Gravity wave induced instability of the stratospheric polar vortex edge

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ABSTRACT: We report on a previously undocumented process capable of mixing Northern Hemisphere (NH) winter Ertel potential vorticity (EPV)—instabilities introduced along the stratospheric polar vortex edge by breaking gravity waves (GWs). As horizontal resolution has increased, global scale atmospheric models and data assimilation systems (DAS) are now able to capture some aspects of GW generation, propagation, and dissipation, as well as mesoscale EPV disturbances. This work examines resolved GWs, their breaking, and their interaction with the stratospheric polar vortex as seen in the NASA Global Modeling and Assimilation Office DAS during the 2021–2022 NH winter. This analysis shows that tropospheric generated GWs, breaking in the stratosphere over a substantial area, created a significant disruption of the polar vortex EPV, in turn triggering baroclinic instabilities near the edge of the polar vortex. The instabilities take the form of mesoscale vortices propagating on the edge of the stratospheric polar vortex. This work reveals two new features in the EPV analysis: high and low fluctuations at the smallest model scale created by resolved GW breaking, and high values associated with mesoscale vortices along the edge of the polar vortex.

SIGNIFICANCE STATEMENT: The northern hemisphere (NH) winter stratospheric polar vortex is typically disturbed by global scale waves that displace, distort, and weaken the vortex, however, as the resolution of global models has increased, the role played by smaller scale waves in disturbing the stratospheric vortex can now be evaluated. As one example, the NH winter of 2022 had unusually weak global scale waves along with strong smaller scale waves generated by flow over mountains, providing an ~~idea~~ ideal case for evaluating the effects brought about by the smaller scale waves. Our examination of the 2022 NH winter reveals that the waves generated by flow over mountains, located under the stratospheric vortex, propagated up to the middle stratosphere where they broke down, interfering significantly with the vortex flow. This distortion of the vortex flow created an unstable region that led to the formation of "mesoscale vortices", relatively small eddies on the edge of the polar vortex, that then propagated coherently around the stratospheric vortex. The importance of these, small scale wave generated, mesoscale vortices may lie in their potential to mix trace gases across the stratospheric vortex boundary.

1. Introduction

Past studies of the stratosphere have emphasized the importance of Ertel's potential vorticity (EPV) as a well conserved dynamical tracer (Hoskins et al. 1985). These early studies often dealt with limited horizontal resolution making the identification of important global EPV features remarkable at the time. For Example, McIntyre and Palmer (1983) characterized the EPV fields used in their discovery of breaking planetary waves as ". . . resembling a blurred view of reality seen through a pane of knobbly glass . . . ". This "knobbly glass" has been smoothed considerably over the following decades based on data assimilation techniques in conjunction with high horizontal resolution global models. Indeed, recent data assimilation reanalysis of the McIntyre and Palmer (1983) breaking wave examples provides dynamically consistent confirmations of their breaking planetary wave discovery (Butchart 2022).

While the planetary scale waves are well resolved in modern EPV fields, the question arises as to the possibility of increased model resolution leading to new discoveries. That is, can "magnification" of current EPV fields provide further insights into stratosphere and mesosphere dynamics. Here we investigate two new features resulting from increased horizontal resolution:

signatures of breaking gravity waves (GW) followed by the formation of mesoscale vortices on the polar vortex edge.

The Northern Hemisphere (NH) stratospheric polar vortex forms every winter, however, considerable vortex variability exists, especially in years with stratospheric sudden warmings (SSWs). During SSW events, high ~~Ertel potential vorticity (EPV)~~ EPV in the stratospheric polar vortex is mixed down to lower latitudes by global-scale planetary waves. The planetary waves are said to be "breaking" when they create regions where the latitudinal EPV gradient is reversed and these reversed gradient regions can lead to instabilities in the wave breaking region (see Butchart 2022, and references therein).

Here we report on another process capable of mixing NH winter EPV—instabilities introduced along the polar vortex edge by breaking gravity waves (GW). GWs are generated by flow over orography, convection, fronts, or flow instabilites (Alexander 2010). Their successful vertical propagation depends on the background atmospheric flow. Under the right conditions GWs can transfer significant momentum and energy from the troposphere to the middle atmosphere. As vertically propagating GWs encounter lower densities or approach a critical layer, they increase in amplitude until they become unstable and ~~”break”~~“break”, depositing momentum and energy to the background flow and hence providing the possibility of disrupting the winter stratospheric polar vortex. Parameterizations of this GW momentum drag attempt to capture these effects, playing a major role in the upper stratosphere momentum budget and a significant role in some SSW events (Albers and Birner 2014; Achatz et al. 2024).

As noted above, global scale atmospheric models and data assimilation systems (DAS) routinely resolve the main features of the stratospheric polar vortex along with planetary wave variability and breaking. As the horizontal resolution has increased over time these models are now able to capture convective systems and some aspects of GW generation, propagation, and dissipation ~~(Holt et al. 2017; Stevens et al. 2019; Shibuya and Sato 2019; Okui et al. 2023)~~ (Watanabe and Miyahara 2009; Holt et al. 2017; Stevens et al. 2019; Shibuya and Sato 2019; Okui et al. 202 . Here we report on resolved GWs, their breaking, and their interaction with the stratospheric polar vortex as seen in the NASA Global Modeling and Assimilation Office (GMAO) near real time forward processing (FP) system during the 2021–2022 NH winter.

Our plan is to examine a somewhat atypical NH winter (2021–2022), where planetary wave activity was relatively weak and the stratospheric polar vortex strong, allowing GWs to dominate the polar vortex disturbances. The working hypothesis is that orographically generated GWs, breaking in the mid-to upper stratosphere, distorted the edge of the polar vortex, creating regions of unstable EPV gradients. These in turn generated a series of what will be called here mesoscale vortices, incorporating signatures of latitudinal mixing, on the edge of the polar vortex.

The process of longitudinally localized GWs acting to generate larger-scale, planetary waves has been observed and modeled in the mesosphere (Smith 1996; Siskind et al. 2010; Matthias and Ern 2018; Sato et al. 2018). These studies demonstrate the ability of GWs to make significant changes at larger scales. Here we extend these studies to examine the role of GWs in the creation of mesoscale vortices near the edge of the stratospheric polar vortex using a high horizontal resolution data assimilation system.

As will be shown below, the mesoscale vortices generated by the breaking ~~gravity waves~~ GWs developed centers with extremely high EPV. While EPV is often well conserved in the stratosphere (Haynes and McIntyre 1990), diabatic and frictional forces can change the EPV of an air parcel (Haynes and McIntyre 1987) and such non-conservation processes must be occurring here. The development and propagation of the high EPV mesoscale vortices will be documented below, however, a detailed EPV budget is left for future studies.

In the following, Section 2 provides a description of the DA systems and models used. The main DAS is the NASA GEOS (Global Earth Observing System) FP system, however some lower horizontal resolution MERRA-2 (Modern-Era Retrospective analysis for Research and Applications) output is included for comparison. To investigate the potential for baroclinic instability near the polar vortex edge, results are presented from a linear quasi-geostropic beta plane model, also described in Section 2. The results are presented in Section 3, with subsections on the 2021-2022 NH winter, the resolved GWs, the structure of the mesoscale vortices, dependence on resolution, and the linear instability model. A summary of the results along with conclusions are presented in Section 4.

2. Global Assimilation Products and Data

a. GEOS FP System

The NASA GMAO GEOS FP DAS routinely produces global, near-real-time, meteorological analysis fields and forecasts available at three hourly intervals. This system updates frequently (approximately every six months) to better incorporate new data types and the latest model developments. The DAS utilizes a full suite of observation types including aerosol, temperature, pressure, radiances, winds, moisture, radio occultation, and ozone measurements. Each six hourly analysis assimilates roughly two million observations. Zhu et al. (2022) provides a current description of the GEOS DAS.

The system used during the NH winter of 2021–2022 was run at ~12 km horizontal resolution on a cubed sphere grid (Putman and Lin 2007) with meteorological fields saved on a 5/16 by 1/4 degree longitude by latitude horizontal grid and on either the full 72 model levels (model top at 0.01 hPa) or vertically interpolated to 42 pressure levels. A description of the model physics can be found in Arnold et al. (2020). The most recent two weeks of forecasts are available on the NASA Center for Climate Simulation (NCCS) data portal. The specific archived analysis fields used in the study are available as described in the Open Research Section.

Taking the horizontal grid resolution for GEOS FP as ~12.5–14 km and the system's effective resolution as ~ 7× the grid resolution, yields ~87.5–98 km as the effective system resolution. The width of the Scandinavian ridge is about 300 km while the gravity waves resolved waves examined below have a horizontal scale of ~300–500 km , both well within the effective resolution of GEOS FP.

To investigate the dependence on horizontal resolution, EPV fields are shown from a test DAS (x0048) run at half the GEOS FP system resolution (24 km). While the GEOS FP (~1/8 degree) and the test system (~1/4 degree) are run with different horizontal resolutions, the results are saved on the same output grid. Note that the MERRA-2 system (~1/2 degree), described below, is also included in the resolution comparisons.

b. MERRA-2

The MERRA-2 system provides ongoing global atmospheric reanalyses starting in 1980. Unlike the FP system, the MERRA-2 system is frozen, with only the input data changing with time. The

MERRA-2 vertical levels are the same as in FP, however MERRA-2, with fields saved at 5/8 by 1/2 degree longitude by latitude, has more coarse horizontal resolution than FP. An overview of MERRA-2 is given by Gelaro et al. (2017). Here we used the monthly averaged pressure level fields (GMAO 2015b) when comparing the NH winter 2022 climate with other winters and the instantaneous model level EPV fields (GMAO 2015a) when comparing specific time EPV fields between FP and MERRA-2.

c. Linear Instability Model

The potential for baroclinic instability near the disturbed vortex edge is investigated using a quasi-geostropic, beta-plane, linear instability model. This is the same model used and described in McCormack et al. (2014) and is based on the adiabatic and frictionless, linearized potential vorticity equation (see Andrews et al. 1987, equation 3.4.5 and following equations):

$$q'_t + \overline{u} q'_x + v' \overline{q}_y = 0. \quad (1)$$

where q is quasi-geostrophic potential vorticity, u and v are the longitudinal and meridional velocity components, and x, y, t, are the longitudinal and meridional directions and time. The overbars denote a zonal average and the primes the deviation from a zonal average. Since q' and v' depend linearly on the geostropic stream function, ψ, assuming a wave solution for ψ with phase speed c and zonal wavenumber k allows the x and t derivatives to be evaluated. With $\overline{u}$ and $\overline{q}_y$ then specified as the environment to be tested for instability, and suitable boundary conditions, Eq. 1 can be finite differenced for a chosen value of k as:

$$\mathbf{A}\psi = c\mathbf{B}\psi \quad (2)$$

where the matrix, $\mathbf{A}$, depends on $\overline{u}$ and $\overline{q}_y$, the matrix, $\mathbf{B}$, depends on the Laplacian operator, and ψ is the vector of stream function values at each point in the two dimensional, latitude and altitude, domain being investigated.

Eq. 2, can be solved for ψ and c, using standard routines. For simplicity we assume that the instability is located far enough from the latitude and altitude domain boundaries that we can take ψ

equal to zero on all boundaries. Examination of the imaginary part of c allows for the identification of the fastest growing mode structure, ψ, for each value of k specified.

d. AIRS data

For confirmation of the DAS resolved GWs we examined the GW signature found in the AIRS (Atmospheric Infrared Sounder on the NASA Aqua satellite) 4.3 μm brightness temperature signal. Horizontal resolution is 13.5 km at the nadir point below the satellite, similar to the resolution of the FP system, and resolution decreases toward the measurement swath edges so that the average resolution is ~20 km. The data are low-noise multi-channel averages with weighting functions that peak between 30–40 km altitude (Hoffmann et al. 2014). Brightness temperature wave anomalies are attenuated relative to sensible temperature anomalies, with attenuation that is inversely proportional to vertical wavelength. These channels are most sensitive to the longer vertical wavelength (≥15 km) GWs and are not expected to highlight wave breaking regions where the vertical wavelength decreases. Note also that selected AIRS channels are assimilated in the DAS so that the AIRS observations shown here are not entirely independent of the data assimilation output, nevertheless, the AIRS observations shown here can be regarded as an independent analysis of the GWs in the FP system forecasts.

3. Results

a. The 2021–2022 Northern Hemisphere Winter Stratosphere

The zonal mean of the zonal wind component at 10 hPa, 60°N provides a useful measure of polar vortex strength that can be used to characterize the NH winter stratosphere. Winters with high seasonally averaged DJF (December, January, February) winds either lack SSWs or have them occurring late in the winter season. The 2021-2022 NH winter had the largest mean seasonal wind seen in the 1980-2023 MERRA-2 time period, with a mean seasonal wind of 46.3 ms^{-1}, more than 1.5 standard deviations above the average value of 30.3 ms^{-1}.

As with the winds, the planetary-scale wave forcing from the troposphere can be considered over the DJF season and variability is expected depending on interannual tropospheric variability. Here we consider the zonally averaged meridional heat flux at 100 hPa and 60°N as a measure of the wave forcing of the stratosphere. The NH 2021–2022 winter season had the lowest meridional heat flux seen in the 1980-2023 MERRA-2 time period, with a mean seasonal heat flux of 17.2 Kms^{-1}, more than 2 standard deviations below the average value of 24.3 Kms^{-1}. The record low 2021–2022 planetary-scale wave forcing at 100 hPa and 60°N is consistent with the strong stratospheric winds.

The strong winds and low wave forcing conjure up a picture of an undisturbed zonally symmetric polar vortex. Nevertheless, the January 2022 stratospheric polar vortex transformed from a zonally symmetric high Ertel potential vorticity (EPV) configuration (Fig. 1a) on 11 January to a much more disturbed vortex (Fig. 1d) on 27 January. While there is an overall elongation of the 27 January high EPV region, the most striking features are the ragged edge of the vortex (the high EPV region) and the existence of four very high, localized EPV mesoscale vortices along the polar vortex edge. On 11 January the maximum 850K EPV was ~2,000 PVU while by 27 January the maximum had more than doubled to 4,780 PVU with the highest values associated with the strong EPV mesoscale vortex at 45°W.

b. Resolved gravity waves

Between 11 and 27 January 2022 small regions of extremely high and low EPV values occurred along the vortex edge, especially over Northern Europe with a maximum value of over 13,000 PVU on 14 January (Fig. 1b). The polar vortex edge distorted in response to these perturbations, creating separation of the high EPV from the main vortex on 14 January from 0°–135°E. By 17 January, the vortex edge became even more distorted as the high and low EPV perturbations continued occurring over Northern Europe (Fig. 1c).

Looking more closely at the 850K EPV on 14 and 17 January (Fig. 2), alternating regions of high and low EPV are seen near the polar vortex edge. The EPV values at these times are as much as 8,000 PVU below and 12,500 PVU above the polar vortex edge value. On the 14th (Fig. 2a) a high EPV feature is seen equatorward and then east of the disturbance region corresponding to the EPV filament identified in Fig. 1b.

That these small-scale EPV disturbances are related to resolved GWs can be seen in the undulations in the height of the 850K potential temperature surface (Fig. 3). The GWs in the height field do not disturb the entire EPV field, as non-dissipating GWs should not be visible in the EPV field, however, the EPV field is disturbed in the more northern part of the GW field where the GWs are likely breaking in a non-EPV conserving manner. Note that the EPV varies on a smaller scale

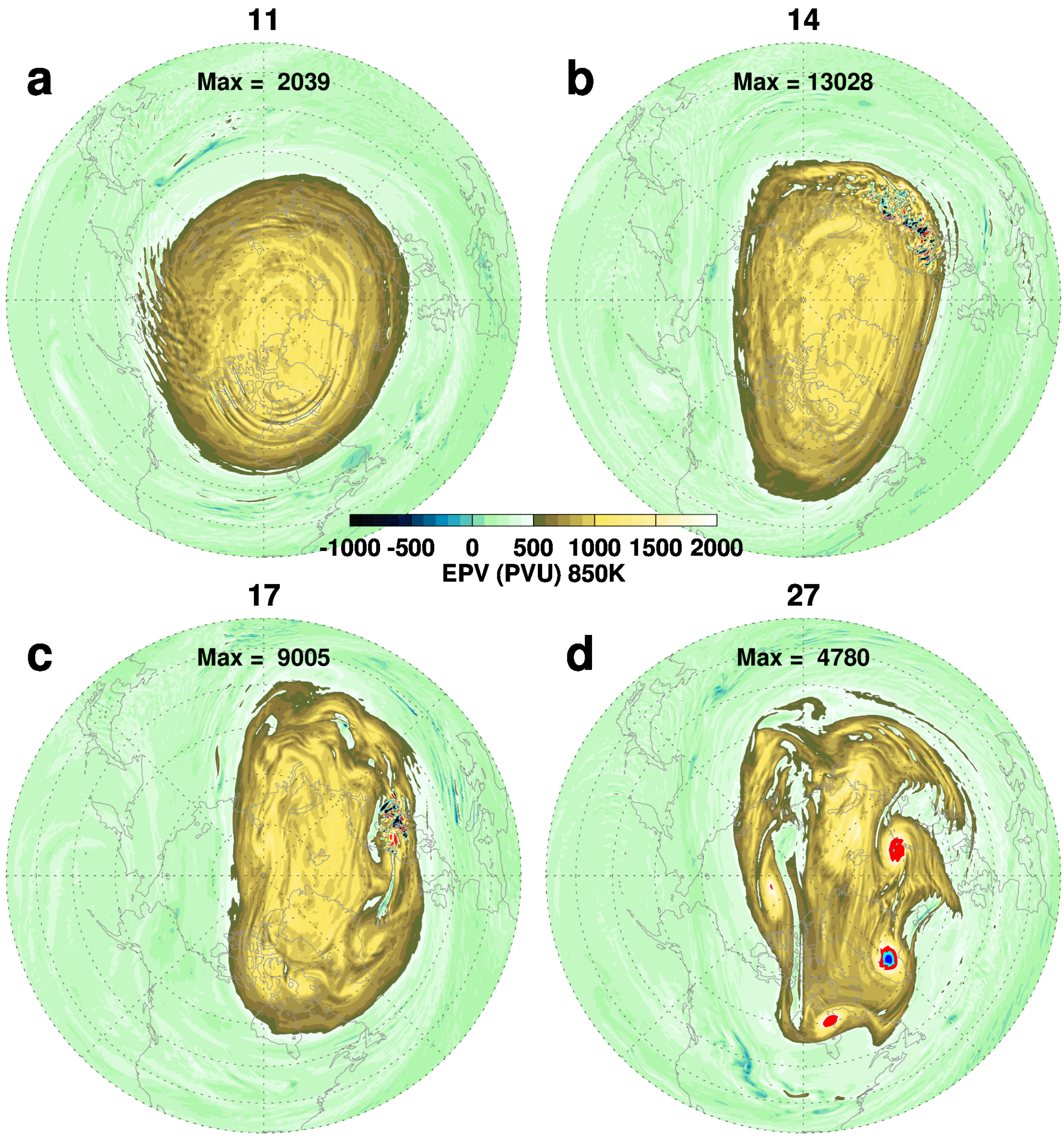

FIG. 1. EPV on the 850K potential temperature surface for a) 11, b) 14, c) 17 and d) 27 January 2022 in potential vorticity units (PVU) where one PVU is equal to $10^{-6} m^2 s^{-1} K kg^{-1}$. The high EPV values are: red: 2000–3000 PVU, cyan: 3000–4000 PVU, blue: 4000–5000 PVU, and yellow: above 5000 PVU.The vortex edge on 11 January 2022 is located at 500 PVU based on the method of Nash et al. (1996).

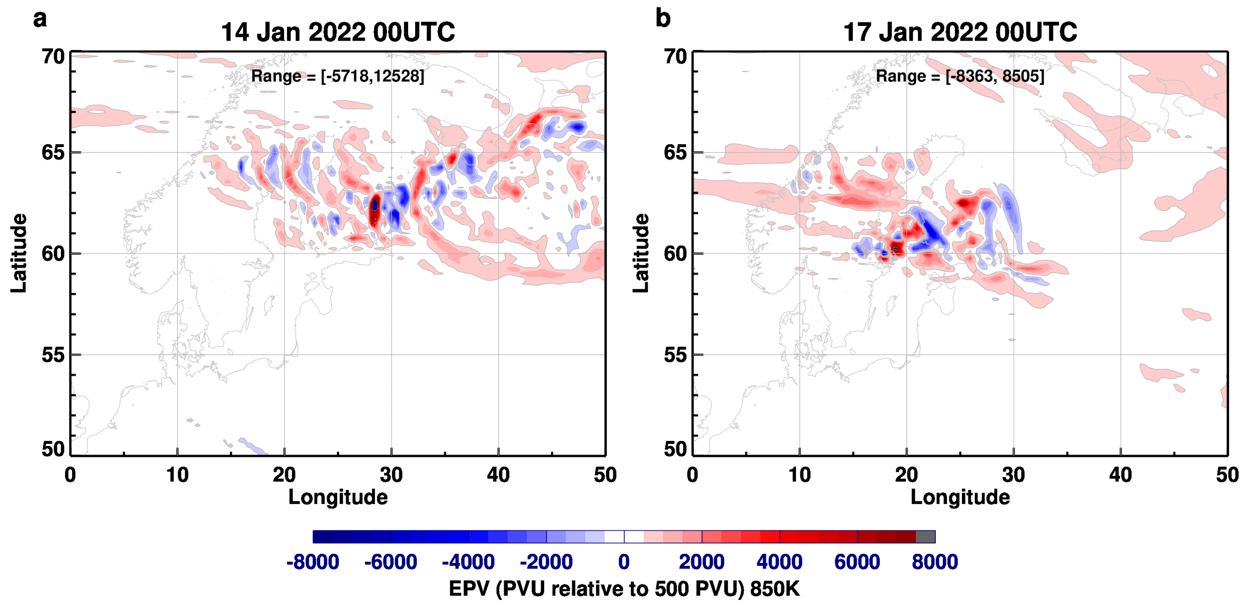

FIG. 2. Latitude (50-70°N) longitude (0°–50°E) projection of EPV on the 850K potential temperature surface for a) 14 January 2022 and b) 17 January 2022. The EPV contours are relative to 500 PVU, the value defining the vortex edge on 11 January 2022.

than the scale of the GWs seen in the potential temperature surface oscillations and furthermore that the orientation of the EPV oscillations differs from the orientation of the GWs. This relation between the GW signature and the scale and orientation of the small-scale EPV field is consistent with ~~detailed~~ 3D shear instability model studies of GW breaking and with GW observations (Fritts and Alexander 2003, and references therein).

These model resolved GWs can also be seen directly in the AIRS observations (Fig. 4). These wave patterns highlight regions over southern Scandinavia where the strong GWs have the largest vertical wavelengths. Note that these brightness temperatures correspond well with the regions of potential temperature height surface variations shown in Fig. 3. In the regions where EPV fluctuations are large the AIRS GW signal is weak. This is more evidence that the EPV fluctuations characterize regions where GWs are breaking and hence have small vertical wavelengths there.

The vertical cross sections of potential temperature and zonal wind on 14 and 17 January (Fig. 5) highlight the stratospheric breaking wave region, topped by the strong easterly vertical wind shear and reversal of the zonal wind direction near the stratopause that inhibits the vertical propagation of orographic GWs. Thus the GWs are required to break in the stratosphere at this time. On both

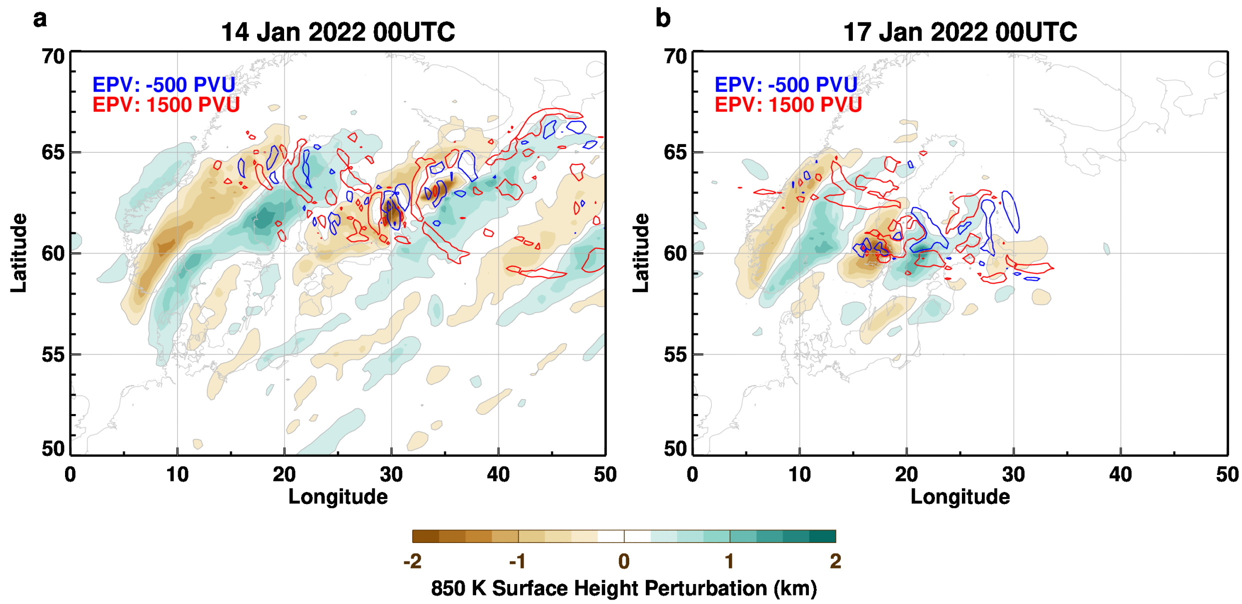

FIG. 3. Latitude (50-70°N) longitude (0°W–50°E) projection of the height of the 850K potential temperature surface (filled contours) and the -500 (blue) and 1500 (red) PVU contours on a) 14 January 2022 and b) 17 January 2022.

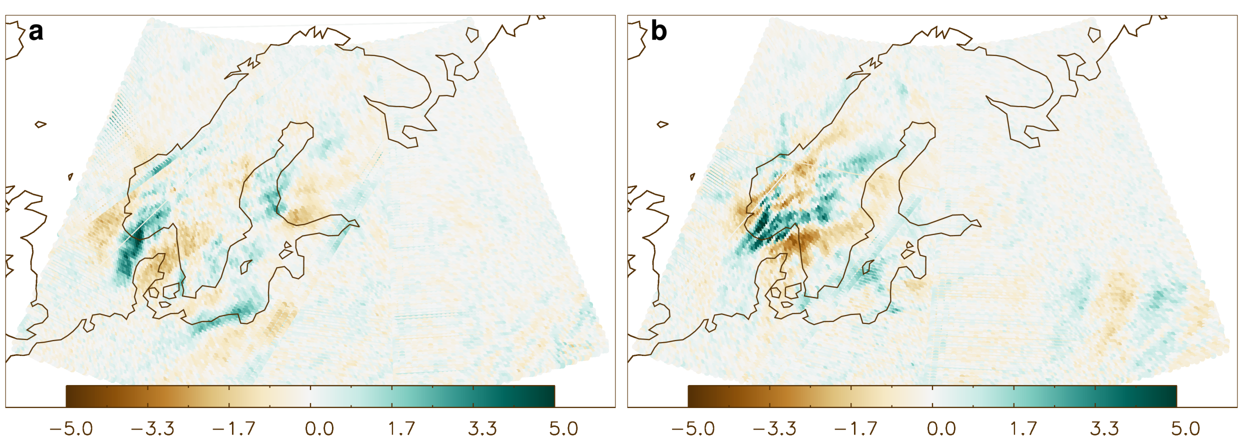

FIG. 4. AIRS 4.3 μm brightness temperature anomalies on descending (nighttime) overpasses on a) 14 January and b) 17 January showing large amplitude mountain waves over southern Scandinavia. The UT times listed are the overpass times that cover the mountain waves. These are low-noise multi-channel averages described in Hoffmann et al. (2014) with weighting functions that peak between 30–40 km altitude.

the 14th and the 17th the strong stratospheric westerlies at 10°W are reduced after crossing the GW region and are much weaker ~~by~~ at 50°E ~~, an indication that the wave breaking may be reducing~~

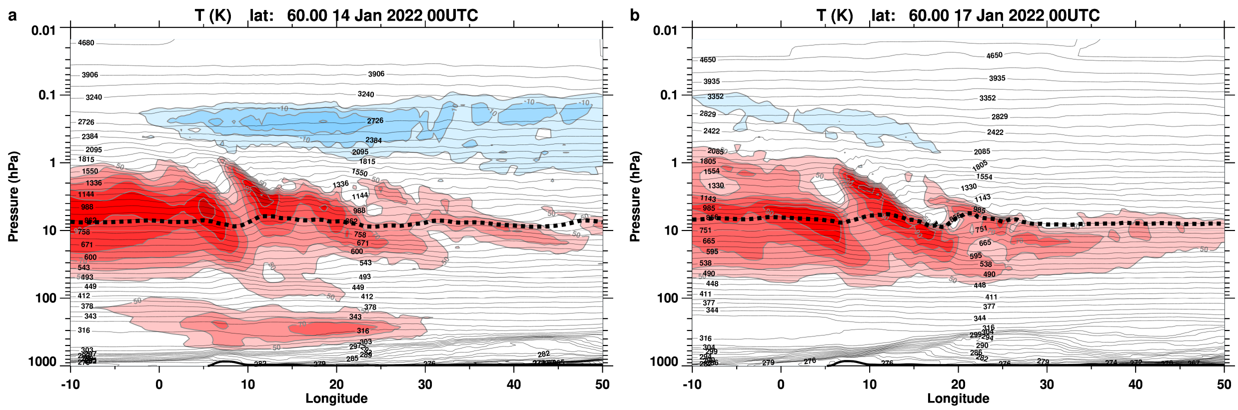

Fig. 5. Longitude (10°W–50°E) altitude (1000–0.01 hPa) cross section at 60°N of potential temperature (gray contours) and zonal wind (filled contours). The dotted black curve denotes the 850K potential temperature surface. The contour interval for the zonal field is 10 ms^{-1} and only winds great than 50 ms^{-1} (red shades) and less than 0 ms^{-1} (blue shades) are shown.

~~the zonal wind~~ than at 10°W, qualitatively consistent with an expected reduction of the zonal wind created by breaking GWs in the upper stratosphere. Nearly vertical potential temperature surfaces are also found on both the 14th and 17th (Fig. 5) indicating breaking gravity waves at 60°N and likely at nearby latitudes as well, including the 60–65°N regions of small scale EPV features seen in Fig. 3.

These relatively large amplitude GWs in the stratosphere were generated by strong tropospheric northwesterly winds over Scandinavia (Fig. 6). The synoptic weather situation at this time was ideal for GW generation with a large, upper-air, high pressure system just west of the European orography. The westerly wind component in both the troposphere and stratosphere allowed wave propagation into the upper stratosphere.

While the 60°N zonal wind during 2021–22 was relatively strong, it did weaken during January 2022, especially over the breaking gravity wave region (Fig. 7a). This weakening of the zonal wind after 11 January corresponds to the time of the peak vertical momentum flux over Europe (Fig. 7b). These strong vertical momentum fluxes are characteristic of GWs. Note that this momentum flux is greatest in the upper stratosphere and weakens above 1 hPa in the mesosphere, consistent with the GW wave structure shown in Fig. 5. While the zonal wind changes and peak momentum fluxes line up closely, the largests GW flux peak occurs about two days after the winds begin to decrease

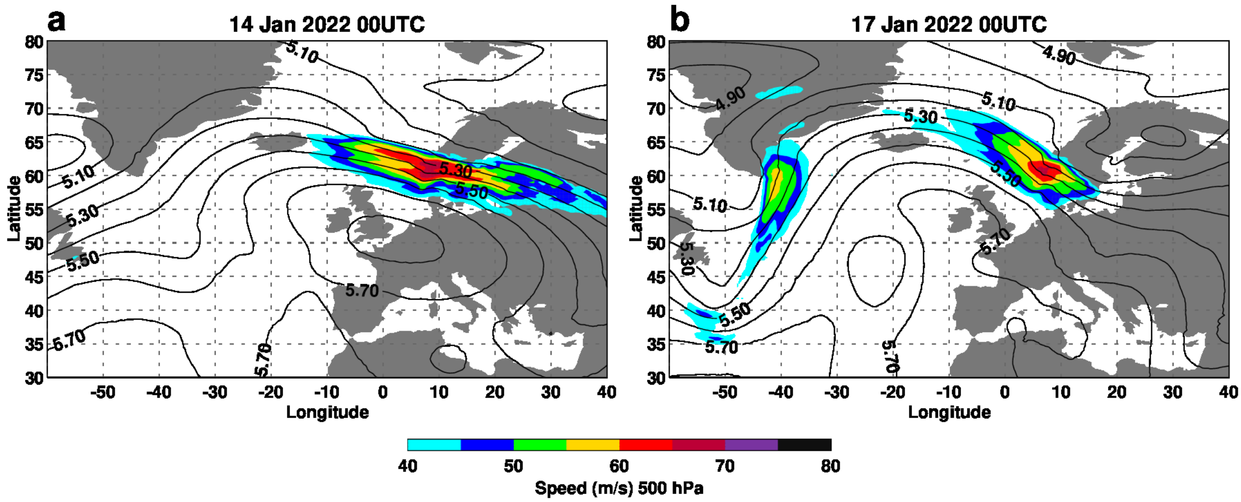

FIG. 6. Wind speed and geopotential heights at 500 hPa for a) 14 January 2022 and b) 17 January 2022.

indicating that other factors in the zonal momentum budget, including planetary wave actively would be needed for a complete momentum budget.

The small scale GWs and mesoscale vortices as seen in Fig. 1d can be identified by the occurrence of high values of enstrophy, the square of the vorticity (Fig. 8a). There is a January 2022 burst of enstrophy coincident with the strong vertical momentum flux and these upper stratospheric strong enstrophy values continue to the end of January created by both continued GW activity and the development of the mesoscale vortices. The ~1/2 degree horizontal resolution MERRA-2 system lacks the higher (~1/8 degree) horizontal resolution of the ~~NRT~~ GEOS FP system, hence the small scale features seen in the ~~NRT~~ GEOS FP system's enstropy (Fig. 8a) are not seen in MERRA-2 (Fig. 8b). MERRA-2 captures some of the mesoscale vortices as seen by the slightly high than average enstrophy values during the last third of January at 10 hPa, however, it misses the very strong enstrophy values characteristic of GW breaking near mid-January.

Note that the identification of breaking GW regions with small-scale, large positive and negative EPV fluctuations, does not imply that these are being realistically modeled as the scale of the fluctuations is near the limit of the model resolution. Rather they are taken here as a signature of GW breaking. Much higher vertical and horizontal resolution simulations are needed to accurately model the GW breaking process and its effect on EPV. Note that, while both MERRA-2 and GEOS-FP incorporate orographic GW parameterization (McFarlane 1987), these parameterized

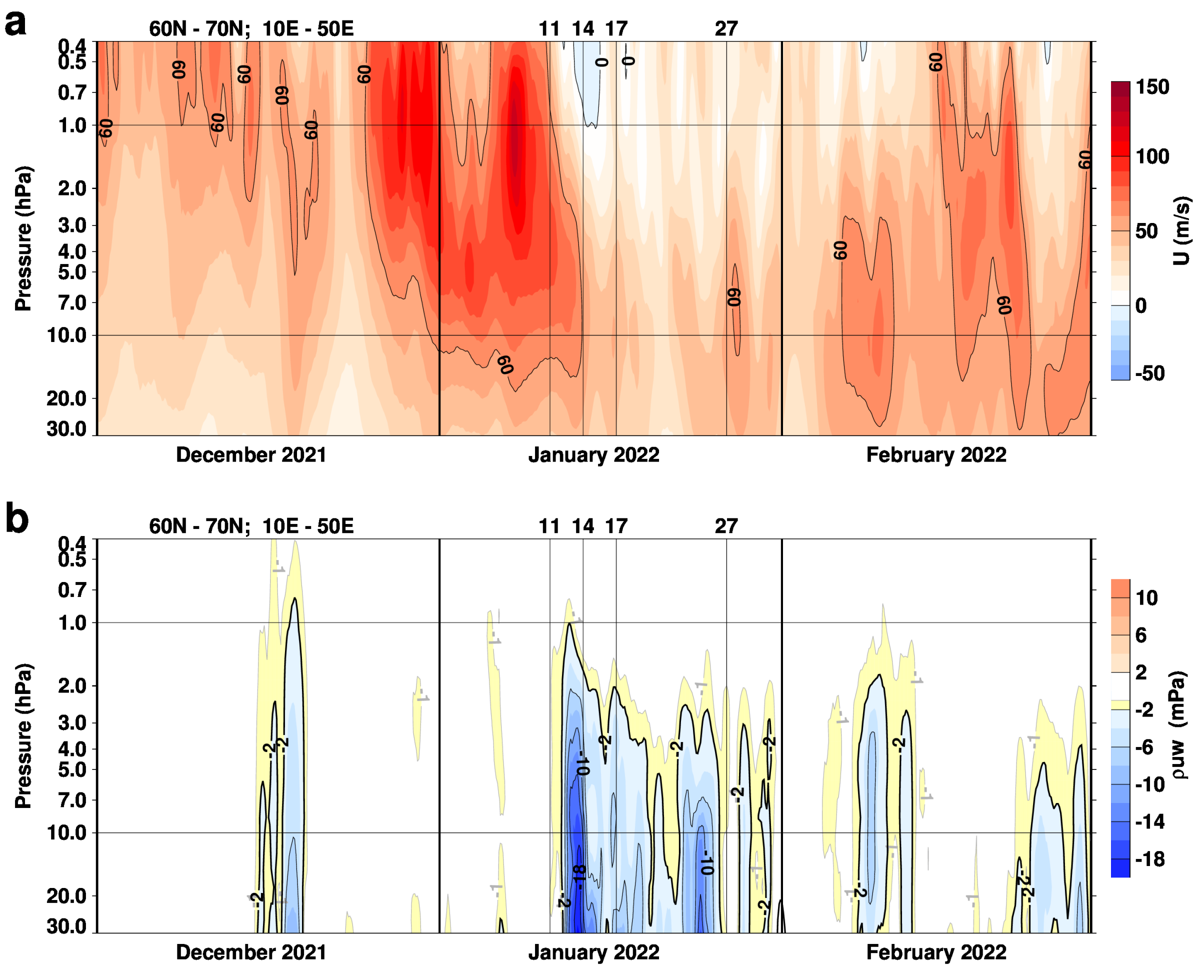

FIG. 7. Time (DJF) pressure (30–10 hPa) cross sections averaged over 60°–70°N and 10°–50°E for a) zonal mean zonal wind (ms^{-1}) and b) the zonal component of the density weighted vertical momentum flux (mPa). Note that in b) the dark contour is at -2 mPa, not zero, and that the the -1 mPa contour has been added (filled yellow).

GW drag effects remained localized over the orography at an altitude just above the wind maximum but below the main resolved breaking region.

c. *Mesoscale vortices*

d. ~~*mesoscale Vortices*~~

The mesoscale vortices develop and propagate along the edge of the vortex, just poleward of the edge value delineating the low and high EPV regions. They begin to form by 14 January 2022

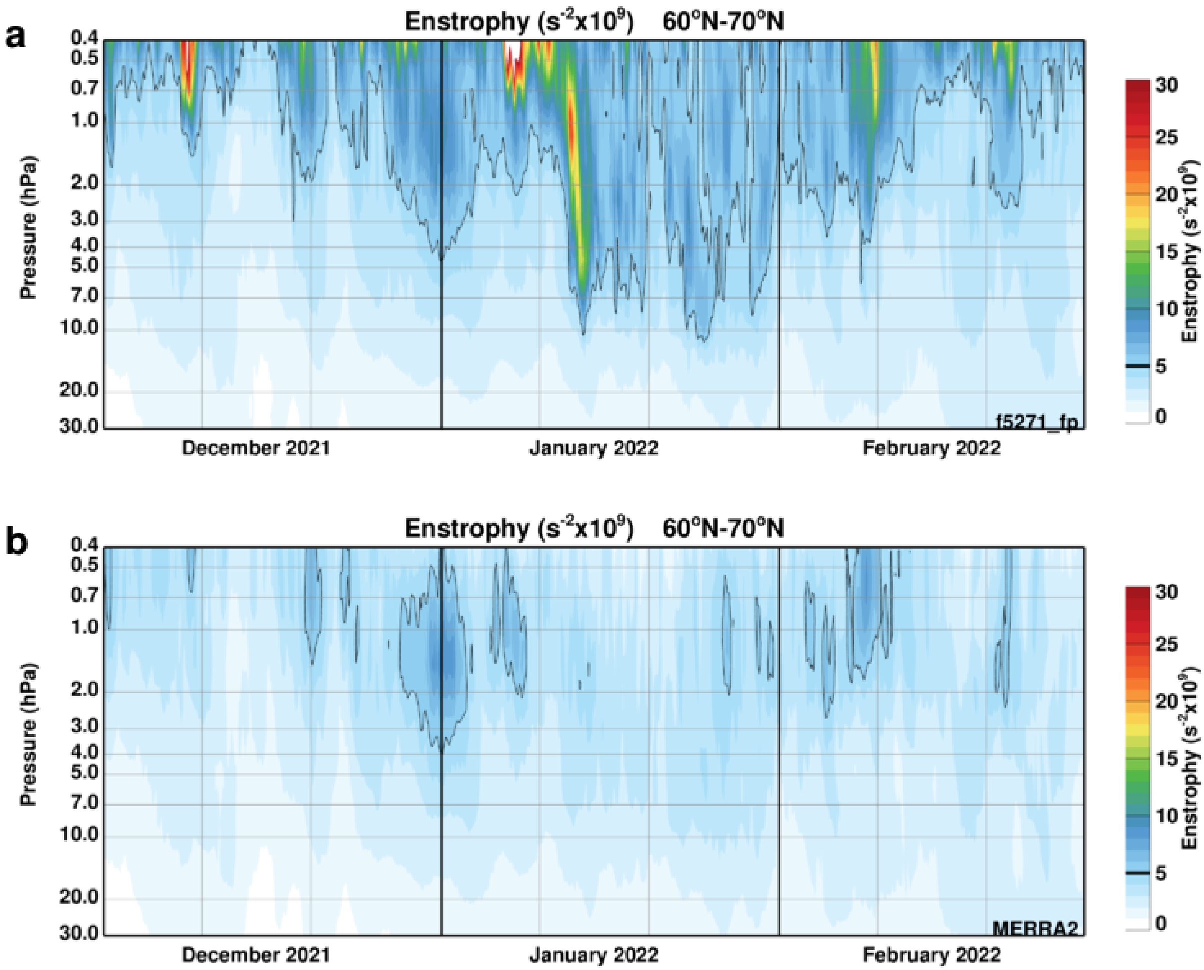

FIG. 8. Time (DJF) pressure (30–10 hPa) zonal averages of enstrophy ($s^{-2} \times 10^6$) over 60–70°N for a) the ~~GMAO NRT~~ GEOS FP system and b) MERRA-2.

when the EPV begins to separate from the vortex (Figs. 1b and c) and continue to develop and propagate around the vortex throughout the rest of the month. An example of the growth and propagation of the mesoscale vortices from 24–27 January is shown in figure 9.

EPV undulations, identified by the letters, A, B, and C can be seen on 24 January (Fig. 9a) in a region of EPV that has separated from the main high EPV region by gravity wave breaking (EPV fluctuations at the smallest resolvable scale) from Greenland to Northern Europe. Note that that these three EPV undulations can be tracked back at in time at least once around the vortex before experiencing the growth shown here after 24 January. By 25 January (Fig. 9b), the three mesoscale vortices have propagated about 90° in longitude around the main vortex. After crossing the main breaking GW region the mesoscale vortices have increased in amplitude, moving in response to the larger EPV values of the polar vortex. The mesoscale vortices, A, B, and C continue to increase in amplitude (the value of their central EPV) on the 26 January (Fig. 9c) and there is also at this time the identification of an additional trailing EPV region labeled D. On the last day shown, 27 January (Fig. 9d), the mesoscale vortices continue their eastward propagation with A and D increasing in amplitude while B and C decrease slightly in amplitude. Note that some of the mesoscale vortices are associated with "breaking wave" signatures in the EPV field: A in panel c), and A, B, and C, in panel d). In each of these mesoscale vortices EPV from the main vortex is being pulled off and lower EPV mixed into the main vortex.

The trajectory of the mesoscale vortex B carried it nearly twice around the main vortex (Fig. 10). After ~2 days increasing in strength (24–26 January) , mesoscale vortex B kept it's amplitude nearly constant until ~28 January before weakening and crossing over the North Pole on 29 January and eventually dissipating near Northern Europe. Mesoscale vortex B existed for about seven days making its average period for a circulation around the globe approximately three and half days, implying a propagation speed of 45 ms^{-1} at 70°N. This speed is close to the mean polar vortex speed at this time, indicating that mesoscale vortex B has a well-conserved EPV structure during this time.

Cross sections of mesoscale vortex B on 26 January highlight typical vertical structure of the mesoscale vortices during their largest amplitude (Fig. 11). The EPV anomaly extends from ~10–1.5 hPa in the upper stratosphere while the potential temperature shows large perturbations starting just above 20 hPa and extending through the upper stratosphere. The temperature perturbation field is consistent with the potential temperature field with cool air below and warm air above. The wind anomalies are located south and north of the axis of the temperature perturbation consistent with the cyclonic circulation of the EPV anomalies. The strongest wind gradients (in the horizontal) coincide with the strongest temperature gradients (in the vertical) consistent with the thermal wind relation. The wind change across the mesoscale vortex is ~80 ms^{-1}. The mesoscale vortices are located in the upper stratosphere with little extent into the lower stratosphere.

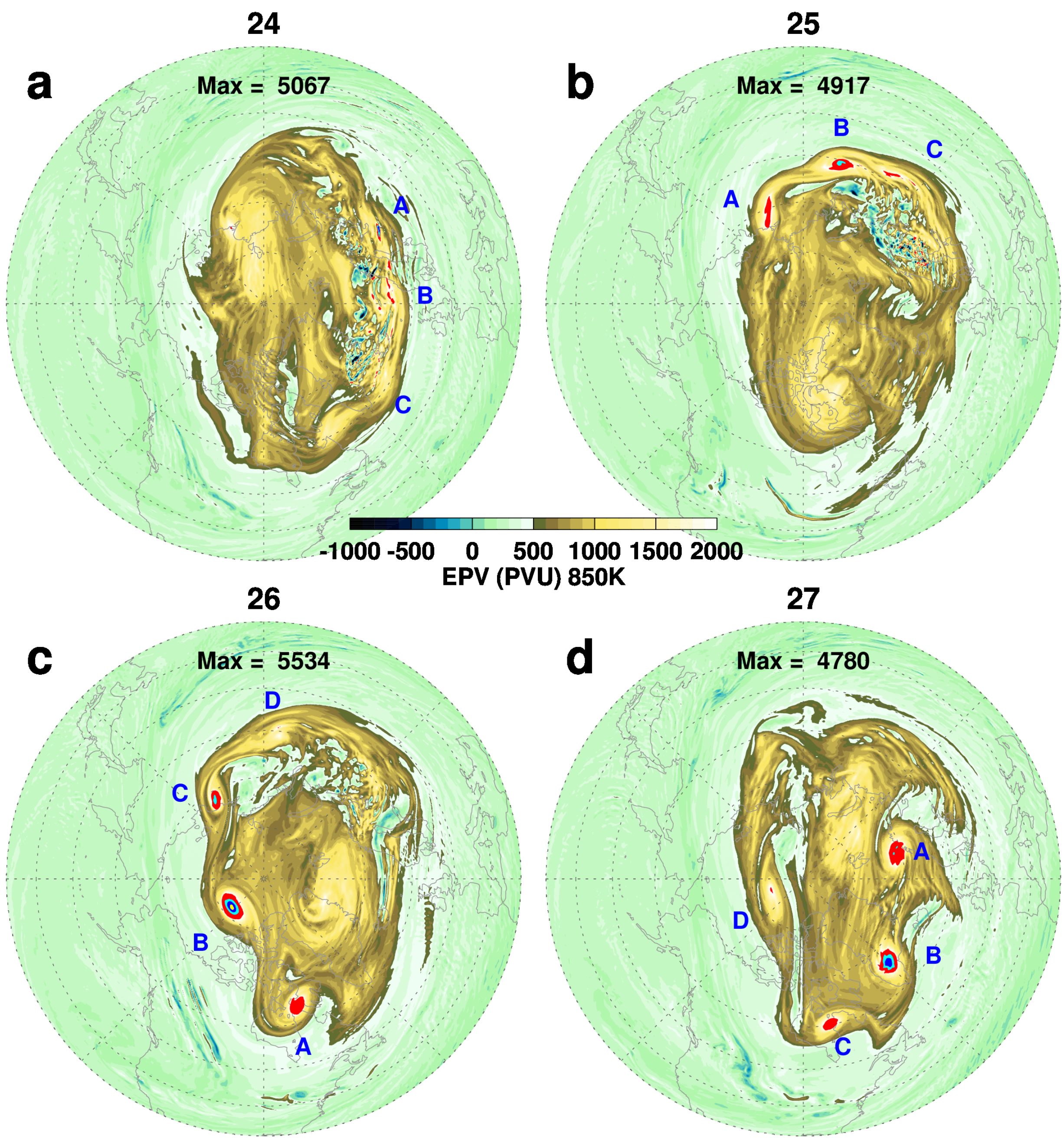

FIG. 9. EPV on 850K potential temperature surface for a) 24, b) 25, c) 26, and d) 27 January 2002 00UTC. The high EPV values are: red: 2000–3000 PVU, cyan: 3000–4000 PVU, blue: 4000–5000 PVU, and yellow: above 5000 PVU. Features tracked across panels are labeled A, B, C, and D.

d. Resolution

High horizontal resolution is needed to identify the breaking GW signature and to reveal the detailed structure of the mesoscale vortices. Figure 12 shows the 850 K potential temperature

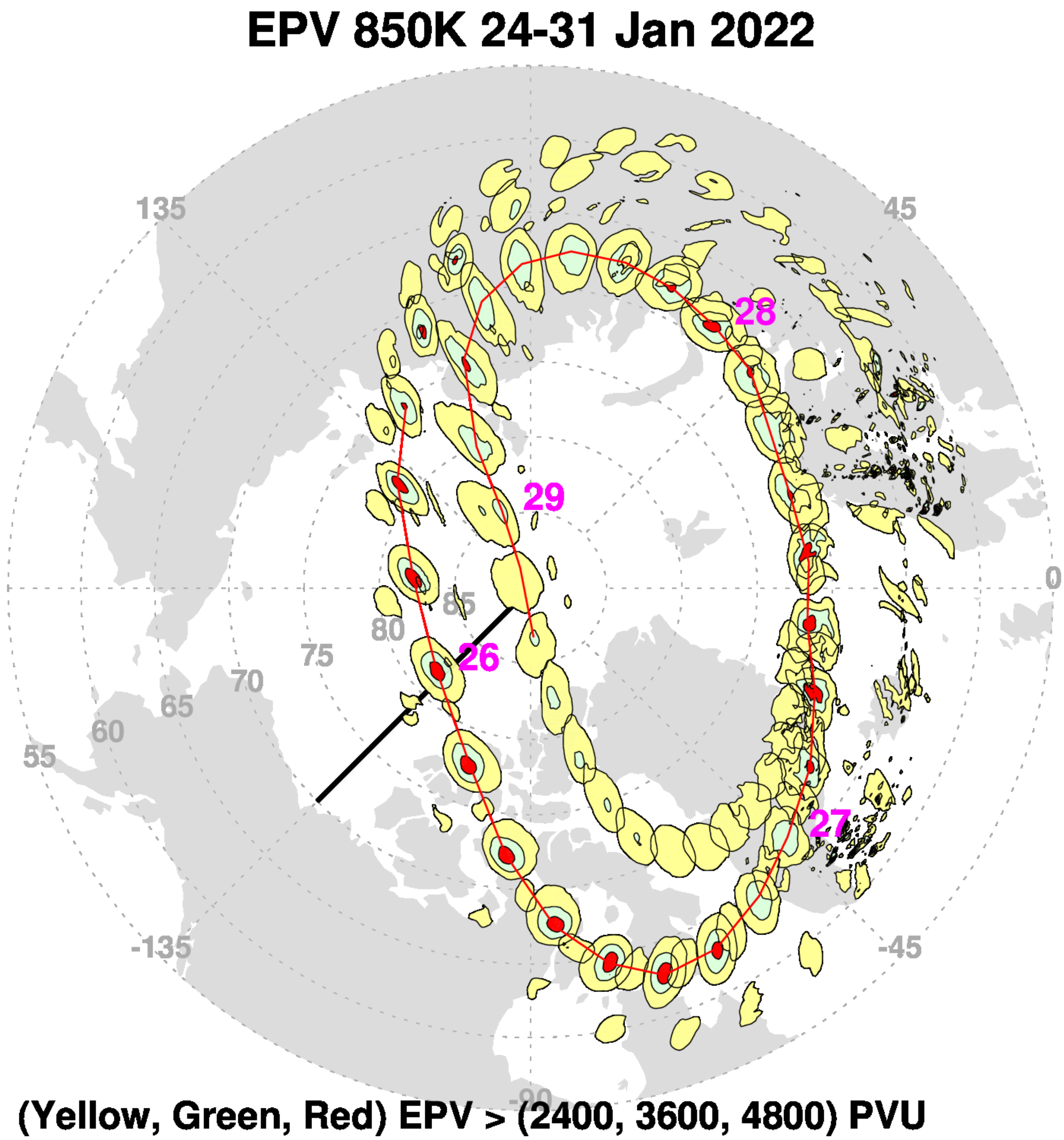

FIG. 10. EPV on the 850K potential temperature surface for 24–31 January 2022 contoured every three hours. EPV values are colored between 2400–3600 PVU (yellow), 3600–4800 PVU (green), and greater than 4800 PVU (red). The red curve connects the maximum EPV locations from 25 January 15 UTC to 29 January 6 UTC. The locations of the highest EPV at 0 UTC on 26, 27, 28, and 29 January are marked. The black line denotes the location of the cross section shown in Fig. 11.

surface EPV field at ~ 1/2, 1/4, and 1/8 degree resolution (low, intermediate, and high). At the lowest resolution, there is no evidence of breaking GWs and while there is some appearance of the

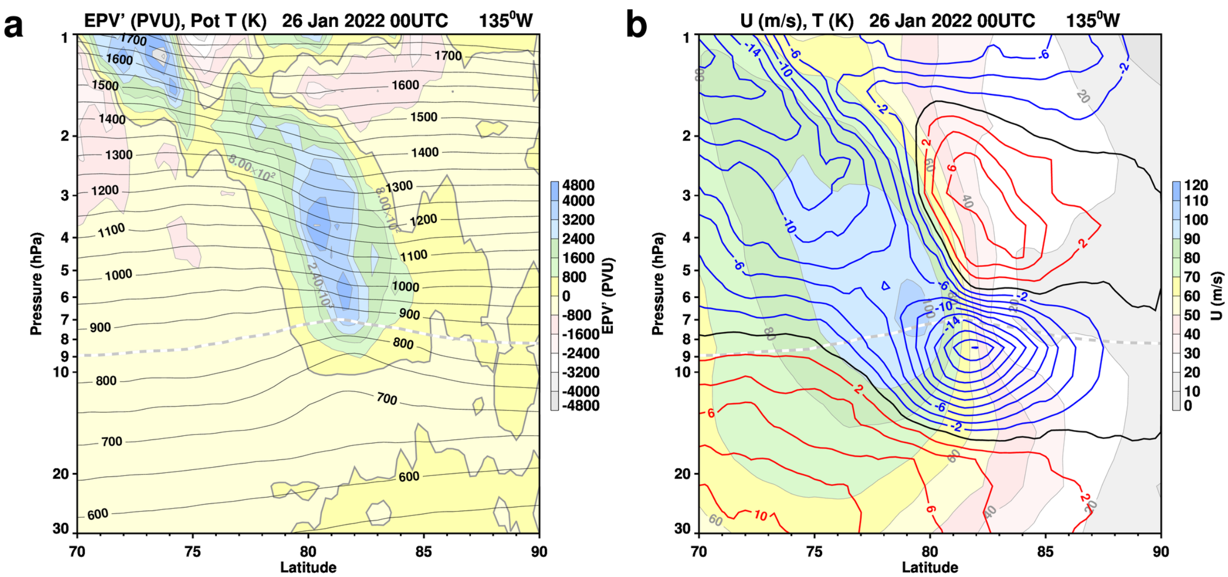

FIG. 11. Latitude (70°–90°N) pressure (30–1 hPa) cross section at 135°W of a) EPV deviation from the zonal mean (PVU, filled contours) and potential temperature (K, black contours) and b) zonal wind (ms^{-1}, filled contours) and temperature deviation from the zonal mean (K, red positive, blue negative). The dashed gray curve denotes the 850K potential temperature.

EPV fluctuations at the intermediate resolution, they are much more evident at the high resolution. The well-defined mesoscale vortices only appear at the intermediate and high resolution and have the highest central EPV values at high resolution. All three resolutions, even the lowest, capture the strong EPV region near A, B, and C, separated from the main vortex, creating a reversal in the latitudinal EPV gradient.

Later, on the 27th, the mesoscale vortices have propagated along the main vortex edge as identified by the letters (Fig. 13). They are very faint but present at low resolution, however both the intermediate and high resolutions agree well suggesting that the size of mesoscale vortices are converging with resolution and may not change much in even higher resolution systems. While the overall structure of the mesoscale vortices are similar at intermediate and high resolution, the central peak EPV values are still larger at the high resolution. Note that the maximum EPV values, occurring at mesoscale vortex "B", increase from 3,014 at intermediate to 4,780 PVU at high resolution.

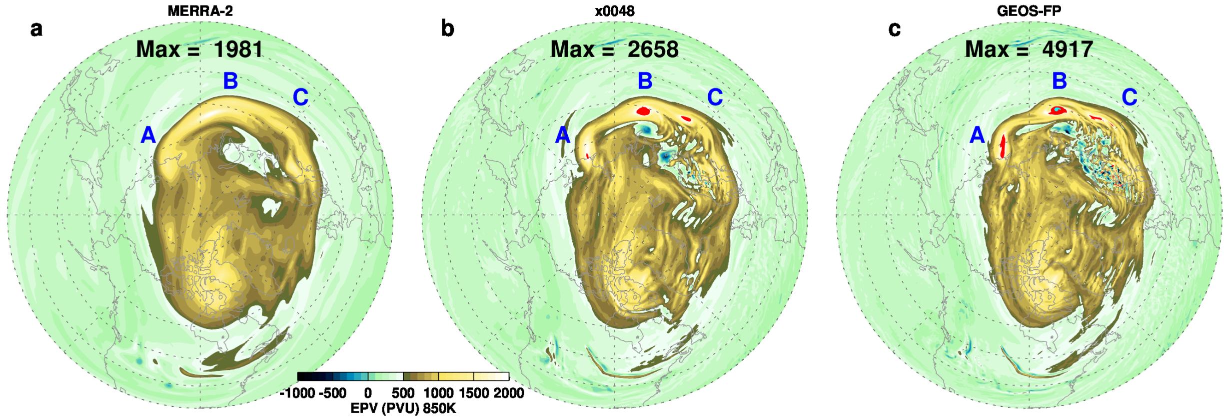

FIG. 12. EPV on 850K potential temperature surface for GEOS DAS analyses at three horizontal resolutions with nominal values of a) 1/2, b) 1/4, and c) 1/8 degrees on 25 January 2022 00UTC. Contours are the same as in Fig. 9

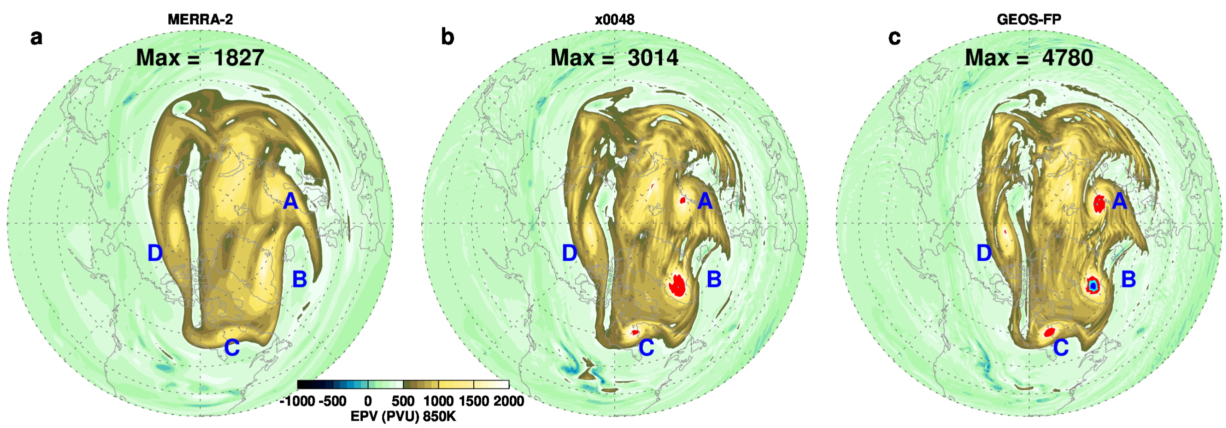

FIG. 13. Same as Fig. 12 but for 27 January 2022 00UTC

e. Instability Considerations

The formation of the mesoscale vortices from the smaller scale gravity waves presents a challenge. One possible mechanism, suggested by the reverse EPV latitudinal gradient over a substantial area, is that the mesoscale vortices are initially generated by baroclinic instability. The idea presented here is that the tropospheric generated GWs break in the stratosphere over a substantial area, creating a significant disruption of the polar vortex EPV, in turn triggering instabilities near the edge of the polar vortex. The instability then produces the mesoscale vortices. As a simple test of the instability of the flow, a linear instability model was ~~examine~~ examined for different zonal wind profiles and times. One result is shown in figure 14. Since the reversed EPV gradient is localized, the zonal winds near the GW activity, 10°–60°E, were average for the background state. The time chosen was for 25 January as the wave perturbation, especially the perturbations labeled C and D in figure 9, were still growing at that time. Other choices include time averaging of the zonal winds or selecting a different longitude range. In addition the model evaluates instability over a limited latitude and pressure range, here chosen to be 58°–68°N and 20–2 hPa. As in McCormack et al. (2014) the boundary conditions were simply taken to be zero at all boundaries of the box. The interior of the box includes a region of negative $\overline{q}_y$ (Fig. 14a) and a reversal of the EPV gradient (Fig. 14b).

For the above choices the fastest growing unstable wave was found at wavenumber 9, with an e-folding growth rate of 1.4 days, a phase speed of 35 ms^{-1}, and a period of 5.5 days. Examining the spacing of the mesoscale vortex locations of 25 January (Fig. 9b), the wavenumber 9 result is not unrealistic, however the spacing between the mesoscale vortices does increase with time (Fig. 9d) suggesting a smaller wavenumber. The growth rate is reasonable, however the phase speed appears to be somewhat slow, leading to a period that is longer than observed when compared to the just over 3-day circuit of the globe taken by the mesoscale vortex B (Fig. 9) from 26–29 January (Fig. 10). The amplitude structure is confined to the lower region of the model's domain in contrast to the larger vertical extent seen in figure 11. Overall, the instability model results, while not comprehensive, illustrate the potential for instability created by the breaking GW induced reversal in the local EPV latitudinal gradient.

Note that this instability model cannot ~~reproduced~~ reproduce the observed growth in EPV as no diabatic processes are included. In the this simple model, the EPV is rearranged to correspond to the growing amplitude wave. The finite amplitude behavior of the instability requires a more sophisticated model.

Another possible mechanism for the origin of the mesoscale vortices is vortex roll-up (Dritschel and Polvani 1992), a shear instability occurring in some vorticity strips. These are usually seen in EPV filaments well outside of the main polar vortex that are pulled off the polar vortex by breaking planetary waves (McIntyre and Palmer 1983). This differs from the situation in January 2022 where the EPV is split while still aligned with the main vortex flow, however the end result is an isolated strip of EPV and hence, potential shear instability. It is likely that a combination of instability mechanisms is at play during the complex dynamics of January 2022.

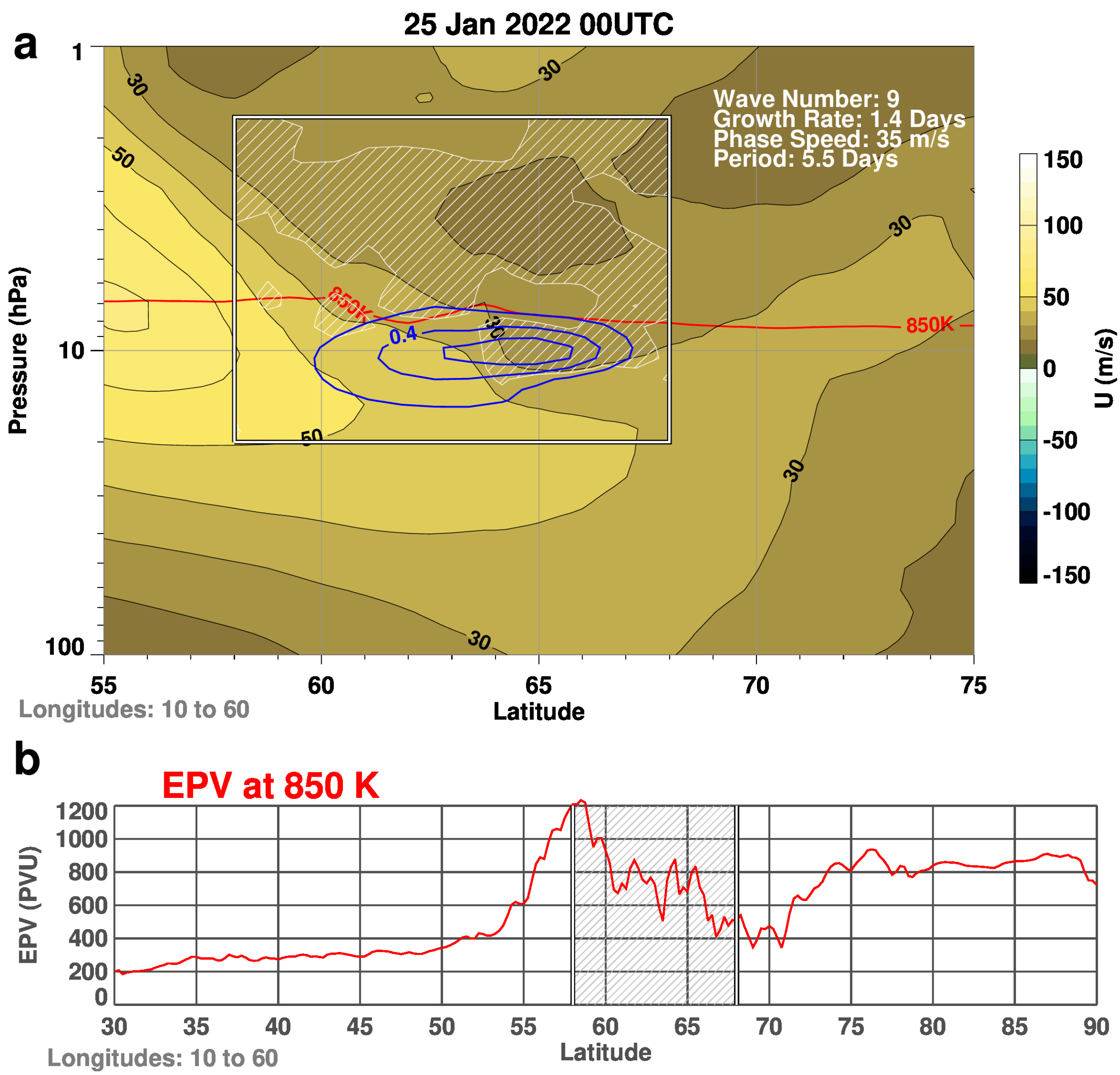

FIG. 14. a) zonal mean wind averaged over 10–60°E (filled contours), the region of negative $\overline{q}_y$ (shaded), the 850K potential temperature (red contour), the non-dimensional fastest ~~gowing~~ growing wave amplitude (blue contours), and b) EPV (PVU) averaged over 10–60°E as a function of latitude. The box in a) and the shaded region in b) denotes the stability model domain used

4. Summary and Conclusions

This study based on the 12 km resolution DAS revealed two new features in the EPV analysis: high and low fluctuations at the smallest model scale associated with GW breaking, and high values associated with mesoscale vortices along the edge of the polar vortex. In this case both types of

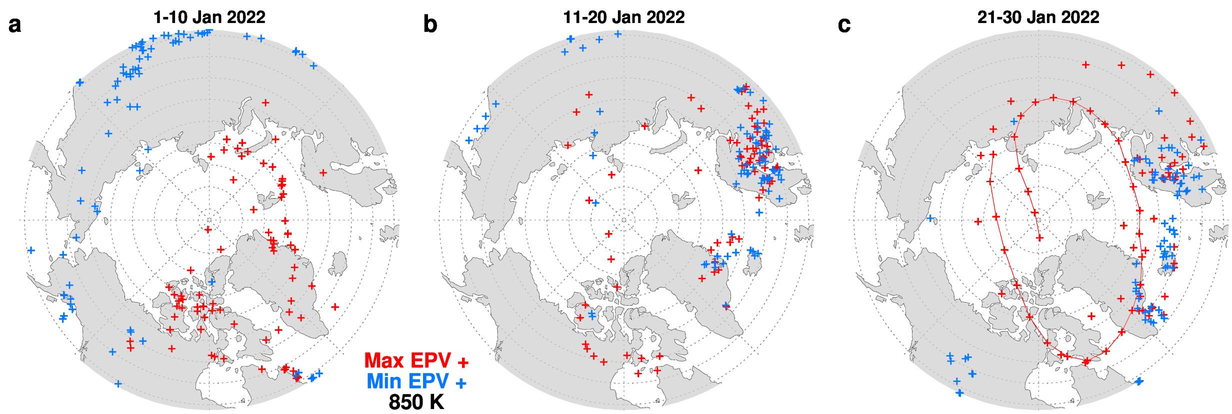

FIG. 15. The locations of the maximum (red) and minimum (blue) values of EPV on the 850K potential temperature surface at each analysis time for a) 1–10, b) 11–20, and c) 21–30 January 2022. The minimum locations are restricted to the area shown on the map projection. The red curve connects the maximum EPV locations from 25 January 15 UTC to 29 January 9 UTC.

anomalous EPV values were related, as the persistent GW breaking created a region of reversed EPV gradient that triggered the formation of the mesoscale vortices.

The location of NH maximum and minimum values of 850K EPV at each analysis time provides a convenient overview of the breaking GW regions during January 2022 (Fig. 15). During the first ten-days the highest EPV values are at the highest latitudes and lowest EPV values are at the lower latitudes, consistent with the NH climatological poleward gradient of EPV. By the middle of January, however, the distribution has changed with maximum and minimum EPV locations close together over Northern Europe, the Greenland coast, and Iceland. These indicate regions of strong GW breaking as seen in the EPV field. Later in January, these ”salt and pepper” patterns continue with the addition of several days (25–29 January) when the maximum EPV value was associated with a propagating mesoscale vortex.

The maximum value of 850K EPV can ~~characterized~~ characterize the overall NH winter of 2021–22 with a nominal maximum value of just under 2000 PVU for most of the winter season (Fig. 16). Starting on 14 January, values that are 5× higher appear, coincident with the appearance of GW breaking. These spikes continue for the remainder of the month with the addition of a more consistent in time bulge of high EPV, a signature of the persistent mesoscale vortices. These dramatic events are mostly over by the start of February.

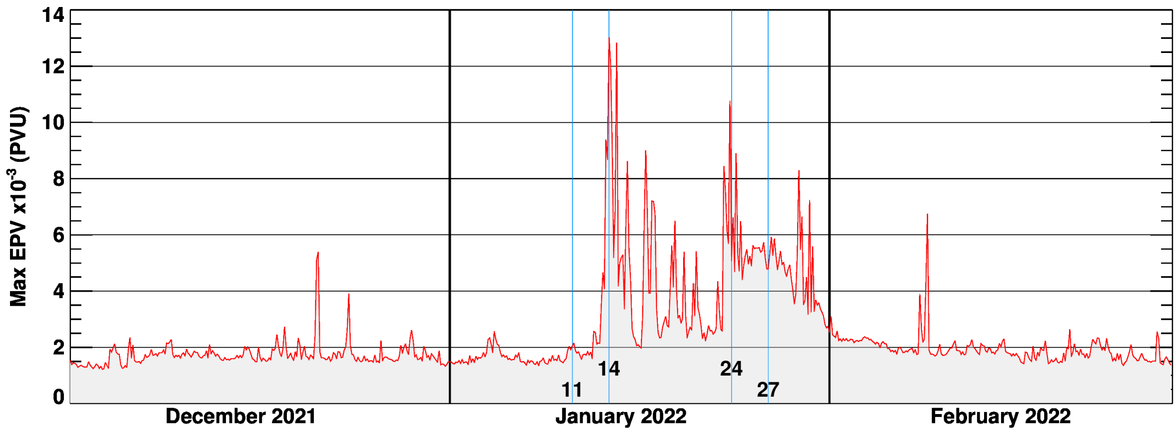

FIG. 16. Maximum EPV value on the 850K potential temperature surface as a function of time (10^{-3} PVU). 11, 14, 24, and 27 January 2022 are denoted by blue vertical lines.

How realistic are these very high EPV values seen in DAS? It is difficult to be definitive at this time. The very smallest scale EPV fluctuations, occurring in association with GW breaking, are likely greatly ~~influence~~ influenced by the limited model resolution. However, higher horizontal resolution leads to more sharply defined mesoscale vortices with higher central EPV values (Fig. 13). Comparison of the evolution of the mesoscale vortices in FP with the lower resolution MERRA-2 EPV fields (Fig. 13) shows that at lower resolution the FP mesoscale vortices can be identified as a smoothed version of the higher resolution system. If the wind change is approximately the same across a mesoscale vortex but the doubled horizontal resolution allows for a doubling of the gradient, then the EPV values can be expected to double as well.

~~The~~ Only one potential mechanism for the creation of the ~~very high mesoscale vortex EPV values is left for future investigation. In isentropic coordinates the rate of change of the parcel EPV is given by~~ mesoscale vortices was investigated here. Other, perhaps very different, mechanisms are possible. Additionally, the simple linear instability model examined here lacks the ability to follow the perturbation to finite amplitude and to grow the EPV values, a distinctive feature of the vortices that needs explanation. Consider the equation for EPV in isentropic coordinates (Andrews et al. 1987, Equ 3.8.5):

$$\tilde{D}P = (\sigma a \cos\phi)^{-1}[-(X\cos\phi)_{\phi} + Y_{\lambda} - Q_{\lambda}v_{\theta} + Q_{\phi}u_{\theta}\cos\phi] + PQ_{\theta} - QP_{\theta},$$

where $\tilde{D}$ is the time derivative following the isentropic flow, P is potential vorticity, σ is the isentropic density, a is the radius of the earth, ϕ is latitude, λ is longitude, θ is potential temperature, X and Y are the latitude and longitude frictional forces, u and v are the velocity components, and Q is the diabatic forcing. Neglecting frictional forces and scaling for quasi-geostropic motion (Haynes and McIntyre 1987), the equation becomes:

$$\tilde{D}P \approx PQ_{\theta} - QP_{\theta}$$

While time averaged diabatic heating terms are typically saved in the DAS output, the quadratic terms are not save so additional output would be useful. In addition, the non-geostropic terms may contribute to the mesoscale vortices. ~~Along~~ It should be noted that, along with the mesoscale high EPV, some regions of mesoscale low EPV stand out. This is especially noticeable in Fig. 12b, the intermediate resolution experiment, near “B” and “C”, suggesting that isentropic redistribution of EPV is playing a role rather than problematic model numerics in creating the high EPV features and supporting the concept of rearrangement of EPV as part of the development of the mesoscale vortices.

The different orientation and scale of EPV fluctuations from the associated GWs needs further investigation. Detailed three dimensional models of GW breaking (Fritts et al. 2009a,b) resolve the small scale, rapid, variability created during the breaking process and the generation of EPV by breaking GWs has been recently modeled by Waite and Richardson (2023). These studies suggest that “spanwise”, that is disturbances along the wavefront, commonly develop, however relating these to global scale EPV is not yet clear. While we have focused on a single NH winter in which planetary wave activity was relatively weak to highlight the GWs and their effects on the polar vortex, it is likely that breaking GWs in the mid to upper stratosphere are fairly common and routinely contribute to mixing at the edge of the polar vortex.

In future studies we plan to examine other years when high resolution FP DAS fields are available along with results from test model and assimilation experiments at higher horizontal and vertical resolution. More evaluation of the amount of mixing along the polar vortex edge by the mesoscale vortices is also needed. Even though the scale of these vortices is relatively small, the amount of mixing could be substantial as these mesoscale vortices form where tracer gradients are large. In addition, since some evidence of the mesoscale vortices can be found at low resolution such as in Fig. 13a, it may be possible to develop a climatology of when these events occur by searching the longer time record of the lower resolution MERRA-2 DAS. Such a climatology would provide information of the role played by the mesoscale vortices in observed climatological stratospheric tracer distributions.

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Data availability statement. The GEOS data used in this study/project have been provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center. The Forward Processing (FP) DAS output are archived at `https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/das` and the system used in this study is labeled f5271_fp. The MERRA-2 data is available from the NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC, https://disc.gsfc.nasa.gov/datasets?project=MERRA-2). Specific MERRA-2 data sets used are contained in the references. The AIRS brightness temperatures are available from `https://datapub.fz-juelich.de/slcs/airs/gravity_waves/html/view_2022_014.html` The IDL (Interactive Data Language) code used for the quasi-geostrophic instability model is archived at `https://gmao.gsfc.nasa.gov/gmaoftp/larrycoy/instability_code/stability_package.pro`. The x0048 DAS fields used to construct intermediate resolution EPV fields on 25 and 27 January 2022 are archived at `https://gmao.gsfc.nasa.gov/gmaoftp/larrycoy/mesoscale_vortices`.

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