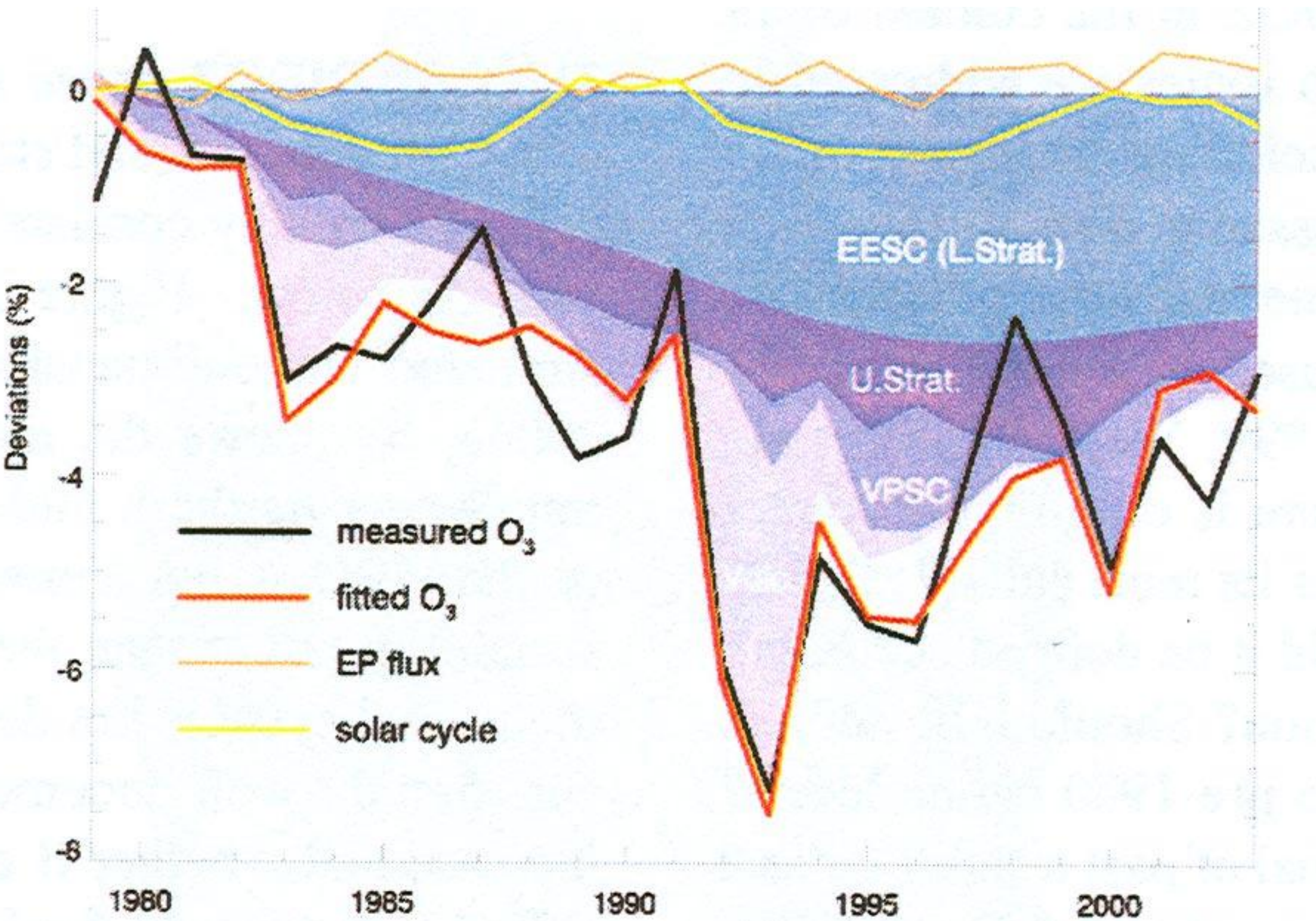


Longitudinal variation of deviations of foE trends from the average trend in foE (ionosondes between 30-75^{o}N) and of total ozone trends (ERA40, 30-75^{o}N). Bremer and Peters (2008).

Clear anticorrelation between foE trend deviations and total ozone trend deviations.

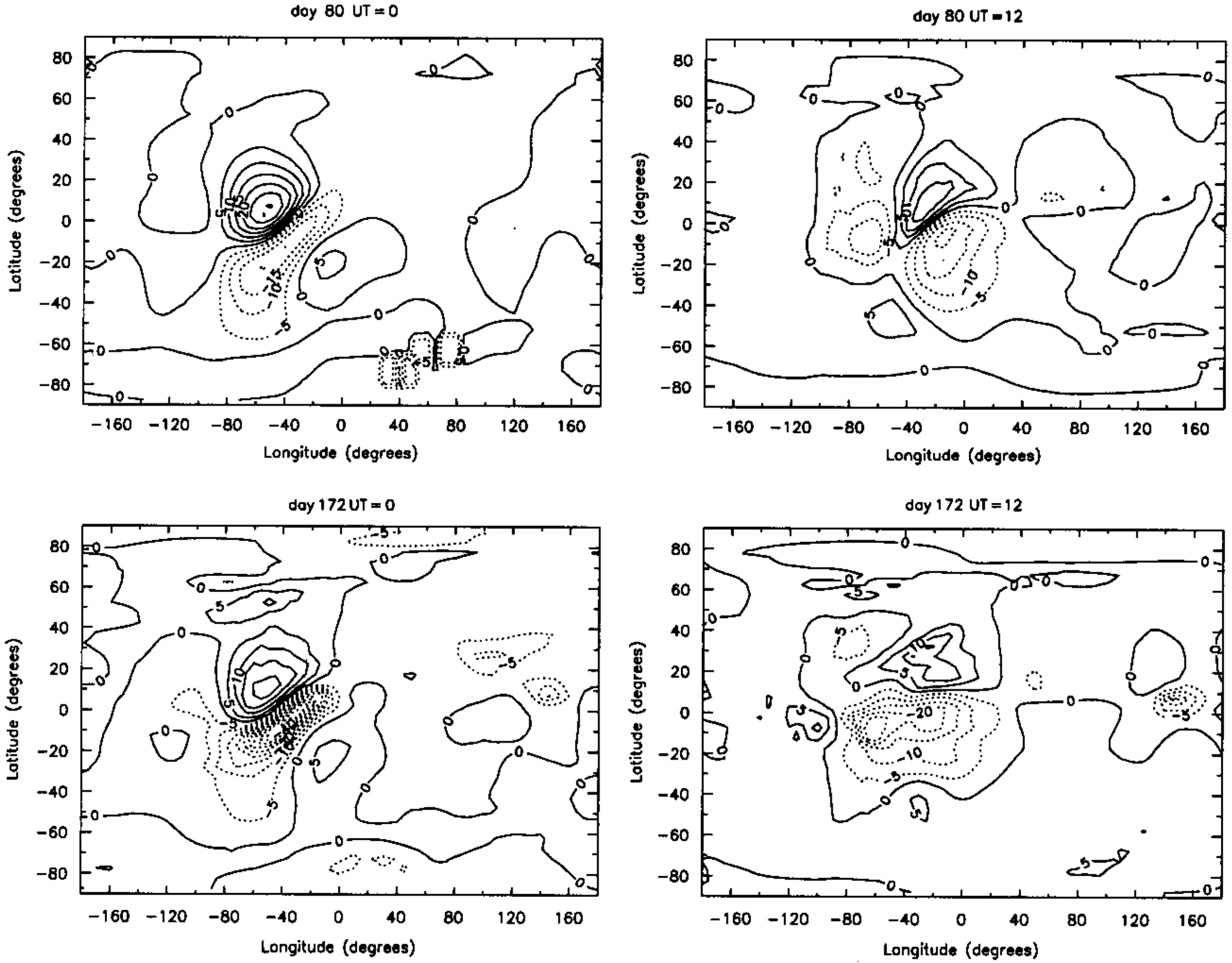
No relation has been observed in the F1 region (Bremer, 2008).

Annual evolution of northern midlatitude (36-60ºN equivalent latitude) **total ozone anomalies, 1979-2003,** calculated by a multiple regression analysis of the CATO data set. After Harris et al. (2008).



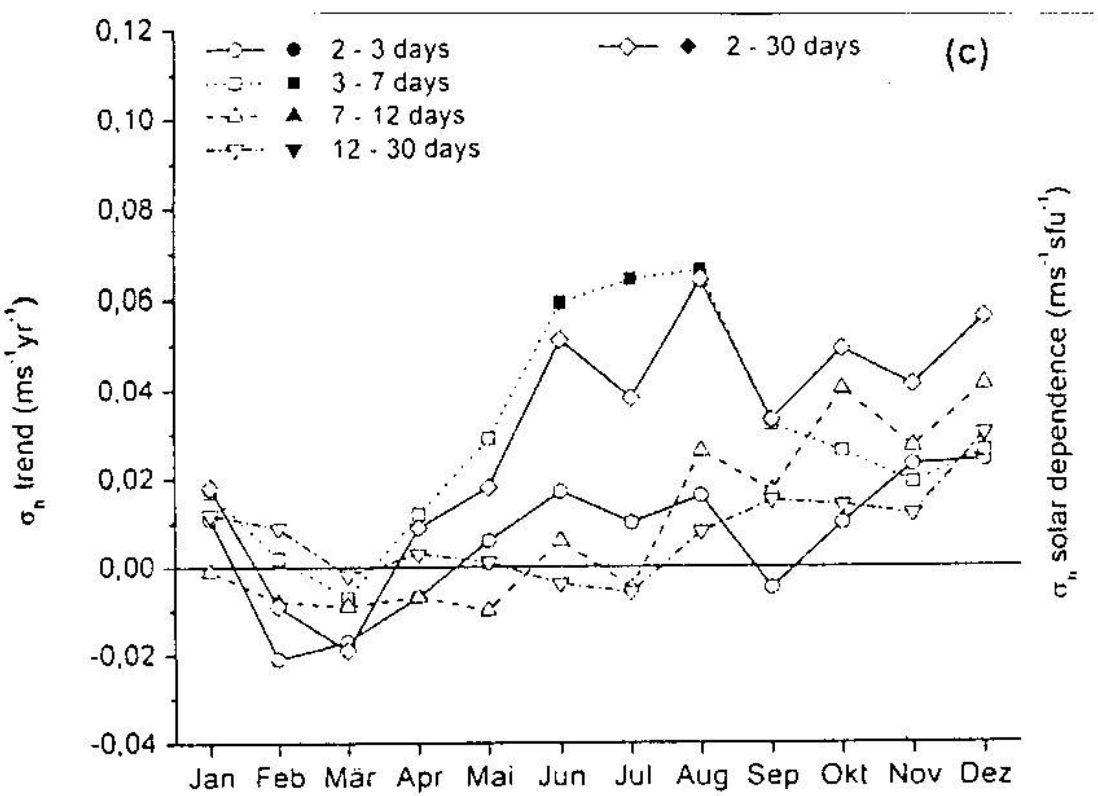
Turnaround of trends occurs near 1995 (minimum in 1993 – effect of Pinatubo) – appears to be a change caused predominantly by atmospheric dynamics.

Impact of long-term (secular) changes of the Earth’s magnetic field is ingnificant 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** after model calculations (TIE-GCM) by Cnossen and Richmond (JASTP, 2008).



Effect of the Earth’s magnetic field in **hmF2, 1957 → 1997**

Atmospheric waves strongly affect winds; waves are main agent of vertical coupling in the atmosphere; waves are capable of influencing trends in large majority of upper atmospheric and ionospheric parameters. However, **trends in planetary, tidal and gravity wave activities are highly uncertain, seasonally dependent, largely unknown, and very probably changing/unstable.**



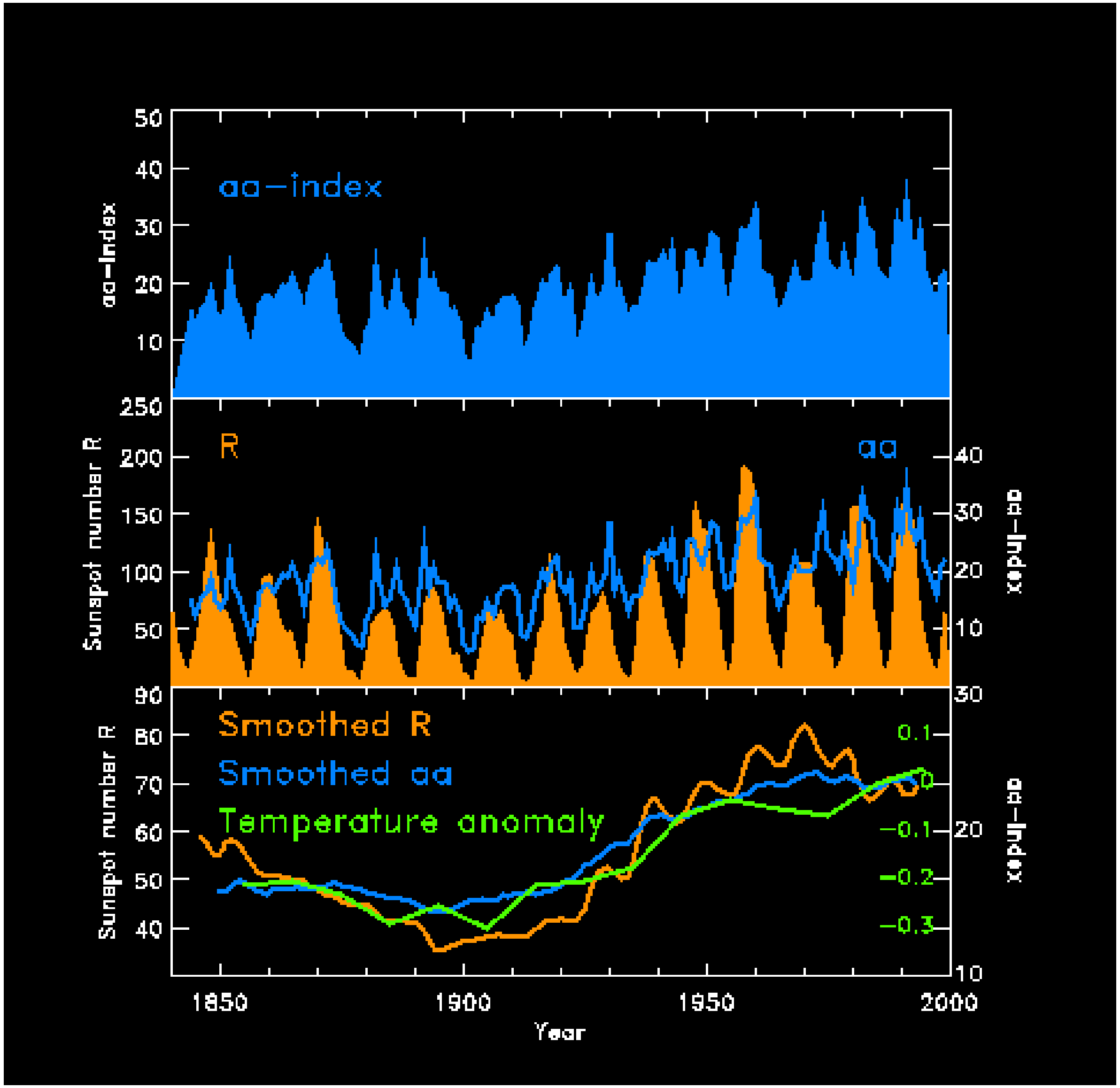
Trend in planetary wave activity (total wind, Collm) is slightly positive in average but strongly season- and period-dependent with little statistical significance (Jacobi, 2008).

There are almost no studies of long-term **trends in gravity wave activity**. 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 did not reveal any significant trend (Gavrilov et al., 2002); Hoffman et al. (2010) found for Juliusruh (MLT wind) a weak positive trend at 80-90 km and they mention that some stations display trends, some not. Offermann (2011) reported a positive trend from OH measurements above Wuppertal (Germany). As trends/long-term changes of winds at various northern midlatitude stations differ significantly, we may expect the gravity wave activity trends to differ as well. Some mechanisms of trends in GW activity, like changes of storm tracks at midlatitudes, **may result in different trends in GW activity at different stations even as to sign – caution!**

Insufficient information about trends and long-term changes in atmospheric wave activity is the key problem of trend studies in the upper atmosphere-ionosphere system.

Role of solar activity in trends

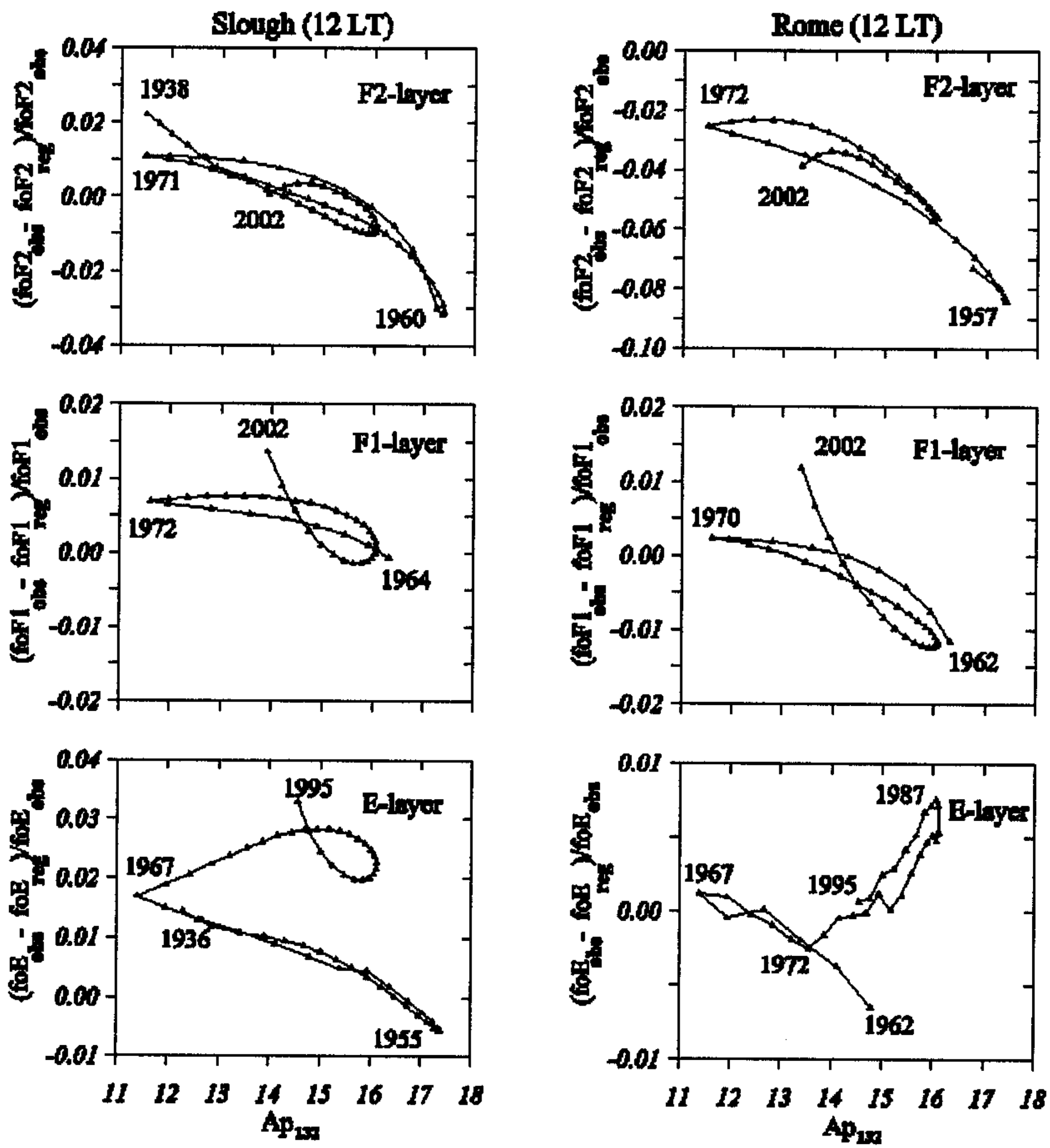
Geomagnetic activity (aa) was increasing throughout the 20th century. Solar activity was increasing only till 1957-58 (IGY).



After Pulkkinen (2002)

The increase of geomagnetic activity leveled off and it might even decrease at present.

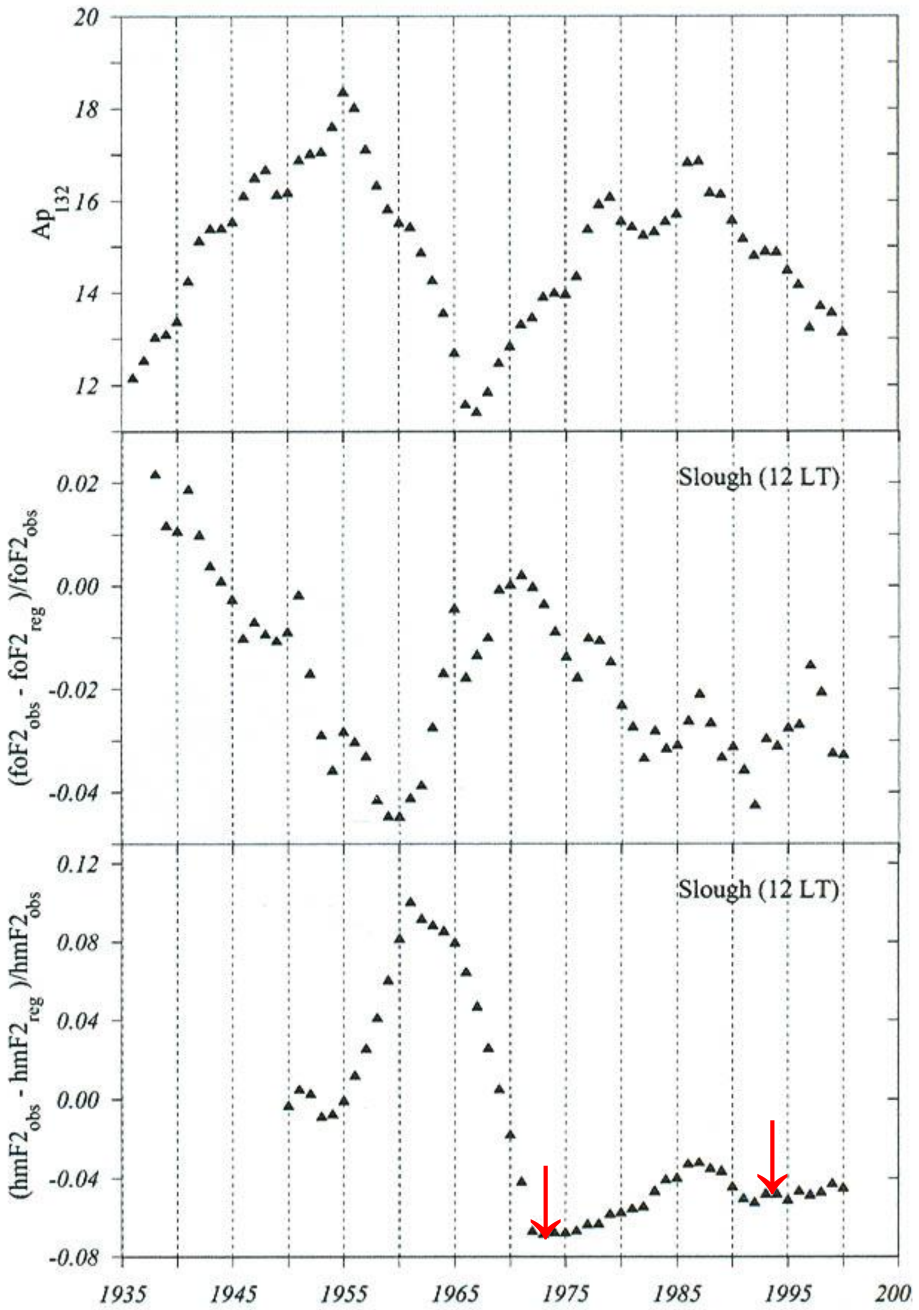
Scaling of aa was probably wrongly modified in the late 1950s; its real increase was likely somewhat lower (Martini and Mursula, 2008).



Relationships between δfoF2 (top panels), δfoF1 (middle panels) and δfoE (bottom panels), and Ap132 variations for Slough (left panels) and Rome (right panels). Noontime values. After Bremer et al. (2009).

The change in the type of the dependences came later for higher altitudes. Trends in the F2 region appear to be controlled until ~2000 by geomagnetic activity, whereas in recent years the greenhouse gas control dominates.

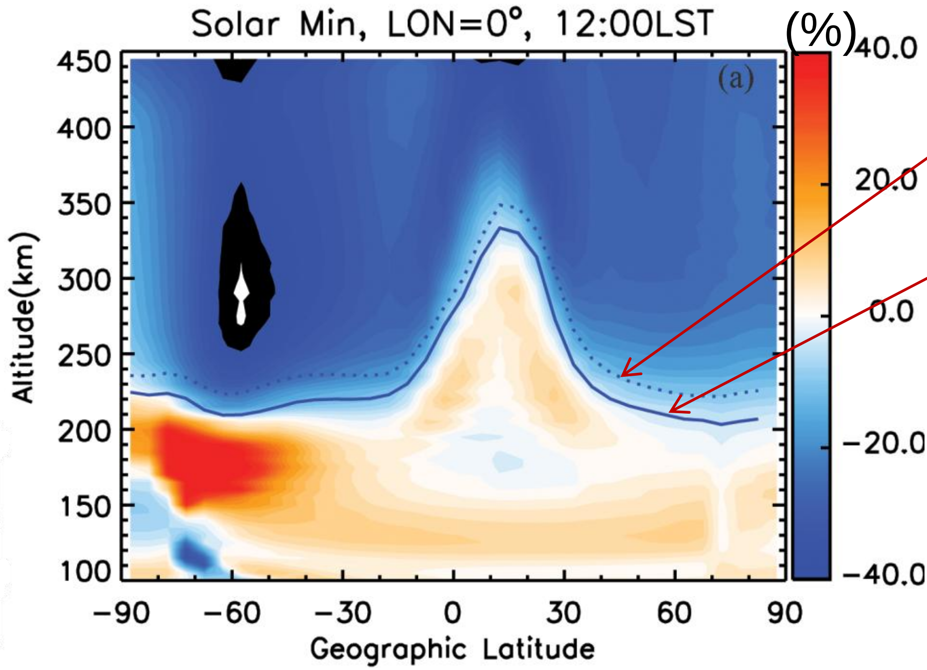
Ionospheric trends seem to be longitude-dependent (Jarvis, 2009).



11-year running means (132 months): Ap_{132} (top panel), $\Delta foF2_{132}$ (middle panel) and $\Delta hmF2_{132}$ (bottom panel) long-term variations at noon for Slough (U.K.). Mikhailov et al. (2006, AG).

ΔfoF2132 mirrors Ap132 with delay of 4-5 years, but ΔhmF2132 (bottom panel) copies with the same delay Ap132 only till the early-mid 1970s, than this geomagnetic control is largely lost, particularly after the early-mid 1990s (see red arrows).

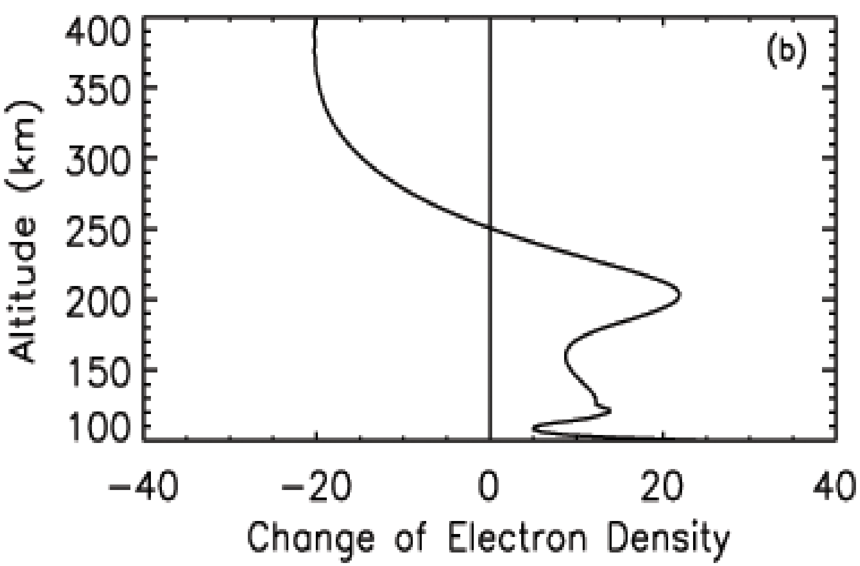
Simulation Results: Understand F2 region trends



hmF2: base

hmF2: double

$$\Delta NE(\%) = \frac{(double - base)}{base} \times 100$$



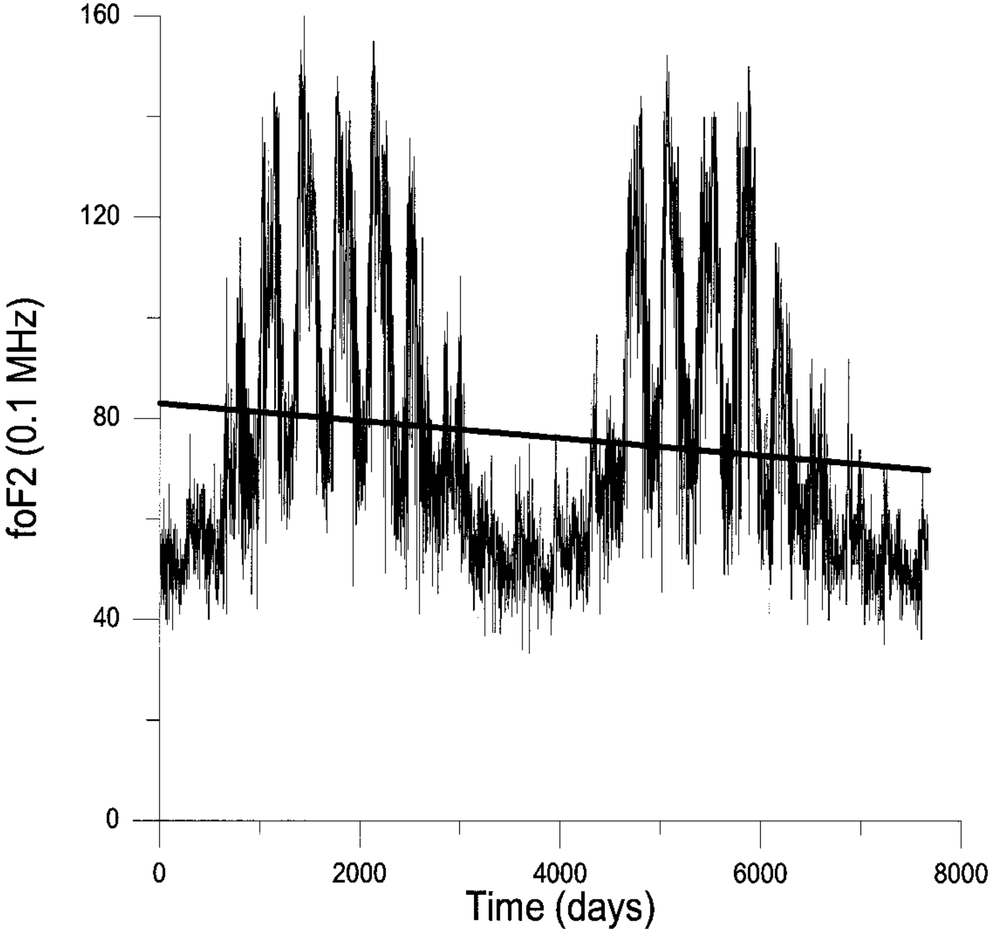
Daytime (noon):

$\Delta NE:$ Negative at F2 peak and above
Positive in the E and F1 regions

$\Delta hmF2:$ Negative

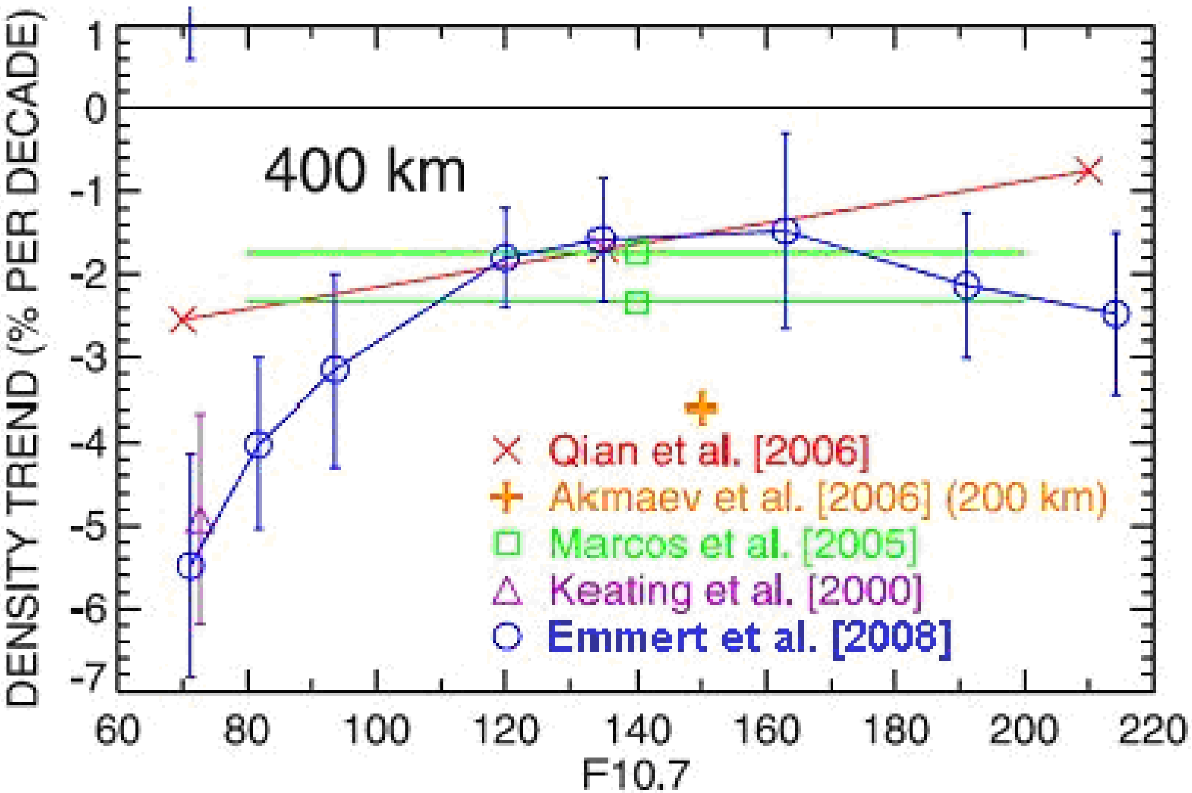
Qian et al., 2008

Even though solar cycles 21 and 22 were very similar, the trend in foF2 computed without reduction to solar activity was three-times as high as real trend.



Laštovička et al. (2006).

Thermospheric neutral density trends near 400km derived from satellite drag over three solar cycles – Emmert et al. (2008).

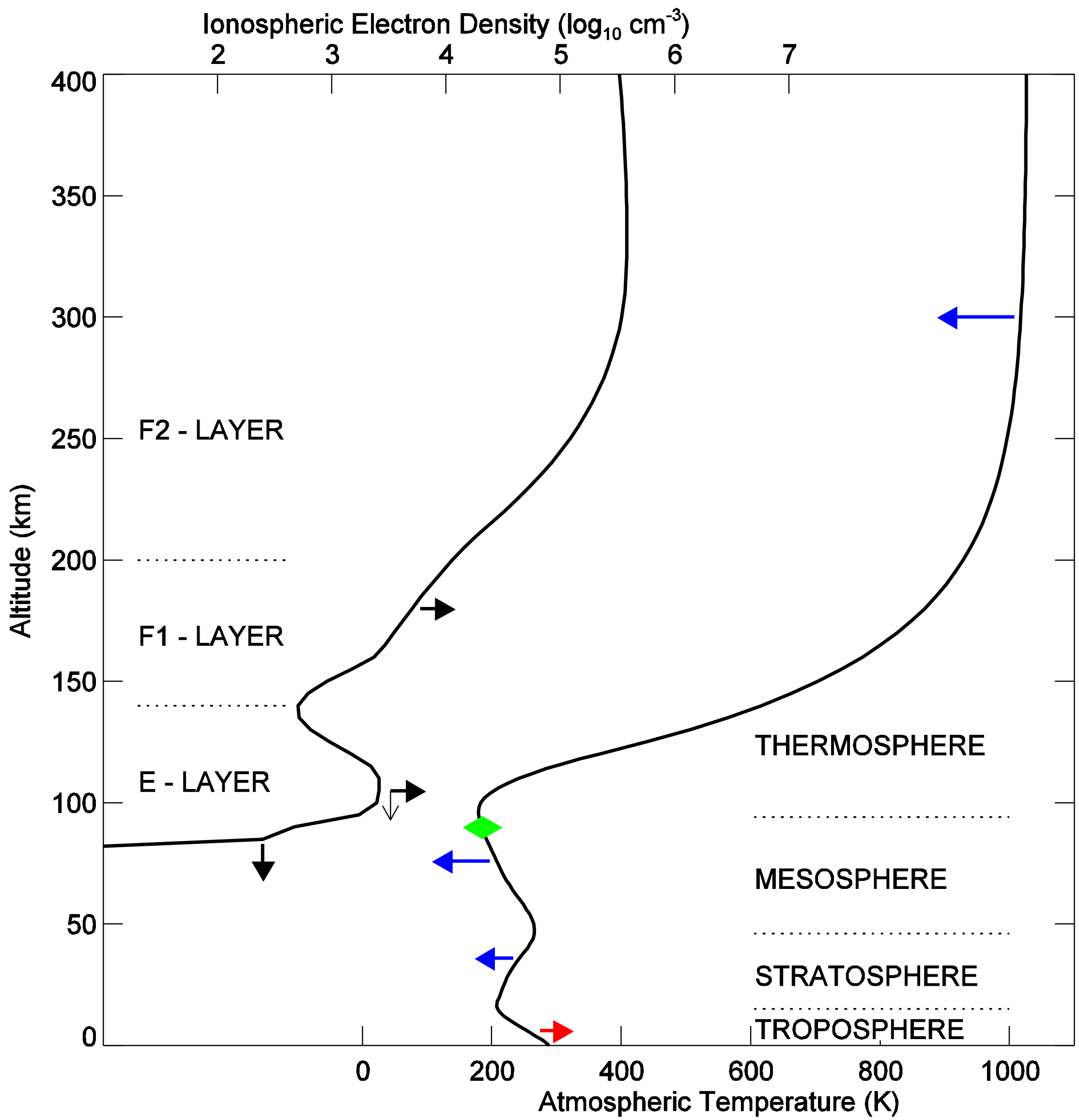


Trends are negative for any level of solar activity but they are substantially stronger under solar minimum conditions due to larger relative role of CO_2 in radiative cooling.

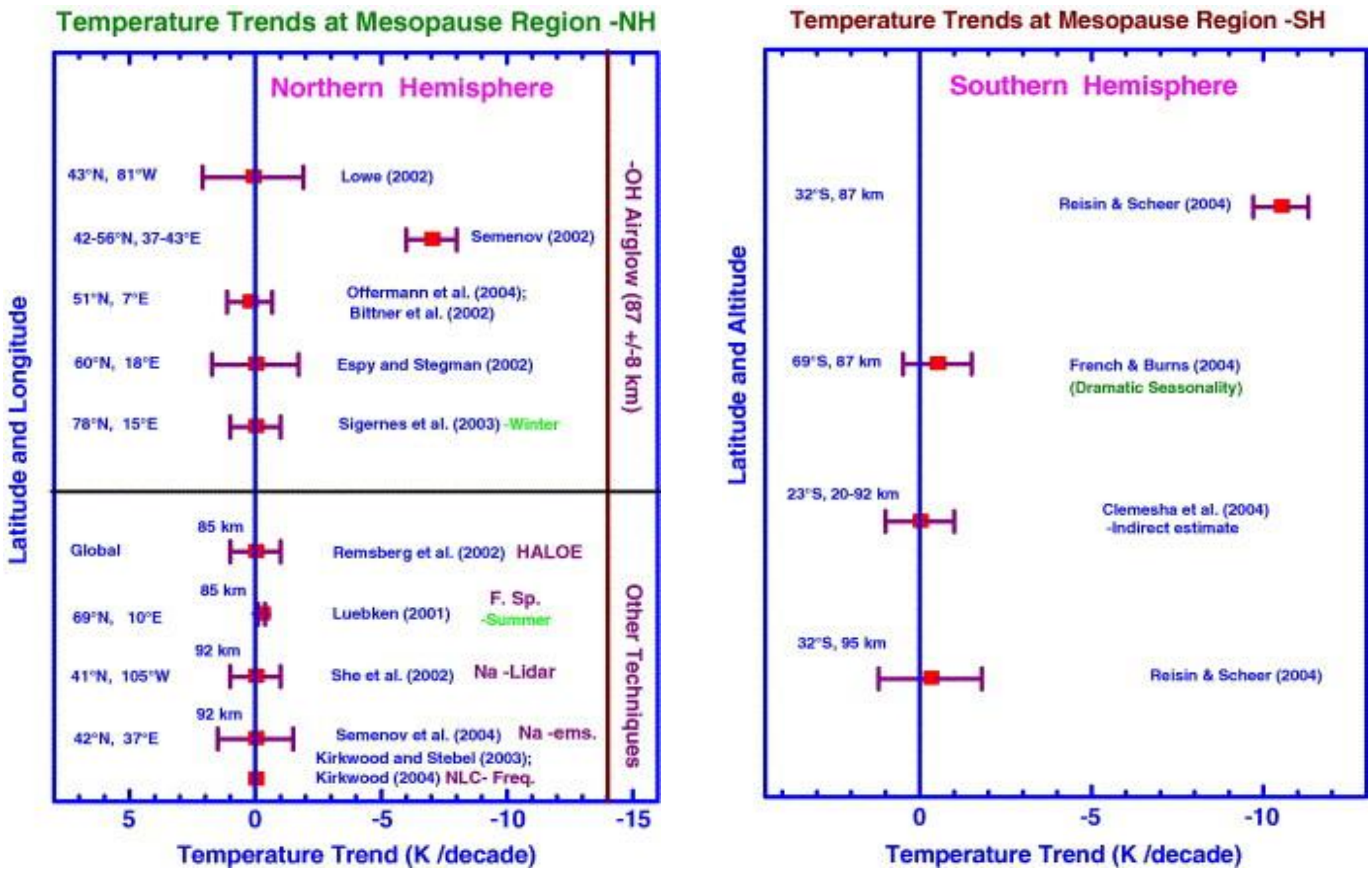
NO radiative power decreased by almost an order of magnitude 2002 → 2009, whereas CO_2 radiative power decreased by ~35% (SABER, Mlynczak et al., 2010).

Components of global scenario of trends

Global trend scenario



Summary of consistent mesospheric, thermospheric and ionospheric trends, which form the global pattern/scenario



Trends in the NH (left) and SH (right) mesopause region temperatures (Beig, 2006, PCE).

Impact of the ozone trend change (1995-1997 for NH) on temperatures:

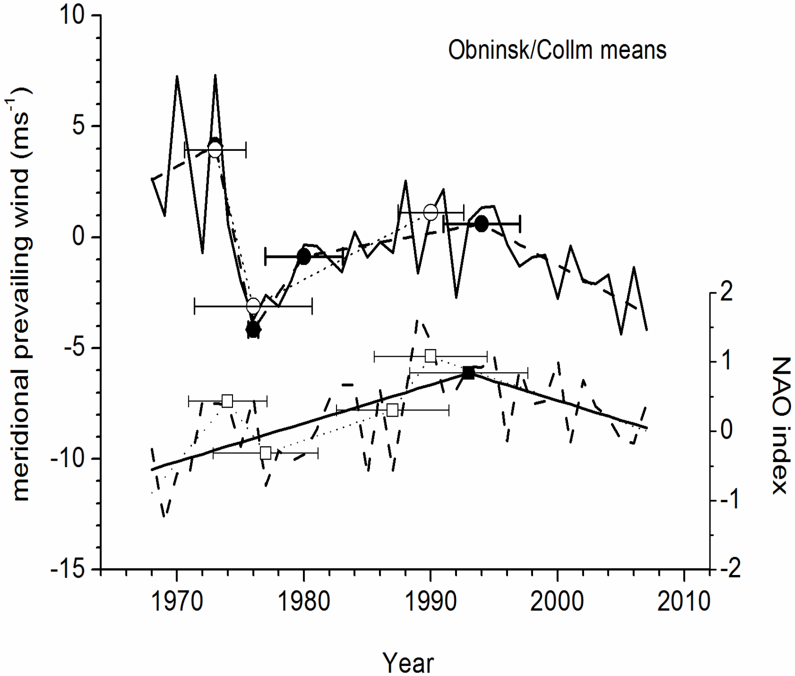
Stratosphere – leveling off of trends (Yoden, 2010).

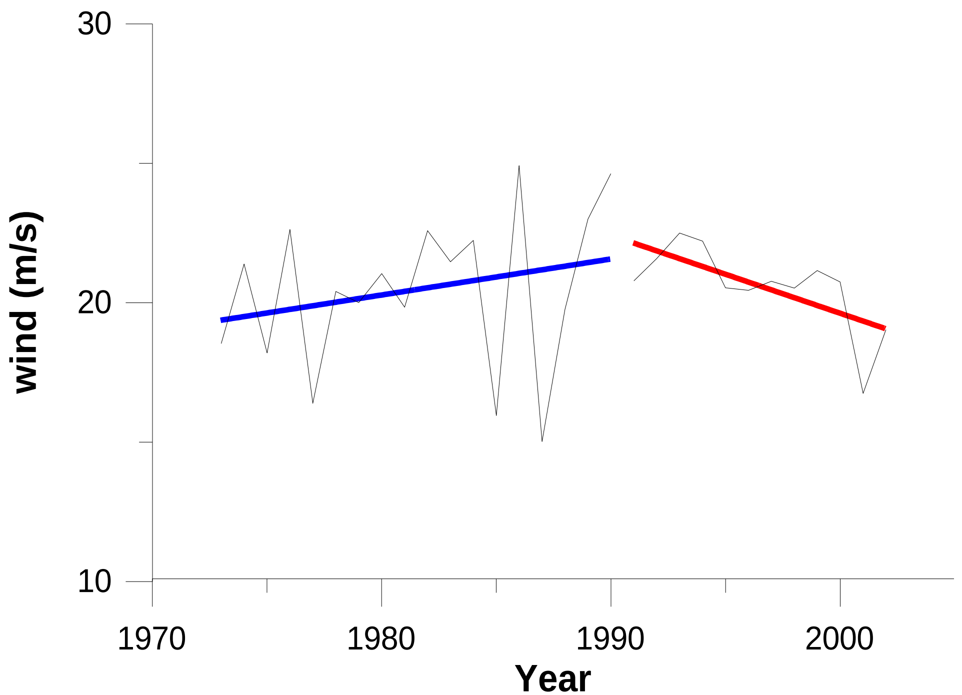
Mesosphere – HALOE trends weaker than older rocket and lidar trends, as ozone effect over HALOE period was close to none (Remsberg, 2009). Rocket soundings at Volgograd – trends are weaker after ~1995 (Yushkov, 2011).

Mesopause – trend changed from no trend to a (slight) negative trend (Beig, 2010). For low latitudes it was confirmed by Venkat Ratnam et al. (2010). NDMC is working on.

The change of the mesopause region trends means a modification (but not change) of the global scenario of trends.

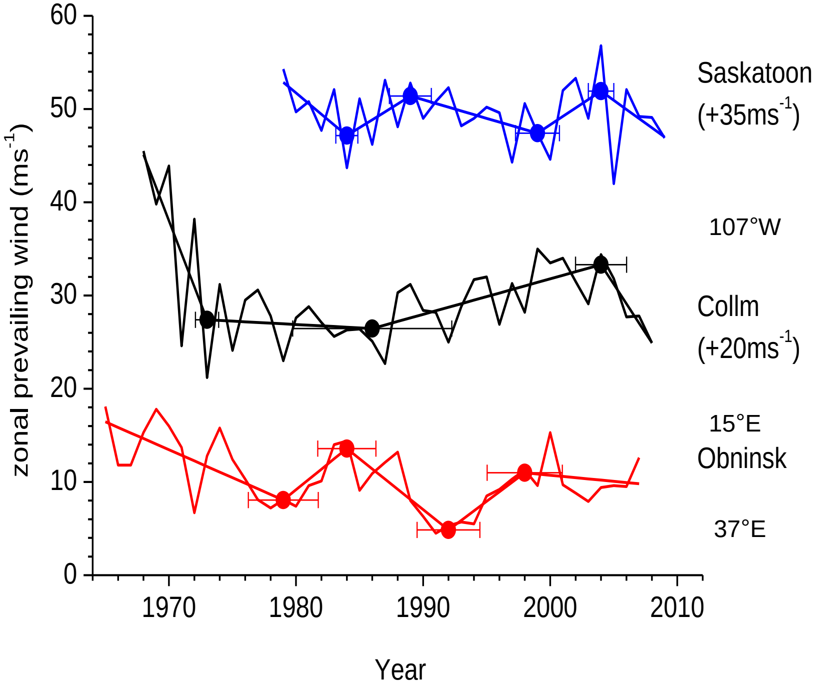
Trends in winds

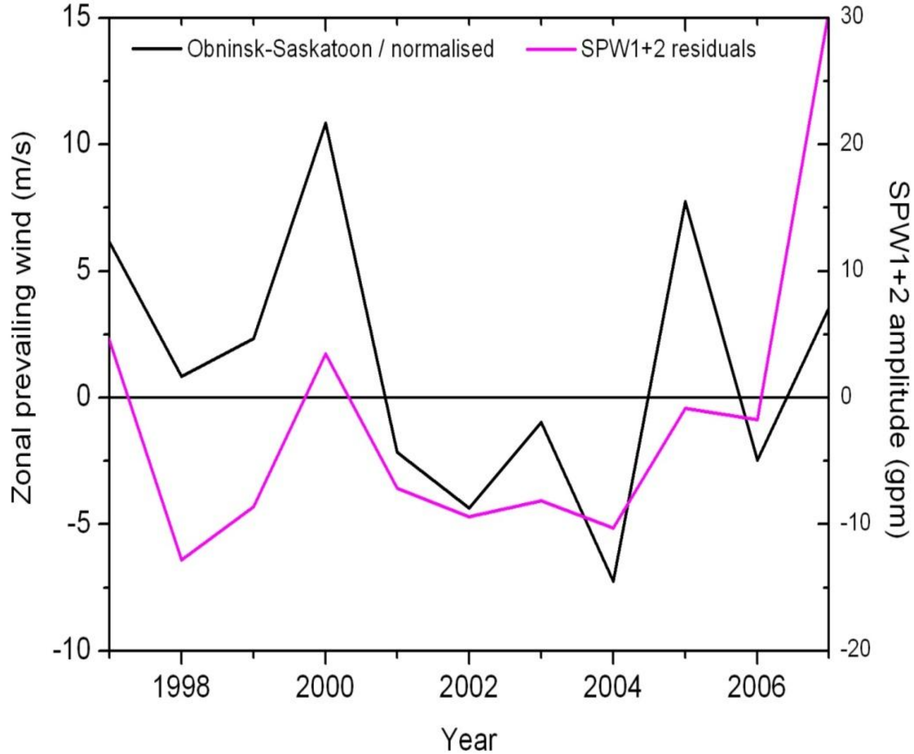




Piecewise linear trend analysis of European MLT winds (Obninsk/Collm) show joint breakpoints in the 1990s similar to time series of tropospheric parameters (here NAO index).

Time development of the winter (October-March – ERA-40) average wind speed, 100 hPa, sector 0^o-90^{o}E, 52.5^{o}N, 1973-2002; wind trend – blue 1973-1990, red 1990-2002.



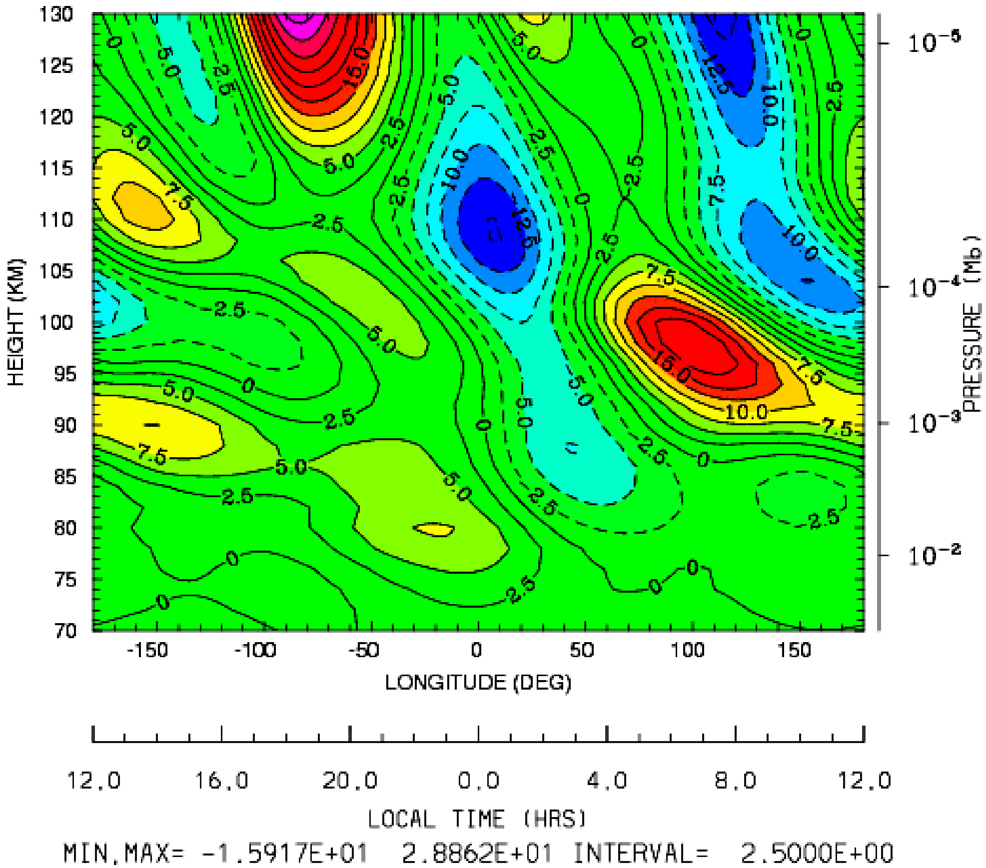


Zonal wind trends strongly differ between Europe (Collm and Obninsk) and Canada (left) and even between Euroepan stations Collm and Obninsk. Differences between stations are connected with stationary planetary waves in the stratosphere (right – difference Obninsk-Saskatoon).

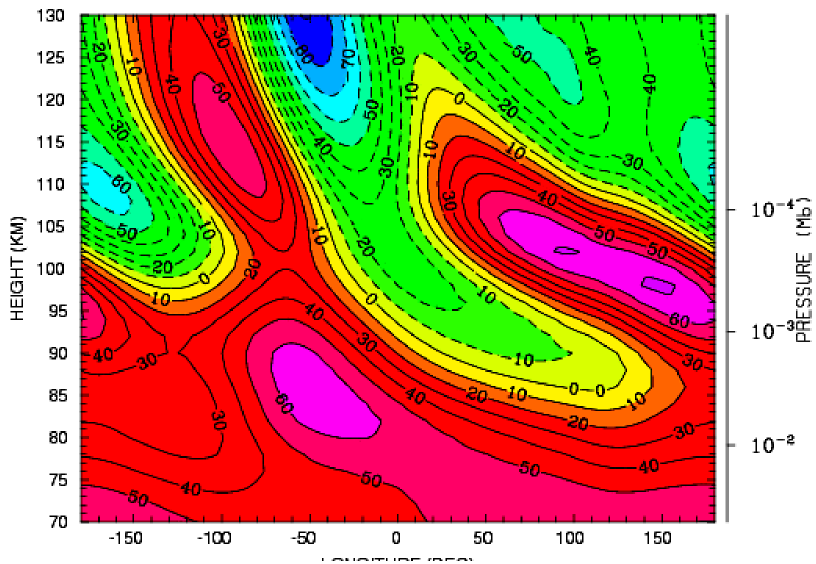
Simulation Results
–MLT Dynamics

Qian et al. (2010)

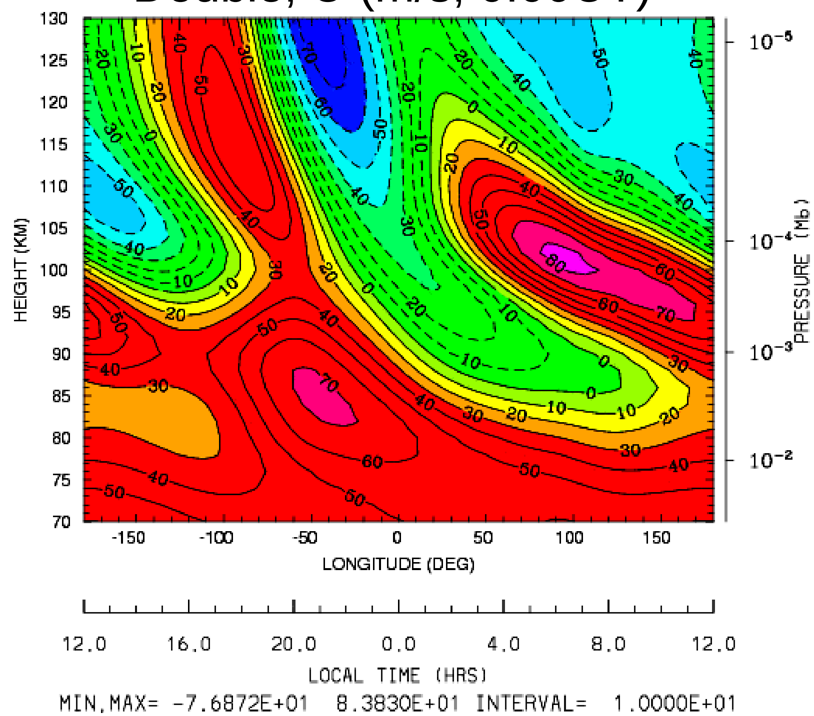
Difference, U (m/s, 0:00UT)



Base, U (m/s, 0:00UT)



Double, U (m/s, 0:00UT)



Zonal Wind at 41.25°N

Noctilucent clouds (NLC) and Polar mesospheric clouds (PMC)

The same phenomenon, seen from below (ground-based – NLC) and from above (PMC - satellites). **In spite of that NLC and PMC trends were reported to differ.** There was no detectable trend in the NLCs over 1961-2000 (Kirkwood and Stebel, 2003). The satellite observations indicated an increase in PMC occurrence frequency and brightness over 1978–2003 (DeLand et al., 2006).

Recent analyses of data (e.g., Shettle et al., 2009) show that the **apparent discrepancy is caused mainly by the latitudinal dependence of** both PMC occurrence/brightness and PMC **trends**. This has been confirmed by model calculations of Lübken and Berger (2011); they also showed that the latitudinal variation of trends was primarily determined by induced water vapor trends.

28 years of observations of PMCs from SBUV + SBUV/2

Shettle et al. (2009, GRL)

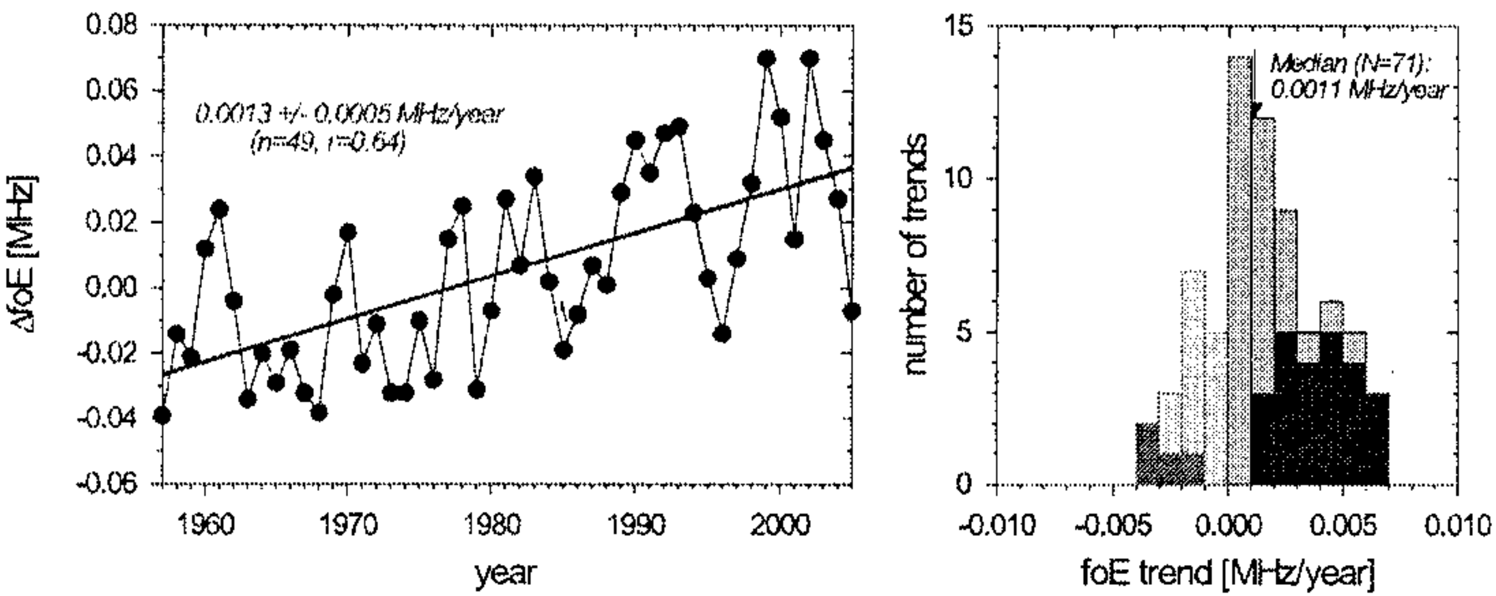
Trends are much weaker and insignificant at lower (NLC) latitudes.

Occurrence ratio 54-64 : 64-74 : 74-82 = 1 : 2 : 4

Latitudes (^{o}N)	Trend coefficient	Trend %/decade	95% confidence per decade	Statistical significance
54-64 - NLC	0.017 0.014	9.9	12.4	Insignificant
64-74	0.022 0.018	6.7	9.2	Insignificant
74-82	**0.134 0.031**	**19.7**	**9.1**	**Significant**
54-82	**0.069 0.021**	**15.6**	**9.3**	**Significant**

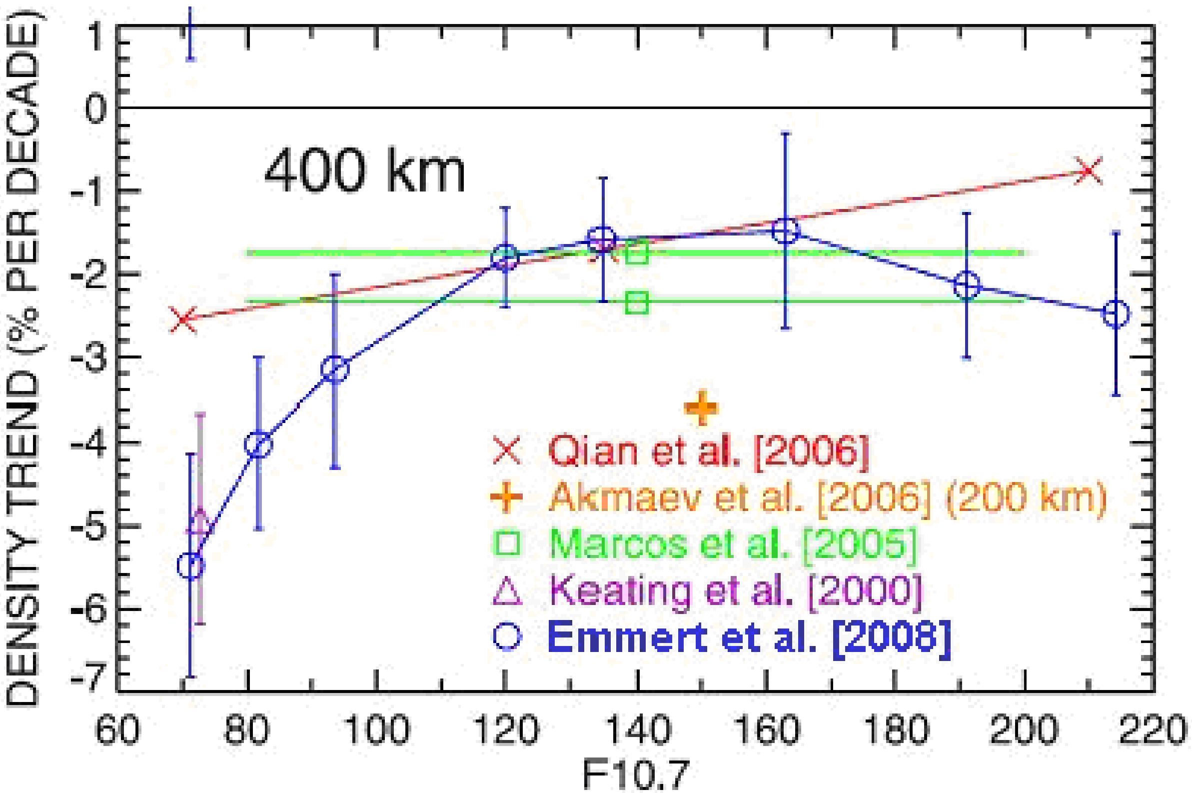
Trends in the E-region ionosphere

Trends in foE are very predominantly positive (in **hmE negative** due to thermal contraction) (Bremer, 2008) except for high latitudes (Tromso, longest data series – negative trend; Hall et al., 2011). **In F1 similar trends**.



Global mean foE trend (left) and histogram of individual foE trends at 71 ionosonde stations (right – black is statistically significant, white insignificant) after Bremer (2008).

Thermospheric neutral density trends near 400km derived from satellite drag over three solar cycles – Emmert et al. (2008).



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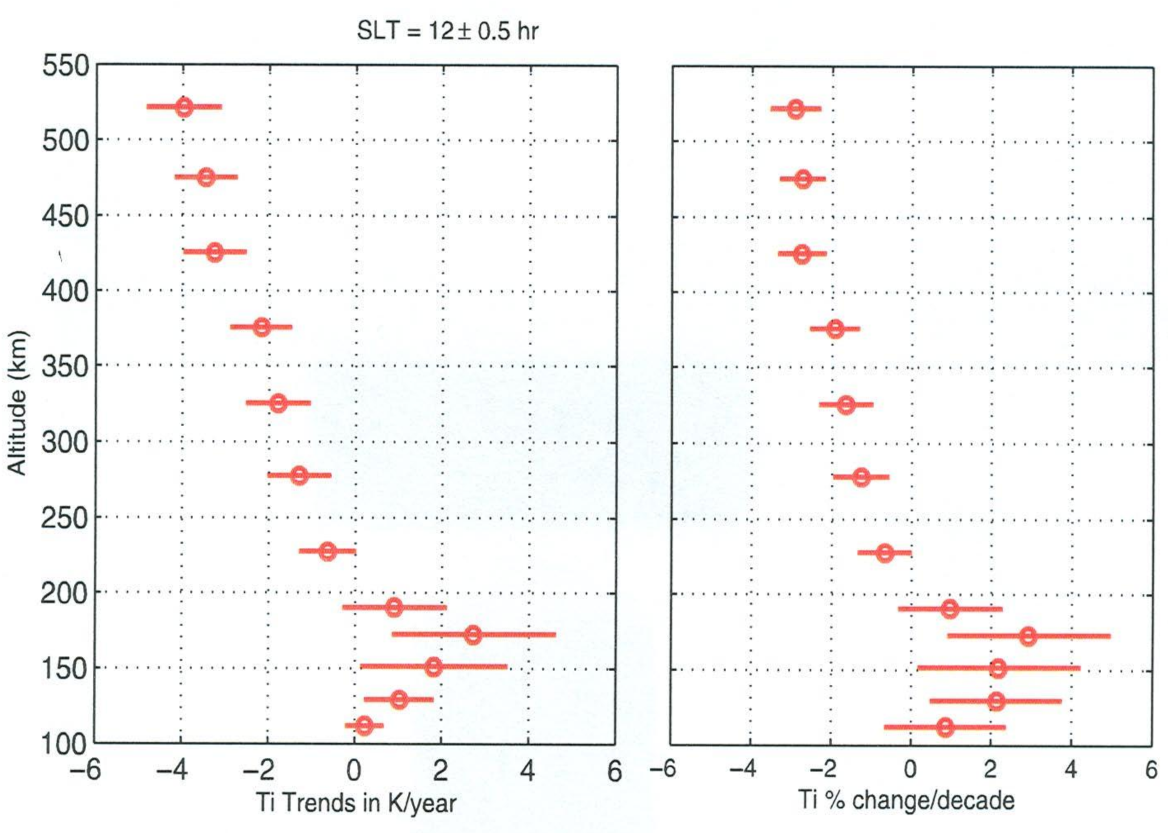
Trend will result in increasing number of space debris orbiting the Earth.

Trends in ion temperature

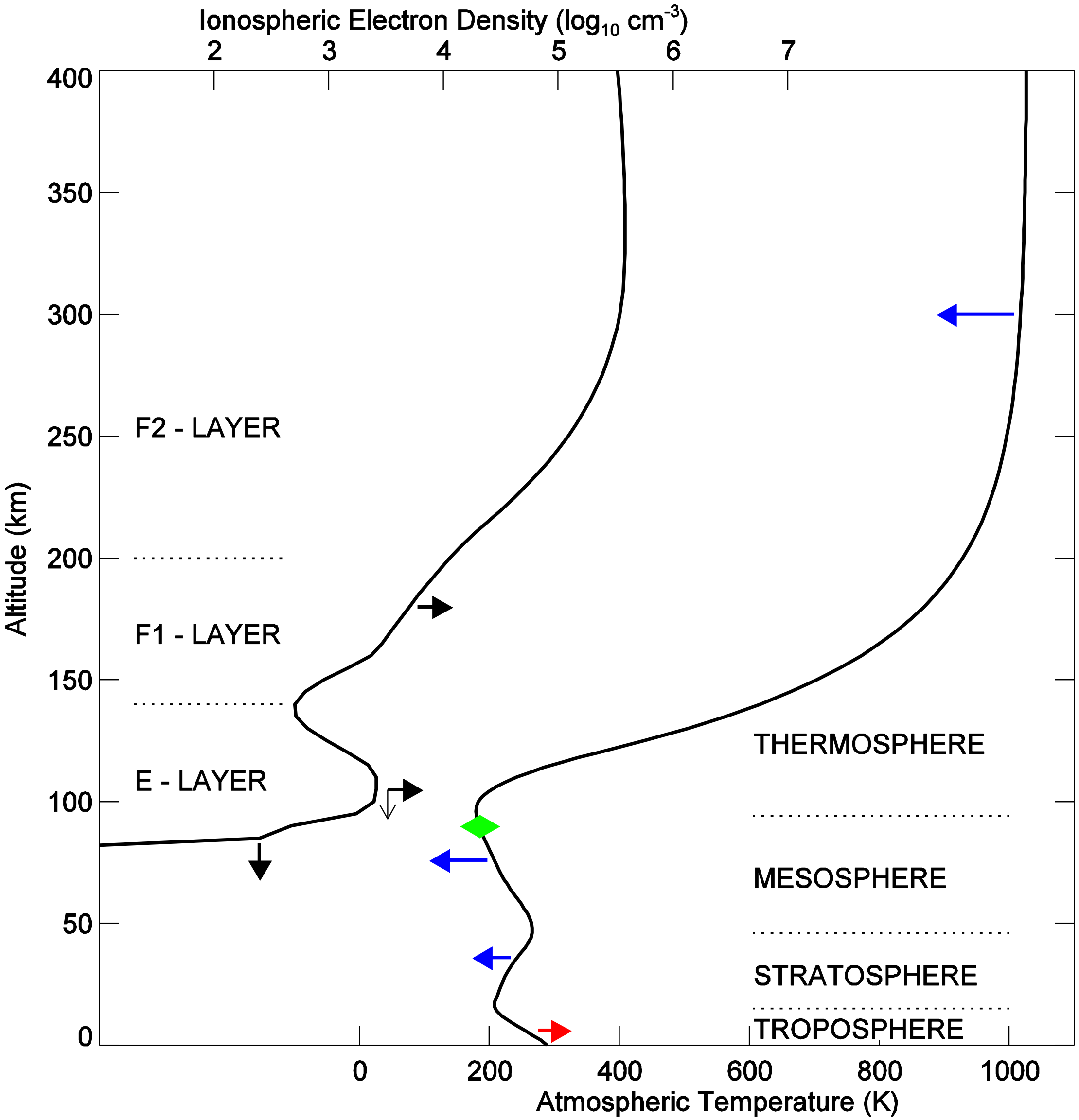


ISR radar Millstone Hill, trends 100-550 km, 1968-2006 (Zhang et al., 2011).

Trends are negative and increasing with height above 200 km.

Trends are apparently positive below 200 km as they are observed at fixed heights and the thermosphere is shrinking (i.e. warmer layers move downward) + some change in chemical composition.

Global trend scenario



Summary of consistent mesospheric, thermospheric and ionospheric trends, which form the global pattern/scenario

Conclusions

1. **Current long-term trends in the upper atmosphere and ionosphere are predominantly caused by the increasing concentration of greenhouse gases but other sources of trends including solar/geomagnetic activity and stratospheric ozone trends also play a role.**
2. **Greenhouse gases produce cooling, not warming, in the upper atmosphere contrary to the troposphere.**
3. **Long-term changes of solar and geomagnetic activity affect mainly trends at high altitudes or in the ionized component, the ionosphere. Their importance in the observed trends is decreasing with time from the past towards the future.**
4. Presence of other trend drivers, which are unstable in time (e.g. ozone) or space (e.g. Earth's magnetic field) makes the trends in the upper atmosphere and ionosphere changing. These trends cannot be characterized by a simple trend straight line, they usually need piecewise linear regression, i.e. composition of a few linear lines.