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The Need for Better Monitoring of Climate Change in the Middle and Upper Atmosphere

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Key Points:

- More research is necessary on the impacts of climate change and anthropogenic emissions in the middle and upper atmosphere
- Lack of observational capabilities precludes a better understanding and monitoring of long-term trends
- The accumulation of space debris is a problem, and anthropogenic emissions worsen it

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Anthropogenic greenhouse gas emissions significantly impact the middle and upper atmosphere. They cause cooling and thermal shrinking and affect the atmospheric structure. Atmospheric contraction results in changes in key atmospheric features, such as the stratopause height or the peak ionospheric electron density, and also results in reduced thermosphere density. These changes can impact, among others, the lifespan of objects in low Earth orbit, refraction of radio communication and GPS signals, and the peak altitudes of meteoroids entering the Earth's atmosphere. Given this, there is a critical need for observational capabilities to monitor the middle and upper atmosphere. Equally important is the commitment to maintaining and improving long-term, homogeneous data collection. However, capabilities to observe the middle and upper atmosphere are decreasing rather than improving.

Plain Language Summary Greenhouse gas emissions are making the middle and upper parts of the atmosphere cooler, which leads to a series of important changes. The cooling causes the atmosphere to shrink, affecting its structure, including the stratosphere and the density of the thermosphere. A thinner thermosphere means that satellites and debris in low Earth orbit stay up longer, increasing the risk of collisions. These changes also affect radio signals and GPS systems. Unfortunately, we do not have enough accurate long-term data to fully understand the impacts on this part of the atmosphere, and the situation is getting worse due to fewer observations.

1. Introduction

Anthropogenic emissions of greenhouse gases (GHGs) have important effects on the middle and upper atmosphere, as was first shown theoretically long ago (Manabe & Wetherald, 1967; Roble & Dickinson, 1989). Increased greenhouse gas concentrations cause the middle and upper atmosphere to cool and also lead to circulation changes. Cooling of the middle and upper atmosphere causes several important follow-on effects associated with thermal shrinking, such as changes in the vertical structure of the atmosphere. Atmospheric contraction modifies the vertical ionospheric electron density structure and causes a decrease in the thermosphere density at fixed heights. The long-term reduction in thermosphere density prolongs the natural lifetime of objects in low Earth orbit (LEO) adding to the problem of space debris accumulation (Brown, 2023; Lewis et al., 2011). The ionosphere impacts radio signal propagation, as used by long-distance communication and global positioning satellite systems. In the long term, characteristics of ionospheric irregularities leading to scintillation and maximum usable frequencies could undergo subtle changes. Long-term trends in the middle and upper atmosphere have implications for future space law, space policy, and the space insurance industry (Mlynczak. et al., 2021). However, the limited availability of complete and accurate data sets that enable long-term analysis of trends precludes a proper evaluation of the situation and the threats that these phenomena pose. Unfortunately, the availability of observations of the middle and upper atmosphere suitable for long-term trend analysis is deteriorating rather than improving.

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2. Impacts of Climate Change

Recent research shows that there are various ways in which the upper layers of Earth's atmosphere are changing, such as changes in the thickness of the layers, including tropospheric expansion (Añel et al., 2006; Meng et al., 2021; Santer et al., 2003), changes of the energy modes and baroclinicity of the middle atmosphere (Castanheira et al., 2009), and cooling and contraction of the stratosphere (Pisoft et al., 2021; Santer et al., 2023), mesosphere and thermosphere (Bailey et al., 2021; Mlynczak et al., 2022; Qian et al., 2021), and a decline in thermosphere density (Emmert, 2015). In the stratosphere and mesosphere, it is also important to consider the complex role of ozone. The ozone concentration can be affected by decreasing temperatures in different ways (i.e., increasing or decreasing), depending on the region (Randel & Wu, 1999; WMO, 2022), while changes in ozone concentration themselves in turn affect the temperature trends (Garcia et al., 2019). Further, its distribution in the lower stratosphere is linked with dynamical processes (e.g., the Brewer-Dobson circulation (BDC)), which are also affected by climate change. Figure 1 summarizes the trends in several of these variables, together with the trend in CO_2 concentration and variation in solar activity, expressed through the F10.7 index.

Climate models indicate that changes in the temperature structure of the lower and middle atmosphere are interrelated with the circulation and dynamics therein, and possibly even outside this region, due to upward propagating waves. For instance, projected long-term changes in the BDC have been linked to the expansion of the troposphere (Oberländer-Hayn et al., 2016) and contraction of the stratosphere (Eichinger & Šácha, 2020). This link is supported also by changes in the recent past, diagnosed from reanalyses (Šácha et al., 2024). Shepherd and McLandress (2011) demonstrated how the vertical structure changes can impact the dynamics via an upward shift of the critical layers for transient wave breaking in the subtropical lower stratosphere. More recent results have pointed out how the stratospheric contraction is accompanied by decreasing wave propagation times and hence a decrease in the period of the quasi-biennial oscillation (Zhou et al., 2021). Dynamical impacts above the stratosphere are not yet well understood, although it is conceivable, for instance, that long-term changes in gravity wave activity could have effects on eddy diffusion in the upper mesosphere/lower thermosphere region, and therefore on vertical mixing, atmospheric composition and mass density (Oliver et al., 2013). However, we do not currently have a clear global picture of long-term gravity wave activity changes, nor the required data to be able to detect their potential impacts at higher altitudes against a background of a lot of shorter-term variability.

Some of the long-term changes in the middle and upper atmosphere have practical implications. For example, increasing water vapor and ice-crystal contents at mesospheric levels, due to increasing transport of water vapor (Yu et al., 2022) and methane (Thomas et al., 1989; Yue et al., 2019), are driving a positive trend in polar mesospheric summer echoes, which interfere with radars and can disturb military operations (Danilov & Berbeneva, 2021). Changes to the ionosphere, particularly in the electron number density and the height of peak density, can affect global positioning systems and radio communications (Laštovička, 2023). Also, a possible relationship between decreasing density and greater penetration of meteoroids into the atmosphere (decreasing peak altitudes) has been pointed out (Dawkins et al., 2023).

However, perhaps the most important problem caused by middle and upper atmosphere climate change is its effect on the space debris. Increasing CO_2 related cooling and contraction in the stratosphere, mesosphere and thermosphere leads to a decrease of density at constant geometric altitudes in the thermosphere for all future emission scenarios (Brown et al., 2021, 2024). This increases the orbital lifetimes of satellites due to the reduced atmospheric drag, and thereby increases the number of LEO objects to be monitored, as well as the risk of collisions. Collisions could potentially cause unexpected and costly disruptions to global satellite services, and would also produce additional debris. This is especially important given the increasing number of satellite constellations already deployed or planned (Falle et al., 2023), with some of them composed of thousands of objects. While drag from the thermosphere naturally clears all space debris in orbits below 500–600 km within a decade or two, thermosphere contraction and the resulting reduced neutral densities will slow this process. It can be noted that density reduction due to GHG-induced trend is much smaller in magnitude than the reduction due to solar activity, but the secular trend leads to longer lifetimes, increasing debris and risk of collision, in addition to the usual debris environment's reaction to solar activity changes. As an example, according to the filings of the Federal Communications Commission, Starlink satellites had to maneuver 25,000 times between 1 Dec. 2022, and 31 May 2023 to avoid potentially dangerous approaches to other spacecraft and orbital debris. Most maneuvers are based on human planning and decision-making and with increasing objects in LEO the need for them is increasing substantially. Although the probability of a catastrophic collision is currently still relatively low,

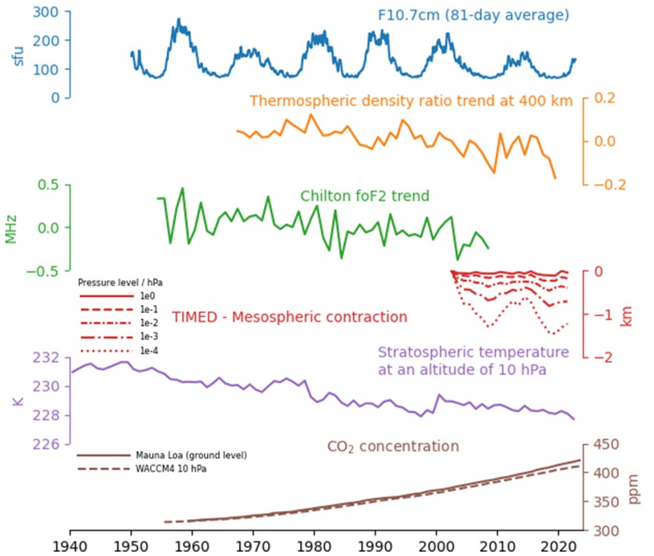

Figure 1. Times series of the 10.7 cm radio flux (F10.7) solar activity proxy, select upper atmosphere trend observations ((Emmert et al., 2021; Mlynczak et al., 2022), https://www.ukssdc.ac.uk/), and CO_2 concentration at Mauna Loa (https://gml.noaa.gov/ccgg/trends/data.html). Thermospheric density ratios and Chilton foF2 data have been detrended using a cubic function of F10.7. 12-month average temperature at 10 hPa for the period 1940–2022 from ERA5.1 (Hersbach et al., 2020).

each collision will significantly increase the probability of additional collisions, potentially leading to the scenario of a sequence of unstoppable cascading collisions known as the "Kessler syndrome" (Kessler, 1991; Kessler & Cour-Palais, 1978).

3. Observational and Data Limitations

While there is mounting evidence of changes in the upper layers of our atmosphere, we lack knowledge on the coupling between atmospheric layers. It is therefore not clear how climatic changes in the middle and upper atmosphere might affect the troposphere. We are also lacking sufficient information on global long-term changes in upper atmosphere composition and dynamic variables, such as winds and gravity waves. Instead of addressing these problems and expanding our capabilities to monitor the entire atmosphere system, we are in fact losing some of this capability. Over the next decade, we will face a substantial gap in observations, unless new observational platforms are planned and deployed and we maintain the few existing ones. The situation has worsened recently, as we have lost some of the few satellite missions intended to monitor this region of our atmosphere: ICON, which was expected to operate until 2029, was lost in November 2022, AIM has been decommissioned, and AURA will be decommissioned in less than two years. TIMED is over 20 years old and its future is uncertain. Also, on 28 February 2024, a catastrophic collision between the TIMED spacecraft and the Russian Cosmos 2221 satellite was only narrowly avoided by a margin estimated at just 20 m, less than the uncertainty in the position of the satellite. Without capability to maneuver, such a collision could be unavoidable and would have substantially increased the space debris in orbit, and the probability of additional collisions in LEO (NASA, 2024). Additionally, the destruction of TIMED would have represented an invaluable loss from a scientific point of view. TIMED is the oldest mission and one of the few to monitor the middle and upper atmosphere, providing the most extended time series of observations of many important atmospheric variables. After AURA and TIMED cease to operate our ability to monitor middle atmosphere temperature, and therefore the radiative impact of GHGs throughout the middle atmosphere, from satellites, including trends, will virtually disappear.

Figure 2 shows at a glance the satellite instruments that we currently have for monitoring the middle and upper atmosphere. Six of the 20 missions currently flying with capabilities to monitor the middle and upper atmosphere were launched more than 15 years ago and are well beyond their expected operational life. Nine satellites launched more than 5 years ago encompass most of the capabilities to monitor the stratosphere, and only two new satellites that could monitor this layer are expected to be launched over the next years. The missions currently planned are intended to serve different purposes than their predecessors, and so they do not allow for long-term or homogeneous measurements. In addition, the capabilities of these missions are limited, and they provide little information on variables relevant for atmospheric dynamics, which are significantly impacted by climate change. As for the mesosphere, only eight missions are currently monitoring this layer, with seven over their expected end of life. Three of them are older than 20 years and only one mission (ALTIUS) is funded to be launched in 2026. The thermosphere is being observed by nine missions, of which seven are over their expected end of life. Five of these are 5 years old or more. The ionosphere is covered by seven missions; five were launched more than 5 years ago, and only one new mission is scheduled to be launched (Ionosphere-M).

Most of these missions are focused on measuring a few variables. O_3 is by far the best monitored one, with 12 of the mentioned missions measuring it. H_2O is measured by eight, and four missions monitor CO_2, CO, CH_4 and trace gases. The most common measurement in the middle thermosphere is total neutral density, since it can be derived from satellite accelerations. Electron density is the most prominent ionospheric in-situ measurement. Only very few measurements of composition, wind or ion drift are available at these heights. The lack of missions to monitor dynamical variables in the upper atmosphere is notable, despite the growing acknowledgment of the importance of understanding the coupling between the troposphere and the middle atmosphere or topics such as

Figure 2. Timeframe for satellite missions with middle atmosphere and upper atmosphere observation capabilities.

propagation of planetary and gravity waves into the upper layers. These are critical for improving weather and climate models.

The Observatory for Atmosphere Space Interaction Studies (OASIS) has reported the need to measure mean temperature, winds and gravity wave fluxes from 30 to 150 km with high accuracy to be able to monitor and understand climate change in the middle and upper atmosphere (OASIS, 2014). Most of the knowledge that we

Table 1
Correlations of the Annual Global Mean Stratopause Height for the Period 1980–2022 From Four State-Of-The-Art Atmospheric Reanalyses for Tropical and Extratropical Regions

	ERA51	MERRA2	JRA3Q	JRA55
30°N–30°S				
ERA5.1	1			
MERRA2	−0.06	1		
JRA-3Q	0.20	0.11	1	
JRA-55	−0.07	0.16	0.19	1
30°N–60°N				
ERA5.1	1			
MERRA2	0.06	1		
JRA-3Q	0.20	0.11	1	
JRA-55	−0.07	0.16	0.19	1
30°S–60°S				
ERA5.1	1			
MERRA2	−0.25	1		
JRA-3Q	0.16	0.27	1	
JRA-55	0.18	0.42	0.55	1

have regarding the impacts of anthropogenic emissions on the upper atmospheric layers is built on theory and models. Fortunately, the last-generation climate models with coupled chemistry have begun to provide information up to the mesopause and above. On the other hand, reanalyses, as a primary tool for studying the atmosphere, suffer severe limitations when reproducing higher levels of the stratosphere and above due to the lack of homogeneous observational data at these altitudes. The last Stratospheric Processes And their Role on Climate (SPARC) report on reanalyses intercomparison (SPARC, 2021) states that the most up-to-date atmospheric reanalyses are hardly useful to evaluate long-term trends. Even the last generation of reanalyses published do not agree on metrics to understand the middle atmosphere such as the stratopause height, a reflection of the temperature field. These reanalyses show very poor correlation values, even when produced by the same research centres (e.g., JRA-55 and JRA-3Q) (see Table 1), therefore impeding a coherent analysis of how this region of the atmosphere evolves. Observational data of the middle and upper atmosphere are mostly collected by satellites, which have their own limitations, as there were very few observations before the introduction of Earth-observing satellites in the 1980s, making it difficult to assess global long-term trends in this part of the atmosphere. Given the mentioned gaps, ground-based observations offer critically important long-term data records, but their global distribution is limited. For instance, ionospheric incoherent scatter radars, which can measure multiple ionospheric and thermospheric parameters across a broad height range above 100 km, provide ideal monitoring of the upper atmospheric climate (S.-R. Zhang et al., 2016), but are only sparsely available worldwide. Also, the radio wave radars and lidars of the recently established Chinese Meridian Project (Wang et al., 2024) will allow to collect information on temperature, winds, and density, although with limited regional coverage.

4. Addressing the Knowledge Gaps and Challenges

Over the years, the need to monitor the ozone hole and understand the processes associated with it has provided a unique justification for monitoring the stratosphere. The availability of observations of ozone has boosted the research and knowledge of other issues, such as a better understanding of stratosphere-troposphere coupling and the dynamics of this region, enabling advances in research fields that nowadays have great relevance and societal impact, such as sub-seasonal predictability. Similarly, a new program of climate monitoring at higher altitudes is likely to bring great advances, not only in our understanding of long-term trends, but also in our understanding of shorter-term processes and coupling with the lower atmosphere.

To enable this, observational capabilities will need to be expanded, while, perhaps even more importantly, the few existing ones are maintained to ensure long-term homogeneous data. Maintaining stability (e.g., stability of orbit and data retrieval algorithms in satellite observations) and implementing cross-calibration within the observing system are equally vital aspects (Mlynczak et al., 2020; S.-R. Zhang et al., 2023). In addition, new observations must be specifically designed to measure trends in temperature, density, and other parameters to generate high quality data sets from which change can be confidently determined (Mlynczak et al., 2023). Trend measurement typically requires much higher absolute accuracy and the ability to demonstrate stability of calibration over the lifetime of the mission, in addition to overlap and continuity of sensors. The tropospheric climate community is now developing a series of space-based missions to begin the accurate measurement of climate trends (e.g., CLARREO Pathfinder (Shea et al., 2020), TRUTHS (Fox et al., 2011), FORUM (Palchetti et al., 2020), and Libra (P. Zhang et al., 2020)). The scientific community studying the middle and upper atmosphere and geospace can draw on the lessons learned from these efforts in designing future observing strategies. To significantly advance the understanding and the science of the middle and upper atmosphere, the community must promote the development of geospace data records (GDRs) (Mlynczak et al., 2023). The GDR concept is drawn from the analogous climate data record (National Research Council, 2004). Specifically, a GDR/CDR is a "time series of measurements of sufficient length, consistency, and continuity to determine geospace/climate variability and change." The development of such records requires substantial attention to achieving GDR data quality as an objective of the design of a mission or instrument from its inception. To date, all space missions observing the middle and upper atmosphere have been designed to answer specific science questions requiring short timespans, typically 2–5 years of observations. There have not been missions or programs designed specifically to measure long-term change, particularly from space. All this would benefit the usefulness of the reanalyses of these layers, making it possible to monitor subtle long-term trends and understand better the influences of several factors, such as the solar cycle (as large solar cycle variability can make it difficult to estimate long-term trends in the lower thermosphere (Mlynczak et al., 2022)), secular changes in the Earth's main magnetic field (Cnossen, 2022), and disentangle the contribution of ozone depleting substances and CO_2 on the cooling of these layers (Ramesh et al., 2020). There is also a need for more complete and comprehensive atmospheric high-top models, that represent better these layers and their dynamical and chemical processes, allowing us to understand the coupling between them better, for example, coupling between the mesosphere and the stratosphere.

Improved monitoring of Earth's upper atmospheric layers has many other benefits, such as contributing to reducing the large uncertainty in estimates of the aerosol burden from volcanic eruptions (Marshall et al., 2022), or even the possibility of using satellites as a surveillance tool if climate intervention techniques are tested or deployed, such as sulphur aerosol injection in the stratosphere. Also, improved monitoring would provide a better understanding of polar mesospheric clouds, which are increasing due to greenhouse gases, and their relationship with CH_4, increasing water vapor concentrations and decreasing mesospheric temperatures (Yu et al., 2023; Yue et al., 2019). Moreover, understanding the impacts and changes in thermospheric density and contraction of the atmosphere is of the utmost importance for better forecasting potential impacts on the future space debris environment in LEO (Añel et al., 2023), and predict impacts on probabilities of the occurence of a Kessler syndrome, something that currently is not adequately quantified. Lastly, satellites deposit various materials directly into the middle and upper atmosphere during re-entry, such as Al and NO_x, which can affect O_3 concentrations (James et al., 2018; Plane et al., 2015; Shutler et al., 2022), and therefore may affect temperature trends in this part of the Earth's atmosphere. Further, Murphy et al. (2023) recently estimated that about 10% of the aerosol particles in the stratosphere currently contain aluminum and other metals that originated from the burn-up of satellites and rocket stages during reentry. They predicted that planned increases in the number of LEO satellites within the next few decades could cause up to half of stratospheric sulfuric acid particles to contain metals from reentry. We do not understand yet what impacts this may have, but this will only be possible to investigate with rigorous monitoring.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

For this work we have used the publicly available ERA5.1 (Copernicus Climate Change Service, Climate Data Store, 2023; Hersbach et al., 2020), MERRA2 (Gelaro et al., 2017; Global Modeling and Assimilation Office (GMAO), 2015), JRA3Q (Kosaka et al., 2024; Numerical Prediction Division, Information Infrastructure Department, 2022) and JRA55 (Kobayashi et al., 2015; Numerical Prediction Division, Information Infrastructure Department, 2015) reanalyses data sets. Also, we have used data of solar activity from the UK Solar System Data Centre (UK Solar System Data Centre (UKSSDC), 2024) the Mauna-Loa CO_2 data set (Dr. Xin Lan, NOAA/GML (gml.noaa.gov/ccgg/trends/) and Dr. Ralph Keeling, 2024).

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