



**Peer Review** The peer review history for this article is available as a PDF in the Supporting Information.

### 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.

### Correspondence to:

J. A. Añel,  
[j.anel@uvigo.gal](mailto:j.anel@uvigo.gal)

### Citation:

Añel, J. A., Cnossen, I., Antuña-Marrero, J. C., Beig, G., Brown, M. K., Doornbos, E., et al. (2025). The need for better monitoring of climate change in the middle and upper atmosphere. *AGU Advances*, 6, e2024AV001465. <https://doi.org/10.1029/2024AV001465>

Received 21 AUG 2024

Accepted 30 JAN 2025












### Author Contributions:

**Conceptualization:** Juan A. Añel, Ingrid Cnossen, Juan Carlos Antuña-Marrero, Gufran Beig, Matthew K. Brown, Eelco Doornbos, Scott Osprey, Shaylah Maria Mutschler, Petr Šácha, Viktoria Sofieva, Laura de la Torre, Shun-Rong Zhang, Martin G. Mlynczak

**Funding acquisition:** Juan A. Añel, Ingrid Cnossen, Gufran Beig, Matthew K. Brown, Eelco Doornbos, Shaylah Maria Mutschler, Petr Šácha, Viktoria Sofieva, Laura de la Torre, Shun-Rong Zhang, Martin G. Mlynczak

**Investigation:** Juan A. Añel, Ingrid Cnossen, Juan Carlos Antuña-

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

Juan A. Añel<sup>1</sup> , Ingrid Cnossen<sup>2</sup> , Juan Carlos Antuña-Marrero<sup>1</sup>, Gufran Beig<sup>3</sup> , Matthew K. Brown<sup>4</sup> , Eelco Doornbos<sup>5</sup> , Scott Osprey<sup>6,7</sup> , Shaylah Maria Mutschler<sup>8</sup> , Celia Pérez Souto<sup>1</sup>, Petr Šácha<sup>9</sup> , Viktoria Sofieva<sup>10</sup> , Laura de la Torre<sup>1</sup>, Shun-Rong Zhang<sup>11</sup> , and Martin G. Mlynczak<sup>8,12,13</sup> 

<sup>1</sup>EPhysLab, CIM-UVigo, Universidade de Vigo, Ourense, Spain, <sup>2</sup>British Antarctic Survey, Cambridge, UK, <sup>3</sup>National Institute of Advanced Study (NIAS), Indian Institute of Science Campus, Bengaluru, India, <sup>4</sup>SERENE, University of Birmingham, Birmingham, UK, <sup>5</sup>KNMI, De Bilt, The Netherlands, <sup>6</sup>AOPP, University of Oxford, Oxford, UK, <sup>7</sup>National Centre for Atmospheric Science, Leeds, UK, <sup>8</sup>Space Environment Technologies, Los Angeles, CA, USA, <sup>9</sup>Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic, <sup>10</sup>Finnish Meteorological Institute, Helsinki, Finland, <sup>11</sup>Haystack Observatory, MIT, Cambridge, MA, USA, <sup>12</sup>Retired, NASA Langley Research Center, Hampton, VA, USA, <sup>13</sup>International Space Science Institute, Bern, Switzerland

**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.

© 2025. The Author(s).

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Marrero, Gufran Beig, Matthew K. Brown, Eelco Doornbos, Scott Osprey, Shaylah Maria Mutschler, Celia Pérez Souto, Petr Šácha, Viktoria Sofieva, Laura de la Torre, Shun-Rong Zhang, Martin G. Mlynczak

**Methodology:** Juan A. Añel, Juan Carlos Antuña-Marrero, Gufran Beig, Matthew K. Brown, Eelco Doornbos, Scott Osprey, Shaylah Maria Mutschler, Celia Pérez Souto, Petr Šácha, Viktoria Sofieva, Laura de la Torre, Shun-Rong Zhang, Martin G. Mlynczak

**Project administration:** Juan A. Añel, Ingrid Cnossen, Laura de la Torre

**Resources:** Juan A. Añel, Laura de la Torre

**Supervision:** Juan A. Añel

**Visualization:** Juan A. Añel, Matthew K. Brown, Eelco Doornbos

**Writing – original draft:** Juan A. Añel, Matthew K. Brown, Martin G. Mlynczak

**Writing – review & editing:** Juan A. Añel, Ingrid Cnossen, Juan Carlos Antuña-Marrero, Gufran Beig, Matthew K. Brown, Eelco Doornbos, Scott Osprey, Shaylah Maria Mutschler, Celia Pérez Souto, Petr Šácha, Viktoria Sofieva, Laura de la Torre, Shun-Rong Zhang, Martin G. Mlynczak

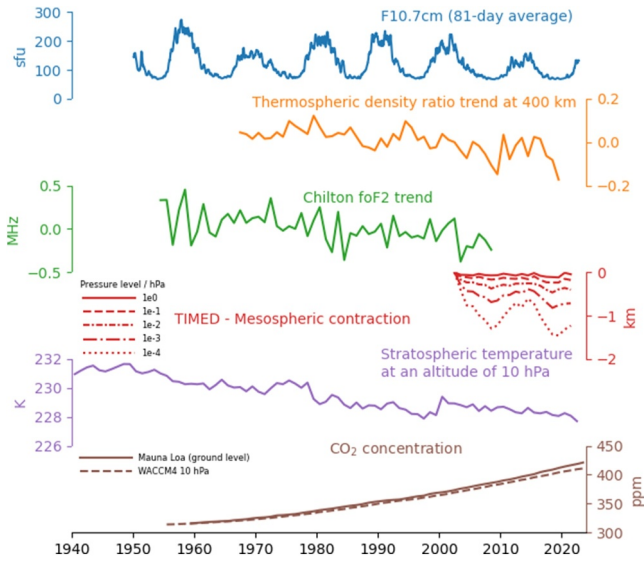
## 2. Impacts of Climate Change

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<sub>2</sub> 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 inter-related 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<sub>2</sub> 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<sub>2</sub> 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<sub>3</sub> is by far the best monitored one, with 12 of the mentioned missions measuring it. H<sub>2</sub>O is measured by eight, and four missions monitor CO<sub>2</sub>, CO, CH<sub>4</sub> 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
<b>30°N–30°S</b>				
ERA5.1	1			
MERRA2	−0.06	1		
JRA-3Q	0.20	0.11	1	
JRA-55	−0.07	0.16	0.19	1
<b>30°N–60°N</b>				
ERA5.1	1			
MERRA2	0.06	1		
JRA-3Q	0.20	0.11	1	
JRA-55	−0.07	0.16	0.19	1
<b>30°S–60°S</b>				
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<sub>2</sub> 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<sub>4</sub>, 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 occurrence 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<sub>x</sub>, which can affect O<sub>3</sub> 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.

**Acknowledgments**

This work is supported by the International Space Science Institute (ISSI) in Bern through the ISSI International Team project #544 (Impacts of climate change on the Middle and Upper Atmosphere and Atmospheric Drag of Space Objects). J.A. A., L.dlT., P.S., and C.P.S. are supported through a grant from the Spanish Research Agency (CHESS, PID2021-124991OB-I00). The EPhysLab is supported by the Government of Galicia (Grant: ED431C 2021/44). M.G.M. is supported by the TIMED Project of the NASA Heliophysics Division. S.R.Z. is supported by the NASA LWS Grant 80NSSC21K1315 and US NSF award AGS-1952737. I.C. is supported by a Natural Environment Research Council (NERC) Independent Research Fellowship (NE/R015651/1). C.P.S. is supported by the Government of Galicia (Grant: ED481A-2024-246). P.S. is supported by the Czech Science Foundation JUNIOR-STAR Grant 23-04921M and Charles University Research Centre program No. UNCE/24/SCI/005. M.K.B. is supported by the UK Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) Programme, National Environmental Research Council (NERC) Grant (NE/V002708/1). We thank Rolando R. García from the National Center for Atmospheric Research for comments on early versions of this manuscript. Also, we thank comments from three anonymous reviewers.

**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<sub>2</sub> data set (Dr. Xin Lan, NOAA/GML (gml.noaa.gov/ccgg/trends/) and Dr. Ralph Keeling, 2024).

**References**

Añel, J., Cnossen, I., Antuña-Marrero, J. C., Beig, G., Brown, M. K., Doornbos, E., et al. (2023). Documenting the impacts of climate change on the middle and upper atmosphere and atmospheric drag of space objects. *SPARC Newsletter*(61), 10–13.

Añel, J., Gimeno, L., de la Torre, L., & Nieto, R. (2006). Changes in tropopause height for the Eurasian region from CARDS radiosonde data. *Naturwissenschaften*, 93(12), 603–609. <https://doi.org/10.1007/s00114-006-0147-5>

Bailey, S. M., Thurairajah, B., Hervig, M. E., Siskind, D. E., Russell, J. M., & Gordley, L. L. (2021). Trends in the polar summer mesosphere temperature and pressure altitude from satellite observations. *Journal of Atmospheric and Solar-Terrestrial Physics*, 220, 105650. <https://doi.org/10.1016/j.jastp.2021.105650>

Brown, M. K. (2023). *Climate change in space: The impact on space debris* (Doctoral dissertation). University of Southampton. Retrieved from <https://eprints.soton.ac.uk/493602/>

Brown, M. K., Lewis, H. G., Kavanagh, A. J., & Cnossen, I. (2021). Future decreases in thermospheric neutral density in low Earth orbit due to carbon dioxide emissions. *Journal of Geophysical Research: Atmospheres*, 126(8), e2021JD034589. <https://doi.org/10.1029/2021JD034589>

Brown, M. K., Lewis, H. G., Kavanagh, A. J., Cnossen, I., & Elvidge, S. (2024). Future climate change in the thermosphere under varying solar activity conditions. *Journal of Geophysical Research: Space Physics*, 129(9), e2024JA032659. <https://doi.org/10.1029/2024JA032659>

- Castanheira, J. M., Añel, J. A., Marques, C. A. F., Antuña, J. C., Liberato, M. L. R., de La Torre, L., & Gimeno, L. (2009). Increase of upper troposphere/lower stratosphere wave baroclinicity during the second half of the 20th century. *Atmospheric Chemistry and Physics*, 9(23), 9143–9153. <https://doi.org/10.5194/acp-9-9143-2009>
- Cnossen, I. (2022). A realistic projection of climate change in the upper atmosphere into the 21st century. *Geophysical Research Letters*, 49(19), e2022GL100693. <https://doi.org/10.1029/2022gl100693>
- Copernicus Climate Change Service Climate, Data Store. (2023). ERA5 hourly data on single levels from 1940 to present [Dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. <https://doi.org/10.24381/cds.adbb2d47>
- Danilov, A., & Berbeneva, N. (2021). Some applied aspects of the study of trends in the upper and middle atmosphere. *Geomagnetism and Aeronomy*, 61(4), 578–588. <https://doi.org/10.1134/S0016793221040046>
- Davidson, P. A. (2024). Geophysical data [Dataset]. *The Dynamics of Rotating Fluids*, 503–504. <https://doi.org/10.1093/9780191994272.005.0003>
- Dawkins, E. C. M., Stober, G., Janches, D., Carrillo-Sánchez, J. D., Lieberman, R. S., Jacobi, C., et al. (2023). Solar cycle and long-term trends in the observed peak of the meteor altitude distributions by meteor radars. *Geophysical Research Letters*, 50(2), e2022GL101953. <https://doi.org/10.1029/2022GL101953>
- Dr. Xin Lan, NOAA/GML ([gml.noaa.gov/ccgg/trends/](http://gml.noaa.gov/ccgg/trends/)) and Dr. Ralph Keeling. (2024). Trends in atmospheric carbon dioxide (CO<sub>2</sub>) [Dataset]. <https://gml.noaa.gov/ccgg/trends/data.html>
- Eichinger, R., & Šácha, P. (2020). Overestimated acceleration of the advective Brewer–Dobson circulation due to stratospheric cooling. *Quarterly Journal of the Royal Meteorological Society*, 146(733), 3850–3864. <https://doi.org/10.1002/qj.3876>
- Emmert, J. (2015). Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag. *Journal of Geophysical Research: Space Physics*, 120(4), 2940–2950. <https://doi.org/10.1002/2015JA021047>
- Emmert, J., Dhadly, M., & Segerman, A. (2021). A globally averaged thermospheric density data set derived from two-line orbital element sets and special perturbations state vectors. *Journal of Geophysical Research: Space Physics*, 126(8), e2021JA029455. <https://doi.org/10.1029/2021JA029455>
- Falle, A., Wright, E., Boley, A., & Byers, M. (2023). One million (paper) satellites. *Science*, 382(6667), 150–152. <https://doi.org/10.1126/science.adi4639>
- Fox, N., Kaiser-Weiss, A., Schmutz, W., Thome, K., Young, D., Wielicki, B., et al. (2011). Accurate radiometry from space: An essential tool for climate studies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences*, 369(1953), 4028–4063. <https://doi.org/10.1098/rsta.2011.0246>
- García, R. R., Yue, J., & Russell, J. M. (2019). Middle atmosphere temperature trends in the twentieth and twenty-first centuries simulated with the whole atmosphere community climate model (WACCM). *Journal of Geophysical Research: Space Physics*, 124(10), 7984–7993. <https://doi.org/10.1029/2019ja026909>
- Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, 30(14), 5419–5454. <https://doi.org/10.1175/JCLI-D-16-0758.1>
- Global Modeling and Assimilation Office (GMAO). (2015). inst3\_3d\_asm\_Cp: MERRA-2 3D IAU state, meteorology instantaneous 3-hourly (p-coord, 0.625x0.5L42), version 5.12.4, Greenbelt, MD, USA: Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC) [Dataset]. <https://doi.org/10.5067/VJAFPL11CSIV>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- James, A. D., Brooke, J. S., Mangan, T. P., Whale, T. F., Plane, J. M., & Murray, B. J. (2018). Nucleation of nitric acid hydrates in polar stratospheric clouds by meteoric material. *Atmospheric Chemistry and Physics*, 18(7), 4519–4531. <https://doi.org/10.5194/acp-18-4519-2018>
- Kessler, D. J. (1991). Collisional cascading: The limits of population growth in low Earth orbit. *Advances in Space Research*, 11(12), 63–66. [https://doi.org/10.1016/0273-1177\(91\)90543-S](https://doi.org/10.1016/0273-1177(91)90543-S)
- Kessler, D. J., & Cour-Palais, B. G. (1978). Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research*, 83(6), 2637–2646. <https://doi.org/10.1029/JA083iA06p02637>
- Kobayashi, S., Ota, Y., Harada, Y., Ebata, A., Moriya, M., Onoda, H., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan. Ser. II*, 93(1), 5–48. <https://doi.org/10.2151/jmsj.2015-001>
- Kosaka, Y., Kobayashi, S., Harada, Y., Kobayashi, C., Naoe, H., Yoshimoto, K., et al. (2024). The JRA-3Q reanalysis. *Journal of the Meteorological Society of Japan. Ser. II*, 102(1), 49–109. <https://doi.org/10.2151/jmsj.2024-004>
- Laštovička, J. (2023). Progress in investigating long-term trends in the mesosphere, thermosphere, and ionosphere. *Atmospheric Chemistry and Physics*, 23(10), 5783–5800. <https://doi.org/10.5194/acp-23-5783-2023>
- Lewis, H. G., Saunders, A., Swinerd, G., & Newland, R. J. (2011). Effect of thermospheric contraction on remediation of the near-earth space debris environment. *Journal of Geophysical Research*, 116(A2). <https://doi.org/10.1029/2011JA016482>
- Manabe, S., & Wetherald, R. T. (1967). Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *Journal of the Atmospheric Sciences*, 24(3), 241–259. [https://doi.org/10.1175/1520-0469\(1967\)024<0241:teotaw>2.0.co;2](https://doi.org/10.1175/1520-0469(1967)024<0241:teotaw>2.0.co;2)
- Marshall, L. R., Maters, E. C., Schmidt, A., Timmreck, C., Robock, A., & Toohey, M. (2022). Volcanic effects on climate: Recent advances and future avenues. *Bulletin of Volcanology*, 84(5), 54. <https://doi.org/10.1007/s00445-022-01559-3>
- Meng, L., Liu, J., Tarasick, D. W., Randel, W. J., Steiner, A. K., Wilhelmson, H., et al. (2021). Continuous rise of the tropopause in the Northern Hemisphere over 1980–2020. *Science Advances*, 7(45), eabi8065. <https://doi.org/10.1126/sciadv.abi8065>
- Mlynczak, M., Yue, J., McCormack, J., Liebermann, R. S., & Livesey, N. J. (2021). An observational gap at the edge of space. *EOS*, 102. <https://doi.org/10.1029/2021EO155494>
- Mlynczak, M. G., Daniels, T., Hunt, L. A., Yue, J., Marshall, B. T., Russell, J. M., III, et al. (2020). Radiometric stability of the SABER instrument. *Earth and Space Science*, 7(2), e2019EA001011. <https://doi.org/10.1029/2019ea001011>
- Mlynczak, M. G., Hunt, L. A., Garcia, R. R., Harvey, V. L., Marshall, B. T., Yue, J., et al. (2022). Cooling and contraction of the mesosphere and lower thermosphere from 2002 to 2021. *Journal of Geophysical Research: Atmospheres*, 127(22), e2022JD036767. <https://doi.org/10.1029/2022JD036767>
- Mlynczak, M. G., Marshall, B. T., Garcia, R. R., Hunt, L., Yue, J., Harvey, V. L., et al. (2023). Algorithm stability and the long-term geospace data record from TIMED/SABER. *Geophysical Research Letters*, 50(5), e2022GL102398. <https://doi.org/10.1029/2022gl102398>
- Murphy, D. M., Abou-Ghanem, M., Cziczo, D. J., Froyd, K. D., Jacquot, J., Lawler, M. J., et al. (2023). Metals from spacecraft reentry in stratospheric aerosol particles. *Proceedings of the National Academy of Sciences of the United States of America*, 120(43). <https://doi.org/10.1073/pnas.2313374120>
- NASA. (2024). NASA's TIMED spacecraft to make close pass with satellite. Retrieved from <https://blogs.nasa.gov/sunspot/2024/02/28/nasas-timed-spacecraft-to-make-close-pass-with-satellite/>

- National Research Council. (2004). *Climate data records from environmental satellites: Interim report*. The National Academies Press. <https://doi.org/10.17226/10944>
- Numerical Prediction Division, Information Infrastructure Department. (2015). The Japanese 55-year reanalysis (JRA-55) [Dataset]. <https://search.diasjp.net/en/dataset/JRA55>
- Numerical Prediction Division, Information Infrastructure Department. (2022). The Japanese reanalysis for three quarters of a century [Dataset]. *Data Integration and Analysis System (DIAS)*. <https://doi.org/10.20783/DIAS.645>
- OASIS. (2014). Exploring the interaction of Earth's atmosphere with space (Tech. Rep.).
- Oberländer-Hayn, S., Gerber, E. P., Abalichin, J., Akiyoshi, H., Kerschbaumer, A., Kubin, A., et al. (2016). Is the Brewer-Dobson circulation increasing or moving upward? *Geophysical Research Letters*, *43*(4), 1772–1779. <https://doi.org/10.1002/2015gl067545>
- Oliver, W. L., Zhang, S., & Goncharenko, L. P. (2013). Is thermospheric global cooling caused by gravity waves? *Journal of Geophysical Research: Space Physics*, *118*(6), 3898–3908. <https://doi.org/10.1002/jgra.50370>
- Palchetti, L., Brindley, H., Bantges, R., Buehler, S., Camy-Peyret, C., Carli, B., et al. (2020). Unique far-infrared satellite observations to better understand how Earth radiates energy to space. *Bulletin of the American Meteorological Society*, *101*(12), E2030–E2046. <https://doi.org/10.1175/bams-d-19-0322.1>
- Pisofit, P., Šácha, P., Polvani, L. M., Añel, J. A., de la Torre, L., Eichinger, R., et al. (2021). Stratospheric contraction caused by increasing greenhouse gases. *Environmental Research Letters*, *16*(6), 064038. <https://doi.org/10.1088/1748-9326/abfe2b>
- Plane, J. M. C., Feng, W., & Dawkins, E. C. M. (2015). The mesosphere and metals: Chemistry and changes. *Chemical Reviews*, *115*(10), 4497–4541. (PMID: 25751779). <https://doi.org/10.1021/cr500501m>
- Qian, L., McInerney, J. M., Solomon, S. S., Liu, H., & Burns, A. G. (2021). Climate changes in the upper atmosphere: Contributions by the changing greenhouse gas concentrations and Earth's magnetic field from the 1960s to 2010s. *Journal of Geophysical Research: Space Physics*, *126*(3), e2020JA029067. <https://doi.org/10.1029/2020ja029067>
- Ramesh, K., Smith, A. K., Garcia, R. R., Marsh, D. R., Sridharan, S., & Kishore Kumar, K. (2020). Long-term variability and tendencies in middle atmosphere temperature and zonal wind from WACCM6 simulations during 1850–2014. *Journal of Geophysical Research: Atmospheres*, *125*(24), e2020JD033579. <https://doi.org/10.1029/2020JD033579>
- Randel, W. J., & Wu, F. (1999). Cooling of the arctic and Antarctic polar stratospheres due to ozone depletion. *Journal of Climate*, *12*(5), 1467–1479. [https://doi.org/10.1175/1520-0442\(1999\)012<1467:cotaaa>2.0.co;2](https://doi.org/10.1175/1520-0442(1999)012<1467:cotaaa>2.0.co;2)
- Roble, R. G., & Dickinson, R. E. (1989). How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? *Geophysical Research Letters*, *16*(12), 1441–1444. <https://doi.org/10.1029/GL016i012p01441>
- Šácha, P., Zajíček, R., Kuchař, A., Eichinger, R., Pišoft, P., & Rieder, H. E. (2024). Disentangling the advective Brewer-Dobson circulation change. *Geophysical Research Letters*, *51*(12). <https://doi.org/10.1029/2023gl1105919>
- Santer, B., Po-Chedley, S., Zhao, L., Zou, C.-Z., Fu, Q., Solomon, S., et al. (2023). Exceptional stratospheric contribution to human fingerprints on atmospheric temperature. *Proceedings of the National Academy of Sciences of the United States of America*, *120*(20), e2300758120. <https://doi.org/10.1073/pnas.2300758120>
- Santer, B., Wehner, M., Wigley, T., Sausen, R., Meehl, G., Taylor, K., et al. (2003). Contributions of anthropogenic and natural forcing to recent tropopause height changes. *Science*, *301*(5632), 479–483. <https://doi.org/10.1126/science.1084123>
- Shea, Y., Fleming, G., Kopp, G., Lukashin, C., Pilewskie, P., Smith, P., et al. (2020). CLARREO Pathfinder: Mission overview and current status. In *IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium* (pp. 3286–3289).
- Shepherd, T. G., & McLandress, C. (2011). A robust mechanism for strengthening of the Brewer-Dobson circulation in response to climate change: Critical-layer control of subtropical wave breaking. *Journal of the Atmospheric Sciences*, *68*(4), 784–797. <https://doi.org/10.1175/2010jas3608.1>
- Shutler, J. D., Yan, X., Cnossen, I., Schulz, L., Watson, A. J., Glaßmeier, K.-H., et al. (2022). Atmospheric impacts of the space industry require oversight. *Nature Geoscience*, *15*(8), 598–600. <https://doi.org/10.1038/s41561-022-01001-5>
- SPARC. (2021). SPARC reanalysis intercomparison project (S-RIP) final report. SPARC Report No. 10, WCRP-6/2021 (Tech. Rep.). <https://doi.org/10.17874/800dee57d13>
- Thomas, G. E., Olivero, J. J., Jensen, E. J., Schroeder, W., & Toon, O. B. (1989). Relation between increasing methane and the presence of ice clouds at the mesopause. *Nature*, *338*(6215), 490–492. <https://doi.org/10.1038/338490a0>
- Wang, C., Xu, J., Chen, Z., Li, H., Feng, X., Huang, Z., & Wang, J. (2024). China's ground-based space environment monitoring network—Chinese meridian project (CMP). *Space Weather*, *22*(7), e2024SW003972. <https://doi.org/10.1029/2024SW003972>
- WMO. (2022). Scientific assessment of ozone depletion: 2022 (Vol. 278; (Tech. Rep.)).
- Yu, W., Garcia, R., Yue, J., Russell, J., III, & Mlynczak, M. (2022). Variability of water vapor in the tropical middle atmosphere observed from satellites and interpreted using SD-WACCM simulations. *Journal of Geophysical Research: Atmospheres*, *127*(13), e2022JD036714. <https://doi.org/10.1029/2022JD036714>
- Yu, W., Yue, J., Garcia, R., Mlynczak, M., & Russell, J., III. (2023). WACCM6 projections of polar mesospheric cloud abundance over the 21st century. *Journal of Geophysical Research: Atmospheres*, *128*(15), e2023JD038985. <https://doi.org/10.1029/2023jd038985>
- Yue, J., Russell, J., III, Gan, Q., Wang, T., Rong, P., Garcia, R., & Mlynczak, M. (2019). Increasing water vapor in the stratosphere and mesosphere after 2002. *Geophysical Research Letters*, *46*(22), 13452–13460. <https://doi.org/10.1029/2019GL084973>
- Zhang, P., Lu, N., Li, C., Ding, L., Zheng, X., Zhang, X., et al. (2020). Development of the Chinese space-based radiometric benchmark mission LIBRA. *Remote Sensing*, *12*(14), 2179. <https://doi.org/10.3390/rs12142179>
- Zhang, S.-R., Cnossen, I., Laštovička, J., Elias, A. G., Yue, X., Jacobi, C., et al. (2023). Long-term geospace climate monitoring. *Frontiers in Astronomy and Space Sciences*, *10*, 1139230. <https://doi.org/10.3389/fspas.2023.1139230>
- Zhang, S.-R., Holt, J. M., Erickson, P. J., Goncharenko, L. P., Nicolls, M. J., McCready, M., & Kelly, J. (2016). Ionospheric ion temperature climate and upper atmospheric long-term cooling. *Journal of Geophysical Research: Space Physics*, *121*(9), 8951–8968. <https://doi.org/10.1002/2016ja022971>
- Zhou, T., DallaSanta, K., Nazarenko, L., Schmidt, G. A., & Jin, Z. (2021). The impact of increasing stratospheric radiative damping on the quasi-biennial oscillation period. *Atmospheric Chemistry and Physics*, *21*(9), 7395–7407. <https://doi.org/10.5194/acp-21-7395-2021>