Boundary Layers, Transport and Mixing - part 2

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The eight ingredients of eddy/wave – zonal-mean flow interaction

1. **Planetary *wave-guide***
2. **The existence of *planetary waves* on the wave guide**
3. ***Mixing of potential vorticity* (PV) by breaking planetary waves**
4. **Zonal mean *ageostrophic response* to the PV-mixing (the secondary circulation)**
5. **Creation and/or intensification of jets at the *edge of the mixing zone***
6. ***Net meridional vorticity (PVS) flux***
7. ***Net meridional mass flux***
8. **Diabatic effects: the *cross-isentropic mass flux***

1

First ingredient of eddy/wave – zonal-mean flow interaction

Planetary wave guide: meridional PV-gradient

Winter 2006-2007

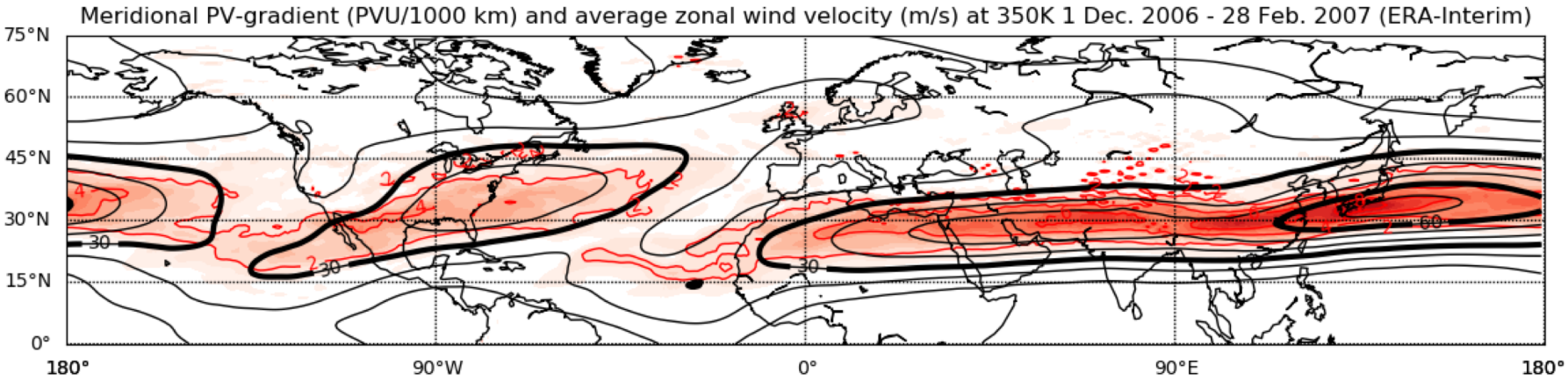


Fig12_39AD[2021].

1

First ingredient of eddy/wave – zonal-mean flow interaction

Planetary wave-activity on the planetary wave guide

Winter 2006-2007

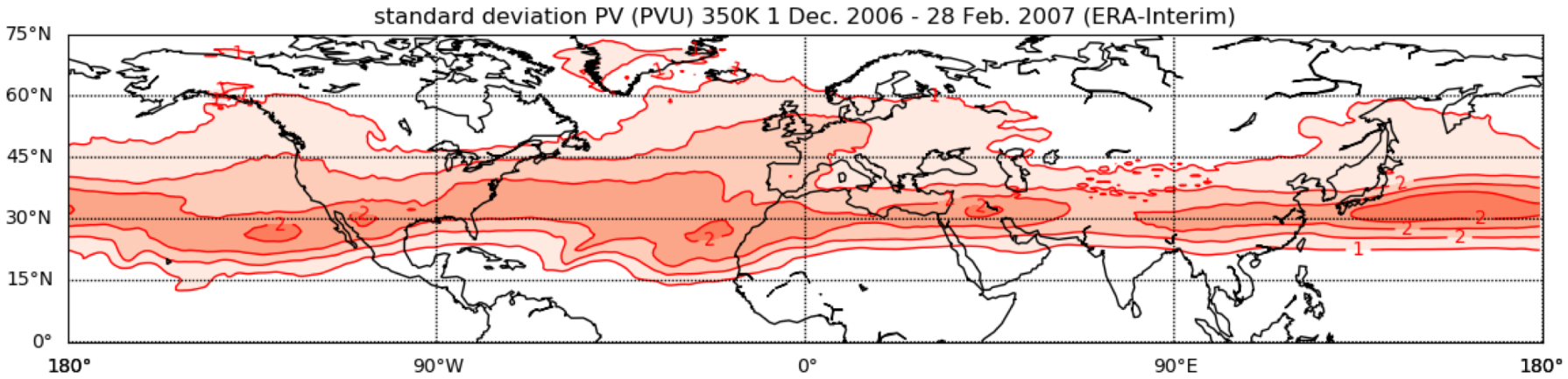


Fig12_40AD[2021].

2

Second ingredient of eddy/wave – zonal-mean flow interaction

Existence of *planetary waves* on the wave guide

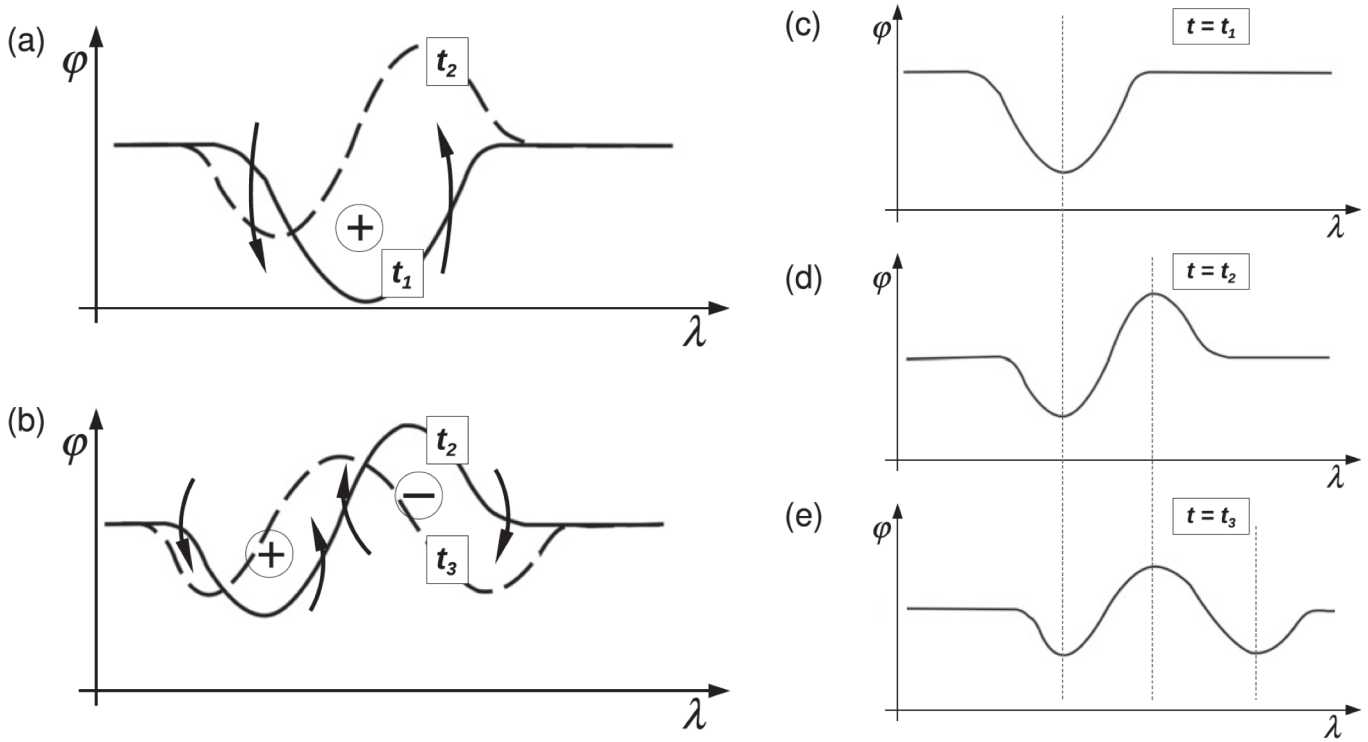


FIG. 8. Qualitative explanation of barotropic downstream development in the framework of PV thinking. Each panel represents a latitude–longitude map with the lines depicting contours of PV at different times t_i ($i = 1, 2, 3$). The PV gradient of the background atmosphere is northward (i.e., upward in the figure). (left) The circled plus and minus signs represent PV anomalies; the curved arrows represent the wind field associated with these PV anomalies; the solid PV contour depicts an early stage, while the dashed contour represents the situation a short time later (i.e., after the wind had some time to advect the initial contour). (a) The time interval $t_1 \rightarrow t_2$ and (b) time interval $t_2 \rightarrow t_3$. (right) The scenario in a frame of reference in which the phase of the troughs and ridges is stationary.

Wirth, V, M. Riemer, E.K.M. Chang and O. Martius, 2018: Rossby Wave Packets on the Midlatitude Waveguide – a Review. **Mon.Wea.Rev. 146**, 1965-2001

2

Second ingredient of eddy/wave – zonal-mean flow interaction

Existence of *planetary waves* on the wave guide

Ideal sinusoidal waves do not exist because the waves are deformed by background flow

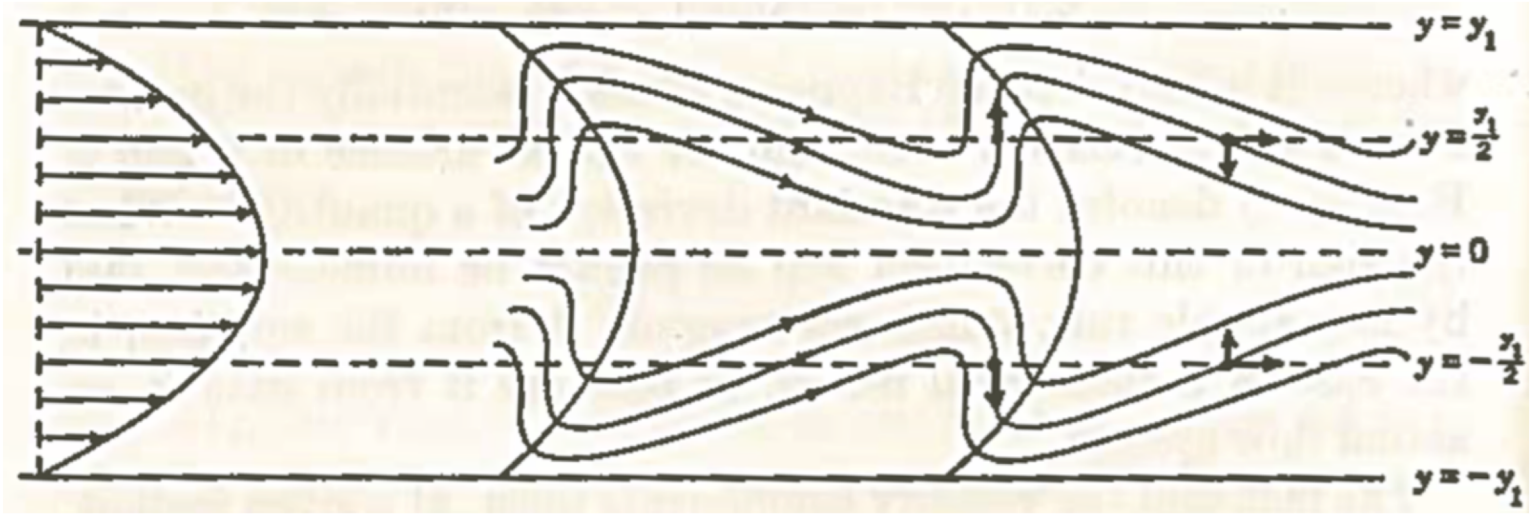
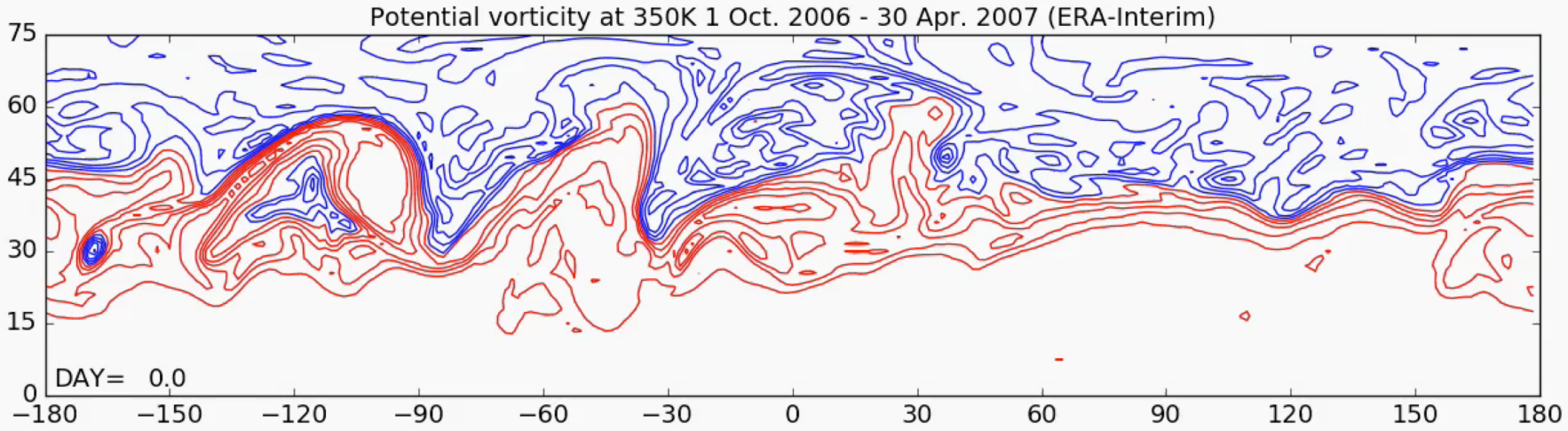


FIGURE 12.42. Idealised jet-like flow in a channel of width, $2y_1$, with superposed waves with tilted ridges-axes. The zonal velocity profile of the jet is shown at the left. The wavy streamlines, which are deformed by the background zonal flow, possess a shape that produces a correlation of the downstream and the cross-channel velocity components, as is demonstrated by the heavy arrows. The associated eddy momentum flux, $[u^*v^*]$, is equatorward north of the jet-core and poleward south of the jet-core. The jet is at least partially "eddy-driven" because convergence of the eddy momentum flux occurs in the core of the jet stream (Starr, V. P., 1968: **Physics of Negative Viscosity Phenomena**. MacGraw-Hill, 256 pp).

2

Second ingredient of eddy/wave – zonal-mean flow interaction

Existence of *planetary waves* on the wave guide



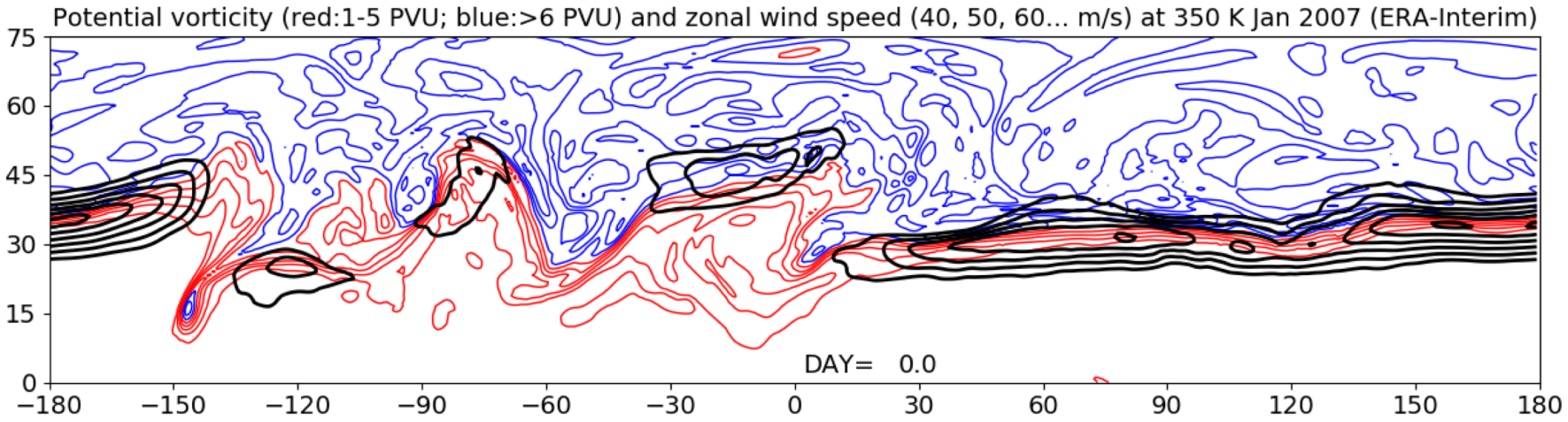
Red: PV=1-4 PVU; **Blue: PV=5-8 PVU**

PV350K2006-2007 (Converted).mov

2

Second ingredient of eddy/wave – zonal-mean flow interaction

Existence of *planetary waves* on the wave guide



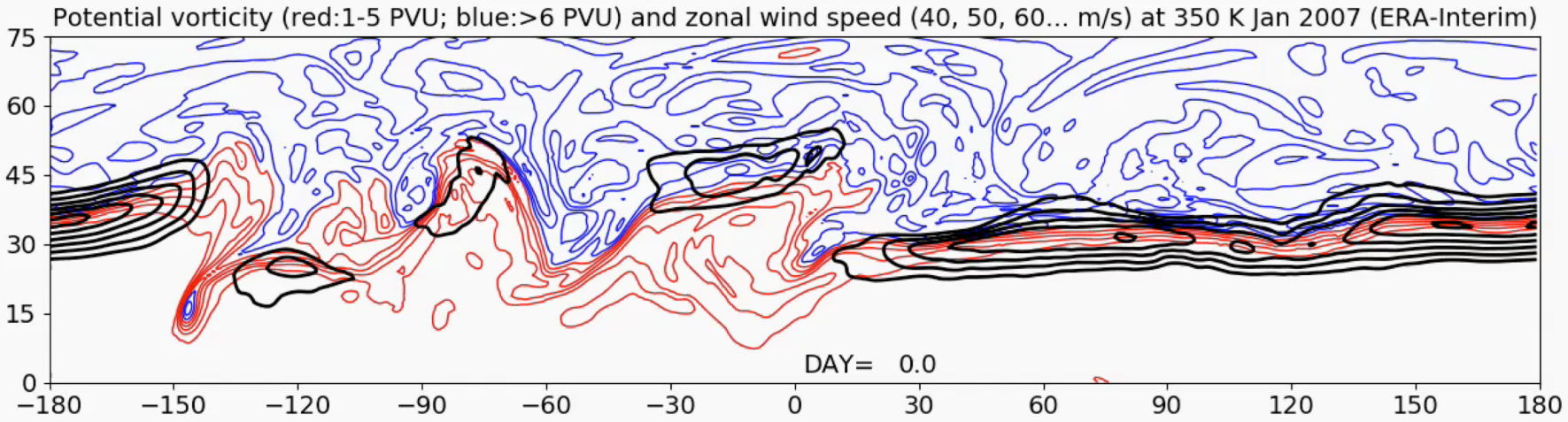
Red: PV=1-4 PVU; **Blue: PV=5-8 PVU**

2

Second ingredient of eddy/wave – zonal-mean flow interaction

Existence of *planetary waves* on the wave guide

Animation of planetary waves on the wave guide, including jetstreaks

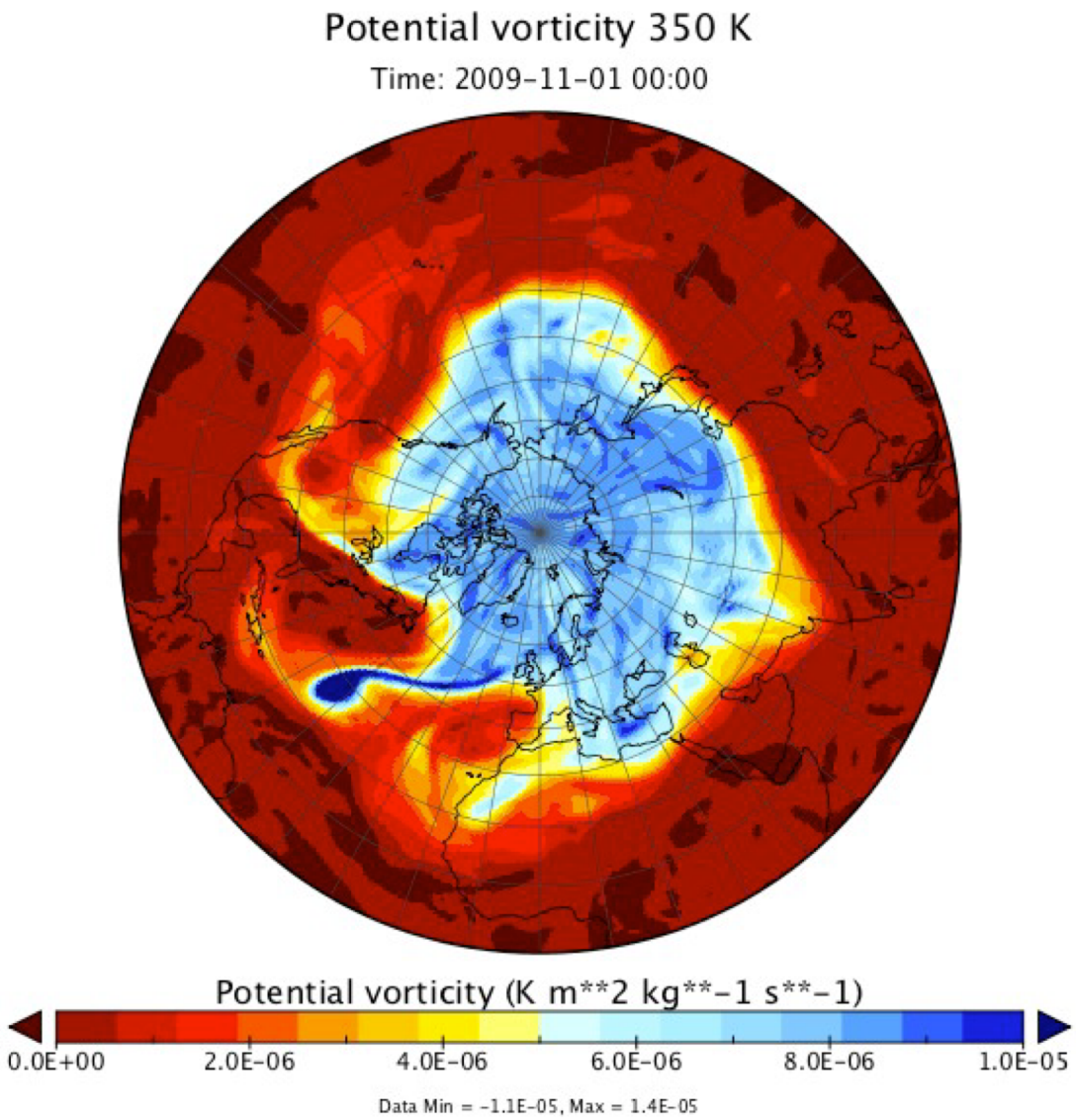


Red: PV=1-4 PVU; **Blue: PV=5-8 PVU**

3

PV-mixing by planetary waves

Third ingredient of eddy/wave – zonal-mean flow interaction



PotentialVorticity_350K_01112009-28022010.mov

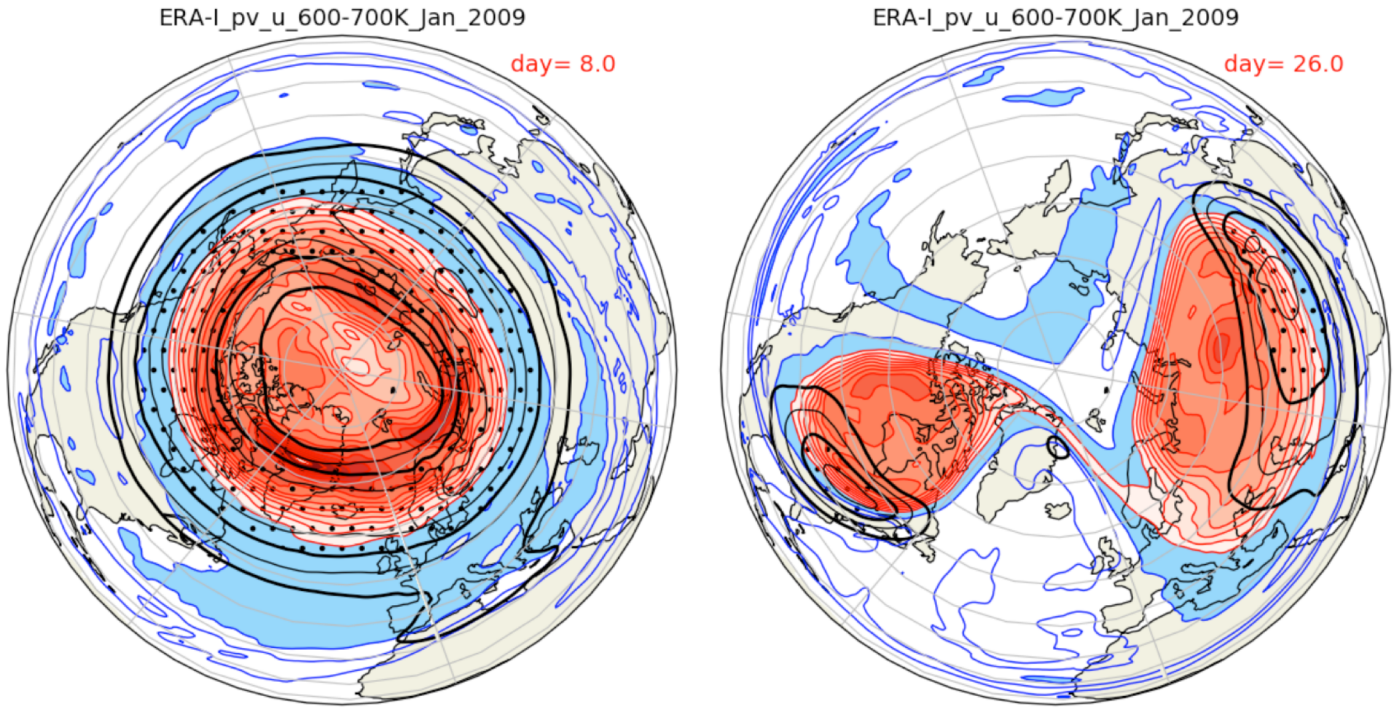
3

Third ingredient of eddy/wave – zonal-mean flow interaction

PV-mixing by planetary waves

PV-mixing encompassing the Pole

reduces the meridional PV-gradient



(this is an example of extreme "PV-mixing")

FIGURE 1.82. Potential vorticity distribution (red and blue contours and shading) and zonal (x-) component of the wind velocity (black contours and hatching) in the layer between the isentropic surfaces at 600 K and at 700 K over the Northern Hemisphere on January 8, 2009, 00 UTC (left panel) and on January 26, 2009, 00 UTC (right panel). PV-contour interval is 40 PVU, starting at 40 PVU (blue), first red PV-contour at 120 PVU. Red shading corresponds to high PV-values. Contour-interval of wind velocity (black) is 10 m s^{-1}; first contour at 20 m s^{-1}; hatching if u>40 m s^{-1} (thicker contours correspond to [u]=20 m s^{-1} and [u]=40 m s^{-1}. Based on the ERA-Interim reanalysis (https://apps.ecmwf.int, Plot_vo_pv[Orthographic]_ERA-I.py).

3

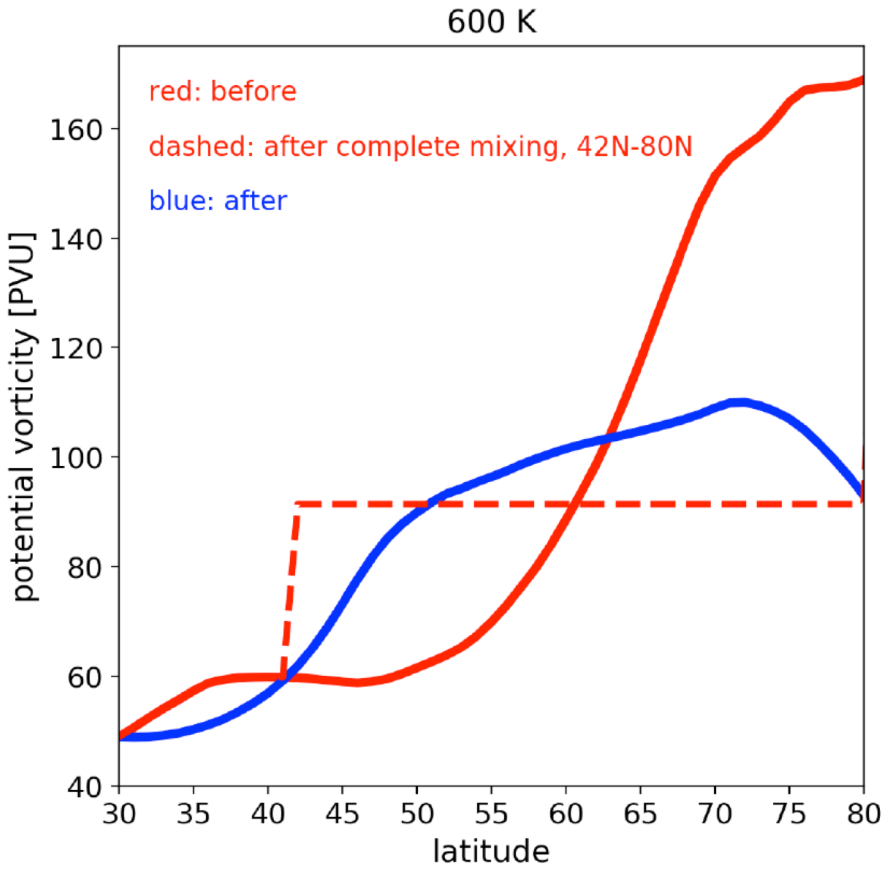
Third ingredient of eddy/wave – zonal-mean flow interaction

PV-mixing by planetary waves

PV-mixing encompassing the Pole

reduces the meridional PV-gradient

Ultimately this **eliminates the wave guide** and kills the waves



(see also figure 1.125)

Figure 1.124. Zonal mean potential vorticity at θ=600 K ***before*** (**red solid curve**) (average for 4-5 January 2009) and ***after*** (**blue solid curve**) (average for 23-24 January 2009) a Sudden Stratospheric Warming. The dashed red line represents the zonal mean potential vorticity if the zonal mean potential vorticity ***before*** the SSW is mixed completely between 42°N and 80°N under the constraint of material conservation of potential vorticity. This gives rise to a "PV-step" at 42°N. A PV-step exists in reality, but is much less pronounced.

3

PV-mixing by planetary waves

PV-mixing encompassing the Pole

Reduces amplitude of the positive Polar PV-anomaly

Isentropic density over the Pole increases
Vorticity over the Pole decreases

(see section 1.26)

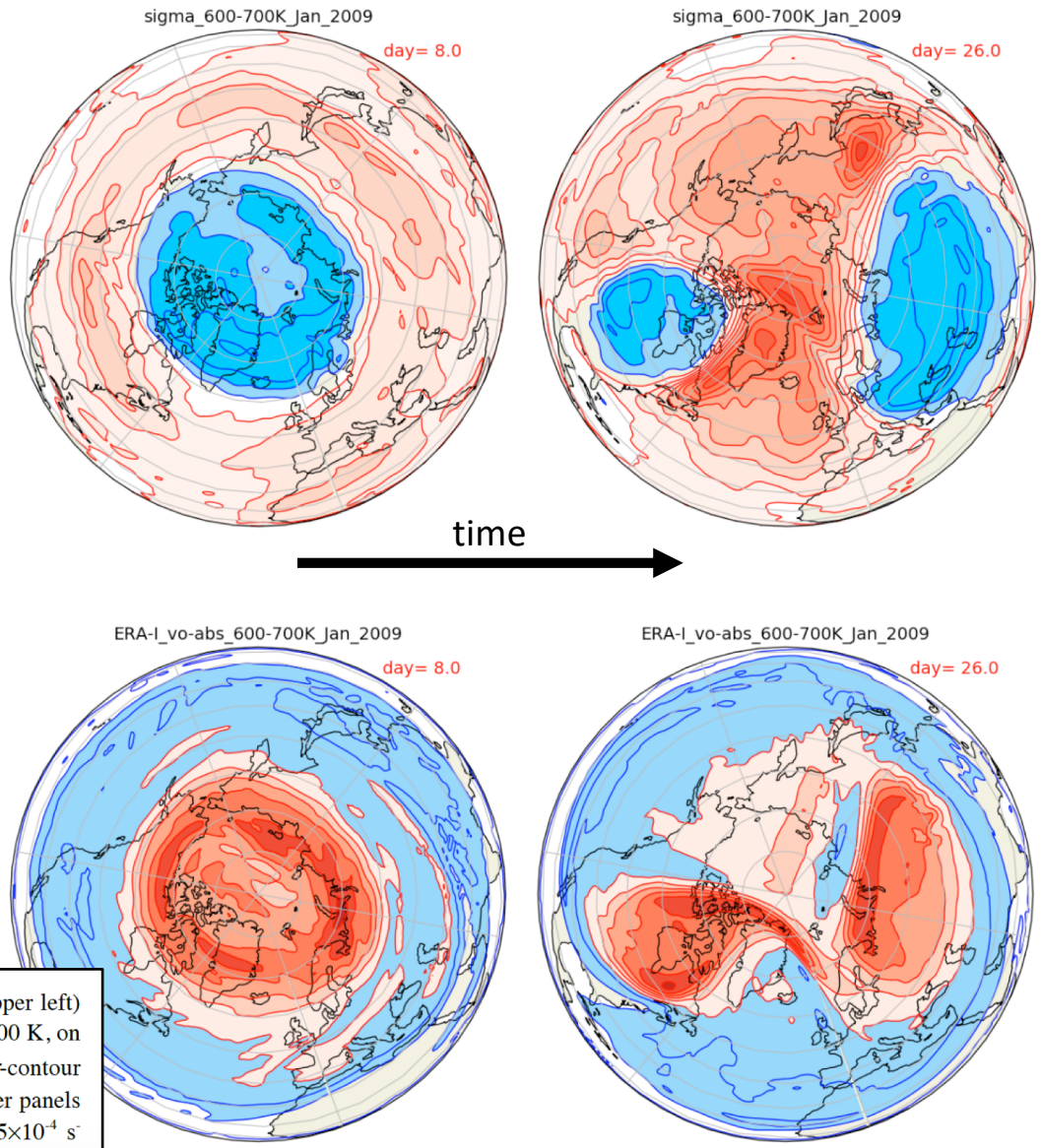


FIGURE 1.83. Upper panels: Isentropic density, σ, in the layer, 600-700 K, on 8 January (00 UTC) (upper left) and on 26 January (00 UTC) (upper right). Lower panels: absolute vorticity, $(\zeta_\theta + f)$, in the layer, 600-700 K, on 8 January (00 UTC) (upper left) and on 26 January (00 UTC) (upper right). In the upper panels the σ-contour interval is 0.1 kg m^{-2} K^{-1}, starting at 0.1 kg m^{-2} K^{-1}. Blue: σ<1 kg m^{-2} K^{-1}. Red: σ>1 kg m^{-2} K^{-1}. In the lower panels the contour interval is 2×10^{-5} s^{-1} if $(\zeta_\theta + f)>10^{-4}$ s^{-1}. Red shading: $(\zeta_\theta + f)>10^{-4}$ s^{-1}. Blue shading: 0.5×10^{-4} $s^{-1}<(\zeta_\theta + f)<10^{-4}$ s^{-1}. Based on the ERA-Interim reanalysis (https://apps.ecmwf.int).

3

PV-mixing by planetary waves

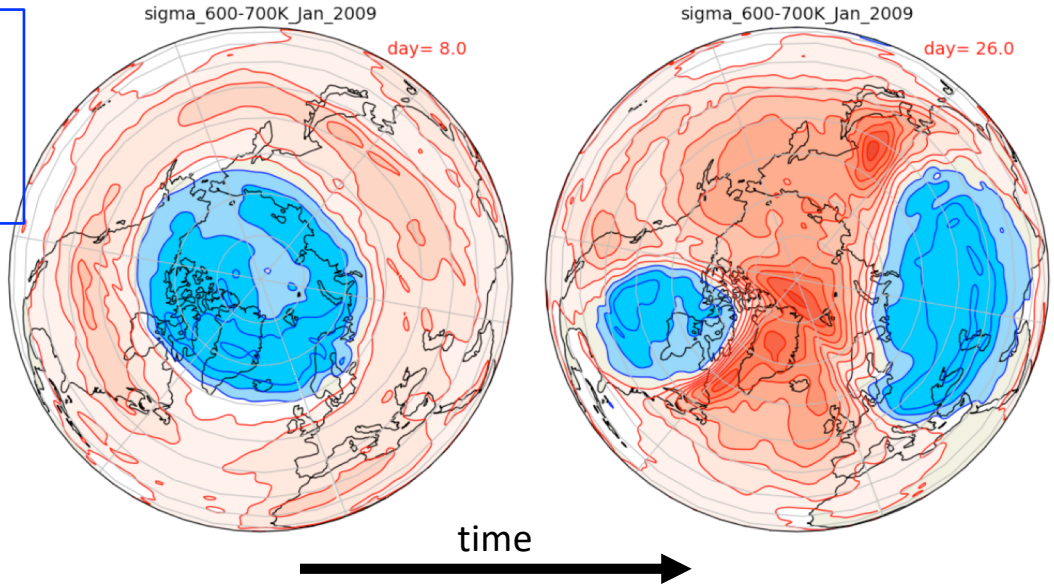
PV-mixing encompassing the Pole

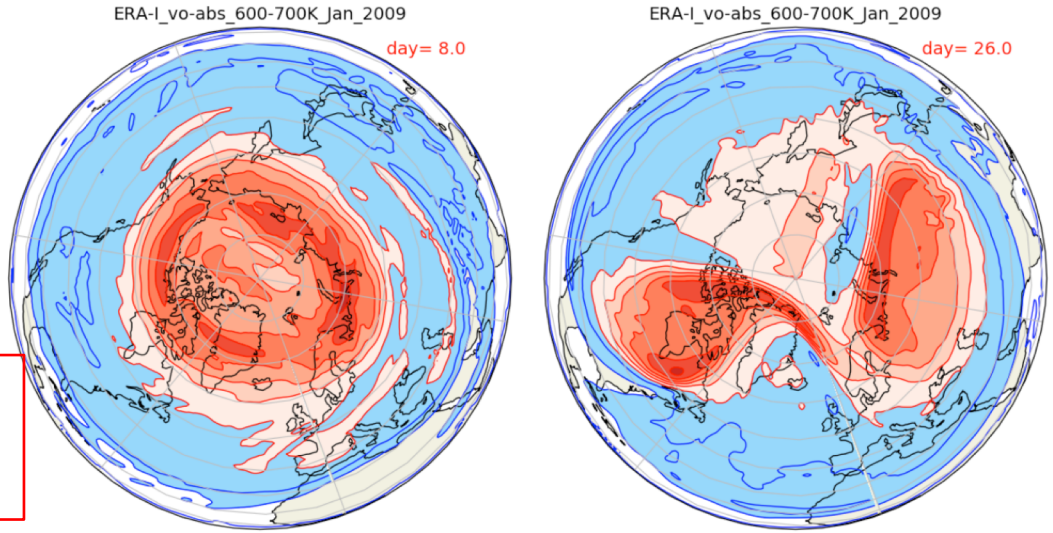
Reduces amplitude of the positive Polar PV-anomaly

Isentropic density over the Pole *increases*
Vorticity over the Pole *decreases*

PV-mixing manifest as mass-flux *and* vorticity (PVS)-flux !

Blue: negative isentropic density anomaly





Red: positive abs. vorticity anomaly

3

Third ingredient of eddy/wave – zonal-mean flow interaction

PV-mixing by planetary waves

A thought experiment

(page 60-61)

How does the meridional mass flux change $[u]$?

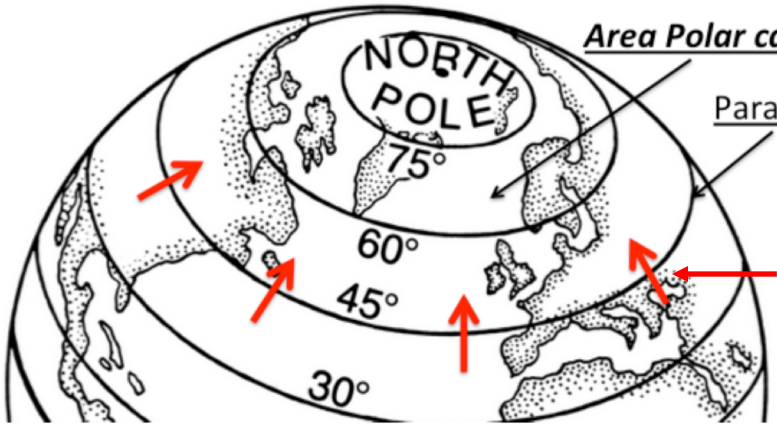


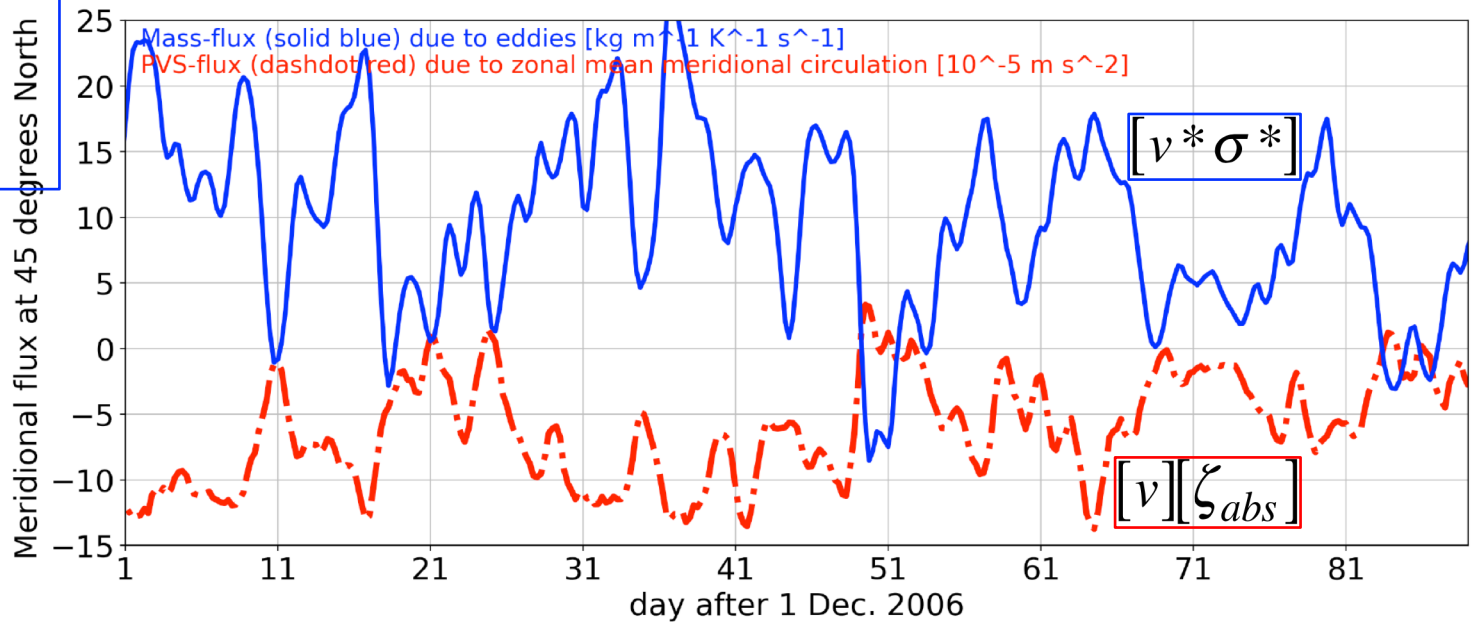
FIGURE 12.33. The North Polar cap, the boundary of which is a parallel, indicated by the letter l. The area over the Polar cap, enclosed by l, is indicated by the letter S. The **red arrows indicate an isentropic density flux** across l into S, which produces a positive isentropic density anomaly over the Polar cap. This, in turn, implies a reduction of the average potential vorticity over the Polar cap.

3

Third ingredient of eddy/wave – zonal-mean flow interaction

PV-mixing by planetary waves

Meridional eddy mass flux is mostly poleward and indeed anticorrelated with *mean* meridional vorticity (PVS) flux.



PV-mixing encompassing the Pole is associated with a poleward eddy mass flux. The response to PV mixing consists of an equatorward flow ("the *ageostrophic response*"), which carries vorticity equatorward. This should lead to a decrease of $[u]$.

FIGURE 12.34. Running daily means of the poleward isentropic ***eddy*** mass flux [in units of kg m^{-1} K^{-1} s^{-1}] (solid blue) and the mean poleward isentropic vorticity-flux due to the zonal mean meridional "secondary" circulation [in units of 10^{-5} m s^{-2}] (dashdot, red), at θ=350 K, at 45°N, between 1 December, 2006 and 28 February, 2007. The correlation coefficient between the eddy mass flux (blue) and mean vorticity flux (red) is r=-0.86. Based on six-hourly ERA-Interim re-analysis.

3

Third ingredient of eddy/wave – zonal-mean flow interaction

PV-mixing by planetary waves

Meridional eddy mass flux is mostly poleward and indeed anticorrelated with *mean* meridional vorticity (PVS) flux.

The *ageostrophic response*" is required to maintain zonal mean thermal wind balance,

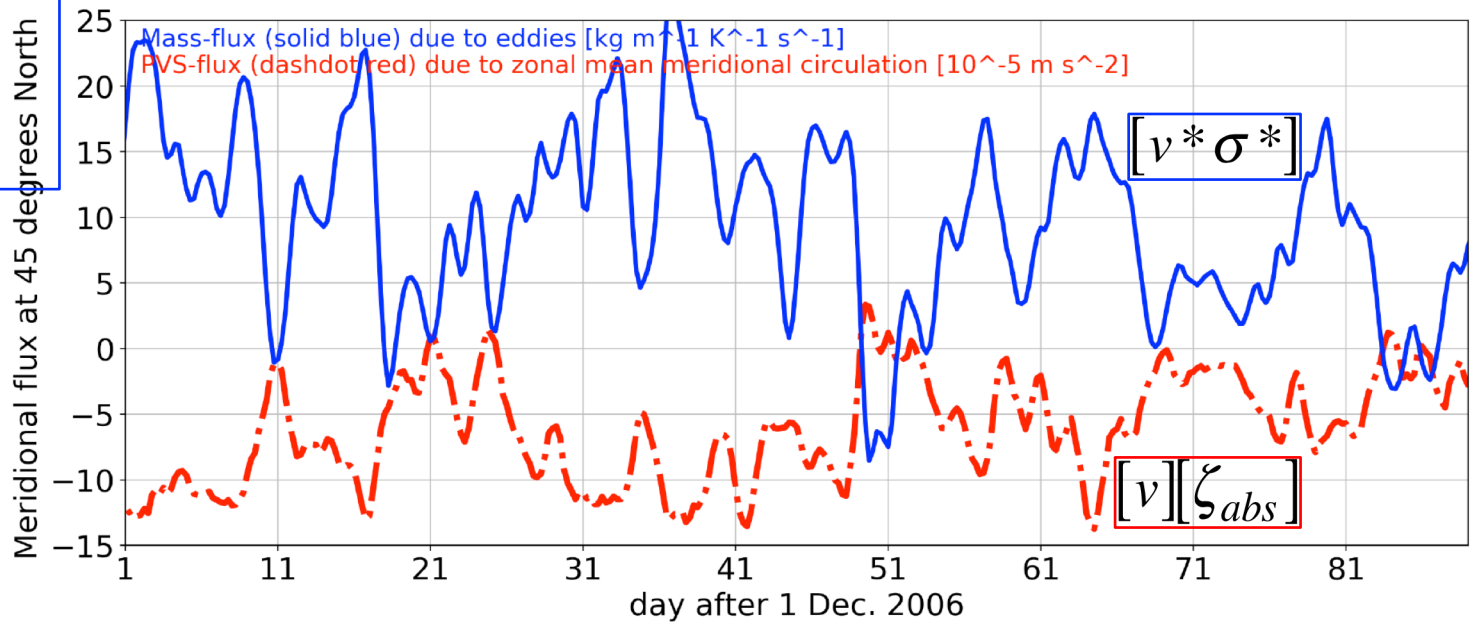


FIGURE 12.34. Running daily means of the poleward isentropic ***eddy*** mass flux [in units of kg m^{-1} K^{-1} s^{-1}] (solid blue) and the mean poleward isentropic vorticity-flux due to the zonal mean meridional "secondary" circulation [in units of 10^{-5} m s^{-2}] (dashdot, red), at θ=350 K, at 45°N, between 1 December, 2006 and 28 February, 2007. The correlation coefficient between the eddy mass flux (blue) and mean vorticity flux (red) is r=-0.86. Based on six-hourly ERA-Interim re-analysis.

4

Fourth ingredient of eddy/wave – zonal-mean flow interaction

Zonally symmetric a-geostrophic response

Things are a bit more complicated than in the thought experiment !

Eddy flux of PVS is also polewards!

Net flux of PVS is a **small residual** of **eddy**- plus **mean**- contribution.

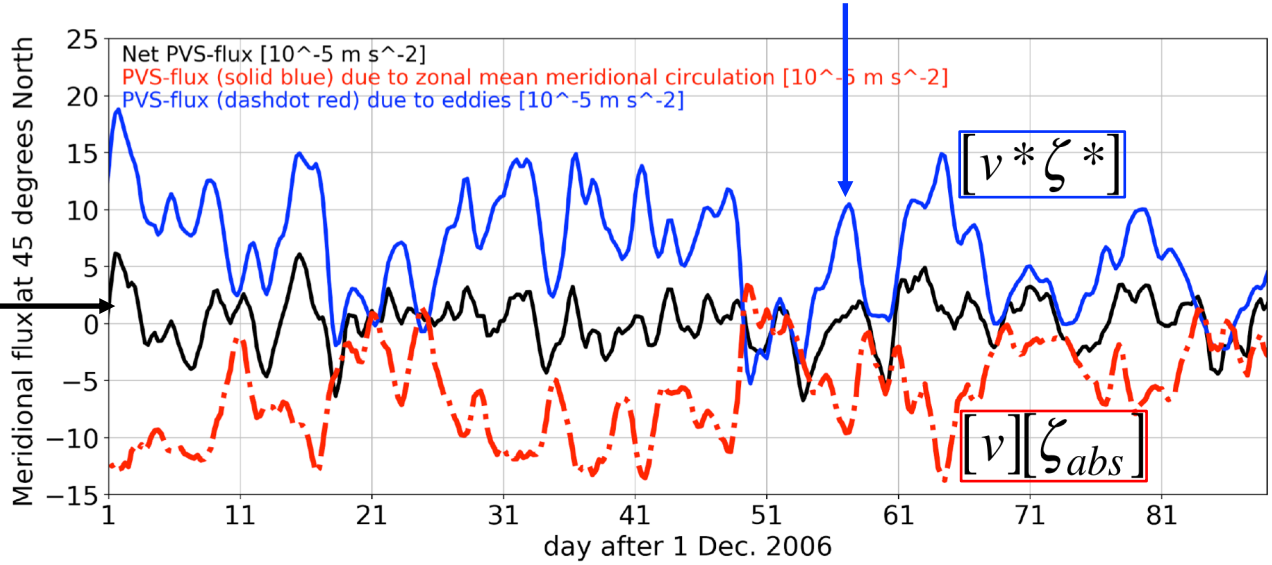


FIGURE 12.35. Running daily means of the poleward isentropic ***eddy*** vorticity flux (solid blue) , the poleward isentropic **mean** vorticity-flux due to the zonal meridional "secondary" circulation (dashdot, red) [in units of 10^{-5} m s^{-2}] and the difference between these fluxes, i.e. the net PVS-flux (solid black), at θ=350 K, at 45°N, between 1 December, 2006 and 28 February, 2007. The ***eddy*** vorticity flux and ***mean*** vorticity flux are anticorrelated with correlation coefficient, r=-0.88. Based on six-hourly ERA-Interim re-analysis.

4

Fourth ingredient of eddy/wave – zonal-mean flow interaction

Zonally symmetric a-geostrophic response

$$[v\zeta_{abs}] = [v][\zeta_{abs}] + [v^*\zeta^*]$$

net mean

Balance is almost exact all the time!

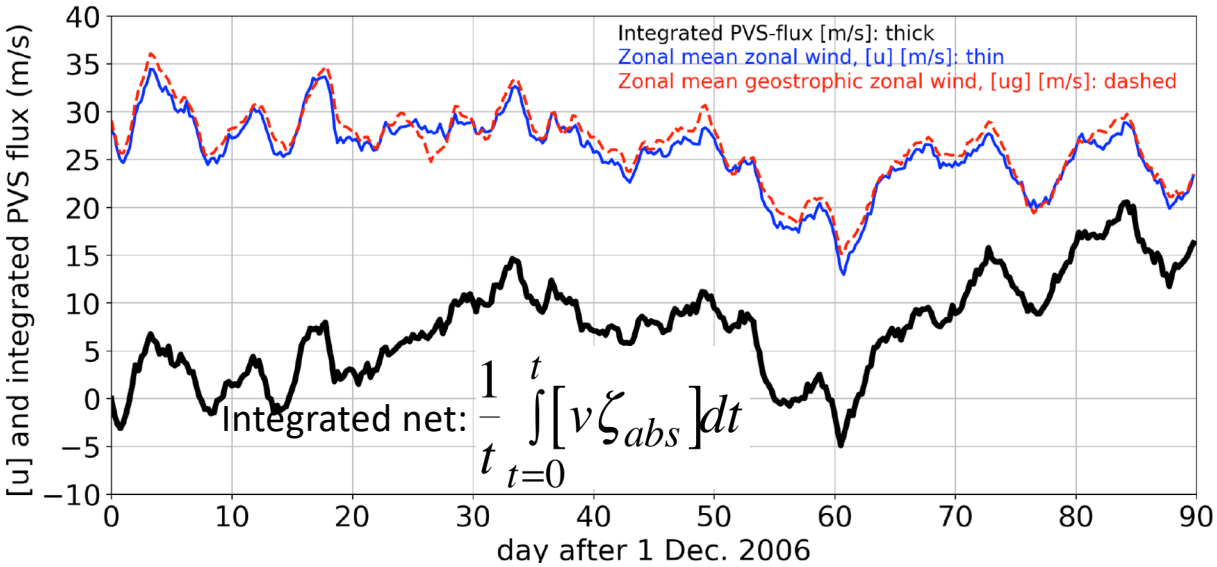


FIGURE 12.36. Zonal-mean zonal wind velocity (**blue thin line**), **zonal-mean geostrophic zonal wind velocity** (**red dashed line**) and the **time integral of the net meridional vorticity (PVS)-flux** (black thick line) between 1 December 2006, 0 UTC and 28 February 2007, 18 UTC at θ=350 K and 45°N. The resolution in time of the data is 6 hours. Note: $[u]$ and $[u_g]$ are almost identical, despite strong eddy PVS-fluxes in the order of +5 m s^{-1} day^{-1} (**figure 12.35**). Note also, that the integrated PVS flux across the 45°N parallel appears to determine the zonal-mean zonal wind at 45°N, as it should, according to the circulation theorem. Based on the six-hourly ERA-Interim re-analysis (http://apps.ecmwf.int/datasets/).

5

PV-mixing intensifies the PV-gradient at the edge of the mixing zone

(see slides 31-34 of lecture 5)

Fifth ingredient of eddy/wave – zonal-mean flow interaction

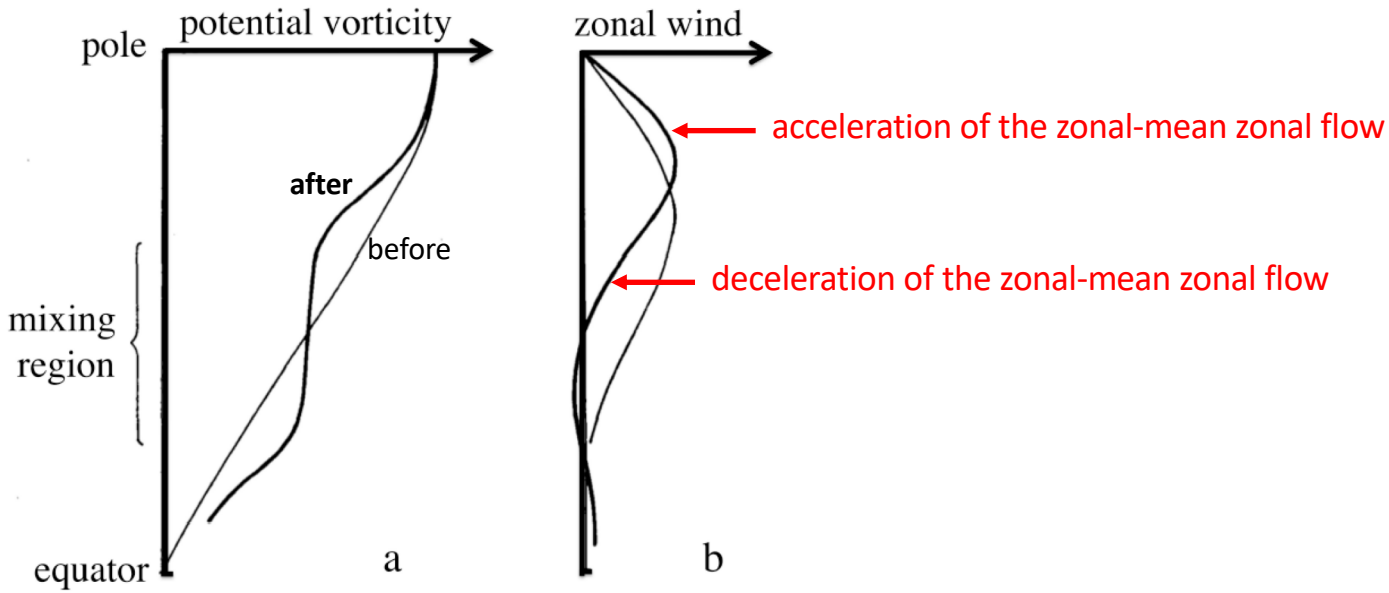


FIGURE 12.44. The left panel (a) shows schematic meridional profiles of PV before (thin) and after (thick) PV-mixing in the mixing zone indicated on the left. The right panel (b) shows schematic (*hypothetical*) meridional profiles of [*u*] before (thin) and after PV-mixing. In this example mixing is restricted to a latitude band and, therefore, does not encompass the Pole. When PV-mixing encompasses the Pole, the meridional PV-gradient increases only at the equatorward edge of the mixing zone. In the example illustrated here the mixing zone is bounded at two latitudes, which implies that the meridional PV-gradient increases at both bounding latitudes of the mixing zone. At these latitudes [*u*] *increases* due to PV-mixing by eddies and waves, while [*u*] *decreases* due to PV-mixing in between. Source of this figure: M.E. McIntyre, 1982: How well do we understand the dynamics of stratospheric warmings. **J.Meteorol.Soc.Japan**, **60**, 37-65. See **section 1.41**.

6 **Sixth** ingredient of eddy/wave – zonal-mean flow interaction

Mean annual cycle 1979-2015 at θ=600 K (ERA-Interim)

Net meridional vorticity (PVS)-flux

Late winter: equatorward *net* PVS flux (highly variable!)
Summer: very weak poleward meridional PVS flux

Late winter: deceleration of the zonal-mean zonal wind
Summer: acceleration of the zonal-mean zonal wind

Eddies accelerate the zonal-mean zonal flow!

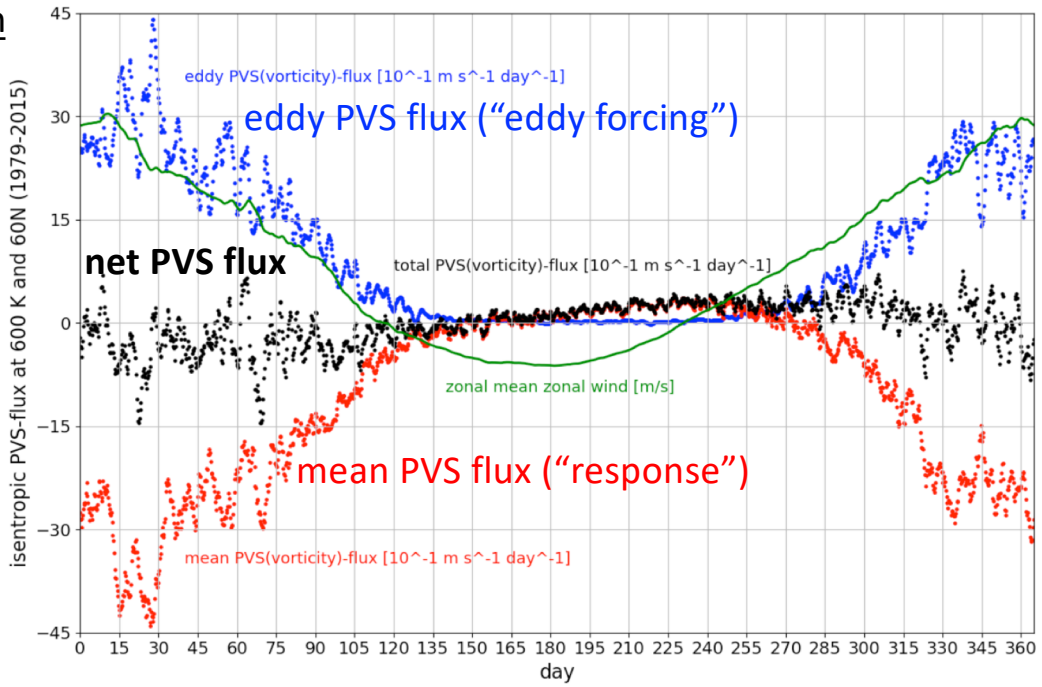


FIGURE 12.37. Ensemble average yearly cycle **for the years, 1979-2015** of the daily mean zonal mean meridional eddy PVS-flux, $[v^* \zeta_a^*]$ (**blue**), the zonal mean mean meridional PVS-flux, $[v][\zeta_a]$ (**red**), the total (or net) meridional PVS-flux (**black**) and the zonal mean zonal wind, $[u]$ (green) at 600 K and 60°N. Based on the ERA-Interim re-analysis (http://apps.ecmwf.int/datasets/). Despite the fact that the yearly cycle of the PVS-fluxes, displayed in this graph, represents an average over 37 years, the curves are not at all smooth. This is because PVS-fluxes are dominated by very intense events, called "**Sudden Stratospheric Warmings**", in which *eddy* PVS-fluxes are poleward and far exceed +10 m s^{-1} per day. Note that the ensemble mean *eddy* PVS-flux is poleward. This means that eddies accelerate the zonal mean zonal flow at this latitude and level (**section 1.35**). Note also that eddy PVS-fluxes are non-existent in summer when $[u]<0$. The actual acceleration of the zonal mean zonal wind is the result of the net PVS-flux (eq. 1.292), shown in black, which is positive very roughly between day 175 (25 June) and day 360 (25 December). This corresponds to the period in which $[u]$ increases from -6 m/s to +30 m/s. Reversals of the zonal mean zonal wind occur on day 115 (25 April) and on day 235 (end of August). Roughly between day 175 and day 255 the poleward PVS-flux completely due to the secondary meridional circulation (see **problem 12.5**).

7 **Seventh** ingredient of eddy/wave – zonal-mean flow interaction

Mean annual cycle 1979-2015 at θ=600 K (ERA-Interim)

Net meridional mass-flux

Net mass flux is **always poleward.** In the middle of summer the net mass flux falls to nearly zero due to absence of planetary wave forcing.

Net mass flux is poleward because this is **required for maintaining zonal mean thermal wind balance** in the presence of PV-mixing by planetary waves.

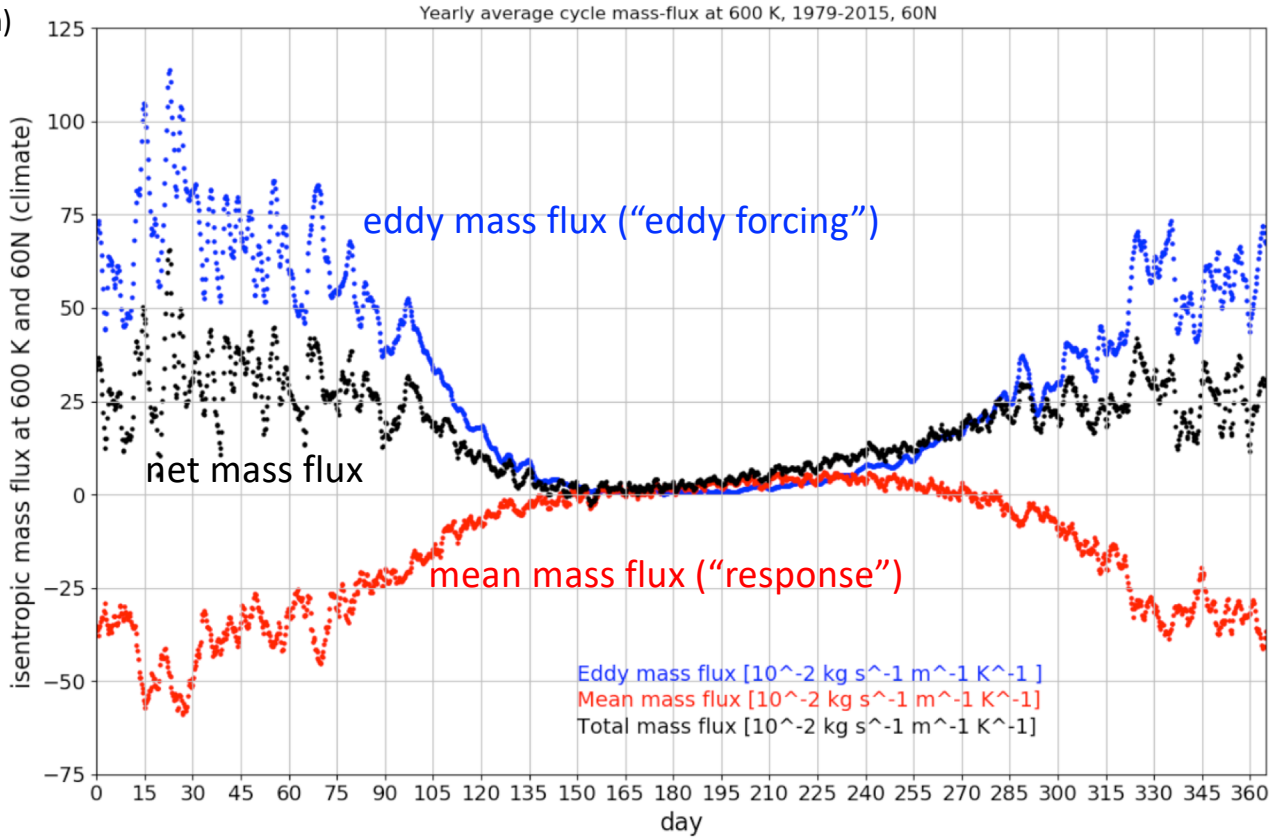


FIGURE 12.43. Ensemble average yearly cycle **for the years, 1979-2015** of the daily mean zonal mean eddy isentropic density-flux, $[v^* \sigma^*]$ (**blue**), the zonal mean mean vorticity-flux, $[v][\sigma]$ (**red**) and the net (total) isentropic density-flux (**black**) at 600 K and 60°N. Note that the *net meridional mass flux is always poleward* except for a short period in June. Based on the ERA-Interim re-analysis (http://apps.ecmwf.int/datasets/).

8 **Eighth** ingredient of eddy/wave – zonal-mean flow interaction

Diabatic effects
(cross-isentropic mass flux)

Poleward migration and weakening of the zonal-mean subtropical jet in spring in the Northern Hemisphere and the formation and intensification of the polar winter stratospheric vortex in Autumn are "driven" by cross-isentropic mass flux divergence, which intensifies the "*ex-UTLS PV-anomaly*" in autumn and weakens the "*ex-UTLS PV-anomaly*" in spring, *and* creates the planetary wave guide at the equatorward edge of this PV anomaly.

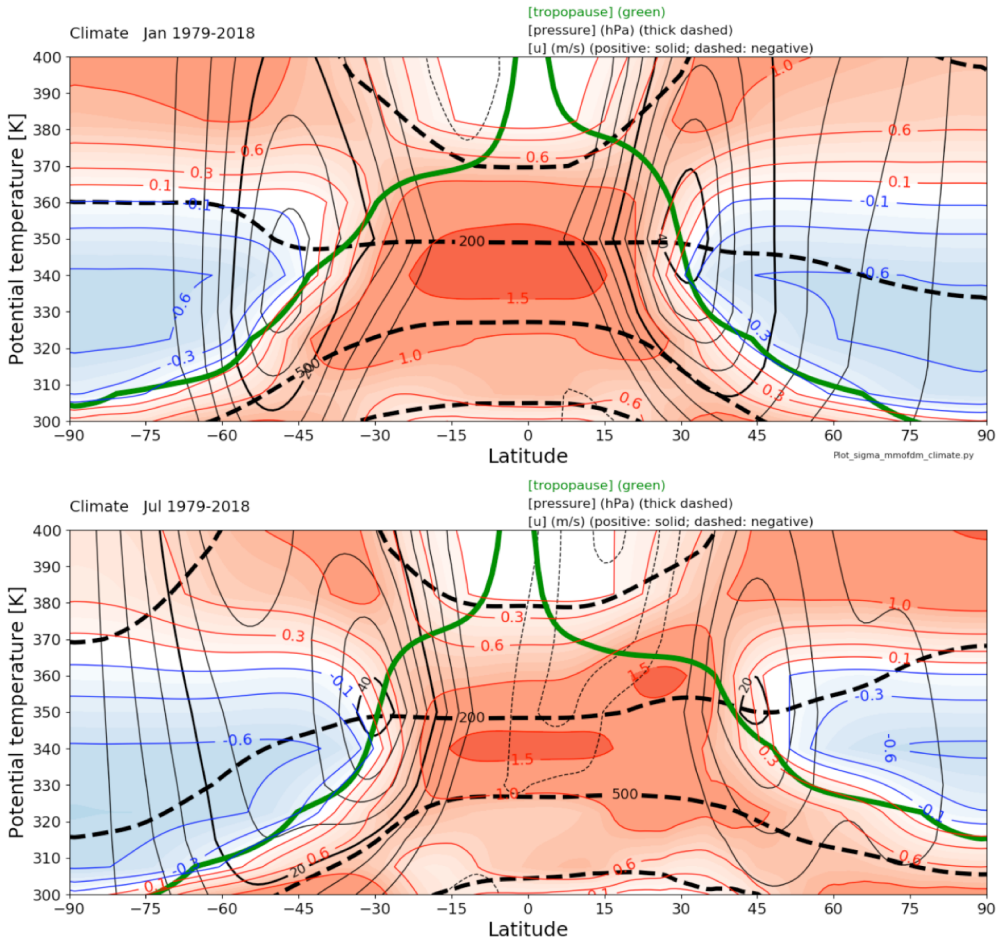


FIGURE 1.67. The 40-year mean (1979-2018) zonal mean distribution of mass, in terms of the normalised isentropic density-anomaly, $\sigma^+=[\sigma']/\sigma_{ref}$, in **January** (upper panel) and in **July** (lower panel). Red shading indicates a **positive isentropic density-anomaly**, while blue shading indicates a **negative isentropic density-anomaly**. Contours are drawn at σ^+=-0.6, -0.3, -0.1, +0.1, +0.3, +1, +1.5. The **dynamical tropopause**, indicated by the **green contour**, coincides with Z_θ=±2 PVU. The **dashed contours** represent **isobars**, labeled in hPa drawn at 850, 500, 200 and 100 hPa. The black contours represent isopleths of equal $[u]$, labeled in m/s (contour inteval is 5 m/s). Note that the dynamical tropopause coincides with the lower and tropical boundary of the negative isentropic density anomaly in both hemispheres (ERA-Interim re-analysis).

Assignment 4 of BLT&M-2

Deadline: Friday 2 July 2021

PROBLEM 12.18. Is the term "planetary wave drag" a metaphor of reality?

In sections 12.9-12.11 the established concept, "planetary wave drag", is criticised. According to a textbook theory (the quasi-geostrophic "TEM-theory"), this term describes, in a nutshell, the influence of planetary (Rossby) waves on the zonal-mean zonal flow. In **section 12.11** it is concluded that this phrase is a "scientific metaphor", which is a figure of speech that describes an action in a way that is not literally true, but helps to explain an idea. A plan exists to turn **sections 12.9-11** into a paper, which will be submitted for publication as a follow-up paper of the third paper in the list of references to this chapter, which has the title, *PV-θ view of diabatic-dynamical interaction in the general circulation*. What title would you give this paper? Do you think that this paper will meet with resistance from the reviewers. In other words, in how far are the arguments, especially in **section 12.11**, consistent and convincing? Is the evidence (based on re-analyses) for the eight ingredients of wave – zonal-mean flow sufficient and convincing. If accepted for publication, will the paper create a controversy (see the list of controversies in Climate Science in problem 12.17), or does the paper stand a chance of being ignored after publication, as is the case until now (2021) with the previous 2014-paper? Why?