Improving ionospheric predictability requires accurate simulation of the mesospheric polar vortex

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Synopsis

The mesospheric polar vortex (MPV) plays a critical role in coupling the atmosphere-ionosphere system, so its accurate simulation is imperative for robust predictions of the thermosphere and ionosphere. While the *stratospheric* polar vortex is widely understood and characterized, the *mesospheric* polar vortex is much less well-known and observed, a short-coming that must be addressed to improve predictability of the ionosphere. The winter MPV facilitates top-down coupling via the communication of high energy particle precipitation effects from the thermosphere down to the stratosphere, though the details of this mechanism are poorly understood. Coupling from the bottom-up involves gravity waves (GWs), planetary waves (PWs), and tidal interactions that are distinctly different and important during weak vs. strong vortex states, and yet remain poorly understood as well. Moreover, generation and modulation of GWs by the large wind shears at the vortex edge contribute to the generation of traveling atmospheric disturbances (TADs) and traveling ionospheric disturbances (TIDs). Unfortunately, representation of the MPV is generally not accurate in state-of-the-art general circulation models (GCMs), even when compared to the limited observational data available. Models substantially underestimate eastward momentum at the top of the MPV, which limits the ability to predict upward effects in the thermosphere. The zonal wind bias responsible for this missing momentum in models has been attributed to deficiencies in the treatment of GWs and to an inaccurate representation of the high-latitude dynamics. Such deficiencies limit the use of these models to study the role of the MPV in the transport of constituents and in wave-mean flow interactions, and to elucidate the mechanisms by which the atmosphere-ionosphere system is interconnected. In the coming decade, simulations of the MPV must be improved. This can be accomplished by constraining the model temperature and wind fields in the mesosphere and lower thermosphere (MLT) with a more extensive suite of satellite and ground-based observations. In addition, improvements to current model GW parameterizations are required to more accurately simulate the processes that govern the generation, propagation, and dissipation of GWs.

1. Background and Motivation

While the stratospheric polar vortex has been extensively studied since the 1950s (e.g., Labitzke & Naujokat, 2000 and references therein), it was only recently documented that the polar vortex also extends well into the mesosphere (Harvey et al., 2015; 2018). Figure 1 shows that the polar vortex as depicted in the 2013 decadal survey only extends up to the stratopause. It is now known that the polar vortex broadens with increasing altitude into the upper mesosphere. High-top models such as the Whole Atmosphere Community Climate Model (WACCM) properly simulate the mesospheric polar vortex (MPV) up to middle mesospheric altitudes, but fail to reproduce observations above ~80 km (Harvey et al., 2019; Hindley et al., 2022) especially when the vortex is strong (Harvey et al., 2022). Descent in the polar winter mesosphere, depicted by the arrow in Figure 1 marked "circulation", is part of a global wave-driven pole-to-pole circulation characterized by ascent over the summer pole, cross-equatorial flow from the summer to the winter hemisphere, and descent in the winter high latitudes. At winter mesopause altitudes the upper-most reaches of the polar vortex can manifest as troughs in traveling planetary waves (PWs) (Harvey et al., 2021). Descent in the longitude sectors of these wave troughs into the top of the MPV can be 5 times stronger than at other longitudes. While much progress has been made in diagnosing and understanding the vortex in the mesosphere, more work is needed to fully characterize both its mean state and variability and how it is coupled to regions both above and below.

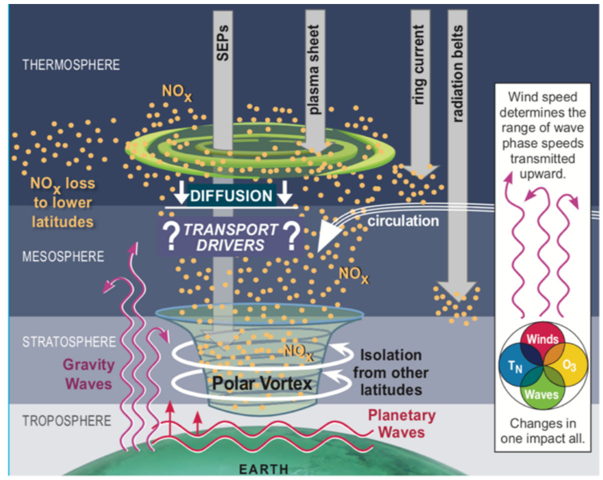

Figure 1. *Adapted from Figure 8.5 of the 2013-2022 Solar and Space Physics decadal survey.*

The MPV often behaves differently than the vortex in the stratosphere; the MPV can be strong when the stratospheric vortex is weak, and vice versa. It is not yet known if MPV strength could be a predictor for variability in the ionosphere and thermosphere (IT) system, but sudden stratospheric warming (SSW)-induced variability in the mesosphere has been associated with dynamical variability at stratopause altitudes (e.g., Tweedy et al., 2013; Stray et al., 2015; Limpasuvan et al., 2016; Zülicke et al., 2018; Harvey et al., 2022) rather than at 10 hPa where SSWs are traditionally defined. This suggests that dynamical proxies defined at the base of the MPV may be a better predictor of IT variability than SSW definitions.

1.1 The Energetic Particle Precipitation "Indirect Effect"

The MPV plays an important role in coupling the atmosphere-ionosphere system from the top-down. As depicted in Figure 1, the MPV acts to couple the atmosphere via the transport of nitrogen oxides (NO_x) produced by energetic particle precipitation (EPP) from the mesosphere and lower thermosphere (MLT) down to the stratosphere where the NO_x can destroy ozone. Understanding why models underestimate this EPP "indirect effect" was identified as a priority in the last decadal survey but has yet to be fully realized (Randall et al., 2015; Pettit et al., 2019;

2021). Underestimates in simulated NO_x are likely due to a combination of erroneous transport (Siskind et al., 2015) and electron source specifications.

Since the last decadal survey, studies have focused on eliminating model underestimates in the descent of NO_x in the MPV. For example, Smith-Johnsen et al. (2022) modified model dynamics by decreasing the amplitude of non-orographic gravity waves (GWs) and decreasing the Prandtl number (a measure of vertical mixing by GW breaking), both of which resulted in better agreement with nitric oxide (NO) observations in the polar winter mesosphere. In the mesosphere, NO_x is primarily comprised of NO. Improved simulation of NO by decreasing the amplitude of non-orographic GWs (so they break higher) was also demonstrated by Meraner et al. (2016). On the other hand, Pettit et al. (2021) showed that including medium energy electron (MEE) sources of ionization in WACCM resulted in better agreement between simulated and observed NO concentrations in the polar winter mesosphere, though midlatitude NO was still underestimated in the model. A study that imposes both improved dynamics and MEE sources is long overdue. Unfortunately, preliminary results suggest that NO_x underestimates persist despite combining the enhanced dynamics of Smith-Johnsen et al. (2022) and the MEE sources of Pettit et al. (2021). Thus, more work is needed to accurately simulate the EPP-IE (see section 3.4).

1.2 Lower atmosphere impacts on the IT system depend on vortex strength

It is well known that the polar vortex modulates GW and PW fluxes and tidal amplitudes and that each of these waves behaves differently during weak vs. strong polar vortex states (e.g., Pedatella & Harvey, 2022). A weakening or reversal of the polar night jet (PNJ) during SSWs leads to anomalous GW propagation and dissipation that, in turn, modifies the global residual circulation and can lead to cooling in the polar winter mesosphere (Labitzke, 1972). Tides are also modulated through nonlinear interactions with PWs during weak polar vortex states (Lieberman et al., 2015). Vortex dynamics also affect the composition, such as water vapor concentrations in the polar mesosphere, which affects ozone (Smith et al., 2018). It is important to note that SSWs induce global changes that extend beyond the MPV winds and composition. It has been demonstrated, for example, that changes in solar and lunar atmospheric tides act to couple SSWs to variability in the ionosphere from the tropics (Pedatella & Liu, 2013; Liu et al., 2014) to mid-high latitudes of the summer hemisphere (Goncharenko et al., 2022). Goncharenko et al. (2010), Chau et al. (2012), and Siddiqui et al. (2015) illustrate coupling between stratospheric PW activity and ionospheric variability during SSWs when the vortex is weak. In the last decade, many other studies have confirmed and expanded upon these provocative results (Goncharenko et al., 2021). While much progress has been made in understanding the far-reaching effects of weak polar vortices on variability throughout the atmosphere-ionosphere system (e.g., Baldwin et al., 2021; Chandran et al., 2014; Pedatella et al., 2018), this is only the tip of the iceberg.

1.3 The polar vortex is a source of GWs that can lead to Traveling Ionospheric Disturbances

The geographic distribution of GWs in the polar winter stratosphere depends strongly on the location, strength, and stability of the PNJ that encircles the polar vortex. These waves are prevalent in the vortex jet region because (1) persistent westerlies from the surface to the mid stratosphere allow tropospheric GWs to propagate vertically without breaking, (2) GW propagation directions are focused toward faster wind speeds (Sato et al., 2009), and (3) GWs are refracted to longer vertical wavelengths, so they can grow to larger amplitudes before breaking (Whiteway et al., 1997). These provide ideal conditions for surface-generated GWs to reach the mesosphere. GWs may also be generated in-situ in the PNJ by local instabilities in the jet exit region (Plougonven and Snyder, 2007) or as secondary GWs (SGWs) generated by breaking primary GWs above the jet core (Becker and Vadas, 2018; Vadas and Becker, 2018). Generation and modulation of GWs by the fast winds at the polar vortex edge has been shown to give rise to daytime medium-scale traveling ionospheric disturbances (MSTIDs). Frissell et al. (2016) showed that MSTID activity depends on vortex strength rather than geomagnetic activity and that higher MSTID activity occurs when the vortex is strong. Since the state of the polar vortex can be forecasted out 2 weeks with some accuracy (Domeisen et al., 2020), the vortex-TID relationship adds predictability to the ionosphere.

2. The Problem

Unfortunately, representation of the polar vortex in the upper mesosphere is generally not accurate in state-of-the-art global models. In fact, in many models the zonal winds blow in the wrong direction in the polar winter upper mesosphere (Eswaraiah et al., 2016; Harvey et al., 2019; 2022; Hindley et al., 2022; Lieberman et al., 2015; Liu, 2016; Marsh et al., 2013; Noble et al., 2022; Rüfenacht et al., 2018; Smith, 2012; Yuan et al., 2008; Griffith et al., 2021; McLandress et al., 2006; McCormack et al., 2017; 2021; Pedatella et al., 2014; Schmidt et al., 2006; Stober et al., 2021) compared to observations (e.g., Wilhelm et al., 2019) or meteorological analyses that use data assimilation (Eckermann et al., 2018, Stober et al., 2020). Important impacts of this easterly (westward) wind bias are (1) a reduction in the vertical extent of the MPV (Harvey et al., 2019), (2) an increase in the vertical wind shear, which alters the spectrum of GWs and PWs (e.g., Chandran et al., 2013; France et al., 2015), (3) persistent negative meridional potential vorticity gradients at mid-to-high latitudes, which can generate PWs via baroclinic or barotropic instability (e.g., Charney and Stern, 1962), and (4) a reduction in the amplitude of the migrating wavenumber 2 semidiurnal tide (SW2) in Arctic winter (Zhang et al., 2021).

It is strongly suspected that the easterly wind bias is due to inaccurate or incomplete treatment of parameterized GWs in community models. This limits the use of such models to study the role of the MPV in constituent transport, wave-mean flow interactions, and vertical coupling mechanisms in the atmosphere-ionosphere system. An interesting aspect of the model easterly wind bias is that it varies as a function of time and is most egregious when the vortex is strong (Harvey et al., 2022). Figure 2 illustrates the relevant zonal wind and GW filtering processes during strong (left) and weak (right) polar vortices. Between 80 and 100 km the modeled and observed zonal winds blow in opposite directions when the vortex is strong, whereas there is reasonable agreement between the model and observations when the vortex is weak (during SSWs). Harvey et al. (2022) provide a detailed discussion of the GW filtering mechanisms, which is summarized in the caption of Figure 2. In the Southern Hemisphere, Hindley et al. (2022) reported a monthly-mean easterly wind bias as large as 60 m/s near 95 km altitude when comparing WACCM to meteor radar wind observations at high southern midlatitudes during winter. Anecdotally, it has also been reported that existing GW schemes in WACCM can either be tuned to simulate accurate polar mesospheric temperatures during winter or summer, but not both, which points to an interesting discrepancy in modeled GW behavior.

One leading hypothesis for the model easterly wind bias in the MLT is that it could be due to an incomplete representation of GW effects, in particular SGWs. Becker and Vadas (2018) showed that there is a significant eastward drag from SGWs in the winter MLT (which cannot be due to primary GWs) that is absent in models, and that the easterly wind bias during strong polar vortex conditions is eliminated when SGW effects are included. Thus, missing eastward forcing from SGWs may account for the easterly wind bias in conventional high-top models. Other factors that may contribute to the easterly wind bias in the model include: the absence of oblique GW propagation (e.g., Sato et al., 2009; Thurairajah et al., 2017; 2020), the need for anisotropic GW source spectra (e.g., Liu & Roble, 2002; Pramitha et al., 2020), the need to impose GW sources at all altitudes (e.g., Ribstein et al., 2022) including the tropospheric jets and the stratospheric polar vortex (e.g., Dörnbrack et al., 2018; Sato and Yoshiki, 2008), and the need to tune GW parameterizations according to simulated tidal variability (e.g., Becker, 2017).

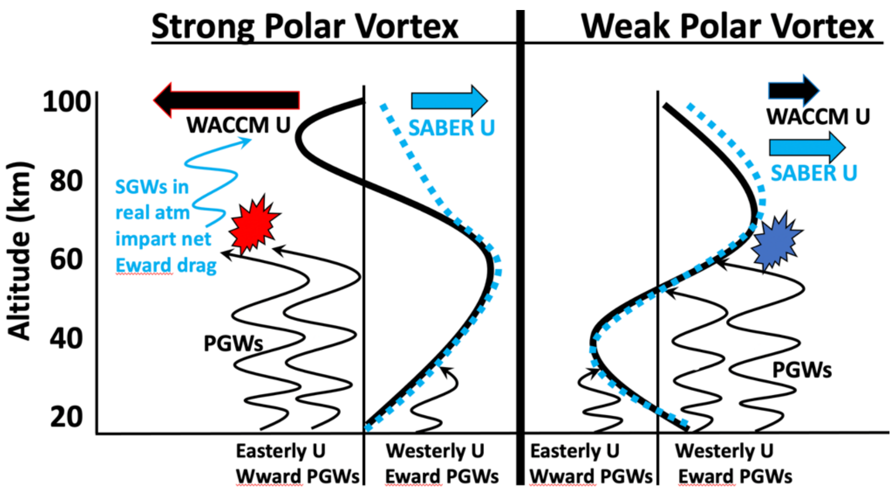

Figure 2. *Schematic illustrating zonal winds and GW processes that modulate the easterly model wind bias in the MLT when the vortex is strong (left) and weak (right). Typical WACCM zonal wind profiles are given in thick black lines. Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) observed zonal wind profiles are given in blue dashed lines. GWs with phase speeds opposite to the zonal wind propagate upward and dissipate. The red (blue) star denotes westward (eastward) GW drag due to the breaking of westward (eastward) primary GWs when the vortex is strong (weak) and zonal winds in the stratosphere are eastward (westward). Secondary GWs in the real atmosphere (blue arrows) impart a net eastward drag in the upper mesosphere but these are not currently included in global models. PGW=Primary Gravity Wave. SGW=Secondary Gravity Wave.*

3. Proposed Solutions

In the coming decade, more extensive wind, temperature, and constituent observations of the MPV are needed as well as scientific studies that utilize both ground-based and space-based observing techniques. In addition to observations of the MPV, spaceborne limb and nadir viewing GW observations (e.g., Kogure et al., 2020) at mid-high latitudes would also be useful to validate simulated GW distributions. Further, new frameworks of GW parameterizations are required to properly simulate the zonal wind in the polar winter upper mesosphere (e.g., Bölöni et al., 2021). Indeed, sufficient observations exist to know the modeled MPV is incorrect, but there are not sufficient observations to determine why the models are incorrect or how to fix them.

3.1 Limitations of current observations

A full observational characterization of the MPV in the MLT and at all longitudes with high temporal resolution (hours) is still elusive. Typical sun-synchronous space-borne observations provide only 1-2 soundings per day at a given location at fixed local times (Livesey et al., 2022). This can determine the mean wind and PW activity, but renders investigations of tidal diurnal and day-to-day variability unfeasible. 24-hour sampling is needed to characterize tidal evolution in tandem with the MPV, and to prevent tidal aliasing of zonal mean temperatures and balanced wind calculations. Ground-based observations provide sufficiently high time cadence to assess short-timescale variability caused by the superposition of migrating and non-migrating tides and GWs, but lack the spatial coverage to provide unambiguous PW wavenumber identification.

3.2 Proposed new observations

We propose new satellite measurements to fully characterize the MPV. Observations that show that the MPV can extend to ~30° latitude in the winter hemisphere, display a PW wavenumber 1 pattern in longitude, and extend to at least 80 km (Harvey et al., 2018). Manifestations of the vortex as troughs in traveling PWs also appear at 90 km (Harvey et al., 2021) and vortex signatures in geopotential height can appear as high as 100 km. Listed in Table 1 are required geophysical quantities, sampling ranges in space and time, horizontal, vertical, and temporal resolutions, and accuracies. Harvey et al. (2015) defined the MPV using horizontal gradients in carbon monoxide (CO) observed by the Microwave Limb Sounder (MLS). However, if the vortex extends above the top of the global residual circulation where descent and horizontal CO gradients weaken, then horizontal winds become necessary to identify the vortex edge. Therefore, both horizontal vector winds and CO are required. We propose satellite observations of these with sufficient spatial and temporal sampling to characterize diurnal and semi-diurnal variations. This temporal coverage will likely require a constellation of 2 or more satellites similar to the DYNAMIC mission concept outlined in the 2013 decadal survey. Diurnal and semi-diurnal variations in the MPV are currently undocumented. A solution for global observations of MLT wind that exceed the requirements in Table 1 is the well-vetted technique called Doppler Wind and Temperature Sounding (Gordley & Marshall, 2011), though this instrument needs to be tested in a space environment. The wind observations are key for: (1) measuring the actual vortex and (2) understanding the interactions between GWs and the large-scale wind. The former requires only winter hemisphere wind measurements and the latter requires global measurements. These new observations will allow for the unambiguous identification of the MPV as a function of longitude, latitude, altitude, and local time and this will, in turn, support a wide range of scientific studies.

Table 1. Satellite Measurement Requirements to Characterize the Mesospheric Polar Vortex

Geophysical Quantity	Possible Observable	Coverage (Range)	Resolution	Accuracy
Limb vector winds	NO emission (5.3 µm)	Horiz: Winter Hem Vert: 60-120 km Time: 24 hours	Horiz: 500 km Vert: 5 km Time: 4 hours	2 m/s
Vortex edge	Carbon Monoxide emission (9117 MHz)	Horiz: Winter Hem Vert: 60-110 km Time: 24 hours	Horiz: 500 km Vert: 5 km Time: 4 hours	10%

3.3 Proposed model improvements

The MPV needs to be accurately simulated. Increased model horizontal and vertical resolution, combined with advanced methods to parameterize sub-grid scales and SGWs, enables the explicit simulation of a new part of the GW spectrum and can eliminate the easterly wind bias (Becker & Vadas, 2018; Liu et al., 2022). However, these models are computationally expensive and GWs remain under-resolved, even at the highest model resolutions. Therefore, it is critical to improve GW parameterizations in the next decade. Improved accuracy in relatively coarse ($\geq 1^\circ$ longitude x 1° latitude) model simulations of the MPV can be accomplished by (1) constraining model wind fields in the mesosphere via nudging techniques and/or improved data assimilation methods, and (2) enhancing model physics related to processes that govern the generation, propagation, and dissipation of GWs. In addition to improved representation of the MPV, improved GW parameterizations would lead to better representation of the mean circulation, chemistry, and large-scale wave dynamics throughout the middle-upper atmosphere. Below is a non-exhaustive list of proposed improvements to current GW parameterizations.

1. Allow oblique GW propagation.
2. Test the impact of anisotropic GW source spectra on polar winter mesopause winds.
3. Include tropospheric jet exit regions and the polar vortex as GW sources.
4. Develop a new framework for GW parameterization to better simulate the generation, propagation, and dissipation of secondary (and higher order) GWs.
5. Improve the simulation of GW-tidal interactions.

3.4 Proposed scientific investigations

While there has been progress in characterizing the mean state of the MPV, more needs to be done to understand its hourly, daily, seasonal, and interannual variability. Model underestimates in the downward transport of EPP-NO_x need to be understood and corrected. For example, we need to understand the role of the MPV in the containment of nitric oxide, how efficient it is, and over what altitude range. A full characterization of local and remote effects during weak and strong vortex events needs to be undertaken. Measurements and models need to be used in conjunction to fully appreciate the mechanisms governing the GW-TID relationship and its dependence on polar vortex strength. A non-exhaustive list of recommended science studies is given below.

1. Evaluate the sensitivity of the easterly wind bias to model horizontal resolution, vertical resolution, and physics-based sub-grid-scale parameterizations. Compare high-resolution GW-resolving models to models with parameterized GWs to understand how polar winter mesopause zonal winds are related to GW effects. Test the hypothesis that eastward momentum deposition from SGWs is necessary to bring models closer to observations.
2. Use simulations from high-resolution global models to identify discrepancies between resolved and parameterized GWs and their impacts on the vortex.
3. Compare observed to modelled GW momentum flux. Because observations can only observe a limited part of the GW spectrum, it is essential to sample model outputs as the observations to make like-for-like comparisons.
4. Combine new satellite observations of the MPV with observations made by ground-based array systems such as SuperDARN meteor radars to understand how the small and large scales evolve together and separately.

5. Identify the MPV as a function of longitude, latitude, altitude, and local time. When and how often does the MPV extend into the lower thermosphere? How predictable is it?
6. Determine the extent to which MPV strength is a predictor for variability in the IT system. Use long-term ionospheric records to quantify daily/weekly ionospheric predictability.
7. In current GW schemes, rapid vertical wave mixing in the MLT is likely underestimated by over an order of magnitude (Liu, 2021). Include this rapid vertical mixing due to higher order GWs into chemistry climate models (e.g., WACCM) and quantify the extent to which the EPP-NO_x underestimate is alleviated.
8. Determine how the polar vortex contributes as a source of primary GWs during strong vortex states. For example, Sato & Yoshiki (2008), Liu (2017), and Becker et al. (2022) observed/simulated in-situ generation of GWs by a disturbed polar vortex.
9. Quantify diffusive vs. non-local advective transport of EPP-NO_x in the polar winter upper mesosphere. Resolve the controversy whereby Smith et al. (2011) showed eddy diffusion to be dominant whereas Meraner & Schmidt (2016) concluded that transport by molecular diffusion and vertical advection dominated.

3.5 Anticipated outcomes

How will the advances outlined above prepare the aeronomy community for future decades?

1. MLT wind measurements at 6+ local times per day will provide sufficient temporal resolution to characterize day-to-day tidal winds within which the MPV is embedded. These measurements will also provide a much-needed constraint on models in the MLT.
2. Model improvements to the representation of the MPV will have far-reaching impacts. They will enable a wide variety of scientific studies involving GWs, PWs, and tides, atmosphere-ionosphere vertical coupling and teleconnections, and constituent transport.
3. Characterization of the MPV will elucidate vertical transport of trace gases from the MLT to the stratosphere and mesosphere, will be useful for studies of wave-mean flow interaction, and will provide a meteorological context for GWs generated and modulated by wind shears at the vortex edge that lead to TID activity.

4. Summary and Recommendations

Given the need to both observe and accurately simulate the MPV, and the current inability to do so, we summarize the following plan for moving forward:

1. Solicit mission proposals to measure temperature, winds, and trace gases in the MLT. NASA critically needs a follow-on to MLS and SABER to observe MLT dynamics and chemistry, especially at high latitudes beyond the scope of ICON. Such a mission should consist of a constellation of satellites that provide sufficient sampling to quantify daily variations in the semi-diurnal tide.
2. Encourage international participation in the deployment of more ground-based observing platforms (radars, lidars, radiometers, imagers, etc.) to complement satellite-based observations and provide high temporal and spatial resolution measurements of the MLT.
3. Solicit studies that explicitly simulate more of the GW spectrum, or more realistic GW generation, propagation, dissipation and higher order GW generation processes in general circulation models. Focus on times when the MPV is strong and quantify local and remote impacts. Evaluate model results by comparing to available observations.

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