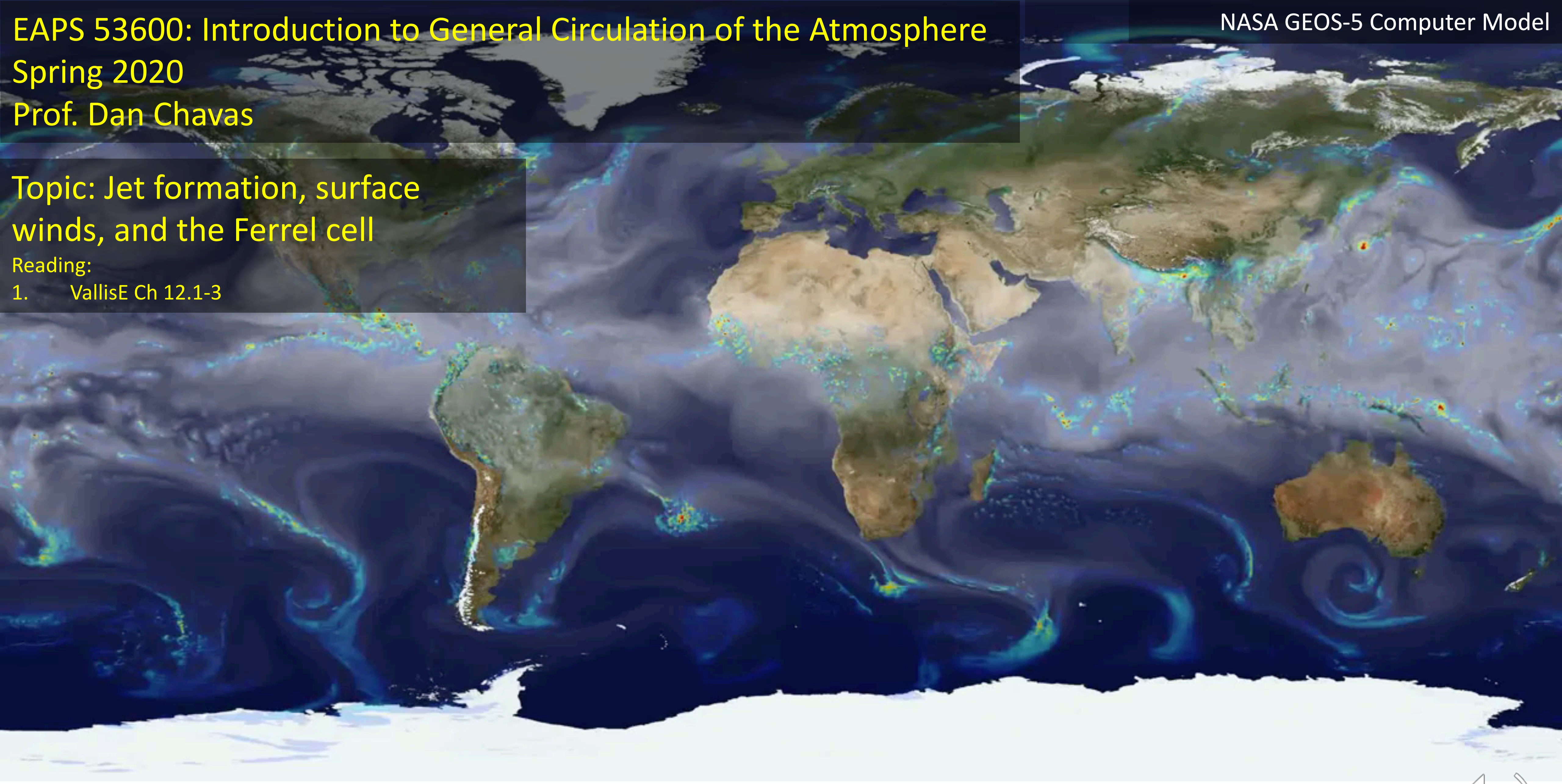
EAPS 53600: Introduction to General Circulation of the Atmosphere
Spring 2020
Prof. Dan Chavas



Topic: Jet formation, surface winds, and the Ferrel cell

Reading:
1. ValllisE Ch 12.1-3

White: total precipitable water (brigher white = more water vapor in column)
Colors: precipitation rate ($0 - 15\frac{mm}{hr}$, red=highest)

Source: https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=30017

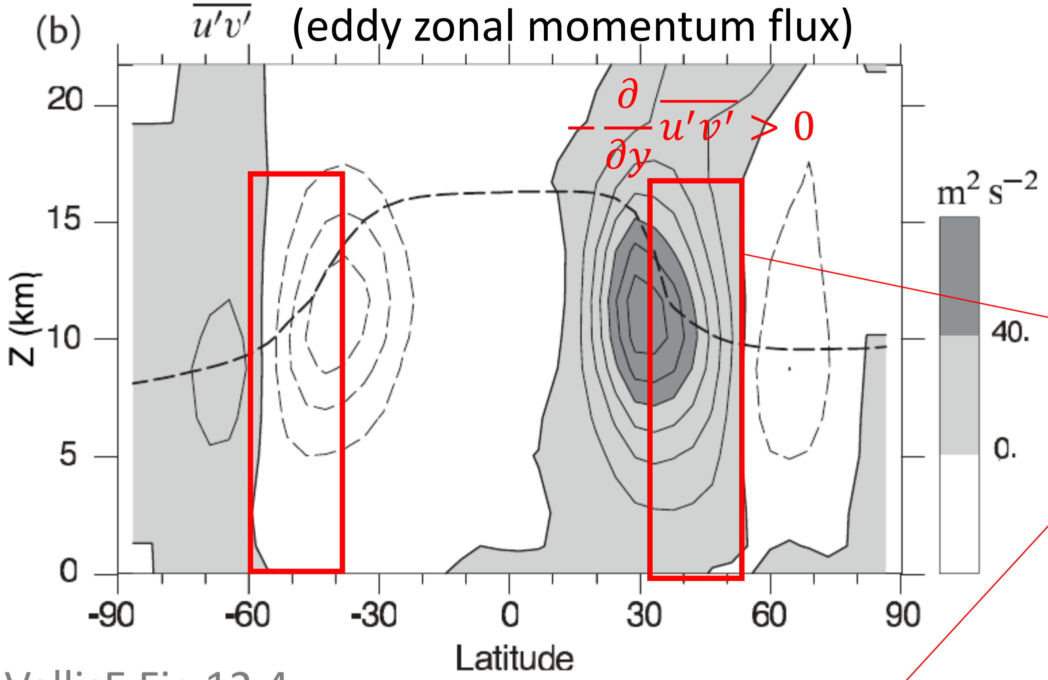
Learning outcomes for today:

- **Explain how eddy effects differ between barotropic vs. baroclinic fluid**
- **Describe what eddy momentum and heat fluxes look like in our atmosphere**
- **Explain what EP fluxes look like in our atmosphere and what that means for the zonal flow**
- **Explain what the Ferrel cell is**
- **Describe the residual overturning circulation and explain how it drives the mid-latitude jet**

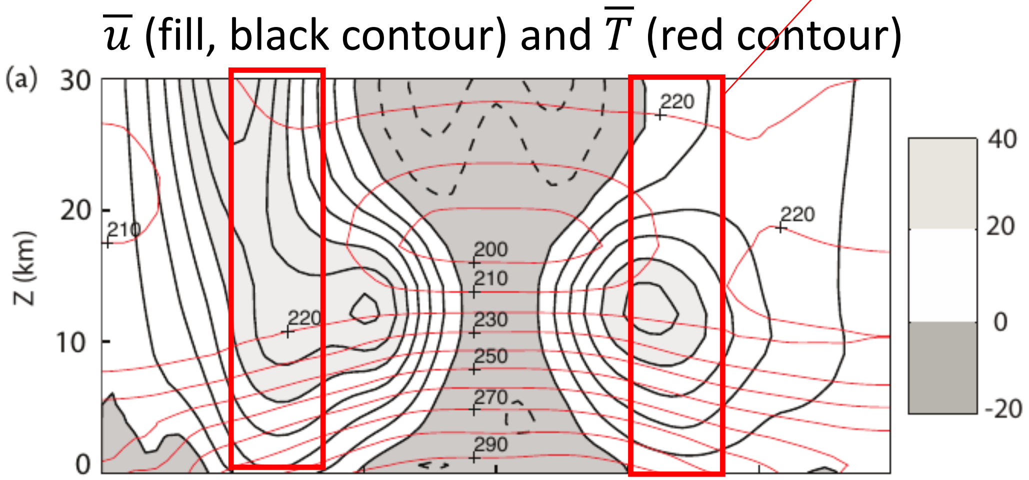
Barotropic fluid

(i.e. ignoring buoyancy effects)

Only eddy effect: momentum transport



VallisE Fig 12.4



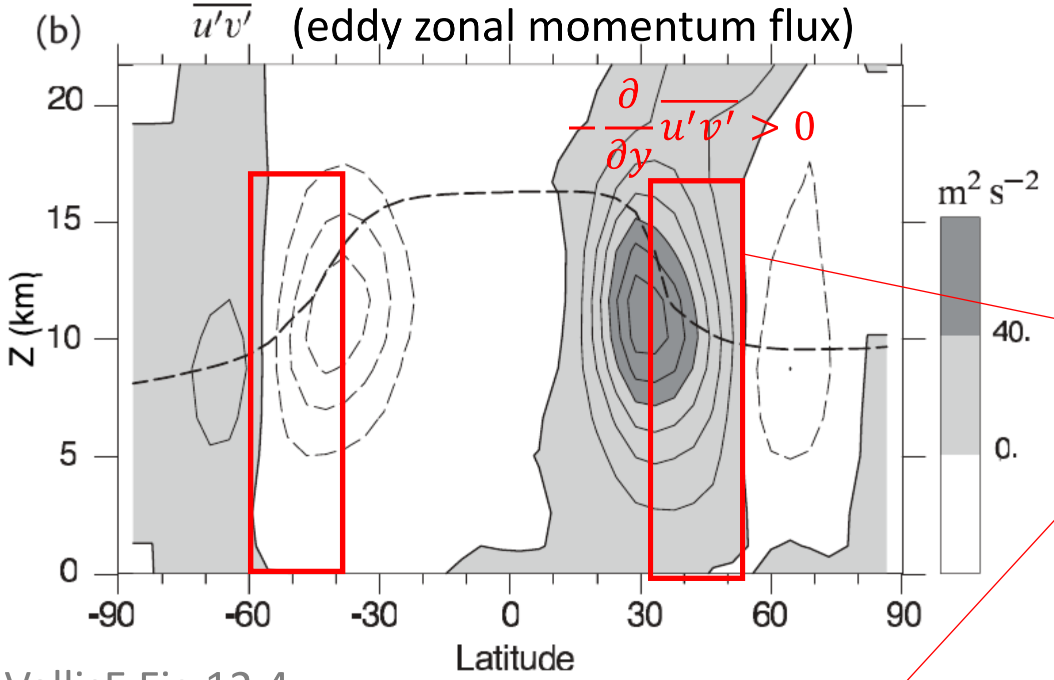
VallisE Fig 11.1

$$\frac{\partial \bar{u}}{\partial t} = \cancel{f_0 \bar{v}^*} + \overline{v'q'} + \bar{F} \qquad \overline{v'q'} = -\frac{\partial}{\partial y}\overline{u'v'} + \cancel{\frac{\partial}{\partial z}\left(\frac{f_0}{N^2}\overline{v'b'}\right)}$$

The eddies converge zonal momentum in the mid-latitudes – accelerating the mean zonal wind near the jet

For the **barotropic case** -- no buoyancy variation, $\overline{v} = 0$ -- there are **no eddy buoyancy fluxes**, only eddy momentum fluxes.

$$\frac{\partial \bar{u}}{\partial t} = \cancel{f_0 \bar{v}^*} + \overline{v'q'} + \bar{F} \qquad \overline{v'q'} = -\frac{\partial}{\partial y}\overline{u'v'} + \cancel{\frac{\partial}{\partial z}\left(\frac{f_0}{N^2}\overline{v'b'}\right)}$$



VallisE Fig 12.4

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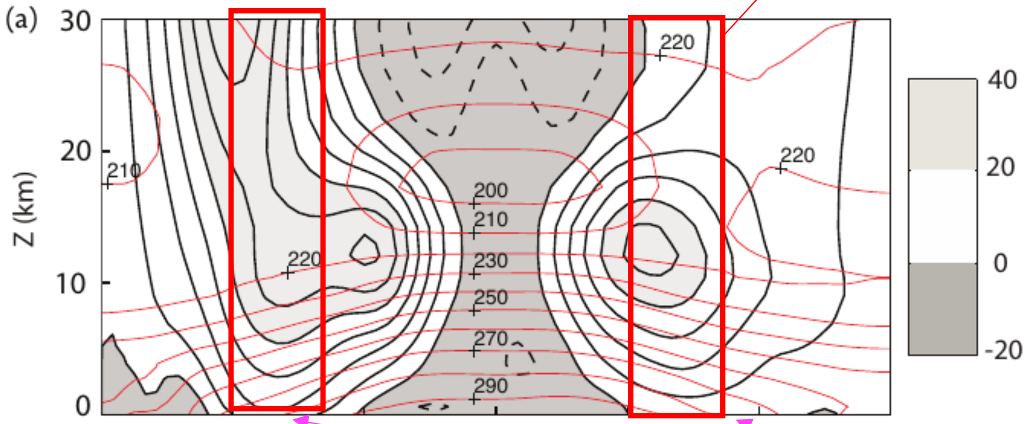
$\bar{u}$ (fill, black contour) and $\bar{T}$ (red contour)



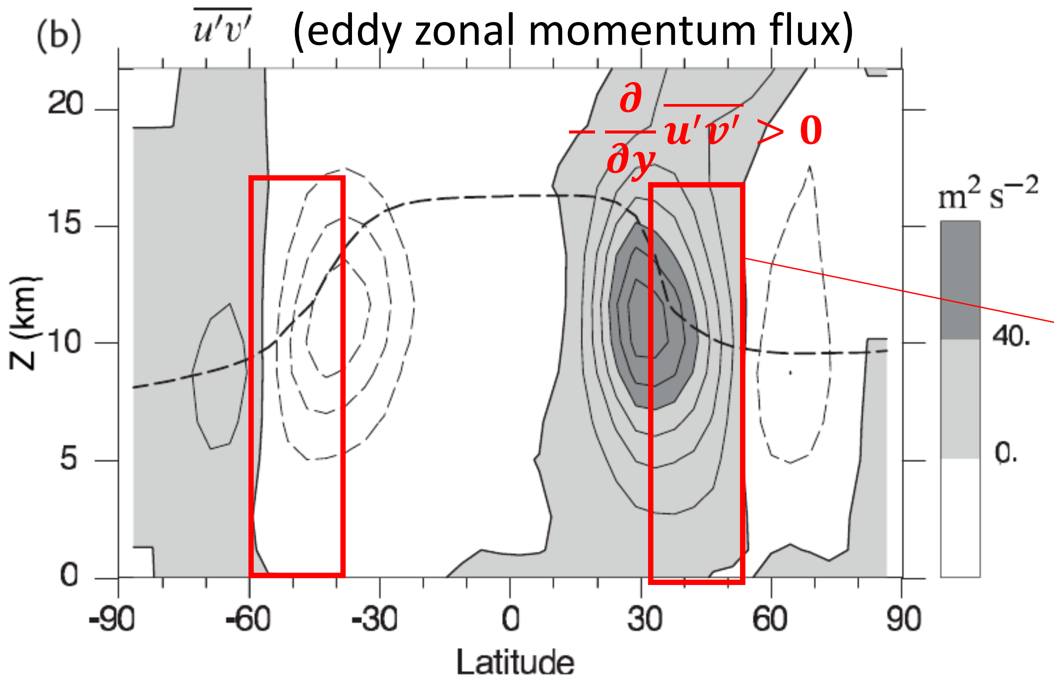
VallisE Fig 11.1

Important: because there is a convergence of momentum here, at steady state this is balanced by the loss of momentum of at the surface due to friction.

This requires <u>westerly surface flow</u> beneath.

Baroclinic fluid

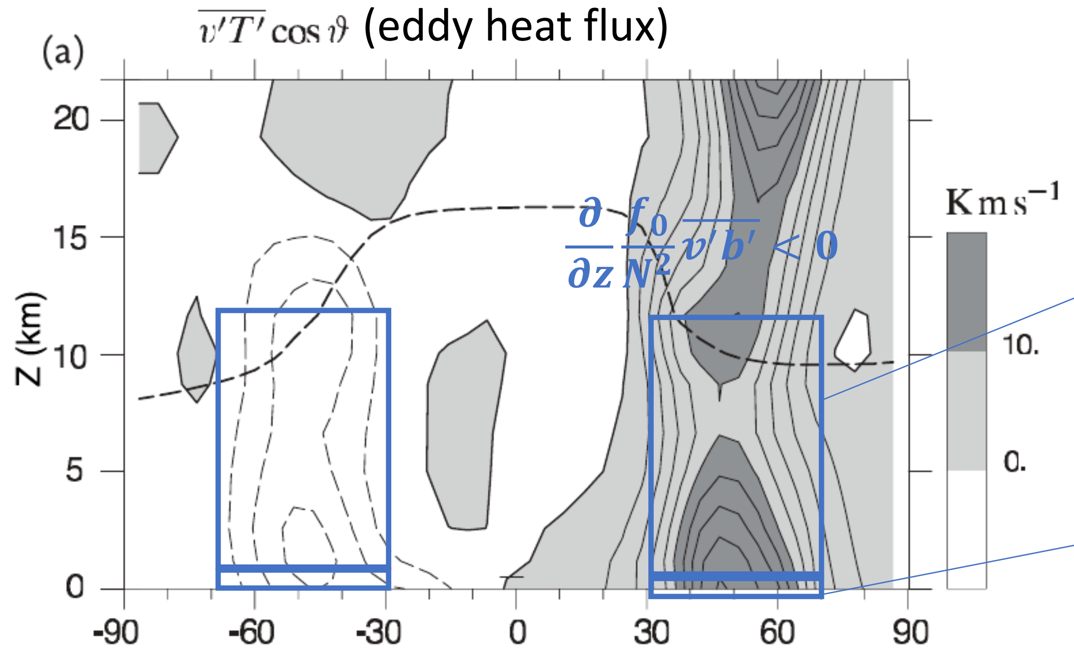
(including buoyancy effects)



$$\frac{\partial \bar{u}}{\partial t} = f_0 \bar{v}^* + \overline{v'q'} + \bar{F} \qquad \overline{v'q'} = -\frac{\partial}{\partial y}\overline{u'v'} + \frac{\partial}{\partial z}\left(\frac{f_0}{N^2}\overline{v'b'}\right)$$

The eddies converge zonal momentum in the mid-latitudes – accelerating the mean zonal wind near the jet

The real atmosphere is **baroclinic**, so we also must include the eddy heat fluxes.



The eddies transport heat poleward throughout the extratropics, and they do so **most strongly at low-levels** (as part of baroclinic instability)**.**

This acts to **reduce the meridional temperature gradient** and, by thermal wind balance, **weaken the jet!**

Exception: near the surface, where it *increases* from zero.

Eddies mix warm and cold air!

VallisE Fig 12.4

Recap: **What do eddies do to the mean zonal wind?**

Dynamically (momentum flux convergence): **strengthen** the mid-latitude jet
Thermodynamically (heat fluxes): **weaken** the mid-latitude jet (except near surface)

Which wins out?!?

Let's look at the <u>combined</u> effect: the **PV fluxes** (EP flux divergence)

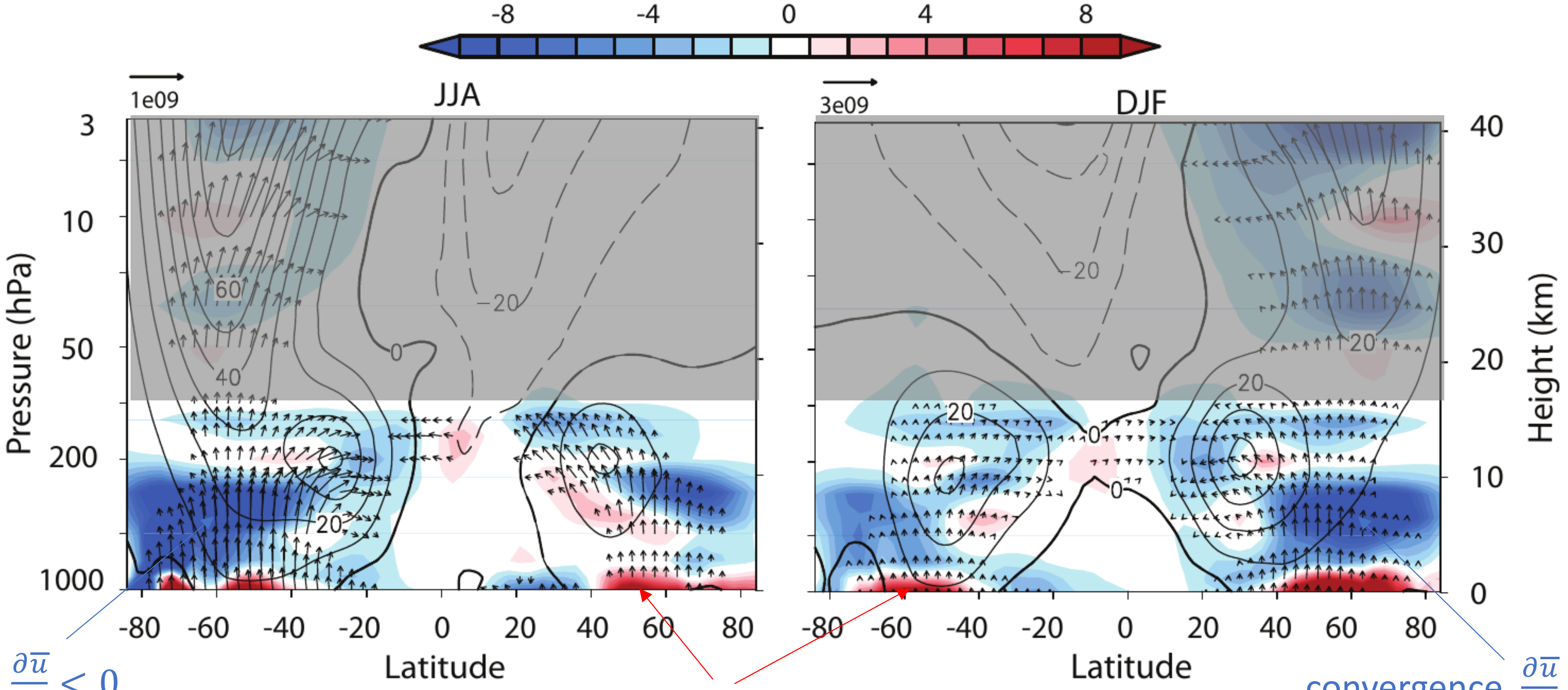
$$\frac{\partial \bar{u}}{\partial t} = f_0 \bar{v}^* + \overline{v'q'} + \bar{F} \qquad \overline{v'q'} = -\frac{\partial}{\partial y}\overline{u'v'} + \frac{\partial}{\partial z}\left(\frac{f_0}{N^2}\overline{v'b'}\right)$$

$$\overline{v'q'} = \nabla \cdot \boldsymbol{\mathcal{F}}$$

Arrows = EP Flux vectors ($\boldsymbol{\mathcal{F}}$)

Colors = EP flux divergence ($\nabla \cdot \boldsymbol{\mathcal{F}}$)

Contours = mean zonal wind ($\overline{u}$)



convergence, $\frac{\partial \overline{u}}{\partial t} < 0$

divergence, $\frac{\partial \overline{u}}{\partial t} > 0$

convergence, $\frac{\partial \overline{u}}{\partial t} < 0$

The net effect of eddies only accelerates the zonal flow near the surface.

Fig. 12.9:

VallisE Fig 12.9

Summary: EP fluxes

Barotropic: eddies generate a mean zonal flow
Baroclinic: eddies generate a mean *near-surface* flow, but otherwise weaken the mean flow aloft

But if eddies weaken the jet in the free troposphere, then what sustains it there?
Let’s first talk about the Ferrel cell.

The Ferrel cell

Thermally-indirect, eddy-driven Eulerian-mean meridional overturning circulation in the mid-latitudes

The Ferrel cell: an eddy-driven overturning circulation – in the Eulerian mean

Eulerian-mean

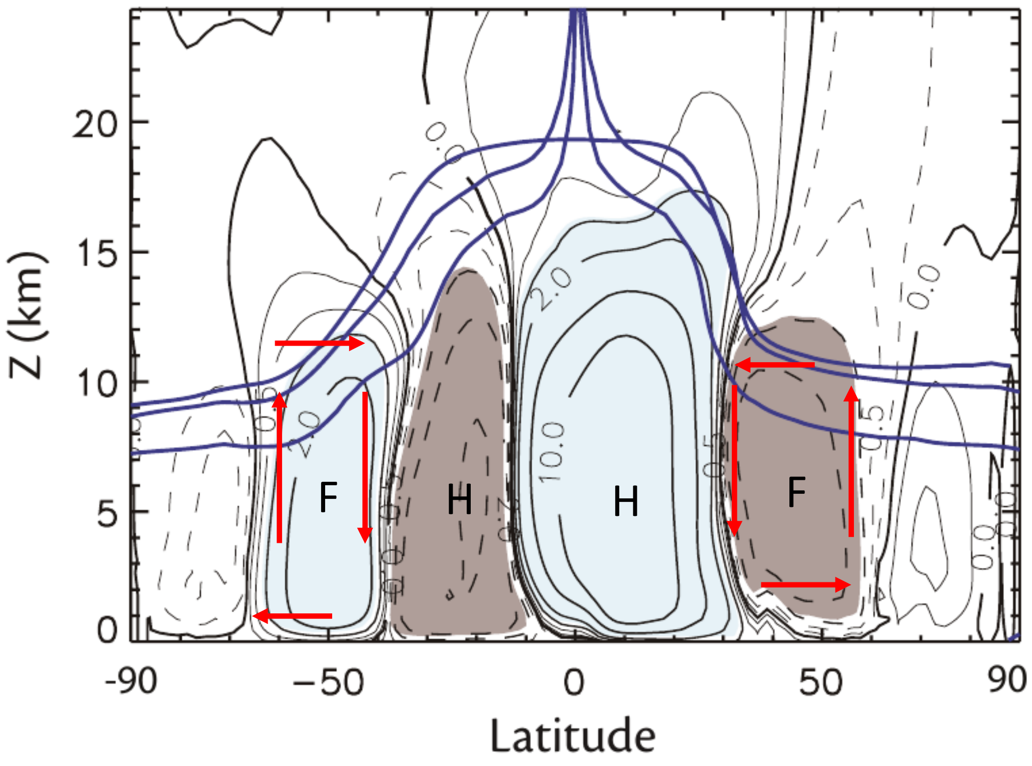


Fig. 12.8:

Fig. 12.8: Left: The observed zonally-averaged, Eulerian-mean, streamfunction in Northern Hemisphere winter (DJF, 1994–1997). Negative contours are dashed, and values greater or less than 10^{10} kg s^{-1} (10 Sv) are shaded, darker for negative values. The circulation is clockwise around the lighter shading. The three thick solid lines indicate various measures of the tropopause. Right: The

Thermally-indirect:
Warm air sinks, cool air rises

The Ferrel cell: an eddy-driven overturning circulation – in the Eulerian mean

Eddies converge momentum ($\frac{\partial \overline{u}}{\partial t} > 0$). This must be balanced by a Coriolis westward acceleration ($\frac{\partial \overline{u}}{\partial t} < 0$).
This requires an equatorward flow.

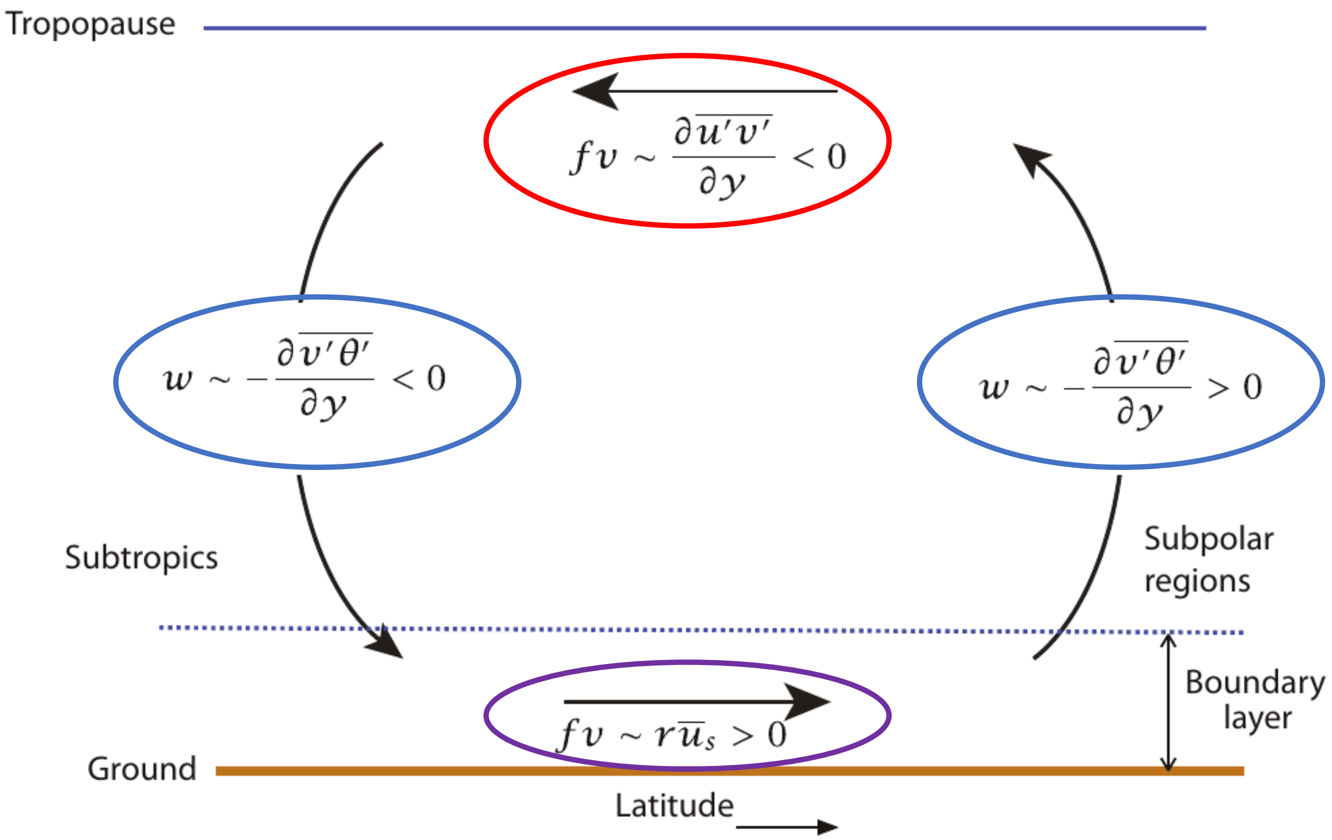


Fig. 12.7:

Eddies diverge heat from low latitudes and converge that heat at high latitudes. This is balanced by vertical motion.
This requires subsidence warming at low latitudes and adiabatic cooling at high latitudes.

Friction removes momentum at the surface. This is balanced by a Coriolis eastward acceleration.
This requires a poleward flow.

This balanced Eulerian-mean overturning ($\overline{v}_{bal}$,$\overline{w}_{bal}$) – the Ferrel cell – is what we **removed** to derive the **Transformed Eulerian Mean (TEM)**.

$$\frac{\partial \bar{u}}{\partial t} = \boxed{f_0 \bar{v} - \frac{\partial}{\partial y}\overline{u'v'}} + \bar{F}$$

$$\frac{\partial \bar{b}}{\partial t} = \boxed{-N^2 \bar{w} - \frac{\partial}{\partial y}\overline{v'b'}} + \bar{S}$$

What's left was a **residual circulation** ($\overline{v}^*$,$\overline{w}^*$).

$$\frac{\partial \bar{u}}{\partial t} = f_0 \bar{v}^* + \overline{v'q'} + \bar{F}$$

$$\frac{\partial \bar{b}}{\partial t} = -N^2 \bar{w}^* + \bar{S}$$

What does this residual circulation look like?

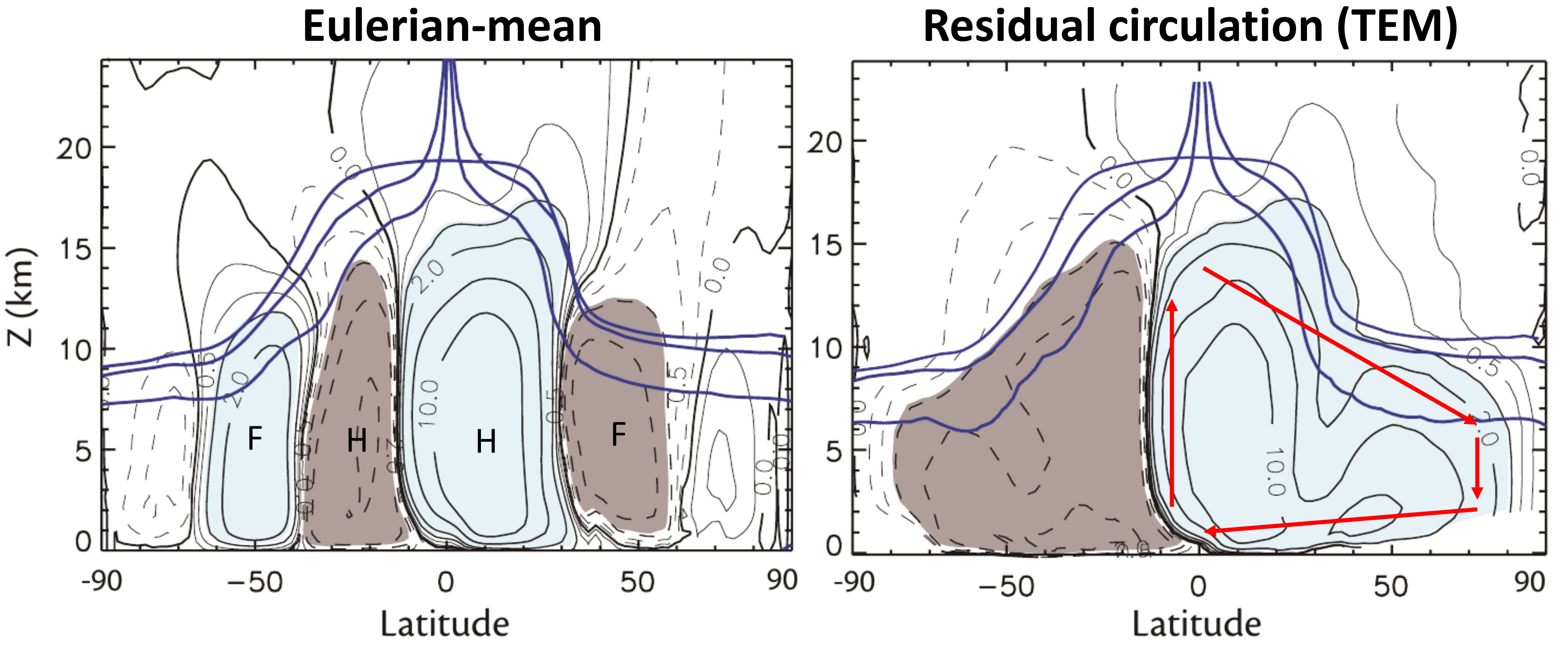


Fig. 12.8: Left: The observed zonally-averaged, Eulerian-mean, streamfunction in Northern Hemisphere winter (DJF, 1994–1997). Negative contours are dashed, and values greater or less than $10^{10}\,\mathrm{kg\,s^{-1}}$ (10 Sv) are shaded, darker for negative values. The circulation is clockwise around the lighter shading. The three thick solid lines indicate various measures of the tropopause. Right: The residual meridional mass streamfunction. (Adapted from Juckes (2001).)

Fig. 12.8:

A thermally-direct overturning circulation that extends from equator to pole!

What drives this residual overturning?

$$\frac{\partial \bar{b}}{\partial t} = -N^2 \bar{w}^* + \bar{S} \xrightarrow{\text{Steady-state}} \overline{w}^* = \frac{\bar{S}}{N^2}$$

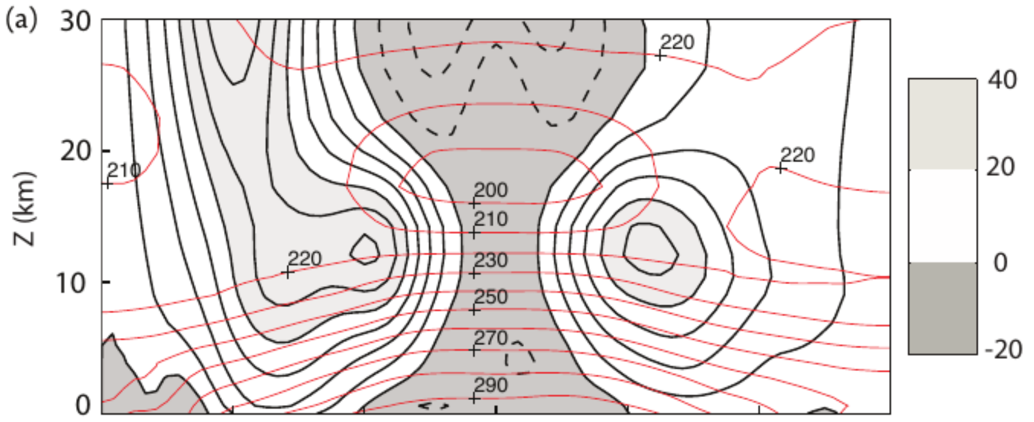
Vertical motion driven by variations in heating ($\bar{S}$).
Warmer air rises, cooler air sinks.
Now at a planetary scale!

$$\frac{\partial \bar{u}}{\partial t} = f_0 \bar{v}^* + \overline{v'q'} \xrightarrow{\text{Steady-state}} \overline{v}^* = -\frac{\overline{v'q'}}{f_0}$$

Poleward flow occurs within the eddy circulations (i.e. intermittent)

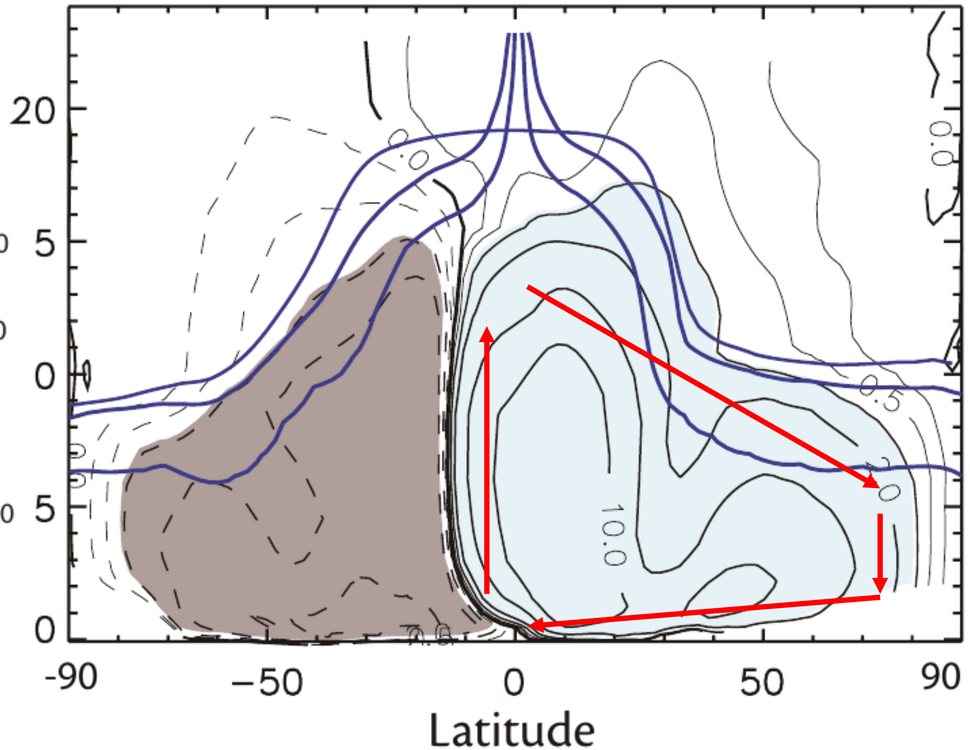
But if eddies weaken the jet in the free troposphere, then what sustains it there?

$\overline{u}$ (fill, black contour) and $\overline{T}$ (red contour)



VallisE Fig 11.1

Residual circulation (TEM)



$$\frac{\partial \bar{u}}{\partial t} = f_0 \bar{v}^* + \overline{v'q'} + \bar{F}$$

>0   <0   negligible

The Coriolis torque acting on the residual poleward flow sustains the mean zonal jet

Since the residual poleward flow is driven by eddy PV fluxes, then **the mid-latitude jet *is* actually eddy-driven!**

Summary: the eddy-driven mid-latitude jet

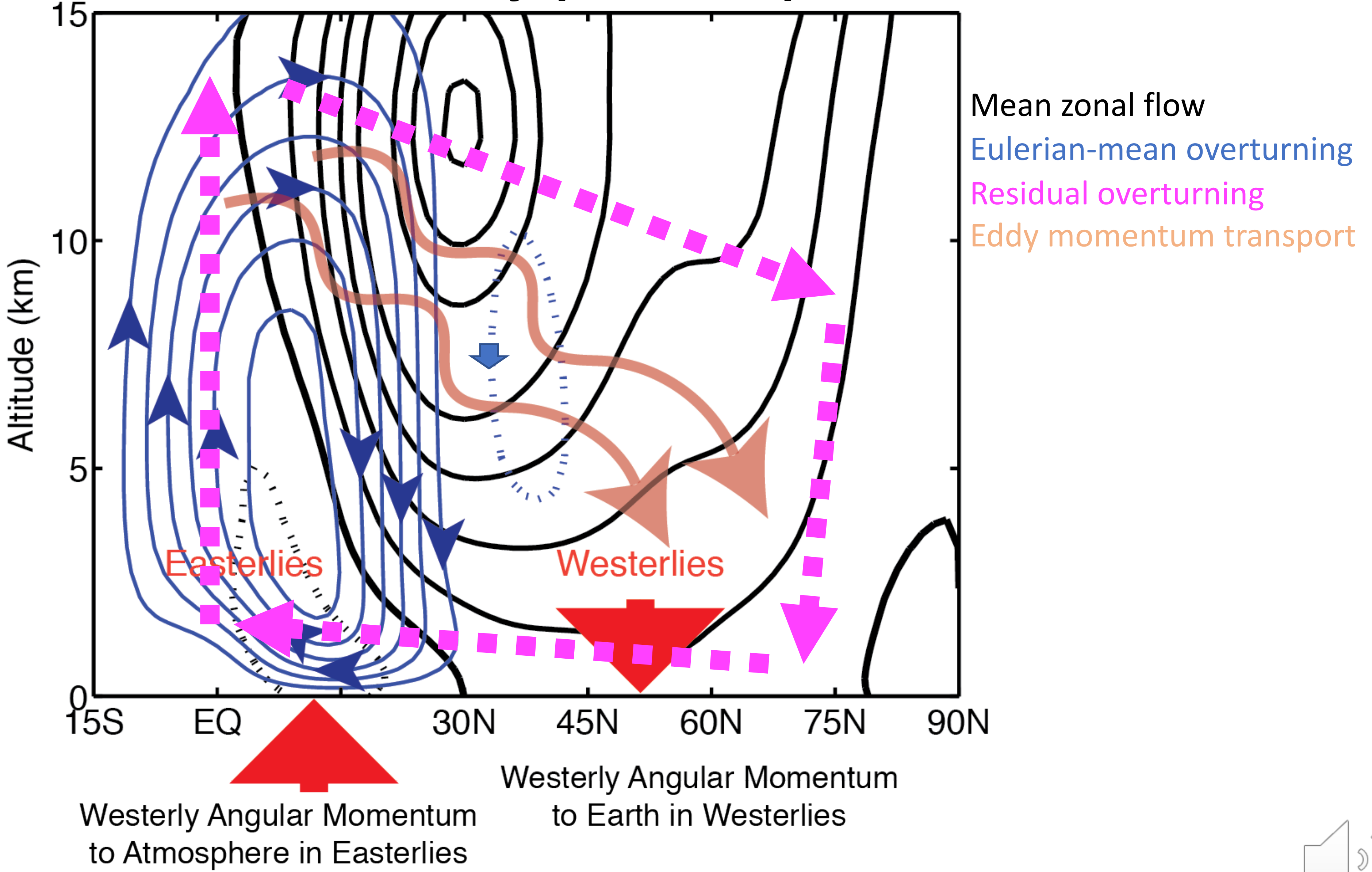
Barotropic:

- mean zonal flow: generated by eddy stirring (momentum transport)

Baroclinic: (e.g. Earth's atmosphere)

- mean *near-surface* zonal flow: generated by eddy stirring (momentum transport) and baroclinically (heat transport)
- mean *free-tropospheric* zonal flow:
    - Eddies drive both the momentum source (Coriolis torque on residual circulation) and momentum sink (eddy PV fluxes: EP flux convergence)

Summary (cartoon)



Now go to Blackboard to answer a few questions about this topic!