

# Transient Flow Patterns of an Annular-like Stratospheric Polar Vortex.

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**Abstract.** A two-component study is undertaken of flow features associated with the wintertime polar-night vortex at upper-stratospheric levels. First, case studies based upon reanalysis data are presented of three disparate flow settings. They suggest that: - (a) sub-planetary scale flow features are prevalent, tend to occur near the periphery of the vortex, possess a distinctive potential vorticity structure, and are associated with the vortex's predilection to develop a structure akin to an annular-like band of enhanced potential vorticity; and (b) planetary scale flow features are influenced by, and can significantly distort such a band. Second, theoretical considerations and numerical model simulations of perturbations of an annular band of enhanced absolute vorticity using a non-divergent barotropic model on a polar  $\beta$ -plane yield results consistent both with the occurrence of the sub-planetary scale features, and with the possible rapid reconfiguration of a pre-conditioned planetary scale flow. The latter result has ramifications for the break-up of the polar vortex during a sudden stratospheric warming event and entails the synergetic combination of strong planetary-scale Rossby-wave forcing from below acting upon the vortex's annular potential vorticity band.

## 1. INTRODUCTION.

20 The general form of wintertime stratospheric polar vortex (SPV) is well established (see e.g. Waugh and Polvani, 2010; Schoeberl and Newman, 2015; Butchart, 2022). It extends from the lower stratosphere at  $\sim 15$ km to well beyond the stratopause at  $\sim 50$ km, attains a maximum wind strength often greater than  $120 \text{ ms}^{-1}$  at stratopause levels, and is characterized in the stratosphere by an inner cold core driven primarily by the lack of ozone-related radiative heating during the polar night.

25 On quasi-horizontal or isentropic surfaces, the SPV's lateral 'edge' has been defined in various ways (Waugh et al 2016; Manney et al 2021). Kinematically it has been associated with the iso-line demarking the strongest wind strength (Waugh et al 2016) or the maximum streamline density (Harvey et al 2002; Harvey et al 2009), cartographically as a feature-based configuration (Serra et al 2017; Lawrence & Manney, 2018), and dynamically as the zone of sharp lateral PV gradient (Butchart & Remsberg, 1986; Manney et al 1994; Nash et al 30 1996). The latter definition arises from regarding the vortex's lateral configuration as an inner core of high potential vorticity (PV) encased by a narrow zone of strong PV gradient that is itself encircled by broad and well-mixed surf zone of lower PV (McIntyre & Palmer, 1984). The adoption of one or another of the above criteria to define the vortex's periphery will depend upon its practical utility or its interpretative value for the specific purpose in hand.

35 The present study is geared to examining the sub-planetary and finer-scaled flow features that are contiguous to, or related to, the structure of the SPV's periphery, and to this end we adopt a PV perspective (Hoskins et al, 1985). The study is framed around the postulate that a, possibly fragmented, annulus of enhanced PV (- i.e. a maximum in the across-jet distribution of the PV) can exist near the periphery. This assertion is rendered plausible by two factors. First, a strong laterally confined jet with a relative vorticity maximum (say,  $\zeta_{\max}$ ) located 40 at a co-latitude  $\chi (< 30^\circ)$  on the vortex's poleward side would connote a maximum of absolute vorticity provided

$(\zeta_{\max}/2\Omega) > 1/2\chi^2$ , and this inequality is readily satisfied (- often by an order of magnitude) in the upper stratosphere. This in turn would connote a PV maximum (*sic* annulus of enhanced PV) if the variation of the stratification on an isentropic surface within the vortex is not comparably large. Second, the presence of such an annular structure on an isentropic surface is a necessary criterion for instability of axisymmetric quasi-geostrophic stratospheric flow (Charney and Stern, 1962), and the realization of the instability could result in a fragmented annulus.

The probable existence of such an annular structure in the polar stratosphere has long been recognized (Hartmann, 1983), and indeed a balanced flow response to a radiative equilibrium (Leovy, 1964) or radiatively determined (Shine, 1987) stratospheric state would possess such a maximum. Such a feature has also been detected in other planetary atmospheres (Sharkey et al 2021; Shultis et al, 2025) and is often a feature in the vicinity of the hurricane's eyewall (Schubert et al, 2018). Moreover, Davies and Spengler (2024) - hereafter denoted DS24 - drew attention to flow features at stratopause elevations that are akin to that of a fragmented annulus.

An annular structure of enhanced PV would be embedded within an SPV that itself exhibits a distinct life cycle (Lu et al 2021), and marked inter-annual variations (Butchart, 2022; Rao et al 2024) particularly those related to the occurrence and aftermath of a Sudden Stratospheric Warming (Baldwin et al 2021). This poses questions as to whether the annular structure or its fragmented counterpart is present at all phases of the life cycle, and what role (if any) it plays in the development of Sudden Stratospheric Warming (SSW) events that have themselves been pointedly linked to a variety of mechanisms and preconditioned states deemed to be more amenable to engendering such events (Plumb, 1981; Fredricksen, 1982; Smith, 1992; Matthewman and Esler, 2011; de la Camara, et al 2017; Lawrence and Manney, 2020; Yessimbet et al 2022).

Again, the annulus occupies the same spatial domain as two classes of shorter-term phenomena, and questions arise regarding the extent of their inter-dependence. One class can be viewed as intrinsic natural modes confined to, and governed by the structure of, the SPV itself such as planetary-scale zonally propagating waves (Venne & Stanford, 1979; Randel & Lait, 1991), smaller scale zonally propagating waves and synoptic-scale features (Lu et al 2021). The second class comprise planetary-scale Rossby waves (PRWs) (see e.g. Hitchcock and Haynes, 2016) and short-term smaller-scale gravity waves (GW) (see e.g. Holton & Alexander, 2000; Eichinger et al 2020) both of which propagate upward from lower elevations and can break on attaining large amplitude. The PRWs tend to break in the mid-to-upper stratosphere and the GWs at even higher elevations, and on breaking can heavily modulate the SPV's structure. Indeed, breaking PRWs (Hitchman and Huesmann, 2007; Greer et al, 2013) strip PV filaments off the vortex edge, create the surf zone (McIntyre & Palmer, 1984), and are endemic to the occurrence of SSW events (Martius et al, 2009). Likewise breaking gravity waves can serve as a drag (GWD) reducing the strength of the SPV's jet.

In this study attention is focused on the presence, role and dynamics of a PV annulus and/or its fragmented counterpart in the wintertime upper stratosphere. It is set against the backcloth of the series of questions posed above, and it has observational and theoretical components. For the observational component, illustrative case studies pertaining to the SPV's annular structure are presented for three different winter settings. For each case attention is drawn to the structure, temporal evolution, and dynamical character of the realized transient sub-planetary and planetary scale flow features.

The theoretical component is prompted by noting that the observationally detected features (DS24) bear comparison with the break-up of a barotropic jet-like flow. The ready inference that an SPV's jet can satisfy a necessary condition for barotropic instability has spawned a fleet of studies for basic states akin to that of either the SPV's jet, the circumpolar jets of other planetary atmospheres (see for example, Pfister, 1979; Davies, 1981; Hartmann, 1983; Michaelangeli et al., 1987; Manney et al., 1988; Seviour et al 2017; Mitchell et al., 2021; Waugh et al., 2023) and the hurricane's eyewall (Schubert et al, 2018). The strategy adopted here is to select an idealized

theoretical model capable of capturing the essence of rapidly growing wave patterns of a barotropic model for  
85 flow settings akin to that of a deep undisturbed SPV. The specific objective is not to replicate (or contrast) the  
results with that of the earlier studies, but rather to seek further basic understanding of, and insight upon, the  
dynamics of the observed features.

Both components are foreshadowed by the recognition that the presence of an annular PV feature in the  
upper stratosphere would not only alter the SPV's structure itself but also influence the character of in-situ  
90 generated phenomena and of waves propagating into the domain. For example, a change in the SPV's structure  
modifies its transmissivity to upward propagating waves (Hitchcock and Haynes, 2016). The strong positive PV  
gradient on the outer side of the annulus constitutes a columnary shaft that favours vertical PRW propagation  
(Abatzoglou and Magnusdottir, 2007), and contrariwise the negative PV gradient on its inner side would serve not  
merely to inhibit, but preclude, propagation into the vortex core, and thereby in principle help isolate the core from  
95 external effects. It is pertinent to note that this 'shielding of the vortex core' associated with the PV gradients  
contrasts markedly with the dynamics at the counterpart tropopause-level sharp PV gradient (and accompanying  
jet stream) located at the break in the mid-latitude extratropical tropopause (Appenzeller and Davies, 1992).

The paper is arranged as follows. Section 2 sets out the observational case studies. Section 3 sets out the  
theoretical results derived using an idealized barotropic model to study the dynamics of both small and finite  
100 amplitude perturbations of an SPV-like basic state. In a final section further remarks are made regarding the study's  
results and their possible implications.

## 2.0 Observed Flow Features.

Three case-studies are presented with the objective of capturing the essence of transient flow features associated  
105 with an annular-like PV structure in the wintertime upper stratosphere.

### 2.1 Data.

Consideration of the flow at stratopause and higher elevations using reanalysis data sets are subject to constraints  
110 arising from the decrease in the number and resolution of sampled meteorological variables and the shortcomings  
of the parent assimilation model at these elevations (- see the overview in S-RIP, 2022). Nevertheless, Reanalysis  
fields have been utilized, albeit with caveats, to examine a range of upper stratospheric diagnostic studies.  
Moreover, DS24 showed examples of three Reanalysis data sets, viz. ERA-Interim (Dee, et al 2011a, b), MERRA  
(Gelaro, 2017), and ERA-5 (Hersbach, 2020), capturing the same sub-planetary and synoptic-scale flow features.

115 Here, we proceed pragmatically, examine only levels at and below the prevailing stratopause and adopt  
the ERA-Interim data set. In Appendix A illustrations are provided of the overall similarity of this study's key PV  
patterns as captured by the ERA-Interim and MERRA2 Reanalysis data sets.

### 2.2 Diagnostic Analysis.

120 The objective is to establish the existence, scale, structure, evolution and dynamics of the sub-planetary transient  
flow features. To this end we exploit the PV perspective (Hoskins et al 1983) so that the structure is defined by  
the three-dimensional PV distribution, its influence upon the flow and that of its sub-features is linked to the in-  
situ deviation of the PV from the ambient field, and its evolution is rendered more transparent when examined on  
isentropic surfaces (Davies et al, 2024).

125 Further insight is provided by examining, where appropriate, aspects of the contemporaneous distribution  
of other flow variables including the relative vorticity, divergence, potential temperature, specific humidity and

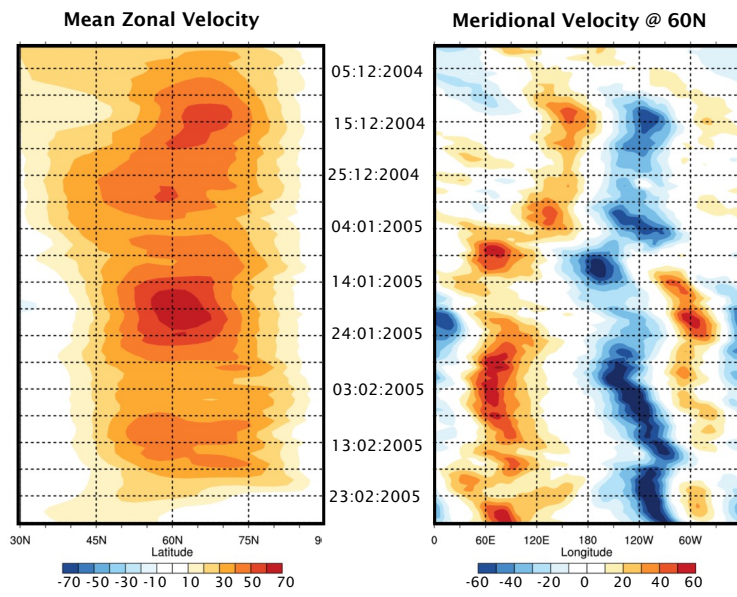
ozone mass mixing ratio. For each case study we present a summary of key features at the 10mb level followed by examples of the structure and evolution of the flow at upper stratospheric levels for specific time windows.

### 130 **2.3 Features of a Mature SPV**

The Boreal Winter of 2004-2005 was comparatively non-descript and there wasn't an SSW event. At the 10mb level the time-latitude pattern of zonal mean velocity (Fig. 1a) increased almost monotonically to a maximum of  $\sim 70 \text{ ms}^{-1}$  by the 19<sup>th</sup> of January and decreased almost uniformly thereafter. The corresponding time-longitude pattern of the meridional velocity at 60N (Fig. 1b) shows evidence of a strong  $m = 2$  pattern by the middle of  
135 December. Its amplitude and phase remained comparatively constant for the remainder of the Winter although it transiently weakened and retrogressed in early January. The onset of the wave and the forementioned transient retrogression was accompanied by a relatively strong upward EP fluxes (not shown).

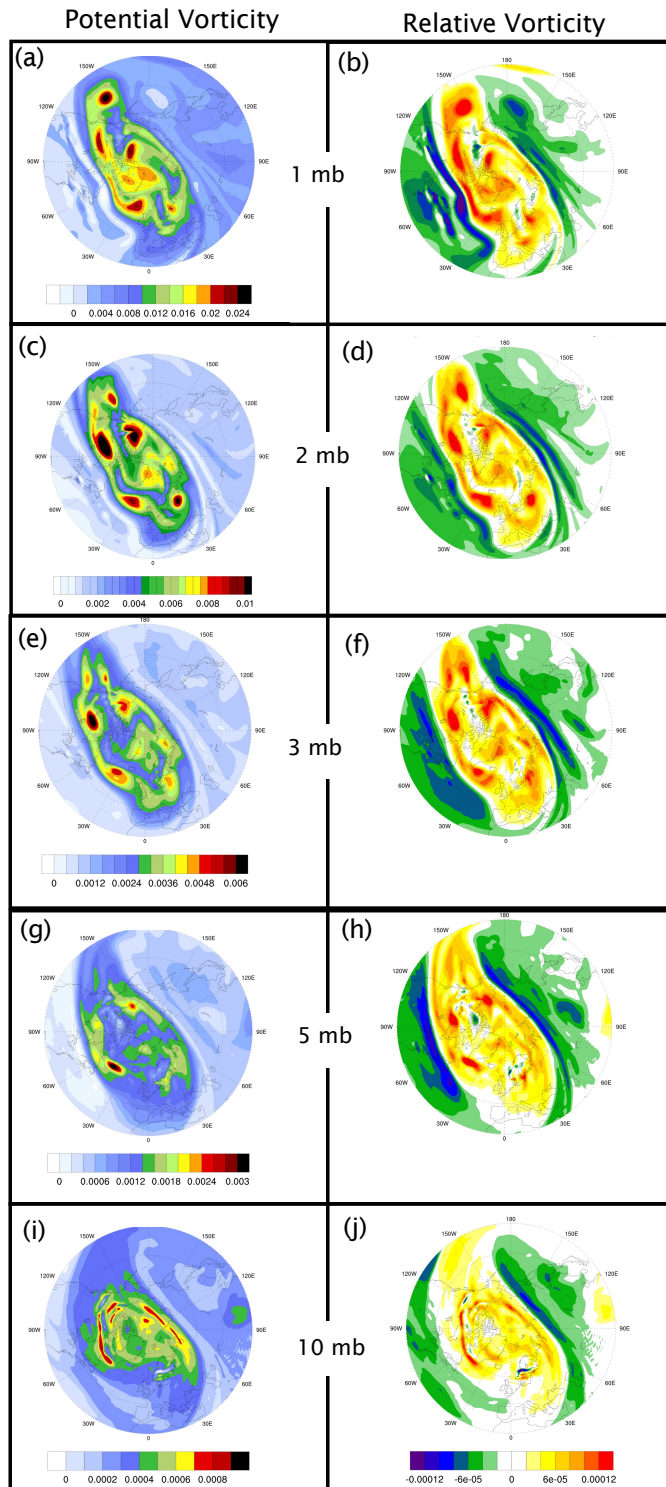
At stratopause elevations, the winter's flow pattern in general showed notable, transient synoptic-scale variations. Here we select the 11<sup>th</sup> January as a not atypical day, and Figure 2 shows the instantaneous patterns of the PV and  
140 the relative vorticity on a sequence of pressure levels at 00Z 11<sup>th</sup> January. At all levels there are planetary scale features (- zonal wavenumber  $m = 1-3$ ) with evidence of finer-scale features embedded within an annular-like structure. The upper two rows (panels a-d) indicate the presence within or on the periphery of the SPV of localized regions of PV maxima with co-located but more diffuse regions of positive relative vorticity. These features resemble those identified in DS24 and are sub-planetary / synoptic in scale, and their relative vorticity values  
145 ( $\sim 1.0 \times 10^{-4} \text{ s}^{-1}$ ) are comparable to that of the earth's rotation. Their spatial scale signify:- (a) via Stokes's circulation theorem, a circulation of  $\sim 25 \text{ ms}^{-1}$ , and (b) a supra-geostrophic flow. Thus, the contemporaneous existence of these features indicates that they are integral dynamical aspect of the SPV's overall structure, and their amplitude and lateral width are indicators of the in-situ jet's sharpness. In principle the flow field attributable to these features can influence the spatial distribution of chemical constituents within the SPV's core and at its periphery.

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Fig. 1 Panel (a) shows the zonal mean velocity as a function of latitude (60-90N) at 10hPa for the  
 160 Boreal Winter of 2004-2005, and panel (b) depicts the meridional velocity field at 60N at the same level for the  
 same winter season. (Based upon the NCEP/NCAR Reanalysis.)



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Fig. 2 Depicted are polar stereographic projections poleward from 30N of the PV in units of  $\text{K m}^2 \text{kg}^{-1} \text{s}^{-1}$  (left column) and the relative vorticity in units of  $\text{s}^{-1}$  (right column) for 00Z 11<sup>th</sup> January 2005 on the 1, 2, 5 and 10 mb surfaces. (Based upon the ERA-Interim Reanalysis.)

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175 Panels (e-j) demonstrate that at this time most of these features are vertically coherent extending down to  
10 hPa (~ 30 km) with the relative vorticity exhibiting comparable amplitude at all levels. This contrasts with the  
expected increase with height of an upward propagating wave's velocity field as the density decreases. Although  
the features are deep, their meridional width diminishes downwards so that they exhibit a stalactite-like structure.  
Again, the character of the features, with their predominantly positive maxima of PV, differ intrinsically from the  
patterns of the corresponding fields astride the tropopause level jet (Appenzeller and Davies, 1992), and this again  
180 points to the different transient dynamics of the two jets.

Figure 3 displays, for the same time instant as Fig. 2, the distributions of the temperature on the 1, 2 and  
3mb pressure surfaces (panels a-c), and the wind vector field (panel d), the specific humidity (panel e) and the  
divergence patterns (panel f) on the 2mb surface. The temperature fields are comparatively smooth and indicate  
that the SPV's cold pool weakened above 2 mb. In general, they do not exhibit the finer-scale features of the  
185 corresponding PV and relative vorticity patterns, and this is in harmony with the forementioned vertical coherence  
of the PV. More trenchantly the stratification / static stability at the PV maxima (not shown), determined in terms  
of the potential temperature difference between the different pressure levels, is typically twice that of the adjacent  
areas.

The wind vector field (Fig. 3d) pinpoints the location of the jet, and it is evident that the jet's overall  
190 strength suffices to substantially conceal the wind signature of the individual SSS features. In passing we note that  
a convenient *ad hoc* measure of the SPV's core is the domain located poleward of zero relative vorticity (- see Fig.  
2 and Fig. 3d). In the ERA-Interim Reanalysis the specific humidity is inert and merely advected with the in-situ  
winds and hence is akin to a flow tracer. Its distribution (Fig. 3e) is suggestive of a well-mixed SPV core that is  
substantially encircled by an elongated streamer of low humidity values advected on a different potential  
195 temperature surface.

The amplitude of the divergence field (Fig. 3f) is typically less than a quarter of the corresponding relative  
vorticity (and absolute vorticity) values, and its spatial pattern is more reminiscent of buoyancy/gravity waves.  
This suggests that the dynamics of the sub-planetary scale features at stratopause elevations is predominantly  
quasi-barotropic, albeit with a balanced flow state beyond that of simple quasi-geostrophy. (This inference lends  
200 a measure of credence to our later adoption of a barotropic theoretical model).

The prior development of the PV pattern depicted in Fig. (2c) is shown in Fig. (4). It displays a 6 hourly  
time-sequence of the corresponding patterns to 00Z 11<sup>th</sup> January. The fragmented annulus is seen to evolve with  
time and the individual embedded SSS features are readily identified exhibiting a measure of temporal coherence  
as they are both advected by and serve to modify the in-situ flow.

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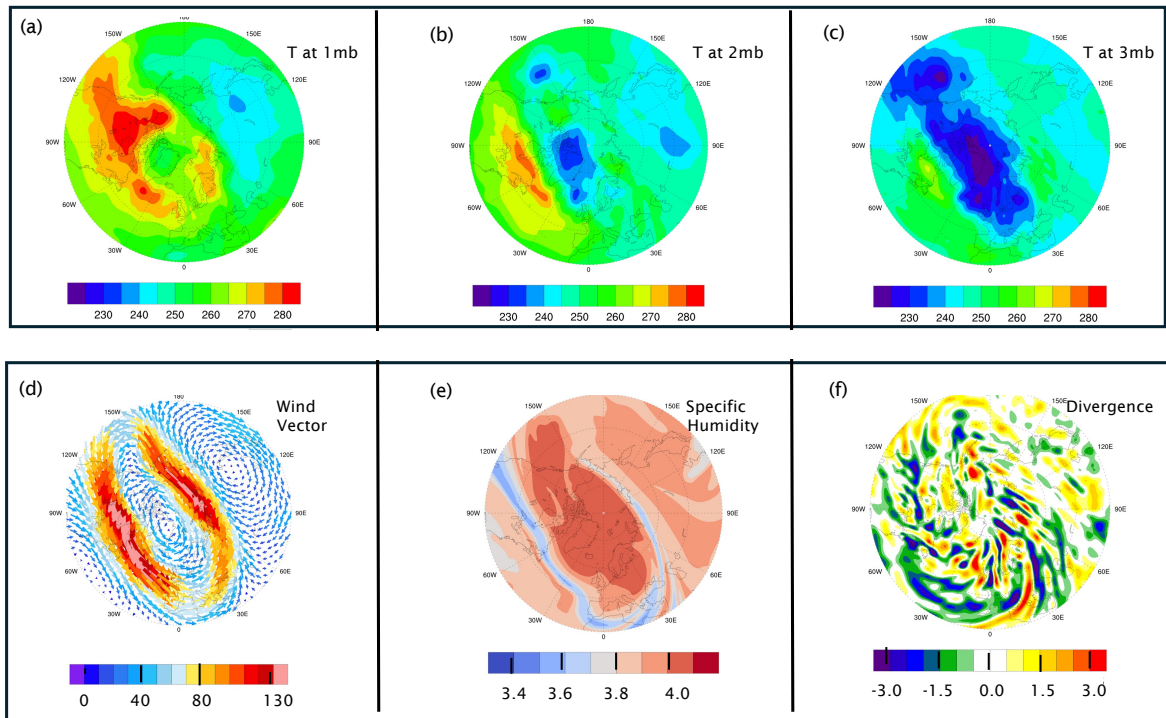


Fig. 3 Distribution of the temperature on the 1, 2 and 3mb surfaces (upper row) and the wind vector ( $\text{ms}^{-1}$ ), specific humidity ( $10^{-6} \text{ kg kg}^{-1}$ ) and divergence ( $10^{-5} \text{ s}^{-1}$ ) on the 2mb surface (lower row) for the same time instant as Fig. 2. (Based upon the ERA-Interim Reanalysis.)

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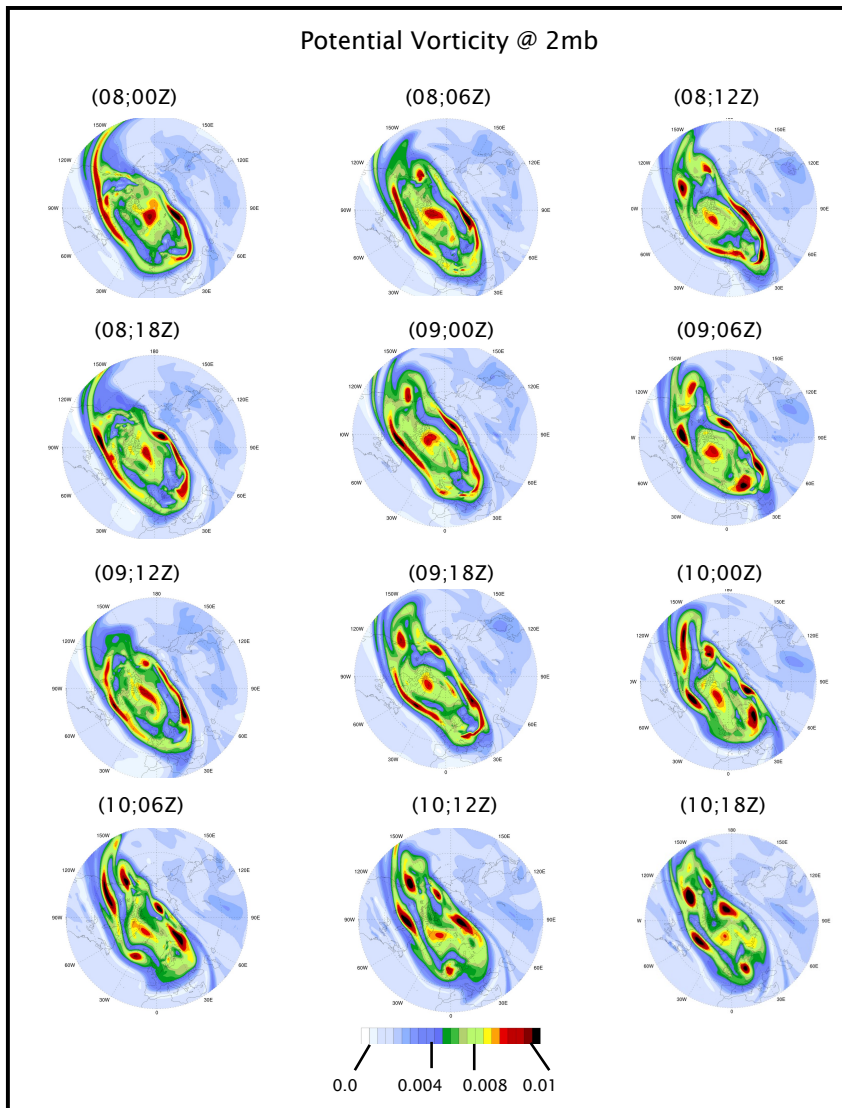


Fig. 4 Evolution of the PV ( $\text{K m}^2 \text{kg}^{-1} \text{s}^{-1}$ ) on the 2hPa pressure surface at 6 hourly intervals from 00Z on the 8<sup>th</sup> January to 18Z on the 10<sup>th</sup> January.

225 **2.4 Features of a nascent SPV**

The Austral winter stratosphere is less subject to PRW forcing from below, and here we examine the SPV during late Spring / early Southern Hemisphere winter of 2018. On the 10mb pressure surface, the nascent SPV in April has a weak pole-centred PV anomaly, and by mid-May the jet's mean zonal flow had increased to  $\sim 60 \text{ ms}^{-1}$  (Fig. 5a). In late April through early May there is evidence of a weak eastward propagating  $m = 1$  wave (Fig. 5b) but it disappeared by mid-month. The accompanying polar temperature had decreased by mid-May to  $\sim 200\text{K}$  with a pole-to-30S temperature difference of some 25K (not shown).

Above, at stratopause levels, the localized region of high PV at the SPV's core began to break apart in early May and thereafter had a fragmented structure. Here the focus is on the synoptic-scale features in mid-month. Fig. (6) shows the PV, relative vorticity, divergence, potential temperature, ozone mass mixing ratio, and wind vector patterns on the 1mb pressure surface at 00Z on 19<sup>th</sup> May. A train of isolated PV centres circumscribes the Hemisphere near 60S with another PV feature in the neighbourhood of the pole (Fig. 6a). The train is also readily identifiable in the relative vorticity pattern (Fig. 6b) with, as in the previous case, peak amplitudes greater than  $1.2 \times 10^{-4} \text{ s}^{-1}$  - a value an order of magnitude stronger than that of the less organized divergence / gravity-wave field (Fig. 6c). The depth of the train itself extends downward at least over a scale depth with similar co-located patterns present on the 2mb and 3mb surfaces.

The potential temperature ( $\theta$ ) field (Fig. 6d) shows that at the 1mb level the train is accompanied by a co-located zonal band of low potential temperature ( $\sim 1650\text{K}$ ). One possible inference is that the forementioned polar PV feature is located on a higher isentropic surface (around  $\theta \sim 1800\text{K}$ ). Saliiently, the contemporaneous distribution of the ozone mass mixing ratio (Fig. 6e), shows not only a rich pattern of lower O3 values within the SPV's core, but also a string of high values coincident with the vortex train itself. The latter is consistent with the presence of raised isentropic surfaces beneath the features of enhanced PV. Finally, the wind vector pattern (- Fig. 6f) is consistent with the existence of strong shear on the poleward side of the jet and the presence of troughs linked to the stronger vortices of the train.

Figure (7) gives an indication of the prior development and movement of the isolated sub-planetary features in the period from the 15<sup>th</sup> to the 19<sup>th</sup> May. It depicts at daily interval the PV pattern on the 1700 isentropic surface and shows that the features advect eastward with and are deformed by the in-situ flow. To a measure they retain their amplitude pointing to their predominantly adiabatic character. Their temporal development is reminiscent of the downstream growth of a vortex train forming on a barotropically unstable shear layer rather than a synchronous development of vortices on such a layer.

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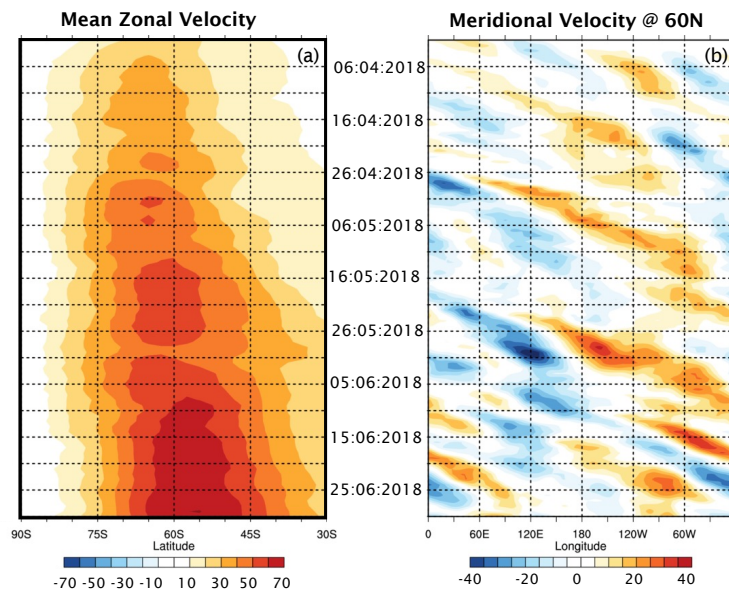
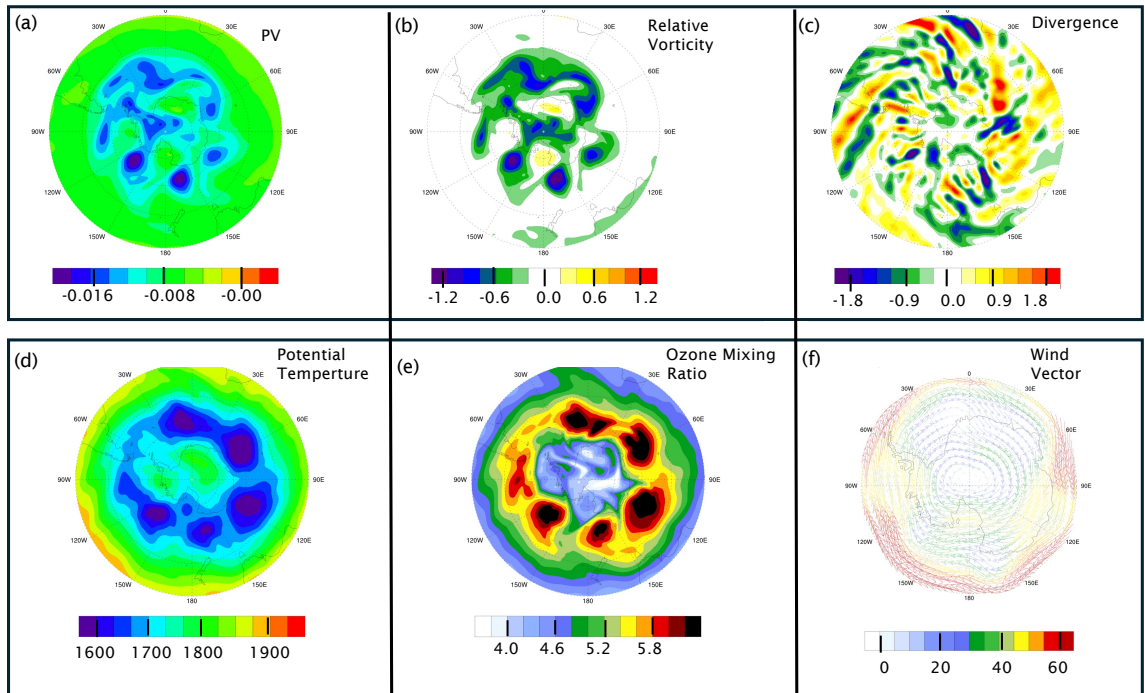


Fig. 5 Counterpart of Fig. (1) but for April-June 2018 in the Southern Hemisphere at 10mb. The zonal velocity  
 265 now pertains to the latitude range 30-90S, and the meridional velocity is for 60S.

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280 Fig. 6 Depiction of the PV( $\text{Km}^2\text{kg}^{-1}\text{s}^{-1}$ ), relative vorticity ( $10^{-4}\text{ s}^{-1}$ ), divergence ( $10^{-5}\text{ s}^{-1}$ ), potential temperature (K), ozone mass mixing ratio ( $10^{-6}\text{ kg kg}^{-1}$ ), and wind vector ( $\text{ms}^{-1}$ ) patterns on the 1mb pressure surface at 00Z on 19<sup>th</sup> May. The panels are polar stereographic projections poleward from 30S, except for panel (f) which is only poleward from 60S.

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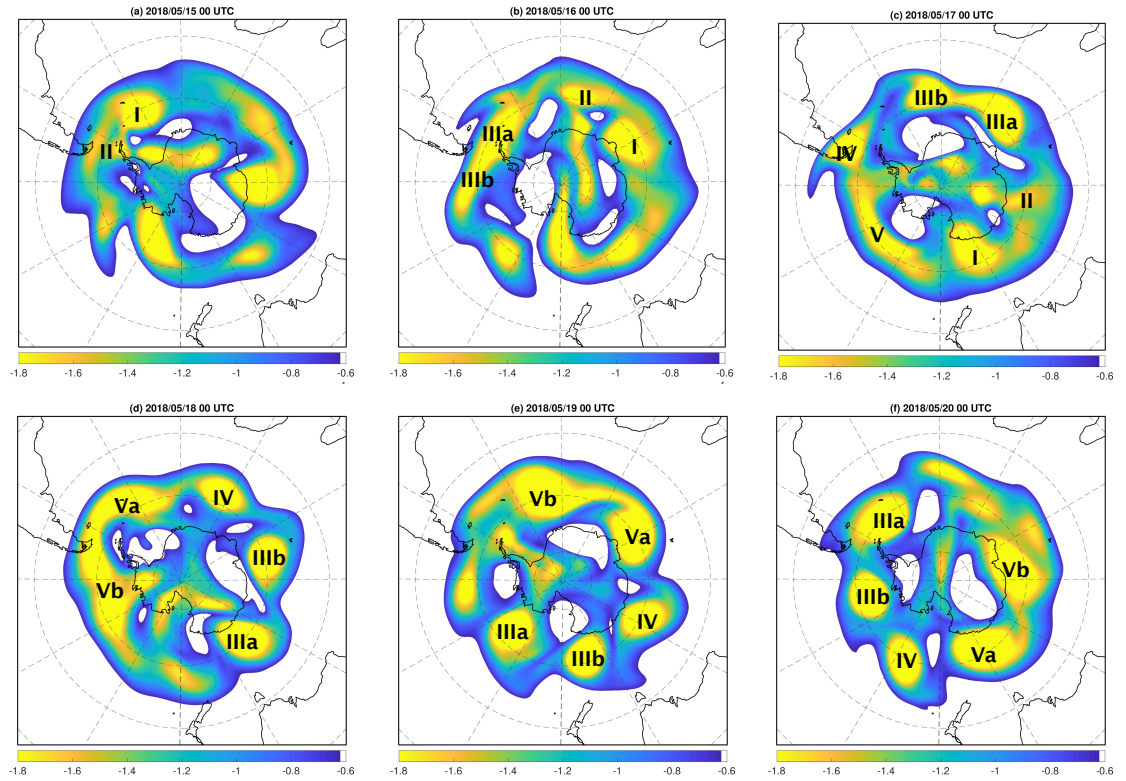


Fig. 7 Evolution of the PV pattern at stratopause levels on the 1700K isentropic surface at daily intervals from 00Z on the 15<sup>th</sup> May to the 19<sup>th</sup> May 2018. The labels I, II etc. attached to the PV maxima indicate the successive locations of the individual features. (Units:  $\text{Km}^2\text{kg}^{-1}\text{s}^{-1} * 10^2$ )

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## 2.5 Features related to an SSW.

A notable Sudden Stratospheric Warming occurred in February 2018, and it has subsequently been the subject of considerable scrutiny. This includes consideration of the event's development (Butler et al 2020), the contribution of GWD (Watanabe et al, 2022), its dynamics and predictability (Rao et al 2018; Karpechko et al. 2018; Knight et al 2020; Erner et al, 2020), the accompanying middle atmosphere chemical signature (Pérot and Orsolini, 2021), its difference to the 2019 SSW (Butler et al 2020), its impact upon the mesosphere (Wang et al, 2019), and role of surface conditions in its occurrence (Lü et al, 2020 ). Here we briefly consider the planetary-scale and annular features of this SSW.

Figure (8) is the counterpart of Fig. 1 but for the 2017-2018 Boreal Winter. It shows that at 10mb the zonal mean velocity (Fig 8a) strengthened during the last week of December, attained a maximum of  $\sim 60 \text{ ms}^{-1}$  in early January, decelerated to  $\sim 30 \text{ ms}^{-1}$  in the period from the 14<sup>th</sup> to the 19<sup>th</sup> of the month, and subsequently oscillated about this value before finally reversing around the 11<sup>th</sup> February. The time-longitude section for the meridional velocity at 60N (Fig. 8b) indicates the presence of significant planetary scale wave patterns. The  $m=1$  wave present in December was supplemented by an  $m = 2$  signal in January and subsequently supplanted by the

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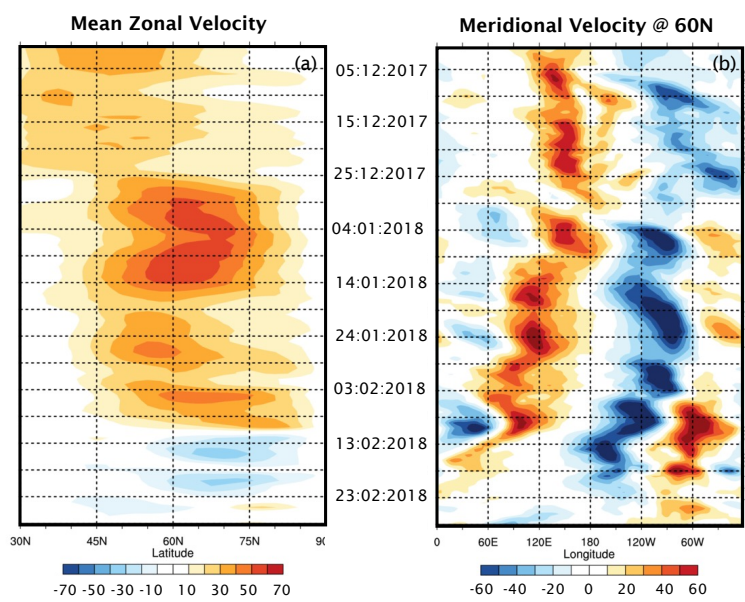
latter ahead of the SSW event. Polar temperature tended to decrease to the 10<sup>th</sup> January, increased by ~15K by the 19<sup>th</sup>, and oscillated thereafter until the onset of the SSW (not shown).

315 Above, at stratopause levels, the presence of the forementioned planetary scale waves were evidenced first by an off-pole PV pattern in December, and a dumb-bell off-pole pattern in January that distorted in the run up to the SSW. Figure (9) shows the patterns of the PV (left column), relative vorticity (centre column) and temperature (right column) on the 1mb (upper row), 2mb (middle row) and 10mb (lower row) surfaces at a time (00Z 12<sup>th</sup> Feb.) shortly after the SPV had satisfied the standard empirical criteria for an SSW. A distinctive and strong split of the SPV's PV distribution is evident at all three levels. The PV patterns on the upper two levels are similar (- as are the relative vorticity patterns), and the range of the temperature fields are also similar. The near-pole temperatures are relatively low (high) at the upper levels (lower level). Together these flow and thermal patterns attest to the vertical coherency of an anomalous PV structure that is 'effectively' centred near or below the 2mb surface.

325 Figure 10 portrays the development of the PV pattern at upper and mid-stratospheric levels at 48-hour intervals immediately ahead of the satisfaction of the SSW criterion. The upper row depicts the patterns on the 1500K isentropic surface at 00Z on the 6, 8 and 10<sup>th</sup> February, and the lower row shows the corresponding patterns on the 850K isentropic surface.

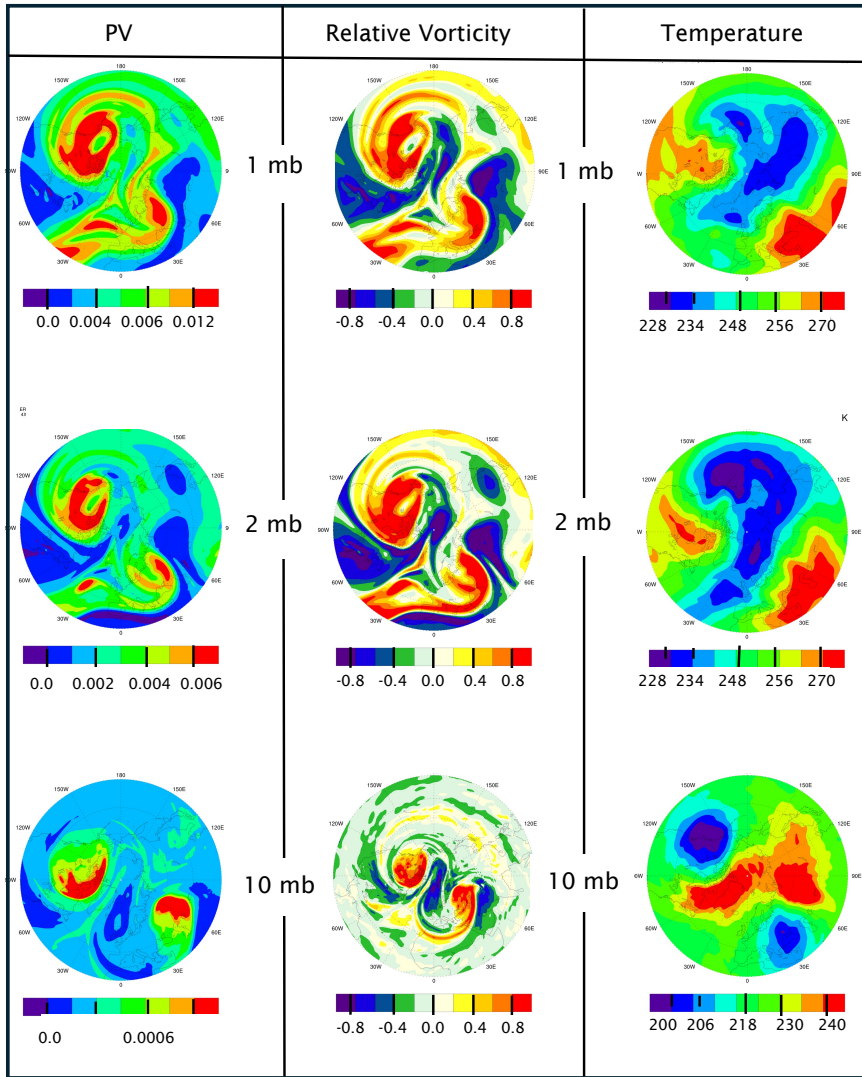
330 On the higher surface an annular-like structure is evident on the 6<sup>th</sup> in the form of an off-pole elliptical structure with embedded sub-planetary scale features. It begins to fragment between the 6<sup>th</sup> and 8<sup>th</sup>, and by the 10<sup>th</sup> notable PV maxima have formed over Canada and western Europe. On the lower theta surface, the initially compact elliptic PV structure (Fig. 10d), first distends (Fig. 10e) and then splits (Fig. 10f). An inference is that the vortex is disrupted earlier and more severely on a higher  $\theta$  surface.

The corresponding thermal patterns (not shown) on the upper (2mb) and lower (10mb) levels possess a dipole structure of opposite polarity that reverses with time. From the 10<sup>th</sup> to the 12<sup>th</sup> February the near polar-  
335 temperature changes at the 1, 2, and 10mb levels are respectively -18K, -32K, and +16K.



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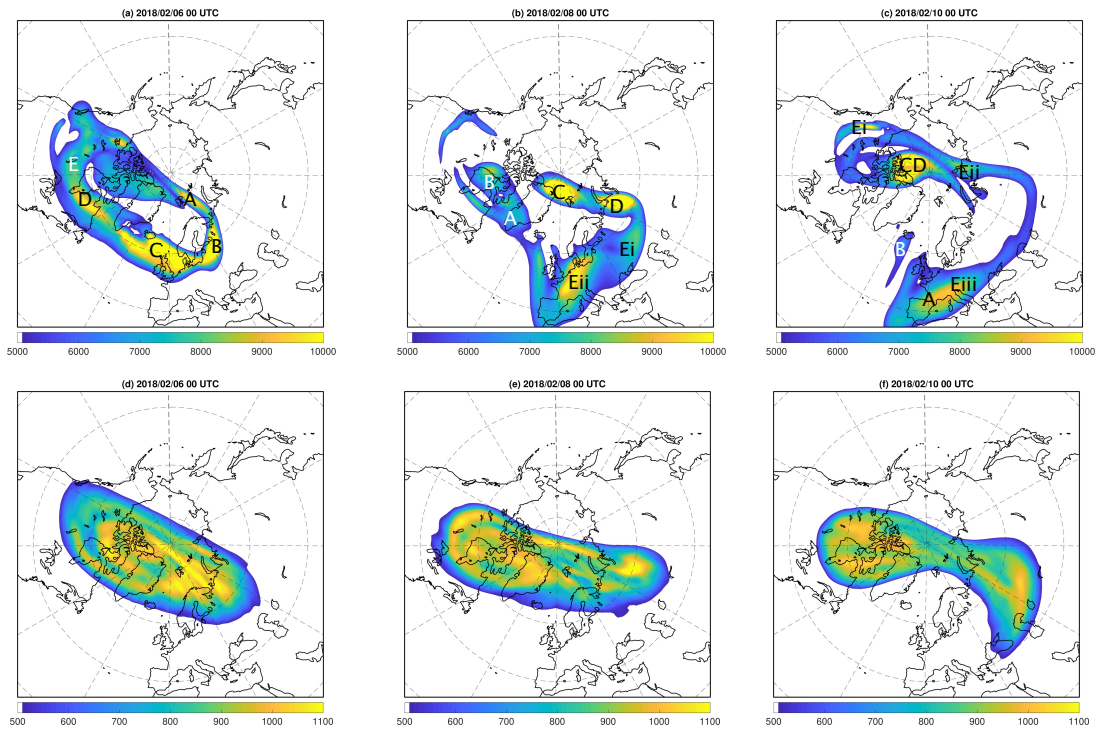
Fig. 8 As for Fig. (1) but for the Winter of 2017-2018.



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Fig. 9 Distribution of the PV( $\text{Km}^2\text{kg}^{-1}\text{s}^{-1}$ ) in the left column, relative vorticity ( $10^{-4}\text{s}^{-1}$ ) in the centre column, and potential temperature in the right column on the 1, 2, and 10mb pressure surfaces at 00Z 12<sup>th</sup> February (- shortly after the SSW).

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Fig. 10 The upper row (panels a-c) displays the PV patterns in the upper stratosphere on the 1500K isentropic surface at 00Z for the 6, 8 and 10<sup>th</sup> February, and the lower row (panels d-f) shows the corresponding pattern but on the 850K surface. The labels A,B,C etc. attached to individual PV maxima identify the successive location of the individual features. (Units:  $\text{Km}^2\text{kg}^{-1}\text{s}^{-1} * 10^6$ )

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## 2.6 Assessment of the Results.

The foregoing case studies are for three fundamentally different flow settings, and are focused on the finer-scaled flow features contiguous to, or related to, the structure of the Stratospheric Polar Vortex's periphery at stratopause levels. In particular, they sought to capture the essence of their structure, temporal evolution, and dynamics.

The results show the features to be present in all three flow settings as synoptic-scale PV extrema located principally on the vortex's periphery in both hemispheres with associated relative vorticity values of  $\sim 10^{-4}\text{s}^{-1}$  and extending typically at least a scale-depth below the stratopause. The thermal and horizontal divergence signatures do not have a comparable localized pattern. The former is consistent with the extended depth of the PV features, and the latter (- in combination with amplitude and synoptic-scale of the vorticity centres and the significantly weaker amplitude of the divergence) suggests that the contribution of the horizontal divergence term to the development of the vertical component of vorticity is weak. This lends a measure of credence to the adoption of

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an idealized barotropic model in the study's theoretical component (Section 3) whilst rendering problematic assuming the flow to be geostrophic and the dynamics to be quasi-geostrophic.

380 Again, the distinctive pattern of the ozone mixing ratio is consistent with the existence and dynamical signature of the isolated PV features whilst the space-time development of the PV pattern itself on key isentropic surfaces sheds light on their translation, development and conservation. In effect these transient sub-planetary and synoptic scale, predominantly monopole, positive PV (and relative vorticity) anomalies translate with and distort the ambient SPV's flow. These observationally-based characterization of the PV features prepares the groundwork for compiling their climatology, and as such constitutes a necessary first step for the task.

385 The presence of the features can in principle contribute to the distribution of chemical constituents within the core. Their prevalence at the core's periphery suggests that they can modify the perceived width of the SPV, potentially help mix air both within the core and across its periphery, and serve to diffuse the jet (Bowman and Chen, 1994; Ishioka K., and Yoden, 1995; Mitsu and Yoden, 2001). The latter surmise points to their possible role, in addition to GWD, in reducing the jet strength at and above the stratopause. Again, the predominantly  
390 monopole structure of the features is consistent with their predilection to evolve from a banded structure of enhanced PV near the SPV's periphery and is strongly reminiscent of the growth to finite amplitude of perturbations of a barotropically unstable flow. Also, the break-up of the stratopause-level annular band of enhanced PV ahead of, during, and after a Sudden Stratospheric Warming indicates the band's possible role in at least the initial development of such an event.

395

### 3.0 Theoretical Model Studies.

Our objective here is to explore the character of perturbations that can evolve on an annular-like flow structure akin to that of a deep, axisymmetric and undisturbed SPV. To this end we parsimoniously adopt an idealized  
400 theoretical model capable of representing fundamental features of such a setting including the occurrence of barotropic instability. The model constitutes non-divergent barotropic flow on a polar  $\beta$ -plane. It can sustain a basic state of a cylindrical (possibly unstable) jet, and it incorporates a suitable representation of the latitudinal variation of the Coriolis effect, but excludes consideration of three-dimensional effects and therefore best represents flows structures that are comparatively deep. These restrictions, together with the model's simple  
405 configuration, imply that our results will constitute a potentially insightful but qualitative guide rather than providing quantitative definitive statements.

#### 3.1 Model Configuration and Methods of Analysis

On a polar  $\beta$ -plane the earth's vorticity is given by  $f = 2\Omega [1 - \frac{1}{2}(r^*/R)^2]$ , where  $r^*$  denotes radial distance on the  
410 plane and  $R$  refers to the Earth's radius. Then the model's governing equation takes the form

$$D(Z^*)/Dt^* = 0, \tag{1}$$

where  $D/Dt^*$  denotes the material derivative for two-dimensional flow, and  $Z^*$  is the 'system-relative' absolute vorticity

$$Z^* = \zeta^* - 2\Omega [1 - \frac{1}{2}(r^*/R)^2].$$

415 Here  $\zeta^*$  denotes the relative vorticity and is such that  $\zeta^* = \nabla^2 \psi^*$  with  $\psi^*$  denoting the stream function. In the following the dimensional starred variables are replaced by non-dimensional unstarred variables:-  $r = r^*/R$ ,  $Z = Z^*/(2\Omega)$ ,  $\zeta = \zeta^*/(2\Omega)$ , and an azimuthal velocity  $V = V^*/(2\Omega R)$ .

To facilitate the derivation of analytical results we let the ‘system relative’ absolute vorticity of the undisturbed circumpolar vortex comprise three concentric zones (see Fig.11) of respective uniform absolute  
 420 vorticity ( $Z_I, Z_{II}, Z_{III}$ ), given by

$$Z_I = 0, \quad \text{for } r < a, \quad (2a)$$

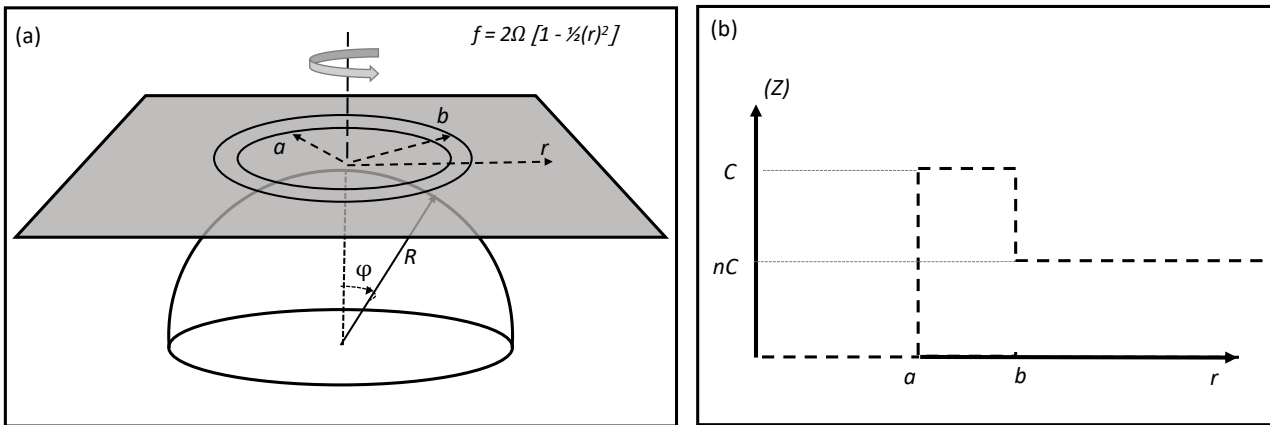
$$Z_{II} = C, \quad \text{for } a \leq r \leq b, \quad (2b)$$

$$Z_{III} = nC, \quad \text{for } r > b. \quad (2c)$$

This represents a relatively quiescent innermost core ( $r < a$ ), an annular region ( $a \leq r \leq b$ ) yielding an absolute  
 425 vorticity maximum, and an outer domain ( $r > b$ ) of weaker vorticity (i.e.  $n < 0$ ).

The accompanying axisymmetric basic flow ( $V_I$ ) takes the form

$$V_I = (1/8)r^3, \quad \text{for } r < a, \quad (3a)$$



430 Fig. 11 Panel (a) is a schematic of the polar  $\beta$ -plane and the geometry for the initial distribution of the vorticity.  
 Panel (b) shows the radial distribution of three concentric zones of uniform  $Z$  such that there is annular  
 band of enhanced  $Z$  located between ( $a < r < b$ ).

435

440

$$V_{II} = \frac{1}{2}Cr [1 - (a/r)^2] + (1/8)r^3 \quad \text{for } a \leq r \leq b, \quad (3b)$$

$$455 \quad V_{III} = \frac{1}{2}Cr [n + (b/r)^2 (\varepsilon - n)] + (1/8)r^3 \quad \text{for } r > b, \quad (3c)$$

It is also pertinent to note that,

$$(V_a/a) = (1/8)a^2, \quad (4)$$

$$(V_b/b) = \frac{1}{2}[C\varepsilon + (1/4)b^2], \quad (5)$$

450 where  $(V_a/a)$  and  $(V_b/b)$  denote respectively the angular velocity at  $r = a$  and  $b$ .

Here  $\varepsilon = [1 - (a/b)^2]$  is a measure of the width of the annular region relative to its radial location, and the  $(1/8)r^3$  term in Eqs (3a-c) is attributable to the  $\beta$ -effect. In effect the parameters  $(a, b, C, n)$  determine the basic state of the vortex core, with typically  $C \leq 2$ ,  $b \sim \frac{1}{2}$ , and  $a$  and  $b$  such that  $\varepsilon$  is capable of spanning across its permissible  $[0, 1]$  range.

455 The parameter  $(nC)$  determines the relative vorticity ( $\zeta$ ) distribution in the exterior (i.e.  $\zeta_{III} = nC + \frac{1}{2} r^2$ ). Its value is bounded by the requirements that the absolute vorticity in the far-field be less than in the polar region ( $nC < 0$ ), and the basic state flow should be inertially stable ( $nC > -1$ ). A more stringent condition is the requirements that at a radial distance, say  $r = r_c$ , the velocity is significantly reduced and  $\zeta$  approaches zero (i.e.  $nC \sim -\frac{1}{2} r_c^2$ ). For such a reduction to occur by say  $\sim 30N$  then typically  $0.7 > r_c > 1.2$ .

460 Figure 12 shows illustrative examples of the basic state flow profiles ( $V$ ) representable by Eqs. (3). For the  $r \leq b$  domain, the jet profiles correspond to maxima of  $90 \text{ ms}^{-1}$  and  $135 \text{ ms}^{-1}$  located at  $b = \frac{1}{2}$  ( $\approx 60N$ ), for wide ( $\varepsilon = 0.91$ ), intermediate ( $\varepsilon = 0.75$ ) and narrow ( $\varepsilon = 0.36$ ) annuli. Note that, for  $C$  in the range  $(\frac{1}{2} - 2)$  and  $\varepsilon$  in the range  $(\frac{3}{4} - 1)$ , then  $v_b \approx 1/4(C\varepsilon)$ , and the velocity profiles shown in the outer domain ( $r > b$ ) span those for realistic values of  $r_c$ . In essence the parameter settings permit a range of appropriate velocity profiles.

465 Results are derived for the linear and non-linear response of perturbations of stipulated basic states. The linear component includes a normal mode analysis that establishes the growth rate and azimuthal wavenumber ( $m$ ) of unstable modes, and an analysis of the response to a specific form of non-normal mode initial perturbation. The non-linear response is simulated using a contour-dynamics technique (Dritschel, 1989) with adjustments of the standard contour advection technique to (a) account for the specification of the absolute as opposed to the relative  
470 vorticity and (b) circumvent the standard contour advection stipulation of non-zero absolute vorticity in the outermost domain. The forward integration is conducted using a 4<sup>th</sup> order Runge-Kutta scheme and, depending upon the purpose of the simulation, the initial state is perturbed by adding either weak amplitude random noise or a finite amplitude displacement to the location of the domain interface at  $r = b$ .

## 475 3.2 Normal Mode Analysis

### 3.2.1 Derivation of the Instability Criterion

Small amplitude perturbations of the governing equation (Eq.1) satisfy the linear equation,

$$\{\partial/\partial t + (V/r)\partial/\partial\theta\}q' + u' \partial/\partial r (Z) = 0 \quad (6)$$

480 Here  $(q', u')$  refer to the perturbation vorticity and radial velocity with  $q' = \nabla^2 \psi'$ . Likewise,  $(Z, V)$  are, as indicated earlier, the basic state absolute vorticity and azimuthal velocity (Eqs. 2 and 3).

Adopting a 'PV Perspective' for the perturbations (Davies and Bishop, 1994) solutions of Eq. (6) are sought for stream-function perturbations ( $\psi'$ ) of the form

$$\psi' = \psi'_{\alpha} + \psi'_{\beta},$$

where the two components represent wave perturbations propagating respectively on the vorticity discontinuities  
 485 at the domain interfaces located at  $r = a$  and  $b$ . The associated stream functions are

$$\psi'_{(a,b)} = F_{(a,b)}(r) \sin(m\theta - \omega t),$$

and for basic states of the form given by Eqs. (3),  $F$  has a  $r^m$  and  $r^{-m}$  dependency respectively within and exterior to the pertinent interface. On applying appropriate conditions at  $r = 0$ , as  $r \rightarrow \infty$ , and at the interfaces, the wave amplitudes at the two interfaces,  $F_{(a,b)} = (A, B)$ , are linked by the relationships,

$$490 \quad (\omega/m)A = (V_a/a)A + \frac{1}{2}(C/m) [A + (1-\varepsilon)^{m/2}B], \quad (7a)$$

$$\text{and} \quad (\omega/m)B = (V_b/b)B - \frac{1}{2}(C/m)(1-n) [B + (1-\varepsilon)^{m/2}A] \quad (7b).$$

The three-terms on the right-hand side in each of Eqs. (7a, b) correspond respectively to :- translation with the ambient angular velocity (Eqs. 3d, e); a ‘Rossby-wave type’ contribution of the in-situ wave; and a far-field ‘Rossby-wave type’ contribution due to the influence of a wave at one interface acting upon that at the other  
 495 interface. In the absence of the latter far-field contributions, equivalence of the phase velocities would require - see Eqs. (4, 5)

$$\mathcal{D} = 0, \quad (8a)$$

$$\text{where } \mathcal{D} = [m \varepsilon (1+\mu) - (2-n)] \quad (8b)$$

$$\text{with } \mu = b^2/(4C).$$

500 We return to consider the import of Eq. (8a) later but proceed here to note that together Eqs (7a, b) yield the linear system’s wave-dispersion relationship. After some manipulation the instability criterion can be written as

$$\Delta > 0, \quad (9a)$$

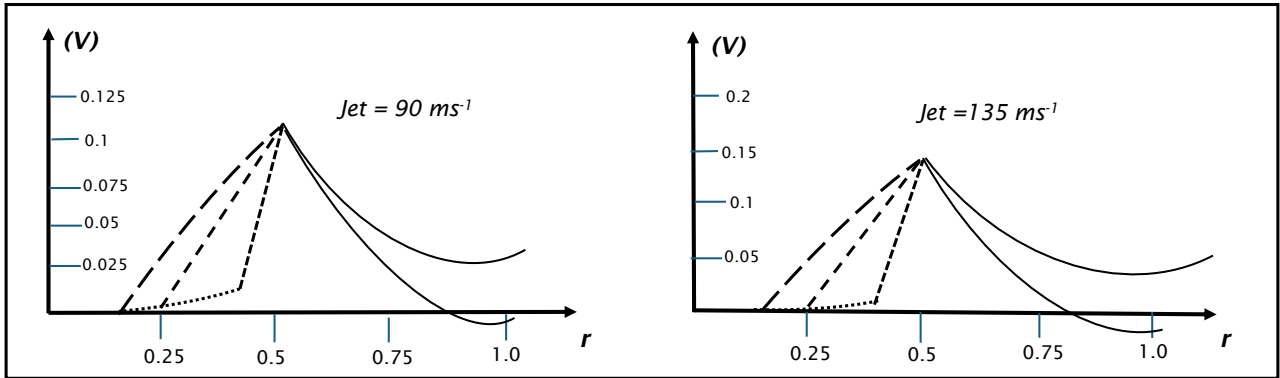
$$\text{with } \Delta = [-\mathcal{D}^2 + 4(1-n)(1-\varepsilon)^m], \quad (9b)$$

and for unstable waves, the growth rate ( $\sigma$ ) and angular phase speed ( $v$ ) are given by,

$$505 \quad \sigma = (1/4) C \sqrt{\Delta}, \quad (9c)$$

$$v = \frac{1}{2} [(V_a/a + V_b/b) + (nC)/m], \quad (9d)$$

In line with the necessary criteria for barotropic instability the annular region needs to be a maximum of absolute vorticity (see Eq. 9b), i.e.  $(1-n) > 0$ .



510

Fig. 12 A sample of the model's possible basic state velocity ( $V$ ) profiles corresponding to a dimensional jet strength of  $90 \text{ ms}^{-1}$  (left) and  $135 \text{ ms}^{-1}$  (right) located at located at  $b = \frac{1}{2}$  ( $\approx 60\text{N}$ ). In each panel the three curves for  $r < b$ , depicted with long, intermediate and short dashes, refer respectively to wide ( $\varepsilon = 0.91$ ), intermediate ( $\varepsilon = 0.75$ ), and narrow ( $\varepsilon = 0.36$ ) annuli, and the dotted line is the velocity profile, where applicable, in the  $r < a$  sector. The two full curves beyond  $r = b$  encompass the physically constrained band (i.e.  $0.7 > r_c > 1.2$ ) of velocity profiles.

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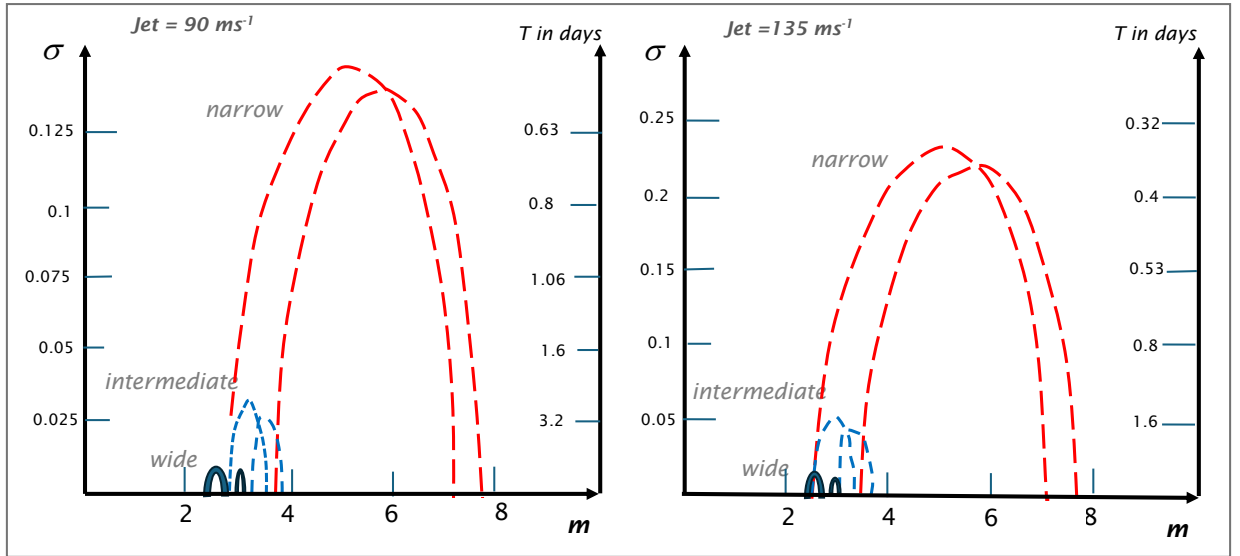


Fig.13 Growth rate ( $\sigma$ ) displayed as a function of the wavenumber ( $m$ ) for a jet of strength  $90 \text{ ms}^{-1}$  (left) and  $135 \text{ ms}^{-1}$  (right) located at  $b = \frac{1}{2}$  ( $\approx 60\text{N}$ ). The narrow (red), intermediate (blue) and wide (black) categories denote respectively  $\varepsilon = (0.91; 0.75; 0.36)$  and the two curves in each category span the range of acceptable  $r_c$  values. Note the differing scale of the ordinates.

535

### 3.2.2 Sample Growth Rate Curves.

A sample of the dependency of the instability upon the configuration of the basic state is illustrated in Fig. 13. It shows the growth rate ( $\sigma$ ) as a function of the wavenumber ( $m$ ) for settings corresponding to those referred to earlier (- see Fig.12). In terms of conventional flow parameters, the growth rate is seen to increase markedly with jet strength, decreases strongly as the sharpness of the jet on its poleward side decreases (i.e. width of the annulus increases), and is less sensitive to the velocity profile in the shear zone (as determined by the value of  $r_c$ ). In effect the sensitivity to the jet skewness is primarily governed by the structure within the core. These results are in qualitative agreement with, and complement those of, earlier barotropic instability studies (see in particular Hartman, 1983) but a significant difference (- discussed further below) is the lack of unstable  $m = 1$  or  $2$  modes.

545 The large growth rate of the sub-planetary modes is notable since a pragmatic lower bound for an unstable mode's growth rate would be that  $\sigma$  should exceed  $\tau$ , where  $\tau \sim (10 \text{ days})^{-1}$  is the radiative decay timescale (Shine, 1987) of deep perturbations within the polar-night vortex in the upper stratosphere.

550 3.2.3 An Instability Interpretation and Ready Reckoner,

Figure 13 provides a useful, but non-exhaustive, display of the instability's sensitivity to the basic state configuration. To pinpoint the dependencies illustrated by, and dynamics underlying, the results displayed in this Figure, we incorporate the PV-based phenomenological interpretation (Lighthill, 1967; Hoskins et al 1985) and mathematical formulation (Davies & Bishop, 1994) of barotropic and baroclinic instability. In this framework the present form of instability is viewed in terms of two counter propagating waves on the opposite-signed PV jumps at  $r=a$  and  $r=b$  that are held stationary relative to one another by the differing in-situ flow at their respective locations. In such a configuration the waves inter-dependency can promote mutual amplification and possibly a modification of their azimuthal phase velocities.

From this perspective it is pertinent to recall that  $\mathcal{D} = 0$  implies that phase locking of the two waves is achieved without an inter-wave contribution so that the two perturbations are in quadrature and their influence is constrained to yield maximal growth. From Eq. (7) we see that a mode with a small (large) wavenumber yields a large (small) in-situ Rossby-type contribution to the phase speed rendering it more difficult (easier) to phase-lock the two interface perturbations.

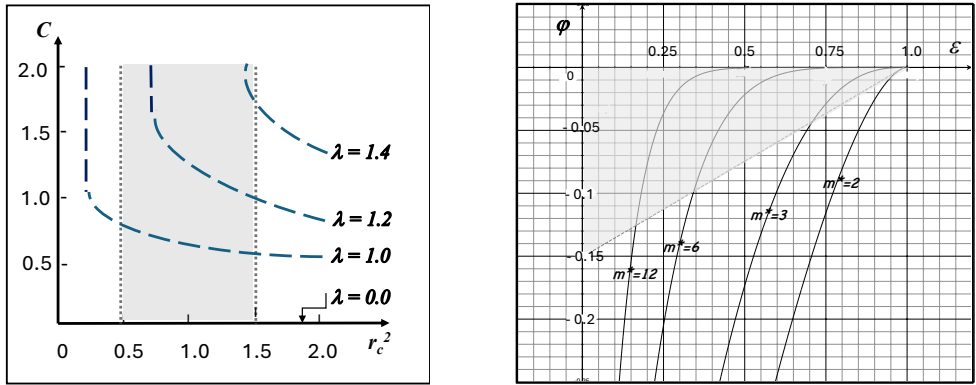
The value of this perspective follows from noting that  $\mathcal{D} = 0$  also implies (Eq. 9b) that there is an azimuthal wave number ( $m_0$ ) for which a wave perturbation is unstable with

$$m_0 = (2 - n) / [\varepsilon (1 + \mu)] \quad (10a)$$

In effect  $m_0$  is the ratio of the sum of the two vorticity discontinuities to the difference in the angular velocities across the annular region. It can be reformulated as

$$m_0 \varepsilon = 2 [1 + r_c^2/(4C)] / [1 + b^2/(4C)] \quad . \quad (10b)$$

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Fig. 14 Left panel displays  $\lambda$  in the space of  $[C, (r_c)^2]$  for  $b = \frac{1}{2}$  with the realistic range for  $r_c$  lightly shaded. Right panel shows  $\varphi$  as a function of  $\varepsilon$  for selected values of the wave number  $m^*$ , and the permissible domain is confined to the lightly shaded wedge-shaped region with  $(m^* \varepsilon) > 2.0$ .

585

Thus, for specified values of the external parameters, satisfaction of Eqs (10a, b) signifies the instability of the wavenumber  $m_0$ . The accompanying growth rate is given by Eq. (9c), so that

$$\sigma = \frac{1}{2} C [(1 - n) (1 - \varepsilon)^m]^{1/2} \quad (11a)$$

In conjunction with Eq. (10b) it will later prove helpful to recast Eq. (11a) in the form

$$\sigma = \frac{1}{2} \{C [C + \frac{1}{4}(r_c^2)] (1 - (m_0 \varepsilon)/m_0)\}^{1/2} \quad (11b)$$

Trenchantly,  $m_0$  provides (for  $m_0 > 2$ ) an excellent estimate of the wavenumber ( $m = m^*$ ) of the most unstable mode. This follows from (a) deducing that

$$(m^*/m_0) = 1 + \lambda \varphi \quad (12)$$

$$\text{where } \lambda = [1 + \frac{1}{2} r_c^2] / \{ [1 + r_c^2/(4C)] [1 + b^2/(4C)] \}$$

$$\text{and } \varphi = (1 - \varepsilon)^{m^*} \ln(1 - \varepsilon) / (\varepsilon) .$$

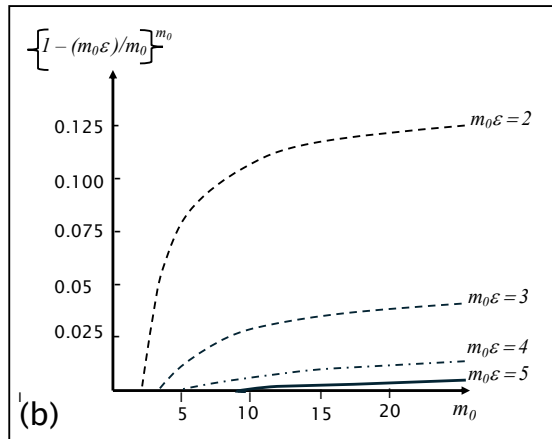
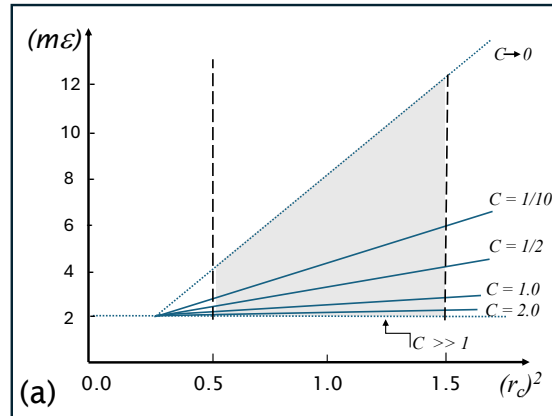
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and (b) noting from Fig. (14) that  $\lambda \approx 1$  and  $\varphi \sim -0.1$  for the range of pertinent basic state settings.

Thus Eqs. (10, 11) enables the simple determination of the most unstable mode and the subsequent evaluation of its attendant growth rate. In effect the two panels of Figure (15) together constitute an instability ‘Ready Reckoner’. For a stipulated specification of the external parameters, the procedure is as follows :-

- 600 (i) Fig. (15a) determines the value of  $(m_0 \varepsilon)$  as a function of  $r_c^2$  and  $C$ ,  
(ii) an estimate of the most unstable wavenumber ( $m_0$ ) is then known given the specification of  $\varepsilon$ ,  
(iii) from Fig. (15b) and in conjunction with Eq. (11b), the factors influencing the associated growth rate can be discerned, and an estimate made of its value.

It is noteworthy that the growth rate is highly dependent upon the value of  $C$ , favoured by higher values  
605 of  $r_c^2$ , and is sensitive to the value of  $m_0$  (- see Fig. 15b). In summary there is: - a preferred normal mode with the largest growth rate; the spectral window ( $\delta m_0$ ) of unstable modes is such that  $(\delta m_0) < 1/2 m_0$ , so that it broadens for narrower annuli; the occurrence of unstable high wavenumbers (say,  $m^* > 8$ ) requires narrower annular regions (- small  $\varepsilon$ ); unstable sub-planetary scale waves (say,  $3 < m^* < 8$ ) exist for a wide range of external settings; and in this limit the graver modes ( $m = 1, 2$ ) are stable. In effect the Ready Reckoner provides a compact indicator of the  
610 scale and growth rate of the most unstable modes over the realistic range of external parameters. Moreover, the results, in conformity with the observational cases studies of Section 2, indicate that sub-planetary and synoptic-scale features can evolve preferentially for a wide-range of realistic annular flow settings.



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Fig. 15 A sensitivity guide to the most unstable normal mode: Displayed in panel (a) is a plot of  $(m_0 \epsilon)$  as a function of  $(r_c)^2$  for a range of  $C$  with  $b = 1/2$ . Again the realistic range for  $r_c$  is the lightly shaded region. Panel (b) depicts the growth factor  $(1 - (m_0 \epsilon)/m_0)^{m_0}$  as a function of the wavenumber  $m_0$ .

620

### 3.2.4 Stability of the $m = 1, 2$ Modes

The character of the gravest modes ( $m = 1, 2$ ) are not adequately represented by Eqs, (10) and (11). However, they  
 625 are of particular interest in connection with the occurrence of an SSW, and therefore merit specific attention. For  
 these two modes the instability criterion, *sic.* the parameter  $\Delta$  (Eqs. 9), equates to,

$$\Delta = - \{ \varepsilon^2 (1 + \mu)^2 - 2\varepsilon [n + \mu(2-n)] + n^2 \} \quad \text{for } m=1,$$

and  $\Delta = - \{ \varepsilon^2 [\mu(2+\mu) + n] - \varepsilon [n + \mu(2-n)] + (n^2/4) \}$  for  $m=2$ ,

$$\text{where, as before, } \mu = b^2/(4C) \text{ and } n = -1/2(r_c^2/C).$$

630 For realistic values of  $\mu$  and  $n$ , generally  $\Delta < 0$ , so that both modes are indeed stable. Notwithstanding  $\Delta$  can be  
 small ( $0 > \Delta > -0.2$ ) for  $m = 2$  across the entire range of  $\varepsilon$  values, and small for  $m = 1$  as  $\varepsilon \rightarrow 0$ . (This will become  
 a significant factor in the next sub-section when we consider a mechanism that runs counter the non-growth of  
 these normal modes.)

### 635 3.3 Initial-value Dependency.

Consider a configuration of our model system that at the initial instant comprises a pre-existing small amplitude  
 wave on the outer ( $r = b$ ) interface but with no perturbation on the inner ( $r = a$ ) interface. The analogue  
 stratospheric setting would be the combination of:- (a) the distortion of the outer interface by, say, a Rossby wave  
 emanating from tropopause elevations and propagating upward preferentially along the waveguide formed by the  
 640 sharp PV gradient on the polar vortex's outer edge; and (b) the inner interface being initially substantially  
 undisturbed being protected by the reversed latitudinal PV gradient on an annular band's inner side.

To replicate the model's evolution of such a configuration we now allow the stream functions of the two  
 interface waves to assume the form,

$$\psi'_1 = \mathcal{A}(t) \sin [m\theta - \delta_1(t)], \quad \text{on } r=a \quad (13a)$$

645 and  $\psi'_2 = \mathcal{B}(t) \sin [m\theta - \delta_2(t)].$  on  $r= b$  (13b)

In effect the waves are allowed to have a time-varying amplitudes ( $\mathcal{A}, \mathcal{B}$ ) and phases ( $\delta_1, \delta_2$ ) at respectively  $r=(a,$   
 $b)$ , with  $\mathcal{B}(0)=\mathcal{B}_0$  and  $\mathcal{A}(0)=0$ . Thus, in contrast to normal mode analysis which allows the time development of  
 perturbations of a fixed spatial form, both the amplitude and shape of the non-normal modes evolve with time.

Substitution into Eq. (6) yields the following triad of predictive equations,

650  $\partial/\partial t (\mathcal{A}) = -1/2 (C\gamma) \mathcal{B} \sin \delta,$  (14a)

$$\partial/\partial t (\mathcal{B}) = -1/2 (C\gamma) (1-n) \mathcal{A} \sin \delta,$$
 (14b)

$$\mathcal{A}\mathcal{B} \partial/\partial t (\delta) = +1/2 C \{ (\mathcal{A}\mathcal{B}) \mathcal{D} - \gamma [(1-n) \mathcal{A}^2 + \mathcal{B}^2] \cos \delta \},$$
 (14c)

$$\text{where } \gamma = (1 - \varepsilon)^{m/2} = (a/b)^m, \text{ and } \delta \text{ is the relative phase-difference } \delta = (\delta_2 - \delta_1).$$

A trenchant inference is that Eqs (14a, b) indicate that the inner and outer waves can grow synchronously provided  
 655 only that that the basic state configuration satisfies the necessary (but not necessarily sufficient) normal mode  
 criterion for instability,  $(1-n) > 0$ , and that  $\delta$  remains in the range  $[-\pi, 0]$  with maximum growth prevailing when  
 $\delta = -\pi/2$ . Significantly this transient growth prevails irrespective of the value of  $\Delta$ , and pertains even for grave ( $m$   
 $=1$  and  $2$ ) perturbations that are stable for normal mode perturbations.

660 The triad possess two temporal invariants,

$$\partial/\partial t [(1-n)\mathcal{A}^2 - \mathcal{B}^2] = 0, \quad (15a)$$

$$\text{and} \quad \partial/\partial t \left\{ \frac{1}{2}(\mathcal{D}/\gamma) [(\mathcal{A}^2 + \mathcal{B}^2)/(2-n)] - \mathcal{A}\mathcal{B}\cos\delta \right\} = 0. \quad (15b)$$

These invariants can be exploited to show that the growth of the wave on the inner interface ( $r = a$ ) is given by,

$$\partial/\partial t (\mathcal{A}) = (1/4)C [\Delta\mathcal{A}^2 + 4\gamma^2\mathcal{B}_0^2]^{1/2} \quad (16)$$

$$665 \text{ so that } \mathcal{A} = (2\gamma/\Delta^{1/2})\mathcal{B}_0 \sinh [\Delta^{1/2}T] \quad \text{for } \Delta > 0 \quad (17a)$$

$$\text{and } \mathcal{A} = (2\gamma/\Delta^{*1/2})\mathcal{B}_0 \sin [\Delta^{*1/2}T] \quad \text{for } \Delta^* = -\Delta > 0 \quad (17b)$$

$$\text{where } T = (1/4)Ct$$

Note that for an unstable configuration ( $\Delta > 0$ ), the factor  $\Delta^{1/2}T$  is the normal mode growth rate (Eq. 9c), and the coupled waves evolve toward a state of exponential growth. For a stable configuration ( $\Delta^* > 0$ ) the amplitude attains  
670 a maximum of

$$\mathcal{A}_{\max} = 2(a/b)^m \mathcal{B}_0 / \Delta^{*1/2} \quad \text{at the time } t = 2\pi / (C\Delta^{*1/2}). \quad (17c)$$

For both settings, the initial short time evolution is given by

$$\mathcal{A} \approx 2(a/b)^m \mathcal{B}_0 T, \quad (17d)$$

675 The dependency upon  $(a/b)^m$  indicates that it is larger for a narrow annular region and planetary-scale modes. Pointedly this growth can be significant. For example, if  $(a/b) = 1/2$  and  $C = 1/2$ , then in dimensional terms  $\mathcal{A}$  would attain the value of  $\mathcal{B}_0$  in  $\sim 2/3$  day for  $m = 1$  and a value of  $\sim 4/3$  days for  $m = 2$ , so that the wave-mean flow interaction would rapidly become non-linear. Together Eqs. (17c, d) establish the form of the basic state that would yield significant transient growth of the  $\mathcal{A}$  wave.

680 The accompanying amplitude of the  $\mathcal{B}$ -wave and the phase-difference are,

$$\mathcal{B}^2 = (1-n)\mathcal{A}^2 + \mathcal{B}_0^2 \quad (17e)$$

$$\text{and} \quad \cos^2\delta = (1/4) (\mathcal{D}/\gamma)^2 (\mathcal{A}/\mathcal{B}_0)^2 / [1 + (1-n)(\mathcal{A}/\mathcal{B}_0)^2] \quad (17f)$$

Eq. (17e) implies that after significant growth the amplitude ratio of the two waves would be

$$(\mathcal{A}/\mathcal{B}) = 1/(1-n)^{1/2} = 1/[1+r_c^2/(2C)]^{1/2}$$

685 so that for a weak vortex the  $\mathcal{B}$  wave would dominate.

A feature of Eq. (17f) is that, for a flow setting with  $\mathcal{D} = 0$ , the  $\mathcal{A}$  and  $\mathcal{B}$  waves are *ab initio* phase-locked with  $\delta = -\pi/2$  and hence the optimum growth criterion is sustained (Eqs. 14a, b).

The seminal deduction of the above analysis is that, for an annular basic state, the initial growth rate and wavenumber of the fastest growing non-normal mode can be, and generally is, significantly different  
690 to that of the fastest growing normal mode. Indeed, for a basic state that would yield a most unstable synoptic-scale normal mode, there can exist  $m = 1$  and 2 non-normal mode perturbations with an initial growth rate surpassing that of the fastest normal mode.

A further implication arises because the stratosphere's transmissivity to upward propagating PRWs serves as a 'scale-selection' mechanism only allowing these gravest waves to reach well into the stratosphere to disturb  
695 the vortex's rim at higher elevations. Thus, it is the gravest waves that could initiate the fore-mentioned significant 'scale-sensitive' growth.

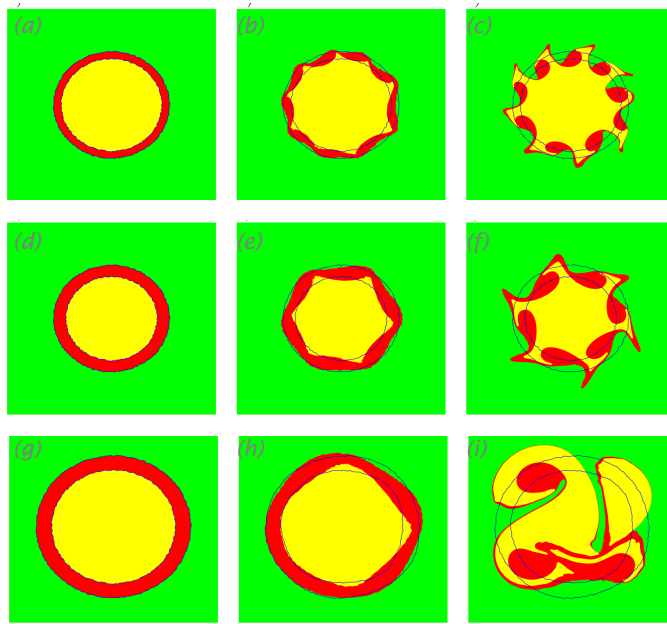
### 3.4 Non-linear Development.

700 For the same model configuration, we examine the non-linear evolution of perturbations to the model's stipulated basic state. In Figure (16) the three rows are for different initial configurations each with a jet of  $120 \text{ ms}^{-1}$  but located at  $b = \frac{1}{2}$  (- first two rows but with different annuli widths) and at  $b = 0.67$  (third row). The three columns depict respectively the initial small amplitude randomly perturbed initial states (left column), an early phase of development (central column) and the mature non-linear (right column) patterns. In accord with the linear normal-  
705 mode instability theory, the upper two rows capture the development of the synoptic-scale most unstable wavenumbers ( $m = 6$  and  $9$ ) that then leads to an aggregation of the bands into quasi-isolated mono-signed vortices each attached to its neighbours by thin filaments. The third row, for which linear theory indicates that only the  $m = 3$  and  $4$  waves are unstable, shows that after an extended time (- the calculated growth rates are weak) there is a complex break-up of the annular structure.

710 Figure (17) shows an example of the evolution of an initial finite amplitude  $m = 2$  perturbations of the  $r = b$  interface but with no perturbation of the inner ( $r = a$ ) interface. This setting is that envisaged in the previous sub-section, and pertains for  $(C, a, b, n) = (1.0, 0.447, 0.5, -0.5)$  that again corresponds to a jet of  $120 \text{ ms}^{-1}$  and perturbed by a wave with an amplitude of  $0.03$ . Again, in harmony with the results derived earlier, the evolution exhibits a notable growth over a period of  $3.2$  days.

715

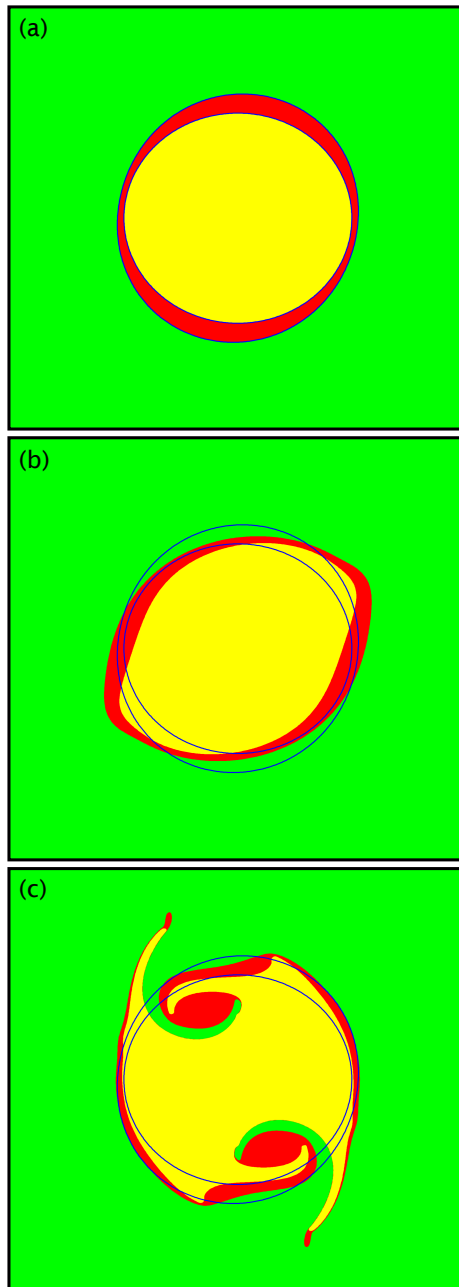
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Fig. 16 Evolution of three different annular bands subjected to initial small amplitude random perturbations. The initial states are shown in panels (a, d and g) for which the external parameters ( $a$ ,  $b$ ,  $C$ ,  $n$ ) take the respective values of  $(0.434, 0.5, 1.71, -0.57)$ ,  $(0.4, 0.5, 1.12, -0.63)$ , and  $(0.53, 0.67, 0.20, -0.65)$ . In each case the jet strength is  $120\text{ms}^{-1}$ . Panels (b, e and h) display an early quasi-linear development phase, and panels (c, f, i) capture a mature non-linear phase.

730



735

Fig. 17 Development of an annular band's absolute vorticity when the outer interface ( $r = b$ ) is subject to an initial finite-amplitude  $m = 2$  wave perturbation. The simulation is for  $(a, b, C, n)$  taking the values  $(0.447, 0.5, 1.0, -0.5)$  with an initial wave amplitude of  $(0.03)$ . Panel (a) displays an initial state, and the patterns displayed in panel (b) and panel (c) are in dimensional terms after 1.3 and 3.2 days.

740

745

It results in the formation of two vortex structures each possessing a trailing filamentary structure, and it relates to the split classifications that can emerge during an SSW event.

750 It is also pertinent to note the results of two null simulations of this case. First for an initial small amplitude random noise perturbation of both interfaces, there evolves the (expected according to our normal mode theory) growth of a wave number  $m = 12$ . The second simulation corresponds to an initial configuration comprising a jet of the same strength at  $r = b$  but now with a uniform absolute vorticity distribution across the entire  $r < b$  domain. When subjected to the same 0.03 amplitude wave perturbation at  $r = b$ , the configuration evolves to a steadily  
755 rotating ellipse with an aspect ratio close to unity. In effect, these ‘null’ simulations indicate that the vortex breakdown is attributable explicitly to the existence of the annular band. This underlines and illustrates the significance of the results presented in sub-section 3.2.4, and points to the efficacy of the gravest-mode Rossby wave forcing to the break-up of an annular stratospheric vortex.

### 760 3.5 Model Critique and Assessment of the Results.

This study’s examination of the possible barotropic instability of the Polar Night Jet was geared not to replicating (or refuting) the results of the previous numerous related studies but rather was aimed at seeking a deeper understanding of the associated processes. Our results are constrained by the simplicity of the adopted polar  $\beta$ -plane configuration and a non-divergent barotropic model, and here we first comment in turn upon these  
765 restrictions.

The polar  $\beta$ -plane is a reasonable assumption for flow features confined substantially to the polar and extra-tropical latitudes because the Coriolis effect is well represented at these latitudes. By way of comparison, for barotropic flow on the sphere :- (a) the Circulation Theorem imposes an integral constraint on the net globally area averaged relative vorticity, and (b) the requirement of inertial/symmetric stability of an axisymmetric basic state the relative vorticity must also be zero at the equator. On a polar  $\beta$ -plane there is no a priori equivalent to the integral constraint whilst a condition of zero relative vorticity imposed at the  $\beta$ -plane’s pseudo-equivalent of the equator (that is,  $r_c^2 = 2$ ) would imply for our model that a state of (unlikely) neutrality to symmetric perturbations pertains in the entire region between  $b$  and  $r_c$  (in effect the surf zone). Our approach has been to select a basic state absolute vorticity profile that ensures a relatively quiescent inner region (i.e.  $Z_l = 0$ , for  $r < a$ ), a jet capable  
770 of spanning the range of observed values, and a value for the absolute vorticity in the outer region that is both consistent with inertial (as opposed to barotropic) stability and yields realistic values for the zonal velocity and /or the relative vorticity at our model’s equivalent of the sub-tropics. The impact of setting,  $Z_l = IC$ , is that the key Eqs. (10, 11) are modified to the form,

$$m_0 = [2 - (l + n)] / [\varepsilon (1 + \mu - l)] \quad (18)$$

$$780 \quad \sigma = \frac{1}{2} / C / [(1 - n) (1 - l) (1 - \varepsilon)^m]^{1/2} \quad (19)$$

In effect for  $l \ll 1$  the changes are minor with a reduced growth rate. The reverse shear across the annulus attributed to the inner region inhibits the instability, and a similar effect was noted in a simpler setting by Dritschel (1989).

The second constraint referred to above is the limitation of non-divergence and barotropy at stratopause-levels. This alleviated somewhat at stratopause elevations by the observationally-based deductions presented in  
785 Section 2 that were based upon the character of the observed features. Paldor (2021) provide a formal comparison of geostrophic, shallow water divergent and non-divergent representations of barotropic instability. In passing we again note that our earlier observational deductions hint that the adoption of pure quasi-geostrophic dynamics may not be appropriate for studying these features, and renders more challenging the specification of the barotropic ‘equivalent depth’ as adopted in some shallow water instability studies (Sharkey et al, 2021). More fundamentally  
790 the assumption of barotropy excludes consideration of baroclinic (c.f. Dickinson, 1983; Simmons 1974) and mixed

barotropic-baroclinic (c.f. Manney & Randel, 1993) instability at these elevations, but the monopole character of the PV features points to a barotropic-like instability mechanism.

Positively, in comparison with some other studies, our model does not need to invoke quasi-geostrophy (c.f. Davies, 1981; Hartmann, 1983), incorporates an acceptable representation of the  $\beta$ -effect (c.f. Dritschel, 1989; 795 Dritschel & Polvani, 1992). The adoption of the polar  $\beta$ -plane configuration, as opposed to spherical geometry (Hartman, 1983; Michaelangeli et al., 1987; Manney et al., 1988; Mitchell et al., 2021; Waugh et al., 2023) enables a simpler derivation and interpretation of analytical solutions for a wide range of relatively realistic basic states velocity fields.

The dependency of the most unstable normal mode to the jet's strength and skewness and to the width of 800 the annular region was noted earlier. More generally the linear normal mode analysis and the non-linear simulations indicate that, for a wide range of external parameters characterizing the model's jet structure, the modes of maximum growth possess space-time scales and structure consistent with that of the observed features. In effect barotropic instability provides an attractive mechanism to account for the observed sub-planetary scale features.

805 An apparent discrepancy is that our normal-mode graver modes ( $m = 1, 2$ ) are stable in contrast with their instability as detected by Hartmann (1983). This can be linked to the form of the basic state adopted by Hartmann that can comprise a second weaker annulus of enhanced PV in mid-latitudes. This specification introduces two possible additional modes of instability associated either with the second annulus (and with a most unstable mode of high wavenumber) or with the broad region of diminished PV located between the two annuli (and with a most 810 unstable mode of low wavenumber). This association was noted by Hartmann. The equivalent for our model configuration is an annulus of reduced absolute vorticity with a jet located at  $r = a$  associated with ( $C \rightarrow -1; l \rightarrow -1; n \ll 1$ ). Inspection of Eqs. (18, 19) suggests, and direct evaluation of  $\Delta$  (- see sub-section 3.2.4) confirms, that the wavenumber  $m = 2$  can be unstable and possess a large growth rate. The interpretation is that this mode's instability is aided by the flow component in the annulus that is attributable to the "shear-effect" of the highly non- 815 quiescent inner region.

Clearly the existence of this unstable mode in an upper-stratospheric setting depends critically on the presence of an annulus of reduced PV. The evidence for such a feature is meagre although an instantaneous N-S section at a given longitude might (incorrectly) suggest such a structure provided there is a trailing streamer of high PV emanating from the core present within the surf zone at that longitude.

820

#### 4.0 Further Remarks.

This study can be viewed as lending credence to two assertions regarding the Stratospheric Polar Vortex. The first is that *the vortex's periphery is very frequently populated with distinctive and dynamically significant sub-* 825 *planetary scale flow features.* Their presence (DS24) and this study's more detailed description of their structure, temporal evolution and dynamics serves to augment and refine the well-established documentation of SPV's overall structure (see Waugh and Polvani, 2010; Schoeberl and Newman, 2015; Butchart, 2022).

The second is that *there is merit in considering the dynamics of a jet-like barotropically unstable flow configuration comprising an annular band of enhanced absolute vorticity to help account for the character of the* 830 *forementioned observed features.* Our linear instability analysis of such a band indicates that, for a wide range of external parameters characterizing the model's jet structure, the readily calculated normal modes yielding maximum growth rates possess space-time scales and structure consistent with that of the observed features. In effect barotropic instability provides an attractive mechanism to account for the observed sub-planetary scale

features. In contrast the model's gravest planetary-scale normal modes ( $m = 1, 2$ ) are shown to be stable and hence  
835 do not of themselves support a small amplitude instability hypothesis associated with SSW events.

In addition, the study relates to two other key themes of contemporary SPV studies. First, for mass and  
chemical composition budget studies and for dynamically studies, it has been customary to identify (- albeit as  
noted earlier in diverse ways) the SPV's 'edge'. The prevalence of sub-planetary scale features near the SPV's  
840 periphery, each associated with a distinctive flow feature, adds further complication to defining the 'edge'.  
Therefore, it would appear appropriate to characterize the vortex's periphery as often comprising "a rim of finite-  
width, that is highly variable in both in space and time, and that corresponds to an annular or fragmented region  
of enhanced PV".

The study also bears upon the instigation and dynamics of SSW events. Our theoretical results support  
845 the conjecture that a vortex breakdown at upper stratospheric levels can result specifically from the synergetic  
combination of strong planetary-scale Rossby-wave ( $m = 1$  or  $2$ ) forcing from below acting upon the vortex's  
annular PV band. In effect for this model, the existence of an annular PV structure favours the development of  
patterns related to a split SSW event. However, this vortex 'breakdown' results, not from a displacement or  
splitting of the SPV's core at stratopause levels, but rather from the aggregation into a few distinct isolated entities  
850 of the annular band's PV on the SPV's periphery. This synergetic mechanism is consistent with the concept of a  
pre-conditioned stratospheric state prevailing ahead of an SSW event. Direct observational corroboration of the  
conjecture is hampered by the almost ubiquitous presence of large deviations away from symmetric circumpolar  
flow of the SPV at stratopause levels.

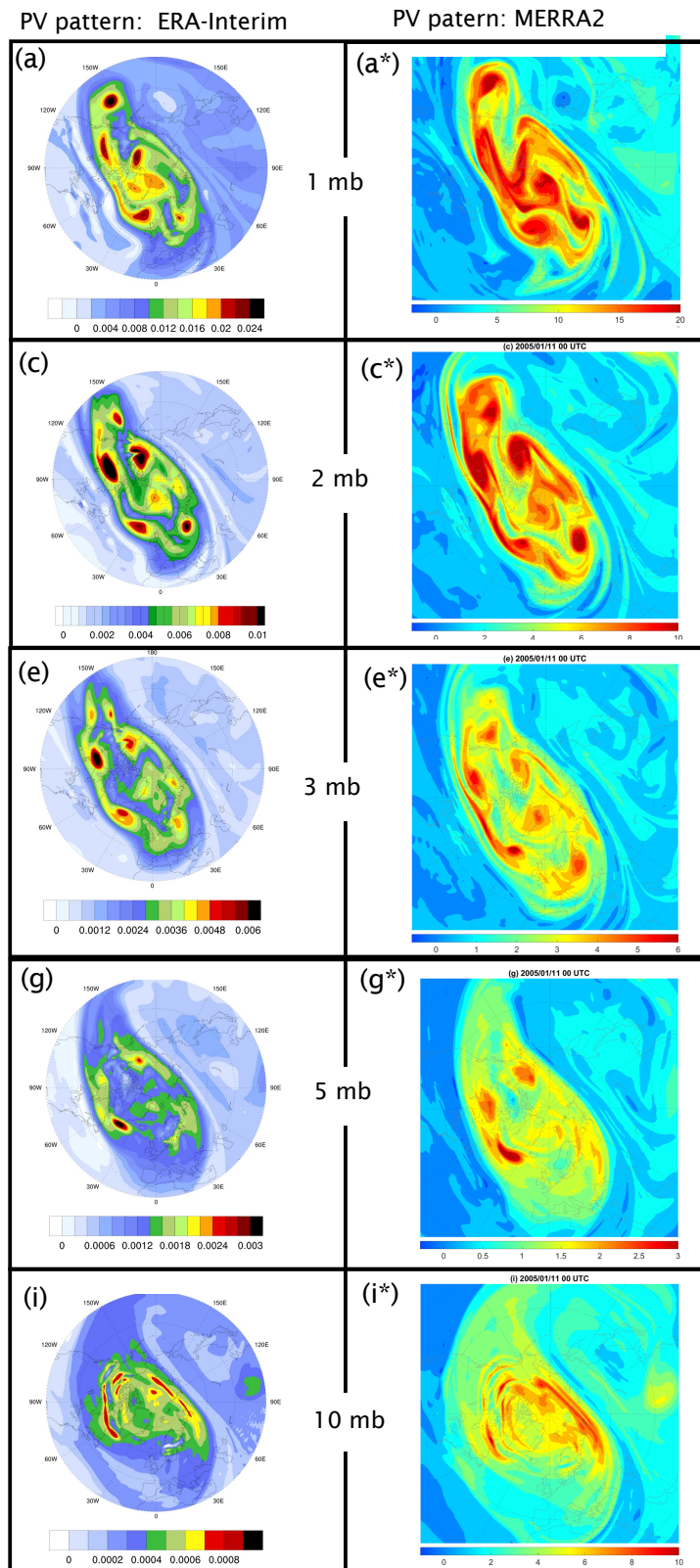
The present study would benefit from more detailed reanalysis-based case studies that include an  
855 evaluation of the influence of the parent model's GWD parameterization at and above the stratopause. Likewise,  
it would be illuminating to perform numerical simulations with a primitive equation model possessing high  
horizontal and vertical spatial resolution of potentially unstable basic flow states (- or realized atmospheric states)  
and undertaken with, and without, strong Rossby wave forcing from below.

860

#### **Appendix A: Comparison of upper stratospheric PV features in two Reanalysis data sets.**

The veracity of Reanalysis data sets at upper stratospheric levels is constrained by the accuracy of the dynamics  
865 and non-parameterized physics of the parent assimilation models, the adequacy of the raw data used for the  
analysis, the fidelity of any upper level phenomenologically based sub-grid scale Gravity Wave Drag (GWD)  
parameterization scheme, and any ad hoc divergence damping scheme of the models. In so-far as the parameterized  
schemes are tuned to match the expected state of the upper atmosphere, they have an artefact element that  
might/could compensate for, or disguise, other physical effects.

870 The Figures recorded in the main text were derived from ERA-Interim Reanalysis (Dee et al, 2011a, b).  
Here we compare this data set's representation of the present study's key flow features with the corresponding  
fields derived from the MERRA2 set (Gelaro et al, 2017). The two assimilation models have horizontal resolutions  
at polar-extratropical latitudes, number of vertical levels, and top-most level of respectively ( $\sim 79\text{km}$ , 60, 0.1hPa)  
for ERA-Interim and ( $\sim 50\text{km}$ , 72, 0.01hPa) for MERRA2. In addition, MERRA2 incorporates improved  
875 stratospheric temperature data, and there are significant differences (see S-RIP 2022, in particular Tables 2.3 and  
2.7) in the treatment of the uppermost levels.



880

Fig. A1. A comparison of the PV patterns derived with ECMWF-Interim data at 1, 2, 3, 5 and 10mb for \*\*\*\* as displayed in Fig. 2 (a, c, e, g, f) with the corresponding PV patterns shown in Fig. 2 ( a\*,c\*, e\*, g\*, f\*) derived from MERRA2 data. (Note the different colour scaling schemes for the two sets).

In Figures (A1, A2 and A3) the PV patterns displayed respectively in Fig 2 (a, c, e, f, g), Fig. 6a and Fig 9 (left column) are set alongside the corresponding MERRA2 patterns. The choice of PV as the elected variable is appropriate since it involves both the rotational component of the velocity and the thermal field whilst avoiding the divergent wind component that can be / is influenced by the differing treatment of inertia-gravity waves at stratopause levels in the various Reanalysis fields.

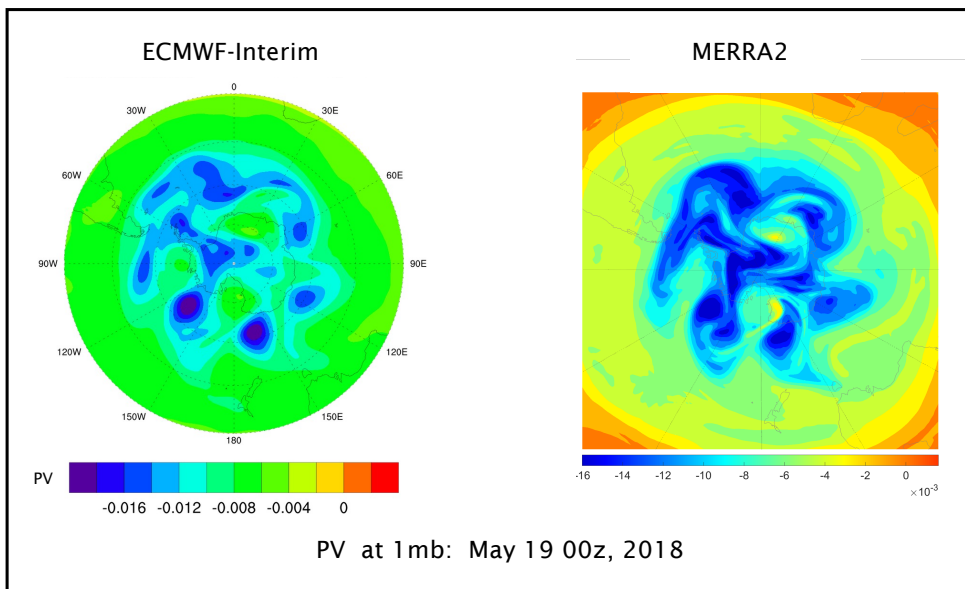
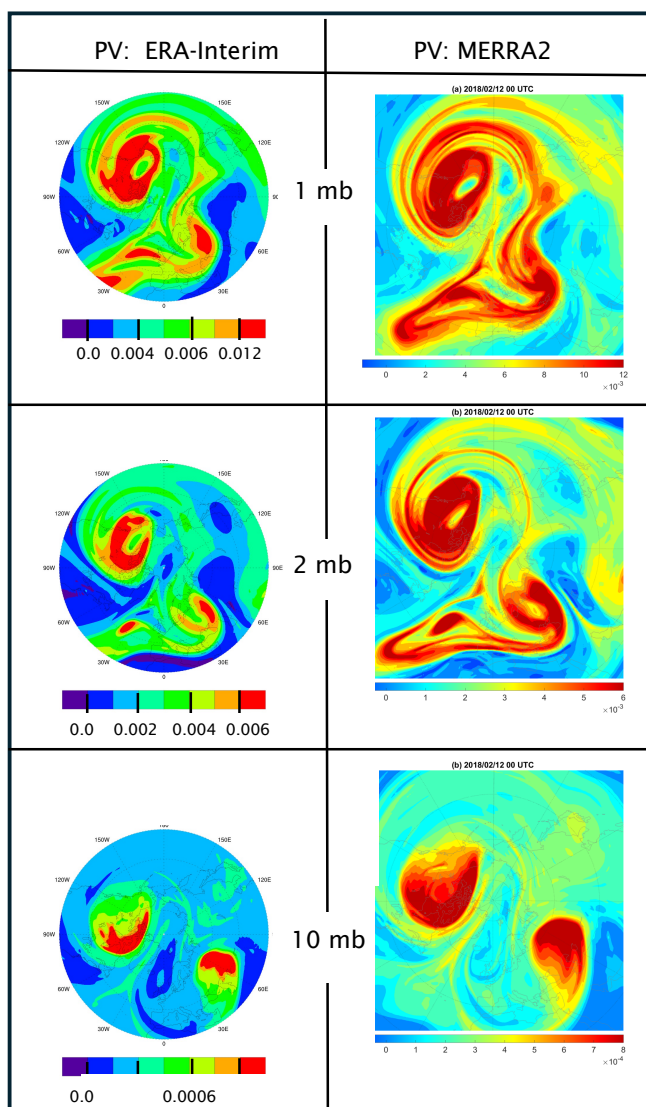


Fig. A2. As for Fig.(A1) but now comparing the PV pattern shown in Fig. (6a).



910 Fig. A3

As for Fig. (A1) but now comparing the PV pattern shown in Fig. (9).

The similarity of these seminal sub-planetary scale PV features in the ERA-Interim and MERRA2 is striking particularly considering the forementioned differences in the procedure for deriving the two Reanalyses. It testifies to the consistency of their representation of these key features and lends credence to their accuracy and to our adoption of the ERA-Interim data set.

*Code and data availability.* The NCAR-NCEP Reanalysis data was accessed via the NOAA Physical Sciences Laboratory (<http://psl.noaa.gov/>). The ERA-Interim data was accessed from the same source, and also directly from the ECMWF data repositories (Dee et al 2011b). The code for the Contour Dynamics simulation is set out in Dritschel (1989).

*Author contributions.* HCD designed and undertook the observational and theoretical components of the study in consultation with MAS, and MAS undertook the contour dynamics simulations. HCD wrote the paper, the figures were prepared jointly, and MAS edited the final version of the text.

*Competing interests.* The contact author has declared that neither of the authors has any competing interests.

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