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INTRODUCTION TO A SPECIAL SECTION

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Long-term Changes and Trends in the Stratosphere, Mesosphere, Thermosphere, and Ionosphere, JGR-Atmospheres/Space Physics, 2014

**Key Points:**

- Long-term change in the middle atmosphere may affect the climate in the troposphere
- Long-term decline in thermosphere density increases space debris lifetimes and associated risks
- Highlights of recent progress on long-term change in the middle and upper atmosphere are given

**Correspondence to:**
I. Cnossen,
inos@bas.ac.uk

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# Introduction to special issue on "Long-term changes and trends in the stratosphere, mesosphere, thermosphere and ionosphere"

**Ingrid Cnossen[1], Jan Laštovička[2], and John T. Emmert[3]**

[1]British Antarctic Survey, Cambridge, UK, [2]Institute of Atmospheric Physics ASCR, Prague, Czech Republic, [3]Space Science Division, U.S. Naval Research Laboratory, Washington, DC, USA

**Abstract** This special issue bundles some of the latest results on decadal-scale variations in the stratosphere, mesosphere, thermosphere, and ionosphere, following on from the 8th Workshop on Long-Term Changes and Trends in the Atmosphere, held in Cambridge, UK, on 28–31 July 2014. Emmert et al. (2015) provided a short report of the workshop. This introduction briefly describes the relevance of the field and highlights some of the recent progress that has been made.

## 1. Introduction

It is clear that increasing concentrations of greenhouse gases, such as carbon-dioxide ($CO_2$) and methane ($CH_4$), have had a warming effect on the troposphere [*Stocker et al.*, 2013]. However, the same gases have a cooling effect on the layers of the atmosphere above, as first predicted by *Roble and Dickinson* [1989]. This is due to increased radiative emission out into space, as the atmosphere at higher altitudes becomes optically thin for the outgoing $CO_2$ infrared radiation. The cooling in the middle and upper atmosphere is stronger, and therefore potentially more easily detectable, than the warming in the troposphere, although trend detection at high altitudes is complicated by the generally larger natural variability and sparser data sets. Still, monitoring the climate of the stratosphere, mesosphere, and thermosphere gives us important clues to the effects that increasing greenhouse gases are having on our atmosphere as a whole. This holistic picture is important because it is becoming increasingly clear that we cannot study the tropospheric climate in isolation. The layers above, certainly the stratosphere, influence processes in the troposphere and thereby affect the climate near the surface [e.g., *Scaife et al.*, 2005].

Another important reason to study climatic changes in the upper atmosphere is the growing amount of advanced, satellite-based technology that operates within this environment (from ~250 km upward). As a result of the increasing activity in near-Earth space, the amount of space debris has also grown dramatically. Space debris poses a significant hazard to operational spacecraft due to the risk of collisions. The only way in which the debris is removed from the near-Earth space environment is via the drag exerted upon it by the Earth's atmosphere, proportional to the ambient atmospheric density. Analysis of satellite orbital data has revealed a long-term decline in atmospheric density of ~1.5–2.5% per decade at 400 km altitude [*Emmert*, 2015], which is linked to the cooling of the upper atmosphere. The decline in density reduces drag and thereby lengthens the lifetime of space debris, with significant consequences for the future space debris population and the risks this brings with it [*Lewis et al.*, 2011].

Detecting long-term trends in the middle and upper atmosphere reliably is challenging because of the limited availability of good-quality long-term data sets and large natural variability, such as due to the ~11 year solar cycle. The data sets needed for trend analysis require a commitment to make measurements in the same way for at least several decades, which is obviously difficult to achieve. Most long-term data sets that are available suffer from data gaps and unknown calibration errors. Even if measurements are made with the same instrument over the full data record, the stability of that instrument is hard to prove. The large natural variability in the middle and upper atmosphere further complicates reliable trend detection. In the upper atmosphere, solar cycle variations dominate the decadal-scale variability. *Roininen et al.* [2015] and *Cnossen and Franzke* [2014] explore new methodologies to extract long-term trends from ionospheric data, accounting in different ways for the large natural variability.

Another key challenge is the correct attribution of observed long-term trends. Until recently, observations showed a decline in global mean thermospheric density that was approximately a factor two larger under solar minimum conditions than models could attribute to the increase in atmospheric $CO_2$ concentration. New, more realistic three-dimensional simulations by *Solomon et al.* [2015] show a considerably larger simulated trend in density at solar minimum, while new results from orbital drag measurements reported by *Emmert* [2015] suggest that the trend at solar minimum is in fact weaker than previously thought. The new modeling results now indicate a stronger thermospheric density trend at solar minimum than the latest observational estimate from orbital drag, which creates a new puzzle that must be solved. However, aside from the discrepancies under solar minimum conditions, there is good agreement between observed and modeled density trends, which suggests that the increasing concentration of $CO_2$ in the atmosphere does play the dominant role in the global mean decline in thermospheric density.

At lower altitudes, long-term changes in ozone concentration play a progressively more important role [e.g., *Akmaev et al.*, 2006], and we must continue to monitor these changes closely. *Berger and Lübken* [2015] discuss how both long-term cooling near 83 km altitude and cooling at lower altitudes, associated in part with trends in stratospheric ozone, affect long-term variations in polar mesospheric clouds.

On regional scales, other drivers of long-term change are potentially important too. *Cnossen* [2014] recently showed that effects of the changing geomagnetic field are generally more important than the increase in $CO_2$ concentration for long-term changes in the ionosphere, especially over the southern Atlantic Ocean, South America, and western Africa, where the magnetic field has changed considerably.

Several other studies have suggested that long-term changes in atmospheric dynamics could help explain some of the features of observed trends in the upper atmosphere. *Danilov* [2015] argues that a decline in atomic oxygen concentration of ~10% per decade is needed to explain seasonal variations in long-term changes in the peak electron density of the ionosphere and suggested that the reduction in atomic oxygen could be produced by a long-term enhancement in eddy diffusion, transporting more atomic oxygen downwards. *Oliver et al.* [2013] discussed how enhanced eddy diffusion, possibly caused by a long-term increase in gravity wave activity, could also help explain the strong cooling found over Millstone Hill based on incoherent scatter radar observations. However, observational evidence for long-term changes in gravity wave activity is limited and appears conflicting so far: *Hoffmann et al.* [2011] found a long-term increase in gravity wave activity in the mesosphere over Juliusruh (55°N, 13°E) in summer, while *Jacobi* [2014] reported a decrease in summer and an increase in winter over Collm (52°N, 13°E). This suggests that trends in gravity wave activity are strongly dependent on location and season. Much more work is needed to build up a more comprehensive picture of long-term changes in atmospheric dynamics and to quantify how these affect the climate of the middle and upper atmosphere. This is currently still a key open problem of the field [see also *Laštovička et al.*, 2012].

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