Measurements of the mean structure, temperature, and circulation of the MLT

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Synopsis:
The region known as the MLT, or mesosphere - lower thermosphere, is a key transition region between the lower and the upper atmosphere. The region spans the altitude range from 50 to 130 km: a zone of very rapid transitions in temperature, composition, and prevalent dynamical and physical processes. Waves and other perturbations generated in the troposphere and stratosphere must propagate through the MLT to reach the upper atmosphere. Likewise, upper atmospheric perturbations due to solar and geomagnetic activity propagate into and through the MLT to affect lower altitudes.

The mean state of the MLT is not just a passive background for wave propagation but a highly dynamic region. The processes of wave breaking and dissipation contribute to the rapid changes in the mean state in both space (all dimensions) and on a broad range of timescales, from minutes to multi-decadal trends. To understand the coupling between the lower and upper atmosphere, we depend on a continual dialog among multidisciplinary theoreticians, modelers, and observationalists. Working together, we can determine how perturbations interact with the mean state and how these interactions affect the downward and upward propagation of perturbations at all scales.

In this document we emphasize a growing concern among researchers about the significant upcoming gap in global measurement capabilities for the MLT. This is an acute situation for global observations. We outline the reasons for concern and give some recommendations for how the decadal survey can best address the pressing needs. Our first recommendation is for continued operation and support of existing satellite instruments for as long as they are providing quality observations. Related to this, we urge support for expanded or improved data products through improved or new retrieval algorithms. Finally, we recommend the accelerated development of new instruments and flight opportunities that can eliminate or shorten the expected gap in observations of the mean state of the MLT.

1. Current challenges

Variations in the atmosphere are referenced against a “mean” background, where the mean is taken in space (e.g., zonal average) and/or time (e.g., diurnal or seasonal average). Knowledge of the mean is necessary to characterize perturbations and also to understand the processes associated with their development. Important perturbations occur at temporal and spatial scales spanning many orders of magnitude: minutes to decades; kilometers to global. The accumulation of multiple measurements is required to determine the mean state. For large-scale perturbations such as tides, planetary waves, and vortex disturbances, the background has global proportions. Waves that have limited spatial dimensions such as mesoscale gravity waves interact with their immediate background but also show major variations in response to large-scale features such as planetary waves, tides, and shears in the zonally averaged wind.

In this paper, we focus on two components of the basic state that are of fundamental importance for all dynamics and energetics: wind and temperature. These control the propagation and dissipation of dynamical waves and affect the composition through transport of chemical species and impact on photochemical reaction rates. Temperature is a key indicator of the energy balance and a key component in determining the energy exchange within the atmosphere. Both temperature and winds are first order indicators of the response of the atmosphere to wave dissipation and external forcing. Temperature and horizontal wind are closely coupled through the thermal wind relation but this relation is not sufficiently tight that observations of one can substitute for the other.

Knowledge of the mean wind and temperature is crucial for achieving two basic goals: 1) to evaluate the background that is relevant for waves and other perturbations and needed for dynamical process studies; and 2) to determine a representative value for characterizing large-scale variations and trends such as the responses of the MLT to increasing greenhouse gases, variable solar activity, and secular geomagnetic field variations. Although these are not the same science motivations, the needs in terms of measurements overlap to a large extent. A primary consideration is the need for near-simultaneous observations spread over a global domain and continuous in time.

1.1 Investigation of atmospheric perturbations

The first step for understanding atmospheric processes requires observing and characterizing differences and variations of temperature and wind in space and time. Strong repeatable variations are generally seen with latitude, altitude, and season but differences on other temporal and spatial scales can also provide important indications of dynamical activity. The second step is investigating how these differences can be explained and predicted. For the MLT, there is still substantial uncertainty about some basic aspects of the zonally and seasonally averaged basic state, such as the strength of the mean circulation, the impact and variability of vertical diffusion, and the seasonal variation of winds in the tropics.

Many dynamical phenomena can be described as waves superimposed on a spatially and temporally uniform background. Important waves for the MLT are gravity waves, atmospheric tides, and traveling and quasi-stationary planetary waves. The interaction of waves with the mean state is a primary driver of the MLT. Waves can transport momentum and energy over vast distances. Their breaking generates turbulence and leads to redistribution of energy and trace gases. Other perturbations that are more usually described as temporal perturbations or anomalies include developments in response to sudden stratospheric warmings, geomagnetic activity, the quasi-biennial oscillation, and other forcing such as the Madden-Julian Oscillation.

Theory and numerical models show the importance of gravity waves in driving the winds in the MLT. However, observations are currently insufficient to determine where the waves originate and how they are influenced by and modify the background atmosphere. While numerical models can often be useful to help interpret observations, the utility of global models to diagnose gravity waves is limited. The waves themselves and the dynamical processes associated with their breakdown and dissipation are not resolved due to the limited horizontal, vertical, and temporal resolution in global high-top models. The impact of gravity waves in global models is instead parameterized. Validation of these parameterization schemes requires knowledge of the mean state. Without adequate observations of the mean state, we cannot assess whether the representation of sub-grid scale gravity waves in global models is realistic.

1.2 Tracking trends and other long-period variations

As first shown in a numerical model by Roble and Dickinson (1989), increasing greenhouse gases will lead to a decrease in the temperature in the MLT. In the decades since, the predictions have been refined with state-of-the-art global models that, importantly, include regional effects as well as feedback of ozone, water vapor, and other reactive chemicals (Lastovicka 2017). Observational confirmation that the MLT is cooling has been presented by, for example, Zhao et al. (2021) and Bailey et al. (2021). Accurate determination of this trend requires sufficient observations and careful analysis to ensure that trend estimates are not biased by uneven sampling by region, season, or local time. Trends in MLT winds are still difficult to determine due primarily to insufficient global observations. Furthermore, the simulations of trends in the zonal wind are not consistent between different models, which is further evidence that the parameterization of gravity wave effects introduces significant uncertainties (Ramesh et al 2020).

Determination of multi-decadal changes usually requires patching together observations made with different instrumentation and, in many cases, different techniques. This process is made simpler and more reliable if a one-to-one comparison is possible when measurements overlap. This was seen in the overlap between observations of temperature from UARS/HALOE and TIMED/SABER during the first few years after the launch of TIMED (Remsberg et al., 2008). Even with overlap and careful screening, sophisticated analysis techniques are needed to obtain the most accurate trend estimates. Such techniques have been more commonly seen in analysis of stratospheric data (e.g., Randel 2016, Ball 2017) but can equally be applied to MLT data (e.g., Bailey et al. 2021).

At intervals, there are updates to the trends calculated from model simulations of the historical past (e.g., Schmidt et al. 2013; Garcia et al. 2019; Ramesh et al. 2020). Such studies are important for detection and attribution and for disentangling the responses to various evolving processes. However, all models show discrepancies against observations even in their simulation of present-day conditions, as shown, for example, by Gettelman (2019) for the WACCM model. The model predictions and attributions cannot be trusted unless and until they are validated by comparison with observations.

1.3 Requirements for the advancement of MLT science:

To be most useful, observations should address the following requirements:

- global measurements of temperature and horizontal winds over a broad vertical domain encompassing the MLT;
- maintain continuity with existing observations for diagnosing trends such as those attributed to anthropogenic composition changes and external perturbations;
- sufficient local time and longitude coverage to separate tidal and planetary wave perturbations from background fields.

The requirement for continuity argues for the continued operation of existing satellite observations and the rapid development and deployment of new instrumentation that can overlap with the current long-term observations.

2. Current space-based assets and the pending gap in observations

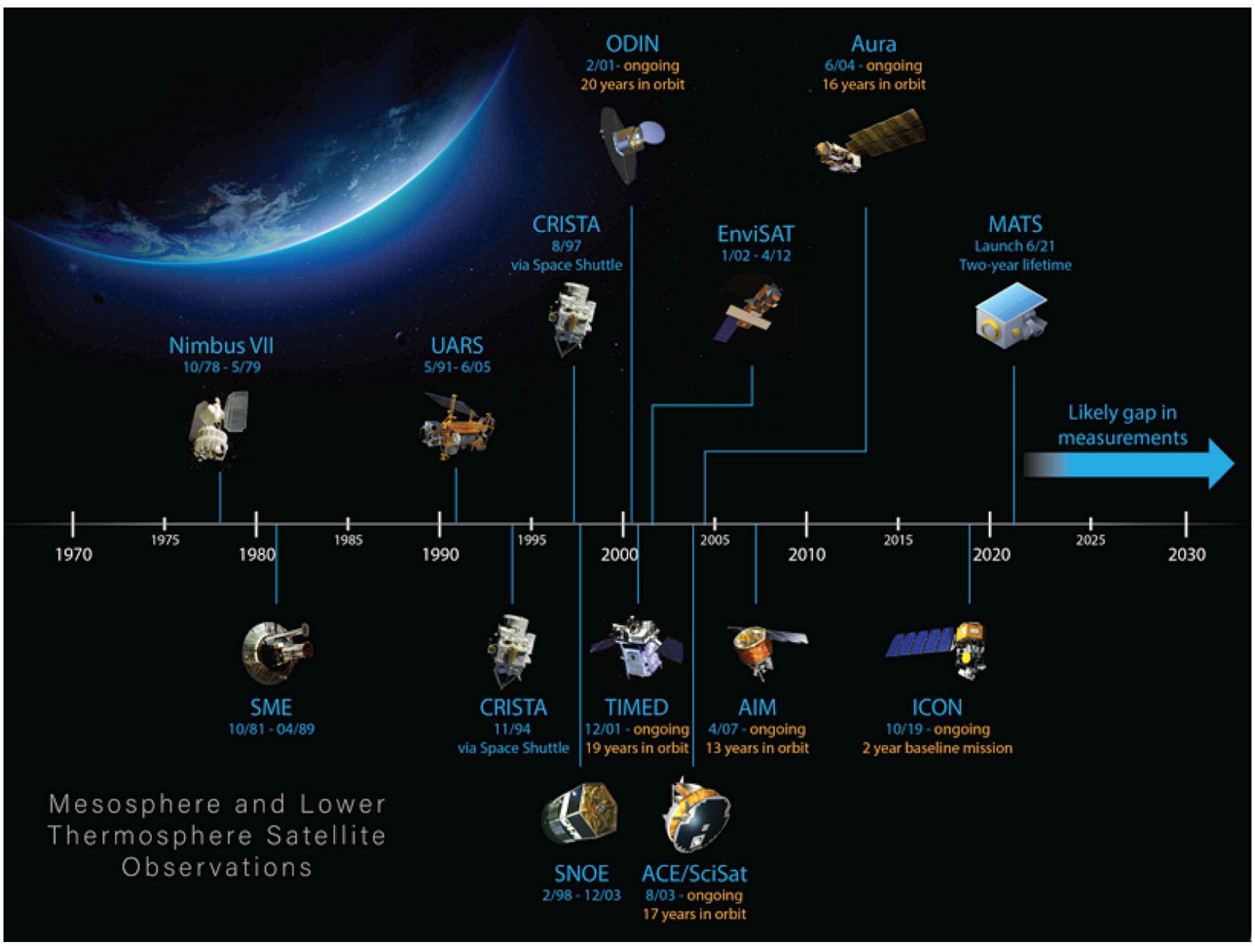

Fig. 1. This timeline shows satellite missions that have collected observations of the terrestrial mesosphere and lower thermosphere (MLT). The Odin, TIMED, ACE, Aura, and AIM missions

are all still operational, but at ages ranging from 13 to 20 years, they are well beyond their nominal design lifetimes. ICON launched in 2019, with a 2-year baseline mission; MATS is scheduled to launch in 2022, also on a 2-year mission. As there are no missions planned or in development beyond these, a long-term gap in observations of the MLT is virtually 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. Figure from Mlynczak et al. (2021).

Mlynczak et al. (2021) raised the alarm of an upcoming gap in satellite measurement capabilities. Figure 1 from their paper gives a timeline of satellites with measurements of the MLT. As described in the caption, several of these are still operating and providing data. Note that the only satellite that has been launched since (2007) is ICON, which measures winds and temperature above 95 km and over a limited latitude range covering the Tropics. The MATS mission (Gumbel et al. 2020) is expected to be launched in 2022 and to have a two-year lifetime.

Several satellite instruments are currently making temperature measurements over extensive parts of the MLT: TIMED/SABER (20-110 km); Aura/MLS (10-100 km); and Odin (25-100 km). Additionally, limited longitude/latitude coverage is provided by solar occultation measurements from AIM/SOFIE and ACE/FTS. These satellites have ages in the range of 13-20 years and are well past their expected lifetimes. Horizontal wind observations are made by TIMED/TIDI (85-105 km) and ICON/MIGHTI (90-300 km).

As described by Mlynczak et al. (2021), there is an imminent gap in MLT measurements since existing observations will soon end and replacements are not currently under development. Given the advanced age of these measurement systems, a gap is practically inevitable since replacement systems are not currently under construction or testing. The first priority is to keep these instruments operating for as long as possible in order to reduce the potential gap. Of those listed, two (TIMED and AIM) are supported by NASA Heliophysics, one (Aura) is supported by NASA Earth Sciences, and the others are operated by entities outside of the US.

The gap under discussion here is essentially a total lack of space-borne observations for a significant part of the atmosphere. This is not solely a problem for U.S. researchers but is reflective of an absence of all research satellite data for the MLT from any source worldwide. Information about the MLT from ground-based instruments (lidar, radar, and optical sensors) can help in some ways but have very limited geographical scope. Since all dynamical processes act over the horizontal dimension, ground-based data are often difficult to interpret without knowledge of the large-scale mean state. Nonetheless, combined ground-based data at different longitudes can complement the satellite-based studies of planetary waves and tides (e.g., Forbes et al., 2021).

3. Potential solutions

We are aware of two observing systems outside of the U.S that are being prepared for upcoming launch.

- MATS (Mesospheric Airglow/Aerosol Tomography and Spectroscopy) is a Swedish satellite mission designed to investigate waves in the mesosphere for two years. The launch is currently scheduled for November 2022. Temperatures will be retrieved over the altitude range 75-110 km (Gumbel et al 2020; see also https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/mats).

- ALTIUS (Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere) will retrieve profiles of temperature and many trace constituents over the range 15-100 km (Fussen 2019). Launch is currently scheduled for 2025.

The potential for missions supported the US has been affected by the delay and uncertain future of the Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC). DYNAMIC is a NASA mission that would provide global measurements of wind and temperature in the 90-300 km region from at least two measurement platforms. This proposed sampling would enable resolution of the large-scale planetary wave and tidal variations.

The US research community has continued to explore new and innovative instrument designs. Several possible instruments are listed here.

- Doppler Winds and Temperature Sounder (DWTS) is designed to measure temperature and horizontal wind over an extended altitude range of 20-250 km (Gordley and Marshall, 2011; https://gats-inc.com/future_missions) with high accuracy and horizontal resolution. A prototype of DWTS is under construction to begin testing.
- Middle Atmosphere Sounder and Thermal Emission Radiometer (MASTER) would follow in the footsteps of TIMED/SABER and make temperature and trace gas observations in the middle atmosphere and MLT (Mlynczak et al. 2014).
- THz limb sounder (TLS) would make observations of lower thermospheric wind, oxygen density, and temperature (Wu et al. 2016).
- The Atmospheric Coupling and Dynamics Across the Mesopause (ACaDAMe) is designed to measure temperature at high horizontal resolution over the altitude range of 70-150 km (Janches et al. 2019).

The European CAIRT (Changing-atmosphere infrared tomography) satellite has been proposed to ESA but the selection process is ongoing. CAIRT is a limb sounder designed to sample temperature and trace gases from the mid-troposphere to above the mesopause (5-120 km) (Sinnhuber et al., 2022). CAIRT is undergoing feasibility studies as one of four possible contenders for Earth Explorer 11. If selected, the eventual launch is scheduled for 2030.

In this paper, we focus on observations made from satellite. We acknowledge the important contributions made to MLT science from ground-based observing systems, including radar, lidar, and optical sensors. Such measurements are often important contributors to validation of measurements from LEO (e.g. Dawkins et al., 2018). However, recommendations for them are beyond the scope of this paper since, by definition, these instruments lack global sampling.

Based on the motivation and situation described above, we point out several actions that could lessen the severity of the crisis. First is to keep existing instruments operating for as long as possible to delay the beginning of the observation gap. Second is to provide resources to enhance the quality of existing and ongoing observations by improving retrieval algorithms. The third is an urgent necessity for the development and deployment of instrumentation that can be used to determine the basic state temperature and winds of the MLT. Without knowledge of the basic state, investigations of waves, trends, etc. cannot proceed.

Because of the time sensitive nature of the impending gap, instruments that have a shorter development and construction time should receive immediate attention.

4. Recommendations

- Support continued operation of existing satellite instruments for as long as they are taking functional observations. Continue to process ongoing observations in a timely manner and provide them to the global research community.
- Support development of improved methods for extracting geophysical information from existing Level 1 data. Support reprocessing of existing and future data as retrieval algorithms are refined based on new information.
- Fund, develop, and build new instrumentation that can be rapidly deployed.

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