Solar and Space Physics (Heliophysics) Decadal Survey

White Paper Regarding

Wave-induced Mixing and Transport in the Middle Atmosphere-Lower Thermosphere (MLT)

By

Chester S. Gardner (Primary author, cgardner@illinois.edu), University of Illinois at Urbana-Champaign
Scott Bailey (Co-author, baileys@exchange.vt.edu), Virginia Polytechnic Institute and State University
Xinzhao Chu (Co-author, xinzhao.chu@colorado.edu), University of Colorado Boulder
Diego Janches (Co-author, diego.janches@nasa.gov), NASA-Goddard Space Flight Center
Daniel Marsh (Co-author, marsh@ucar.edu), Nation Center for Atmospheric Research
John M. C. Plane (Co-author, J.M.C.Plane@leeds.ac.uk), University of Leeds

I. Overview: The middle atmosphere and lower thermosphere (MLT) circulation is driven primarily by gravity wave forcing, so much so that this region is not in radiative equilibrium. Although the major effects of wave forcing are known, there are still large uncertainties in the MLT circulation because the global distribution of gravity waves and their dynamical and thermal effects during dissipation and breaking, are poorly constrained by observations and only crudely parameterized in global circulation models. Consequently, transport by the MLT circulation, which is important for constituent exchanges between the atmosphere and near space environment, is not well-quantified. Accurate characterization of the mean circulation and wave-driven transport is crucial for understanding and quantifying the system-wise transport of chemical species in planetary atmospheres.

Wave-driven transport of momentum, heat and constituents in the atmosphere is important to a wide range of research problems, including general circulation modeling, atmospheric chemistry modeling and thermal balance calculations. It has been known for decades that vertical transport induced by dissipating and non-dissipating gravity waves can be substantial. However, computational cost constraints mean that it has not been practical to include the important small-scale wave transport effects directly into global models. This is a serious shortcoming as the transport of heat and the O_x, NO_x, HO_x, and CO_x species in the MLT, play very important roles in establishing the thermal and constituent structure in this region, affect the concentration of important lower atmospheric species like stratospheric O_3 (Crutzen 1970; Lary, 1997), and the density of the thermosphere by modulating the O/N_2 ratio (Qian et al., 2009; Pilinski & Crowley, 2015). ***Progress has been inhibited theoretically, by the lack of wave transport parameterization schemes suitable for contemporary global chemistry models, and observationally, by the paucity of direct measurements of the vertical fluxes of momentum, heat and constituents throughout the MLT.***

II. Current State of Knowledge: Walterscheid (1981) demonstrated theoretically that dissipating gravity waves induce a downward heat flux regardless of their propagation direction. Walterscheid & Schubert (1989) used a dynamical-chemical model to show that the combined effects of wave dynamics and perturbed chemistry associated with the passage of a gravity wave can result in large downward fluxes of O_3 and OH near 80 km, which alters the mixing ratios of these species and their eddy and molecular diffusion. Hickey et al. (2000) used a 2-D nonlinear model to demonstrate that gravity waves can significantly alter the time averaged atomic O profile in the MLT through the constituent fluxes that the waves induce. Liu & Gardner (2005) and Gardner & Liu (2007) directly measured the vertical heat and Na flux profiles induced by gravity waves in the MLT. Those measurements showed that the heating/cooling rate due to heat flux convergence could exceed ±50 K/day at mesopause heights and that wave transport of Na was significant and considerably larger than transport by eddy and molecular diffusion.

Waves contribute to vertical constituent and heat transport,

1. ***By generating turbulence when they break which leads to the diffusion of heat and constituents via eddy mixing.*** Existing models include this process by estimating the eddy diffusivity (K_{zz}) generated when the waves become unstable and dissipate their energy as turbulence.
2. ***By perturbing constituent mixing ratios thereby enhancing molecular and eddy diffusion.*** The enhancement is proportional to the variance of the wave-induced lapse rate fluctuations $Var(-\partial T'/\partial z)$ and can be estimated from the wave parameterization

schemes employed by the models. Even so, most models do not include this enhancement.

3. ***By inducing strong vertical mixing of the atmosphere by non-breaking gravity waves, which also produces net heat and constituent fluxes.*** Wave mixing is characterized by the thermal (K_H) and constituent diffusivities (K_{Wave}), which are related to the sensible heat and gravity wave energy fluxes. Measurements and theoretical studies of K_H and K_{Wave} are rare and so this important transport process has not yet been incorporated into existing models.
4. ***By perturbing the chemical reactions involving reactive species, which induces fluctuations in the species concentration that are correlated with the vertical wind fluctuations.*** Chemical transport, which depends on the chemistry of the species, is proportional to the variance of the wave-induced temperature fluctuations Var(T') and can be estimated from the wave parameterization schemes employed by existing models. However, few if any models currently incorporate the effects of the chemical fluxes of key species in the MLT such as the O_x, NO_x, HO_x, and CO_x families.

Unfortunately, direct measurements of momentum, heat and constituent fluxes have been restricted to a few small altitude ranges at a few sites globally, where the current generation of radars, balloon sondes, airglow imagers or Doppler lidars could observe the required atmospheric parameters. Simultaneous measurement of the vertical momentum, heat and constituent fluxes has only been achieved in the mesopause region (85-100 km) with a Doppler Na lidar, and only at a single site (Gardner & Liu, 2007; 2010). This lack of data can be ameliorated by significantly enhancing instrument capabilities and deploying the instruments more widely, including on satellites (see **Observational Requirements)**.

III. Outstanding Issues and the Impacts of Addressing Them

1. ***What are the polarization and dispersion relations for dissipating and amplified gravity waves?*** The impact of gravity waves is characterized by the vertical fluxes induced by the waves; viz. the fluxes of horizontal momentum, sensible heat, wave energy, and constituent densities. These fluxes can be computed using the gravity wave polarization and dispersion relations, which relate the magnitudes and phases of the wave components. Unfortunately, these relations have only been derived in detail for non-dissipating waves (e.g. Vadas, 2013) and for waves experiencing damping associated with molecular viscosity and thermal conduction at thermospheric heights (e.g. Hines, 1960; Pitteway & Hines, 1963). However, the momentum diffusion associated with the larger-scale random motions imparted by turbulence and the full spectrum of gravity waves, also degrades the organized bulk motion imparted to the atmosphere by each individual wave and leads to attenuation of the wave (e.g. Weinstock, 1984). To fully understand and predict the impact of dissipation on the vertical fluxes, it will be necessary to derive the polarization and dispersion relations for dissipating and amplified gravity waves. Doing so, would permit the models to directly compute the wave-induced momentum (K_M), heat (K_H), and constituent (K_{Wave}) diffusivities using data from their wave parameterization schemes, thereby including the significant impact of wave-mixing by non-breaking waves, which is currently missing.
2. ***What are the vertical fluxes of momentum, heat, wave energy, and constituents in the stratosphere and mesosphere below 80 km and in the lower thermosphere above 100***

km, where existing observations are rare or non-existent? Observations by balloon sondes, radars, airglow imagers and lidars have provided important information on gravity waves and the vertical fluxes they induce in the troposphere, lower stratosphere, and the mesopause region. However, existing observations are not comprehensive, while measurements are largely lacking in the upper stratosphere, lower mesosphere and lower thermosphere. Instruments capable of making these observations need to be developed and then deployed in latitude or on satellites to provide adequate geographical coverage (see **Observational Requirements**). These observations are crucial for validating the theory and model development described in Issue #1. Addressing these two issues would enable a much more thorough understanding of the impact of gravity waves on the wind, temperature, and constituent structure of the atmosphere, especially in the MLT.

3. ***How does wave transport of atomic oxygen (O) downward out of the thermosphere into the mesosphere impact the O/N_2 ratio and density of the thermosphere?***
   Wave activity in the MLT at midlatitudes exhibits strong annual (AO) and semiannual oscillations (SAO) with maxima at the solstices and minima at the equinoxes (e.g. Tsuda et al., 1990). Since breaking waves are the source of turbulence, it is not surprising that observations of K_{zz} in the MLT also exhibit strong seasonal variations (e.g. Lübken, 1997). More recently, global circulation models coupled with satellite observations of neutral density and the O/N_2 ratio in the thermosphere, have been used to infer the seasonal variations of K_{zz} near 100 km, which also exhibit significant AO and SAO amplitudes (Qian et al., 2009; Pilinski & Crowley, 2015). The major conclusion from these comparisons is that the strong AO and SAO in wave driven diffusivity near 100 km are generally consistent with observations and modeling of the O/N_2 ratio and neutral density in the thermosphere at 400 km. In other words, mixing by breaking (K_{zz}) and non-breaking gravity waves (K_{Wave}) appears to have a significant influence on the transport of atomic O out of the thermosphere into the mesosphere, thereby having a major impact on thermospheric density to altitudes as high as 400 km. This has significant implications for modeling and predicting atmospheric drag in the low Earth orbit satellite environment and for tracking orbital debris. Atmospheric drag is by far the dominant error associated with orbit propagation (Sutton, 2018). For instance, the day/night differences could be an indication that ion and/or viscous drag forces need tuning (e.g. Hsu et al., 2016). These could also be an indication that further tuning of lower boundary conditions on diffusivity (e.g., Pilinski & Crowley, 2015; Qian et al., 2009) or the inclusion of more realistic modeling of tidal forcing below the mesopause (e.g., Jones et al., 2016) is warranted. A primary obstacle for data assimilation techniques in the thermosphere is the scarcity of timely data, which is addressed in Issue #2. Thus, fully characterizing the wave driven transport of O in the MLT, both theoretically and observationally, would lead to a significant improvement in predictions of thermospheric density and the accuracy of tracking and prediction for low Earth orbiting satellites and orbital debris.
4. ***How does wave transport of atomic oxygen impact chemical heating and thermal structure of the mesopause region?*** Atomic oxygen (O) is produced in the thermosphere above 120 km where photo-dissociation of O_2 is at a maximum. Dynamical processes, including molecular diffusion and wave effects, transport O downward into the upper mesosphere, where it is chemically depleted below 95 km, primarily through a series of exothermic reactions leading to the formation of mesospheric O_3 and the OH airglow

layer (OH*). As such, O transport represents a transfer of chemical potential energy from the thermosphere to the mesosphere, and O is central to the chemistry and radiative balance of the MLT. The O, O_3, OH and HO_2 profiles, as well as the brightness of concomitant airglow emissions, are related to the speed of O transport, with faster transport corresponding to higher densities and brighter airglow (e.g. Smith et al., 2013). However, even though the chemistry of O and O_3 is well understood, global models – including NCAR's Whole Atmosphere Community Climate Model (WACCM) - significantly underestimate the observed mesospheric densities of these species, because the modeled downward transport from the thermosphere appears to be too slow (Smith et al., 2015). For example, it has been shown that at mid-latitudes WACCM underestimates night-time O by a factor of 1.4 - 2, and O_3 by a factor of 2 – 4, at 96 km depending on month, when compared to measurements by the SABER instrument on TIMED (Panka et al., 2018). Fully characterizing the wave driven transport of O in the MLT theoretically and observationally, and incorporating that transport into global chemistry models, would lead to significant improvements in our predictions of the O_x densities in the MLT, the thermal structure of this region and the brightness of the associated airglow emissions.

5. ***How does wave transport of nitric oxide (NO) downward out of the thermosphere into the mesosphere and stratosphere affect stratospheric ozone (O_3)?*** NO densities peak in the thermosphere, where it is produced because of energetic particle precipitation and photo-ionization. It is then transported to the middle atmosphere by vertical mixing and the mean circulation where it can catalyze the destruction of stratospheric ozone (Crutzen, 1970; Lary, 1997) and affect the dynamics of the region. This NO transport mechanism is thought to be a pathway by which variable solar forcing in the thermosphere could affect the lower troposphere. Several modeling studies have shown a deficit in the amount of NO in the upper mesosphere compared with measurements by the SOFIE (Solar Occultation For Ice Experiment) spectrometer on AIM (Aeronomy of Ice in the Mesosphere) satellite, which is likely due to ineffective transport across the mesopause associated with errors in the parameterization of unresolved wave transport processes. Improving the characterization of the vertical wave transport in models will very likely reduce the mesospheric NO deficit and improve the representation of this important solar-terrestrial coupling mechanism.
6. ***What is the magnitude of the global cosmic dust influx and what impact does it have on the Earth's atmosphere and climate?*** The Earth formed 4.5 billion years ago by accretion of debris from the solar nebula. Today the Earth continues to accrete dust and small meteoroids whose global mass influx is estimated to exceed 100 metric tons per day. Much of this mass consists of gaseous species that are ablated from high-speed particles when they are heated to high temperatures caused by friction with the atmosphere. The significant impact of cosmic dust is only now beginning to be fully appreciated (Plane, 2012). Meteor deceleration and ablation between 80 and 120 km altitude deposits significant energy, substantial mass, and contributes to a complex chemistry that leads to laminae of metallic ions and neutrals. The ablated atoms are involved in a variety of ion and neutral chemical processes as the meteoric debris is transported downward by advection, turbulent mixing and other wave effects. Below 85 km the neutral chemistry is responsible for the formation of relatively stable chemical reservoirs that are permanently removed from the mesopause region by forming or condensing on meteoric smoke particles (MSP). Eventually the debris settles onto the

Earth's surface. Current estimates of the daily influx of cosmic dust are highly uncertain. Some of that uncertainty arises because of uncertainties in the wave driven processes that transport the ablated atoms from the lower thermosphere and mesopause region to the chemical sinks below 85 km. Reducing the uncertainty in the cosmic dust influx and clarifying its impact has implications for a wide range of geophysical processes including the study of exoplanets. Acquiring detailed measurements of meteoric species, such as Na, Fe, and MSPs and their vertical transport in the MLT, and fully incorporating wave transport processes in global chemistry models of the MLT, will enable the following questions to be addressed; 1) What is the magnitude of the global cosmic dust input? 2) How do wave-induced transport processes affect the distribution of the cosmic dust ablation products in the atmosphere? 3) What impact does cosmic dust have on the Earth's atmosphere and climate?

IV. Modeling Requirements

- **Wave Transport Parameterizations for Global Chemistry Models**

  Wave dissipation is an important process in the atmosphere, which modifies the amplitudes and phases of the wave fluctuations and has a significant impact on wave transport by altering the momentum, heat and constituent fluxes induced by the waves. Unfortunately, the gravity wave polarization and dispersion relations have only been derived in detail for non-dissipating waves or for waves that are being damped by molecular viscosity and thermal conduction. These latter processes are only important in the thermosphere, while damping associated with mixing by turbulence and waves is important throughout the MLT. To fully understand the wave transport processes and to enable their inclusion in global chemistry models, it will be necessary to derive the polarization and dispersion relations for gravity waves that are being damped by the actions of turbulence and wave-induced mixing. This would enable the development of wave transport parameterizations, for both dissipating and non-dissipating waves, so that the wave-induced momentum (K_M), thermal (K_H) and constituent (K_{Wave}) diffusivities can be computed and incorporated into the global models. Similarly, theoretical expressions for chemical fluxes of key reactive species also need to be developed and incorporated into the models to fully account for their chemical transport.

V. Observational Requirements

- **Large Power-Aperture Product Rayleigh, Na and Fe Doppler Lidars**

  Rayleigh Doppler lidars can make momentum, heat and wave energy flux measurements in the stratosphere and lower mesosphere. Their altitude range is limited by signal level, which can be increased by employing higher power lasers and larger aperture telescopes to increase the power-aperture (PA) product. Current instruments employ Nd:YAG lasers with powers ~5-10 W and telescope diameters of ~1 m so their PA products are less than 10 Wm^2. Instruments should be developed with PAs ~200-500 Wm^2 to extend the flux and meteoric smoke particle (MSP) observations well into the mesosphere. The momentum flux observations require pointing the lidar 5-10° off-zenith in the four cardinal directions, while the heat flux is best measured by pointing the lidar to zenith. Multiple large PA systems utilizing steerable, 3-4 m class telescopes, should be developed and deployed in both the northern and southern hemispheres to characterize the fluxes at high-, mid- and low-latitudes and to validate theory and model predictions.

Na and Fe Doppler lidars can also measure the momentum, heat and wave energy fluxes in the upper mesosphere and lower thermosphere. In addition, they are unique because they can also measure the vertical fluxes of atomic Na and Fe. Of particular importance is extending the flux observations into the thermosphere to at least 120 km by developing large PA systems. Existing instruments employ lasers with power ~1-2 W and telescope diameters ~1 m so the PA~1-2 Wm^2. Instruments should be developed with PAs ~100-250 Wm^2 to enable flux observations into the thermosphere to 120-130 km. This could be achieved with ~10-20 W lasers, similar in design to those employed as Na laser guide stars for astronomy, and 3-4 m class steerable telescopes, which can be shared with the Rayleigh Doppler lidars. Multiple systems should be developed and deployed in both the northern and southern hemispheres to characterize the fluxes at high-, mid- and low-latitudes and to validate theory and model predictions.

- **OASIS Class Facility** To make a major step forward in altitude coverage and precision necessary to study the fundamental dynamical and chemical processes in the Earth's atmosphere, the development of an OASIS-class facility should also be explored (OASIS-Exploring the Interaction of Earth's Atmosphere with Space, An Atmospheric and Geospace Sciences Community Report, submitted the National Science Foundation, January 2014, http://cires1.colorado.edu/science/groups/chu/pubs/documents/OASIS_Report.pdf). By focusing on fundamental atmospheric processes, such a facility would facilitate advancements in observations and theory that would also be applicable to the study of exoplanets, especially those potentially capable of harboring life.
- **Spaceborne Na Doppler Lidar** To provide the widest geographical coverage a spaceborne Na Doppler lidar should be developed and flown to measure the global distribution of the important small scale gravity waves and the vertical heat, wave energy and Na fluxes that they induce. A nadir pointing system, with a PA~5-15 Wm^2, orbiting at about 400 km, or deployed on the International Space Station (ISS), would be capable of characterizing a substantial fraction of the gravity wave spectrum in the MLT with a vertical resolution of less than 1 km and a horizontal resolution ~1-5 km. Such a system would also be able to quantify the important 2nd-order statistics of the wave field including the wave-induced fluctuation variances of temperature, vertical wind, and Na density and the wave-driven vertical fluxes of sensible heat, atomic Na, and wave energy. These 2nd-order statistics could be derived at a vertical resolution ~1 km, horizonal resolution ~5-10° and a temporal resolution ~0.5-1 month. By also including multiple beams, directed off-nadir, it would be possible to measure horizontal winds and the vector momentum flux profile. These observations would provide wide geographic coverage, depending on the orbital inclination, while covering the nominal 80-105 km altitude range and higher when sporadic Na layers or thermospheric Na plumes are present. These measurements compliment ground-based lidar, radar, and imager observations by providing a global view, which collectively would enable a comprehensive test of gravity wave theory and model predictions.
- **Spaceborne Imagers**
  Spaceborne imagers in a polar orbit can provide a global view of gravity wave morphology daily. Understanding the global distribution of waves is crucial for understanding the wave impact on circulation and transport. Numerous observables can

be probed to provide gravity wave images including thermal emission, ozone-attenuated Rayleigh Scattering, Polar Mesospheric Clouds, and layered sources such as the mesospheric OH emission layer. Imaging compliments lidar and radar observations by providing the context and global view; it compliments satellite-based limb observations by providing the 2-dimensional wave structure. Imaging at a single wavelength yields gravity wave information at a single altitude for waves with vertical wavelength on the order of 10-15 km and larger; imaging at multiple wavelengths can provide 3D information. Momentum fluxes can also be obtained if the imaging is paired with wind measurements. Current horizontal resolution for middle atmosphere gravity wave images is on the order of 5 km. To capture the full range of important horizontal scales, imaging resolution on the order of 1-2 km is required. The most important need is imagers with identical or similar horizontal and temporal sampling, but utilizing multiple wavelengths so that both the horizonal and vertical global structure can be simultaneously probed. Global wind measurements in the mesosphere and lower thermosphere are also key.

VI. References

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