

Lecture 7: Atmospheric General Circulation

Jonathon S. Wright

jswright@tsinghua.edu.cn

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The climatological mean circulation

Zonal mean energy transport

Zonal mean energy budget of the atmosphere

The climatological mean and seasonal cycle

Deviations from the climatological mean

Transient and quasi-stationary eddies

Eddy fluxes of heat, momentum, and moisture

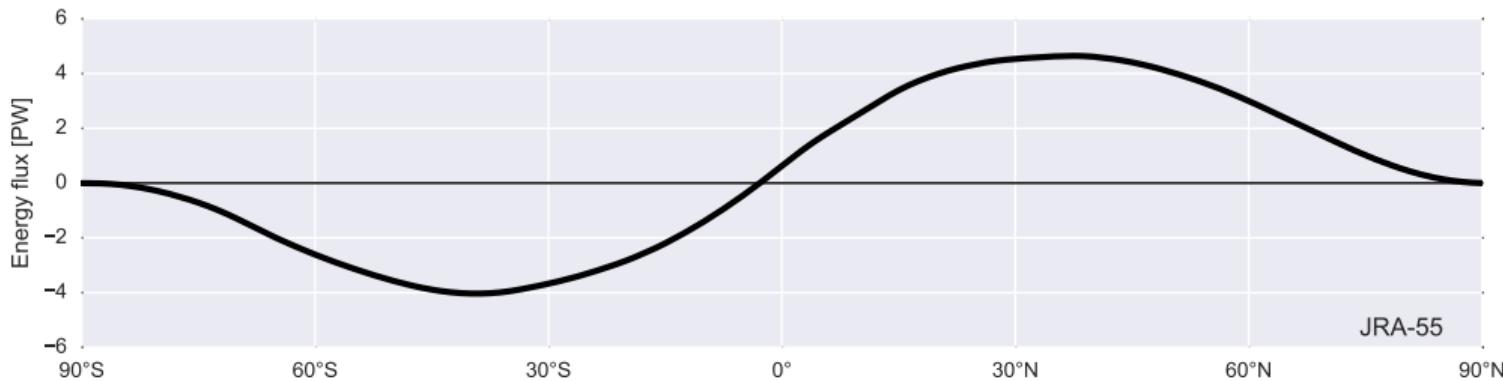
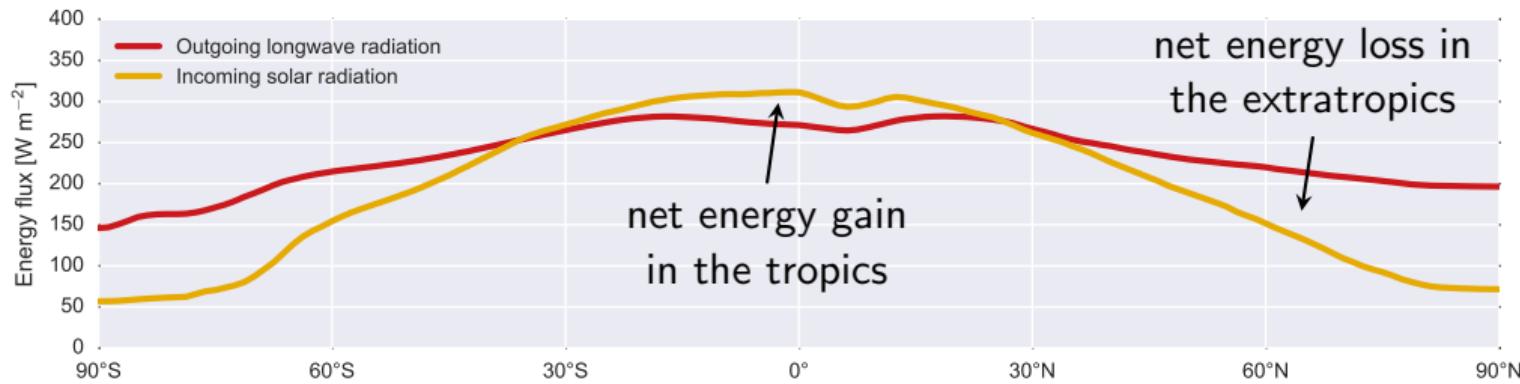
Eddies in the atmospheric circulation

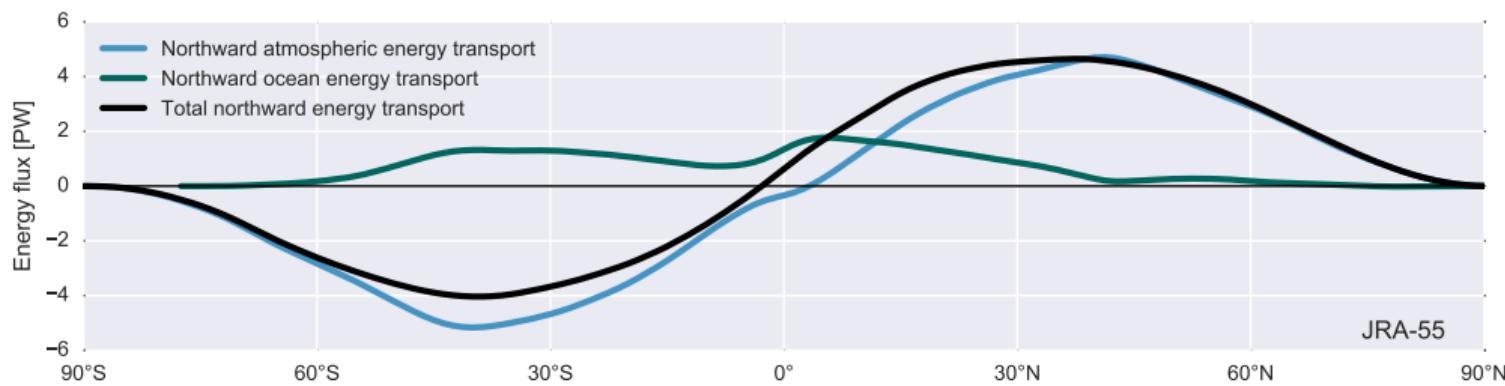
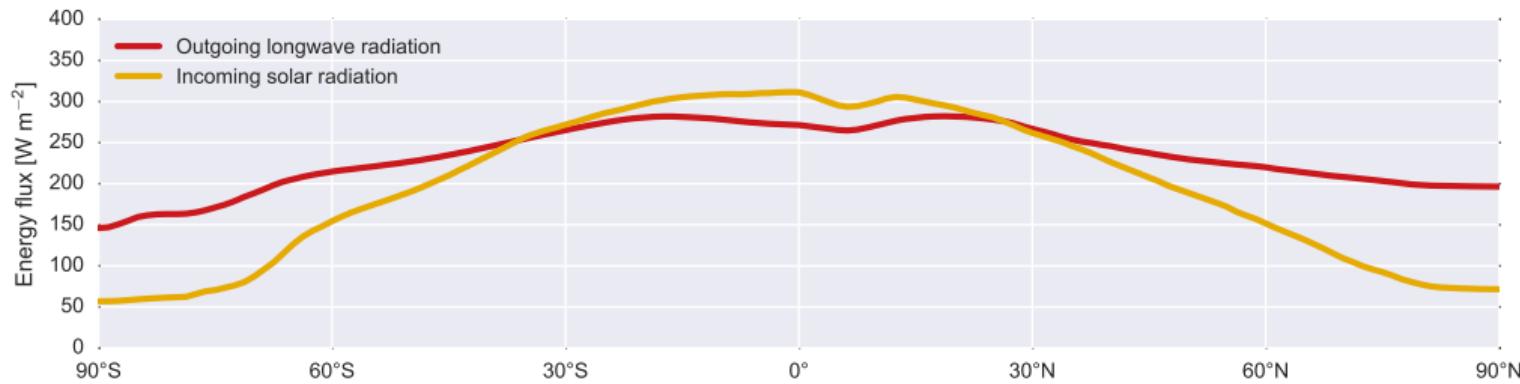
Synthesis: momentum and the jets

Vorticity and Rossby waves

Momentum fluxes

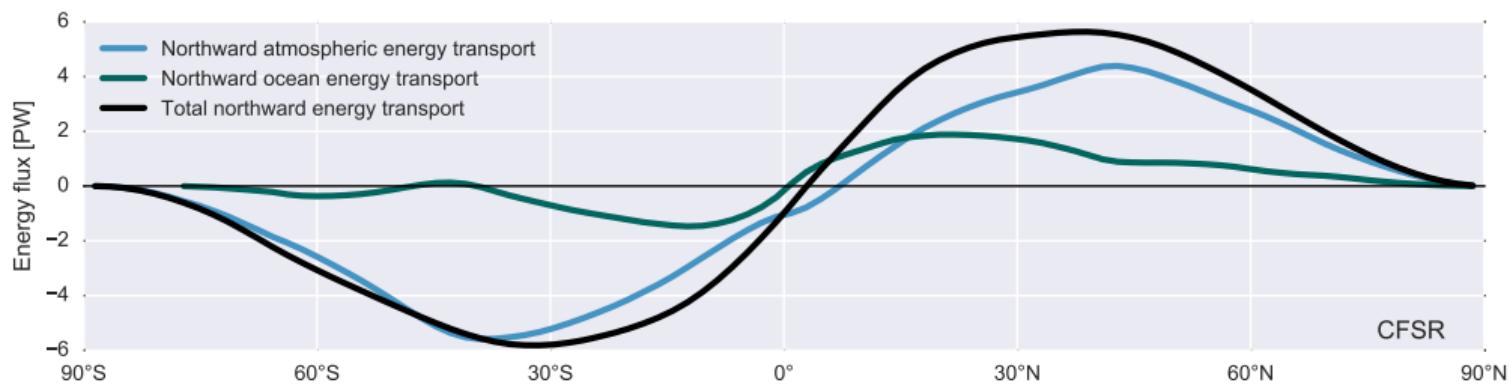
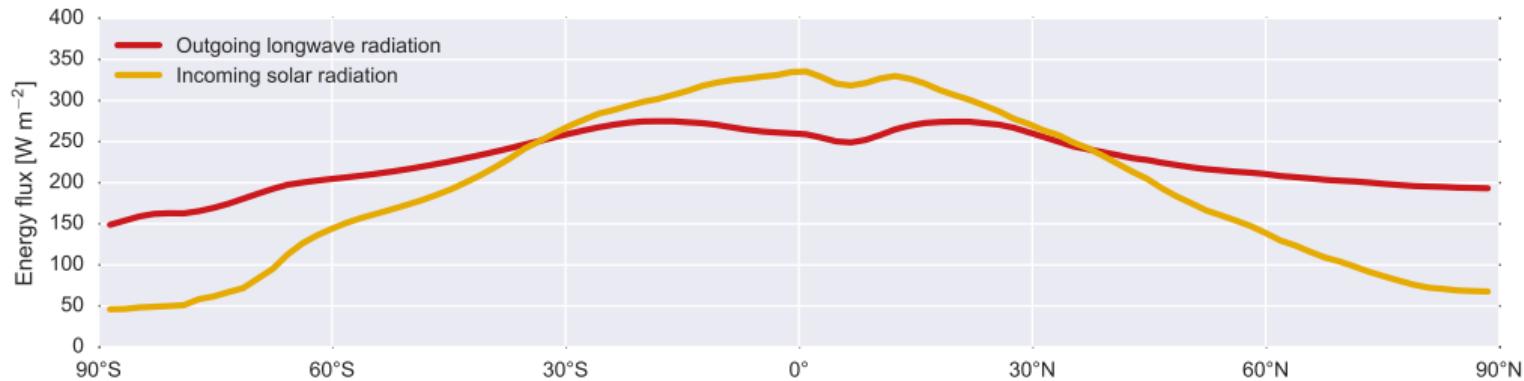
Isentropic overturning circulation





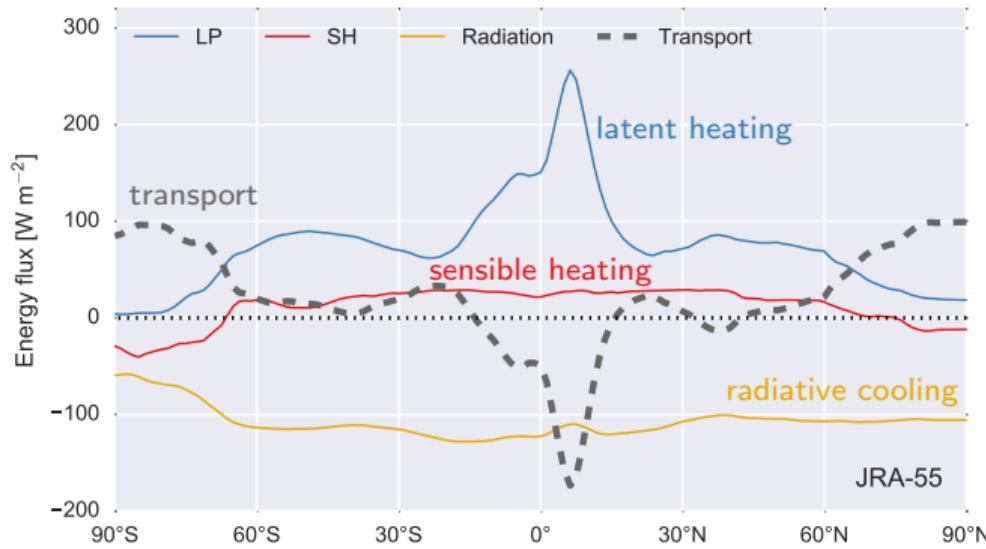
JRA-55

data from JRA-55



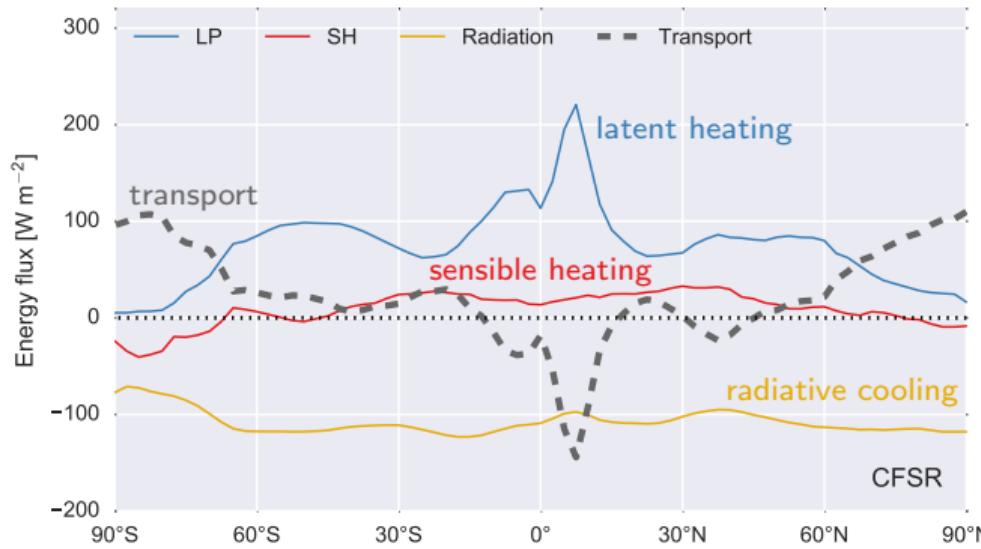
Energy budget of an atmospheric column

$$\frac{\partial E_a}{\partial t} = R_{\text{net}} + \text{LP} + \text{SH} + \text{TR}$$



Energy budget of an atmospheric column

$$\frac{\partial E_a}{\partial t} = R_{\text{net}} + \text{LP} + \text{SH} + \text{TR}$$

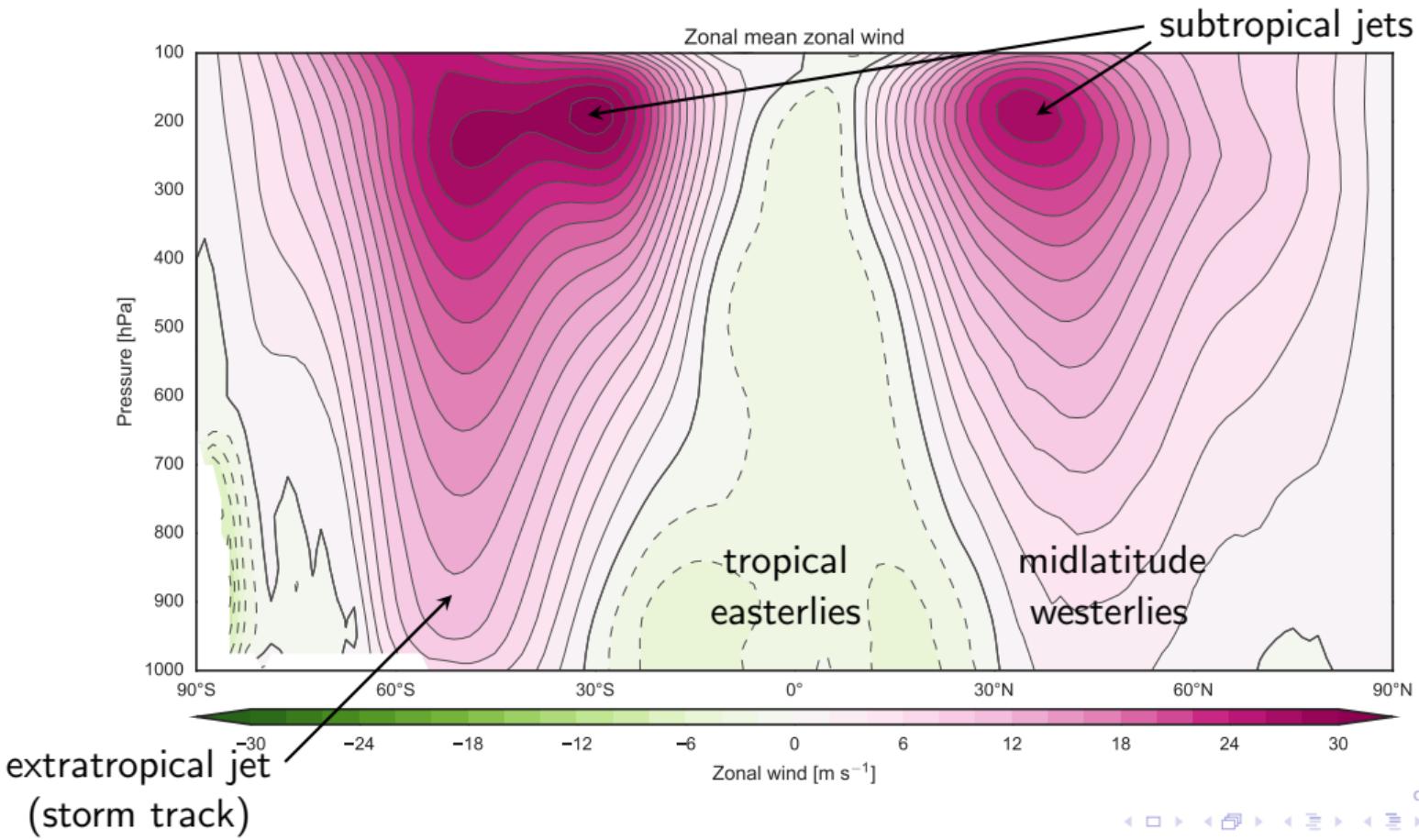


The climatological mean

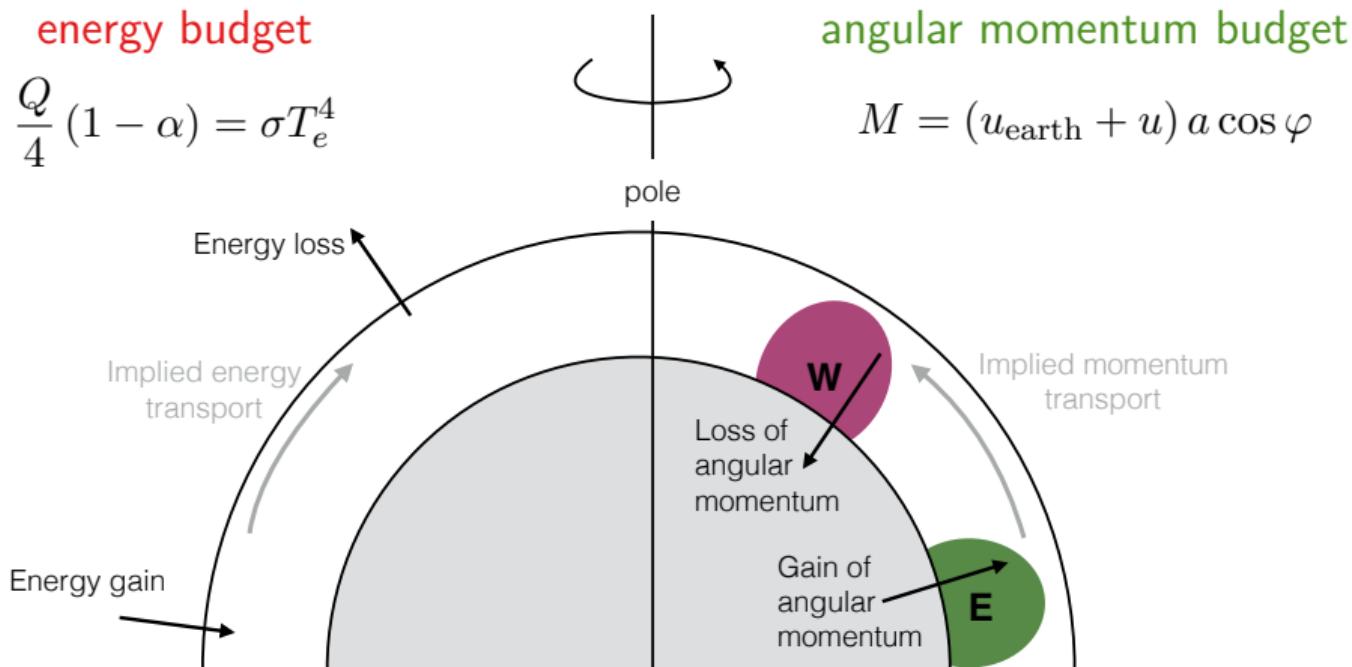
time mean: $\bar{x} = \frac{1}{\tau} \int_0^\tau x dt$

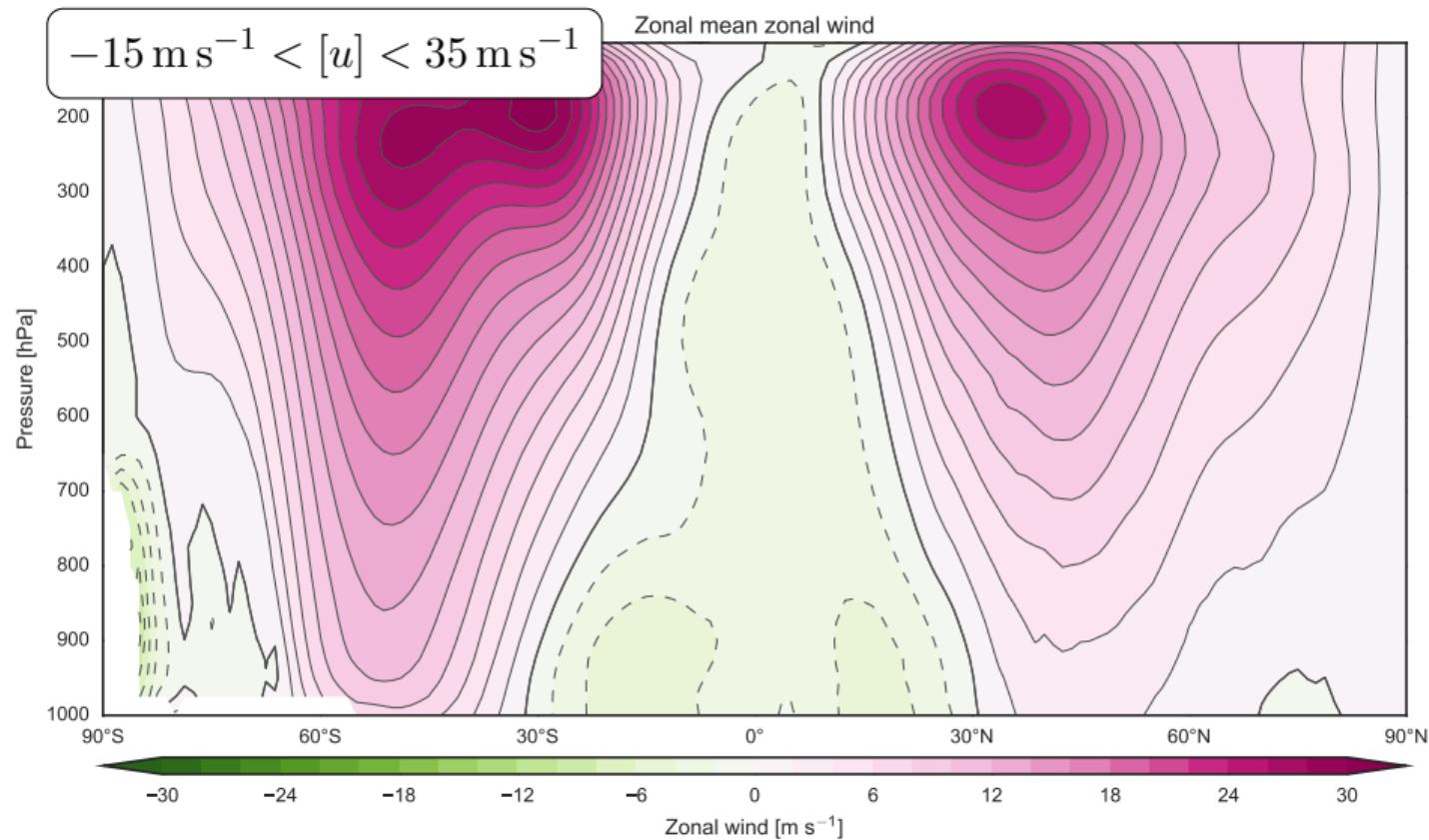
climatological zonal mean: $[\bar{x}]$

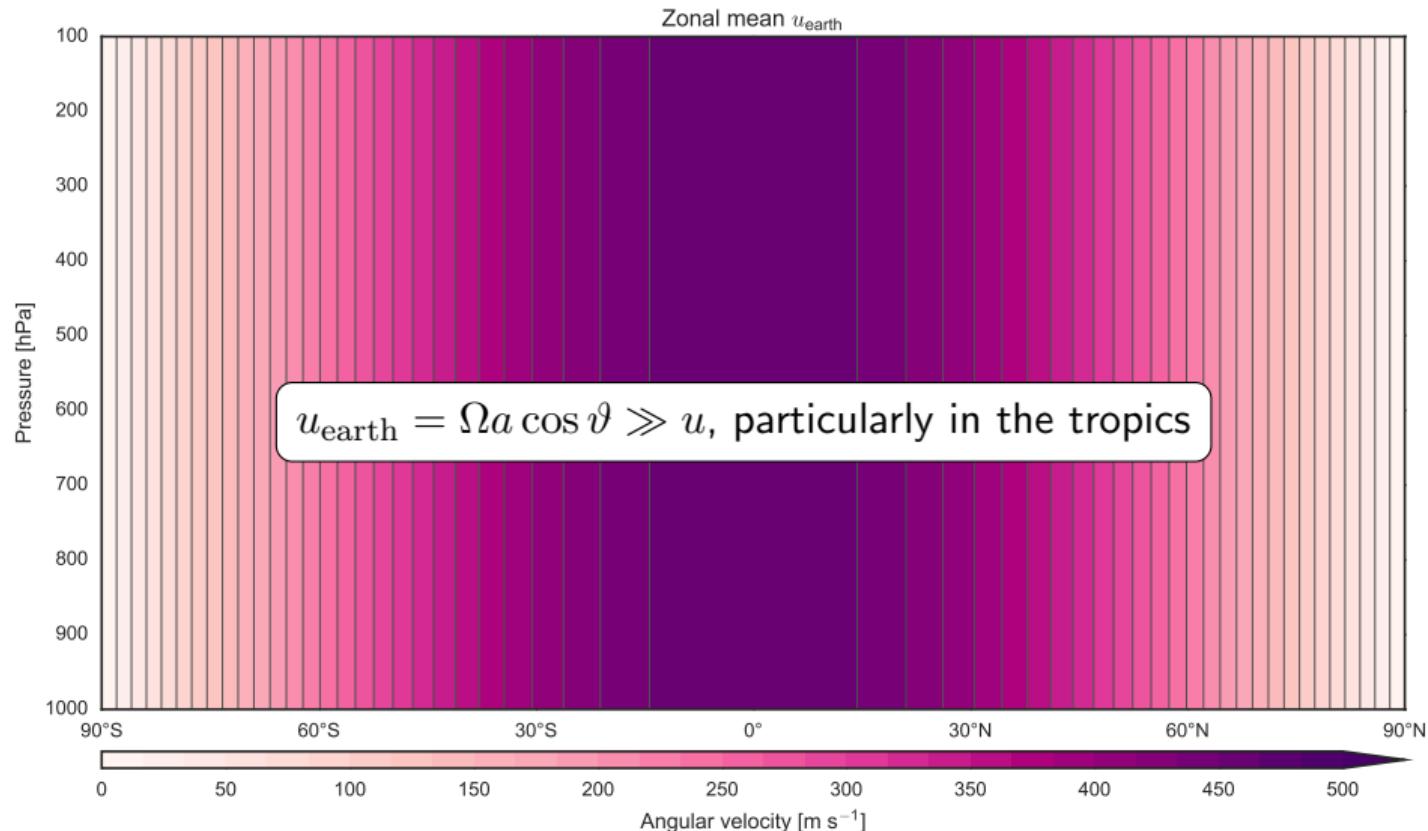
zonal mean: $[x] = \frac{1}{2\pi} \int_0^{2\pi} x d\lambda$

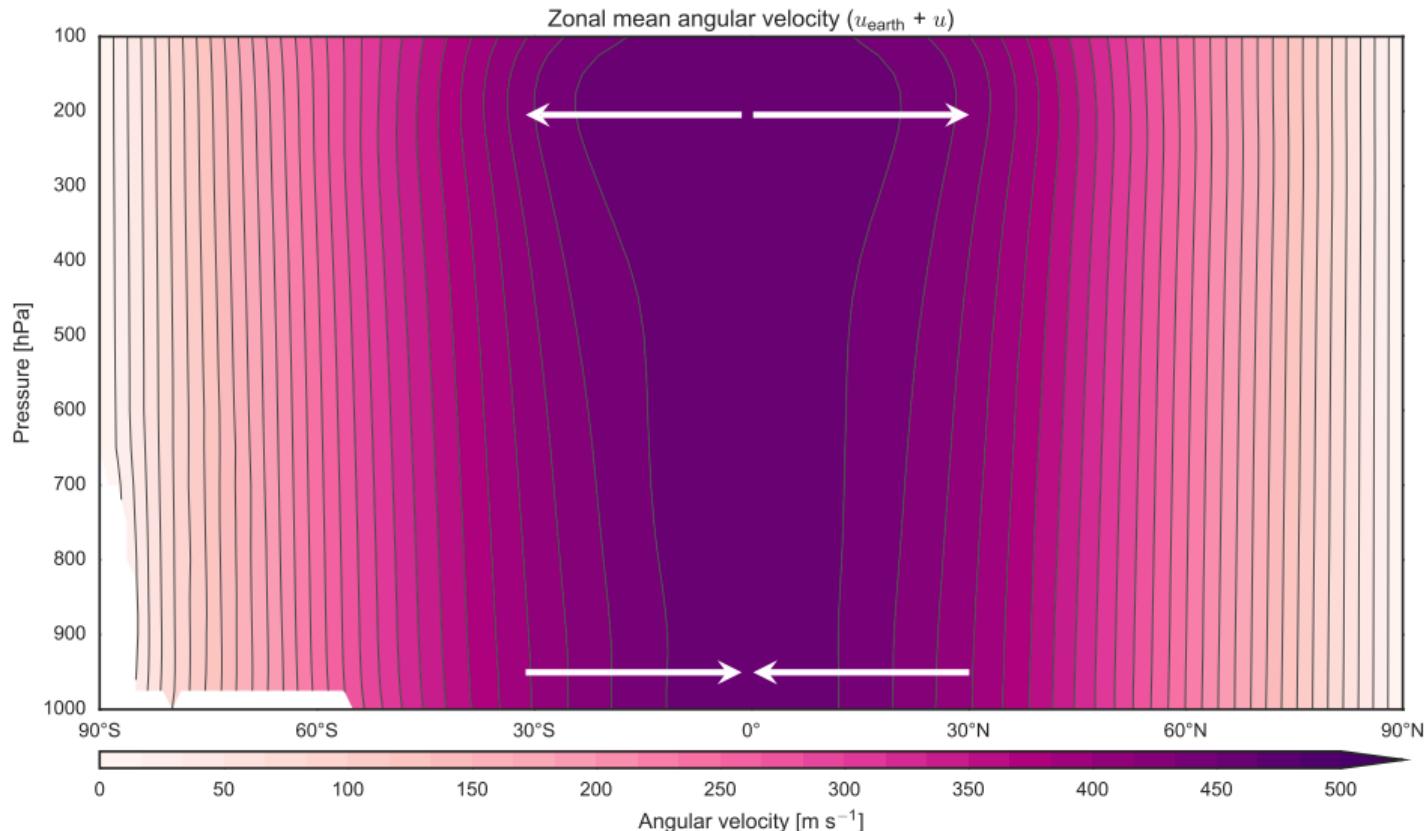


Zonal mean zonal wind: energy and momentum transfer perspectives









The mean meridional circulation

mass streamfunction

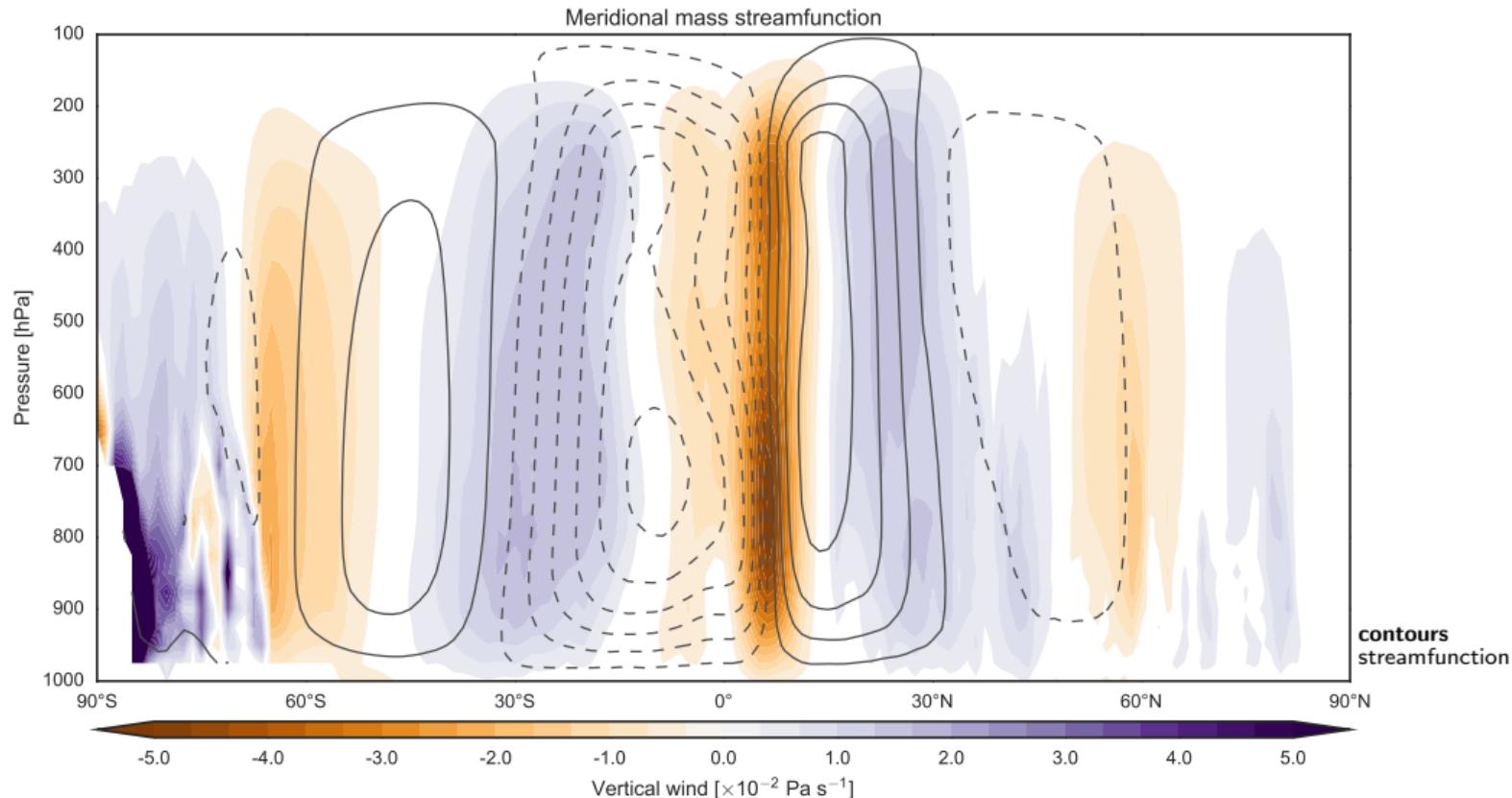


$$\Psi_M = \frac{2\pi a \cos \varphi}{g} \int_0^p [v] dp$$

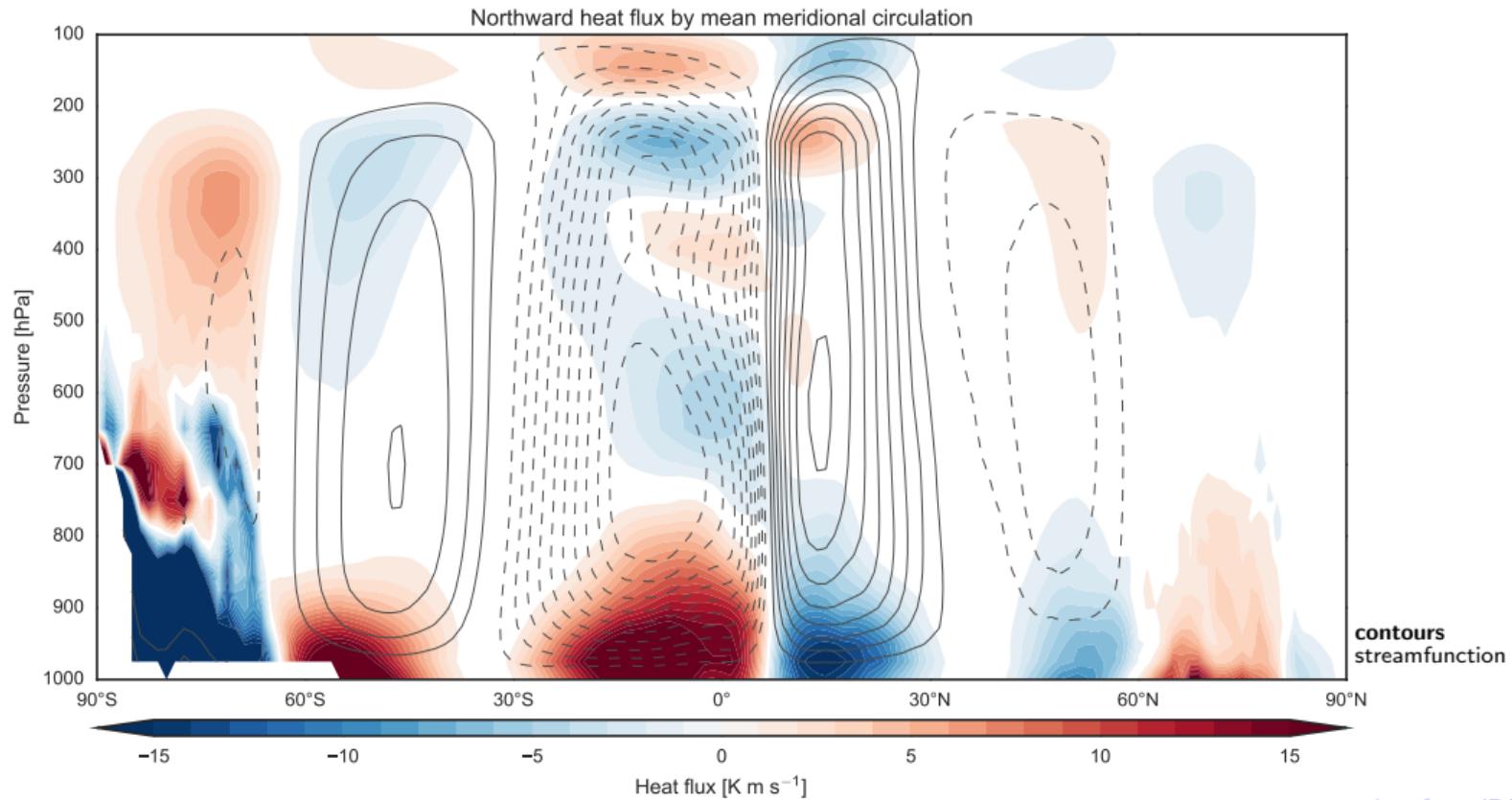
The mass flow between any two streamlines is equal to the difference between the streamlines

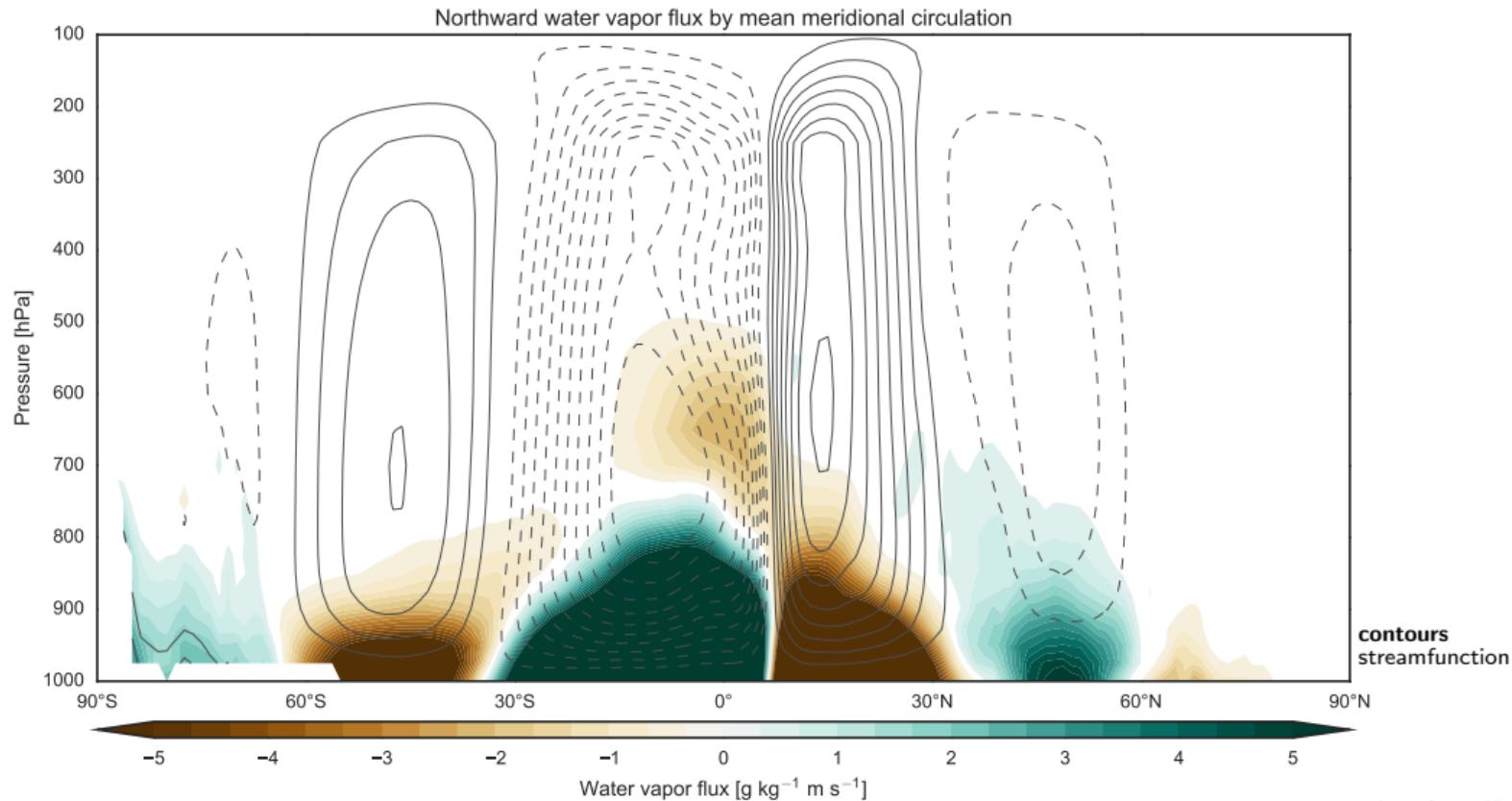
$$[v] = \frac{g}{2\pi a \cos \varphi} \frac{\partial \Psi_M}{\partial p}$$

$$[w] = \frac{-g}{2\pi a^2 \cos \varphi} \frac{\partial \Psi_M}{\partial \varphi}$$

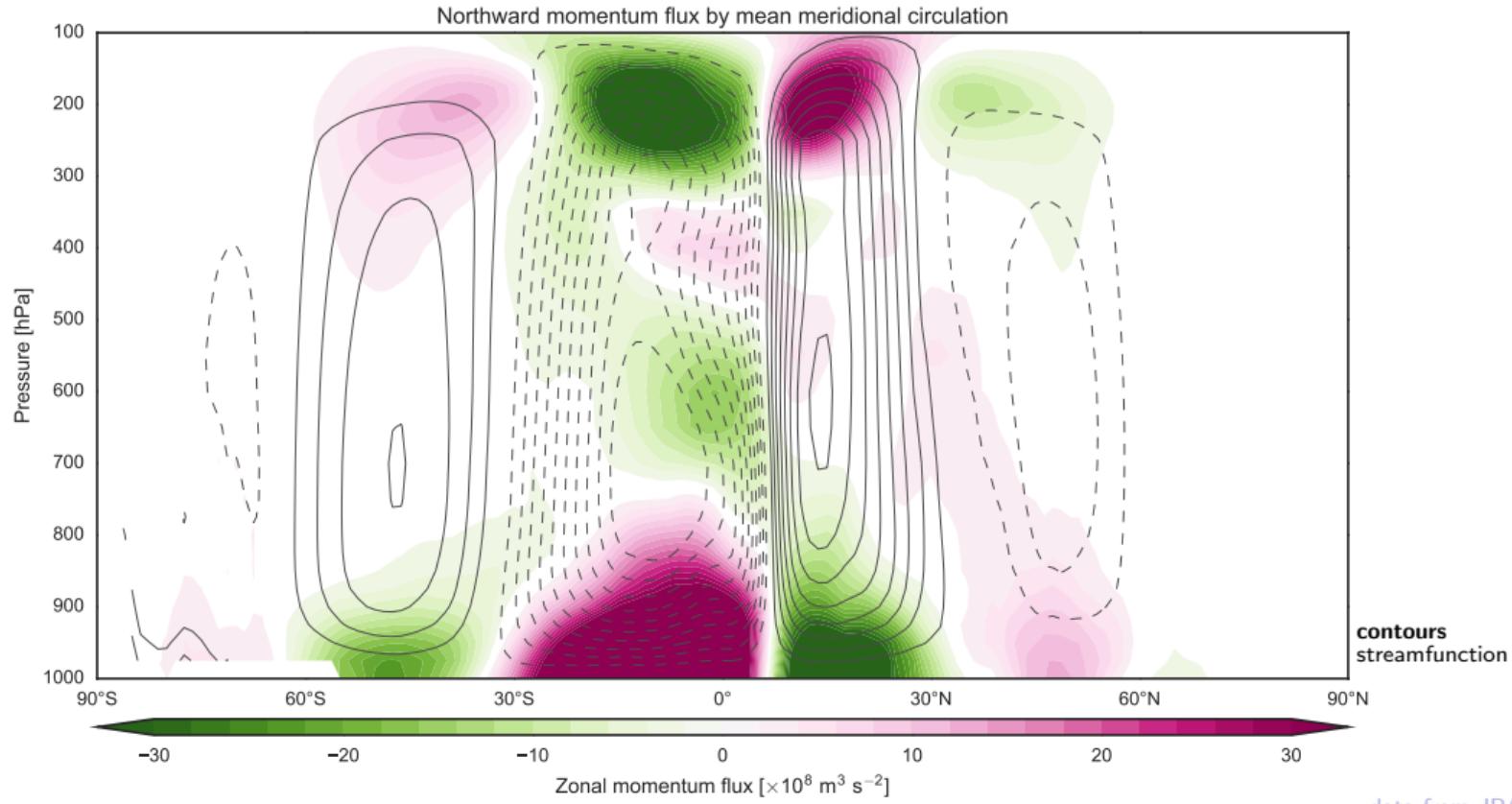


contours streamfunction



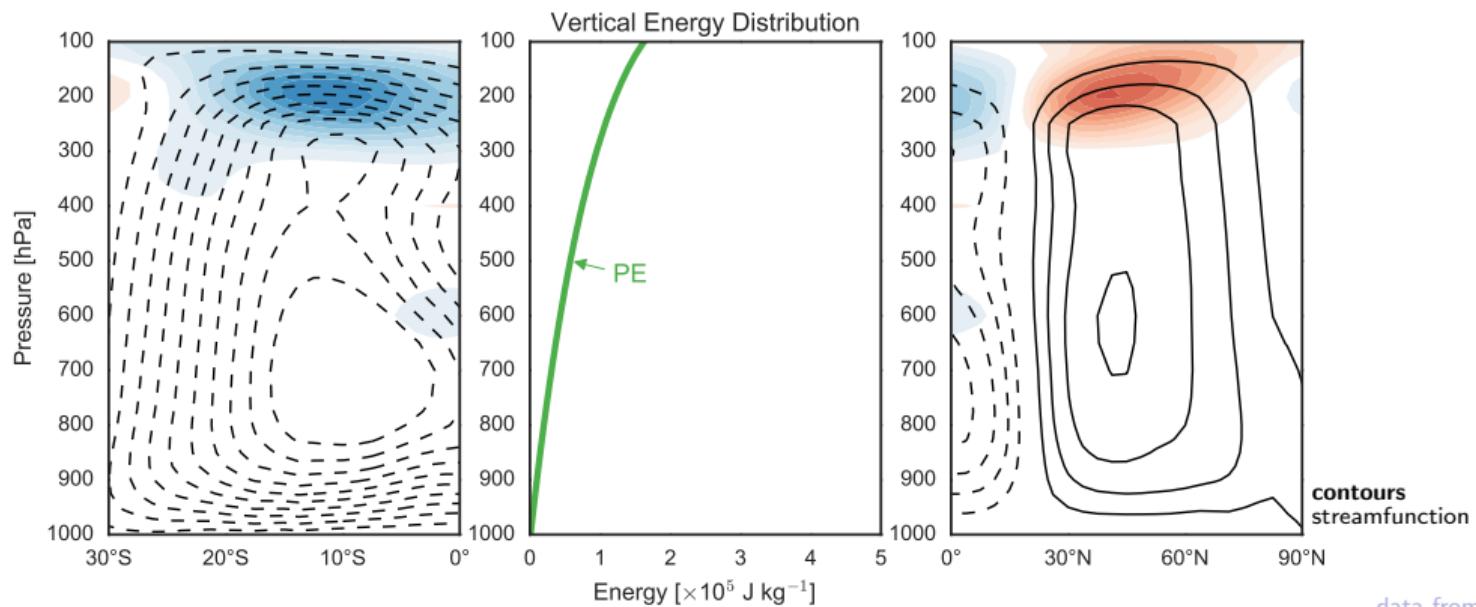


data from JRA-55



The MMC and energy transport

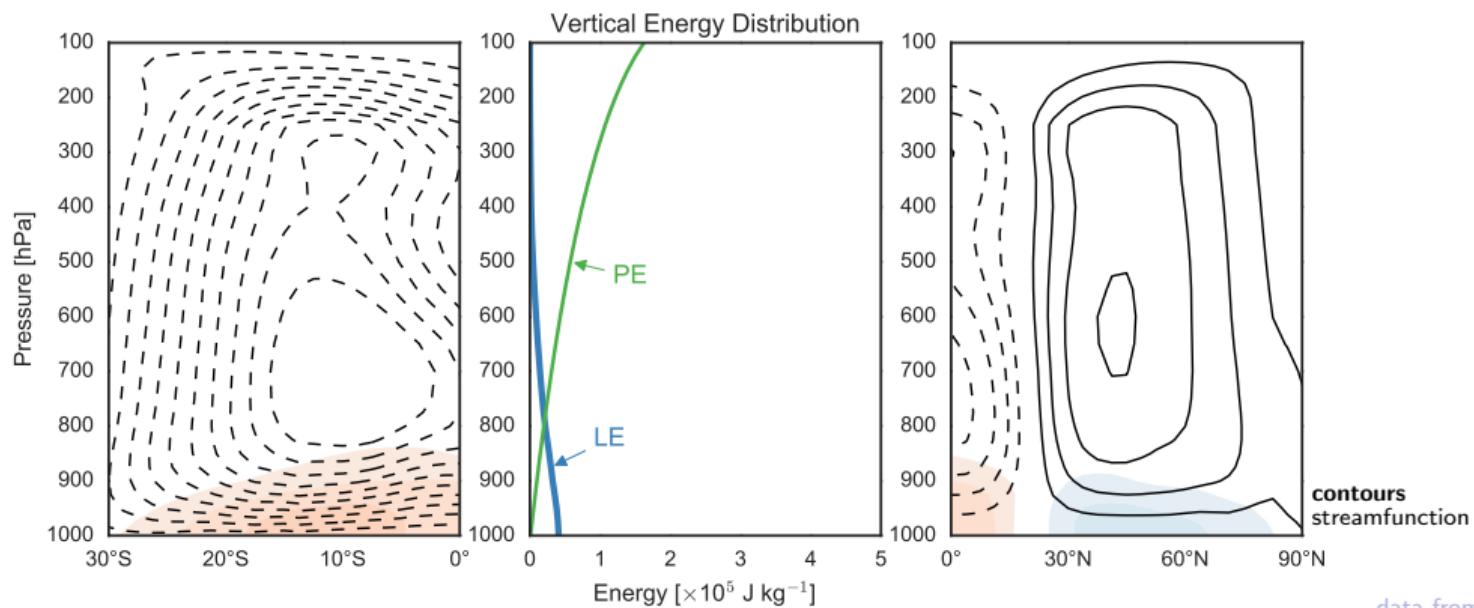
Potential energy: $PE = gz$



data from JRA-55

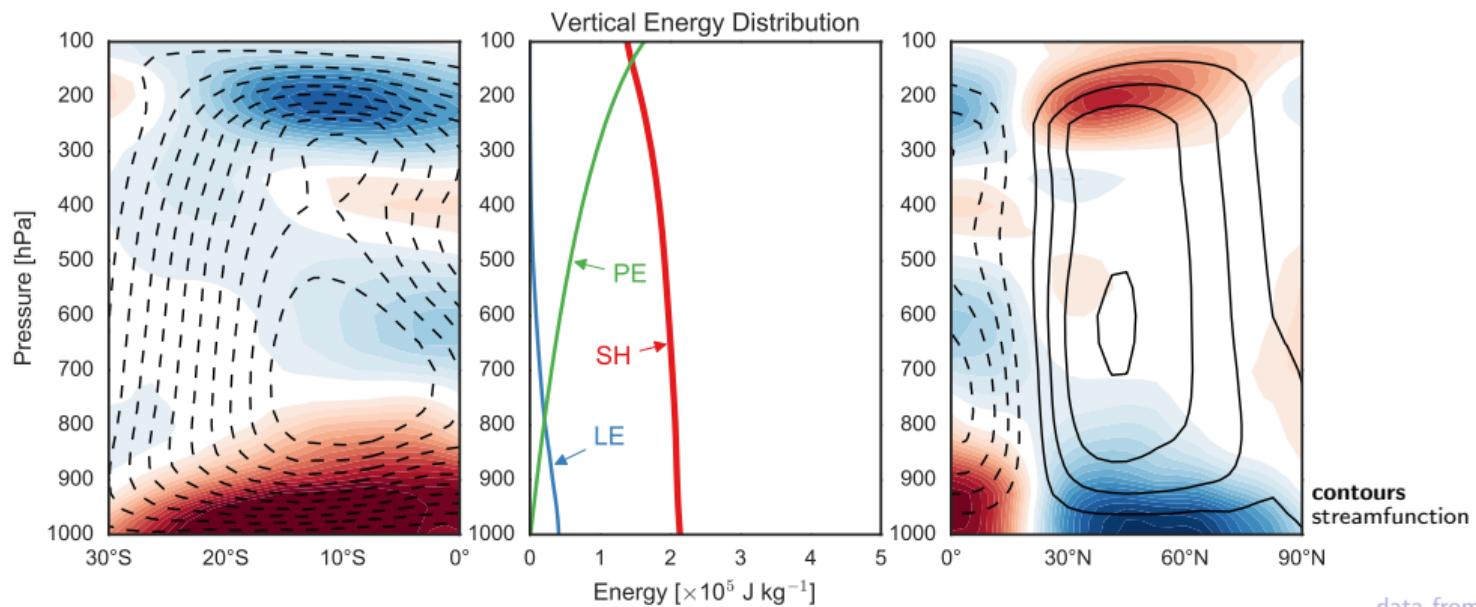
The MMC and energy transport

Potential energy: $PE = gz$ Latent energy: $LE = L_v q$



The MMC and energy transport

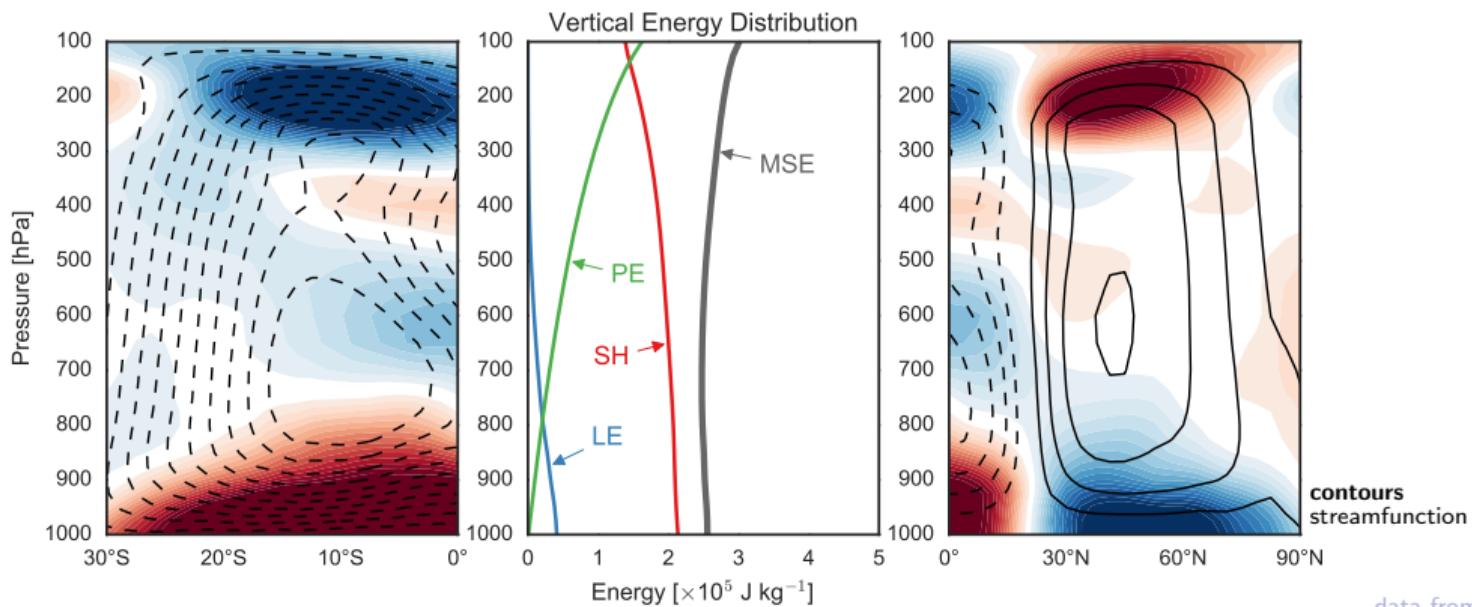
Potential energy: $PE = gz$ Latent energy: $LE = L_v q$ Sensible heat: $SH = c_v T$



The MMC and energy transport

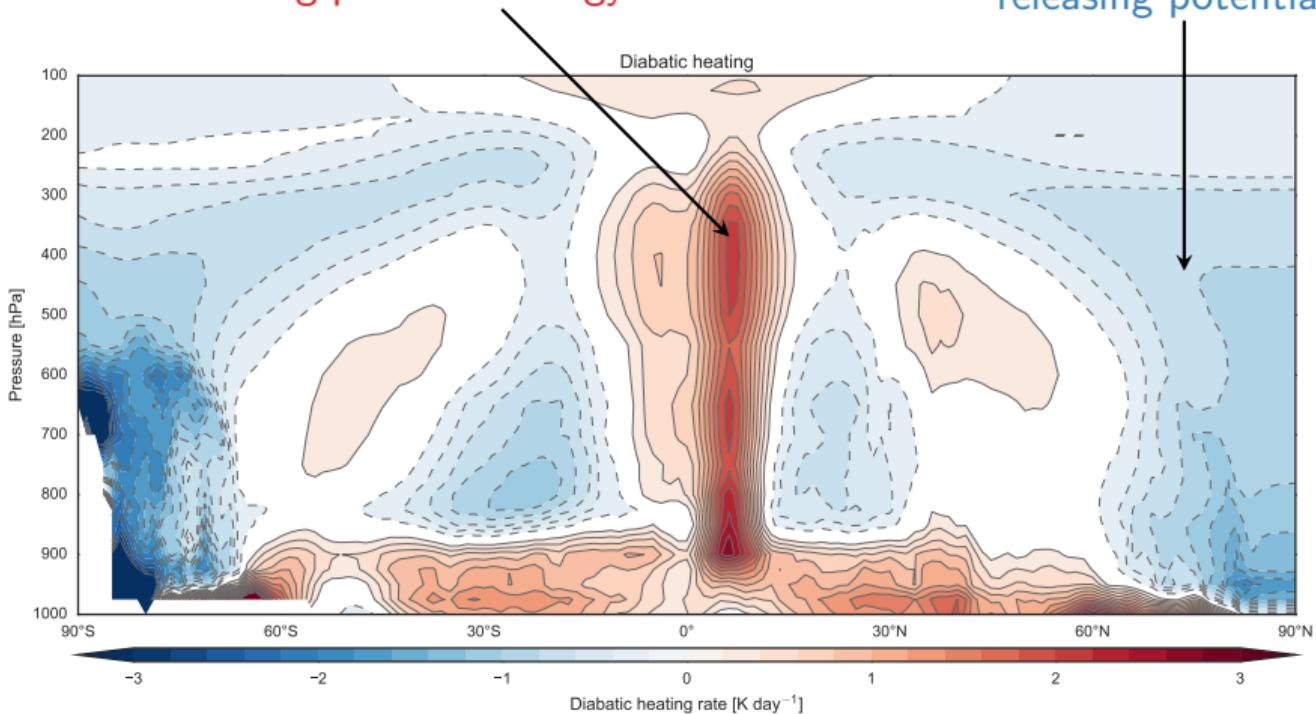
Potential $27.1\% \text{ PE} = gz$ Latent energy $2.5\% \text{ LE} = L_v q$ Sensible heat $70.4\% \text{ H} = c_v T$

moist static energy: $h = gz + L_v q + c_v T$

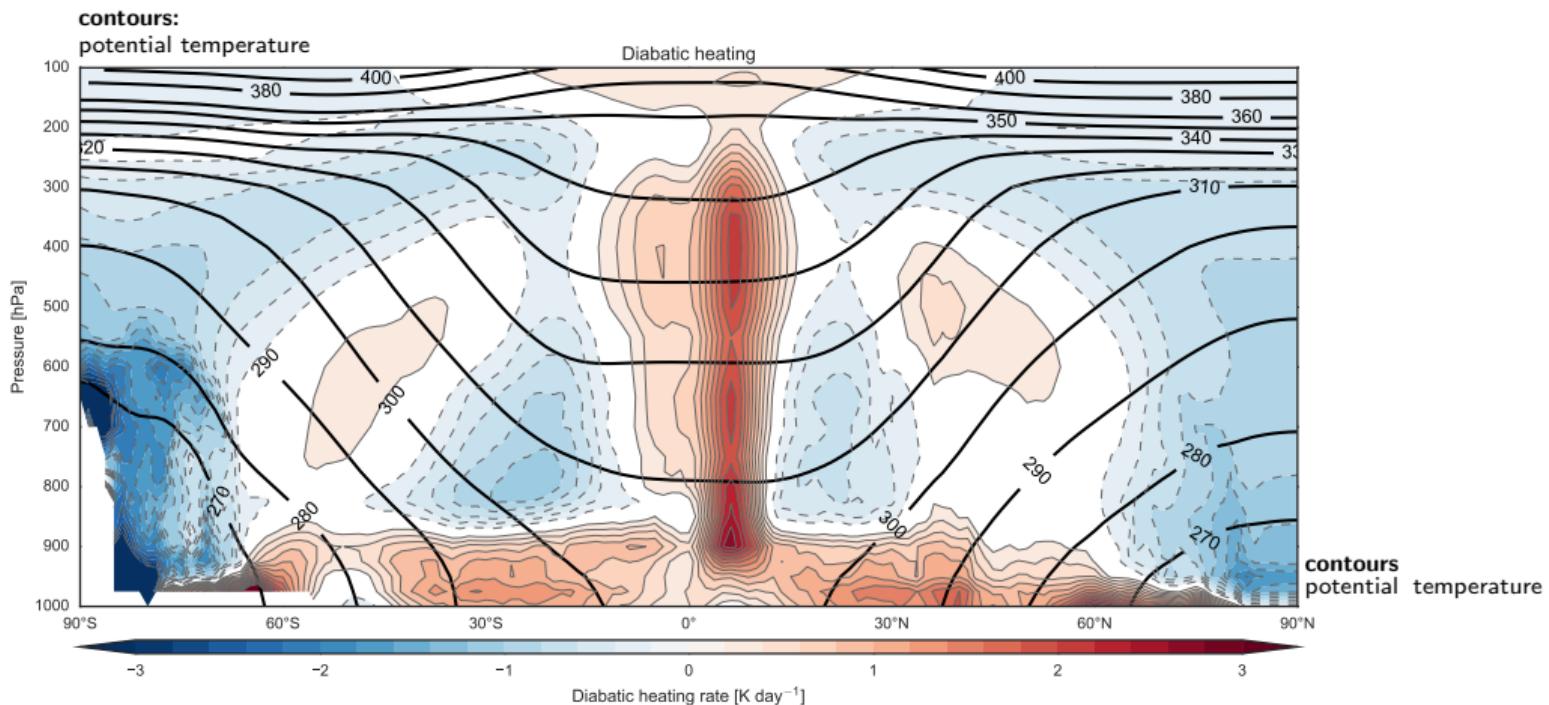


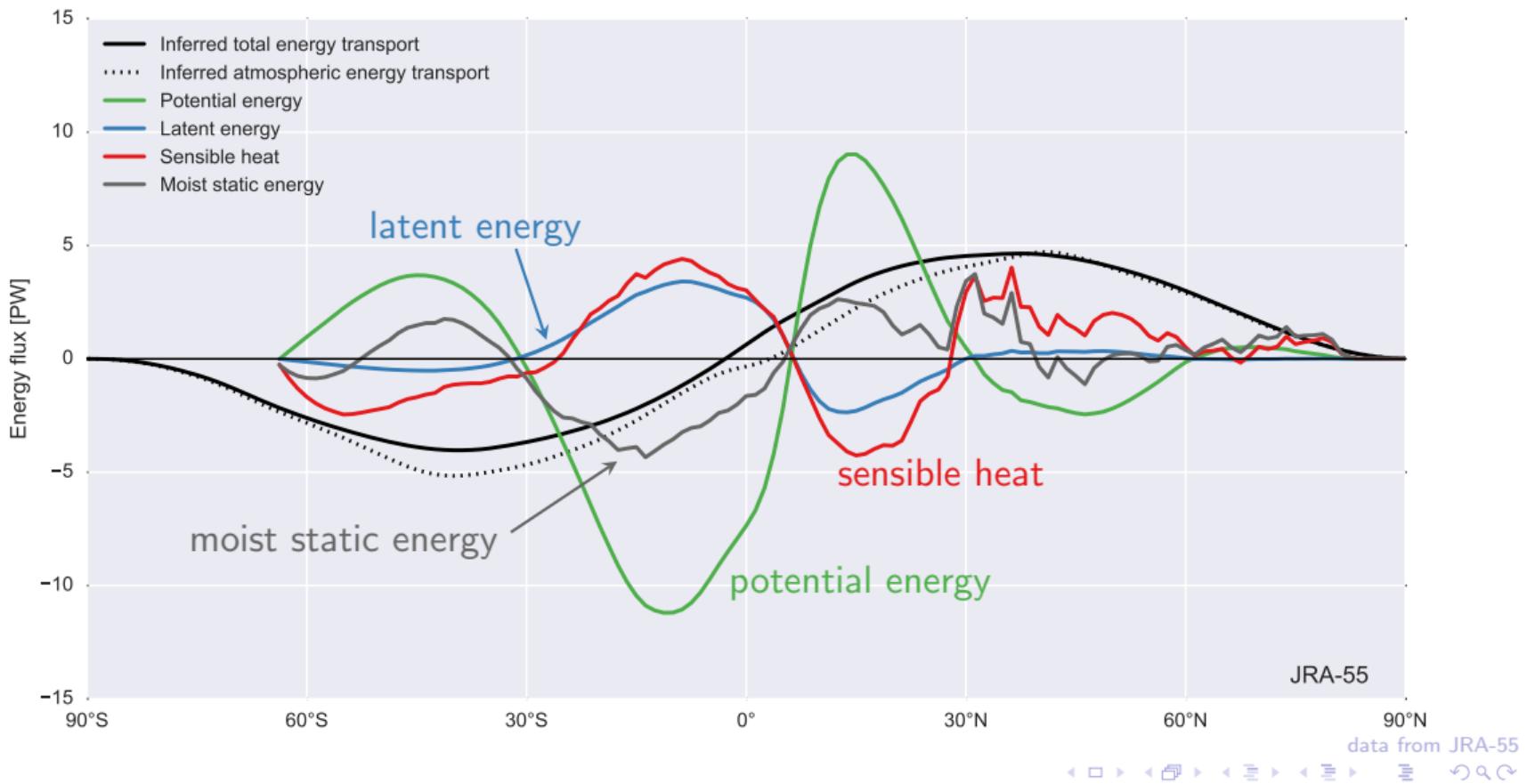
creating potential energy

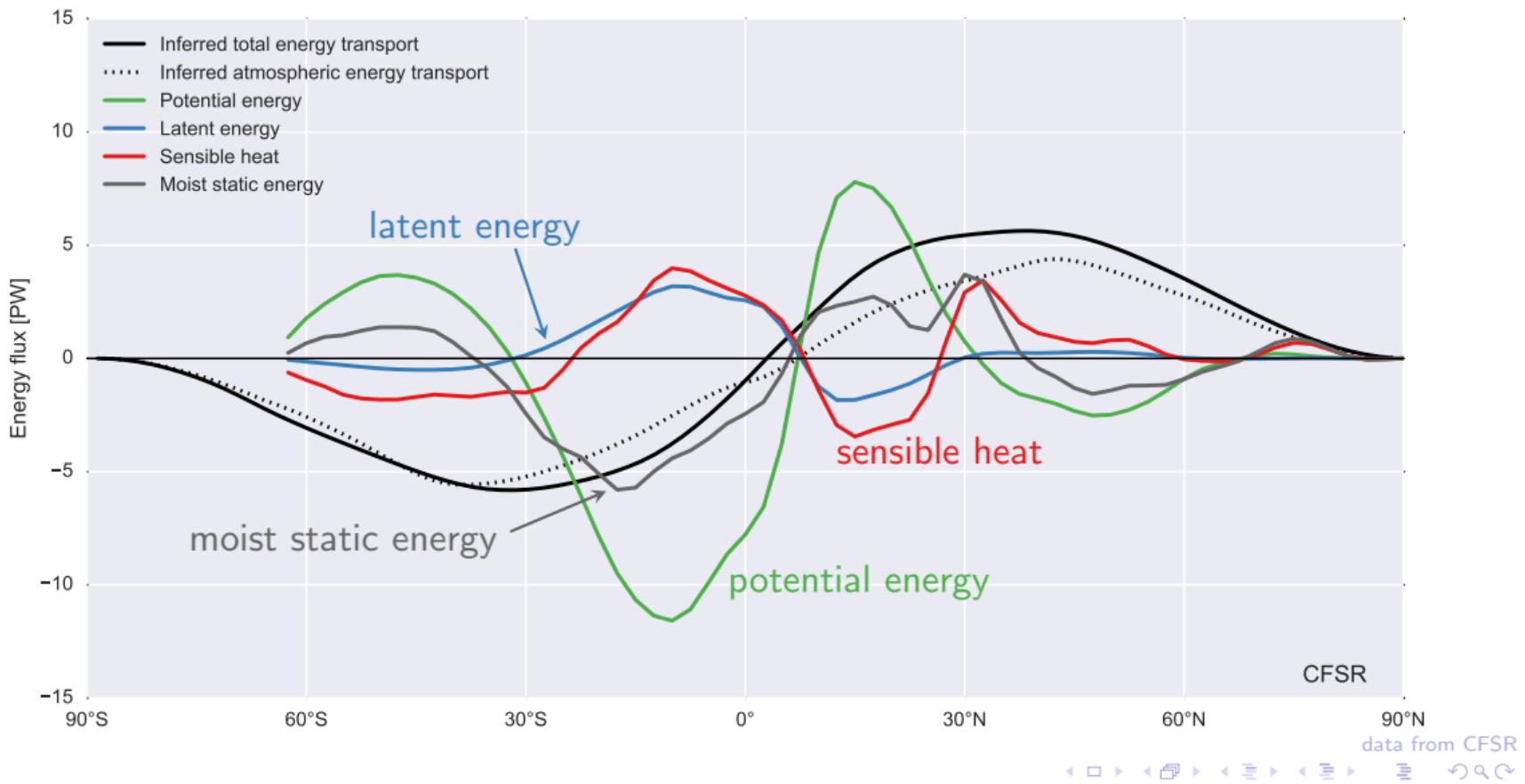
releasing potential energy



diabatic heating creates density gradients that drive the overturning circulation







Eddies

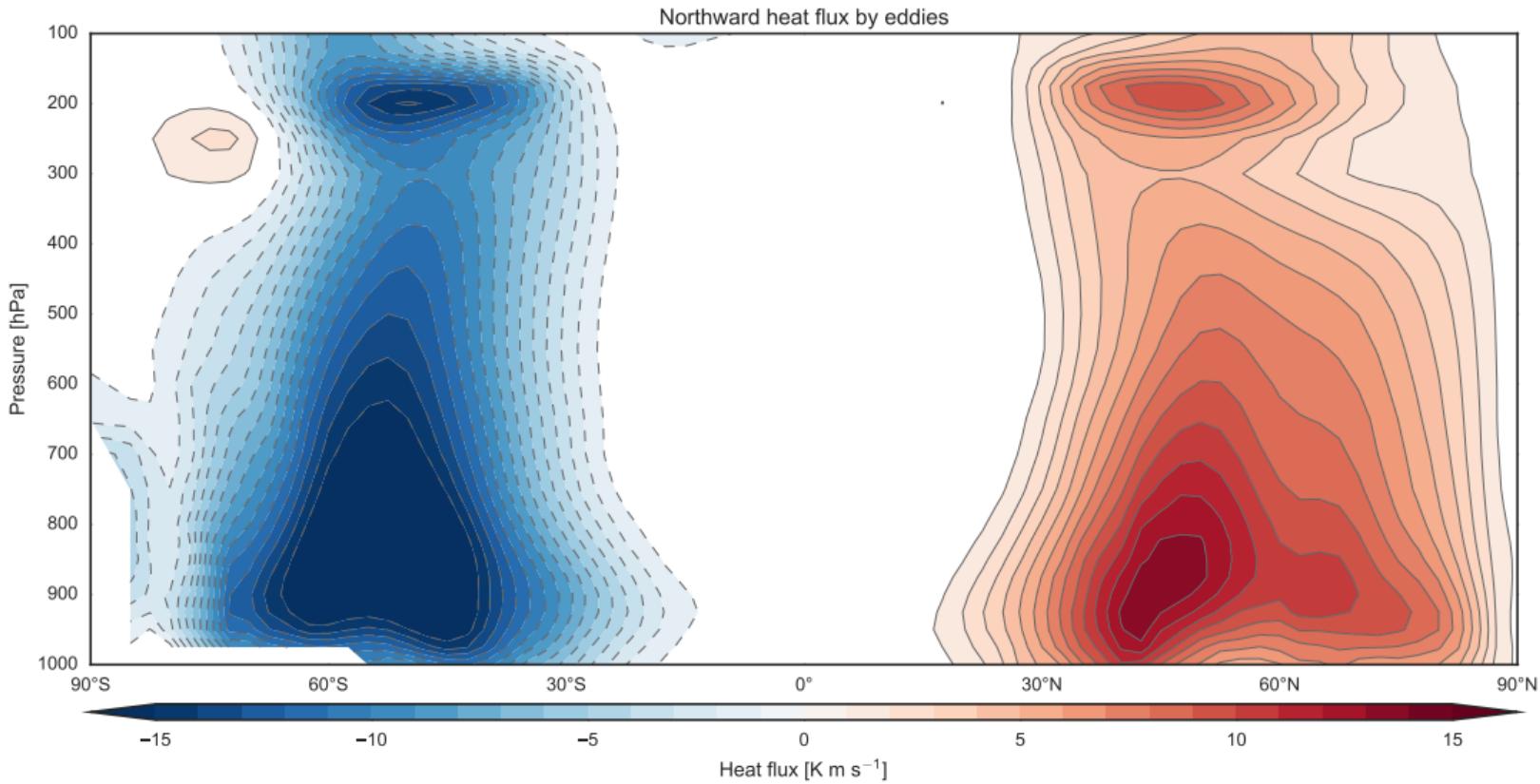
climatological zonal mean: $[\bar{x}]$

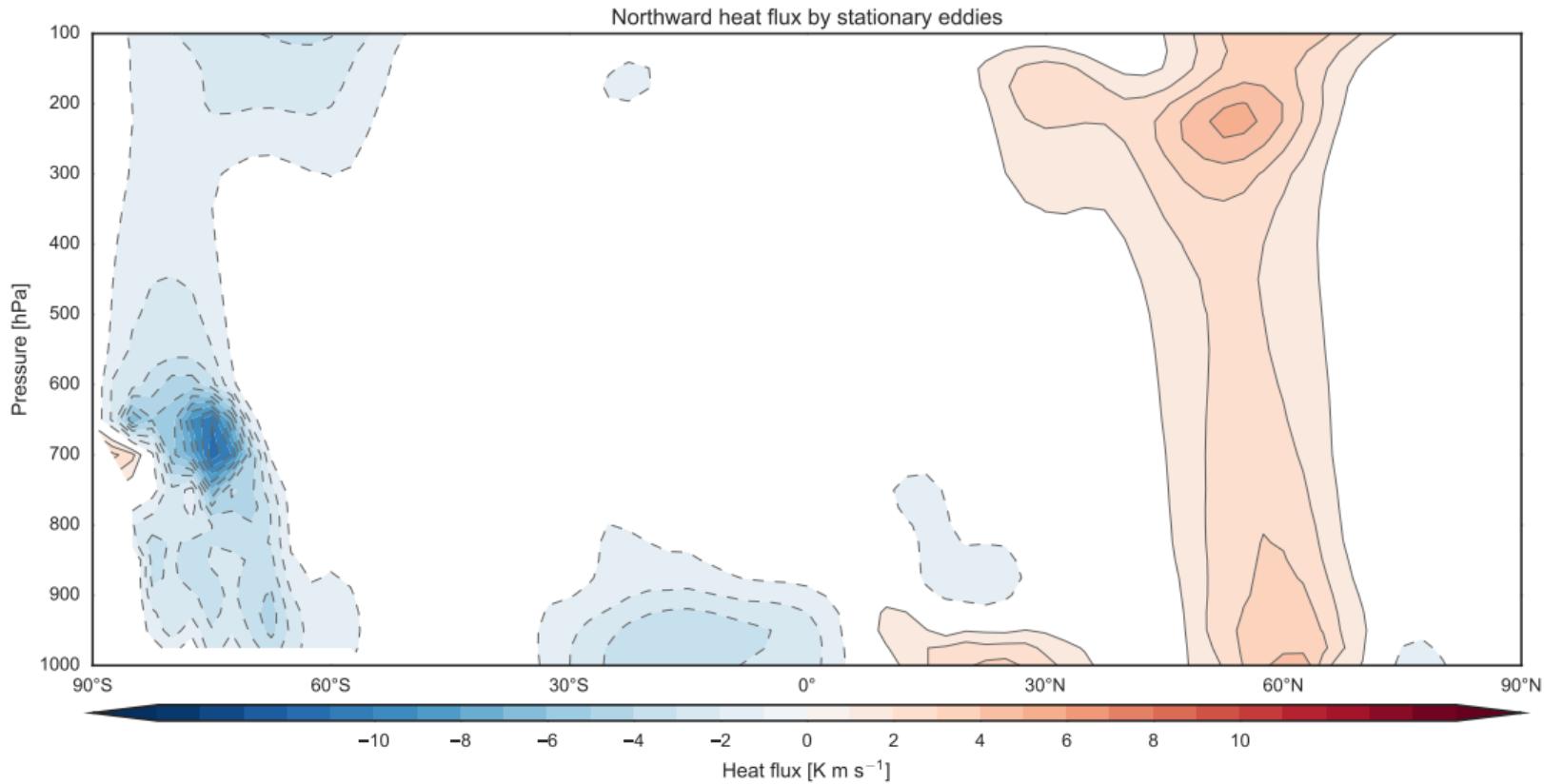
transient eddies: $x' = x - \bar{x}$
deviations from the time mean
(e.g., weather fluctuations)

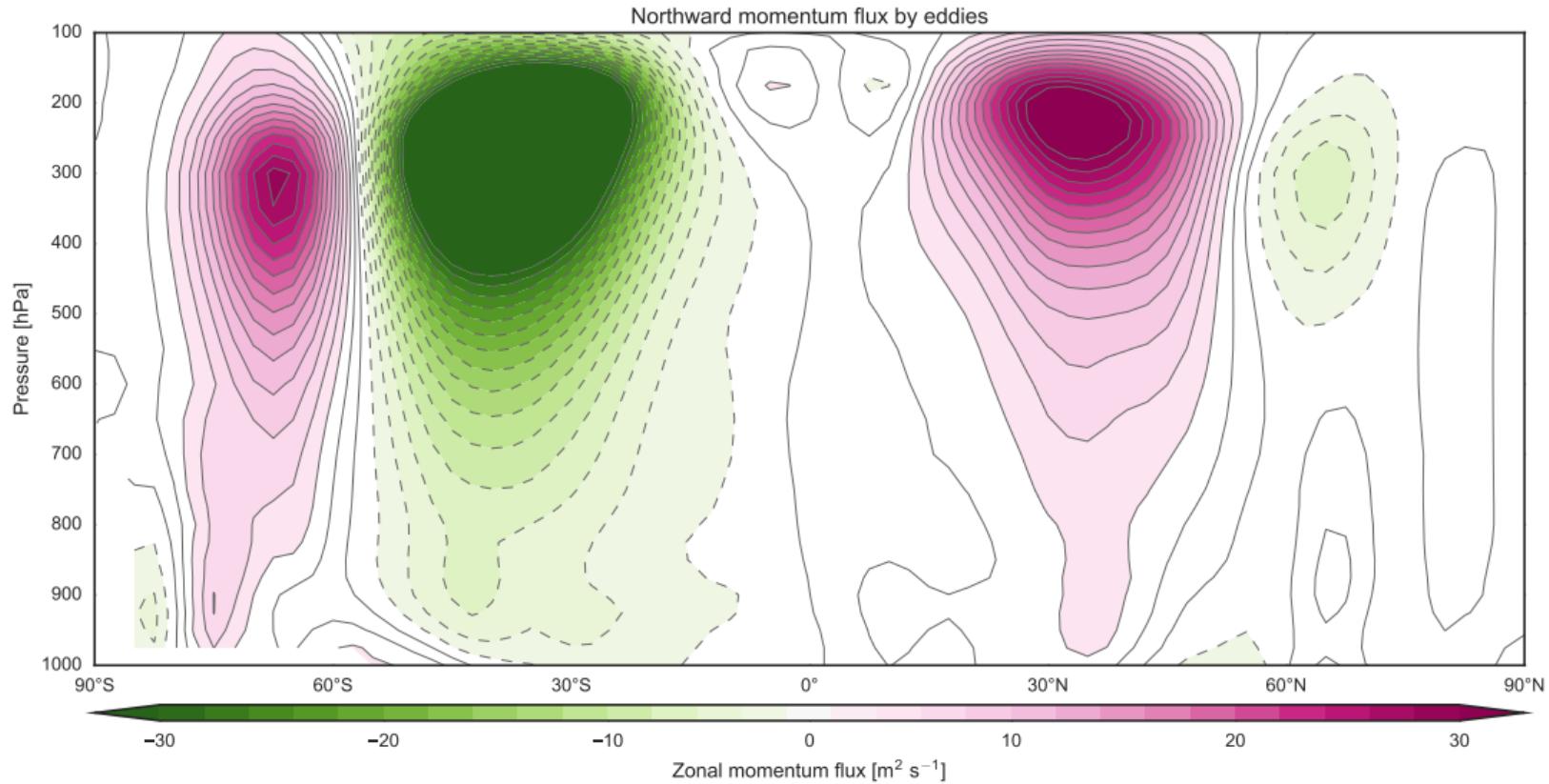
quasi-stationary eddies: $\bar{x}^* = \bar{x} - [\bar{x}]$
deviations from the zonal mean
(e.g., topographic effects)

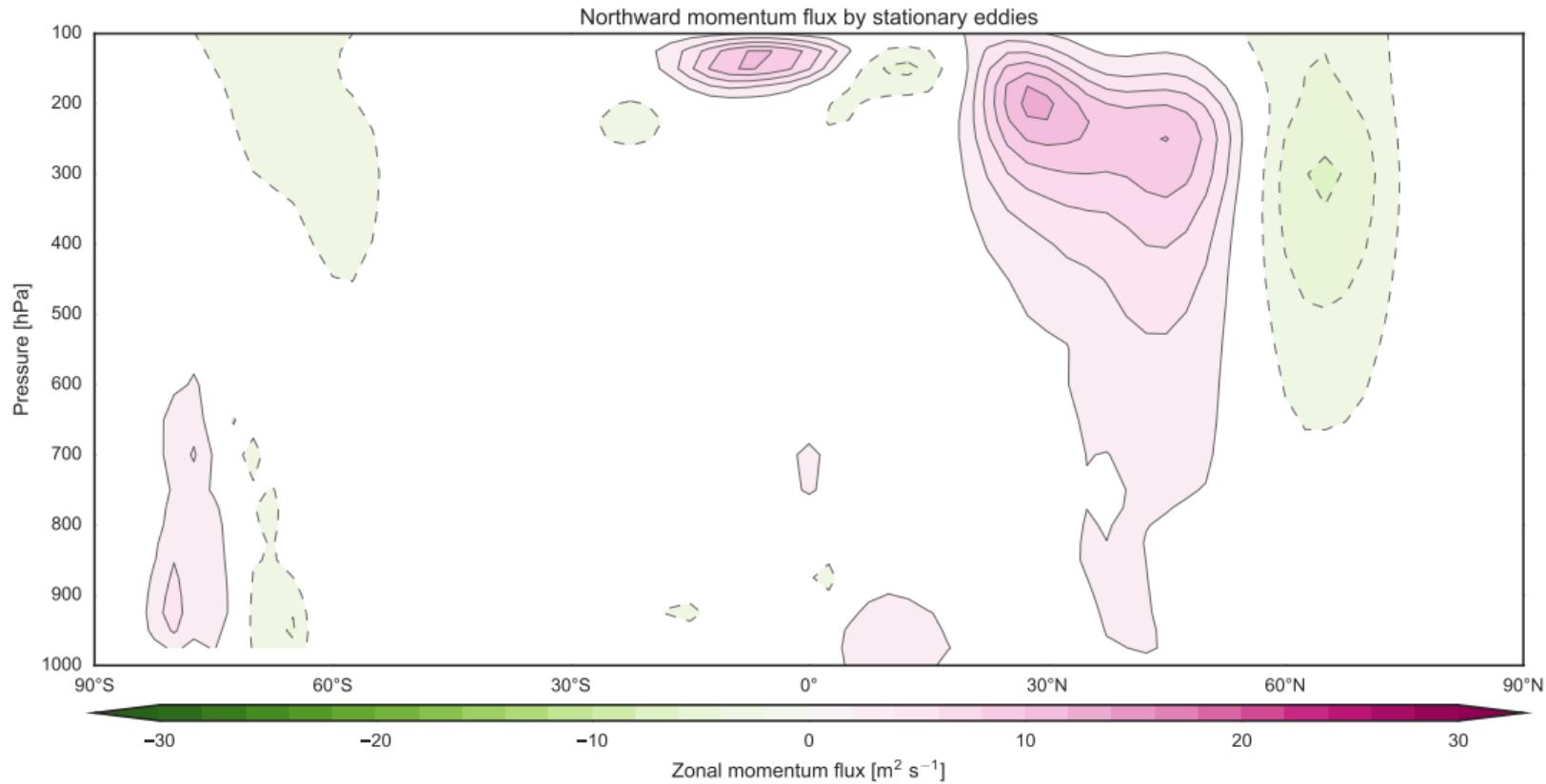
$$[\bar{v}x] = [\bar{v}] [\bar{x}] + [\bar{v}^* \bar{x}^*] + [v' x']$$

flxes by mean meridional circulation fluxes by quasi-stationary eddies fluxes by transient eddies

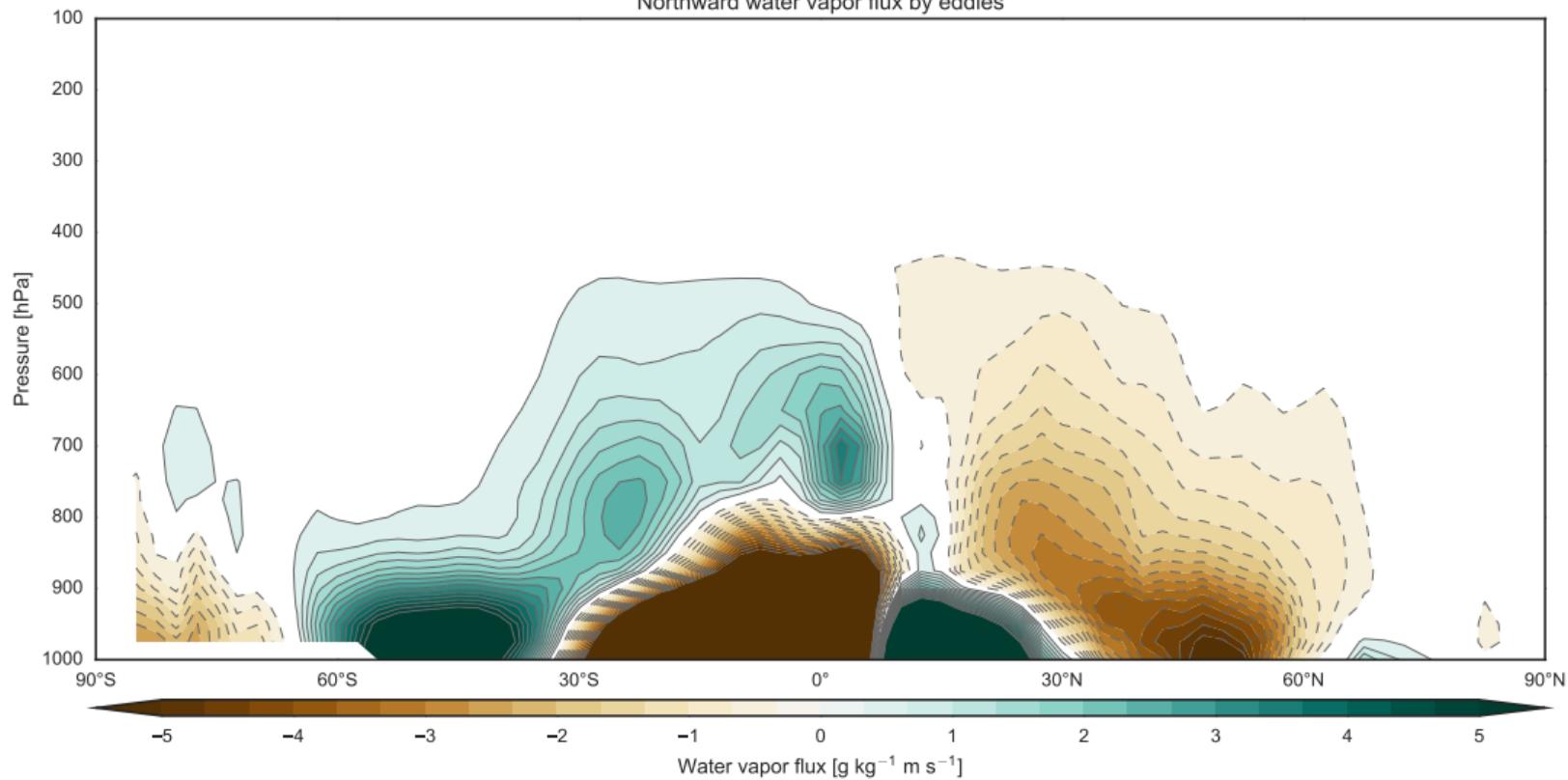




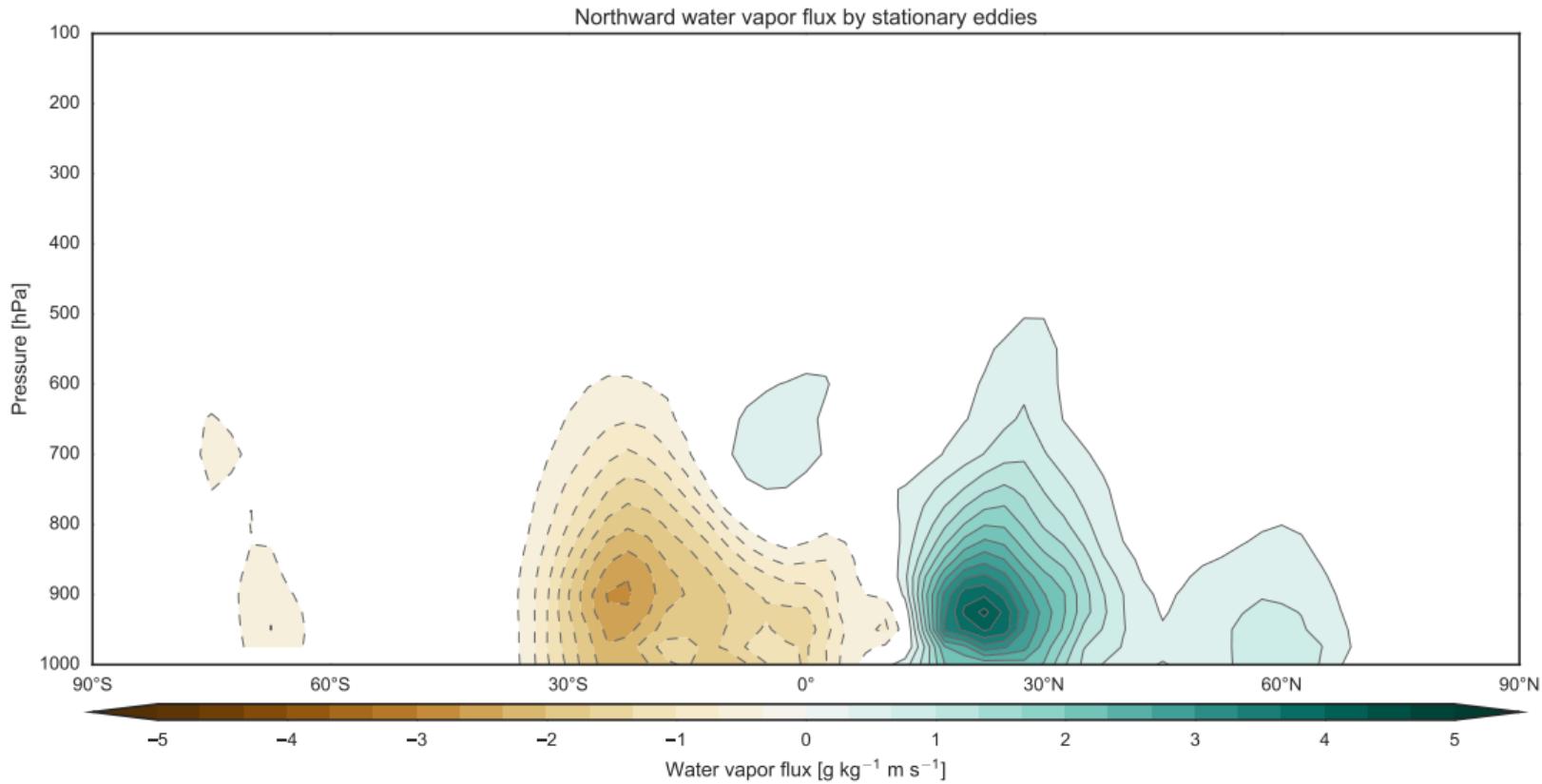




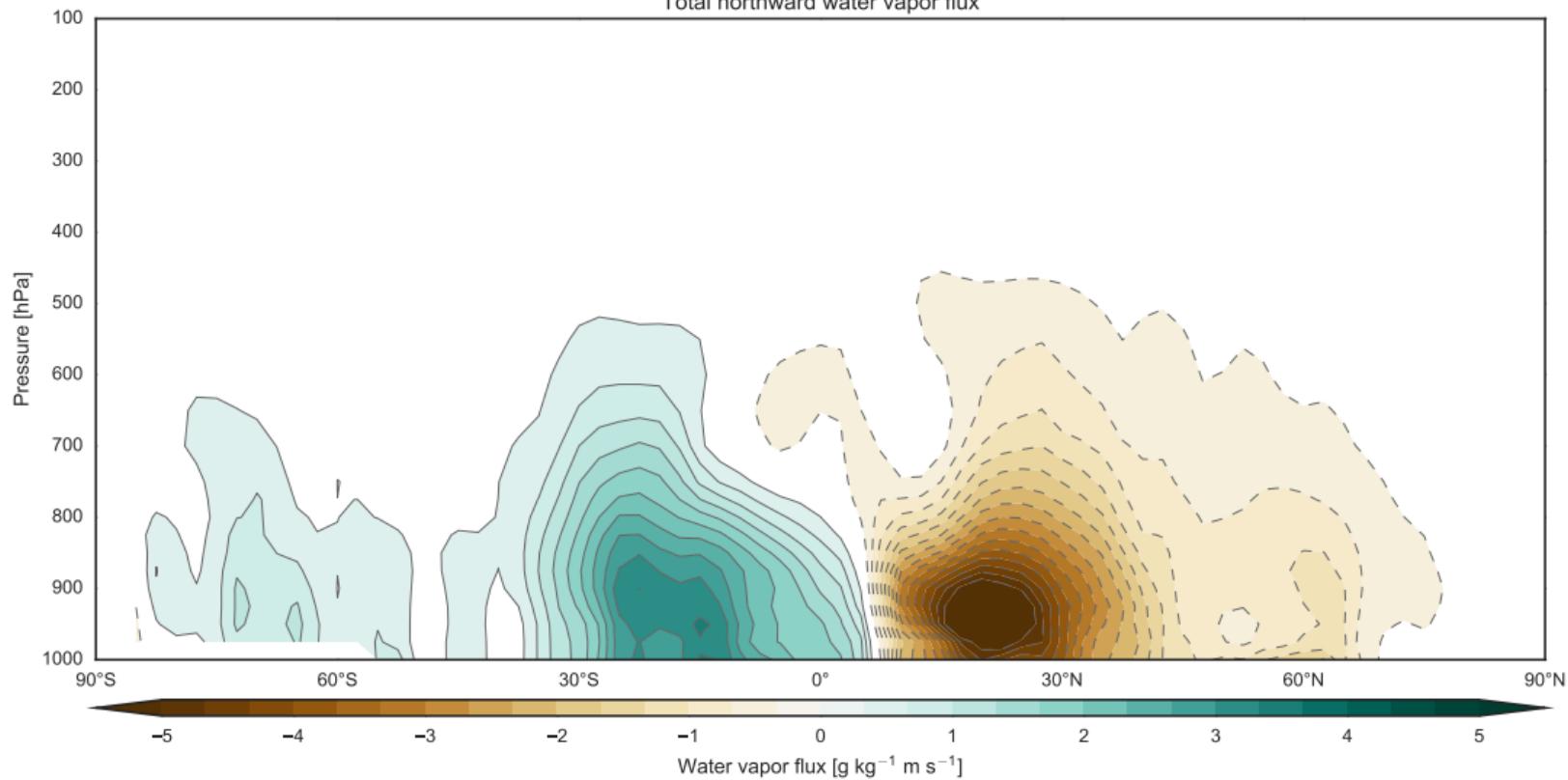
Northward water vapor flux by eddies



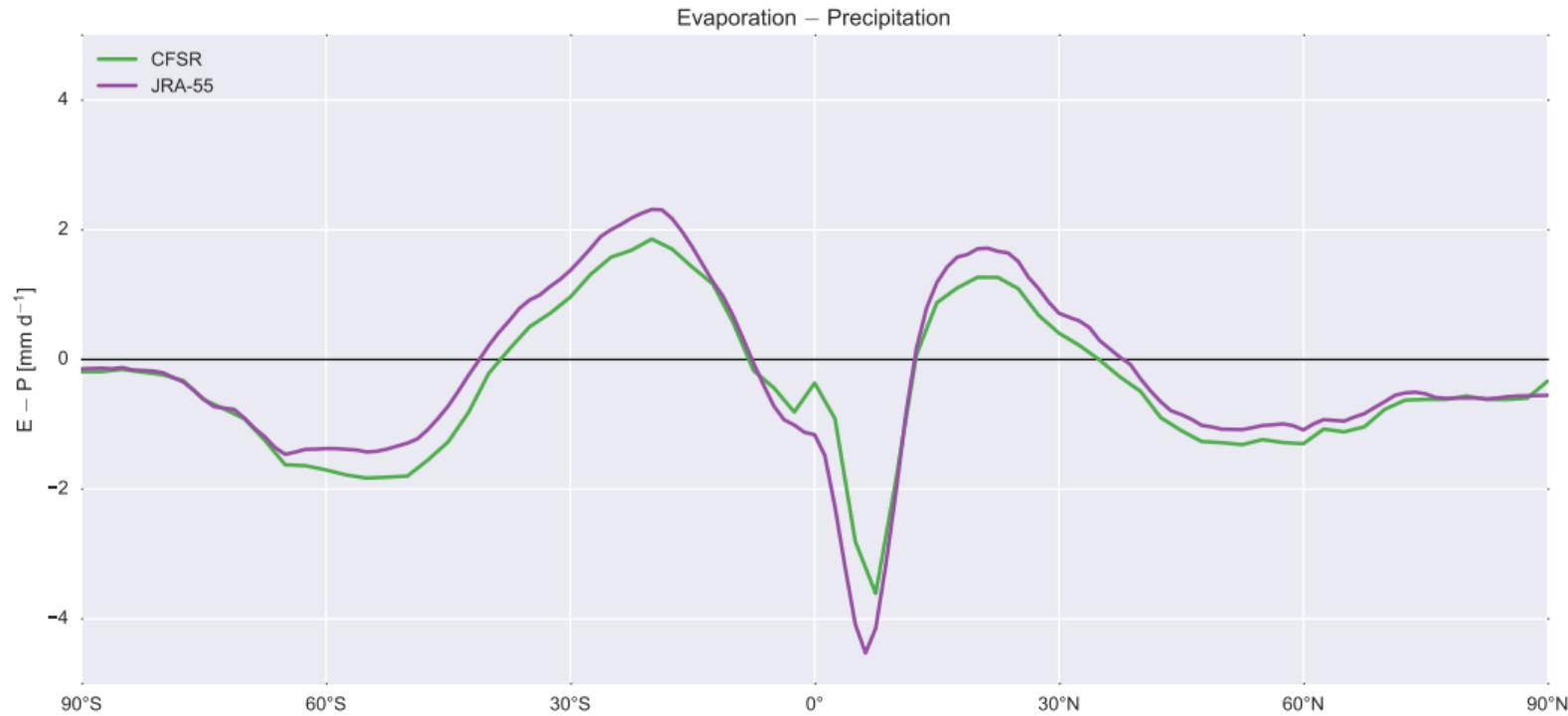
data from CFSR

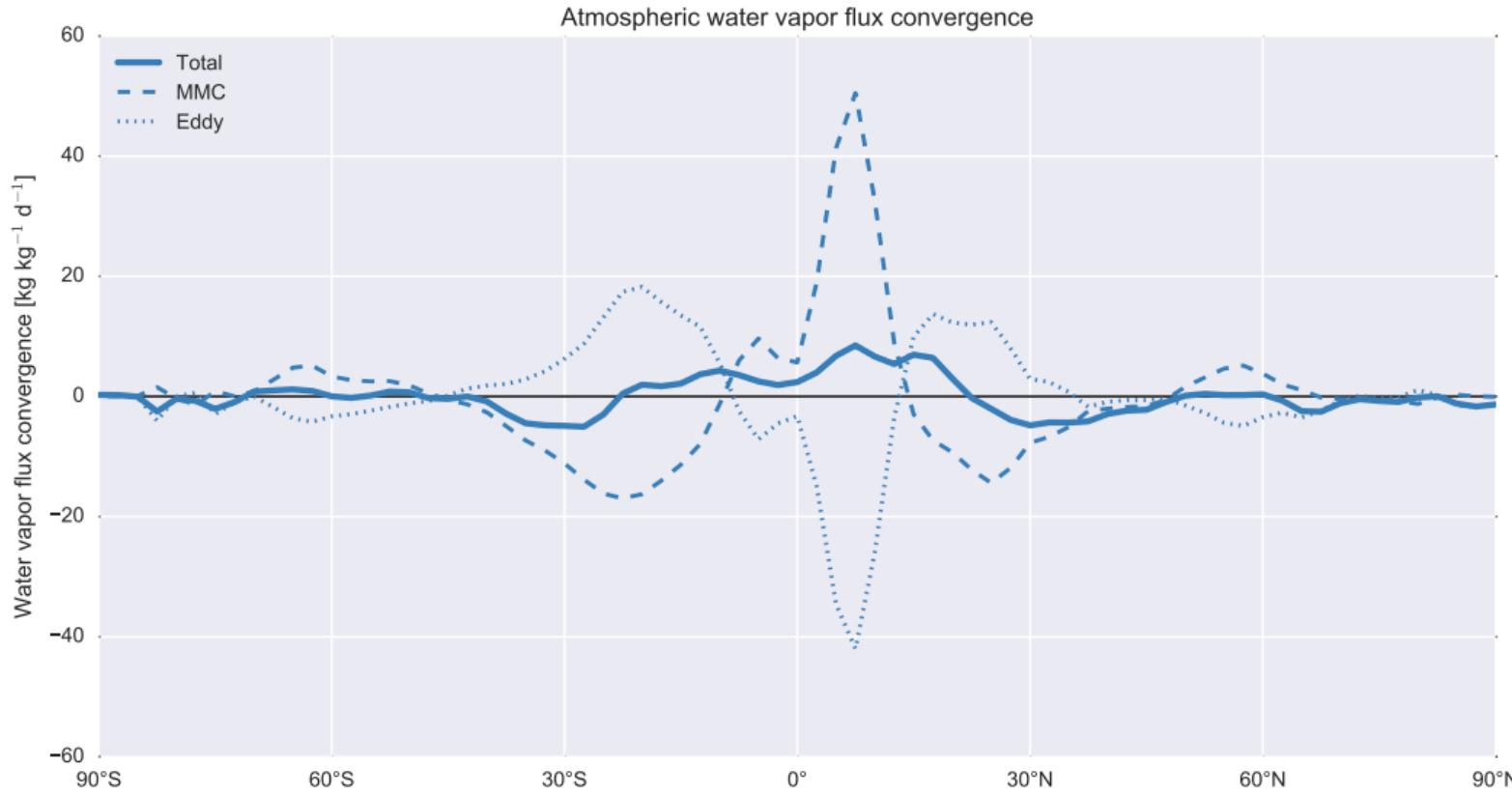


Total northward water vapor flux

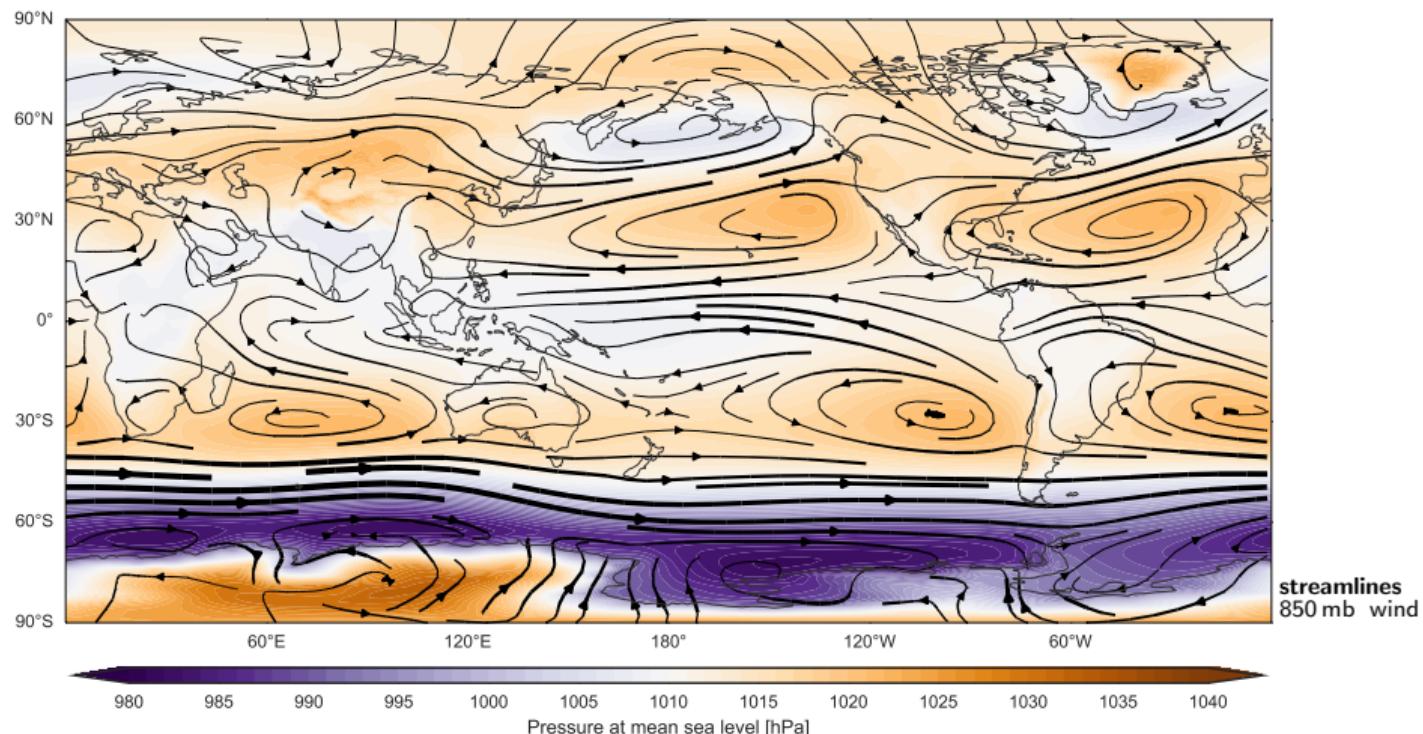


data from CFSR





Standing eddies: subtropical highs and subpolar lows

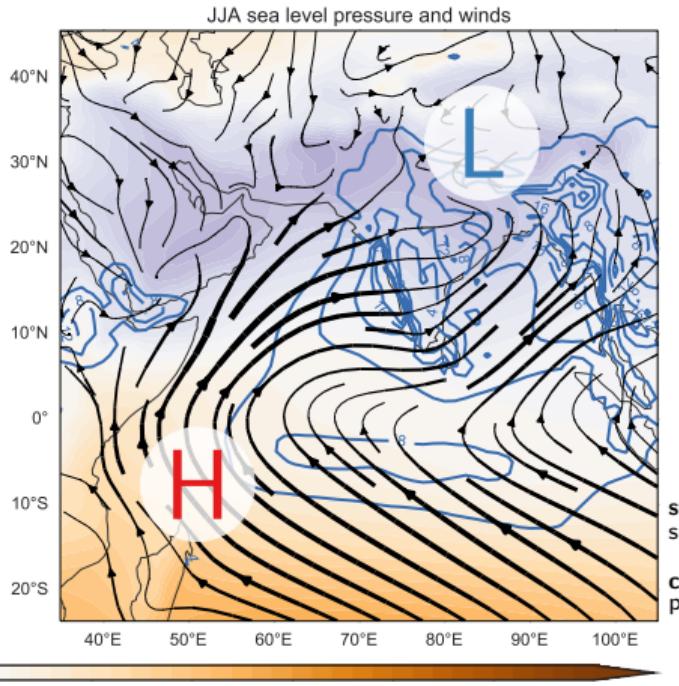
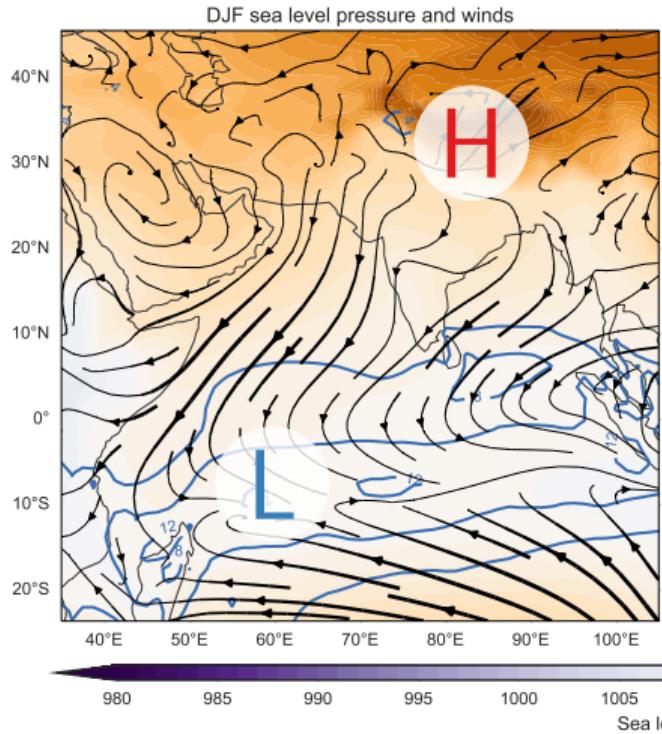


data from JRA-55

Seasonal variations in standing eddies

streamlines
850 mb wind

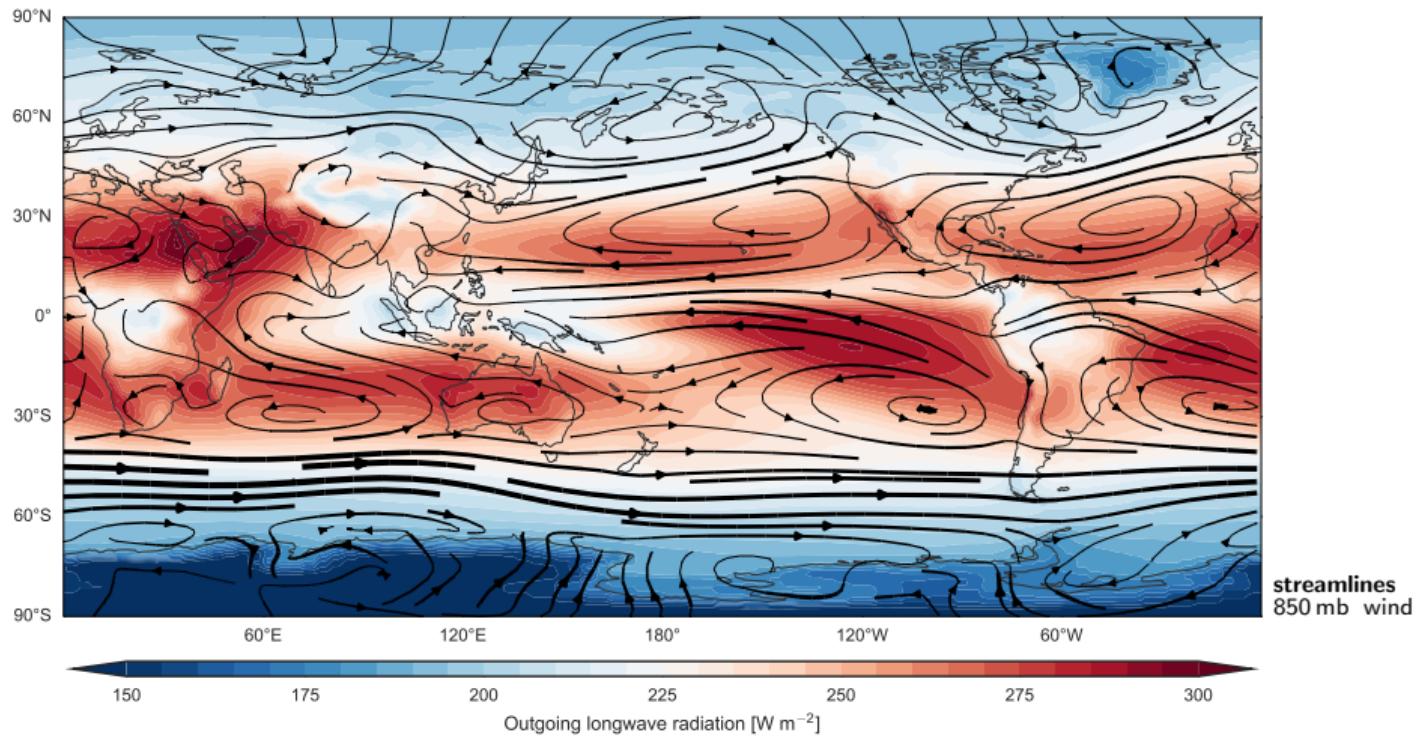
Seasonal variations in standing eddies: monsoons



streamlines
surface wind
contours
precipitation

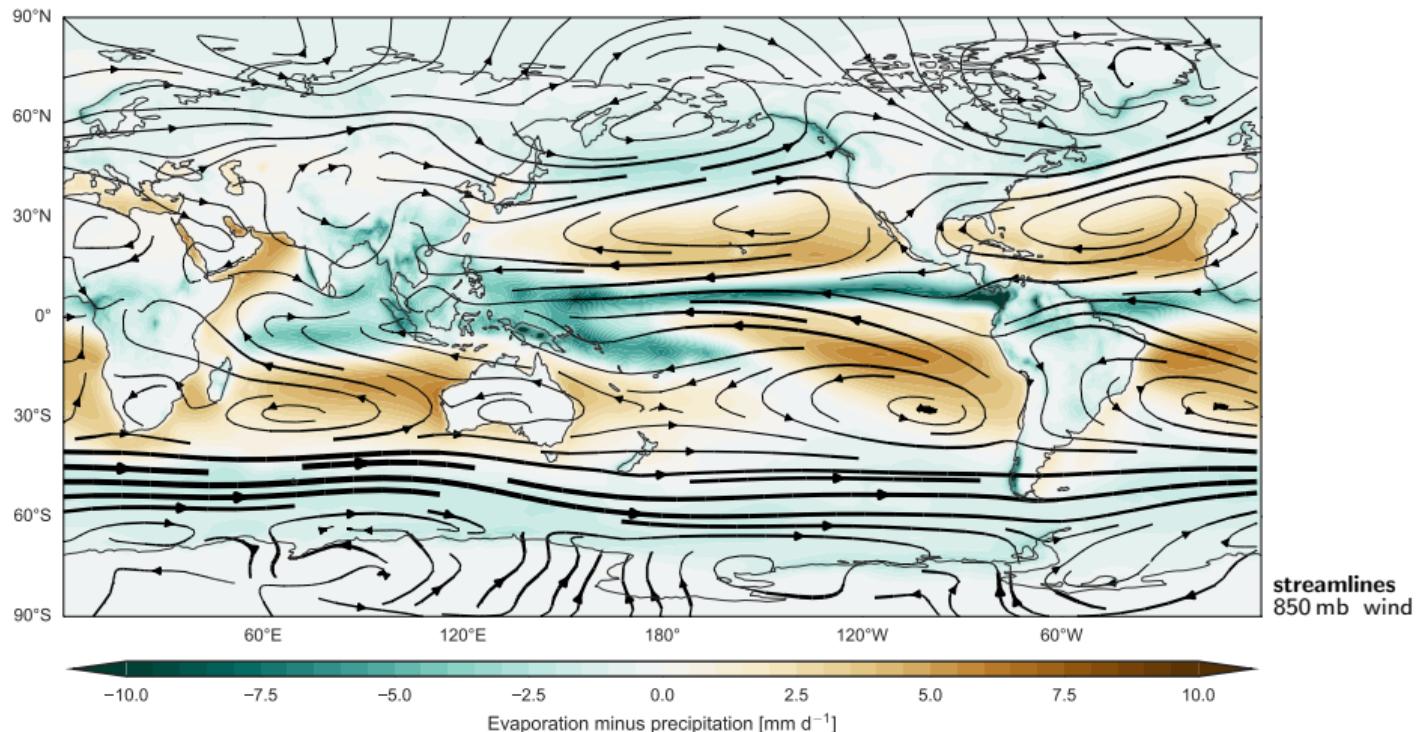
data from JRA-55

Standing eddies: outgoing longwave radiation



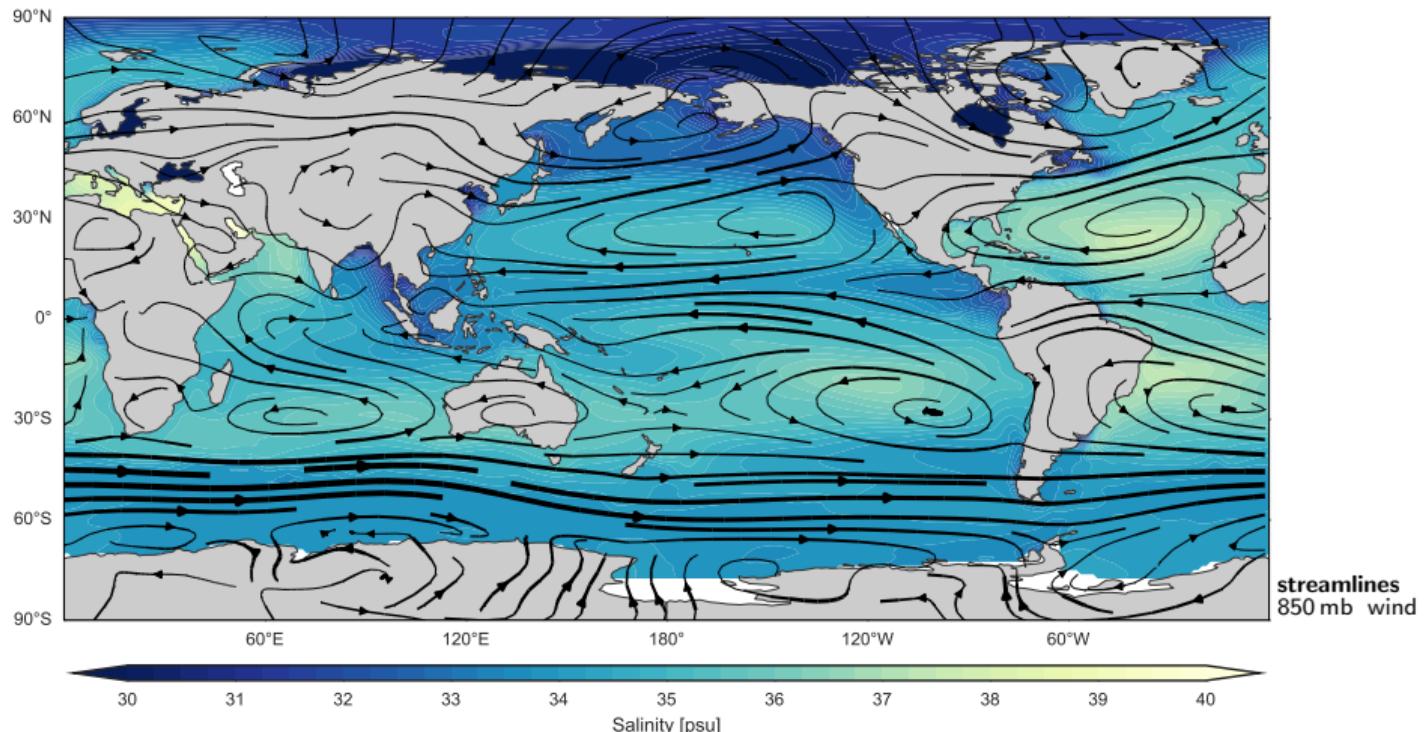
data from JRA-55 and CERES SYN1deg

Standing eddies: the surface water budget



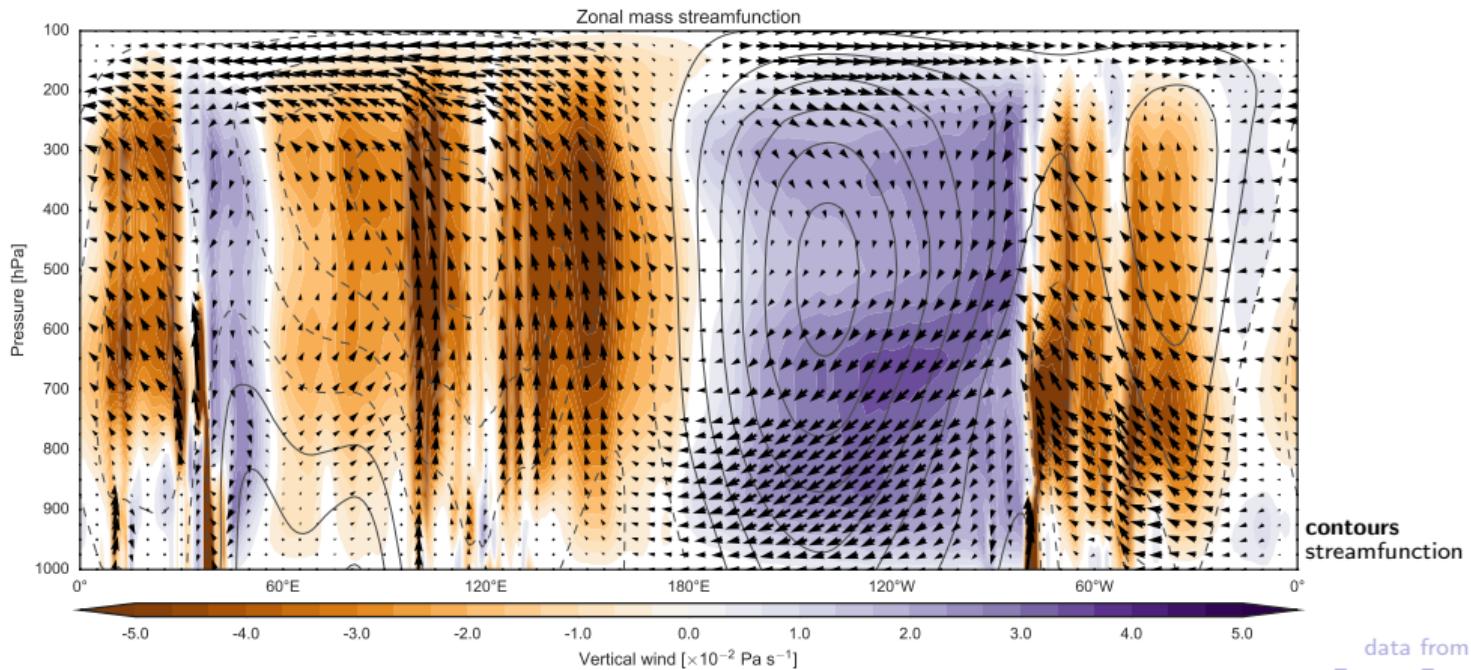
data from JRA-55

Standing eddies: surface salinity

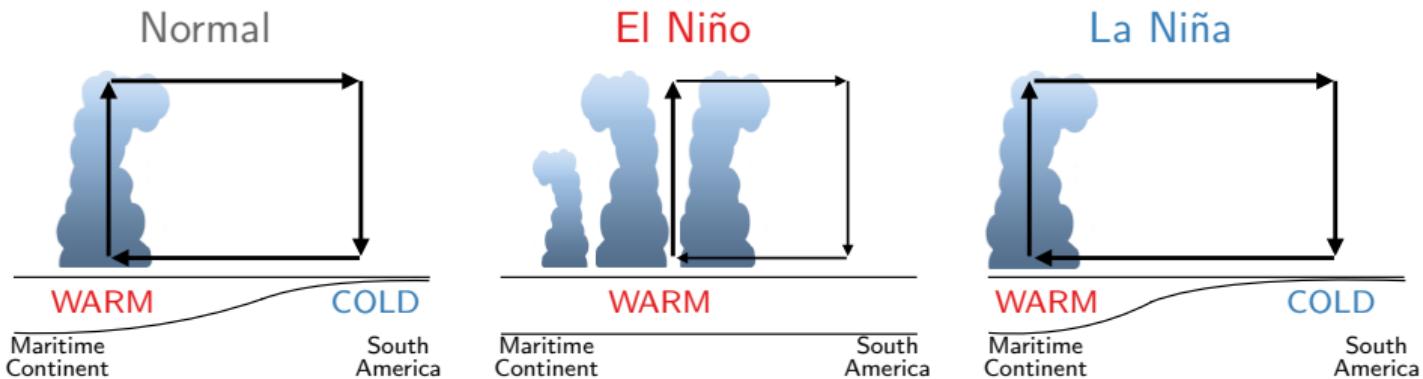
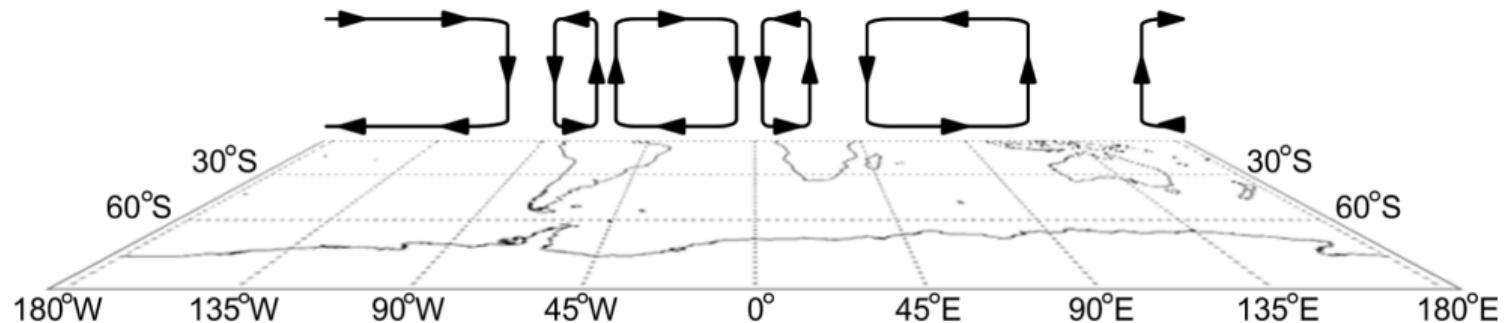


Standing eddies in the tropics: the Walker circulation

Zonal mass streamfunction: $\Psi_Z = \frac{a}{g} \int_{\vartheta_S}^{\vartheta_N} \int_0^p \bar{u}^* dp d\vartheta$

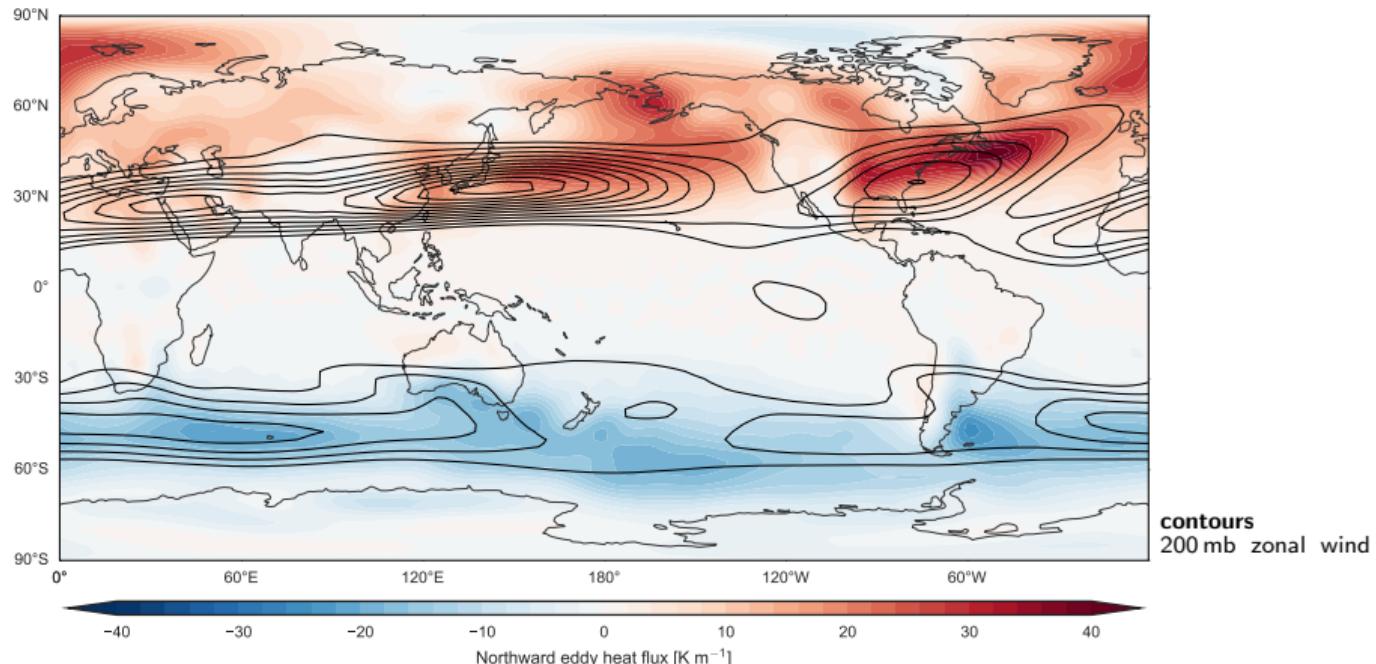


Standing eddies in the tropics: the Walker circulation



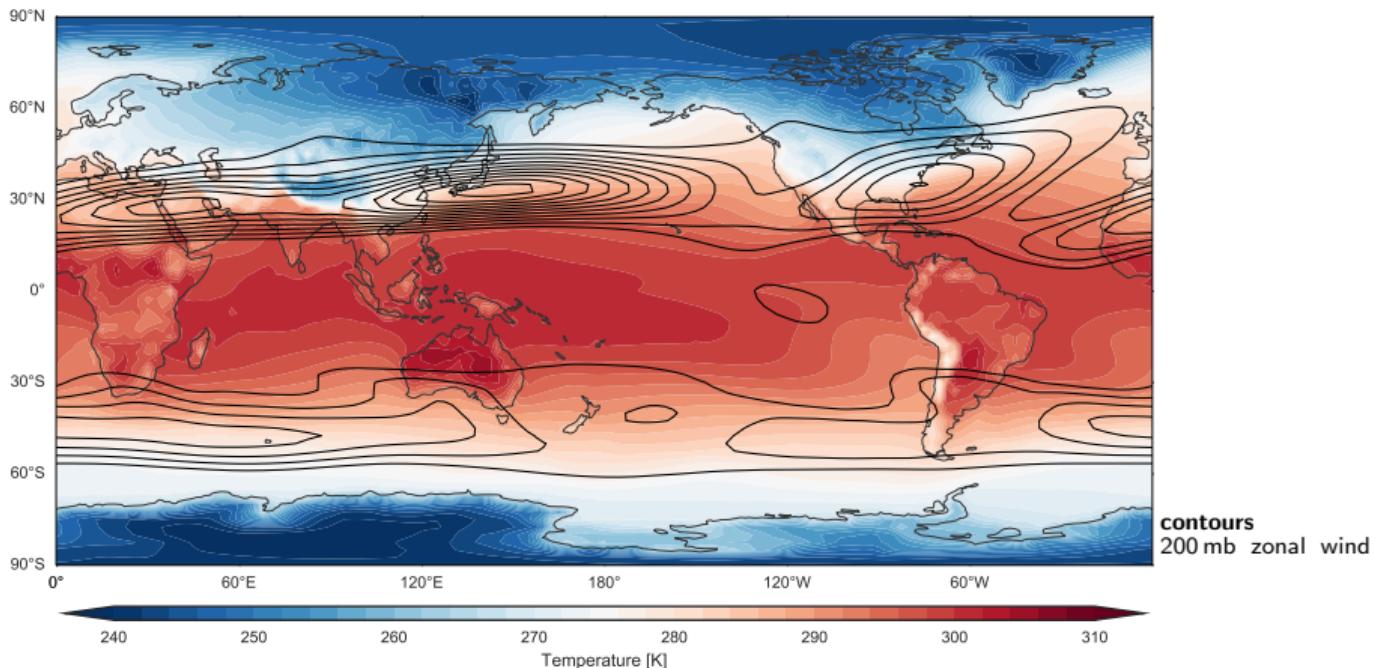
Eddy activity in the extratropics: the storm tracks

Maxima in \bar{u} are collocated with maxima in $\bar{v}^*T^* + \bar{v'}T'$



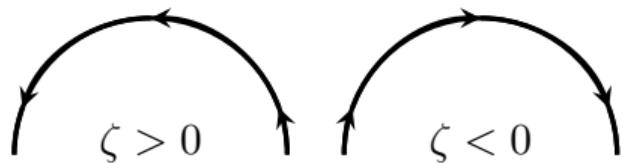
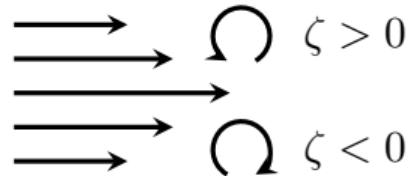
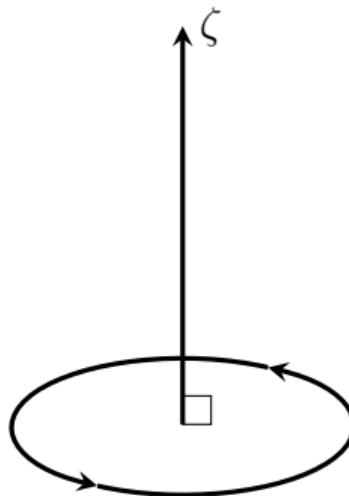
Eddy activity in the extratropics: the storm tracks

The storm tracks also coincide with the sharpest meridional temperature gradients



Relative vorticity

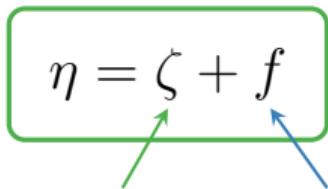
$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$



Absolute vorticity

$$\eta = \zeta + f$$

relative vorticity planetary vorticity

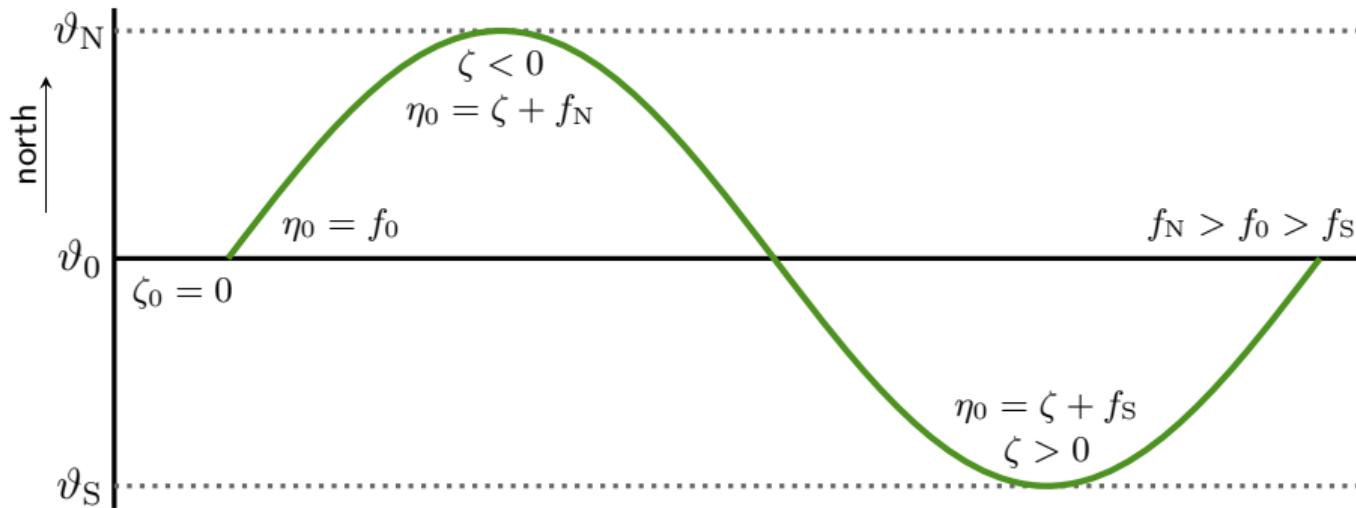


absolute vorticity is conserved in
the absence of sources or sinks:

$$\frac{\partial \eta}{\partial t} + (\mathbf{v} \cdot \nabla) \eta = 0$$

Rossby waves

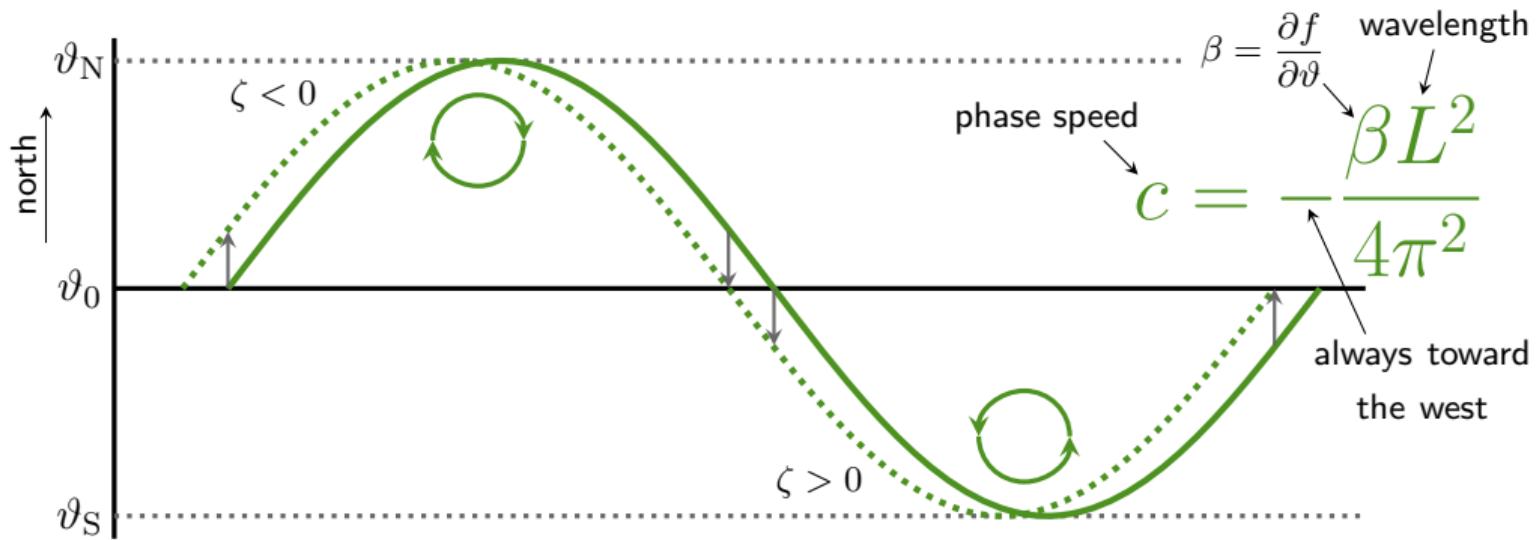
f increases, so ζ must decrease



f decreases, so ζ must increase

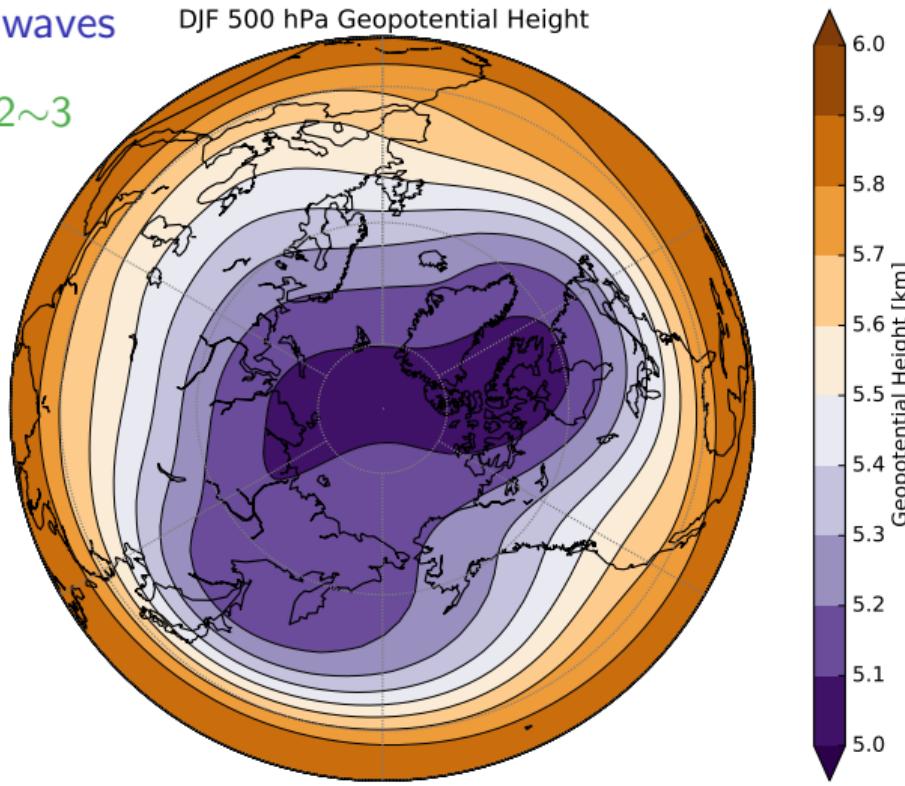
Rossby waves

Rossby waves propagate toward the west relative to the background flow

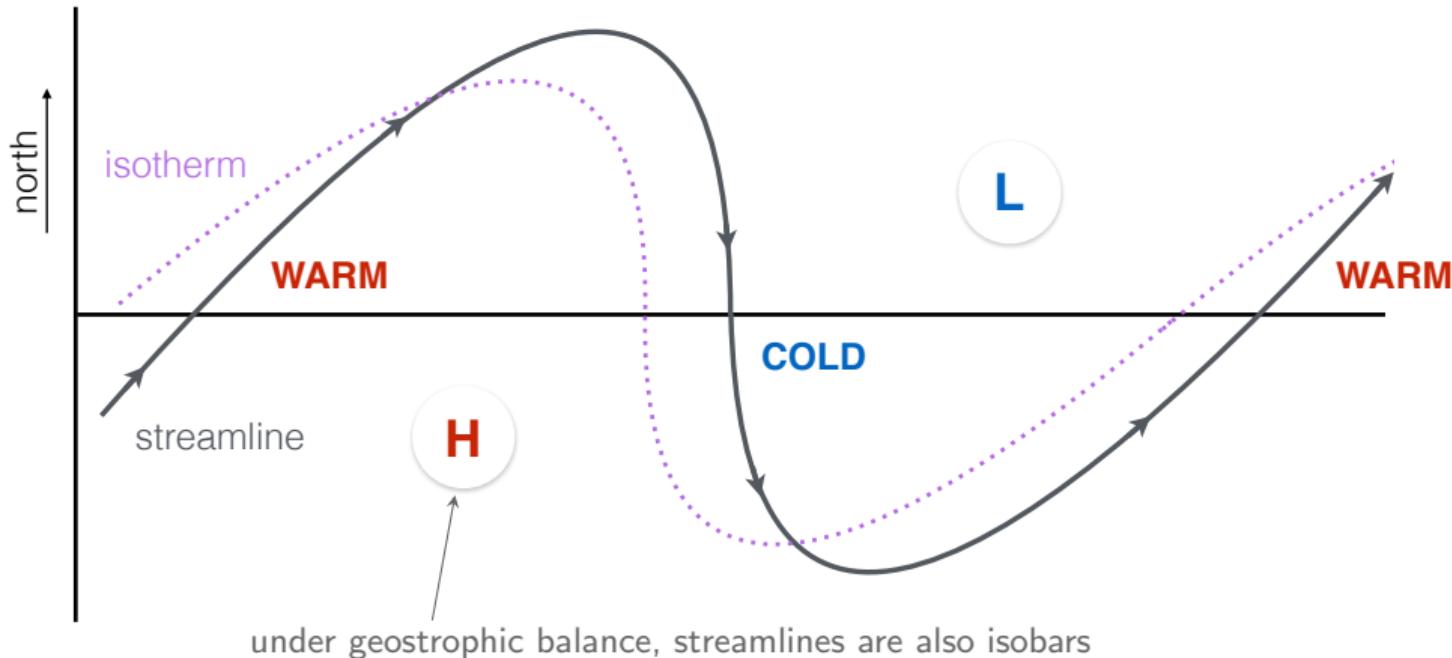


Standing Rossby waves

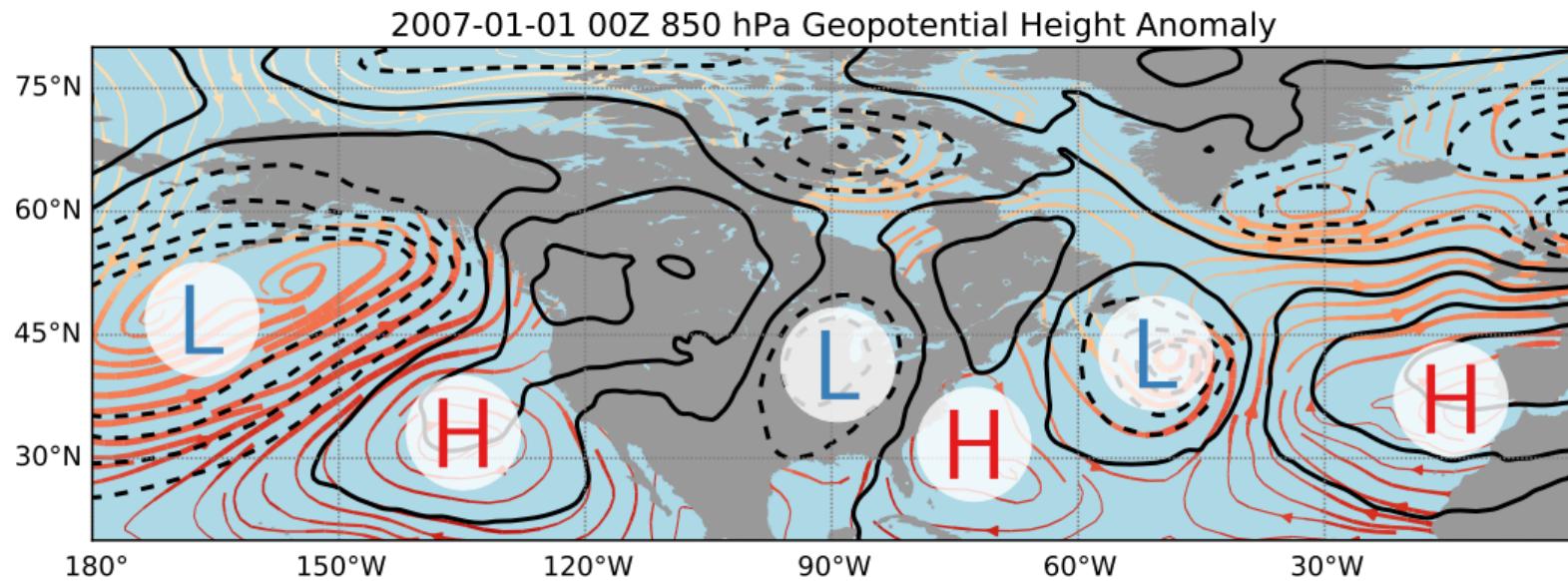
wave number = 2~3

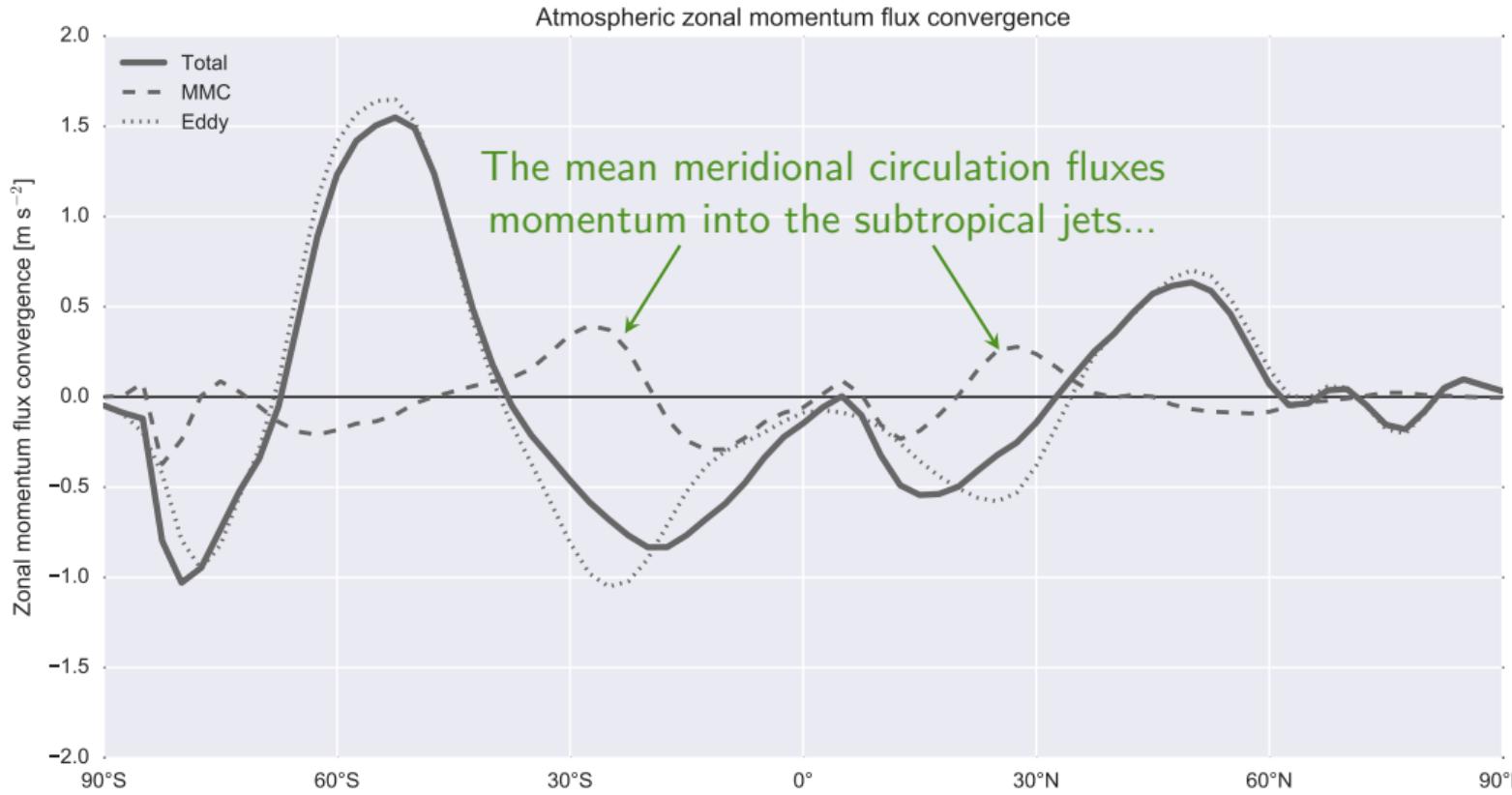


Transient eddies



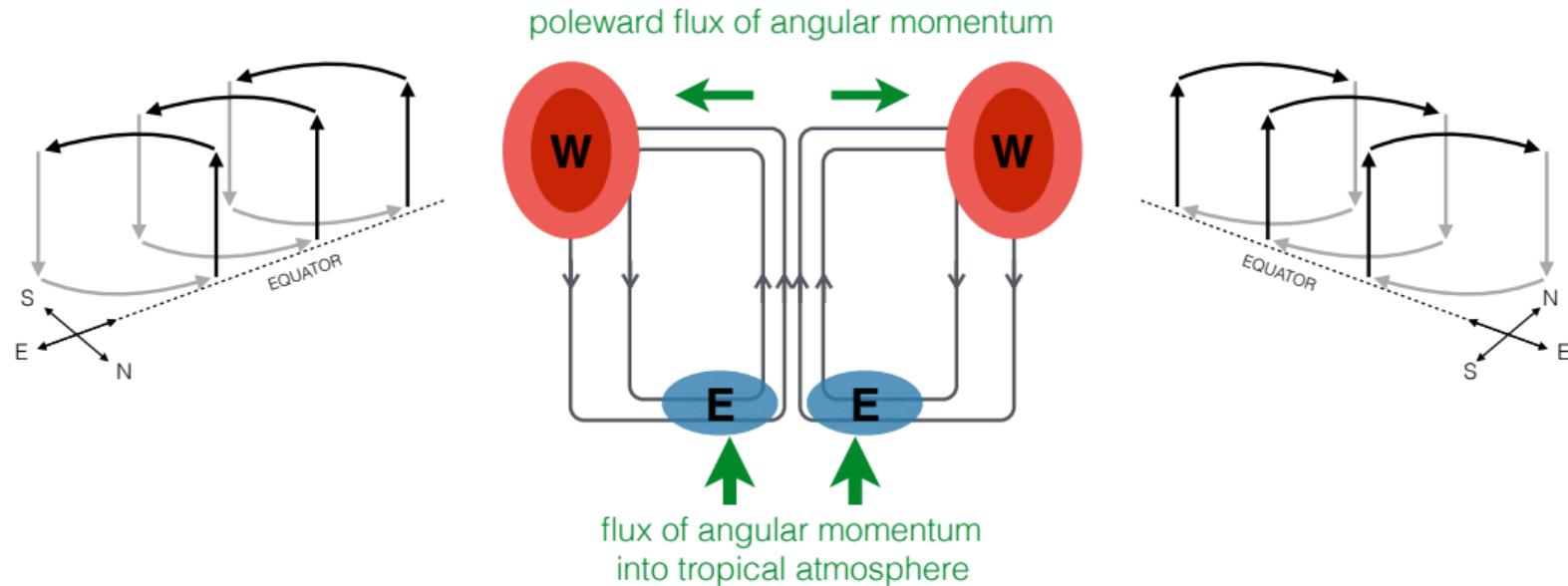
Transient eddies: synoptic systems

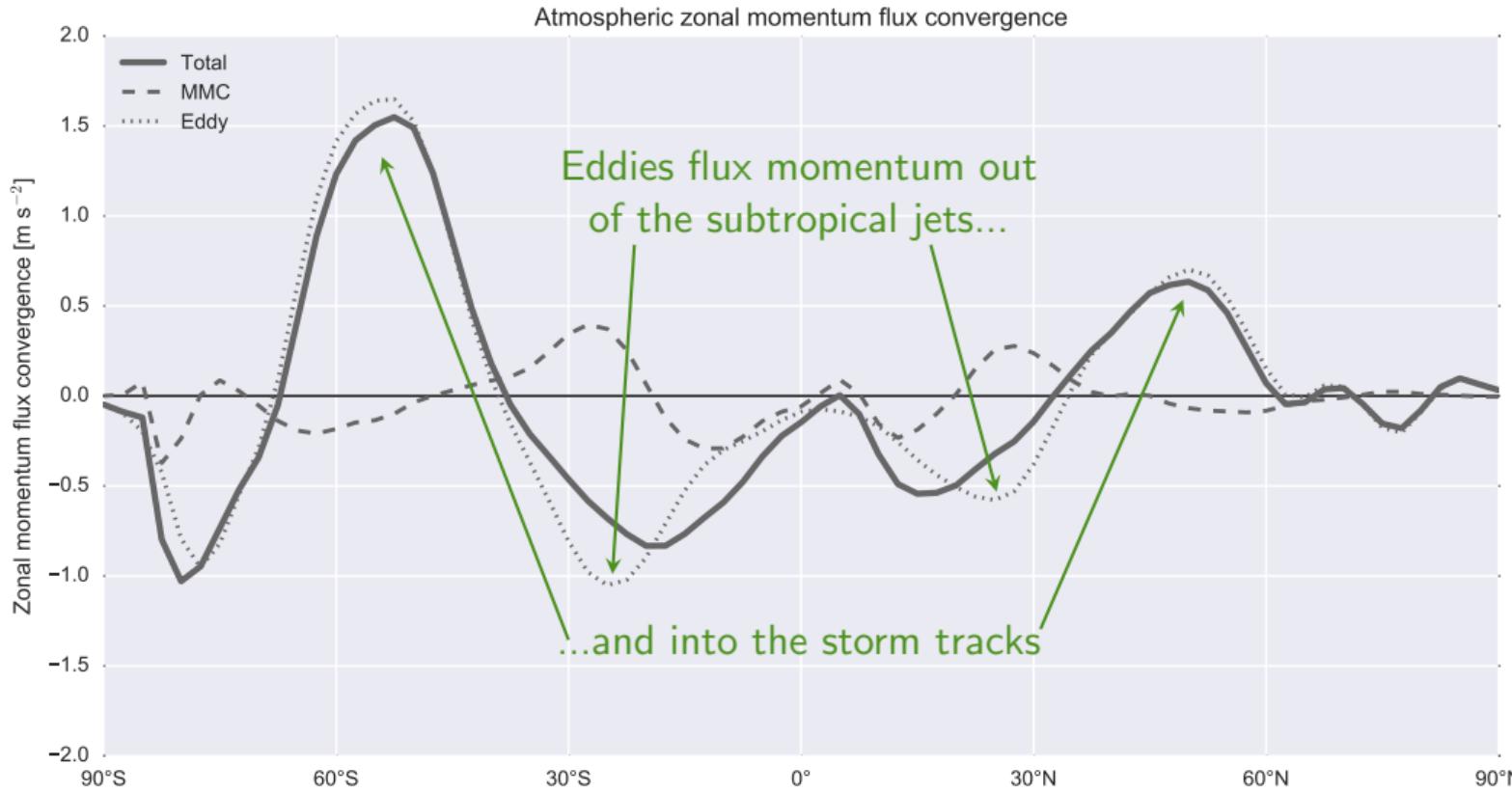




Subtropical jets

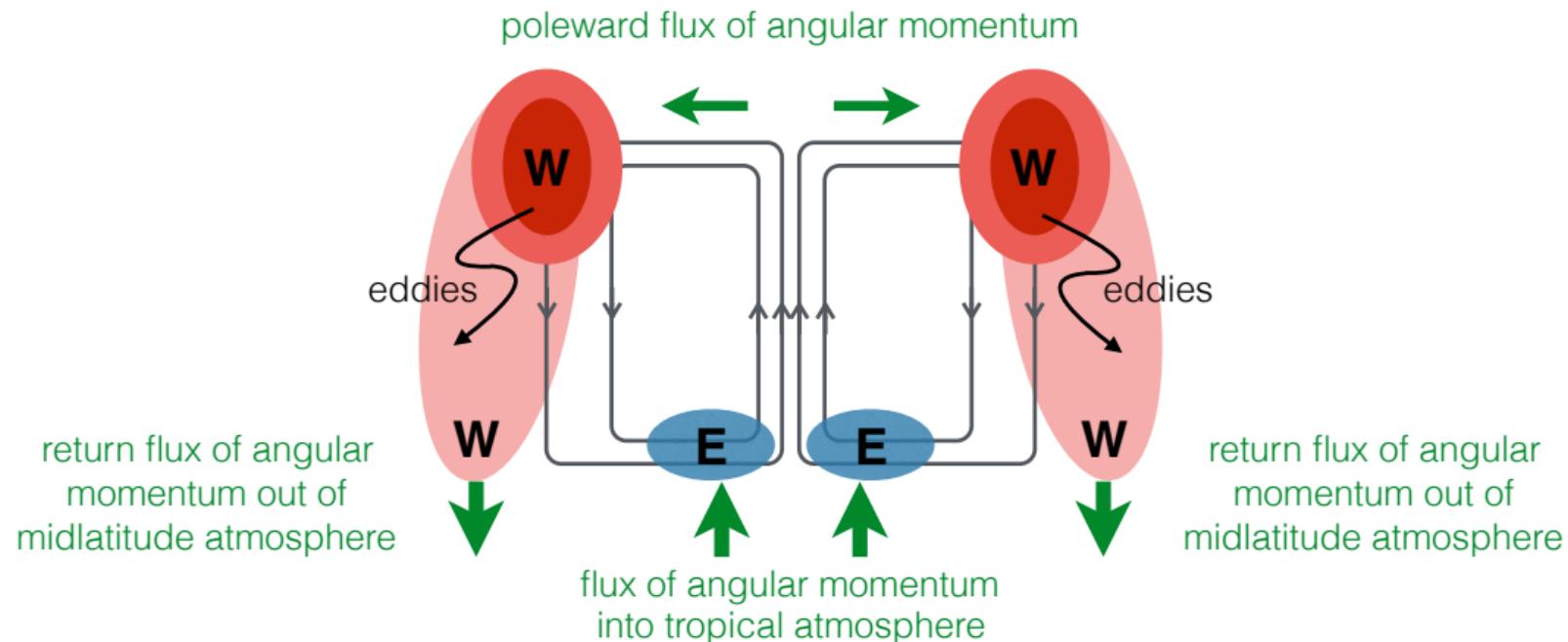
Friction adds angular momentum to the atmosphere in the tropics; the Hadley cell transports this momentum to the jets





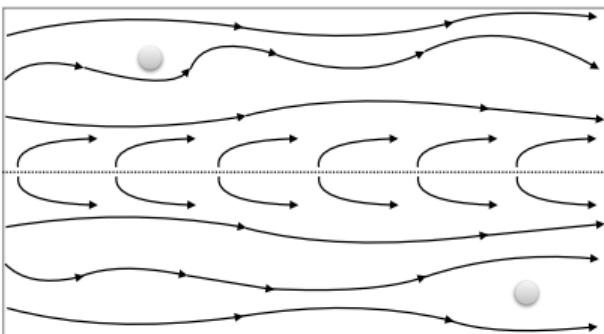
Midlatitude westerlies

Eddies transport angular momentum from the subtropical jets downward and poleward, where it returns to the solid Earth



Upper troposphere

Northern high latitudes



midlatitude westerlies and eddies

subtropical jet

Hadley cell

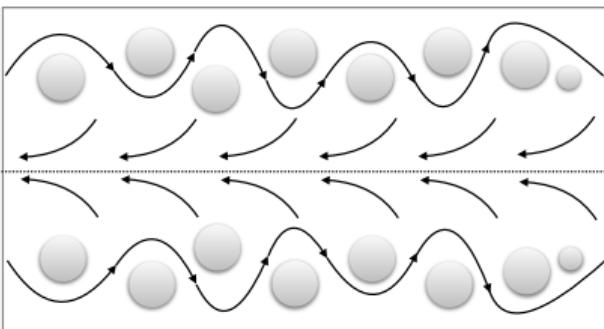
subtropical jet

Southern high latitudes

midlatitude westerlies and eddies

Lower troposphere

Northern high latitudes



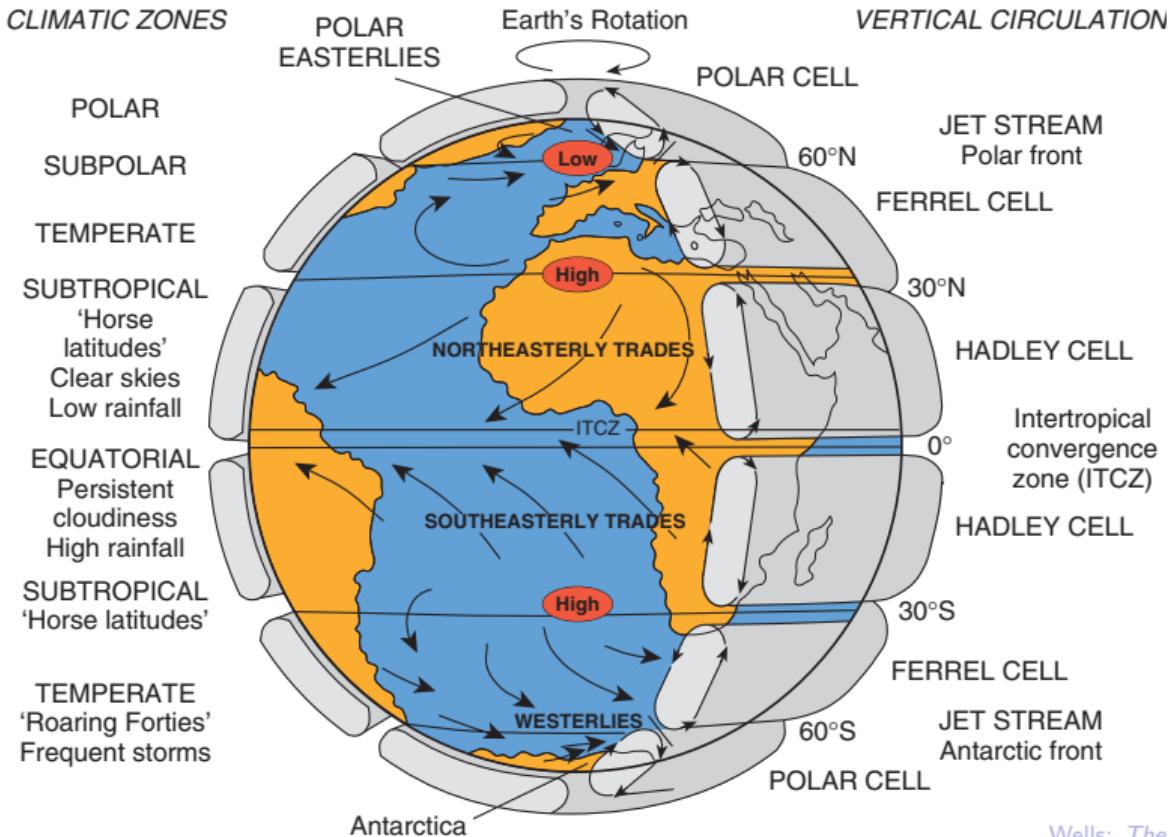
storms and prevailing westerlies

DRY
northeasterly trade winds

WET
southeasterly trade winds

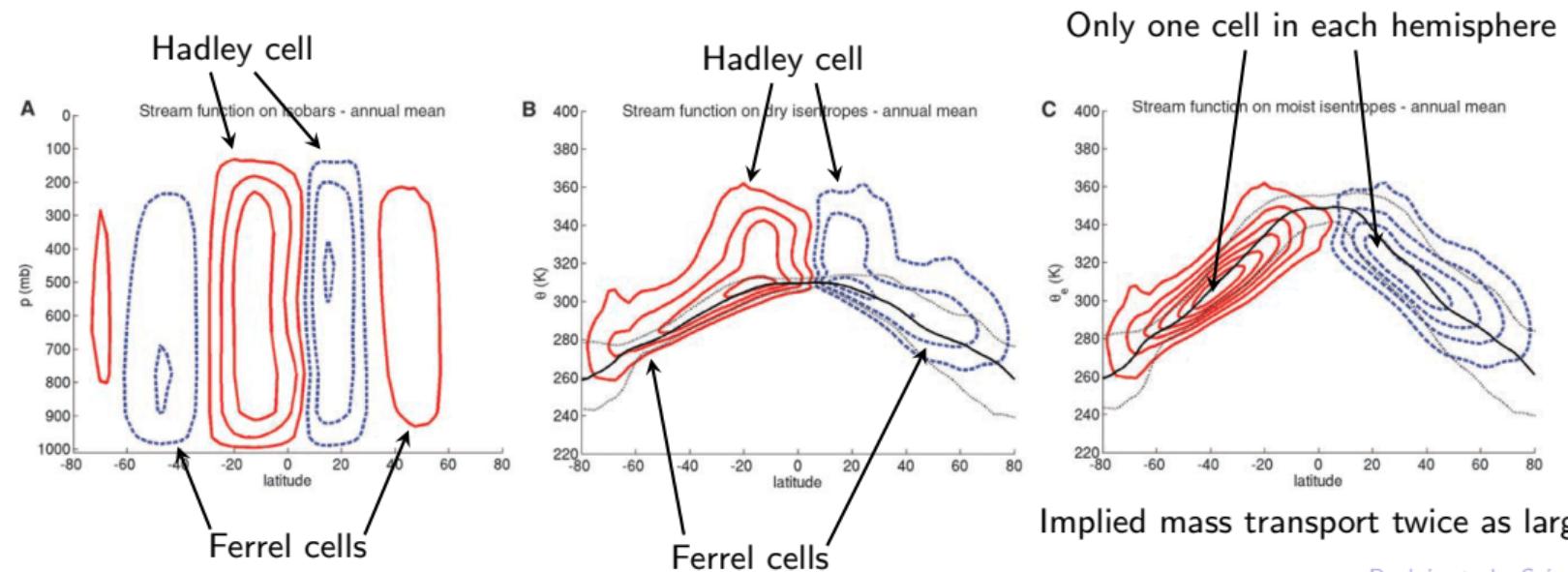
DRY
storms and prevailing westerlies

Southern high latitudes



Isentropic perspectives on the mean meridional circulation

Averaging the MMC in dry or equivalent potential temperature coordinates highlights different aspects of the overturning circulation



ISENTROPIC PERSPECTIVES ON THE MEAN MERIDIONAL CIRCULATION

The MMC on equivalent potential temperature coordinates better accounts for mass transport in moist poleward flow

