Heliophysics Science Community Contributions to Addressing Climate Change

Susan Nossal
Scientist III and Director, Physics Learning Center
University of Wisconsin – Madison
nossal@physics.wisc.edu

Contributing Authors:

Name	**Position**	**Affiliation**
Joe McInerney	Associate Scientist III	High Altitude Observatory National Center for Atmospheric Research
Jia Yue	Research Scientist	NASA Goddard Space Flight Center
Julio Urbina	Associate Professor	Electrical Engineering and Computer Science, The Pennsylvania State University
Martin Mlynczak	Senior Research Scientist	Science Directorate, NASA Langley Research Center
Edwin Mierkiewicz	Associate Professor	Physical Science Department Embry-Riddle Aeronautical University
Arianna Ranabhat	Research Intern	Physics Department University of Wisconsin-Madison
L. Matthew Haffner	Associate Professor	Physical Science Department Embry-Riddle Aeronautical University
Carey Woodward	Professor	Department of Physics and Astronomy University of Wisconsin Oshkosh
Larisa Goncharenko	Research Scientist	MIT Haystack Observatory

Abstract

Given the existential threat of climate change, we urge the heliophysics scientific community to consider ways in which we might further contribute to global efforts to address climate change. Whole atmosphere studies reveal that climate change processes impact even the uppermost regions of the atmosphere. The heliophysics research community now has models spanning the surface through the upper thermosphere and a diversity of observational datasets of the middle and upper atmosphere that span multiple decades. These studies indicate that the middle and upper atmosphere provide multiple vertical footprints for climate change and thus can contribute to an understanding of whole atmosphere climate change processes in the complex atmosphere-land-ocean system. This white paper outlines recommendations for expansion of long-term data sets; simulations of climate with whole atmosphere models; engagement in collaborations with the tropospheric research community; and exploration of the possibility of heliophysics contributions to climate assessment efforts. Additionally, we recommend education and outreach efforts to help members of the wider community become more knowledgeable about climate change; support for efforts to increase the diversity of the heliophysics science community; support for international collaborations, and climate mitigation measures that our science community can implement to reduce greenhouse gas emissions from our research, education, and outreach activities.

Motivational Context

Major climate assessments underscore the urgency of addressing climate change. In response to the release of the 2021 Intergovernmental Panel on Climate Change (IPCC) [*IPCC*, working group I, 2021], the United Nations Secretary-General António Guterres said the report was nothing less than "a code red for humanity. The alarm bells are deafening, and the evidence is irrefutable". He noted that the internationally-agreed threshold of 1.5°C above pre-industrial levels of global heating was "perilously close. We are at imminent risk of hitting 1.5 degrees in the near term. The only way to prevent exceeding this threshold, is by urgently stepping up our efforts, and pursuing the most ambitious path." https://news.un.org/en/story/2021/08/1097362 We are already experiencing a wide range of extreme weather and other severe climate impacts at our present about 1.1°C above pre-industrial times [*World Meteorological Organization*, 2022]. The impacts are significantly worse at 2.0°C than at 1.5°C Celsius. "To keep global warming below 1.5°C this century, the world needs to urgently put additional policies and action in place to almost halve annual greenhouse gas emissions in the next eight years." UN 2021 Emissions Gap Report. Given this existential threat of climate change, we urge the heliophysics scientific community to consider ways in which we might further contribute to global efforts to address climate change.

Understanding and addressing climate change and its impacts on people and the planet requires interdisciplinary knowledge, including sociology, medicine, biology, and other fields, as well as physics. Furthermore, climate change is an issue of social justice, equity, diversity and inclusion that affects racial-ethnic minorities and disadvantaged groups disproportionately. "People and ecosystems least able to cope are being hit hardest," concludes the IPCC's impacts, adaptation, and vulnerability [*IPCC*, working group II, 2022]. Increased heat waves, droughts and floods are already leading to mass deaths in species such as trees and corals and have "exposed millions of people to acute food and water insecurity, especially in Africa, Asia, Central and South America, and on Small Islands in the Arctic." (https://www.ipcc.ch/2022/02/28/pr-wgii-ar6/).

Additionally, there are systemic disparities in the impacts of air pollution caused by fossil fuels with people of color most greatly exposed to ambient fine particulate matter air pollution (PM2.5) in the United States [*Tessum et al.*, 2019, 2021]. As concluded by *Tessum et al.* [2021], "this phenomenon is systemic, holding for nearly all major sectors, as well as across states and urban and rural areas, income levels, and exposure levels."

Introduction

Whole atmosphere studies reveal that climate change processes impact even the uppermost regions of the atmosphere. *Roble and Dickinson's* [1989] seminal study predicted that temperatures would cool in the mesosphere and thermosphere and that there would be an associated decrease in the thermospheric density and changes to atmospheric constituents. Using the National Center for Atmospheric Research's (NCAR) Whole Atmosphere Community Climate Model-eXtended (WACCM-X), *Solomon et al.* [2018, 2019] were able to simulate the atmospheric temperature response to anthropogenic increases in greenhouse gases throughout the atmosphere using one self-consistent model, including the warming of the troposphere and the much larger magnitude cooling in the thermosphere (see figure 1).

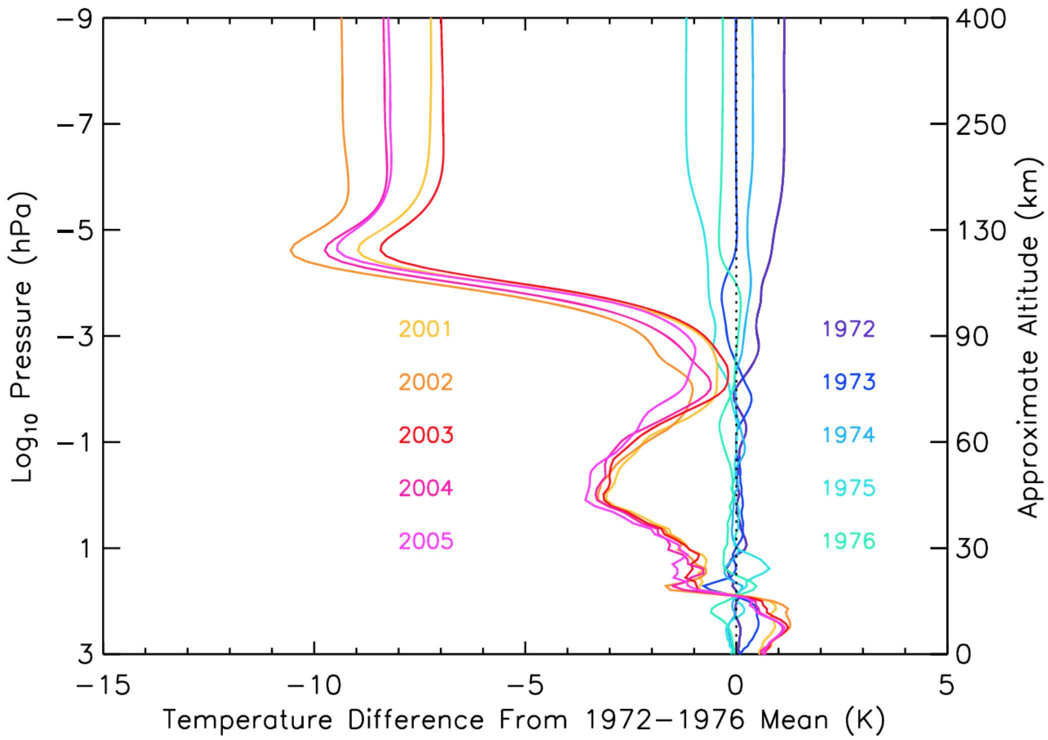

Figure 1: Reprinted Figure 3 from *Solomon et al.* [2018] illustrating the whole atmosphere temperature response to increases in greenhouse gases simulated by WACCM-X under perpetual low solar and geomagnetic activity conditions. The model simulations in this figure show rapid cooling in the upper atmosphere as the troposphere warmed due to increases in greenhouse gases. Temperature is compared to the mean of the 1972-1976 simulated temperature. Please see *Solomon et al.* [2018] for more details.

Understanding anthropogenic climate change in the middle and upper atmosphere also involves knowledge of solar activity, changes to the Earth's magnetic field, volcanos, and seasons as sources of natural variability in these regions. The heliophysics community now has models extending from the surface through the upper thermosphere and a variety of multi-decadal data sets. A few examples are as follows. Analysis of satellite drag by *Emmert* [2015] provides over four decades of thermospheric mass density information with an estimated mass density trend at 400 km of -2.0 +/- 0.5%, consistent with model simulations of thermospheric cooling due to increases in carbon dioxide. Analysis of 28 years of Na lidar data from Colorado State University/Utah State University by *She, et al.* [2019] provides temperature profile information in the mesopause region with some altitudes warming and some cooling with a maximum cooling trend of 1.85 K/decade and 1.09 K/decade, derived from nightly means and 2-hour means centered on midnight, respectively. Based on the same lidar observations, *Yuan et al.* [2019] revealed that the boundary between mesosphere and thermosphere, mesopause, is dropping at the speed of ~ 400 meter/decade, direct evidence of the shrinking atmosphere. Ionospheric temperature trends measured by Incoherent Scatter Radars indicate cooling of larger magnitude than would be expected from greenhouse gases [*Zhang, S.-R., et al.,* 2016]. Geographic patterns in secular changes to the Earth's magnetic field [*Cnossen et al.,* 2015; Qian et al., 2021] also contribute to changes in the ionospheric temperature [*Yue, X., et al.,* 2018; *Yue, J. et al.,*2019].

The densities of constituents such as water vapor and hydrogen are also predicted to change. Stratospheric and mesospheric water vapor have been observed to increase in data sets from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument between 2002 and 2018 and from the Aura Microwave Limb Sounder (MLS) instrument between 2004 and 2018 [*Yue, J., et al.,* 2019]. Thermospheric hydrogen is predicted to increase due both to carbon dioxide cooling and to increases in the source species for hydrogen [*Nossal et al.,* 2016]. Multi-decadal ground-based Fabry-Perot observations of optical emissions from hydrogen in the thermosphere and exosphere indicate a solar cycle variation in the Balmer-alpha column emission intensity and a larger than expected increase in the intensity between two solar maximum periods [*Nossal et al.*, 2019]. The recent special issue of the Journal of Geophysical Research focused on long term trends includes a range of multidecadal observational and modeling studies in the middle and upper atmosphere [https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2169-9402.LTMUPAT1].

As shown above, the middle and upper atmosphere provide multiple vertical footprints for climate change and thus contribute to an understanding of whole atmosphere climate change processes in the complex atmosphere-land-ocean system. Additionally, changes to the atmospheric neutral density impact satellite orbits, space debris, and communication systems [*Yue et al.,* 2019]. There are many ways that the heliophysics research community may contribute to global efforts to address climate change and we include some recommendations below.

Multi-decadal data records

Long-term data records are needed to study natural variability and climatic trends. These studies require understanding instrumental characteristics, observational parameters, calibration, and other sources of uncertainty. The middle and upper atmospheric research communities have now acquired a diversity of data sets spanning multiple decades, some of which are mentioned above in the introduction to this white paper.

In order to study climate, **it is essential that the heliophysics research community continue and extend existing long-term observational data sets of the middle and upper atmosphere, including both satellite and ground-based data sets, as well as expand the number and diversity of such data sets**. Additionally, it is important **to continue and extend observations of solar inputs to the atmosphere** [see for example, the University of Colorado-Boulder LASP Interactive Solar Irradiance Data Center, https://lasp.colorado.edu/lisird/]. When possible, overlapping of observations from different instruments can facilitate inter-calibration and merging of data sets to create longer data records and reduce data gaps. An important part of this effort is to work to better characterize observational uncertainties and understand other geophysical impacts on the observations in order to reduce uncertainties and facilitate more accurate determination and attribution of trends.

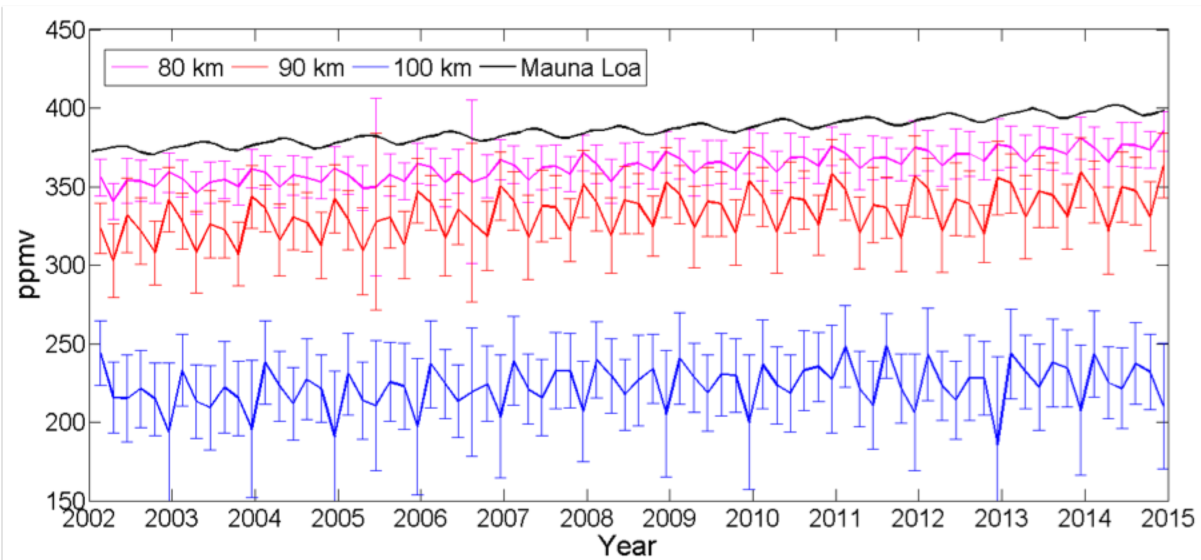

Figure 2. SABER measured CO_2 time series in the mesosphere and lower thermosphere (colored) and at the surface (black) [*Yue et al.*, 2015].

SABER onboard the TIMED satellite has been providing continuous and global measurements of temperature and greenhouse gases such as CO_2 and H_2O in the middle and upper atmosphere for over two decades since 2002, creating the unprecedented longest record in that region. While SABER takes quality measurements every single day, it adds on to this record. To give a few examples, SABER reveals as shown in Figure 2 that CO2 increases in the upper atmosphere at the same rate of 2 ppmv/year as the Earth surface [Yue et al., 2015; Rezac et al., 2018]. Mlynczak et al. [2022] analyzed 20 years of SABER temperature and demonstrated that the upper atmosphere is not only cooling, but also shrinking due to the anthropogenic CO_2 cooling effect and the ideal gas law. The SABER H_2O time series shows that the stratosphere and mesosphere became more humid in the 21st century due to the recovering stratospheric ozone and increasing CO_2 and methane [Yue et al., 2019; Yu et al., 2022]. The long-lasting SABER data enable the new "Space Climate" studies, in addition to "Space Weather". It shares the same challenges of "climate community" of the lower atmosphere or troposphere, for example, how to distinguish natural variability such as strong solar cycles from the long term trend, and sensor/satellite sampling/algorithm stabilities. Due to the difficulty of calibration between two instruments, especially without any overlapping period, the ending of SABER measurements will mark the final date of this special record and state of knowledge will stop there. **We recommend that NASA extend SABER/TIMED as long as possible to create the longest possible global measurements of the middle/upper atmosphere.**

Whole Atmosphere Model Simulations

Extensive model development now enables simulations with a single comprehensive model that extend from the surface through the upper thermosphere. For example, as mentioned above, *Solomon et al.* [2018, 2019] used the NCAR Whole Atmosphere Community Climate Model-eXtended (WACCM-X) to simulate the temperature trend throughout the atmosphere, showing rapid cooling in the upper atmosphere as the troposphere warmed due to increases in greenhouse gases (see Figure 1, above). The simulated temperature decrease in the upper thermosphere (-2.8 K per decade at low solar activity) is of larger magnitude than the simulated warming at the surface (+0.2 K per decade) during the time interval of the early 2000s compared with the early 1970s.

These 1970s to 2000s WACCM-X low solar activity model simulations have been extended to cover nearly the entire 20th century to the early 21st century and analysis is ongoing of the results. In addition, long term WACCM-X future projections through the 21st century, also with low solar activity, are being performed following IPCC scenarios with larger (RCP 8.5) and smaller (RCP 1.9) anthropogenic effects on 21st century to early 22nd century climate. These model results represent the first continuous historical simulations and future projections of greenhouse gas effects in the upper atmosphere through the previous and current centuries and serve as valuable evidence of the effects of human activities on the atmosphere. These WACCM-X simulations employ limited coupling with the other earth system components and are a first step toward the goal of running fully coupled climate system WACCM-X model ensembles, giving a better realization of whole atmosphere climate change.

In addition to carbon dioxide cooling of the upper thermosphere, models predict decreases to the associated mass density with cooling [*Solomon et al.*, 2018, 2019] and changes to atmospheric constituents [*Roble and Dickinson*, 1989]. For example, *Yue et al.* [2019] compare SABER and MLS satellite observations of stratospheric and mesospheric water vapor with modeling by the Whole Atmosphere Community Climate Model, finding areas of agreement and discrepancy with observations. *Nossal et al.* [2016] ran simulations with a one-dimensional global average version of the Thermosphere Ionosphere Mesosphere General Circulation Model, finding that thermospheric hydrogen is predicted to increase due both to carbon dioxide cooling and to increases to the source species for hydrogen from the rise of anthropogenic methane emissions.

Continued development of whole atmosphere modeling and investigations with these models are needed to better our understanding of how anthropogenic activities influence the whole atmosphere system. Such modeling can also potentially identify parameters in the middle and upper atmosphere particularly sensitive to greenhouse gas forcing and to mitigation efforts. This information can identify fingerprints of climate change processes in the middle and upper atmosphere and inform the planning of future observational campaigns.

Collaboration with the Tropospheric Research Community

We recommend fostering greater collaboration with the tropospheric research community to identify further ways that whole atmosphere knowledge might contribute to additional insights about climate processes and to understanding impacts in the middle and upper atmosphere. Our communities can learn from each other's techniques and approaches. For example, the heliophysics community can draw upon the deep knowledge in the climate community on how to successfully achieve continuity in measurements. Merging datasets together to derive trends and uncertainties requires extensive, careful effort that relies upon knowledge of the absolute accuracy of both instruments. Measurement accuracy is a major factor in determining the trend uncertainty, and trend uncertainty is important for guiding policy as well as furthering scientific knowledge. **We encourage development of collaborations with the tropospheric and stratospheric climate communities, similar to present collaborations between the aeronomy and magnetospheric and solar research communities (CEDAR, GEM, and SHINE).** We also encourage collaboration with the SHINE and GEM communities on long term measurements of solar EUV variability and physics-based modeling of this variability, as well as whole geospace modeling.

Contributions to Climate Assessments

International, national and regional climate assessments are used to communicate the state of understanding about climate science, impacts, mitigation, and adaptation to a wider community, including policymakers, the wider scientific community and the public at-large. **We urge the middle and upper atmospheric research communities to explore how we might contribute to climate assessments** such as the Intergovernmental Panel on Climate Change [https://www.ipcc.ch/; *IPCC,* 2021] and the National Climate Assessment [https://science2017.globalchange.gov/; *USGCRP,* 2017] given that data sets in the middle and upper atmosphere now span multiple decades and there are models extending from the surface to the upper thermosphere.

Climate Change Education and Outreach

Climate change impacts everyone. It is important that all stakeholders have knowledge of the fundamentals of climate science, sources of greenhouse gases, mitigation options, impacts, risks, and adaptation strategies. **The heliophysics science community can contribute to helping all members of our community become better informed about climate change, including students, the general public, policy makers, as well as our science community**. We can also learn from the ideas, practices, and concerns of community members. We can draw from resources available to help scientists build their capacities for education and outreach related to climate change. These include the Science Education Resource Center at Carlton College [https://serc.carleton.edu/NAGTWorkshops/climatechange/index.html], Project Drawdown [https://drawdown.org/], and the National Center for Atmospheric Research's Education, Engagement, & Early-Career Development program [https://edec.ucar.edu/].

Fostering a Diverse Science Community

Understanding the complexity of climate change science requires a diversity of perspectives and approaches. This is one of the many reasons why efforts to foster a diverse heliophysics community are essential. Please see the whitepaper, "Recommendations on

Simple but Transformative Diversity, Equity, and Inclusion Measures in Heliophysics over the Next Decade" [*Jones, McArthur, et al.,* 2022] for proposed recommendations regarding improved demographic data collection, a reimagined heliophysics undergraduate internship program, and support for speakers addressing diversity, equity and inclusion topics.

Support for the International Science Community

Earth sciences require an international perspective, including observations from around the globe to enable more comprehensive understanding of the complex Earth system. Long-term data records can be more difficult to acquire in countries with fewer resources for science. **We urge the heliophysics community to support international collaborations, including support for young researchers and the development of mechanisms for quick and efficient support of international scientists on an as-needed basis.** For example, there is an ongoing international and US effort to support researchers working within Ukrainian institutions (*Duszynski et al*., 2022; Joint European and US National Academy of Science Statement from June 13, 2022, available at https://www.nationalacademies.org/news/2022/06/action-steps-for-rebuilding-ukraines-science-research-and-innovation). Given the importance of international networks for addressing earth and space science, we recommend that the heliophysics community join this and similar efforts to support scientists from around the world.

Climate Change Mitigation

We urge the heliophysics science community to seek ways to reduce greenhouse gas emissions from our research, education, and outreach activities. For example, investing in hybrid meeting technology and growing our capacities for facilitating interactive hybrid and online meetings and panels, when possible, can reduce greenhouse gases from travel. The transportation sector was the largest contributor to greenhouse gas emissions in the United States in 2020 [https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10153PC.pdf]. Hybrid options also have the broader impact of increasing inclusivity for those not able to travel to a meeting, including international colleagues. We also suggest creating forums to address strategies for reducing greenhouse gas emissions and adapting to climate impacts within our science community and on individual, local, regional, national, and international levels. We can draw from resources such as Project Drawdown and the American Geophysical Union's Science Policy program.

At this critical moment in our global history, when actions today impact present and future generations of people and ecosystems, we urge the heliophysics community to do all that we can to address the existential threat of climate change.

Supporters

Brandon Myers, Undergraduate Student, Embry-Riddle Aeronautical University
McArthur Jones Jr., Research Physicist, U.S. Naval Research Laboratory
Tao Yuan, Assistant Professor , Utah State University
Chiao-Yao (Joe) She, Professor Emeritus, Department of Physics Colorado State University
Ingrid Cnossen, Natural Environment Research Council (NERC) Independent Research Fellow, British Antarctic Survey, Cambridge, United Kingdom
Shun-Rong Zhang, Principal Research Scientist, MIT Haystack Observatory
Katrina Bossert, Assistant Professor, Arizona State University
Thomas Y. Chen, Research Scholar, School of Engineering & Applied Science, Columbia Univ.

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