P3: Heat and Moisture Transport

The general circulation

12.307- project 3 (data class 2)

Heat transport in the atmsophere

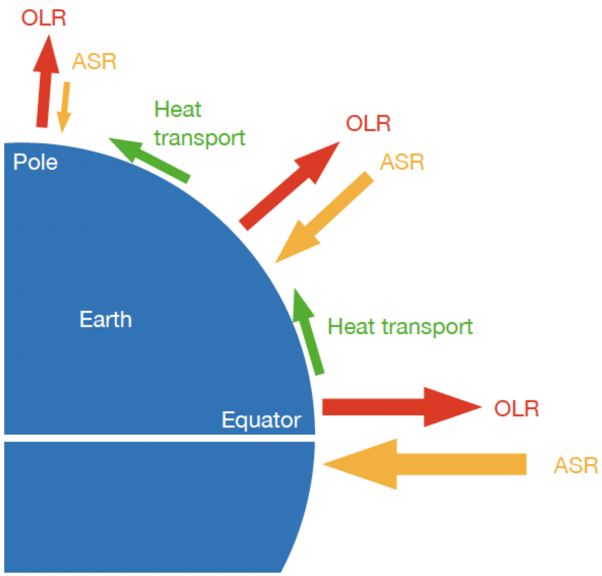
Previous class- The Hadley circulation

- Identify the Hadley circulation (EsGlobe)
- N-S heat transport in the tropics; Two-layer model
- Moisture transport in the tropics

Today's class- Energy transport

- Eddy-regime in the extra-tropics
- Energy transport in the Extra-tropics
- Project 4- brief intro

Reminder-



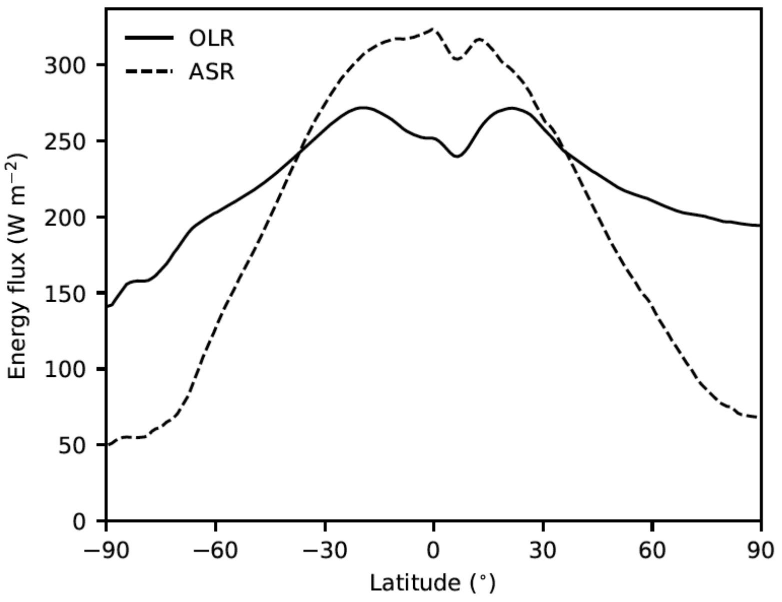
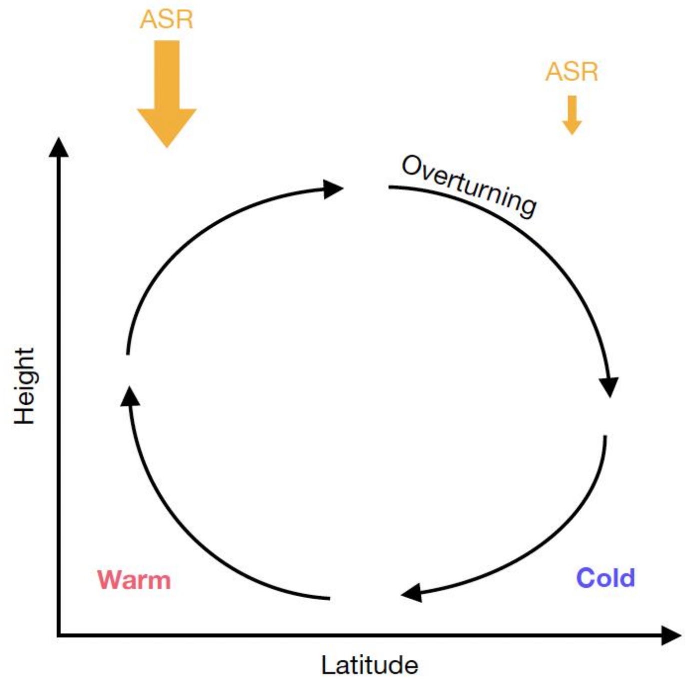


Figure 3: Heat transport in the atmosphere and ocean cools the tropics and heats the extratropics (left) and allows Earth to maintain steady temperatures without requiring a latitude-by-latitude balance between absorbed solar radiation (ASR) and outgoing longwave radiation (OLR) (right).

Heat transport in the atmosphere & ocean cools the tropics and heats the extratropics

Hadley Cell



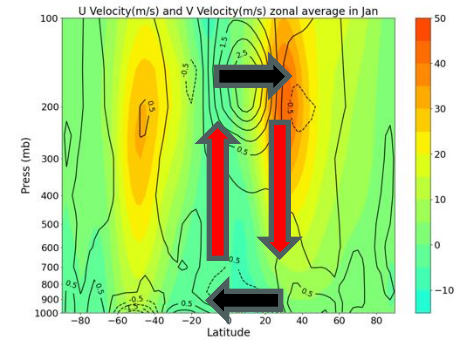
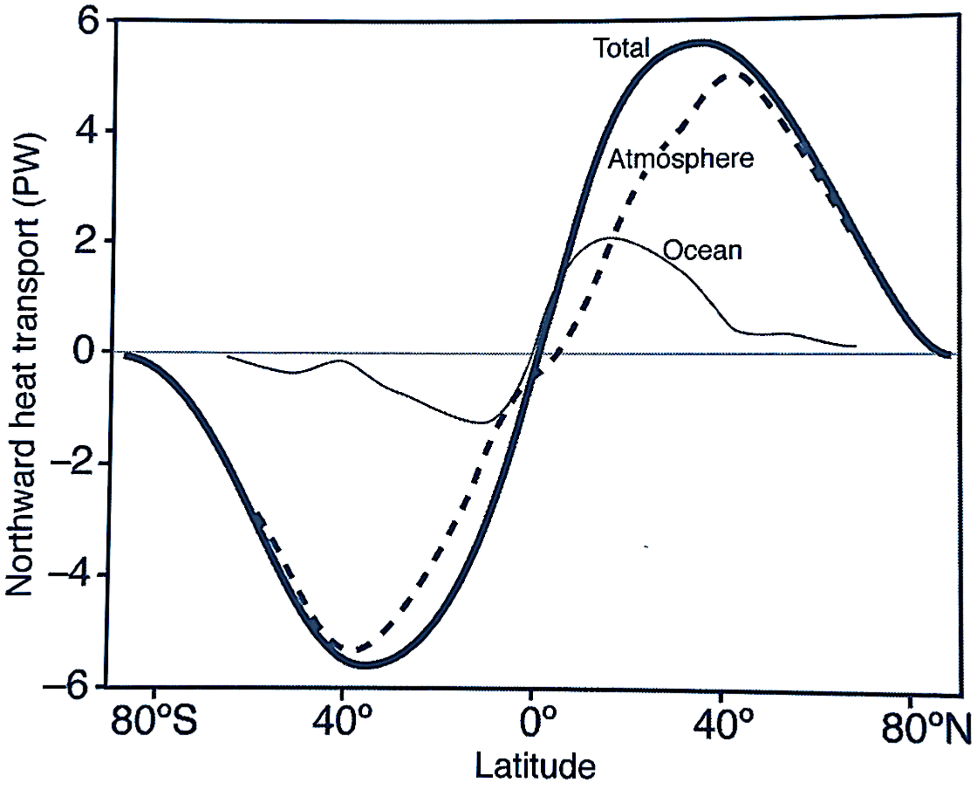


Figure 4: Differential heating, produced on Earth by absorbed solar radiation (ASR) that varies in latitude, can produce overturning circulations, with ascent in warm regions and descent in cool regions, that transport warm air poleward and cold air equatorward.

The resulting overturning circulations transport warm air poleward at upper levels and cold air equatorward near Earth's surface, producing a net transport of heat toward the poles

Heat transport by the atmosphere and ocean



We calculated the total heat transport in the tropics and got:
~8-5.4=2.6 PW (thermal and latent opposing each other)
→ Not a bad rough estimation!

However, the Hadley cell terminates around ~30 N/S

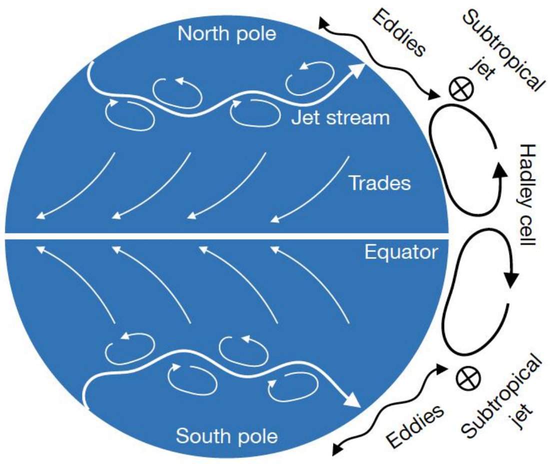


Figure 5: Schematic of the general circulation of Earth's atmosphere. Overturning circulations are most prominent in the tropics, and eddies are most prominent in midlatitudes.

How does the circulation look like in the midlatitude?

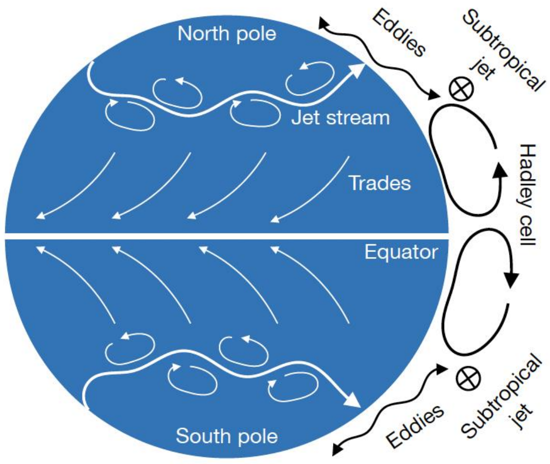


Figure 5: Schematic of the general circulation of Earth's atmosphere. Overturning circulations are most prominent in the tropics, and eddies are most prominent in midlatitudes.

The midlatitude
"eddy regime"

Eddies in the atmosphere

$$KE = \frac{1}{2}\left(\overline{u^2} + \overline{v^2}\right)$$

Kinetic energy (KE)

$$u' = u - \bar{u}$$

$$v' = v - \bar{v}$$

Eddy kinetic energy (EKE)

$$EKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$$

Mean kinetic energy (MKE)

$$MKE = \frac{1}{2}(\bar{u}^2 + \bar{v}^2)$$

Eddies in the atmosphere

$$KE = \frac{1}{2}\left(\overline{u^2} + \overline{v^2}\right)$$

Kinetic energy (KE)

Eddy kinetic energy (EKE)

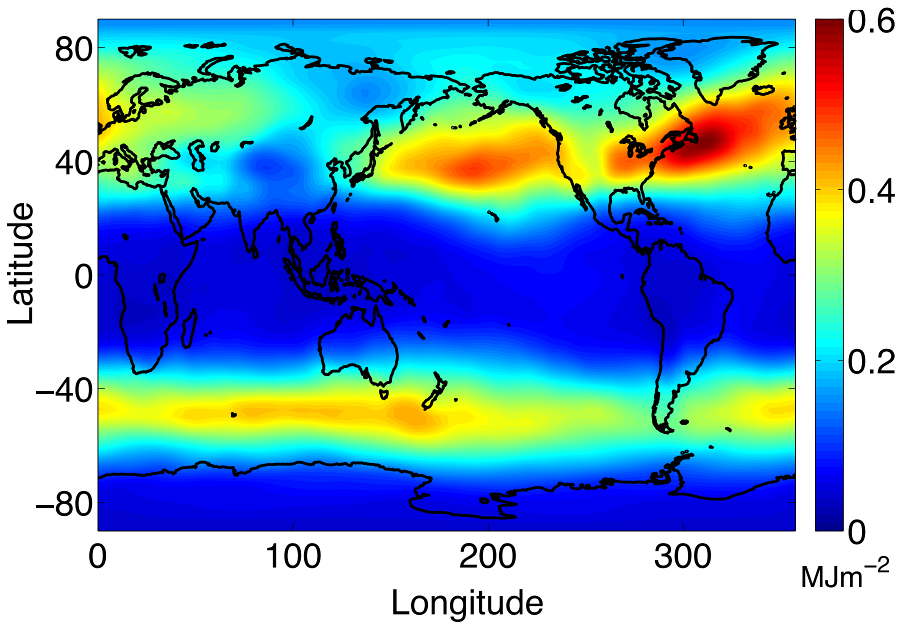
$$EKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$$

- *Regions where EKE is large are dominated by 'eddies'*
- *This regions are characterized by strong weather fluctuations*
- *Responsible for most of the poleward energy and moisture transport*
- *Also known as midlatitudes storm tracks*

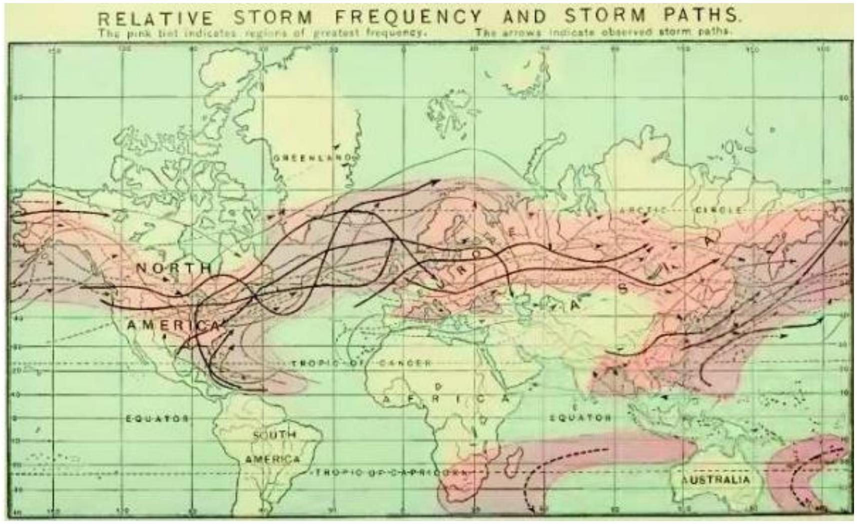
Earth's storm tracks

$$EKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$$

Eddy kinetic energy (EKE)



Cyclone tracks



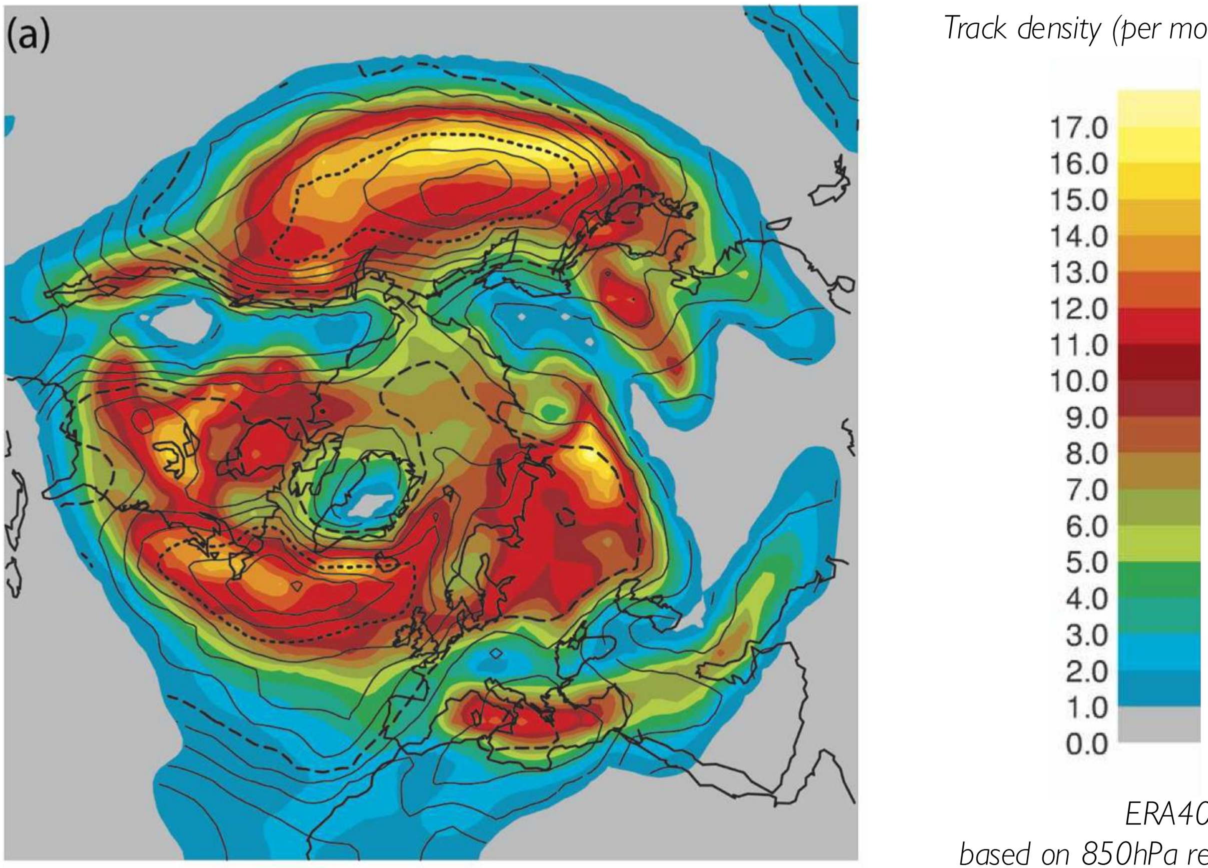
Cyclone frequency and individual cyclone tracks
(Chang 2002; reproduced from Hinman, 1888)

Eularian approach

Lagrangian approach

- Two complementary approaches!
- The Lagrangian approach separates between cyclones and anticyclone

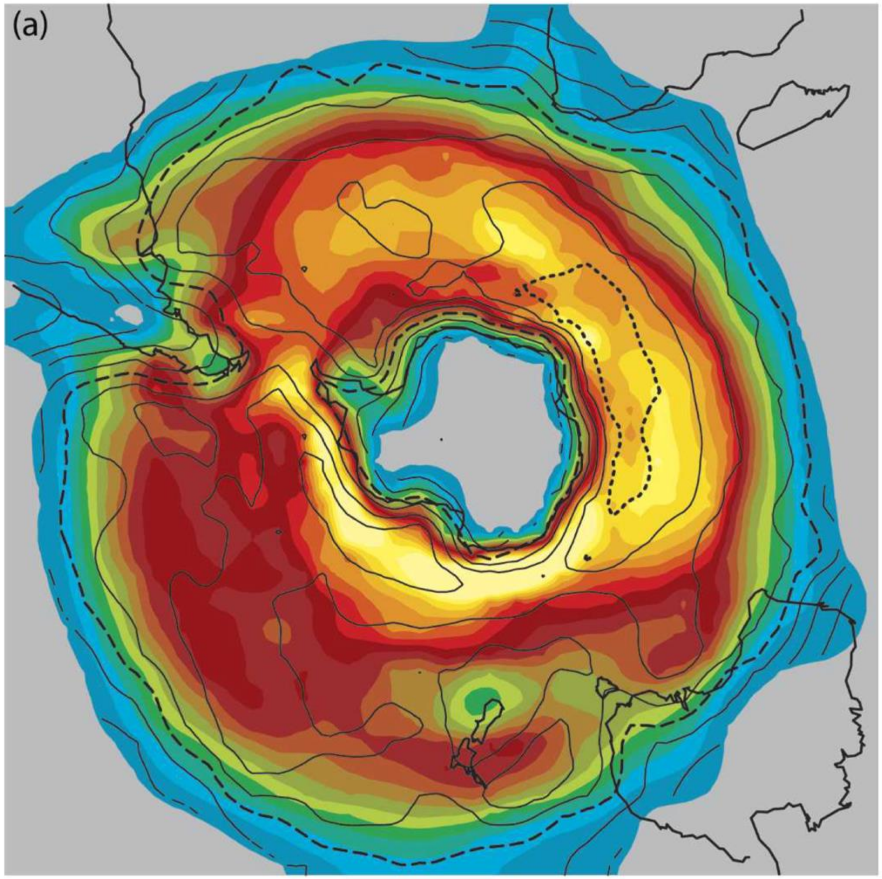
Cyclone tracks: NH DJF



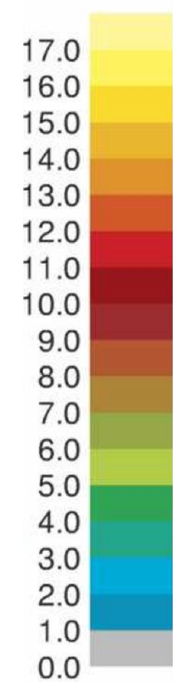
ERA40
based on 850hPa relative vorticity
from Bengtsson et al 2006

Intensity (contours; 10^{-5} s^{-1}) - - - - - - 4×10^{-5} .... 6×10^{-5}

Cyclone tracks: SH DJF



Track density (per month per 10^6 km^2)



ERA40
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Intensity (contours; 10^{-5} s^{-1}) - - - - - - 4×10^{-5} .... 6×10^{-5}

Midlatitude eddies grow through baroclinic instability

Requires: rotation + stratification + horizontal temperature gradient

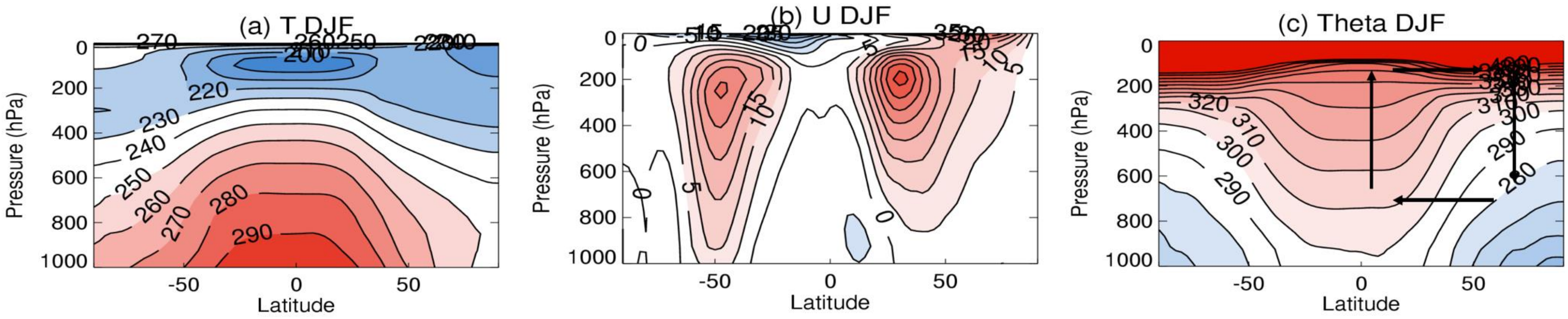


Figure 1: (a) Climatology of zonal mean temperature in DJF on pressure levels from ERA-40. (b) as (a) but zonal mean zonal wind. (c) as (a) but potential temperature. The arrows illustrate, schematically, the overturning circulation that would be set up in the absence of rotation. This would act to flatten the potential temperature contours and reduce the baroclinicity in mid-latitudes. ***Figure from: https://staff.cgd.ucar.edu/islas/teaching/8_baroclinic.pdf***

- *The differential heating creates a geopotential height gradient, but rotation prevents the flow from from flowing directly poleward (i.e., conversion from potential → kinetic energy)*
- *As a result, the geostrophically balanced state still has potential energy associated with it, i.e., thermal wind enables potential energy to be 'locked in' (stored) in the mean state*
- *Without rotation, an equator-to-pole overturning circulation would be set up that would act to flatten the potential temperature contours*

Midlatitude eddies grow through baroclinic instability

Requires: rotation + stratification + horizontal temperature gradient

Figure from: https://staff.cgd.ucar.edu/islas/teaching/8_baroclinic.pdf

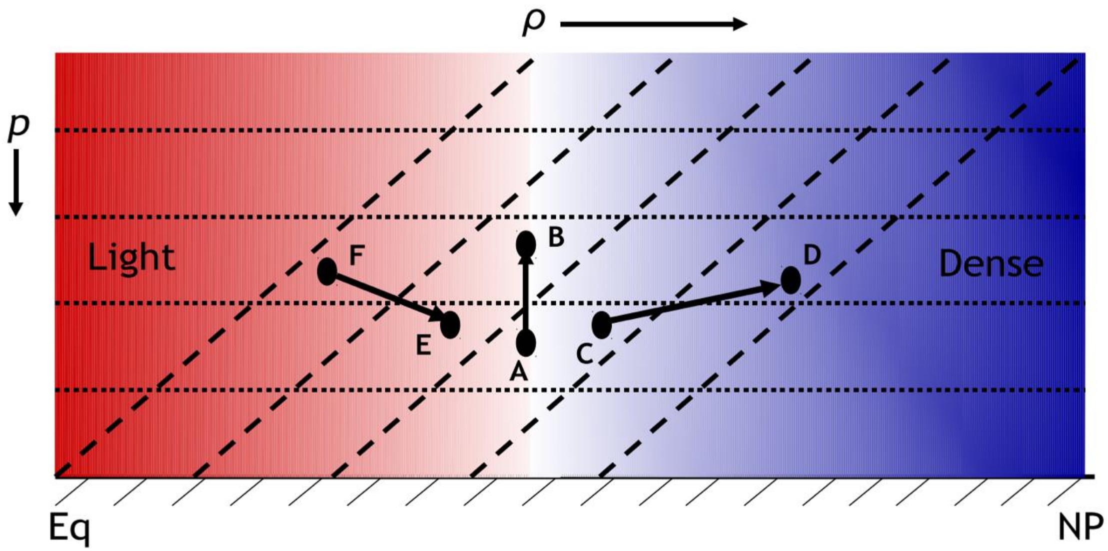


Figure 2: Schematic illustration of sloping convection. Surfaces of constant pressure are illutrated by the dotted lines and surfaces of constant density by the dashed lines.

Path AB: stable (restoring force), path CD: unstable and center of mass is lowered, path FE: unstable but center of mass is increased (requires an energy input)

Midlatitude eddies grow through baroclinic instability

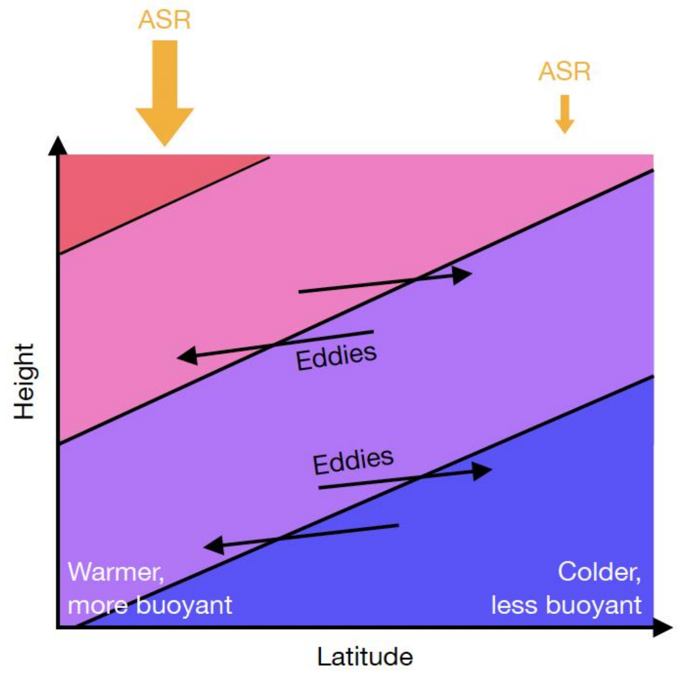
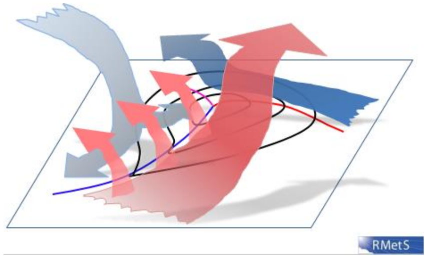


Figure 6: Eddies convert potential energy to kinetic energy by moving cold air downward and warm air upward, and transport heat poleward by moving warm air poleward and cold air equatorward.

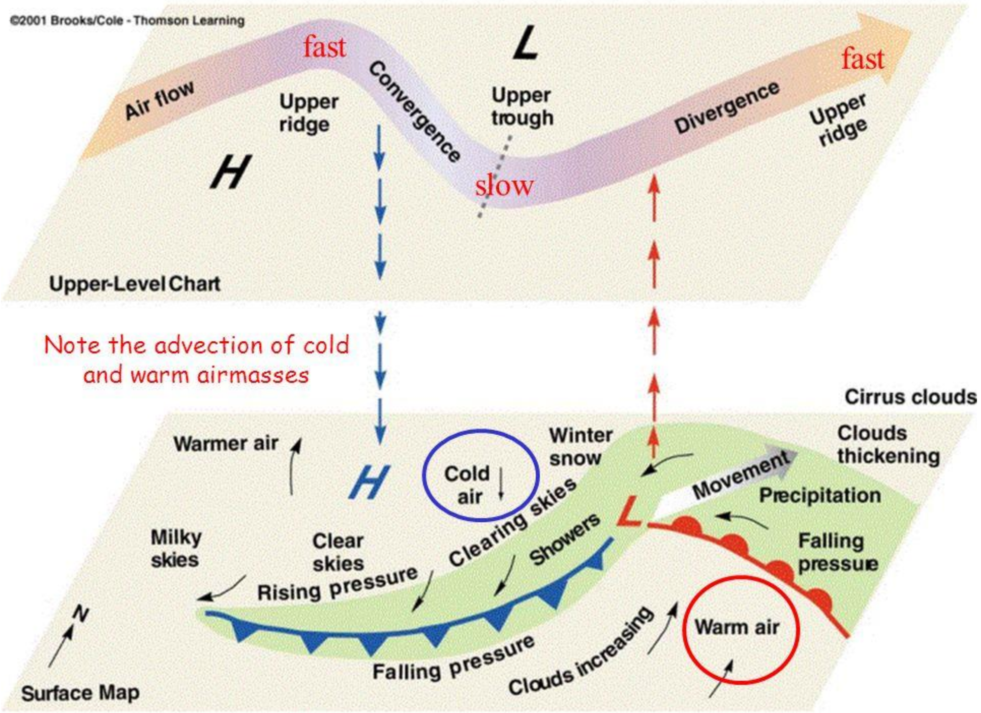


https://www.futurelearn.com/info/courses/come-rain-or-shine/0/steps/15205

Eddies convert potential energy to kinetic energy by moving cold air downward & warm air upward, and transport heat poleward by moving warm air poleward and cold air equatorward

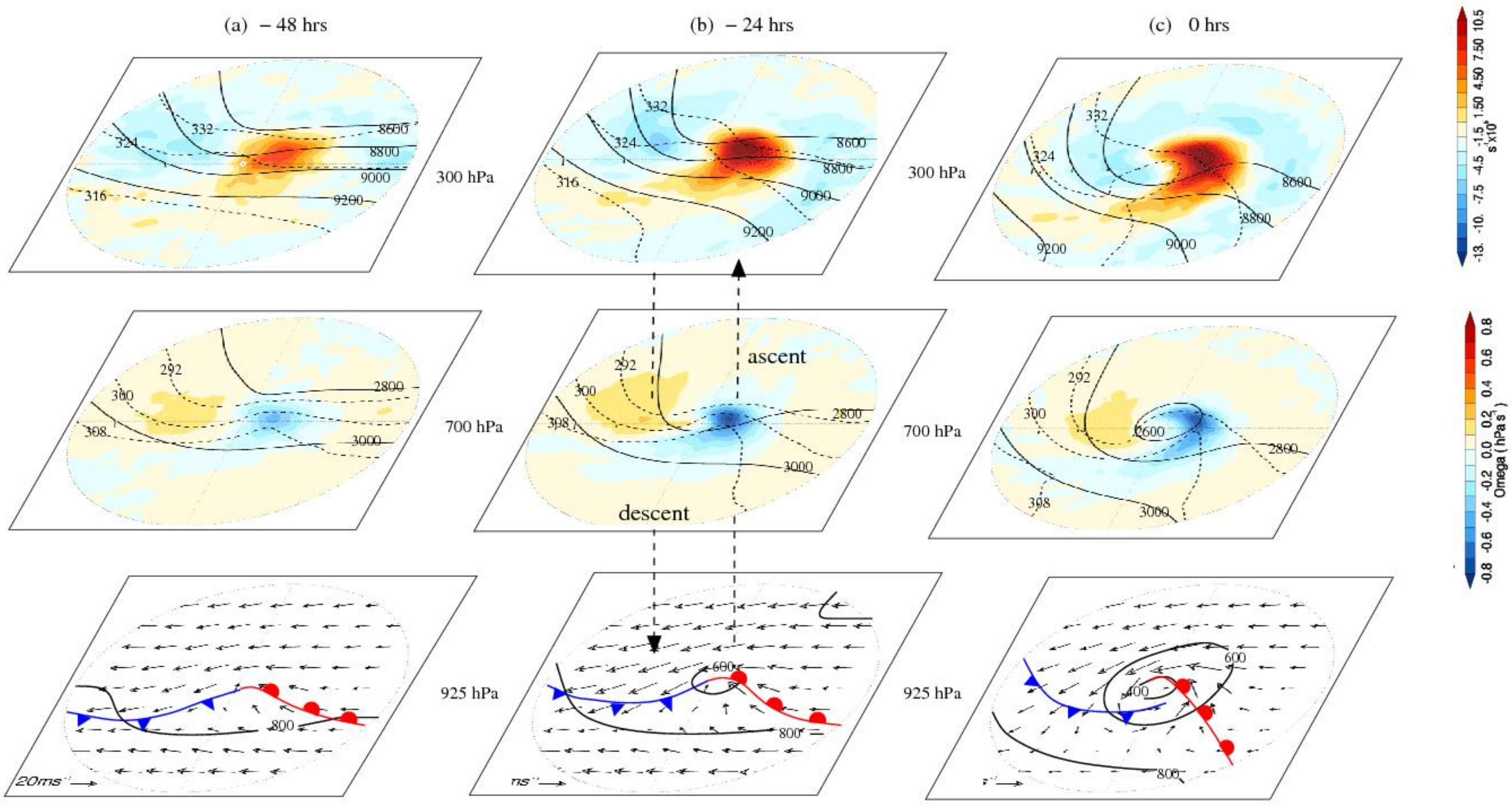
How do midlatitude eddies grow?

Baroclinic instability can be understood as interaction between upper and lower-level disturbances



The upper-level wave and low-level weather systems can interact positively such that the disturbances can grow

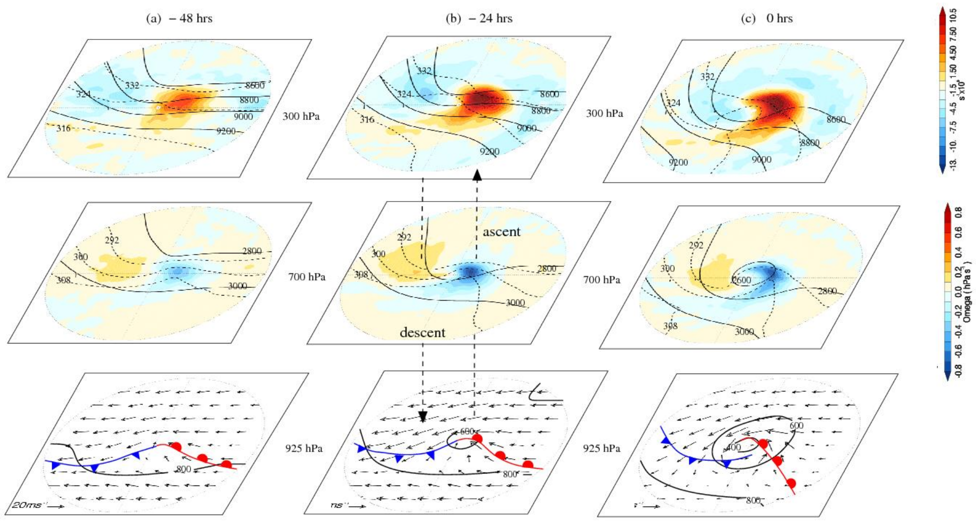
How do midlatitude eddies grow?



Horizontal composites at (a) 48 and (b) 24 hours before the time of maximum intensity, (c) at the time of maximum intensity. Bottom row: 925 hPa geopotential height (solid, at 400, 600 and 800m); system relative wind vectors and frontal positions. Middle row: 700 hPa geopotential height (solid, at 2800 and 3000 m); θe (dashed, at 292, 300 and 308 K) and vertical velocity (filled). Top row: 300 hPa geopotential height (solid, at 8600, 8800, 9000 and 9200 m); θe (dashed, at 316, 324 and 332 K) and divergence (filled).

From: https://www.met.reading.ac.uk/~storms/concep/baro_inst/

How do midlatitude eddies grow?



- *In the initial stage, a weak low-level temperature wave is seen to form downstream of an upper-level trough*
- *As the surface cyclone develops, differential temperature advection to the west and east of the surface cyclone amplifies the upper-level wave*
- *The amplified upper-level wave forces ascent, which intensifies the surface cyclone. Increased low-level wind speeds lead to an amplification of the low-level temperature wave and hence stronger low-level temperature advection which in turn amplifies the upper-level wave*

Therefore, a positive feedback between the processes occurring at upper and lower-levels occurs

How do midlatitude eddies transfer heat poleward?

Let's look again at the mean V structure:

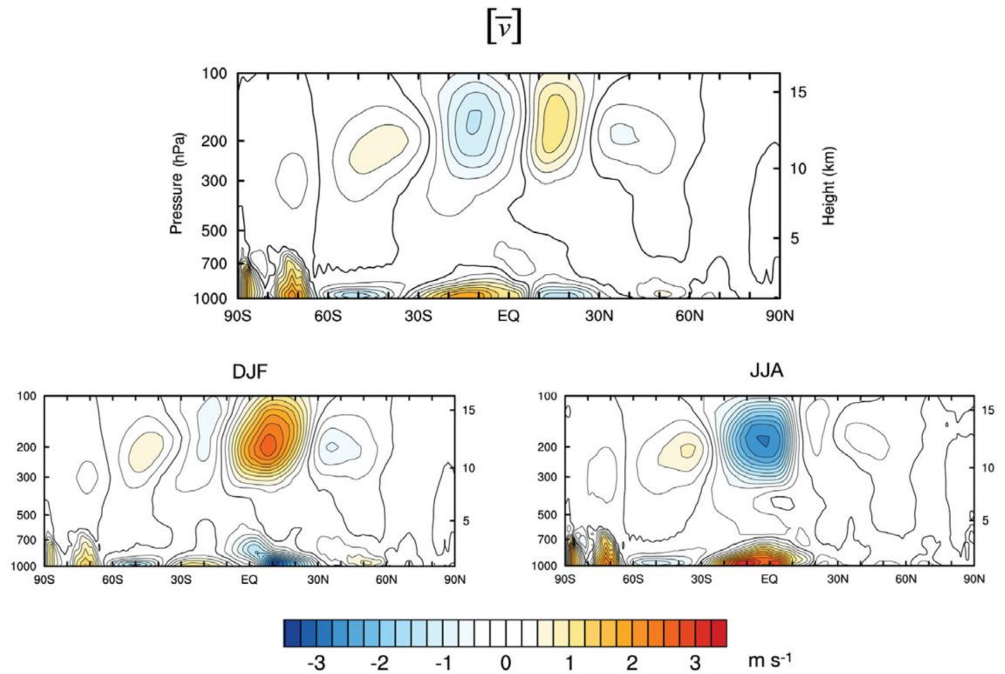
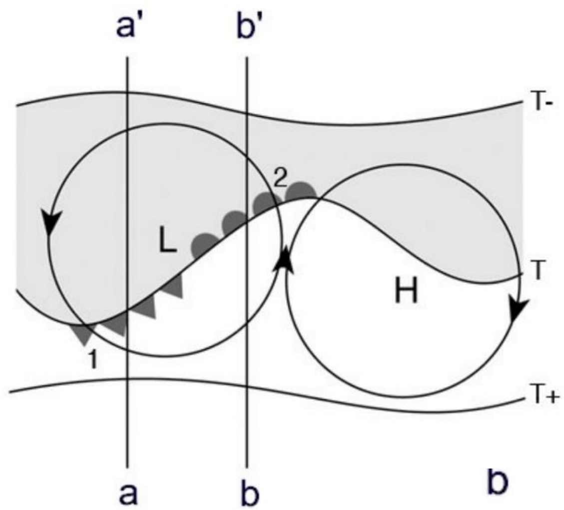


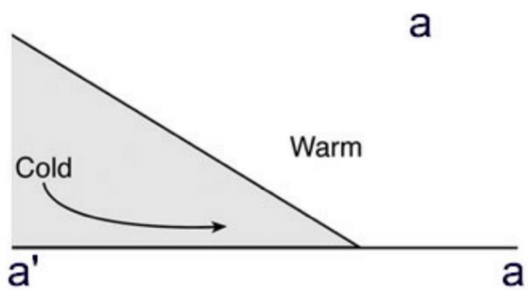
Figure 1.25 Climatological mean zonally averaged meridional velocity $[\bar{v}]$. Contour interval 0.25 m s^{-1}. The zero contour is thickened. Warm colored shading indicates northward and blue shading indicates southward flow. Note that the domain of this and the next three figures extends upward only to 100 hPa.

- V is mainly large in the tropics (in the two 'layers') but generally very small in the midlatitudes (weak 'Ferrel Cell')
- So how can heat be transported poleward??
- In the midlatitudes, $\overline{VT}$ is small since $\bar{V}$, but in fact $\overline{V'T'}$ is not!

How do midlatitude eddies transfer heat poleward?



Cold front



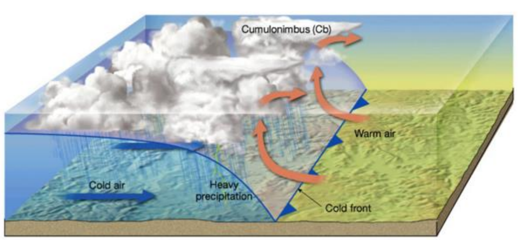
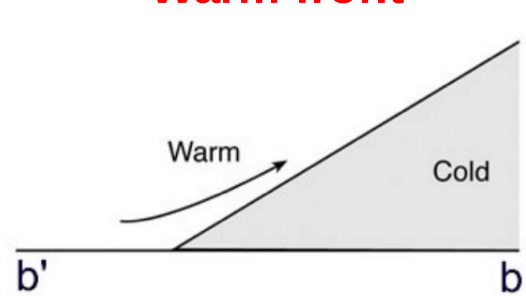


Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

Warm front



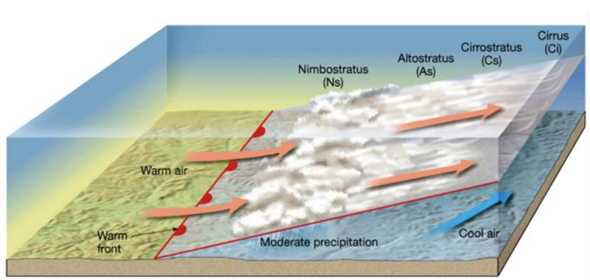
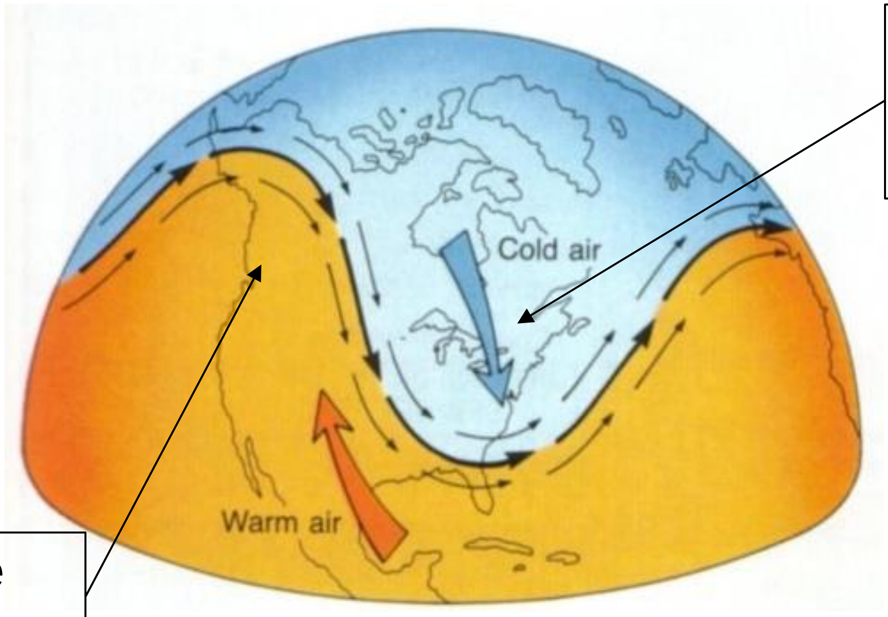


Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

How do midlatitude eddies transfer heat poleward?

$v' < 0$ negative
$T' < 0$ negative
$v'T' > 0$ positive



$v' > 0$ positive
$T' > 0$ positive
$v'T' > 0$ positive

- Warm air is transported poleward, cold air is transported equatorward
- Hence, is both cases, the heat flux is positive (poleward), and acting to reduce the background temperature gradient

Eddy heat transfer in the atmosphere

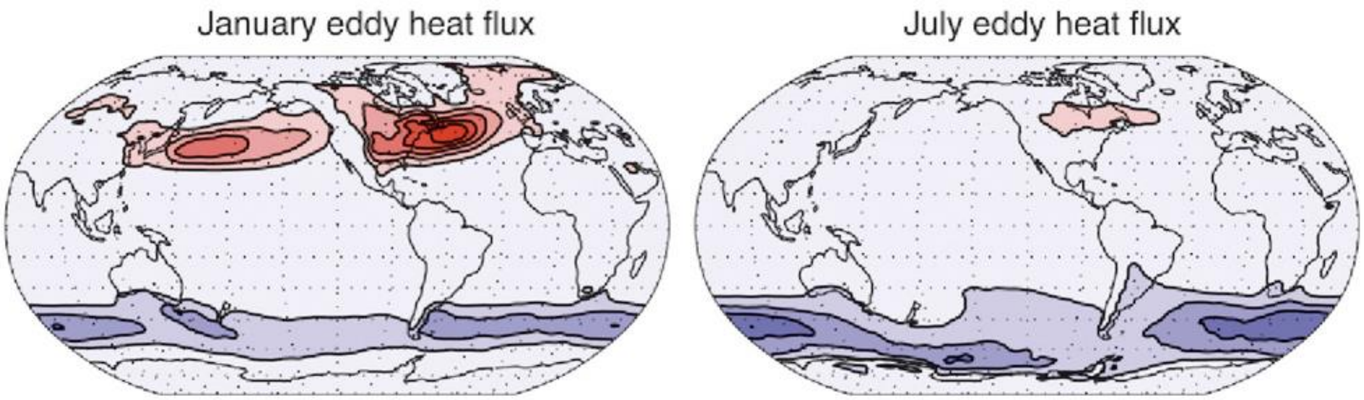
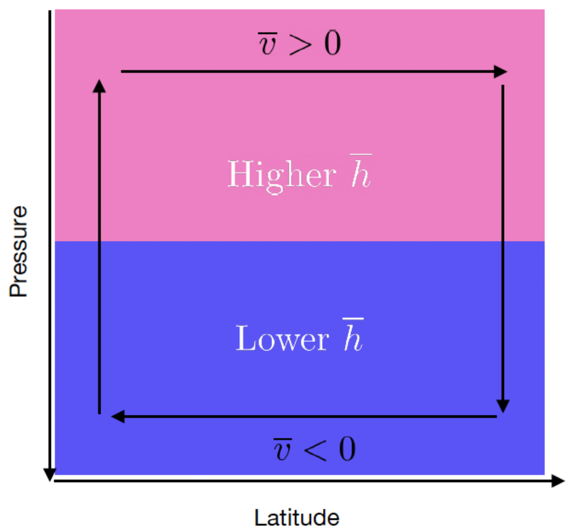


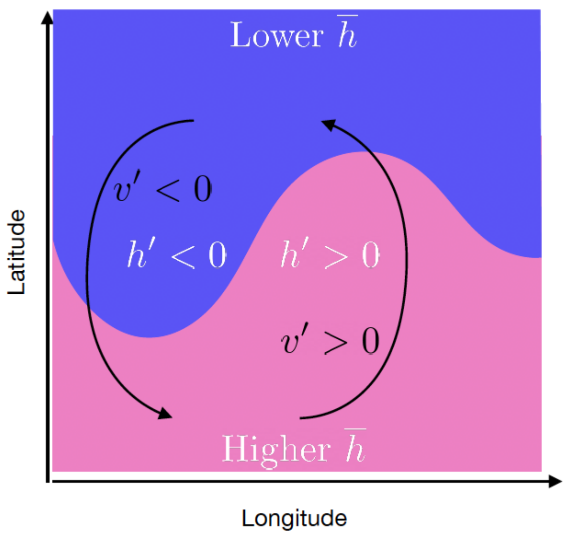
FIGURE 6.18 Average wind speed (top) and northward heat flux by eddies with periods shorter than about 1 week. Contour interval on the top is 10 ms^{-1} and contour on the bottom is 5 $Km\ s^{-1}$, zero contours are not shown and blue shading indicates southward transport. Robinson projection is used. *Data from ERA Interim.*

Heat transport is poleward, maximized in the midlatitudes

Summary: mechanisms for poleward heat transport



Hadley overturning circulations



Midlatitude eddies

$$h = c_p T + gz + L_v q,$$

$$\overline{vh} = \overline{v}\,\overline{h} + \overline{v'h'}$$

Energy transport in the atmosphere

Exercise

$$H = \rho \iint vh dA = \rho \iint vh\, dz dx$$

$$= \mathrm{a} \cos\varphi \int_0^{2\pi} \int_0^{\infty} vh\, dz d\lambda$$

$$= \frac{a}{g} \cos\varphi \int_0^{2\pi} \int_0^{p_s} vh\, dp d\lambda$$

$$= \frac{2\pi a}{g} \cos\varphi \int_0^{p_s} [vh]\, dp$$

$$\boxed{H = \frac{2\pi a}{g} \cos\varphi \int_0^{p_s} \left(c_p[v\theta] + L_v[vq] \right) dp}$$

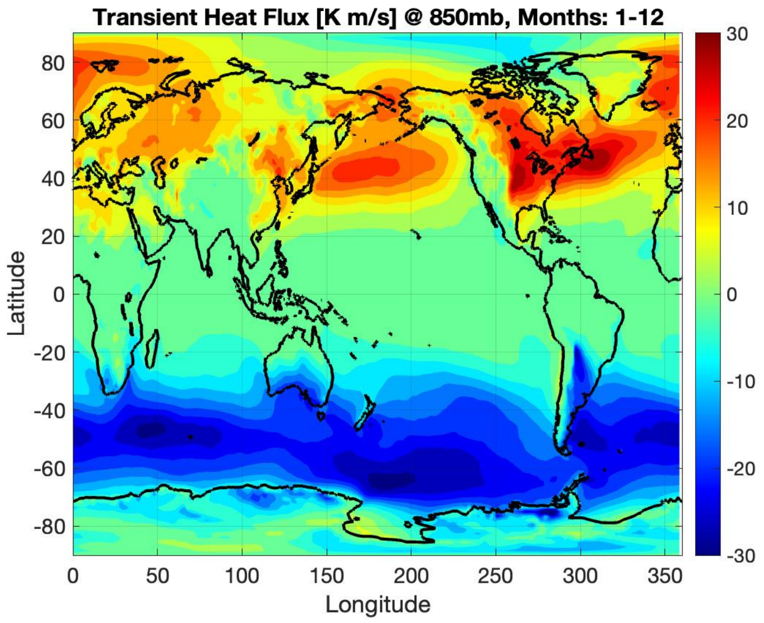
Transient energy transport in the atmosphere- *Exercise*

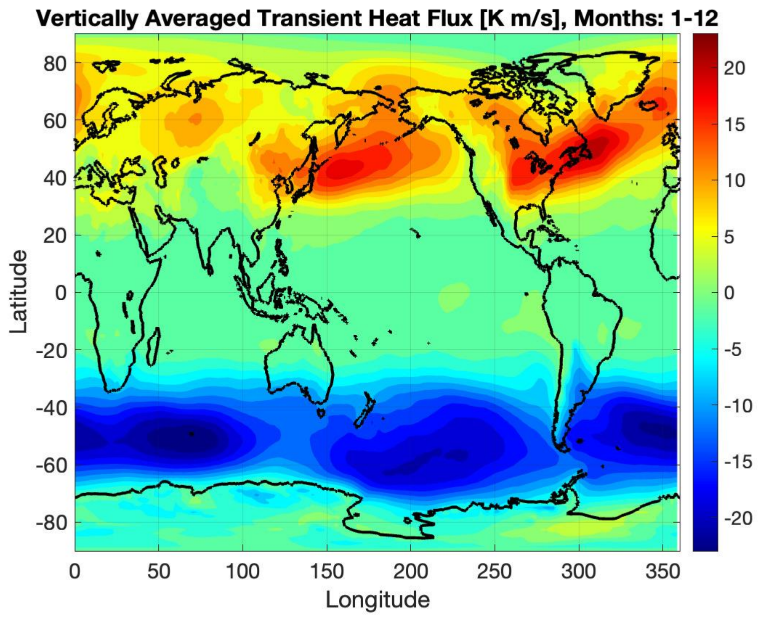
$$H = \frac{2\pi a}{g} \cos\varphi \int_0^{p_s} \left(c_p [\overline{v'\theta'}] + L_v [\overline{v'q'}] \right) dp$$

- Go to Project 3 Observation Data page: [*http://weatherclimatelab.mit.edu/projects/heat-and-moisture-transport/observation-data*](http://weatherclimatelab.mit.edu/projects/heat-and-moisture-transport/observation-data)
- Press the link "[Instructions for plotting transient heat fluxes]()"
- Download the data file, and the Matlab/Python scripts
- Follow the instructions inside the scripts

- The data supplied: annual mean $\overline{v'\theta'}$ and $\overline{v'q'}$ from the ERA5 Reanalysis data over the years 2010-2020

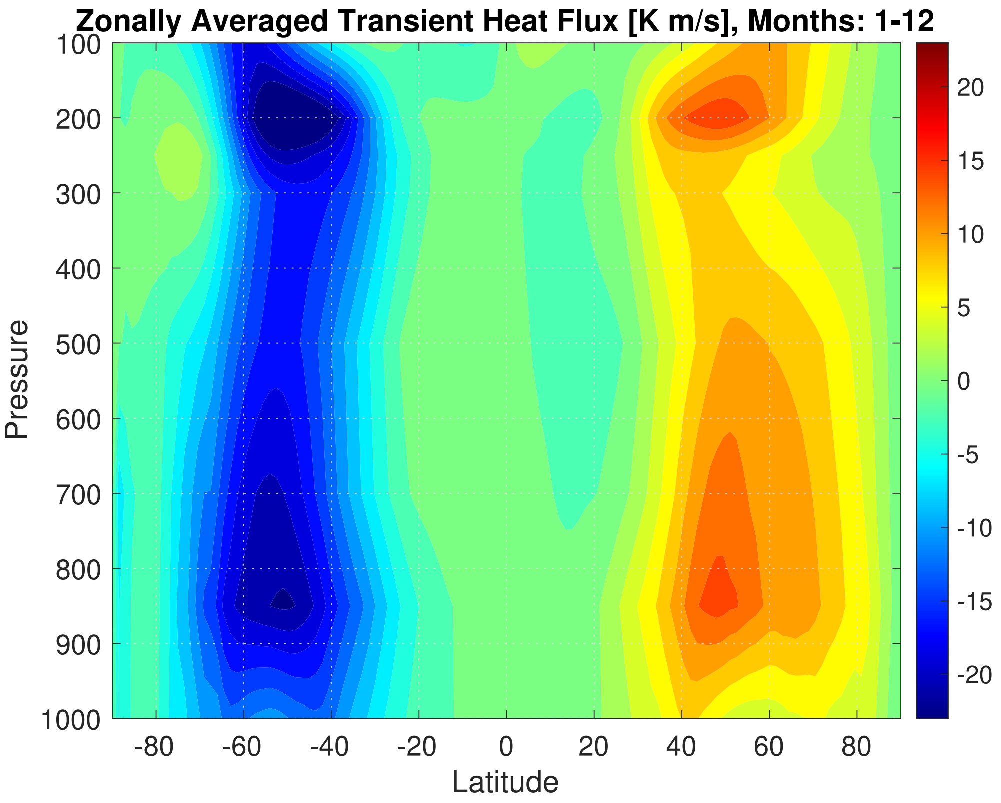
- The script should produce the transient heat flux [K m/s] at a chosen level (e.g., 850 mb below) and vertically averaged





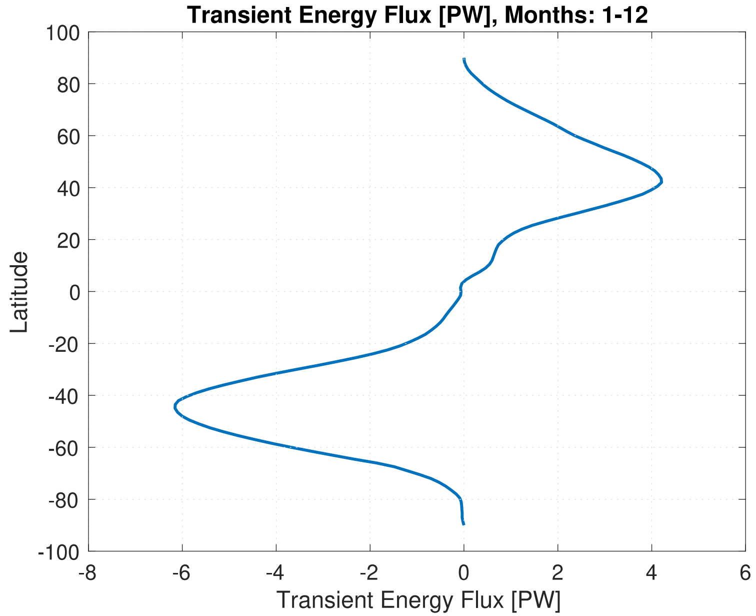
What you need to do:

- Calculate and plot the zonal mean transient heat flux



What you need to do:

- Calculate and plot the total transient poleward energy flux



$$H = \frac{2\pi a}{g} \cos\varphi \int_0^{p_s} \left(c_p\left[\overline{v'\theta'}\right] + L_v\left[\overline{v'q'}\right]\right) dp$$

Optional:

- What is the year-to-year variability?
- Can you identify interesting trends in the observed poleward heat transport?
- Are the trend in latent and thermal energy fluxes similar?

Next: Laboratory abstraction of Earth's general circulation

1. Pole – Equator Temperature Difference
2. Earth rotation