Eos

VOL. 102 | NO. 5
MAY 2021

SCIENCE NEWS BY AGU

Cubism and You

What PIs Can Do
About Systemic Bias

How's the Weather on Titan?

WHAT'S GOING ON IN GEOSPACE?

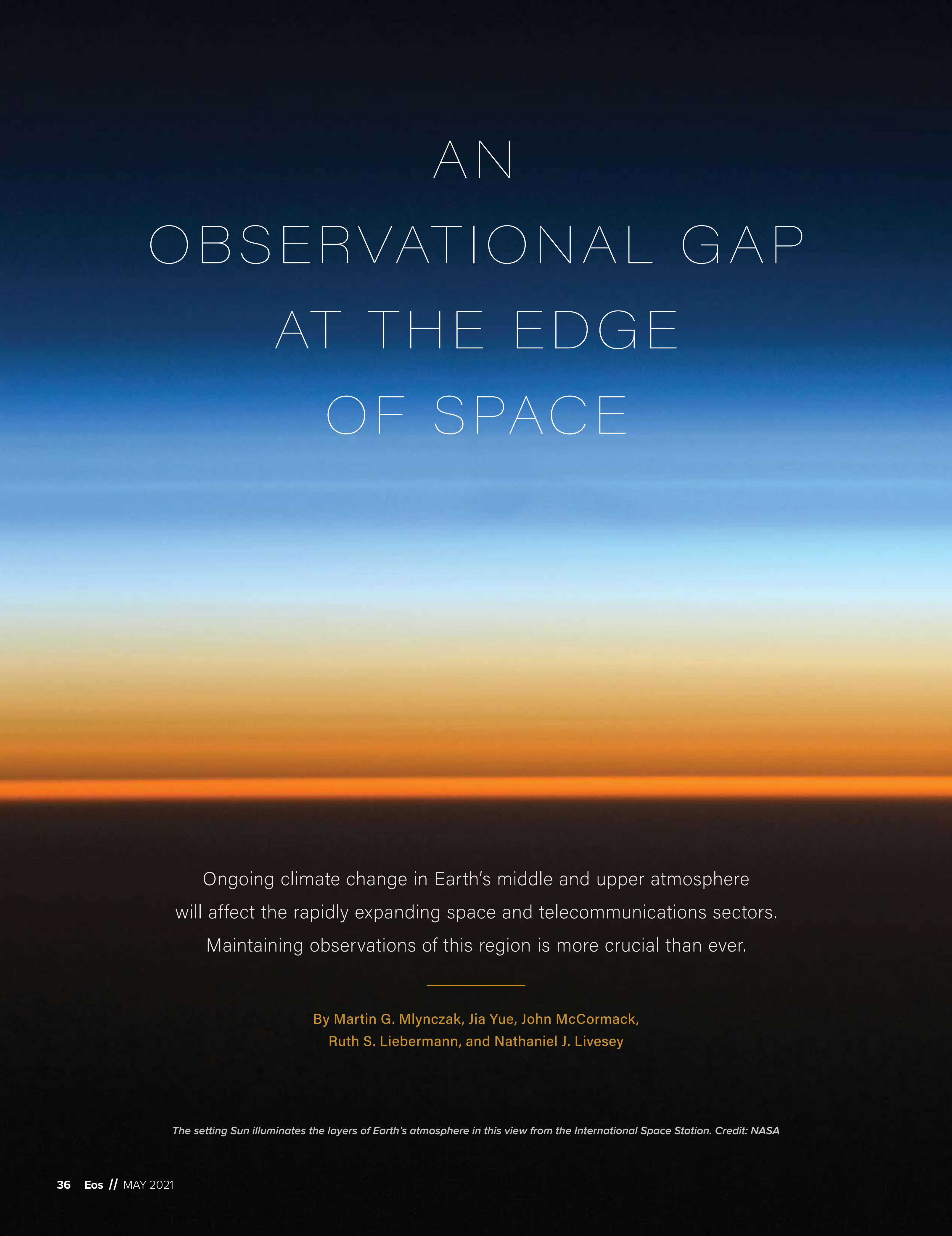
Observational gaps could make it tougher to understand high-altitude climate change and avoid catastrophes in low-Earth orbit.

AGU
ADVANCING EARTH
AND SPACE SCIENCE

AN OBSERVATIONAL GAP AT THE EDGE OF SPACE

Ongoing climate change in Earth's middle and upper atmosphere will affect the rapidly expanding space and telecommunications sectors. Maintaining observations of this region is more crucial than ever.

By Martin G. Mlynczak, Jia Yue, John McCormack,
Ruth S. Liebermann, and Nathaniel J. Livesey



The setting Sun illuminates the layers of Earth's atmosphere in this view from the International Space Station. Credit: NASA

The atmospheric borderland where the sky fades from blue to black is home to a host of satellites. This region, known as geospace, spans altitudes between about 45 and 1,000 kilometers and contains the ionosphere, where high-energy geomagnetic storms can disrupt telecommunications and navigation technologies. Geospace is also sensitive to long-term effects of increasing atmospheric carbon dioxide (CO_2). Thus, knowledge and understanding of the upper atmosphere are increasingly important for many scientific, societal, and commercial needs in our technological society.

In the past 40 years, many space-based observations have been made of the portion of geospace between 45 and 120 kilometers in altitude—that is, Earth's mesosphere and lower thermosphere (MLT)—beginning in 1978 with NASA's Limb Infrared Monitor of the Stratosphere (LIMS) instrument on the Nimbus 7 spacecraft [*Gille and Russell*, 1984] (Figure 1). The past 2 decades especially have seen a revolution in our understanding of the structure and composition of the MLT, largely as a result of these observations. A key example is the satellite data showing long-term cooling of the MLT because of increasing CO_2 levels [*Garcia et al*., 2019], which confirms a fundamental prediction of climate change theory [*Roble and Dickinson*, 1989; *Solomon et al*., 2019, and references therein].

But at present, no new satellite missions or instruments are planned or under development to extend the considerable data records collected by past and current missions. This lack threatens the continuity of space-based observations of the MLT. Here we discuss how this situation could affect vital science and societal applications and introduce considerations to help develop an observing architecture capable of sustaining high-quality MLT data.

A long-term gap in the current set of observations of the mesosphere and lower thermosphere (MLT) seems virtually certain.

A Looming, Long-Term Gap

Since 2001, numerous international missions have observed the MLT, six of which are still operating. These include four NASA-led missions—Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED; launched in 2001); Aura (2004); Aeronomy of Ice in the Mesosphere (AIM; 2007); and the Ionospheric Connection Explorer (ICON; 2019)—as well as the Canadian Atmospheric Chemistry Experiment (ACE)/SciSat mission (2004) and the Swedish-led Odin satellite (2001).

Observations from these missions, including data on temperature and chemical composition, have led to remarkable growth in our knowledge of Earth's MLT. The TIMED mission alone has produced nearly 2,700 peer-reviewed publications worldwide. In addition to informing our understanding of past and ongoing long-term change in the region, these data have become vital for the development of next-generation whole-atmosphere prediction systems for space weather applications [e.g., *McCormack et al*., 2017; *Pedatella et al*., 2019]. The data have also contributed to significant advances in modeling the effects of surface weather on the MLT [*Sassi et al*., 2018].

Three of the four ongoing NASA missions are well past their design lifetimes—for example, TIMED, originally designed as a 2-year mission, is now in its twentieth year. The fourth, ICON, was launched in October 2019 on a 2-year baseline mission to explore sources of variability in the ionosphere. Development of the other active missions began in the late 1980s and early 1990s, and some are now approaching 20 years of on-orbit operations.

The new Mesospheric Airglow/Aerosol Tomography and Spectroscopy (MATS) microsatellite instrument, slated to launch in 2021, will make observations of the MLT with an anticipated 2-year lifetime. The observational timelines of ICON and MATS will overlap existing sensors, and these spacecraft should provide exceptional science returns. However, they are unlikely to significantly extend the current record of MLT observations. Future missions such as the European Space Agency's Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS), Sweden's Stratospheric Inferred Winds (SIW), and current and future Ozone Mapping and Profiler Suite instruments flying aboard NOAA satellites do not regularly and comprehensively observe the MLT.

Thus, considering the time required to advocate, propose, and develop new satellite missions, a long-term gap in the current set of observations of the MLT seems virtually certain.

Forecast: Continued Cooling with a Chance of Debris

Climate change is almost exclusively thought of as comprising the long-term changes to and warming of the very lowest regions of Earth's atmosphere, associated with increasing concentrations of CO_2 and other greenhouse gases. However, effects of CO_2 are manifest throughout the entire perceptible atmosphere.

For example, all available evidence suggests that the MLT has cooled because of rising CO_2, and ongoing cooling of the MLT is predicted to significantly reduce density at altitudes where low-Earth-orbiting satellites fly (about 400–1,000 kilometers) [*Roble and Dickinson*, 1989]. Evidence for this effect on density already exists [*Emmert*, 2015].

Above 120 kilometers in altitude in the thermosphere, long-term changes associated with increasing CO_2 are largely driven by physical processes in the "heat sink region" of the MLT between 85 and 125 kilometers in altitude, where radiative cooling by CO_2 dominates [*Mlynczak et al*., 2018]. Thermal energy at higher altitudes in the thermosphere is naturally transported downward by heat conduction and is ultimately radiated by CO_2 in the heat sink region.

As the amount of CO_2 increases, more energy from the upper thermosphere can thus be transported down and radiated from the heat sink, resulting in cooling and decreased density both in the MLT and in the upper thermosphere, the latter stretching from about 120 kilometers up to the edge of space.

The observed rate of CO_2 increase in the MLT is the same as it is in the troposphere [*Rezac et al*., 2018], and as the rate of increase there is accelerating, we expect the rate of cooling and density change in the MLT and in geospace to increase in the mid-21st century. This scenario will increase the orbital lifetime of satellites—and space debris—which could amplify hazards to all low-Earth-orbiting space assets.

Furthermore, besides CO_2 and water vapor [*Yue et al*., 2019], minor chemical species in the MLT such as atomic oxygen, hydroxyl molecules, ozone, and atomic hydrogen are also critical components of the energetics of the region [*Mlynczak and Solomon*, 1993]. Yet we know little about how concentrations of these species are changing. Along with limited understanding of associated changes in atmospheric dynamics,

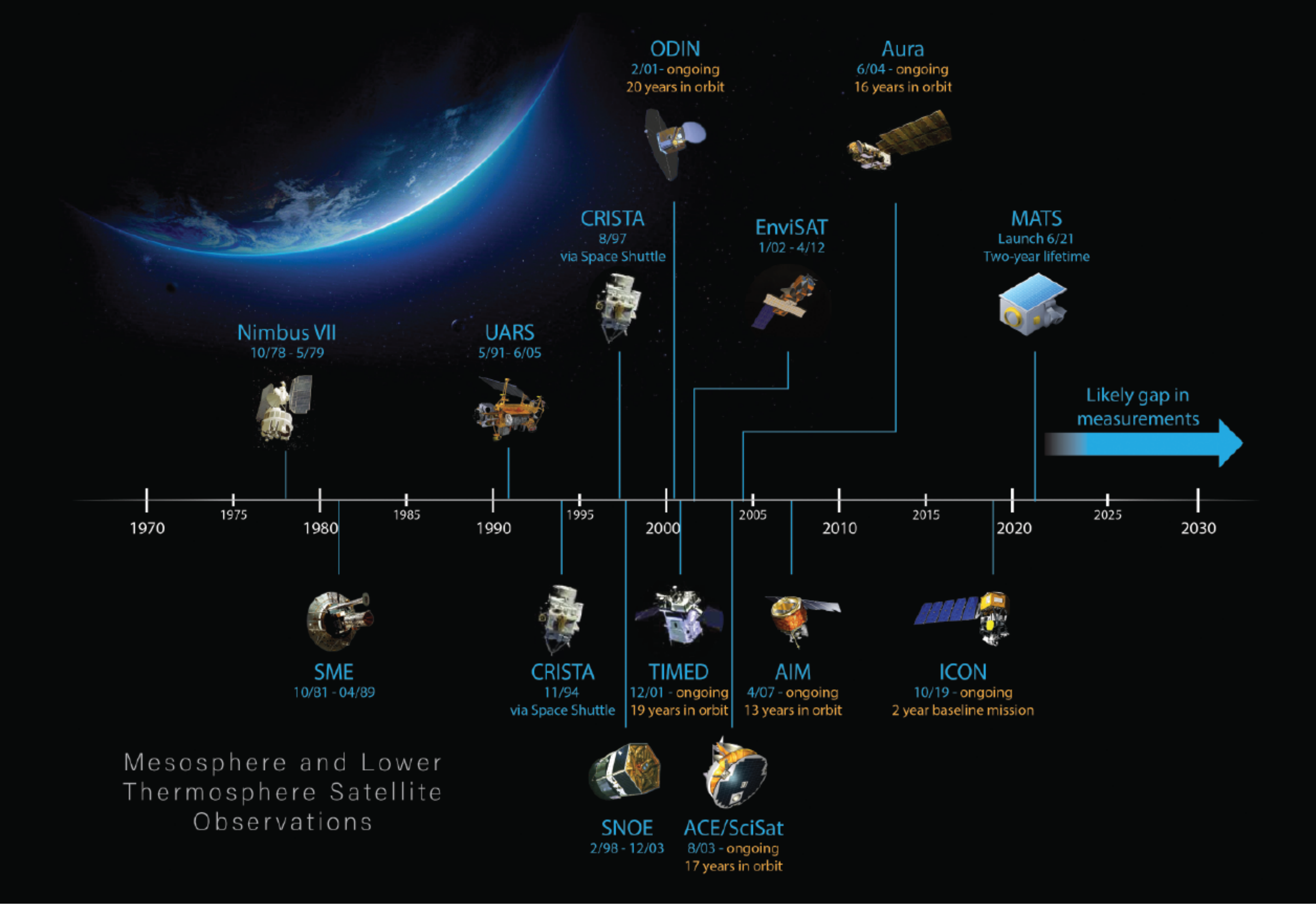


Fig. 1. This timeline shows satellite missions that have collected observations of the terrestrial mesosphere and lower thermosphere (MLT). The Odin, Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED), Atmospheric Chemistry Experiment (ACE), and Aeronomy of Ice in the Mesosphere (AIM) missions are all still operational, but at ages ranging from 13–20 years, they are well beyond their nominal design lifetimes. Ionospheric Connection Explorer (ICON) launched in 2019, with a 2-year baseline mission; Mesospheric Airglow/Aerosol Tomography and Spectroscopy (MATS) is scheduled to launch in 2021, also on a 2-year mission. As no missions are planned or in development beyond these, a long-term gap in observations of the MLT is almost certain to occur in the next 3–5 years. CRISTA = Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere; SME = Solar Mesosphere Explorer; SNOE = Student Nitric Oxide Explorer; UARS = Upper Atmosphere Research Satellite. Credit: NASA Langley Research Center

this lack of knowledge complicates the task of predicting the MLT over the long term. Continuous monitoring of the MLT is essential to quantify its chemical composition, disentangle different mechanisms at play, and understand how these mechanisms influence decreasing air density and aerodynamic drag in the upper thermosphere.

With envisioned fleets of tens of thousands of satellites—providing, for example, global wireless Internet—space traffic and longer-lived space debris will become increasingly important issues in space policy, space law, and the business of space insurance underwriting. An observationally verified capability to predict long-term change in and above the MLT appears to be essential.

Essential Considerations to Ensure Continuity

The key to understanding long-term change in the MLT and the environs above is the ability to reliably separate changes and trends due to increasing CO_2 in the MLT from the natural variability of the atmosphere, such as that driven by the 11-year solar cycle. To do this, we need at least three—and likely four—solar cycles of continuous and accurately calibrated data.

The current continuous missions have observed nearly two cycles, so achieving the needed time series will likely require several successive instruments to follow the ones presently in orbit. We anticipate that future sensors designed to monitor the MLT will be smaller and require lower-cost satellite architectures with life spans much shorter than those of Aura and TIMED. But several questions must be addressed to devise a sustainable, long-term observing system (these will be discussed in detail in a future technical publication):

- What effect will a gap in the current record have on our ability to understand trends in the MLT and above?
- What is the required absolute accuracy of measurements from a new observing system to enable their accurate fusion with prior data sets?
- What spatial and temporal sampling requirements are needed to detect trends confidently in the data, considering the natural variability in the MLT and anticipated measurement uncertainties?
- What is the required calibration stability of instruments in a new system to ensure that changes in an instrument are not falsely interpreted as atmospheric changes?

- What is the required stability of data processing algorithms and their inputs (i.e., spectral line parameters) from one mission to the next to reduce biases between successive data sets?
- What orbital stability is required over the lifetime of individual missions to avoid false trends in the data?

The experience of the tropospheric climate research community indicates that for long-term trend detection, temporal and spatial sampling requirements and some instrument performance metrics may be substantially relaxed in comparison with those metrics for short-term "process" missions, which require a higher density of observations. However, much higher calibration accuracy is likely required for long-term missions to reduce small systematic measurement errors [*Wielicki et al.*, 2013], and gaps in the observation record hinder and may preclude the ability to tie successive data sets together with confidence [*Loeb et al.*, 2009].

Scientists are just now beginning to grasp the extent of ongoing changes in Earth's MLT, using observations from aging satellites with no identified successors.

Mind the Gap

Increasing atmospheric CO_2 is driving dramatic changes in Earth's mesosphere and lower thermosphere that are documented in data sets approaching 2 decades in length. But scientists are just now beginning to grasp the extent of these changes, using observations from aging satellites with no identified successors. Current satellite missions are almost certain to end in the next 3–5 years, leaving an impending gap in future observations of unknown length.

The physics of the MLT govern changes at higher altitudes in geospace, up to the edge of space—changes that will ultimately influence space policy and space law regarding regulation of orbital debris and that may factor into underwriting future satellite insurance policies. Long-term, continuous observation of the MLT is essential for these critical scientific and societal issues.

We recommend that NASA and the National Science Foundation commission a geospace-focused continuity study that addresses the science requirements and architecture considerations described above and recommends possible implementation solutions and agencies. This report would ideally be available as input for the next heliophysics decadal survey, which is anticipated in the 2023 time frame.

Long-term changes in geospace are now occurring and will continue to alter the geospace environment for at least the next century. We are approaching the end of a dramatic era in the observation of Earth's upper atmosphere, but we are only beginning to understand this critical region.

Acknowledgments

M.G.M., R.S.L., and J.Y. acknowledge ongoing support from the NASA Heliophysics Division. Work at the Jet Propulsion Laboratory, California Institute of Technology, was performed under contract with NASA. J.M. acknowledges support from the U.S. Naval Research Laboratory.

References

Emmert, J. T. (2015), Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag, *J. Geophys. Res. Space Phys., 120*, 2,940–2,950, https://doi.org/10.1002/2015JA021047.

Garcia, R. R., J. Yue, and J. M. Russell III (2019), Middle atmosphere temperature trends in the twentieth and twenty-first centuries simulated with the Whole Atmosphere Community Climate Model (WACCM), *J. Geophys. Res. Space Phys., 124*, 7,984–7,993, https://doi.org/10.1029/2019JA026909.

Gille, J. C., and J. M. Russell (1984), The Limb Infrared Monitor of the Stratosphere: Experiment description, performance, and results, *J. Geophys. Res., 89*, 5,125–5,140, https://doi.org/10.1029/JD089iD04p05125.

Loeb, N. G., et al. (2009), Impact of data gaps on satellite broadband radiation records, *J. Geophys. Res.*, *114*, D11109, https://doi.org/10.1029/2008JD011183.

McCormack, J., et al. (2017), Comparison of mesospheric winds from a high-altitude meteorological analysis system and meteor radar observations during the boreal winters of 2009–2010 and 2012–2013, *J. Atmos Sol. Terr. Phys.*, *154*, 132–166, https://doi.org/10.1016/j.jastp.2016.12.007.

Mlynczak, M. G., and S. Solomon (1993), A detailed evaluation of the heating efficiency in the middle atmosphere, *J. Geophys. Res., 98*, 10,517-10,541, https://doi.org/10.1029/93JD00315.

Mlynczak, M. G., et al. (2018), Space-based sentinels for measurement of infrared cooling in the thermosphere for space weather nowcasting and forecasting, *Space Weather, 16*, 363–375, https://doi.org/10.1002/2017SW001757.

Pedatella, N. M., et al. (2019), Error growth in the mesosphere and lower thermosphere based on hindcast experiments in a whole atmosphere model, *Space Weather*, *17*, 1,442–1,460, https://doi.org/10.1029/2019SW002221.

Rezac, L., et al. (2018), On long-term SABER CO_2 trends and effects due to nonuniform space and time sampling, *J. Geophys. Res. Space Phys.*, *123*, 7,958–7,967, https://doi.org/10.1029/2018JA025892.

Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and lower thermosphere?, *Geophys. Res. Lett., 16*, 1,441–1,444, https://doi.org/10.1029/GL016i012p01441.

Sassi, F., et al. (2018), Simulations of the boreal winter upper mesosphere and lower thermosphere with meteorological specifications in SD-WACCM-X, *J. Geophys. Res.*, *123*, 3,791–3,811, https://doi.org/10.1002/2017JD027782.

Solomon, S. C., et al. (2019), Whole atmosphere climate change: Dependence on solar activity, *J. Geophys. Res. Space Phys., 124*, 3,799–3,809, https://doi.org/10.1029/2019JA026678.

Wielicki, B. A., et al. (2013), Achieving climate change absolute accuracy in orbit, *Bull. Am. Meteorol. Soc.*, *94*, 1,519-1,539, https://doi.org/10.1175/BAMS-D-12-00149.1.

Yue, J., et al. (2019), Increasing water vapor in the stratosphere and mesosphere after 2002, *Geophys. Res. Lett.*, *46*, 13,452-13,460, https://doi.org/10.1029/2019GL084973.

Author Information

Martin G. Mlynczak (m.g.mlynczak@nasa.gov), Science Directorate, NASA Langley Research Center, Hampton, Va.; **Jia Yue,** Catholic University of America, Washington, D.C.; also at NASA Goddard Space Flight Center, Greenbelt, Md.; **John McCormack,** Space Science Division, Naval Research Laboratory, Washington, D.C.; **Ruth S. Liebermann,** NASA Goddard Space Flight Center, Greenbelt, Md.; and **Nathaniel J. Livesey,** Jet Propulsion Laboratory, California Institute of Technology, Pasadena

▶ **Read the article at bit.ly/Eos-MLT-gap**