Scenario of global climate change in the Stratosphere-Mesosphere-Thermosphere-Ionosphere system

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Abstract

The increasing concentration of greenhouse gases in the atmosphere causes net heating in the troposphere and net cooling at higher atmospheric levels, which results in long-term changes of many other quantities in the upper atmosphere and ionosphere. Here, we briefly present a scenario of global climatic changes in the Stratosphere-Mesosphere-Thermosphere-Ionosphere system. Changes in all quantities in this system together create a qualitatively consistent scenario. The main driver of these changes is carbon dioxide, but some role is played also by the stratospheric ozone/ozone depleting substances and by the secular change of the Earth magnetic field. Observation-based trends and trends derived from model simulations agree with each other qualitatively and often also quantitatively.

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The effects of increasing carbon dioxide (CO_2) concentrations on the Earth system are now evident in the warming of ocean, surface and the troposphere, and in the cooling and contraction of the stratosphere, mesosphere, and thermosphere. The simultaneous occurrence of tropospheric warming and stratospheric cooling represent a “human fingerprint” on atmospheric temperature, which is virtually impossible to be explained by natural causes. Here we review observations of global trends and long-term changes in many parameters of the terrestrial middle and upper atmosphere, from the stratosphere through to the thermosphere, including the ionosphere. We also discuss their driving mechanisms. While the role of the increasing CO_2 concentration is dominant, some role is played also by changes in ozone concentration/ozone depleting substances, solar activity variations, and the secular variation of the Earth’s magnetic field. Based on all this information together, we establish the first consistent, joint scenario of global climatic changes in the stratosphere-mesosphere-thermosphere-ionosphere system. Papers [1,2] reviewed recent progress in long-term trend studies in the mesosphere, thermosphere, and ionosphere, while papers [3,4] provided reviews of stratospheric temperature and ozone content long-term trends.

The main driver of global climatic change in the Stratosphere-Mesosphere-Thermosphere-Ionosphere system is CO_2 via infrared radiative cooling. The long-term trend of the CO_2 concentration is essentially the same (~5%/decade) in the height interval of 60–110 km as at surface according to satellite observations [5]. There are also other long-term trend drivers, which modulate CO_2-induced trends and/or are important in particular regions. The evolution of stratospheric ozone, mainly associated with the evolution of ozone-depleting substances, plays an important role in stratospheric trends and affects, to some extent, trends in the mesosphere and lower thermosphere. In the ionosphere and to a lesser extent in the thermosphere, the secular change of the main magnetic field of the Earth plays an important role in some regions [6]. Another important phenomenon affecting temporal evolution and trend detection, particularly in the ionosphere and thermosphere, is the strong quasi-11-year solar cycle and the weaker, longer-term solar variations, e.g., the Gleissberg cycle. Solar activity effects must be removed from the data to get trends of anthropogenic origin.

The first global picture of long-term trends in the Mesosphere-Thermosphere-Ionosphere system was briefly presented in 2006 [7]. This scenario included only a limited number of parameters. Since 2006, a lot of new information on trends has appeared both from observations and model simulations, and it has become clear that there is significant coupling between the stratosphere and higher atmospheric levels. Therefore, we can now present a scenario of mutually consistent long-term trends in the Stratosphere-Mesosphere-Thermosphere-Ionosphere system.

Fig 1 shows signs of long-term trends in the main atmospheric parameter, neutral temperature, and the main ionospheric parameter, electron density, for various atmospheric and ionospheric layers. The troposphere is warming while the upper atmosphere layers are cooling at absolute values larger than in the troposphere. The stratosphere is contracting at a pace of more than 100 m/decade [8,9]. Satellite observations indicate that the mesosphere has been cooling by up to -1.2 K/decade at low- to mid-latitudes during the last 20–30 years, in good agreement with model simulations [8]. For the thermosphere, we do not have direct observational evidence for trends in neutral temperature, but simulations indicate that the temperature in the thermosphere at 400 km decreased by ~18 K [10] due to the increasing concentration of CO_2 from the 1920s to the 2010s. Trends in electron densities are weak; in the E and F2 regions maxima, trends in the critical frequencies foE and foF2, which are related to the peak electron densities, are of the order of +0.01 [2] and -0.1 [11] MHz/decade (~ + 0.3 and -1%/decade), respectively. However, ionospheric peak heights show on average decreasing trends, with the F2 peak height getting lower by about 1 km/decade [11]. This is consistent with the cooling trends in the neutral temperature, which cause the middle and upper atmosphere to contract, shifting ionospheric layers downward.

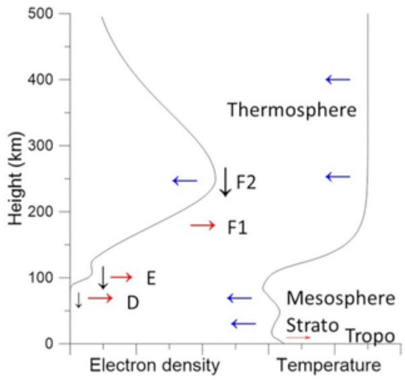

Fig 1. Height profiles (0-500 km) of neutral temperature (troposphere, stratosphere, mesosphere and thermosphere) and electron density (D-, E-, F1- and F2-regions).

Signs of trends: red arrows – heating/increase of electron density; blue arrows – cooling/decrease of electron density; vertical black arrows – decrease of heights of ionospheric regions.

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There are also other parameters showing long-term trends, which are part of the long-term trend/climatic change scenario. In the neutral atmosphere, as a direct consequence of thermal shrinking, the neutral density is decreasing in the thermosphere at a rate of around -2%/decade [12]. The reduced atmospheric drag results in space debris remaining in orbit for longer, leading to an increasing concentration of debris and a higher probability of dangerous collisions with satellites [13]. Also, noctilucent clouds in the upper mesosphere at high latitudes, which only form under very cold conditions, display a positive trend in occurrence and brightness. Another important aspect of climate change is the already mentioned contraction and loss of density of the stratosphere [8,9] and the acceleration of the Brewer-Dobson circulation, which transfers ozone from low to higher latitudes. In addition, the global infrared CO_2 and NO radiative power, which cools the thermosphere, does not reveal a long-term trend, because the emission of infrared radiation is more efficient at lower temperatures; a new equilibrium is reached where more CO_2 molecules still radiate the same amount of infrared radiation, but at a lower temperature [14].

Important roles may be played by trends and long-term changes of atmospheric circulation and atmospheric waves (gravity, tidal, and planetary) but information about them does not provide a consistent pattern; they seem to be regionally, seasonally, and vertically different [2].

In the ionosphere, an unexpectedly strong negative trend in ion temperature has been observed in the F2 peak region and above. This is one area where we have qualitative, but not quantitative, consistency with trends in other parameters. Preliminary results reveal a negative trend in the total electron content (TEC) in low latitudes and no significant trend at higher latitudes [15]. There are other aspects of the ionosphere for which we have only very limited information about trends, such as electron temperature, equatorial plasma bubbles, and topside electron density.

All the above long-term trends create a mutually consistent pattern of climate change, at least in qualitative terms. Observation-based trends and trends derived from model simulations also agree at least qualitatively and often also quantitatively with each other. This qualitative consistency of long-term trends in different atmospheric regions indicates the inter-connections between atmospheric layers and demonstrates the value of establishing a holistic, global picture of climate change.

It should be noted that only some of the quantities provide long time series of measurements to be usable for long-term trend analyses, and many of them are only local, not global; therefore, models are and must be used to help to understand/attribute the changes in the whole system. Improved observational capabilities to monitor the middle and upper atmosphere are also critical.

Future investigations to improve our understanding of the long-term trends in the Stratosphere - Mesosphere - Thermosphere - Ionosphere System should be focused mainly on the following areas:

- Long-term trends in atmospheric circulation and atmospheric wave activity.
- Long-term trends in total electron content and scintillations and their impact on Global Navigation Satellite Systems (GNSS) signal propagation and applications.
- Further development of modeling and understanding of mechanisms of long-term trends, particularly explanation of the discrepancy between observed (large) and simulated (much smaller, especially during daytime) ion temperature trends.
- Potential seasonal and local time variations of trends in the key parameters.
- Stability of trends with potentially changing trends in carbon dioxide and ozone.

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