

Dynamic Meteorology: lecture 10

16/12/2022 (Friday, 09:00-10:45)

Sections 1.25-1.26 (and box 1.12)

Mass conservation in isentropic coordinates

Zonal mean meridional mass flux ("mean" and "eddy" contributions)

Eddy-driven "residual" circulation of mass (Brewer-Dobson circulation) (section 1.26)

(Potential) vorticity equation in isentropic coordinates (section 1.25)

Vorticity equation in flux-form (impermeability theorem) (section 1.26)

Zonal-mean meridional vorticity fluxes ("mean" & "eddy" contributions) (section 1.26)

Relation between net meridional vorticity flux and zonal-mean zonal wind velocity

Tutorial after this lecture (10)

Project 5

Problems 1.17, 1.18 (part D), 1.20, 1.21 (part E)

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p. 153

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(<http://www.uu.nl/~nvdelden/dynmeteorology.htm>)

Breaking Rossby-waves mix potential vorticity on isentropic surfaces



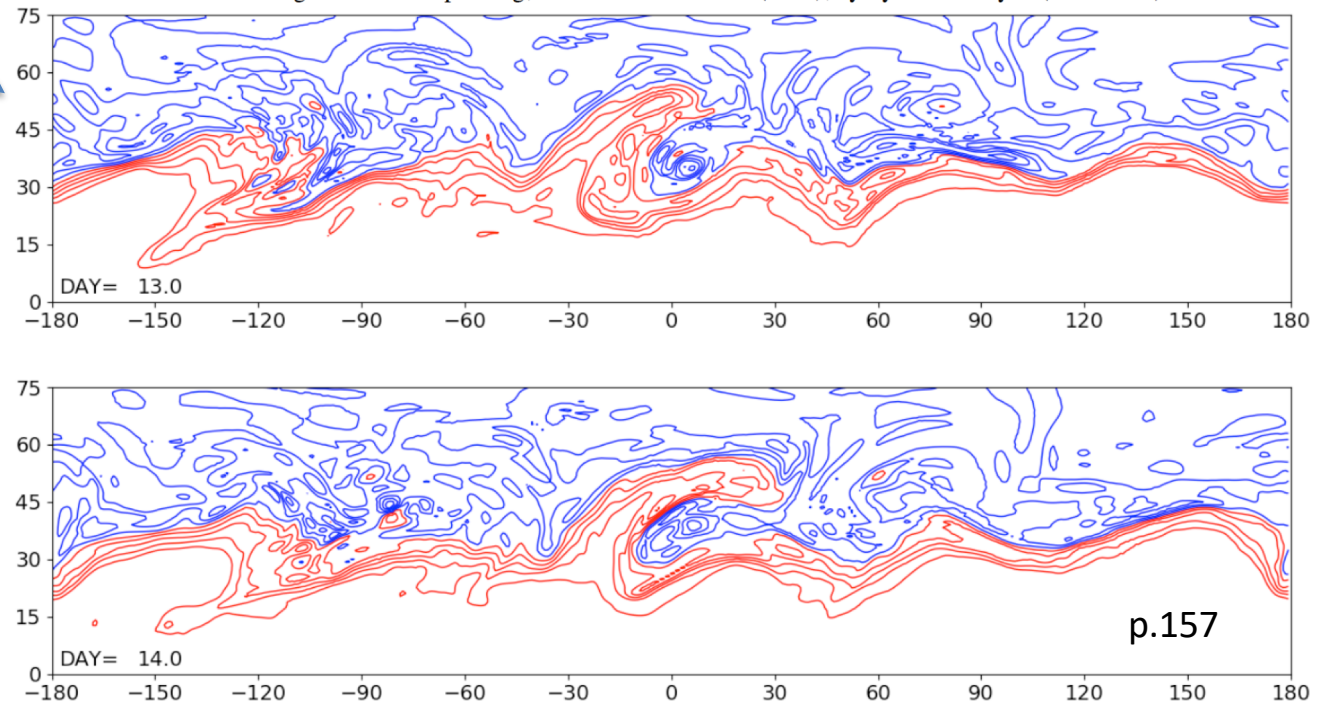
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Breaking waves in the painting, “Mountains and Sea” (1872), by Fyodor Vasilyev (1850-1873).

This lecture is about potential (PV)-mixing, especially the meridional PV-mixing across the isentropic tropopause, which is illustrated on the right.

PV-mixing is manifest as isentropic fluxes of mass and vorticity.

In which way?



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FIGURE 1.57. Potential vorticity (Z_θ) on the 350 K isentropic surface in the “Middleworld” on the Northern Hemisphere (**figure 1.48**), according to the ERA-Interim reanalysis on a Cartesian latitude-longitude grid with a uniform grid distance of 0.75° , at 00 UTC, 13 December, 2006 (upper panel), 00 UTC, 14 December, 2006 (middle panel), and at 00 UTC, 15 December, 2006 (lower panel). Vertical coordinate is latitude ($^\circ\text{N}$) and horizontal coordinate is longitude ($^\circ\text{E}$). **Red contours correspond to 1, 2, 3, 4 and 5 PVU (tropical air). Blue contours correspond to 6, 7, 8, 9, 10 PVU and higher (extra-tropical air).** The **isentropic dynamical tropopause** separates tropical low-PV air from extra-tropical high-PV air. A clear example of **planetary wave breaking** is observed between the longitudes of 30°W and 30°E , which affects a broad band of latitudes between 30°N and 60°N . Data: ERA-Interim reanalysis (<http://apps.ecmwf.int/datasets/>).

Mass-conservation equation in flux-form

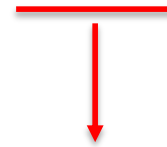
Previous lecture:

$$\frac{\partial \sigma}{\partial t} = - \left(\frac{\partial u \sigma}{\partial x} \right)_\theta - \left(\frac{\partial v \sigma}{\partial y} \right)_\theta - \frac{\partial}{\partial \theta} \left(\frac{d\theta}{dt} \sigma \right) \quad (1.200)$$



$$\frac{\partial \sigma}{\partial t} = -\vec{\nabla} \cdot \vec{I}$$

$$\vec{I} \equiv \left(u\sigma, v\sigma, \frac{d\theta}{dt} \sigma \right)$$



Isentropic (horizontal) mass flux

Meridional isentropic mass flux

Previous slide: $\vec{I} \equiv \left(u\sigma, v\sigma, \frac{d\theta}{dt}\sigma \right)$

meridional mass flux: $v\sigma$

Zonal mean: $[v] \equiv \frac{1}{2\pi} \int_0^{2\pi} v d\lambda$ and $[\sigma] \equiv \frac{1}{2\pi} \int_0^{2\pi} \sigma d\lambda$

Mean + perturbation: $v = [v] + v^*$ and $\sigma = [\sigma] + \sigma^*$

Zonal mean meridional isentropic mass flux

Previous slide: $\vec{I} \equiv \left(u\sigma, v\sigma, \frac{d\theta}{dt}\sigma \right)$

meridional mass flux: $v\sigma$

Zonal mean: $[v] \equiv \frac{1}{2\pi} \int_0^{2\pi} v d\lambda$ and $[\sigma] \equiv \frac{1}{2\pi} \int_0^{2\pi} \sigma d\lambda$

Mean + perturbation: $v = [v] + v^*$ and $\sigma = [\sigma] + \sigma^*$

Zonal mean meridional mass-flux:

$$[v\sigma] = [(v + v^*)(\sigma + \sigma^*)] = [[v][\sigma] + v^*[\sigma] + \sigma^*[v] + v^*\sigma^*] = [v][\sigma] + [v^*\sigma^*]$$

“mean flux”

“eddy flux”

Isentropic mass flux at 45°N, at $\theta=350$ K

Winter of
2009-2010

— $[u]$

— $[v][\sigma]$ **mean flux**

— $[v^* \sigma^*]$ **eddy flux**

$$\Delta M(t) = \int_{t_0}^t [v\sigma] dt \quad \left[\text{kg m}^{-1} \text{K}^{-1} \right]$$

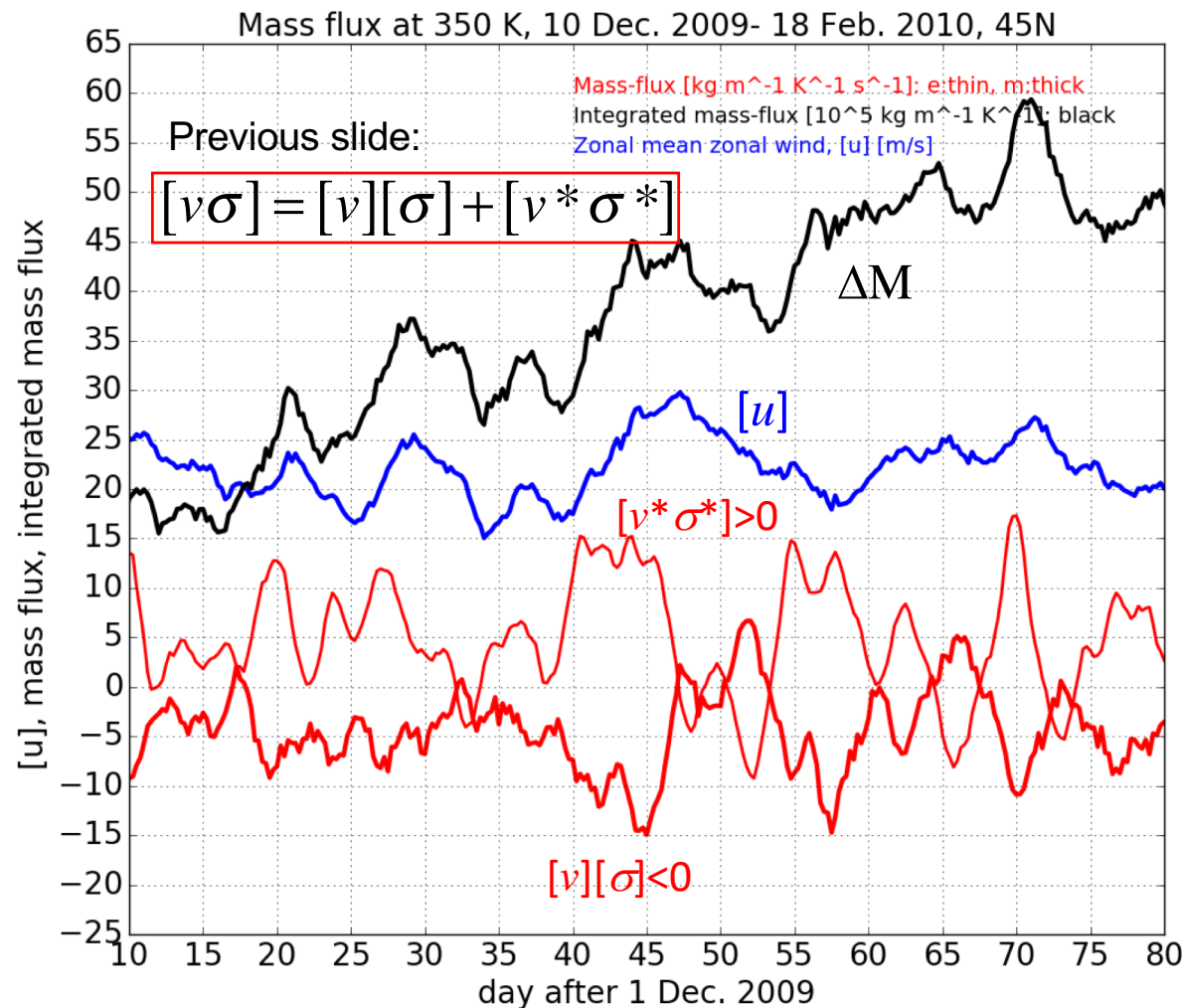


FIGURE 1.55 (alternative version): Running daily mean poleward isentropic mass-flux, at 350 K and at 45°N, during the Northern Hemisphere winter of 2009-2010 (red lines). The **thick red line** represents the contribution from the *Ferrel cell*, while the **thin red line** represents the contribution from *eddies or waves*. The black line represents the time **integrated net flux of mass** after 1 December 2009 (00 UTC). The **blue line** represents the zonal **mean zonal wind**, $[u]$, at 60°N.

Isentropic mass flux at 45°N, at $\theta=350$ K

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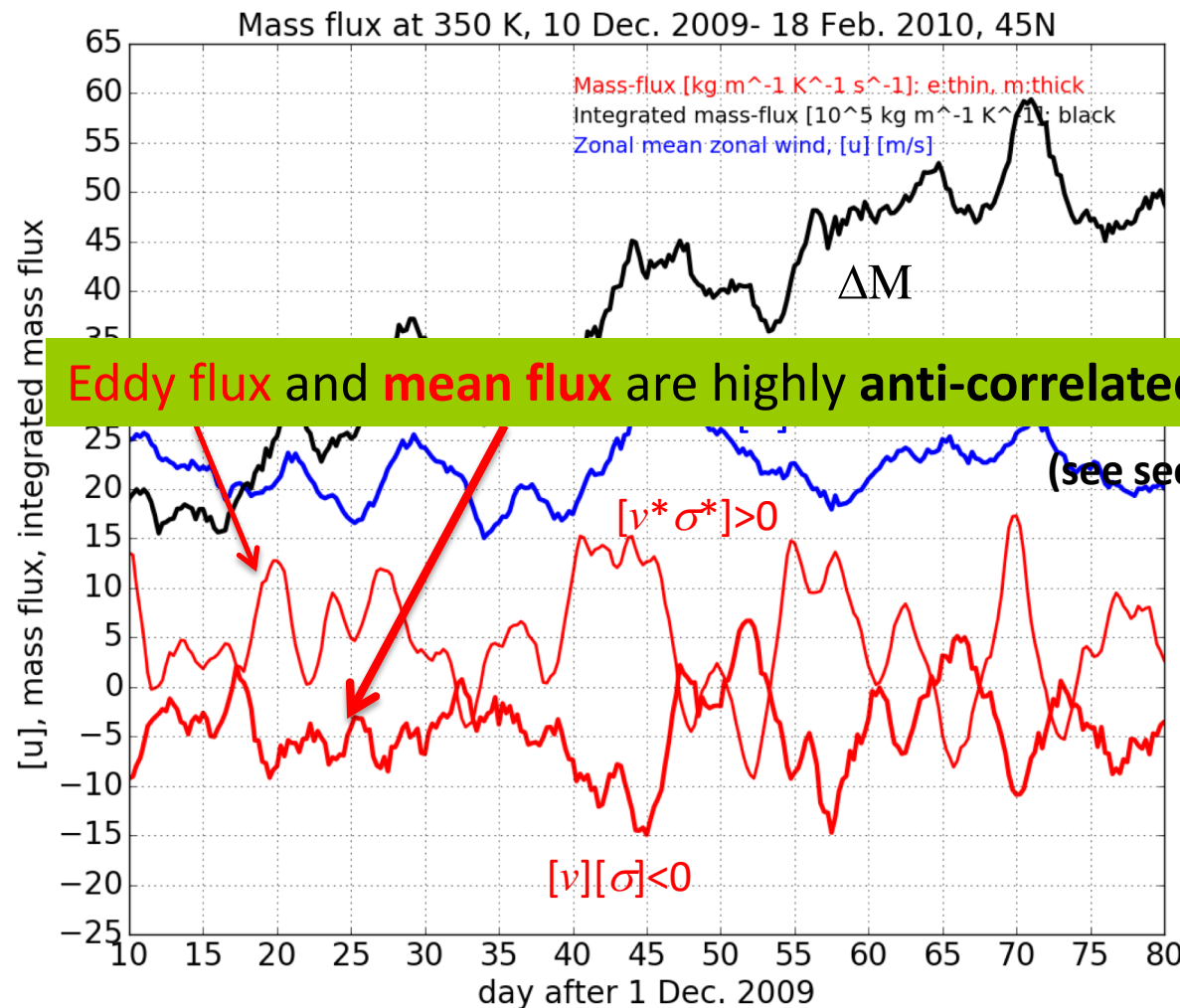
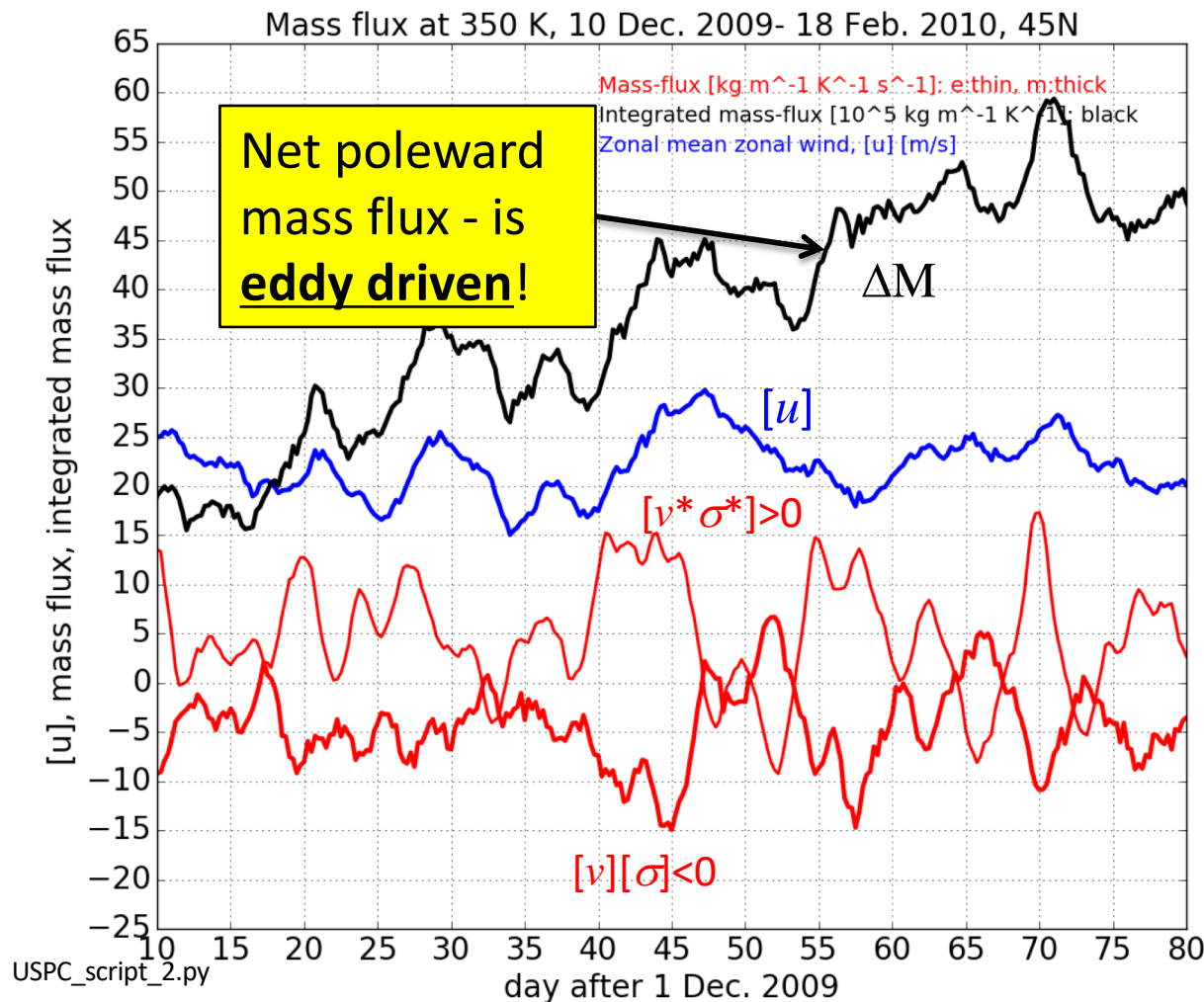


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Isentropic mass flux at 45°N , at $\theta=350 \text{ K}$

— [u] 2009-2010

— [v][σ] **mean flux**

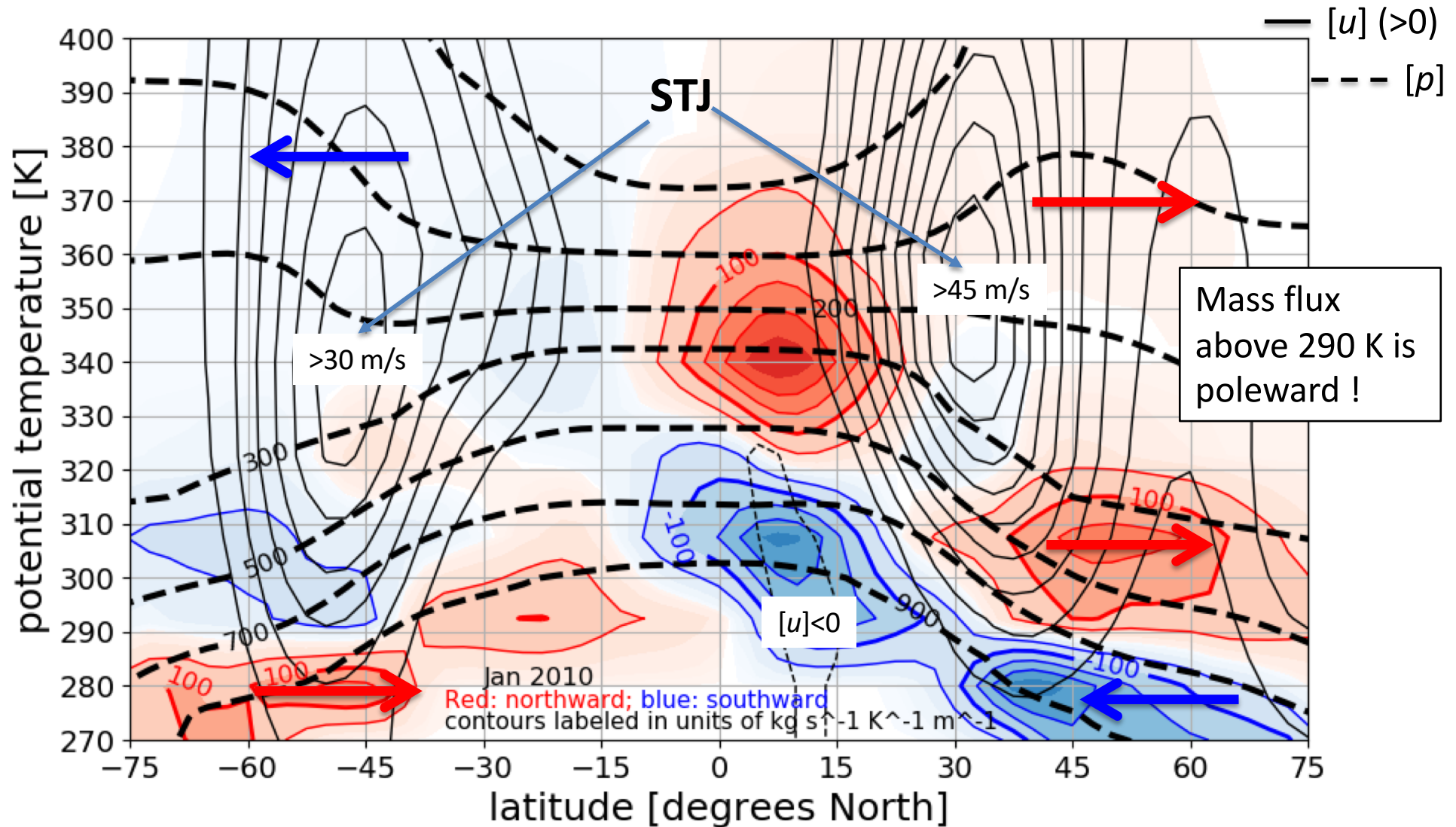
— [$v^* \sigma^*$] **eddy flux**

$$\Delta M(t) = \int_{t_0}^t [v\sigma] dt \quad [\text{kg m}^{-1} \text{K}^{-1}]$$

FIGURE 1.55 (alternative version): Running daily mean poleward isentropic mass-flux, at 350 K and at 45°N , during the Northern Hemisphere winter of 2009-2010 (red lines). The **thick red line** represents the contribution from the *Ferrel cell*, while the **thin red line** represents the contribution from *eddies or waves*. The black line represents the time **integrated net flux of mass** after 1 December 2009 (00 UTC). The **blue line** represents the zonal **mean zonal wind**, [u], at 60°N .

Zonal/time mean meridional mass flux*

(Jan 2010)



$$* = \frac{1}{T_0} \int_0^T [v\sigma] dt \quad [\text{kg m}^{-1} \text{K}^{-1} \text{s}^{-1}]$$

see figs. 1.47 & 1.54

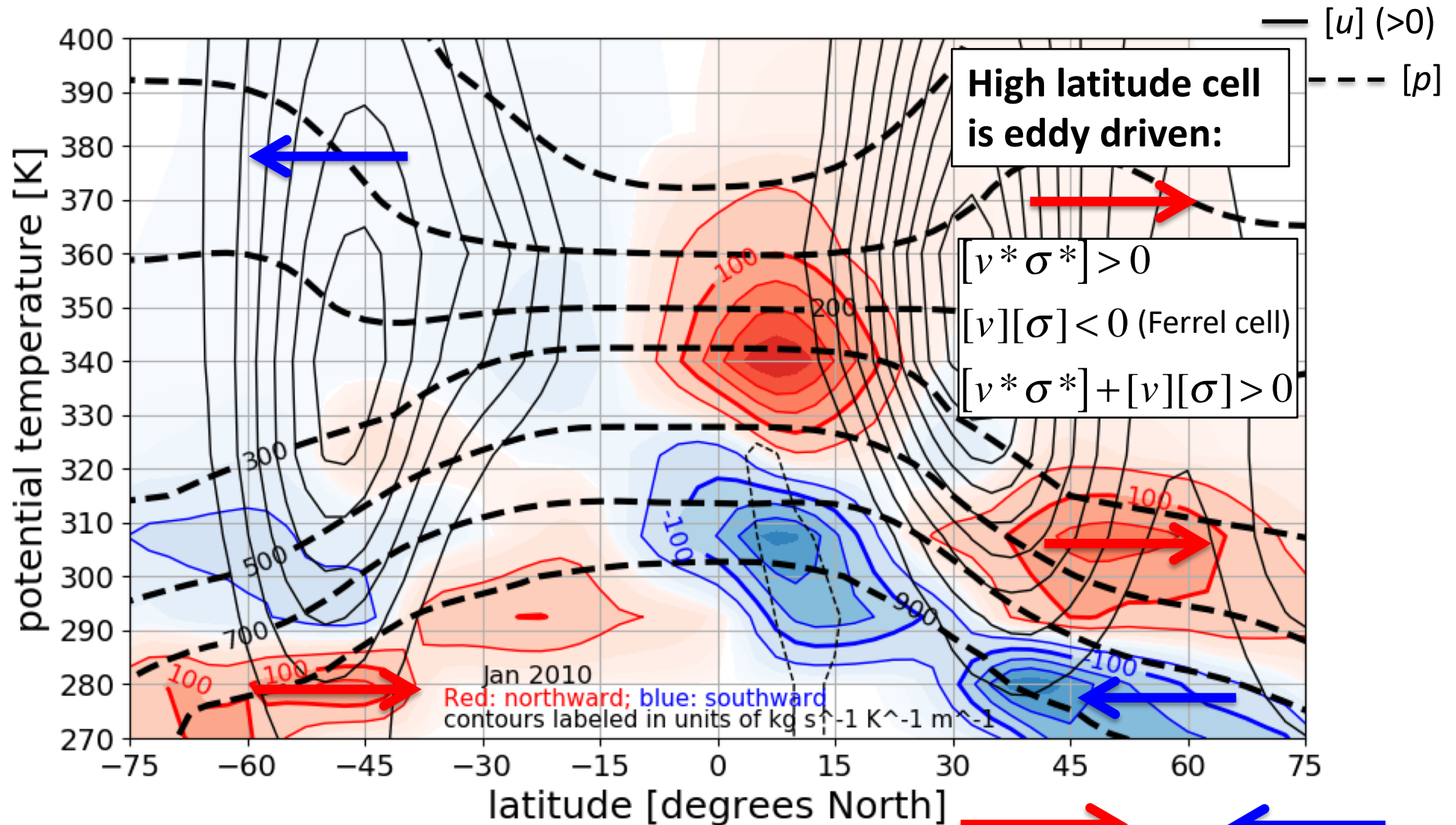
Northward flow

Southward flow

Zonal/time mean meridional mass flux*

(Jan 2010)

Isentropic branches of the “residual circulation of mass”

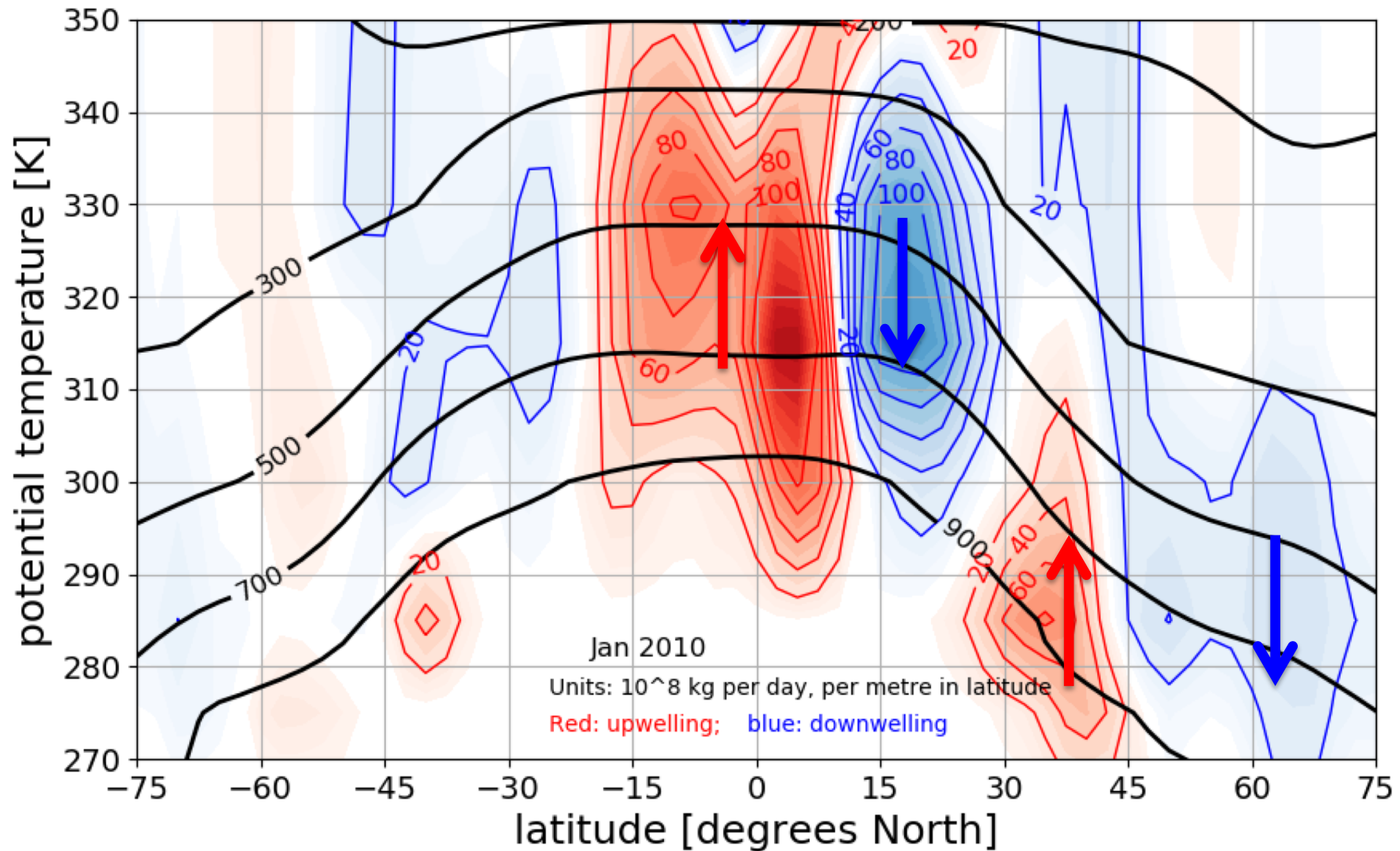


$$* = \frac{1}{T} \int_0^T [v\sigma] dt \quad [\text{kg m}^{-1} \text{K}^{-1} \text{s}^{-1}]$$

see figs. 1.47 & 1.54

Zonal/time mean cross-isentropic mass flux (Jan 2010)

Cross-isentropic branches of the “residual circulation of mass”



see figs. 1.60

The stationary residual circulation in January

Also called: “**Brewer-Dobson circulation (BDC)**”

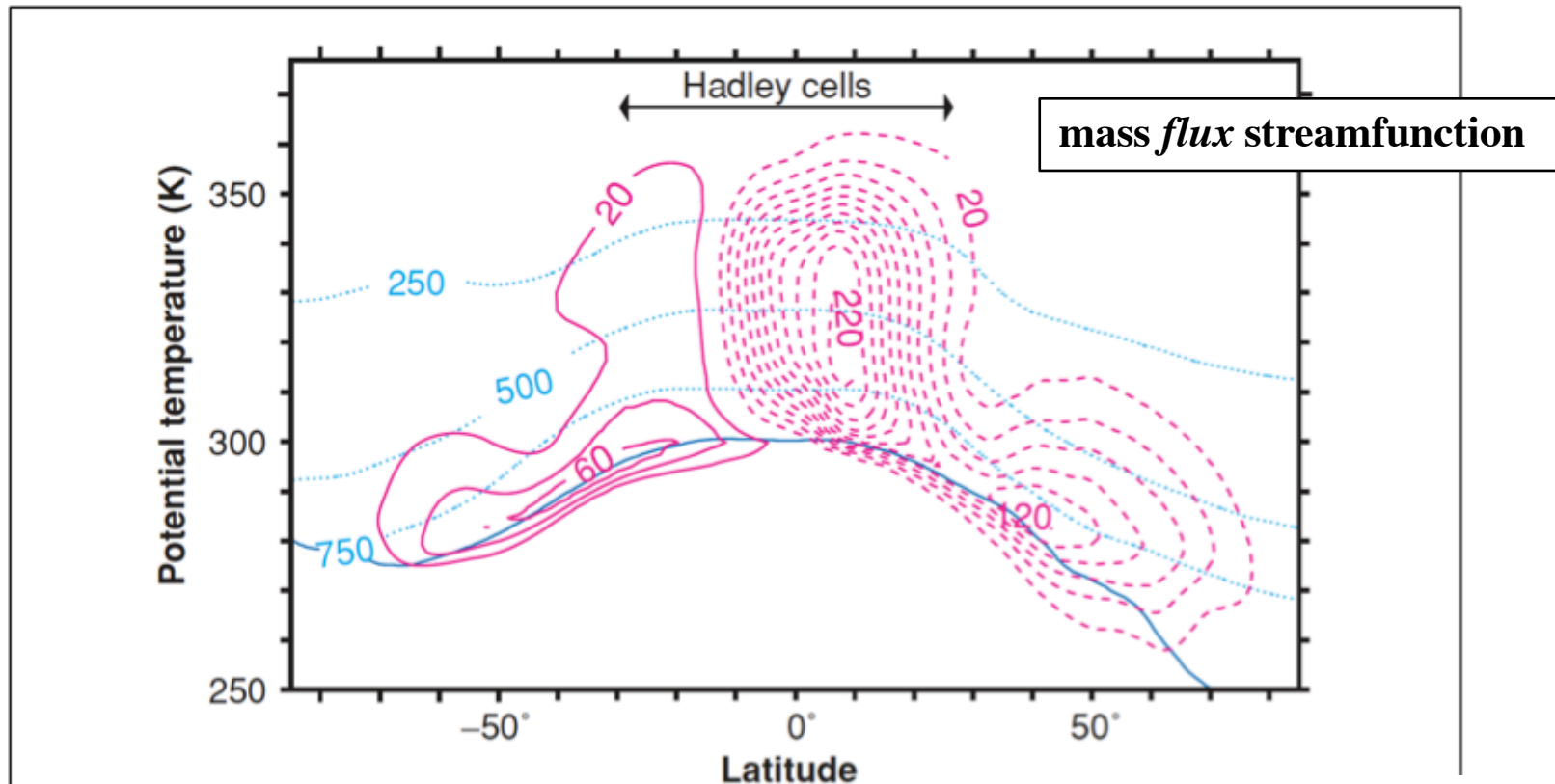


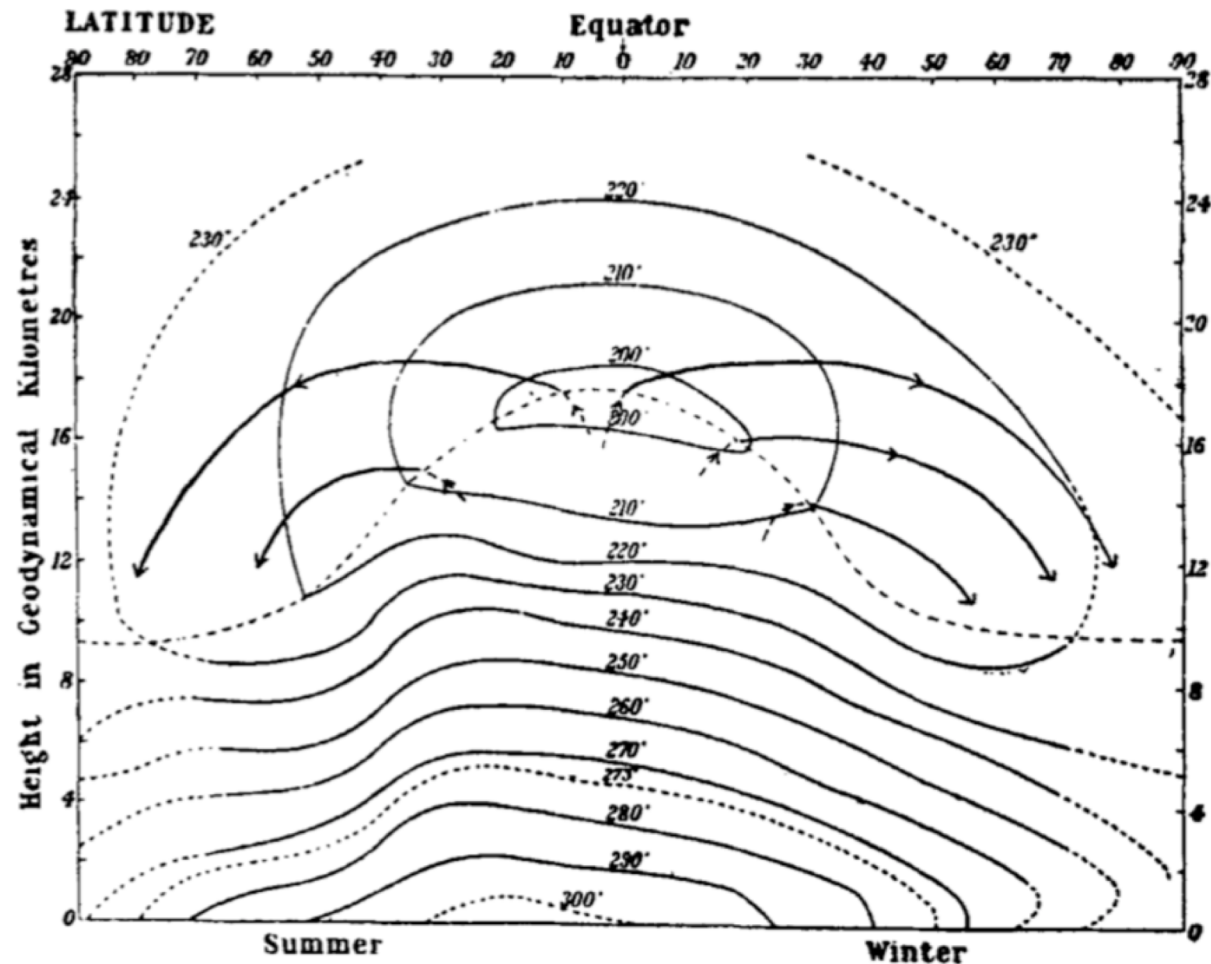
Figure 6

(problem 1.19, p. 153)

Isentropic mass flux streamfunction for January (temporal and zonal mean according to the same reanalysis data as in **Figure 1**). Negative streamfunction values (*dashed magenta contours*) correspond to clockwise rotation, positive values (*solid magenta contours*) to counterclockwise rotation. The contour interval is $20 \times 10^9 \text{ kg s}^{-1}$. The solid blue line is the median surface potential temperature. The dotted blue lines are mean pressure contours (250, 500, and 750 hPa). Tapio Schneider, 2006

Alan Brewers picture (1949) of the “BDC”

Brewer (and Dobson) were the first to find the poleward flow in the stratosphere from observations of water vapour, entering the stratosphere through the tropical tropopause (Brewer), and observations of ozone in the stratosphere (Dobson) from observations of ozone. The associated “circulation” is called “Brewer-Dobson circulation”. Very little was known about the return flow...



The figure: Brewer's (1949) original figure, illustrating what came to be known as the Brewer-Dobson circulation. "A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause". The contours represent isotherms, labeled in units of K. Brewer emphasized the stratospheric branch of a circulation of mass, which is principally tropospheric (see previous slide) and is also not zonally symmetric in the sense that transport due to eddies is just as important as transport due to the mean circulation

Vorticity equation in isentropic (θ) coordinate

Equations of motion:

$$\begin{aligned}\frac{du}{dt} &= \frac{\partial u}{\partial t} + u \left(\frac{\partial u}{\partial x} \right)_\theta + v \left(\frac{\partial u}{\partial y} \right)_\theta + \frac{d\theta}{dt} \frac{\partial u}{\partial \theta} = - \left(\frac{\partial \Psi}{\partial x} \right)_\theta + fv + \overset{\text{friction}}{\downarrow} F_x \\ \frac{dv}{dt} &= \frac{\partial v}{\partial t} + u \left(\frac{\partial v}{\partial x} \right)_\theta + v \left(\frac{\partial v}{\partial y} \right)_\theta + \frac{d\theta}{dt} \frac{\partial v}{\partial \theta} = - \left(\frac{\partial \Psi}{\partial y} \right)_\theta - fu + F_y\end{aligned}$$

Relative vorticity:

(vertical component)

$$\zeta_\theta = \left(\frac{\partial v}{\partial x} \right)_\theta - \left(\frac{\partial u}{\partial y} \right)_\theta$$

Isentropic divergence:

$$\delta_\theta \equiv \left(\frac{\partial u}{\partial x} \right)_\theta + \left(\frac{\partial v}{\partial y} \right)_\theta$$

Vorticity equation derived from the equations of motion (above):

$$\frac{d}{dt} (\zeta_\theta + f) = -(\zeta_\theta + f) \delta_\theta + \frac{\partial u}{\partial \theta} \frac{\partial}{\partial y} \left(\frac{d\theta}{dt} \right) - \frac{\partial v}{\partial \theta} \frac{\partial}{\partial x} \left(\frac{d\theta}{dt} \right) + \frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}$$

Vorticity equation in isentropic (θ) coordinate

Vorticity equation (previous slide):

$$\frac{d}{dt}(\zeta_{\theta} + f) = -(\zeta_{\theta} + f)\delta_{\theta} + \frac{\partial u}{\partial \theta} \frac{\partial}{\partial y} \left(\frac{d\theta}{dt} \right) - \frac{\partial v}{\partial \theta} \frac{\partial}{\partial x} \left(\frac{d\theta}{dt} \right) + \frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}$$

Isentropic divergence: $\delta_{\theta} \equiv \left(\frac{\partial u}{\partial x} \right)_{\theta} + \left(\frac{\partial v}{\partial y} \right)_{\theta}$

Vorticity equation in adiabatic, without friction:

$$\frac{d}{dt}(\zeta_{\theta} + f) = -(\zeta_{\theta} + f)\delta_{\theta}$$

Combine vorticity- and mass-conservation

Vorticity equation in adiabatic , without friction (previous slide):

$$\frac{d}{dt}(\zeta_{\theta} + f) = -(\zeta_{\theta} + f)\delta_{\theta}$$

Continuity (mass-conservation) equation (previous lecture):

$$\frac{d\sigma}{dt} = -\sigma \left(\frac{\partial u}{\partial x} \right)_{\theta} - \sigma \left(\frac{\partial v}{\partial y} \right)_{\theta} - \sigma \left(\frac{\partial}{\partial \theta} \frac{d\theta}{dt} \right)$$

Adiabatic continuity equation:

$$\frac{d\sigma}{dt} = -\sigma\delta_{\theta}$$

Leads to adiabatic potential vorticity equation

Previous slide:

$$\frac{d}{dt}(\zeta_{\theta} + f) = -(\zeta_{\theta} + f)\delta_{\theta}$$

$$\frac{d\sigma}{dt} = -\sigma\delta_{\theta}$$

Potential vorticity:

$$Z_{\theta} \equiv \frac{\zeta_{\theta} + f}{\sigma}$$

easy derivation

$$\frac{dZ_{\theta}}{dt} = 0$$

Conservation of potential vorticity

Potential vorticity-conservation is very useful to interpret output of numerical weather prediction models.

Adiabatic vorticity equation in flux form

Previous slide:

$$\frac{d}{dt}(\zeta_\theta + f) = -(\zeta_\theta + f)\delta_\theta \quad \delta_\theta \equiv \left(\frac{\partial u}{\partial x}\right)_\theta + \left(\frac{\partial v}{\partial y}\right)_\theta$$



$$\frac{\partial \zeta_a}{\partial t} = -u \left(\frac{\partial \zeta_a}{\partial x}\right)_\theta - v \left(\frac{\partial \zeta_a}{\partial y}\right)_\theta - \zeta_a \left(\frac{\partial u}{\partial x}\right)_\theta - \zeta_a \left(\frac{\partial v}{\partial y}\right)_\theta = - \left(\frac{\partial u \zeta_a}{\partial x}\right)_\theta - \left(\frac{\partial v \zeta_a}{\partial y}\right)_\theta$$

Adiabatic vorticity equation in flux form

Previous slide:

$$\frac{d}{dt}(\zeta_\theta + f) = -(\zeta_\theta + f)\delta_\theta$$



$$\frac{\partial \zeta_a}{\partial t} = -u \left(\frac{\partial \zeta_a}{\partial x} \right)_\theta - v \left(\frac{\partial \zeta_a}{\partial y} \right)_\theta - \zeta_a \left(\frac{\partial u}{\partial x} \right)_\theta - \zeta_a \left(\frac{\partial v}{\partial y} \right)_\theta = - \left(\frac{\partial u \zeta_a}{\partial x} \right)_\theta - \left(\frac{\partial v \zeta_a}{\partial y} \right)_\theta$$

which can be written as:

$$\frac{\partial \zeta_a}{\partial t} = -\vec{\nabla} \cdot \vec{J}$$

$$\text{with } \vec{\nabla} \equiv \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial \theta} \right)$$

$$\vec{J} = (u\zeta_a, v\zeta_a, 0)$$



Flux of vorticity

Leads to the *Impermeability Theorem*

Previous slide:

$$\frac{\partial \zeta_a}{\partial t} = -\vec{\nabla} \cdot \vec{J}$$

$$\vec{J} = (u\zeta_a, v\zeta_a, 0)$$



Flux of vorticity has no cross-isentropic component!

This is logical because we have assumed adiabatic conditions

However,

Box 1.12

Impermeability theorem is always valid!

Non-adiabatic and including friction we can also write:

$$\frac{\partial \zeta_a}{\partial t} = -\vec{\nabla} \cdot \vec{J}$$

Flux of vorticity: $\vec{J} \equiv \left(u\sigma Z + \dot{\theta} \frac{\partial v}{\partial \theta} - F_y, v\sigma Z - \dot{\theta} \frac{\partial u}{\partial \theta} + F_x, 0 \right)$ $\dot{\theta} \equiv \frac{d\theta}{dt}$

Flux of vorticity has no cross-isentropic component!

Box 1.12

Impermeability theorem is always valid!

Non-adiabatic and including friction we can also write:

$$\frac{\partial \zeta_a}{\partial t} = -\vec{\nabla} \cdot \vec{J}$$

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Flux of vorticity has no cross-isentropic component!

There cannot be cross-isentropic transport of vorticity

Potential Vorticity Substance

Non-adiabatic and including friction we can also write:

$$\frac{\partial \zeta_a}{\partial t} = -\vec{\nabla} \cdot \vec{J}$$

Flux of vorticity: $\vec{J} \equiv \left(u\sigma Z + \dot{\theta} \frac{\partial v}{\partial \theta} - F_y, v\sigma Z - \dot{\theta} \frac{\partial u}{\partial \theta} + F_x, 0 \right)$

Flux of vorticity has no cross-isentropic component!

There cannot be cross-isentropic transport of vorticity

Vorticity behaves as if it is the density of a substance called “**Potential Vorticity Substance**” (PVS).

Recap.: vorticity- and mass-budget

Non-adiabatic and including friction we can also write:

$$\frac{\partial \zeta_a}{\partial t} = -\vec{\nabla} \cdot \vec{J}$$

Flux of vorticity: $\vec{J} \equiv \left(u\sigma Z + \dot{\theta} \frac{\partial v}{\partial \theta} - F_y, v\sigma Z - \dot{\theta} \frac{\partial u}{\partial \theta} + F_x, 0 \right)$

Flux of vorticity has **no** cross-isentropic component!

Mass budget:

$$\frac{\partial \sigma}{\partial t} = -\left(\frac{\partial u \sigma}{\partial x} \right)_\theta - \left(\frac{\partial v \sigma}{\partial y} \right)_\theta - \frac{\partial}{\partial \theta} \left(\frac{d\theta}{dt} \sigma \right)$$

$$\frac{\partial \sigma}{\partial t} = -\vec{\nabla} \cdot \vec{I}$$

with

$$\vec{I} \equiv \left(u\sigma, v\sigma, \frac{d\theta}{dt} \sigma \right)$$

Mass flux

Only mass can be transported across isentropes

Zonal mean **meridional** isentropic vorticity flux


$$\vec{J} = (u\zeta_a, \underline{v\zeta_a}, 0)$$

Zonal mean: $[v] \equiv \frac{1}{2\pi} \int_0^{2\pi} v d\lambda$ and $[\zeta_{abs}] \equiv \frac{1}{2\pi} \int_0^{2\pi} \zeta_{abs} d\lambda$

Mean + perturbation: $v = [v] + v^*$ and $\zeta_{abs} = [\zeta_{abs}] + \zeta_a^*$

Meridional flux of vorticity:

$$[v\zeta_a] \equiv \left(([v] + v^*) ([\zeta_a] + \zeta_a^*) \right) = [v][\zeta_a] + v^*[\zeta_a] + [v]\zeta_a^* + v^*\zeta_a^* = [v][\zeta_a] + [v^*\zeta_a^*]$$


$$[v\zeta_a] = [v][\zeta_a] + [v^*\zeta_a^*]$$

mean flux

Eddy flux

Meridional flux of potential vorticity substance

$$[v\zeta_a] = [v][\zeta_a] + [v^*\zeta_a^*]$$

↑
mean flux

↑
eddy flux

is the isentropic flux of “potential vorticity substance”

$\zeta_a = \sigma Z$ is called “potential vorticity substance” (PVS)

Isentropic Flux of PVS at 45°N

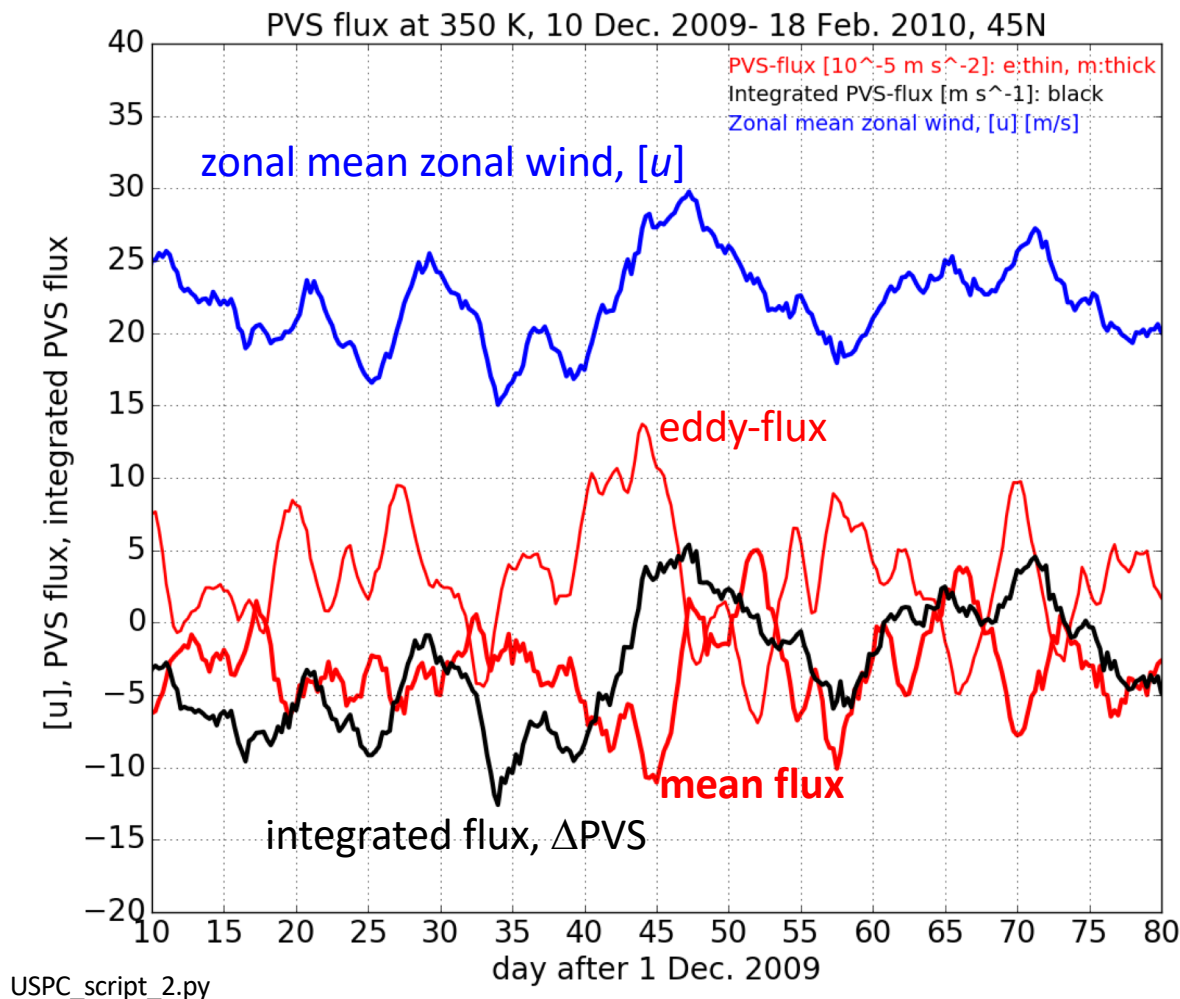
Winter of
2009-2010

— $[u]$

— $[v][\zeta_a]$ **mean flux**

— $[v^* \zeta_a^*]$ **eddy flux**

$$\text{— } \Delta PVS(t) = \int_{t_0}^t [v \zeta_a] dt \quad [\text{m s}^{-1}]$$



USPC_script_2.py

FIGURE 1.55 (alternative version): Running daily mean poleward isentropic vorticity-flux at 350 K and at 45°N, during the Northern Hemisphere winter of 2009-2010 (red lines). The thick red line represents the contribution from the so-called “**Ferrel cell**”, while the **thin red line represents the contribution from eddies or waves**. The **black line represents the time integrated net flux of PVS after 1 December 2009 (00 UTC)**. The **blue line represents the zonal mean zonal wind, $[u]$, at 60°N**. Based on the ERA-Interim reanalysis.

Isentropic Flux of PVS at 45°N

Winter of
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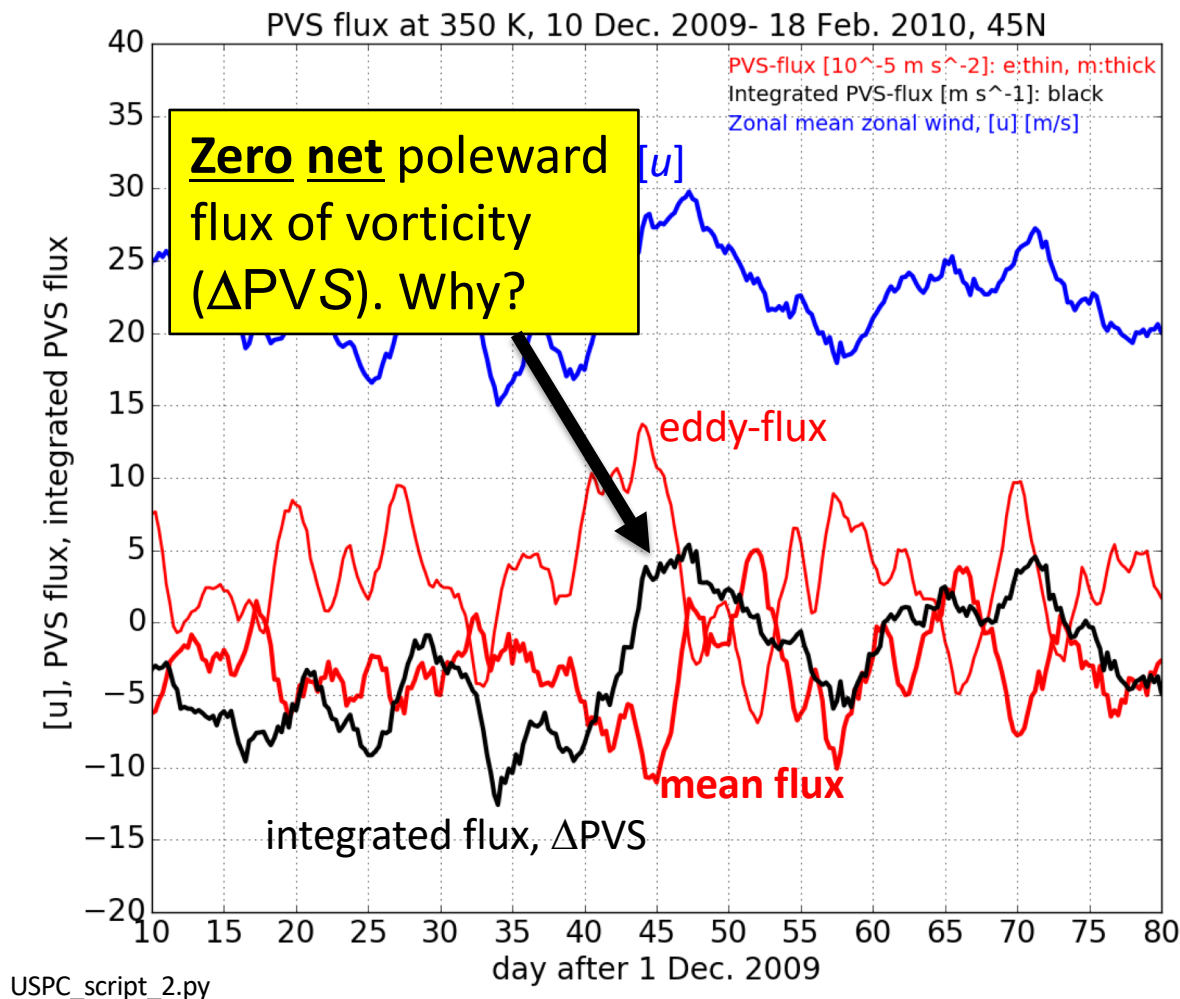


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Isentropic Flux of PVS at 45°N

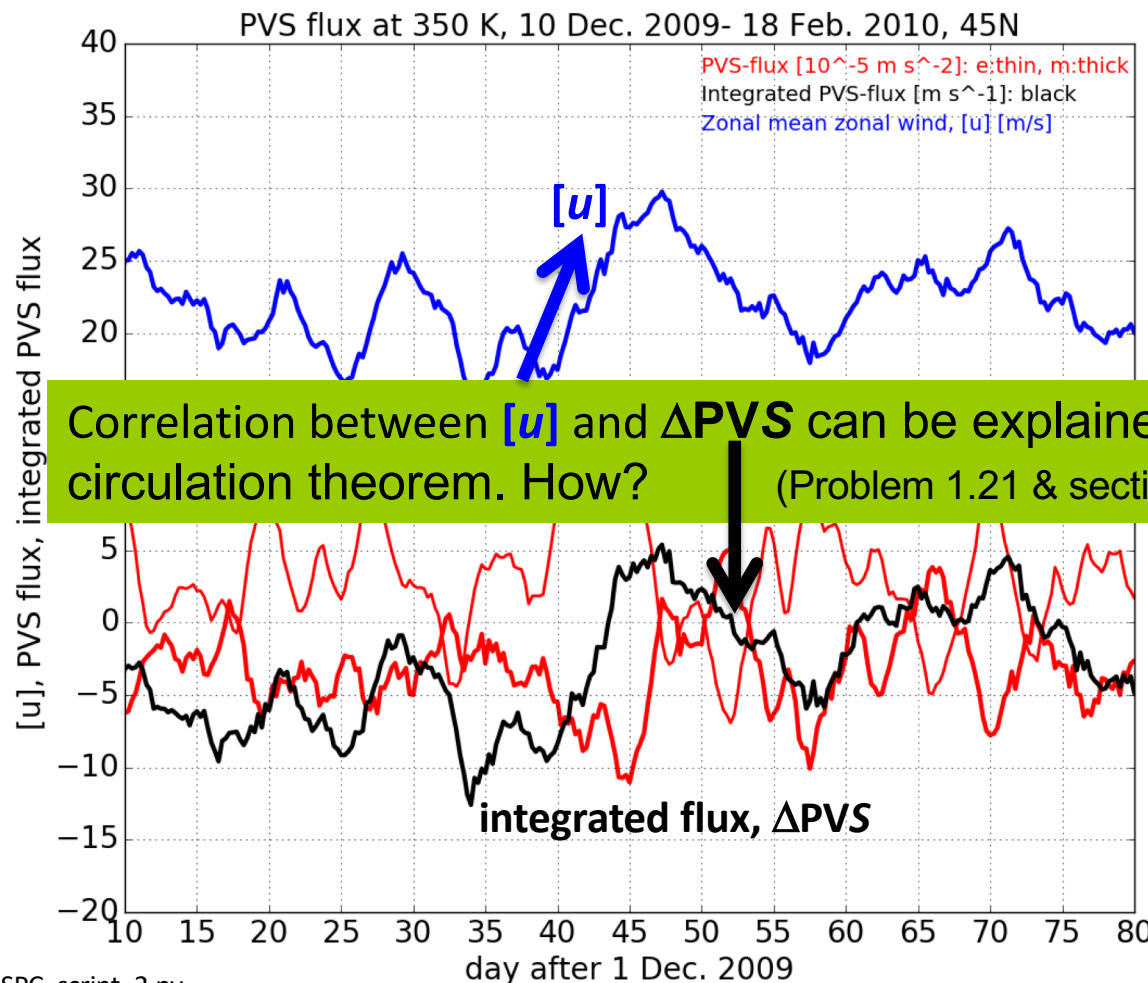
Winter of 2009-2010

— $[u]$

— $[v][\zeta_a]$ **mean flux**

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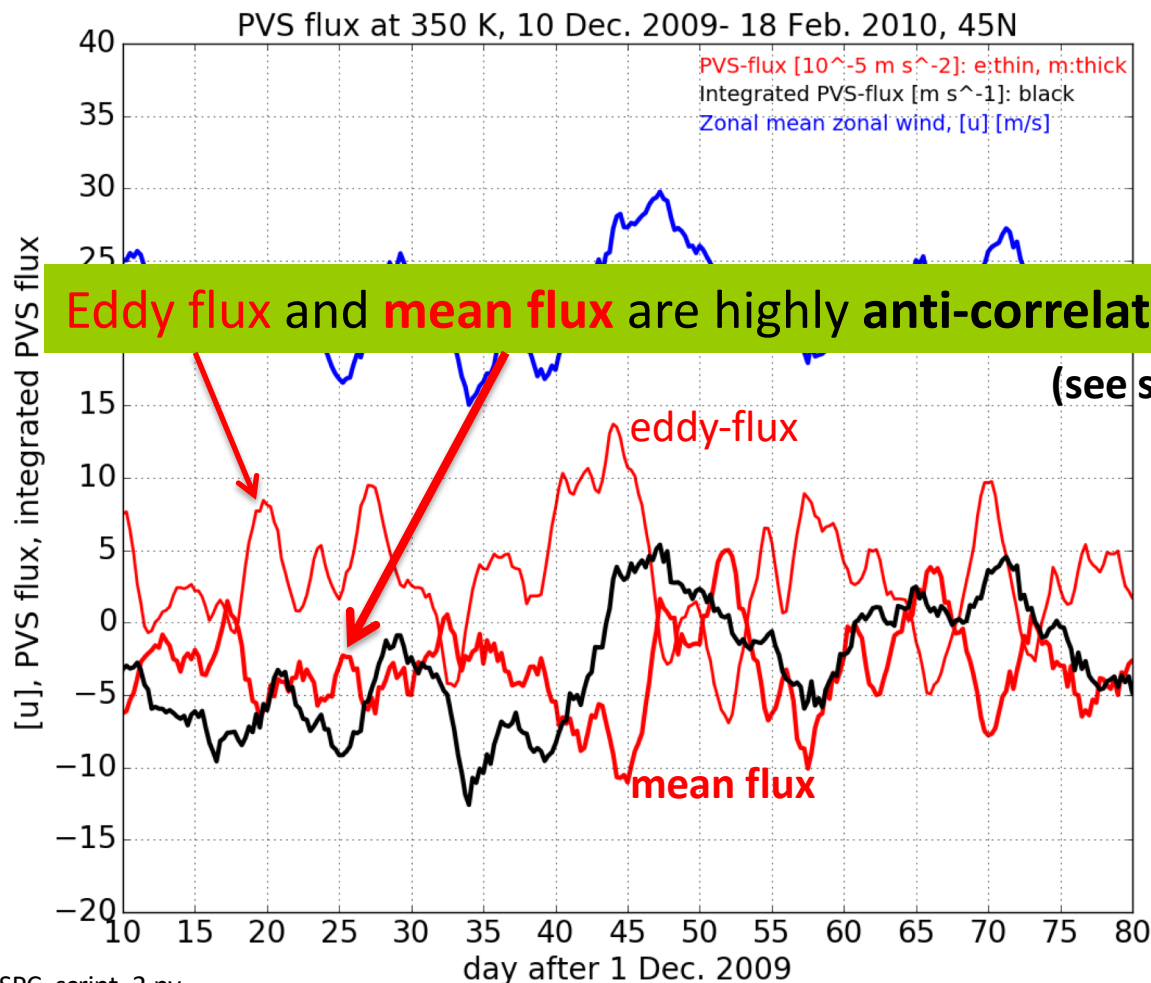


USPC_script_2.py

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Isentropic Flux of PVS at 45°N

Winter of
2009-2010



USPC_script_2.py

[u]

[v][ζ_a] **mean flux**

[$v^* \zeta_a^*$] **eddy flux**

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Most important conclusions of this lecture

The meridional isentropic mass flux is poleward in the upper troposphere, and in the stratosphere. This mass flux represents the upper branch of the “Brewer-Dobson” circulation. The meridional mass flux is poleward due to the eddy-contribution and is thus called “eddy-driven”. Why the mass flux is poleward is explained in section 1.41.

Isentropic surfaces are impermeable to vorticity, but not to mass

The eddy mass fluxes and mean mass fluxes are strongly anticorrelated. This is because the zonal mean state “wants” to **remain in, or close to, zonal mean (thermal wind) balance**.

Balance, or more accurately, quasi-balance, is the subject of the following two lectures: lectures 11 & 12.

Most important conclusions on the dynamics of vorticity fluxes

In the long run, the time mean meridional isentropic vorticity flux is equal to zero on all isentropic surfaces, which do not intersect the earth's surface! This is a consequence of the impermeability of isentropic surfaces to vorticity. The average absolute vorticity on these surfaces is always equal to zero

The meridional isentropic vorticity flux correlates strongly with the zonal mean zonal wind. In fact, the net meridional vorticity flux determines the acceleration or deceleration of the zonal mean zonal flow.

This can be explained using the circulation theorem (problem 1.21), and will be explained also in section 1.35, which is about the interaction between the zonal mean flow and large scale eddies/waves.

Next:

Dynamic Meteorology: lecture 11

21/12/2022 (Wednesday, 13:15)

Sections 1.31, 1.32 and 1.33 (part G)

Quasi-balance and quasi-geostrophic approximation (section 1.31)

Rossby waves (section 1.37)

Excitation of Rossby waves due to baroclinic instability (section 1.38)

Baroclinic life cycle: Norwegian cyclone model (section 1.39)

No lecture or tutorial on Friday 23 December 2022!

Tutorial after this lecture (10)

Project 5

Problems 1.17, 1.18 (part D), 1.20, 1.21 (part E)

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