Understanding upper atmospheric climate and change

A science white paper to the Decadal Review Committee

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Abstract

Both theoretical models and observational evidence have revealed that Earth's upper atmosphere is cooling and thermospheric density and ionospheric electron density are experiencing corresponding long-term changes. These changes will have strong influence on human activities. Addressing this topic of upper atmospheric climate and long-term change is timely and appropriate. It seems to us that the research focus for the next decade should include (1) to obtain a very comprehensive global pattern of the long-term change in both the ionosphere and the thermosphere. Neutral temperature at different heights from above the mesosphere through the upper atmosphere is crucial information; (2) to identify physical causes of the derived trend pattern; (3) to understand upper atmospheric climatology within a changing global environment. Continuously monitoring the upper atmosphere and solar-terrestrial environment remains an essential strategy toward a complete understanding of Earth's climate.

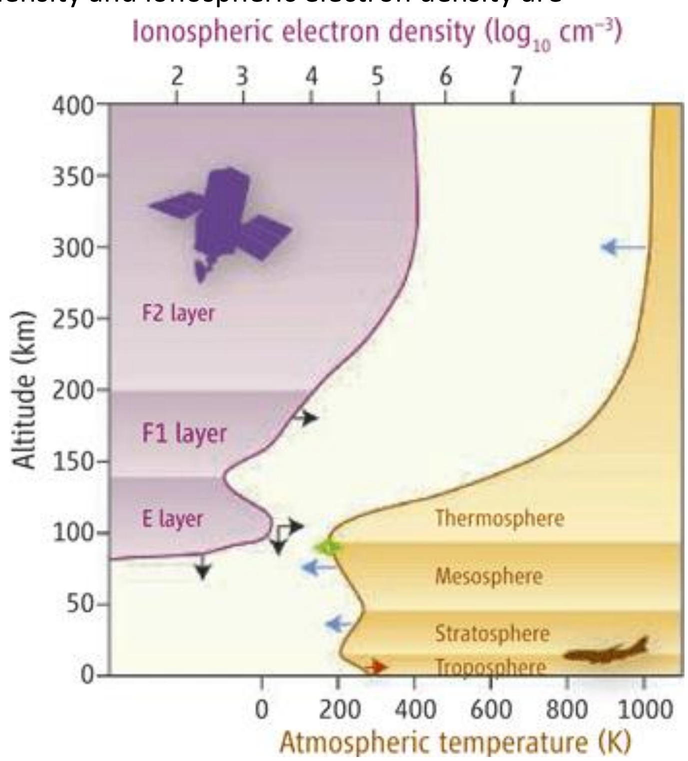

Figure 1 Pattern of ionospheric and thermospheric long-term trend derived from observations. Ionospheric electron density and thermospheric temperature are shown. Arrows to the right indicates "increase" and to the left "decrease". These patterns are qualitatively consistent with the greenhouse gas effect expected from theoretical

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1. Introduction: The falling sky

More and more evidence from recent observations in the ionosphere and thermosphere shows that the earth's upper atmosphere is falling during the recent a few decades. The falling, a clear indication of global climate change, is due to the cooling trend in the upper atmospheric temperature. Climate changes in the upper atmosphere have the potential to affect our increasing activity in space. Upper atmospheric cooling can cause a decrease in neutral density such that satellite orbits and lifetime are modified due to decreased air drag. It can also alter neutral composition such that radio propagation is affected due to changes in the ionospheric electron density. These effects exist whether the climate change is due to natural processes or anthropogenic increases in greenhouse gases.

A number of important topics are relevant to climate change in the upper atmosphere. Some of these are fundamental toward characterization of earth's environment and its direct impact on human activities. These topics include elaborating on the long-term trend in both the ionosphere and thermosphere upper atmospheric climatology, which may have undergone changes at various times scales. In this white paper, we review some of these compelling research topics that need to be addressed for the next decade. A separate white paper by Emmert et al. [2010] addresses a similar topic of geospace climate change, with more emphasis on implication of long-term climate changes on the neutral atmosphere and the need for long-term monitoring a series of important atmospheric parameters.

2. Long-term changes in the upper atmosphere

Greenhouse gases such as CO_2 and CH_4 are increasing in the lower atmosphere due to human activities. The effect of this on the upper atmosphere was first investigated in a theoretical modeling study by Roble and Dickinson [1989], suggesting a major greenhouse cooling in the thermosphere in response to increases in the CO_2 and CH_4 concentration at 60 km. Such a cooling effect causes a global reduction in neutral densities including O, N_2 O_2 and total neutral mass density as the neutral temperature Tn decreases. If greenhouse gas concentrations are doubled, as predicted to happen by the end of the 21st century, Roble and Dickinson indicated that the decrease in thermospheric temperature will be as much as 50 K, and the decrease in thermospheric densities at a fixed height between 200-300km will be 40-50%. The ionospheric consequences, as a result of thermal contraction, include a decrease in the F2 peak height, hmF2 [Rishbeth, 1990; Rishbeth and Roble, 1992], a decrease in topside ionospheric density and an increase in the F1 region ionospheric density, with less change in the maximum density NmF2. Some recent modeling studies using TIMEGCM and a more realistic CO_2 concentration (single site measurements) have essentially confirmed prior model findings [Qian et al., 2006; 2008].

The above results, arising from theoretical considerations, imply that ionospheric parameters can be a sensitive indicator of greenhouse gas atmospheric effects. Many subsequent investigations of long-term ionospheric and thermospheric change have occurred and the area is a very active research topic. Most of these studies are based on long-term ionosonde observations which date to the early days of ionospheric research and are readily accessible. Bremer [1992] published the first such ionospheric long-term trend observational results. Some, but not all, of these results concluded that hmF2 indicated a decreasing trend; other studies did not find a long-term trend or found a trend opposite to the sense predicted by Rishbeth and Roble [1992]. See Laštovička et al. [2006; 2008] for reviews of some recent study (see Figure 1). Observations of thermospheric total mass density by satellites revealed a 2-5% decrease per decade [Keating et al., 2000; Emmert et al., 2004; Emmert et al., 2008] (see Figure 2). These have been considered to be evidence of thermospheric cooling, supporting the Roble and Dickson [1989] theoretical calculations of the greenhouse effects.

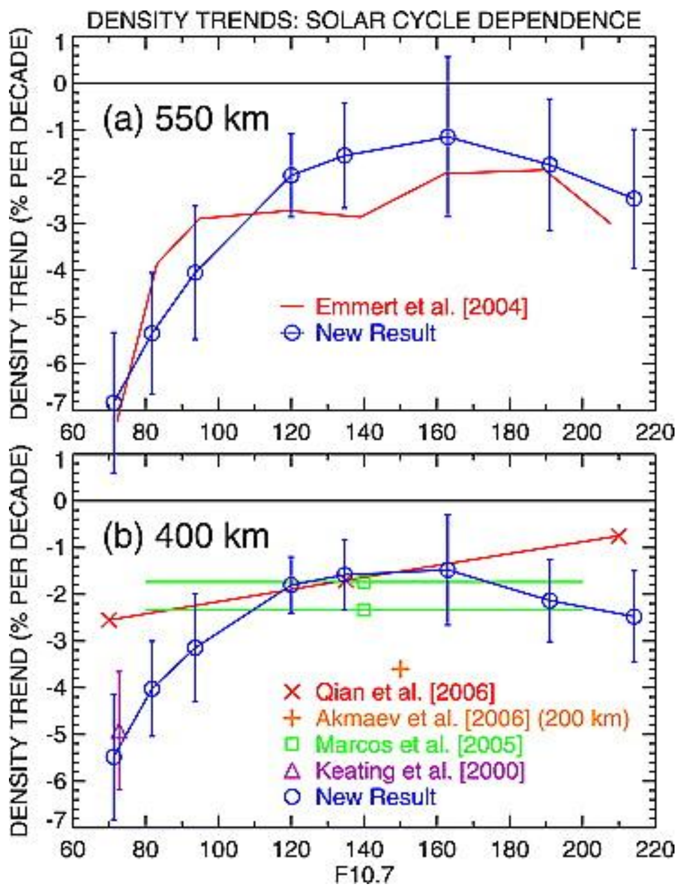

Figure 2 Long term trends in the neutral density at 550km (upper panel) and 400 km (lower panel) as a function of solar activity. (from Emmert et al., 2008)

Some direct evidence of temperature change has been provided by incoherent scatter radar observations. Zhang et al. [2005] provided evidence of the cooling in the ionospheric ion temperature for most altitudes and seasons based on Millstone Hill Incoherent Scatter Radar data. Holt and Zhang [2008] focused on Ti cooling for noontime at the attitude of 375 km, and provided a detailed analysis of confidence level of the estimated cooling trend. Donaldson et al. [2010] conducted an extended study of the ion temperature trend which includes height and time dependency using ISR data from observations made at St. Santin for a two-solar cycle period (1966-1987). Recently, Holt and Zhang [2010] and Zhang and Holt [2010] used Millstone Hill ISR data for the 1964-2010 period to determine the neutral temperature trend (exospheric temperature) and oxygen density variation, and height dependency of ion temperature (see Figure 3). Their direct temperature results revealed unambiguously the cooling in the upper atmosphere and its variability with height and solar activity.

3. Upper atmospheric climatology

Upper atmospheric climatology represents changes that occur repeatedly, persistently and predictably; therefore it may be considered as the background or reference conditions and the most essential information of the earth atmosphere. In the early years of ionospheric and thermospheric researches, many climatology studies focused on the so-called "anomaly" phenomena. Ionospheric electron density variations over time and space have traditionally been termed an anomaly if they do not follow the solar-controlled photochemistry dominated variation pattern. These included, for instance, the equatorial ionization anomaly (EIA), the seasonal anomaly or winter anomaly, and the Weddell Sea Anomaly. Ionosonde parameters were extensively studied. With a large number of observations from other instruments becoming available, especially satellite-based thermospheric and ionospheric density observations, many recent interests in our community have been on the subjects such as annual and semiannual variations which change with latitude, and the annual anomaly (north-south hemispheric asymmetry), etc.

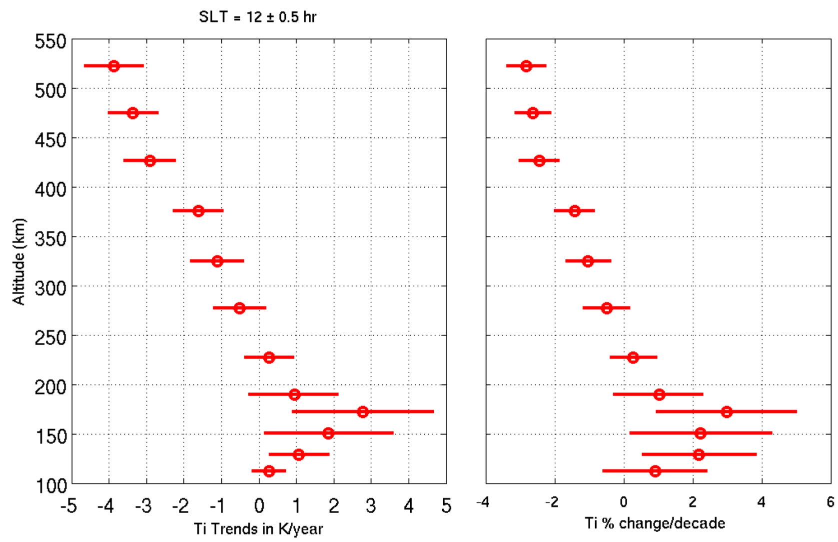

Figure 3 Height profile of long term trend in ion temperature (1964-2007) at noon over Millstone Hill. The cooling trend is significant in the upper F region and increases with height.

Mendillo et al. [2005] noted the hemispheric asymmetry in the GPS TEC and ascribed it to corresponding changes in the neutral composition as a result of global circulation. Liu et al. [2007] reported the enhanced neutral density in the EIA regions. Qian et al. [2009] pointed out the importance of eddy mixing in the mesopause region to account for the observed annual/semiannual variations. Ground-based observations provide insights into local scale but detailed processes of upper atmospheric climatology. Using incoherent radars, Kawamura et al. [2000] investigated meridional winds patterns at mid-lower latitudes in Asia; Zhang et al. [2010] examined the height and latitudinal development of annual and semiannual variations of the ionosphere during the recent International Polar Year.

Empirical models are an important component of climatology studies and they are very useful tools for space weather and variability studies with engineering applications. Over the last decade, a number of models have been updated such as the horizontal wind model (HWM), the mass spectrum and incoherent scatter (MSIS) model, and the International Reference Ionosphere (IRI) model. A number of new models have come online, such as incoherent scatter radar based ionospheric models (ISRIM) [Zhang and Holt, 2007], and the global average mass density model (GAMDM) [Emmert and Picone, 2010]

Our community still maintains very strong momentum, after many years of studies and numerous publications, in further characterizing and understanding this fundamental property of the upper atmosphere.

4. Important science topics

Under the big picture of global change in the whole earth's atmospheric system, addressing the following science topics in the next decade is timely and appropriate.

(1) Characterization of the long-term change in the upper atmosphere

There are still many unknowns in our understanding of ionospheric and thermospheric long-term trends. It is essential to generate a comprehensive view of long-term change in the thermosphere and ionosphere and to provide clues to understanding causative factors for upper atmospheric climate change. More specifically, we should determine long-term trends in neutral and plasma temperatures as direct evidence of climate change, along with trends in ionospheric and thermospheric densities as a result of climate change. It seems that the cooling trend varies with height from the mesopause to 500 km. The thermal status of the topside ionosphere and the E region ionosphere are different due to different sources of heating and cooling. In the 100-160 km height regime, where there exists significant coupling between the lower and upper thermosphere, neutral density and temperature are the key to understanding thermal response to greenhouse gas influences and the resulting ionospheric electron density changes. Other than height dependency, we also need to understand variability with solar activity, season, local time, and geographic location.

These studies will become more feasible in the next decade due to the much better data availability. Determination of the long-term trend requires removing various other variations in the data. This can only be possible with sufficient data (space-based and ground-based) that can clearly exhibit these variation patterns. Supporting solar-geophysical parameters, such as EUV flux, are also important.

(2) Understanding the causes of the long-term changes in the upper atmosphere

A number of possible causes have been proposed, including effects due to anthropogenic changes in greenhouse gases, the ozone layer, water vapor, and natural secular changes in solar-terrestrial magnetic activity, solar activity, and the earth's magnetic field. Indeed this type of research provides a best case study that deals with some fundamental aeronomy questions relevant to the impact of the lower atmosphere. In the next decade, more investigations need to be carried out to examine all these drivers and to identify their relative importance using both additional data and modeling. Efforts need to be made to understand observed features inconsistent with the known general trend pattern in the ionosphere and thermosphere. Additional data include neutral and plasma density and temperature for various heights in the 100-500 km height range; neutral winds and plasma drift also provide important information on the dynamics. Measurements of neutral temperature and its height variation are the key to understanding changes in various ionosphere and thermospheric parameters. Global models with self-consistent coupling between the lower and upper thermosphere, and between the neutrals and the ions, are essential. Sophisticated theoretical modeling requires better specification of key reaction rates and the model boundary conditions, with an appropriate magnetic field model that includes secular changes and low thermospheric composition processes.

(3) The changing upper atmospheric climatology

It can be expected that the best known features of upper atmospheric climatology undergo some changes within the changing environment which modifies the general upper atmospheric circulation. This is because some of the "anomaly" climatology mentioned earlier, such as the winter anomaly, annual and semiannual change and the hemispheric asymmetry, is a result of neutral composition change caused by the circulation. An important task is to reassess those known phenomena and compare the early years to recent years and to further investigate future development. It is known that cooling in the upper atmosphere changes with location, height, solar activity, and local time. Therefore climate change in the upper atmosphere will show some variability as well. Studies such as the significant thermospheric density drop during the current extend solar minimum and behavior at upcoming solar maximum are examples that can allow for accurate definition of some basic characteristics of the earth's atmosphere at extreme solar activity conditions. Long-term changes in the system should be taken into account in sophisticated upper atmospheric empirical models.

5. Summary

Global change in the lower atmosphere has imposed a significant impact on Earth's upper atmosphere for both neutral and ionized particles. Both theory and observation have suggested a significant cooling trend in the upper atmosphere. This upper atmospheric climate change will affect various human activities: satellite orbits can be altered as a result of the long-term decrease in atmospheric density throughout the entire upper atmosphere; changes in the ionospheric electron density modify the radio wave propagation, in particular, the performance of GPS and other space-based navigational or communication systems. Therefore in the decade to come, our research should address this major issue of these long-term changes and their societal influence. We suggest the following main research themes:

(1) To obtain a comprehensive global pattern of the long-term change in both the ionosphere and the thermosphere. It should include dependency on solar activity, season and time. Neutral temperature at different heights from above the mesosphere through the upper atmosphere is crucial information.
(2) To identify physical causes of the derived trend pattern. Studies on greenhouse gas influences and other processes provide us a unique opportunity to further our understanding of coupling between the lower atmosphere and upper thermosphere and ionosphere. Modeling and data analysis remain the essential ways of deal with the problem.
(3) To understand upper atmospheric climatology within a changing global environment. Ionospheric and thermospheric climatology, including empirical models, derived from early observations may need to be revisited or revised.

Long-term monitoring the upper atmosphere and solar-terrestrial environment from space and ground is a prerequisite and indispensable to achieving appropriate understanding of the earth's upper atmosphere. The observations should be made in a continuous and consistent manner for precisely detecting long-term changes in the system.

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