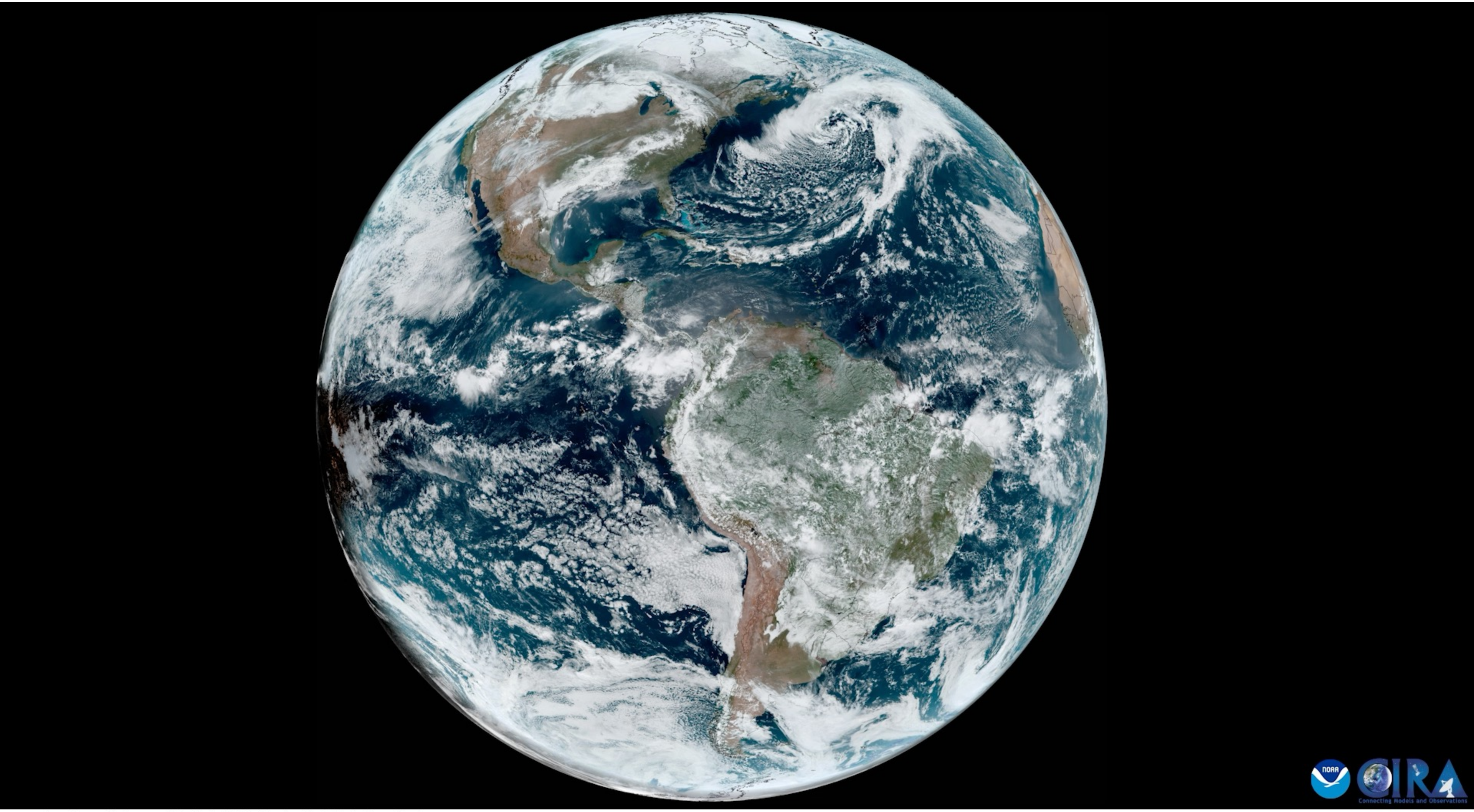
P3: Heat and Moisture Transport
The general circulation

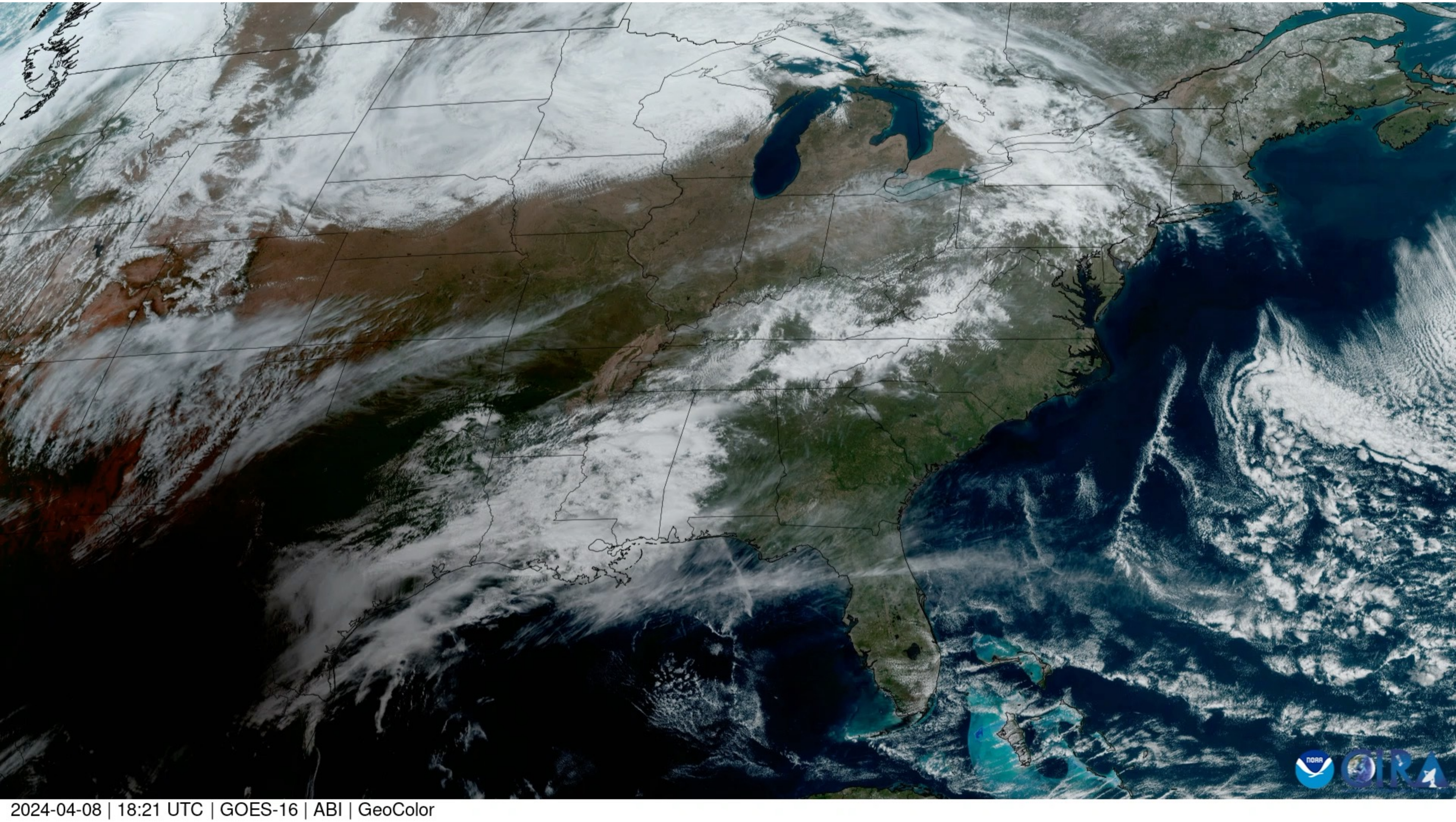
But first…the eclipse! April 8th 2024



2024-04-08 | 16:30 UTC | GOES-16 | ABI | GeoColor

A Complete, Incredible View of The Great North American Eclipse

But first…the eclipse! April 8th 2024



Cloud supression during the eclipse!

12.307- project 3 (data class 1)

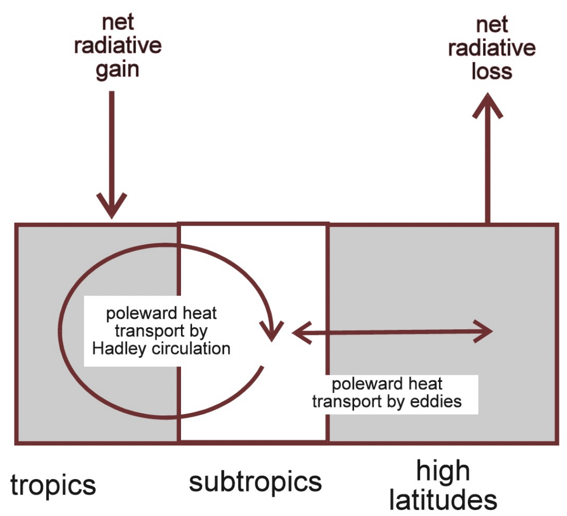
Hadley circulation in the atmosphere:

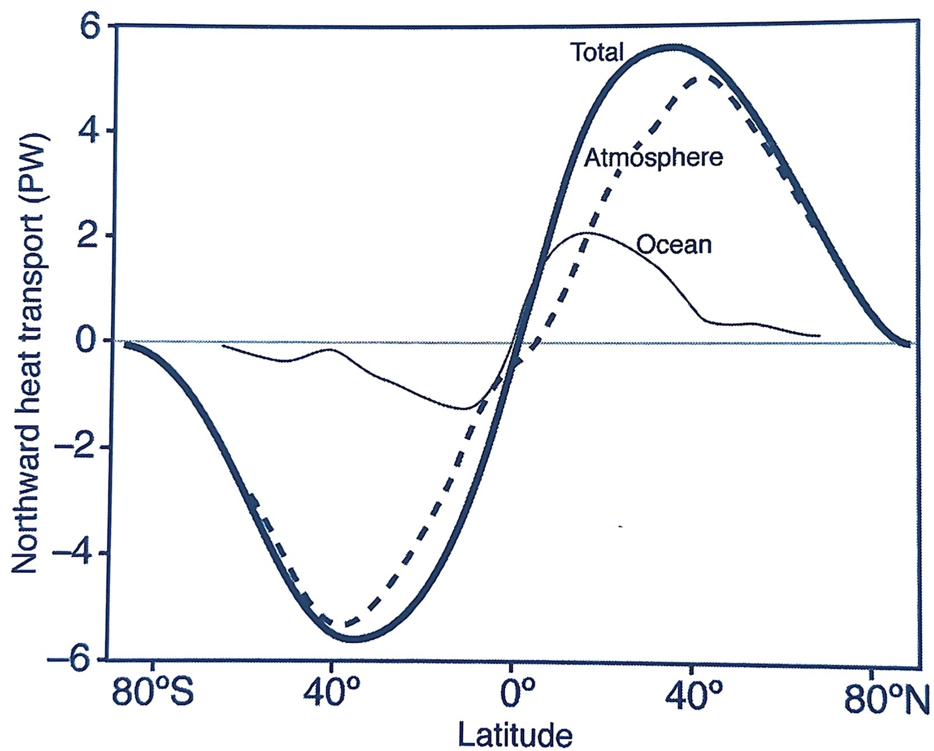
- Connection to Hadley tank experiment
- Atmospheric climatology using EsGlobe
- Identify the Hadley circulation
- Break
- N-S heat transport in the tropics
- Two layer model as in the tank experiment
- Moisture transport in the tropics

•Second class -

- Heat and moisture transport in the tropics - review calculations
- Eddy regime in the extra-tropics

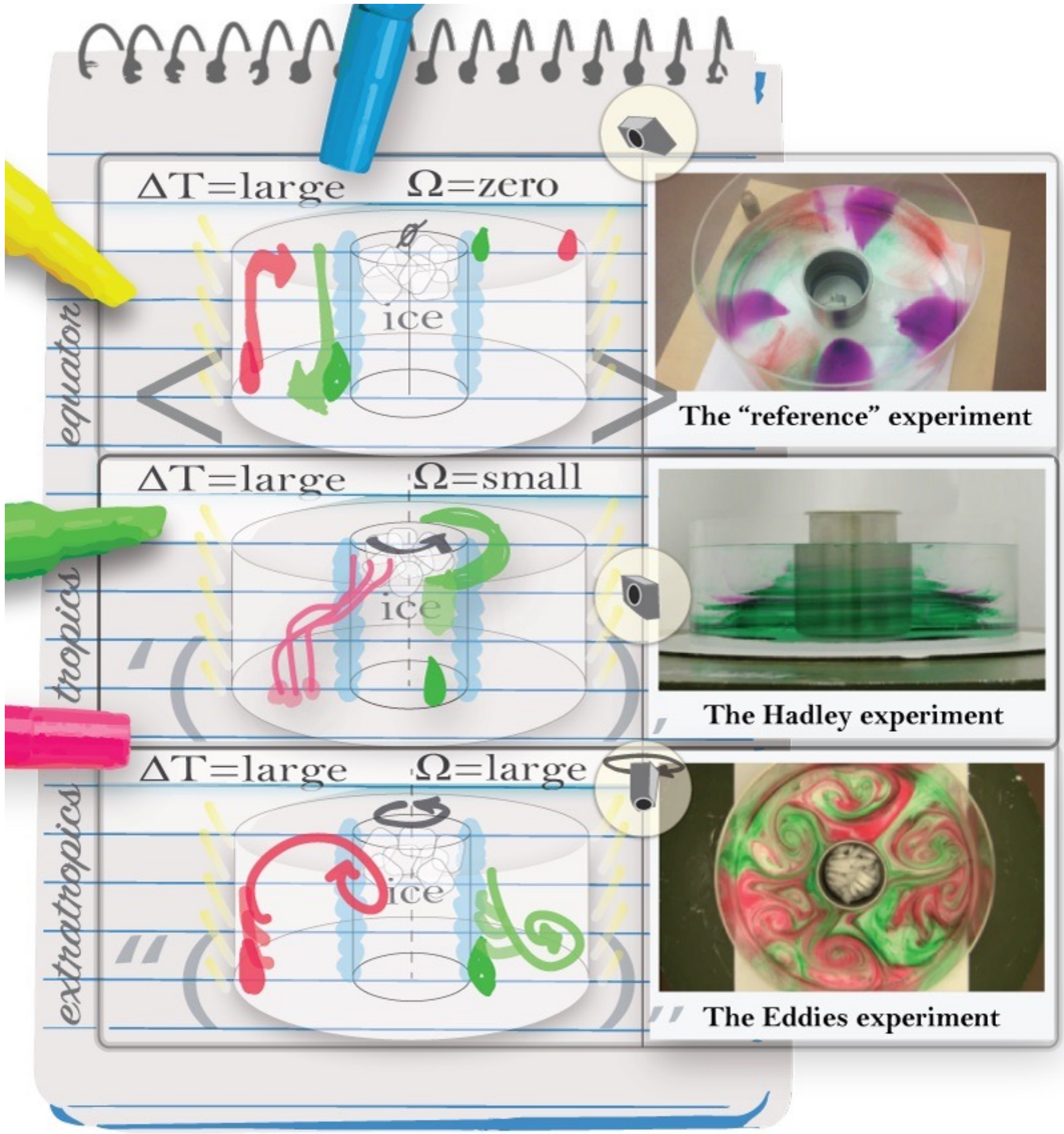
Meridional heat transport





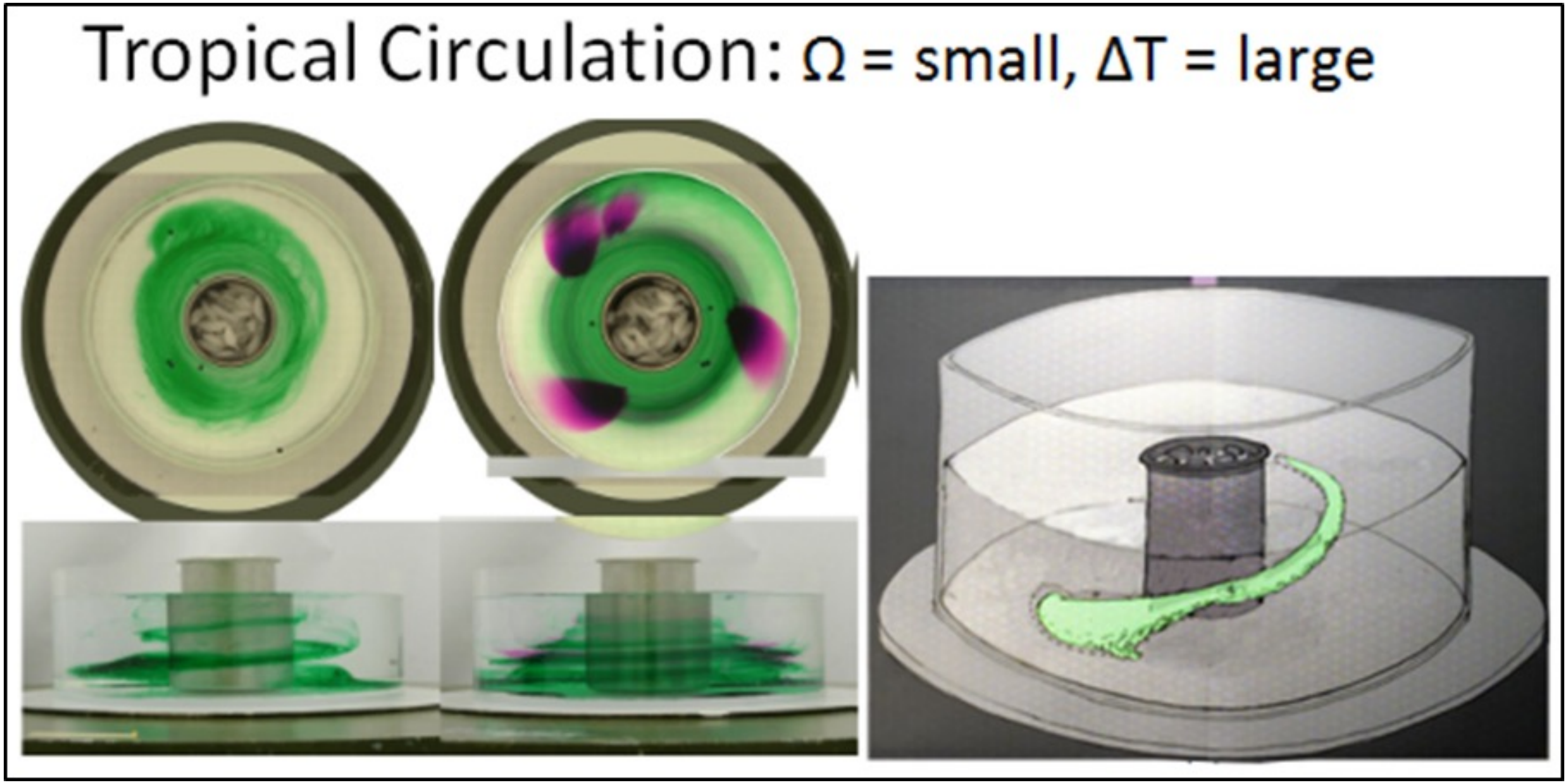
- In the tropics, heat transport is mainly by the Hadley cell
- In the extratropics, heat transport is by the “eddies”
- The atmosphere transfer most of the heat, the ocean also contributes in the tropics

Reminder- the three experiments that we saw in the lab:



[Illari, L., Marshall, J., and W. D. McKenna (2017): Virtually Enhanced Fluid Laboratories for Teaching Meteorology]

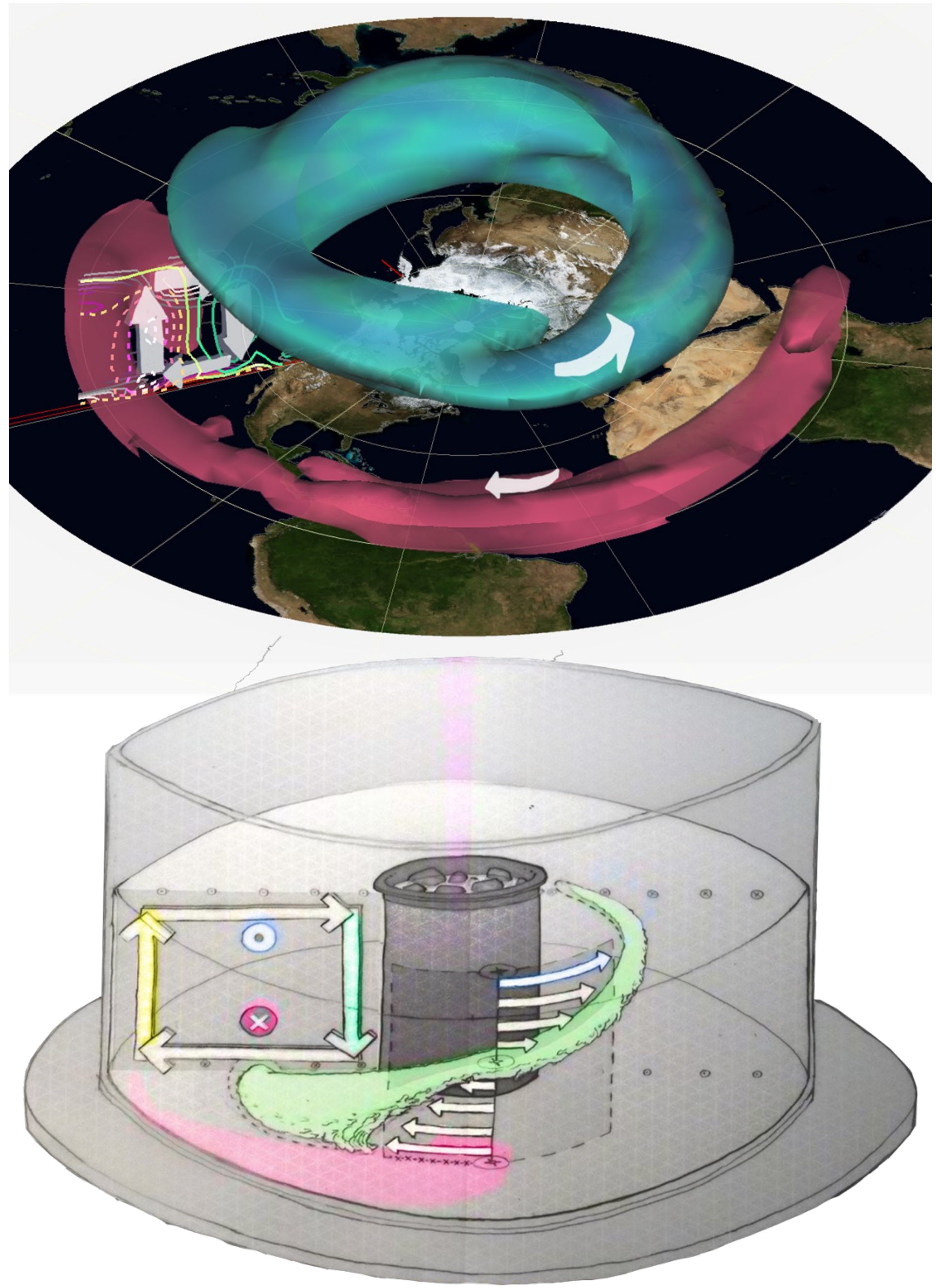
Hadley Cell Experiment



http://lab.rotating.co

We calculated the budget: amount of heat due to melting = the heat transport from the circulation

Connection to the atmospheric circulation



Can we see evidence for this circulation in the atmosphere?

Hadley Cell exercise

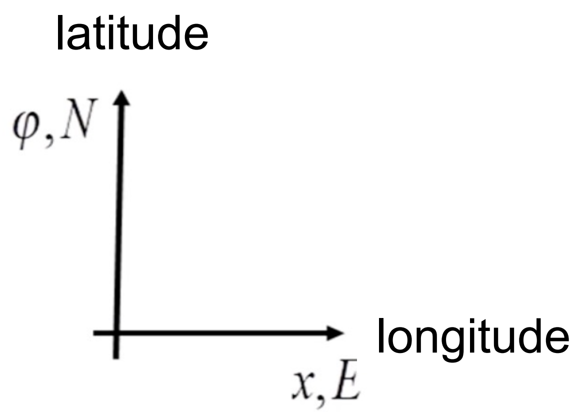
How can we find the Hadley Cell on earth?

Explore the General Circulation of the Atmosphere using climatological data on the EsGlobe
http://eddies.mit.edu/307/

Plot zonally averaged (January and July):

- Temperature (T) and potential temperature (theta)
- Vertical velocity (omega) $\omega = Dp/Dt$
- Meridional velocity (v)
- Zonal velocity (u)

Time mean and zonal mean fields- reminder:



$$T(x,\varphi,p,t)$$

$$\overline{T}(x,\varphi,p) = \int_{t_1}^{t_2} T(x,\varphi,p,t)\, dt$$

Time mean

$$[\overline{T}(\varphi,p)] = \int_{0}^{360} \overline{T}(x,\varphi,p)\, dx$$

Zonal mean
and time mean

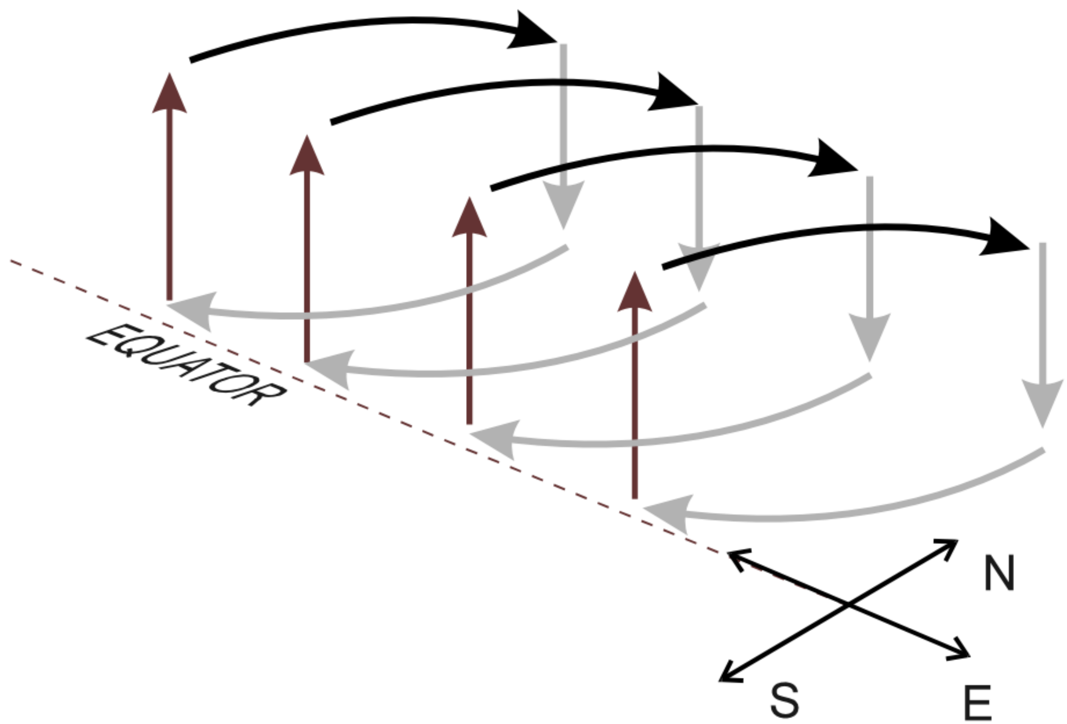


Figure 8: Schematic of the Hadley circulation (showing only the N Hem part of the circulation; there is a mirror image circulation south of the equator).

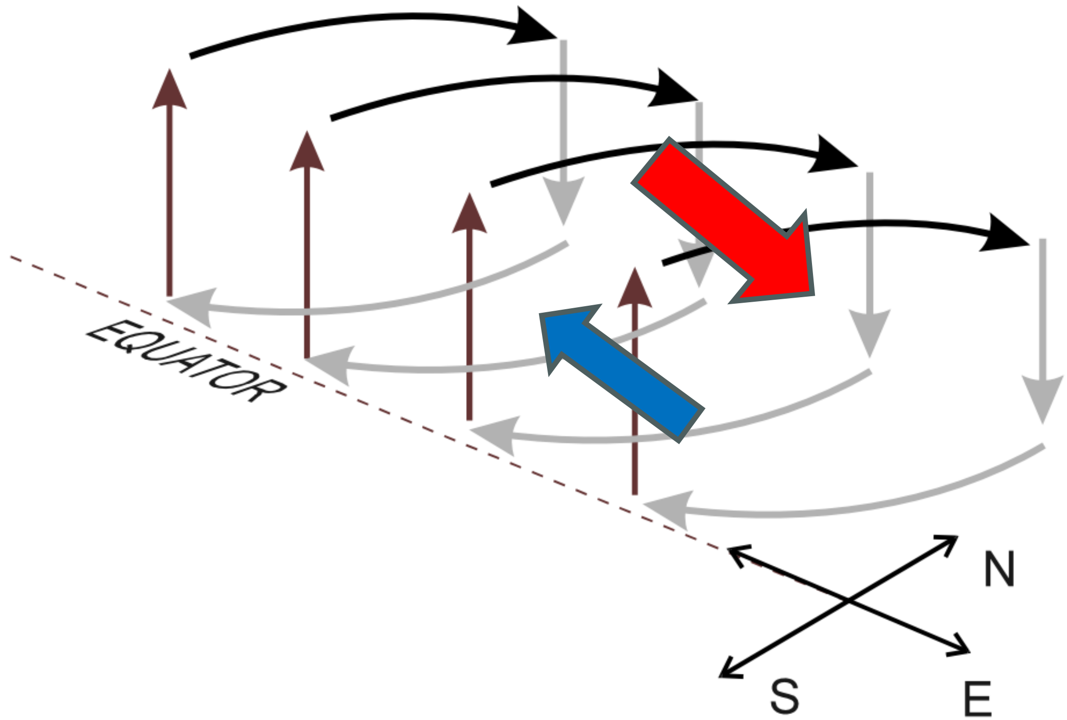
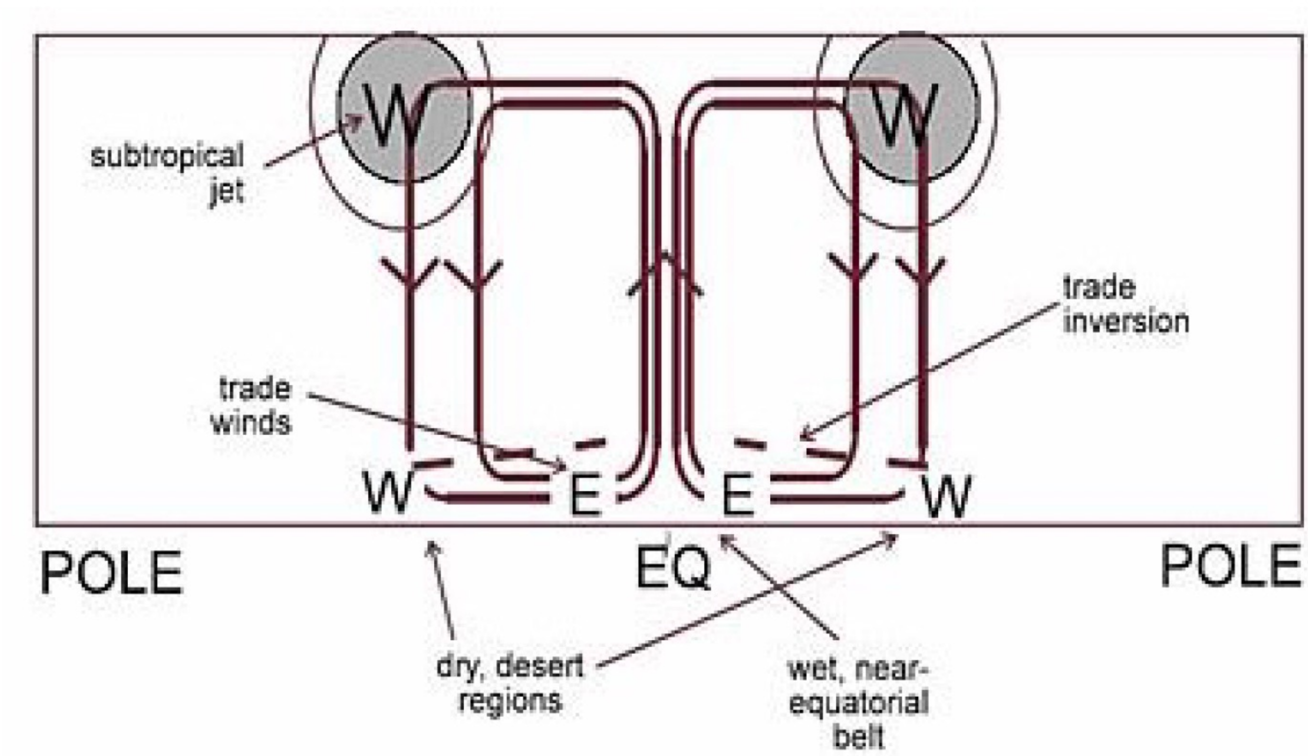


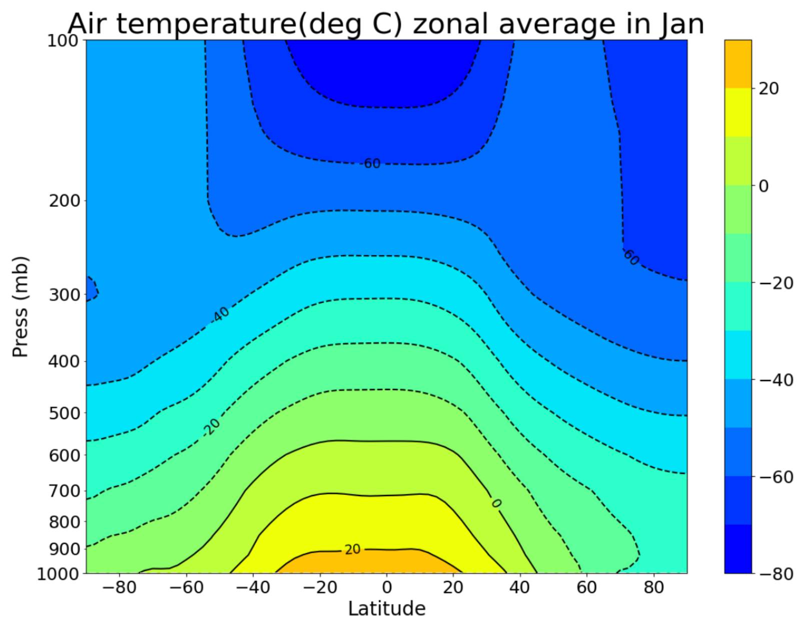
Figure 8: Schematic of the Hadley circulation (showing only the N Hem part of the circulation; there is a mirror image circulation south of the equator).

Can we identify a similar structure in the climatology?

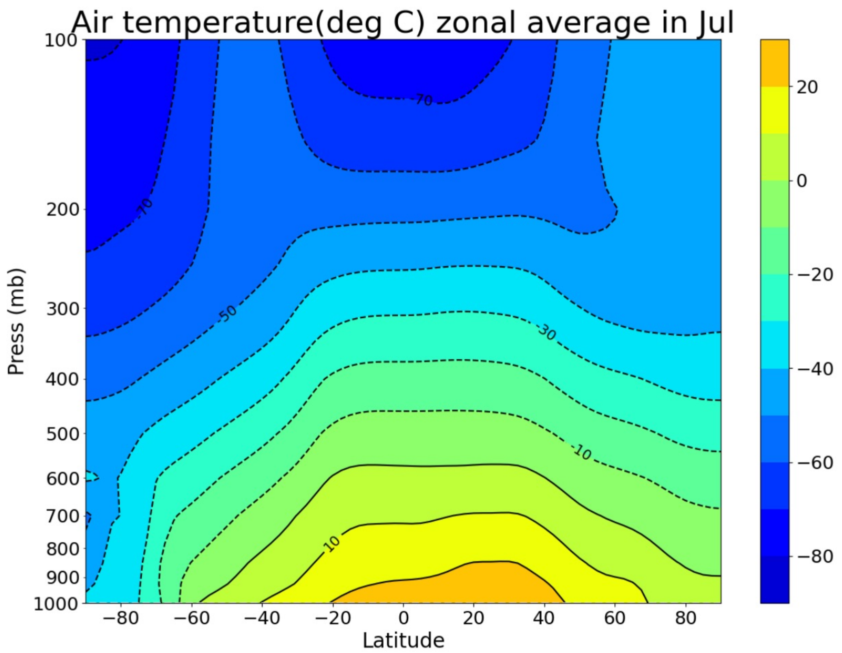


Zonal mean temperature

January



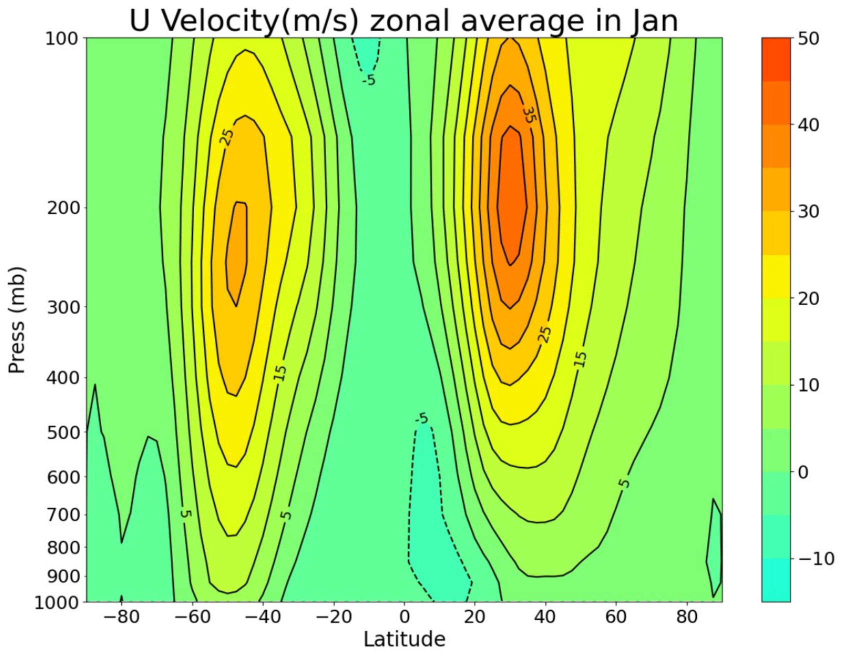
July



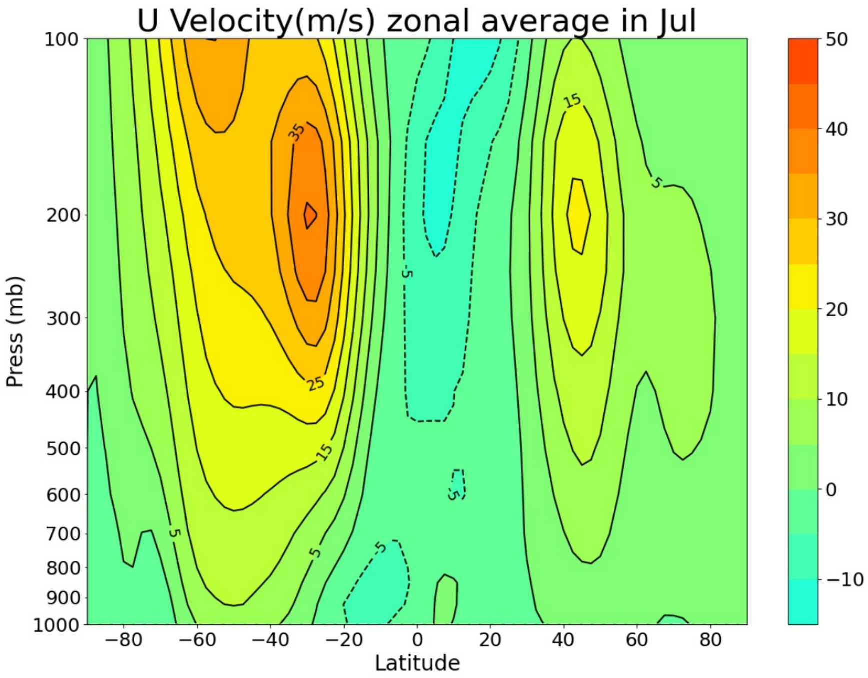
- Temperature more uniform in the tropics, decreases poleward and with height
- Where is the maximum surface temperature in each season?

Zonal mean zonal wind

January



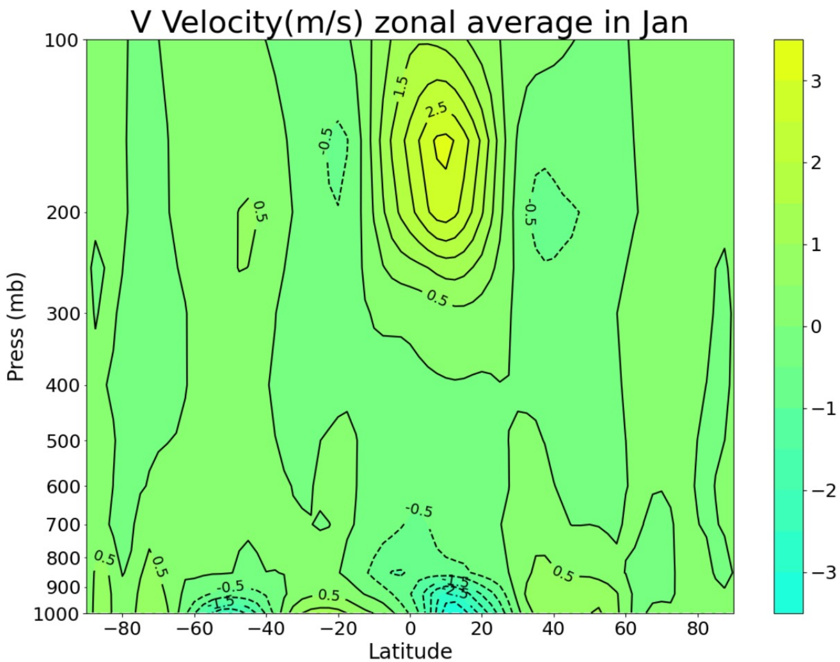
July



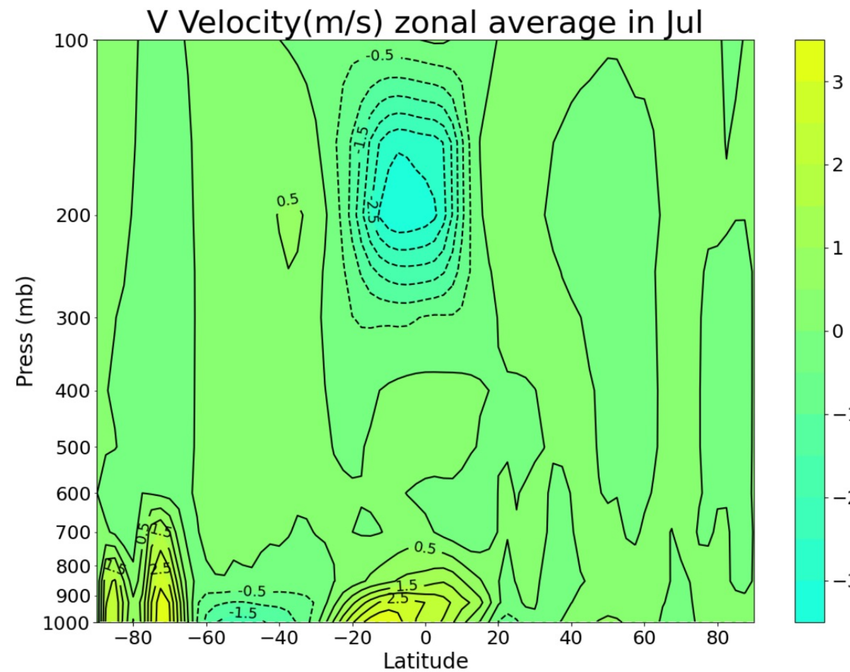
- One main jet stream in each hemisphere
- Can you identify the easterlies/westerlies? Where are they in each season?

Zonal mean meridional wind

January



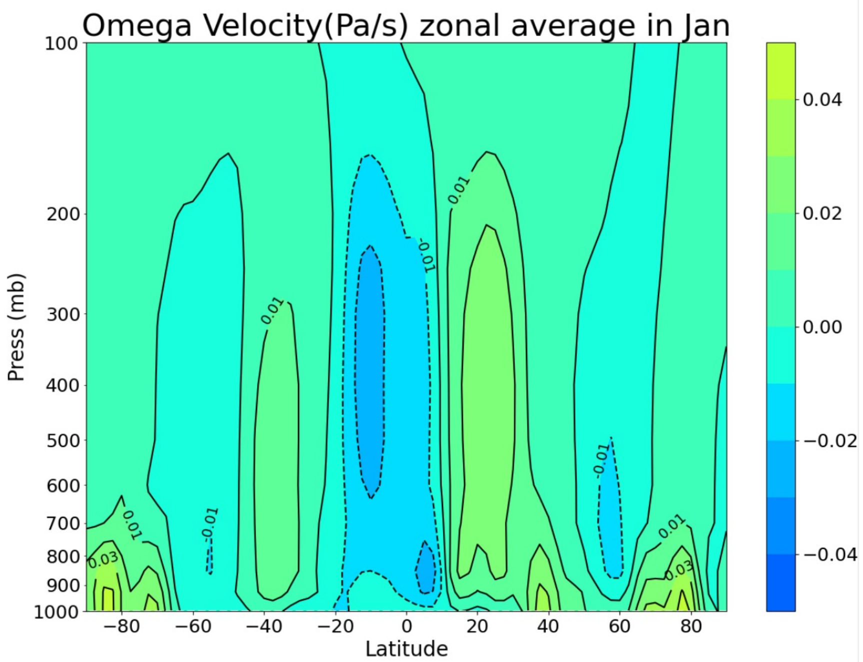
July



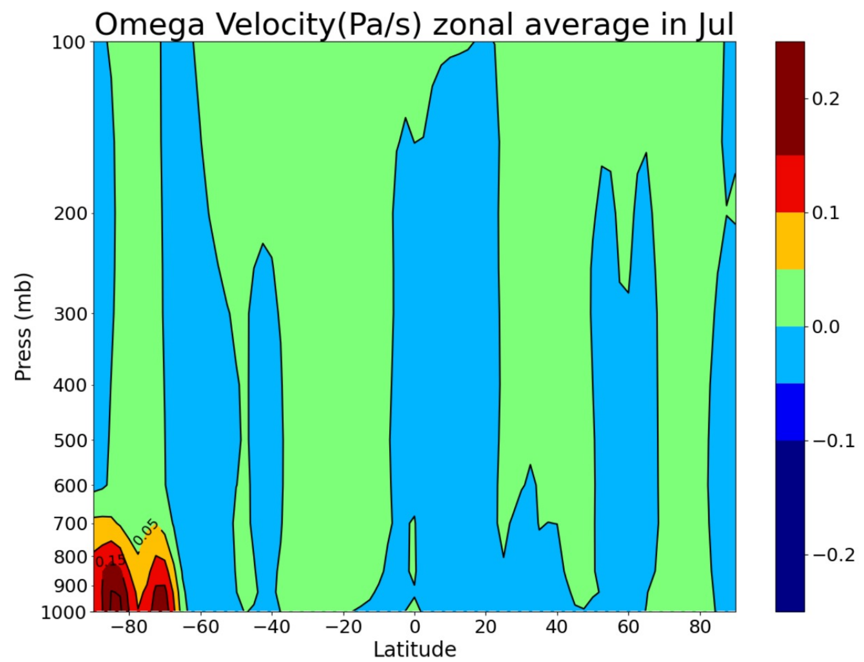
Mean V is only strong in the tropics (Hadley Cell), and mostly confined to either upper level or to the surface- *Two layers!*

Zonal mean vertical wind

January



July



Note: $w = \frac{Dz}{Dt}\left[\frac{m}{sec}\right]$ and $\omega = \frac{DP}{Dt}\left[\frac{Pa}{sec}\right]$ → $\omega = -\rho g w$

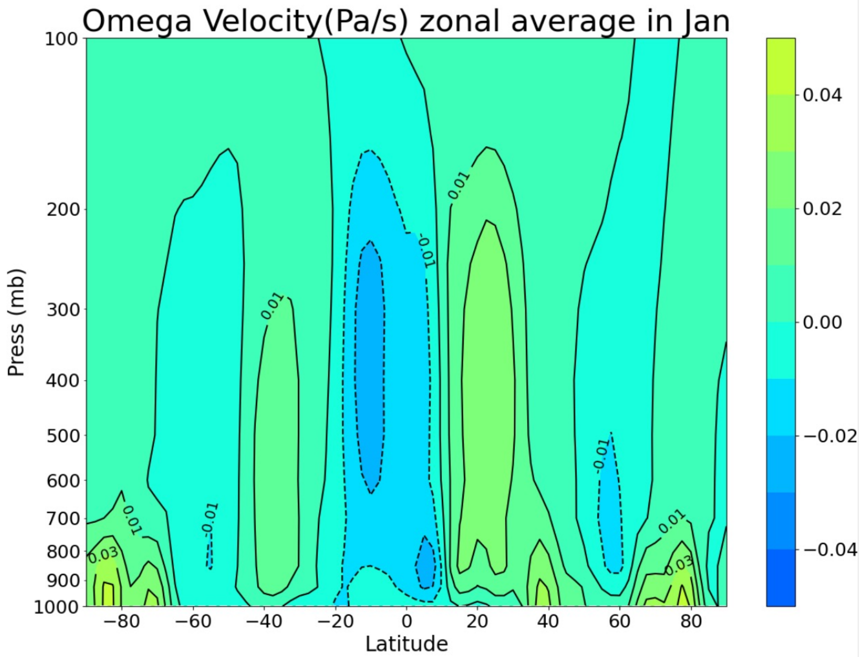
- Where is the air ascending/descending in each season?
- Where do you expect to find deserts?

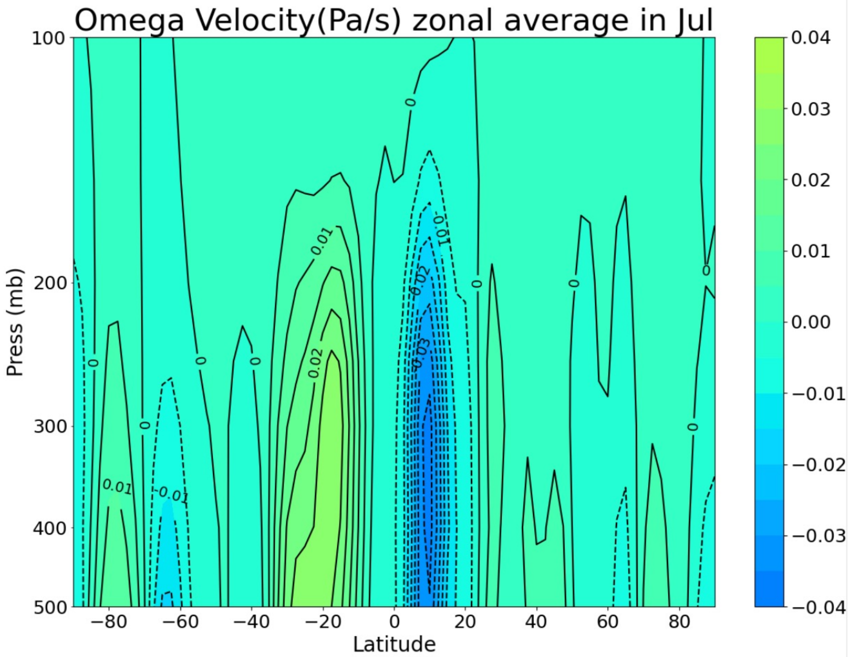
Zonal mean vertical wind

January

July

Zoom in 500-100 mb





Note: $w = \frac{Dz}{Dt}\left[\frac{m}{sec}\right]$ and $\omega = \frac{DP}{Dt}\left[\frac{Pa}{sec}\right]$ → $\omega = -\rho g w$

- Where is the air ascending/descending in each season?
- Where do you expect to find deserts?

Hadley Cell exercise

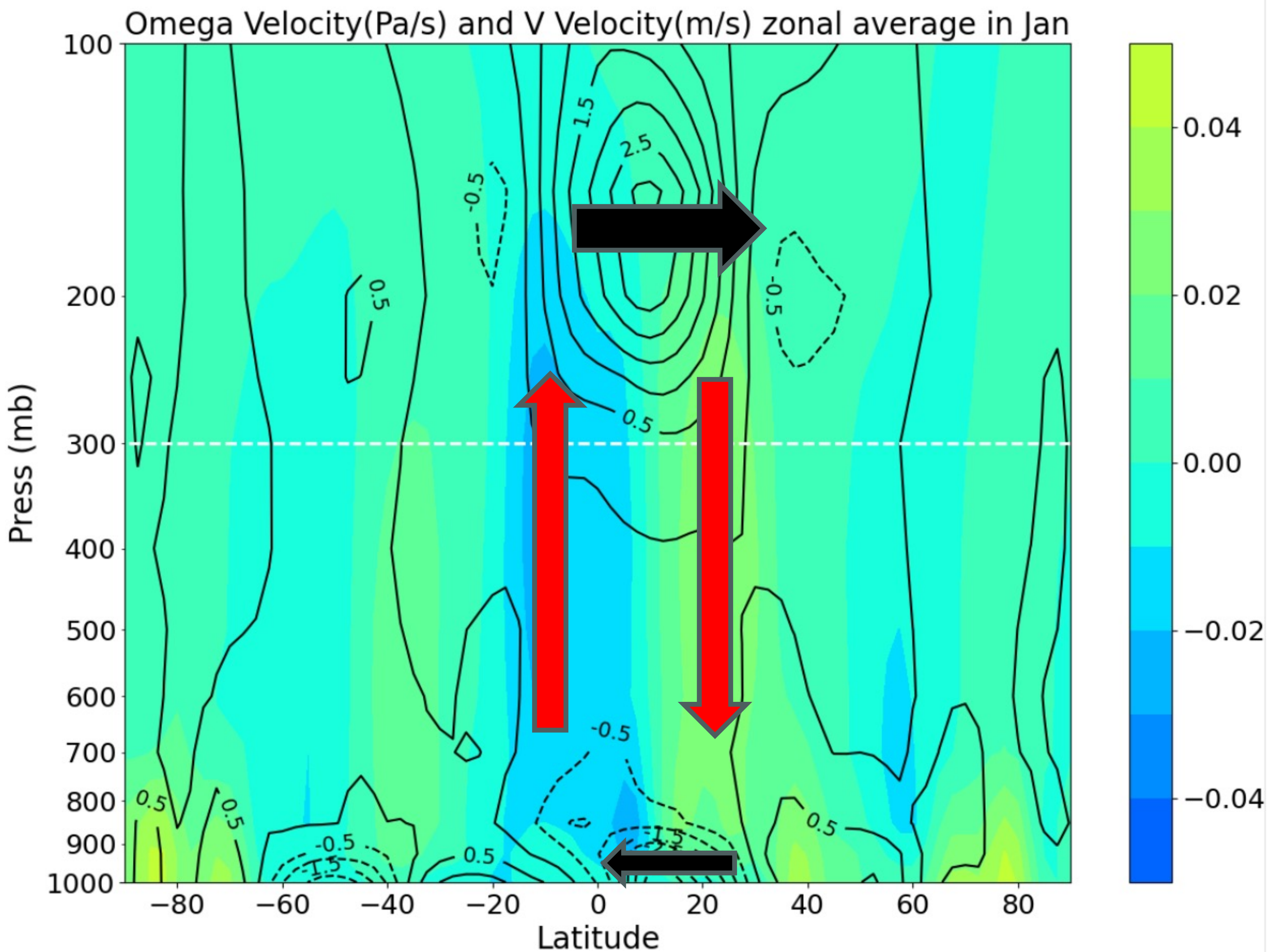
Plot zonally averaged (January and July):

- Temperature (T)
- Meridional velocity (v)
- Vertical velocity (omega) & Meridional velocity (v)
- Zonal velocity (u) & Meridional velocity (v)

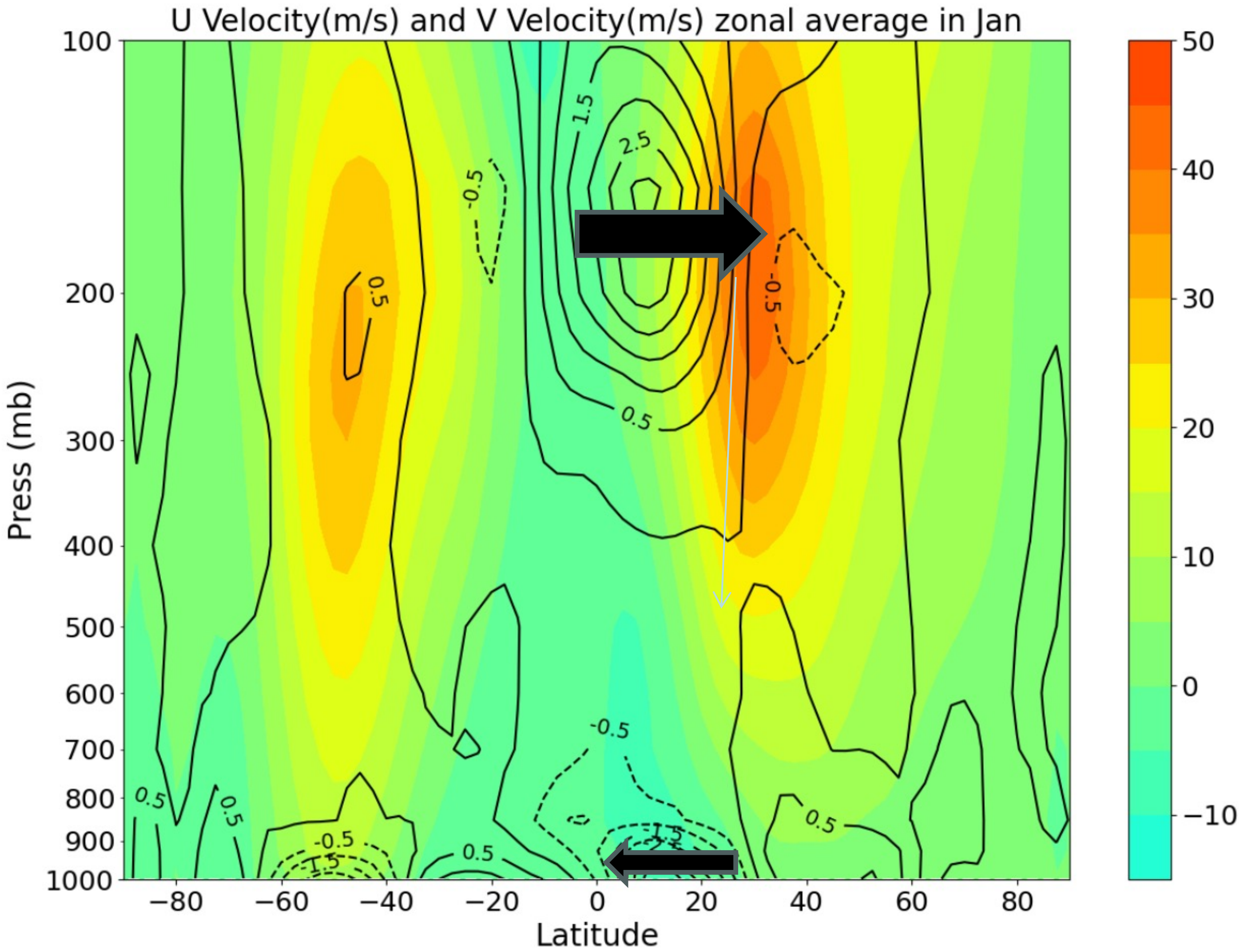
Work in groups to look for:

- Evidence of the Hadley cell
- Evidence of the upper-level westerlies and surface easterly (trade winds)
- Can you identify two layers?

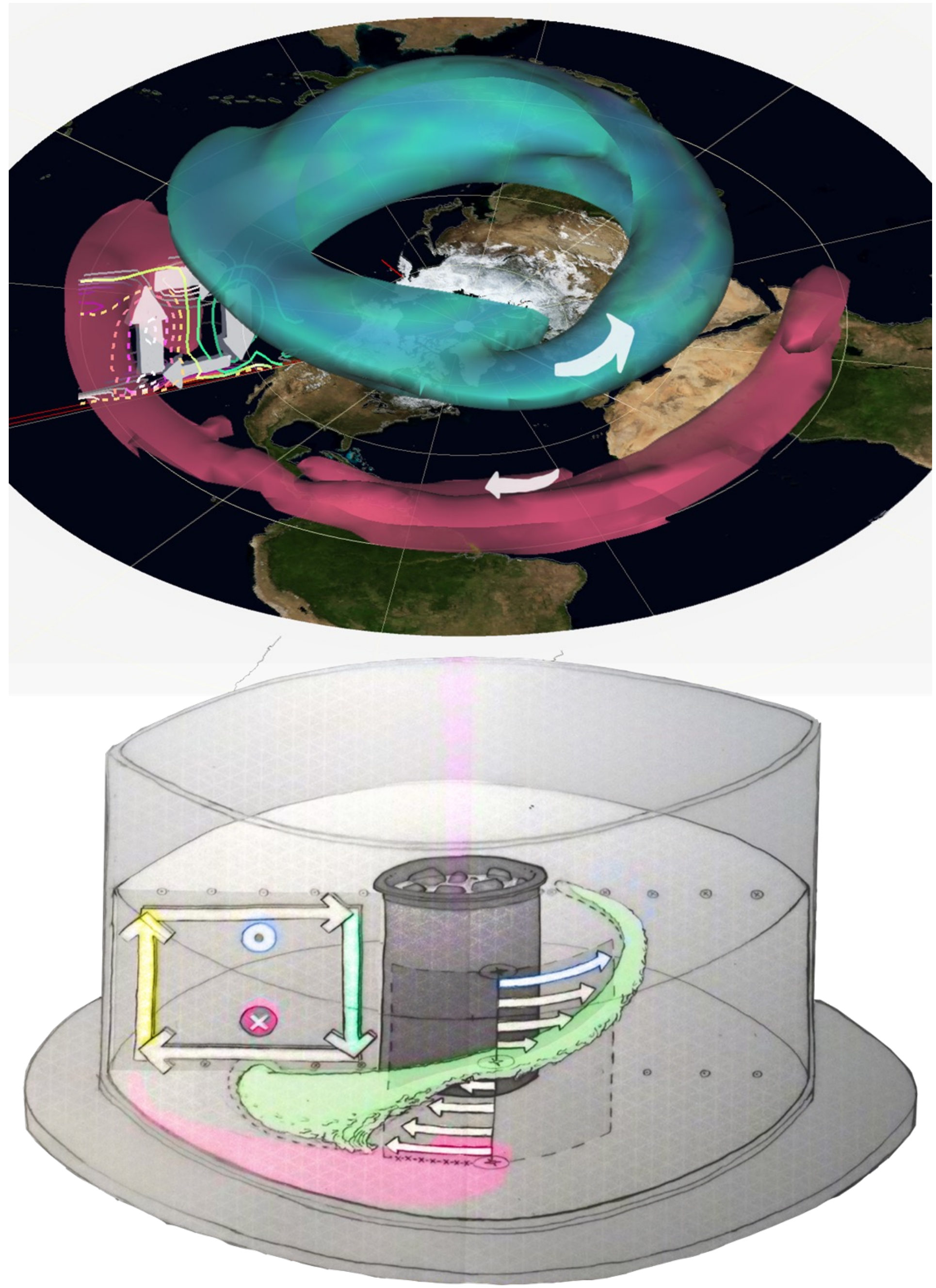
Hadley Circulation! V and W superimposed



Hadley Circulation! V and U superimposed



Connection to the atmospheric circulation



Can we see evidence for this circulation in the atmosphere?

Yes!

Can we estimate the poleward heat flux that this circulation transports?

$$\overline{\mathcal{H}}^{\lambda}_{atmos} = \iint \rho v E \, dA$$

$$= a\cos\varphi \int_0^{2\pi} \int_0^{\infty} \rho v E \; dz \, d\lambda$$

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

$$\rho dz = -dp/g$$

$$\overline{\mathcal{H}}^{\lambda}_{tropics} = \frac{2\pi a}{g}\cos\varphi \int_0^{p_s} v\left(c_p T + gz + Lq\right) \, dp$$

Before that, let's introduce an important quantity-

Potential temperature:

The temperature that a parcel will aquire if it were compressed adiabatically from p and T to a standard pressure p0

$$\theta = T\left(\frac{p_0}{p}\right)^{\kappa}$$

with $k = R/c_p = 2/7$ and conventionally $p_o = 1000mb$.

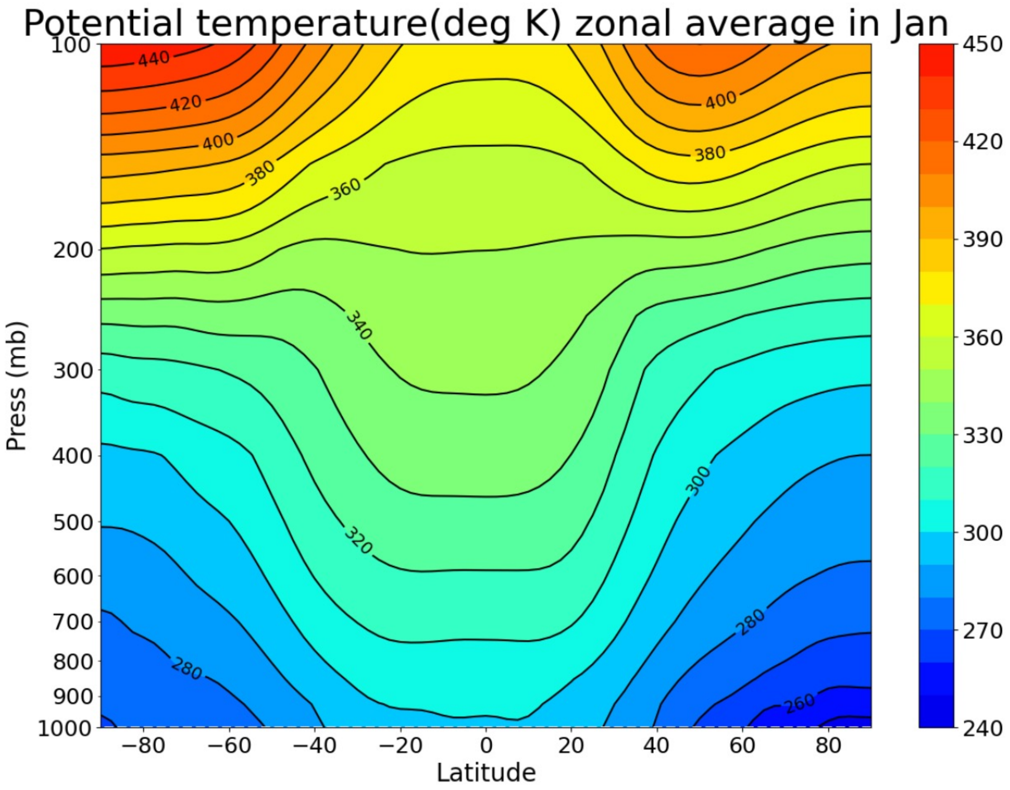
In adiabatic conditions, it follows that:

$$\frac{d\theta}{\theta} = \frac{dT}{T} - k\frac{dp}{p} = 0$$

Potential temperature is conserved in an adiabatic process!

Note that for an adiabatic process, it is also exact to write $C_p\theta = C_pT + gz$

Potential temperature:



- The poles are still colder, but potential temperature now ***increases*** with height

Estimate the poleward heat flux using the EsGlobe and the schematic!

Meridional Heat transport

$$\mathcal{H} = \rho c_p \int_0^\infty \oint \overline{v}\overline{\vartheta} dx dz = \frac{c_p}{g} \int_0^{p_s} \oint \overline{v}\overline{\vartheta} dx dp$$

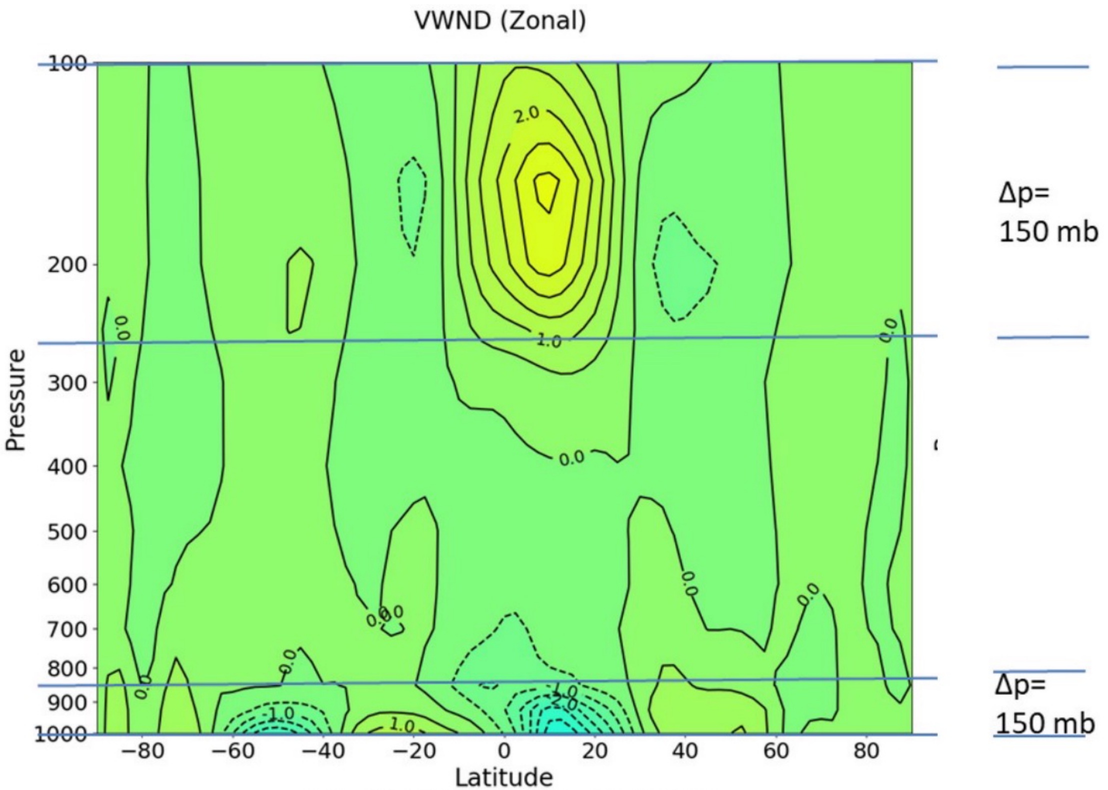
$$= \frac{c_p}{g} \times 2\pi a \cos\varphi \int_0^{p_s} \left[\overline{v}\overline{\vartheta}\right] dp$$

Note:

- Here we used hydrostatic balance to replace dz with dp: $\rho dz = -dp/g$
- The integral is from p=0 (top of the atmosphere) to the surface: $p_s = 1000mb = 10^5\,\mathrm{Pa}$
- The $2\pi a \cos\varphi$ is related to the zonal averaging at latitude φ, i.e. $2\pi r$ at radius $\mathrm{r} = a\cos\varphi$

Two layer model- just like we did in the lab

$$\int_0^{p_s} [\overline{v}][\overline{\vartheta}]dp = ([\overline{v}]_t[\overline{\vartheta}]_t + [\overline{v}]_b[\overline{\vartheta}]_b)\Delta p = [\overline{v}]_t([\overline{\vartheta}]_t - [\overline{\vartheta}]_b)\Delta p$$



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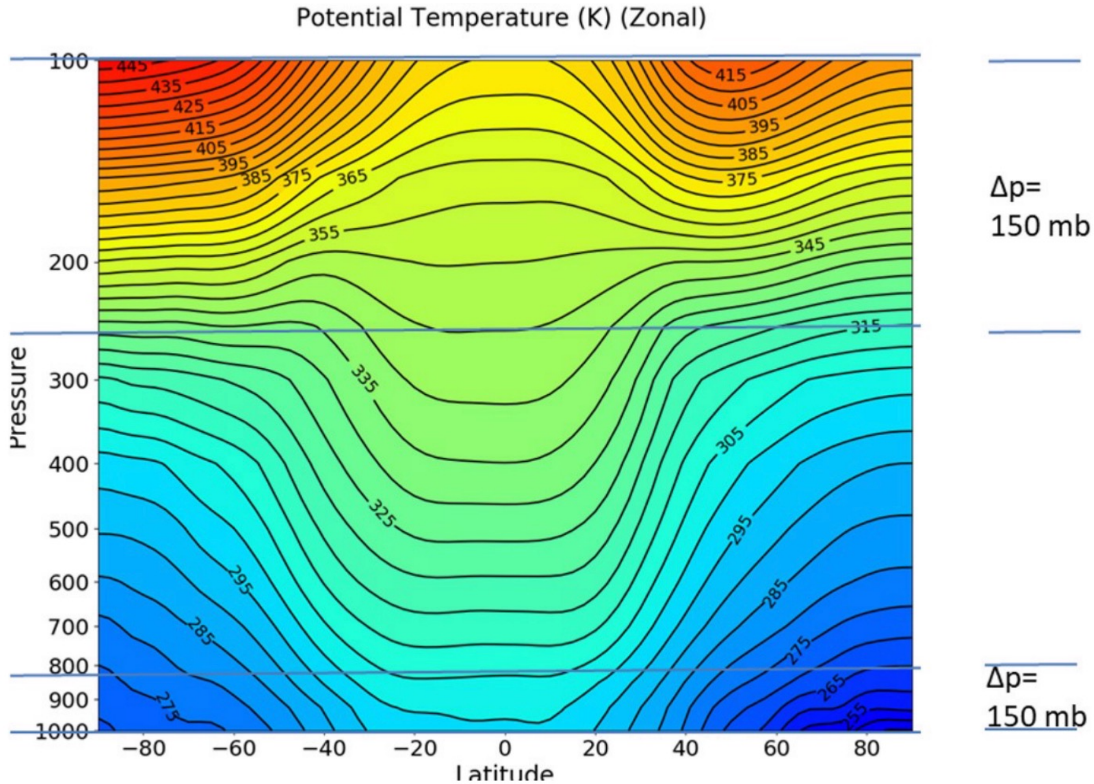
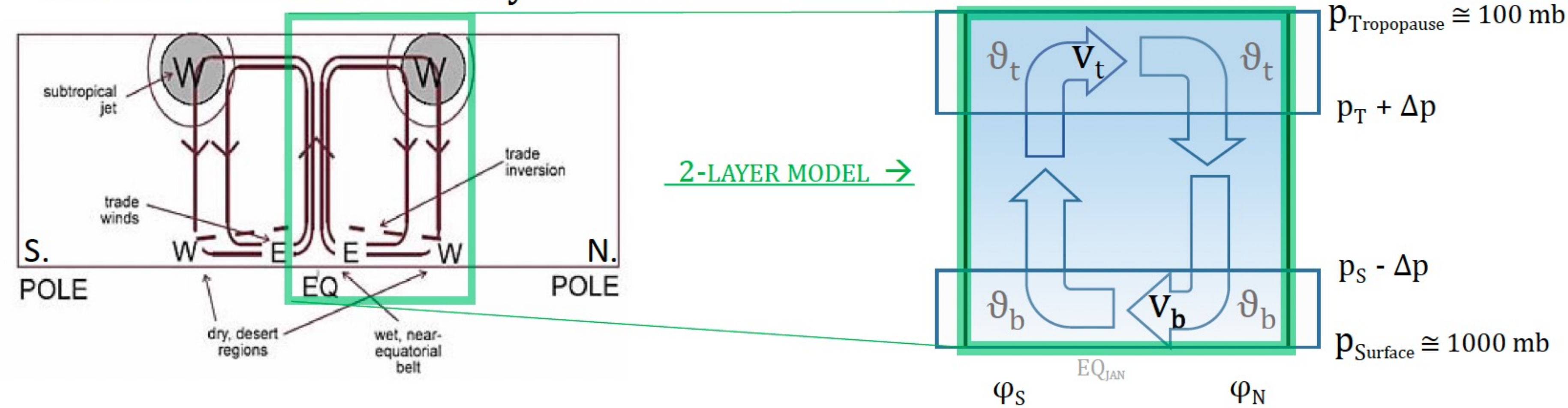
$$\int_0^{p_s} [\overline{v}][\overline{\vartheta}]dp = ([\overline{v}]_t[\overline{\vartheta}]_t + [\overline{v}]_b[\overline{\vartheta}]_b)\Delta p = [\overline{v}]_t([\overline{\vartheta}]_t - [\overline{\vartheta}]_b)\Delta p$$



General circulation – Hadley cell

N. branch – [Jan. Mean]



Eqns. 7 → 8 [pg. 4]

$$\mathcal{H} = \rho c_p \int_0^\infty \oint \overline{v}\overline{\vartheta}\, dx\, dz = \frac{c_p}{g} \int_0^{p_s} \oint \overline{v}\overline{\vartheta}\, dx\, dp = \frac{c_p}{g} \times 2\pi a \cos\varphi \int_0^{p_s} [\overline{v}\overline{\vartheta}]\, dp$$

Constants

Specific heat *(for atmospheric air)*

$c_p = 1005$ J/(kg K)

$g = 9.8$ m/s^2

$a \cong 6.4 \times 10^6$ m
(^ Earth's radius)

Estimate values for:

1 millibar $= 10^2$ Pascals

$[\overline{v}$elocities]	[$\overline{\vartheta}$: potential temp.]	φ : latitude	p : pressure
$\overline{v}_t =$	$\overline{\vartheta}_t =$	$\varphi_{avg} =$	$\Delta p =$
$\overline{v}_b =$	$\overline{\vartheta}_b =$		

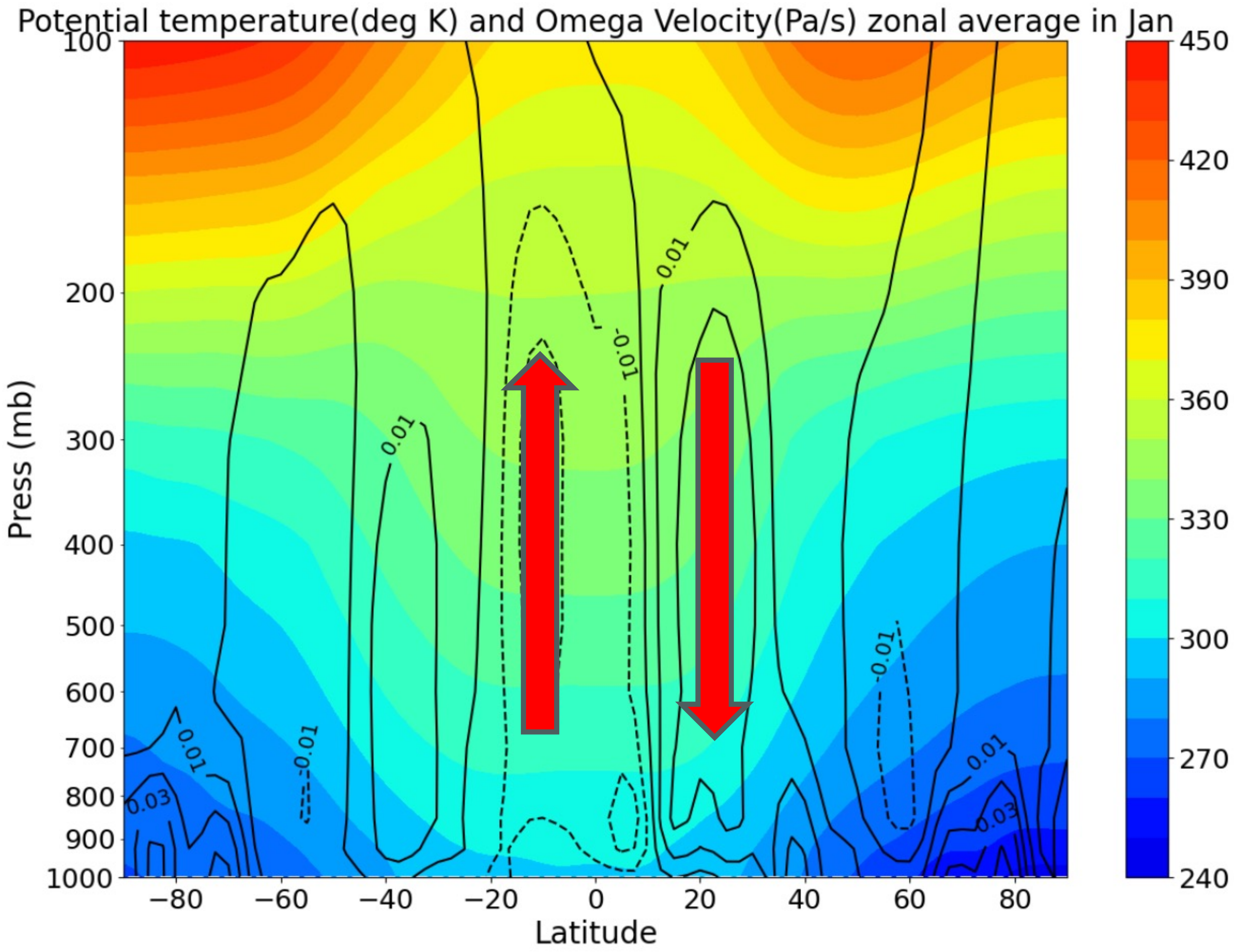
Eqn. 9 [pg. 8]

If $v_t \cong -v_b$ then..

$$\int_0^{p_s} [\overline{v}][\overline{\vartheta}]\, dp = ([\overline{v}]_t[\overline{\vartheta}]_t + [\overline{v}]_b[\overline{\vartheta}]_b)\Delta p = [\overline{v}]_t([\overline{\vartheta}]_t - [\overline{\vartheta}]_b)\Delta p$$

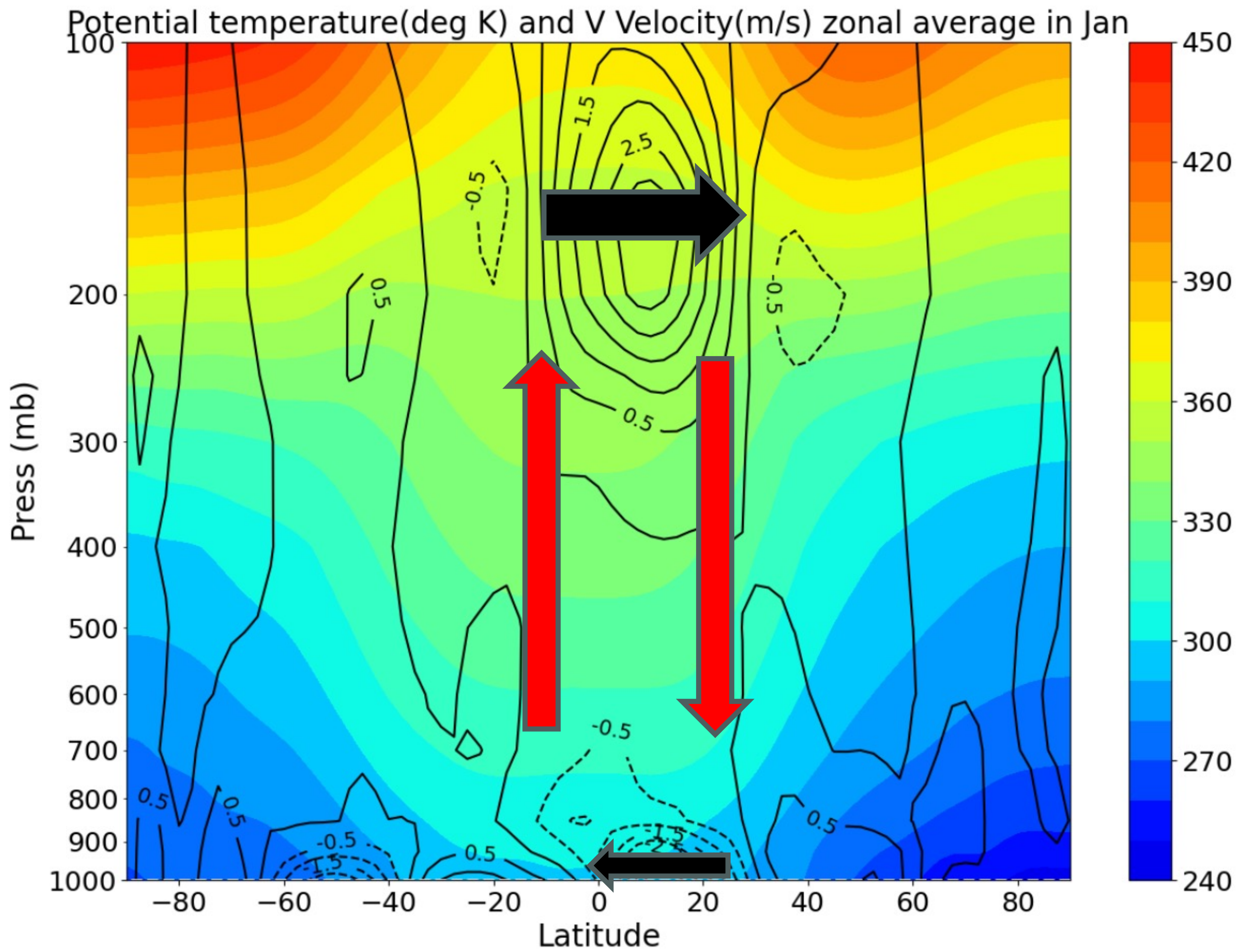
→ Express $\mathcal{H}$ in Petawatts, PW=10^{15} W.

Two layer model to estimate the heat transport



Tip: plot potential temperature + vertical velocity

Two layer model to estimate the heat transport



Tip: plot potential temperature + meridional velocity

12.307- project 3 (data class 2)

Last class

- Connection to Hadley tank experiment
- Atmospheric climatology using EsGlobe
- Identify the Hadley circulation
- N-S heat transport in the tropics

Today

- Heat transport in the tropics (2-layer model)- review calculations
- Moisture climatology and meridional transport
- Eddy-regime in the extra-tropics
- Meridional heat transport by eddies
- Project 4- brief intro

Meridional Heat transport- two-layer approach:

$$\mathcal{H} = \rho c_p \int_0^{\infty} \oint \overline{v}\overline{\vartheta} dx dz = \frac{c_p}{g} \int_0^{p_s} \oint \overline{v}\overline{\vartheta} dx dp$$

$$= \frac{c_p}{g} \times 2\pi a \cos\varphi \int_0^{p_s} \left[\overline{v}\overline{\vartheta}\right] dp$$

$$\int_0^{p_s} [\overline{v}][\overline{\vartheta}] dp = ([\overline{v}]_t [\overline{\vartheta}]_t + [\overline{v}]_b [\overline{\vartheta}]_b)\Delta p = [\overline{v}]_t ([\overline{\vartheta}]_t - [\overline{\vartheta}]_b)\Delta p.$$

H = [(10^3)/10] x (6x6x10^6) x1x (2x60) x (150x10^2)
≈6.5x10^15 W = 6.5 PW

Meridional Heat transport- two-layer approach:

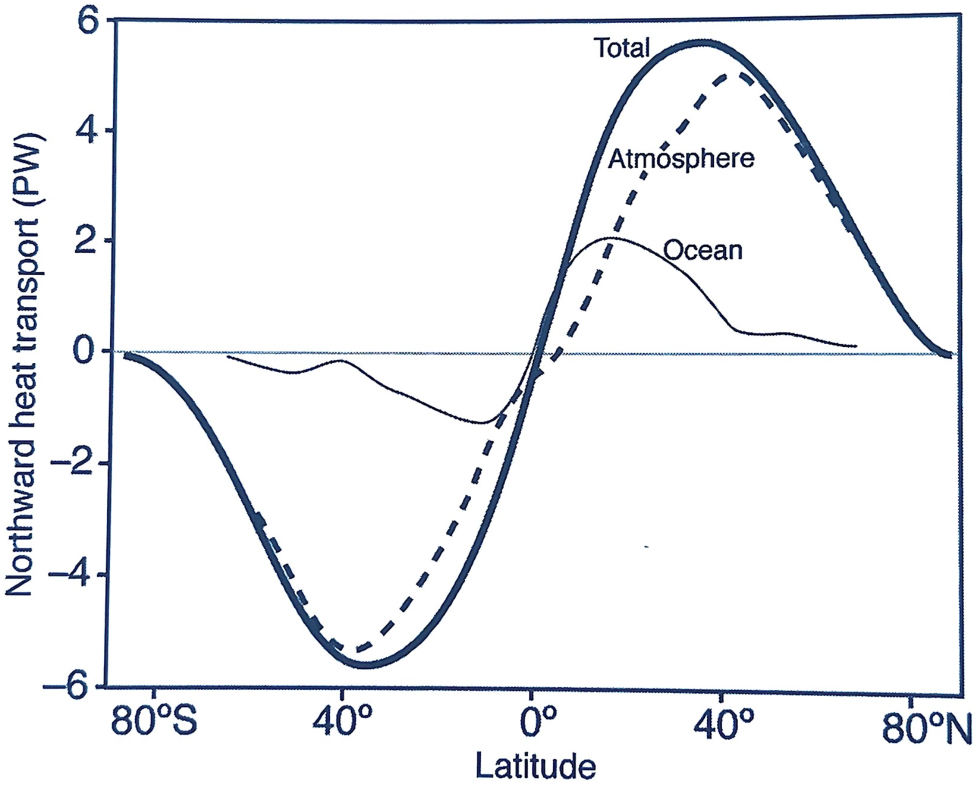
$$\mathcal{H} = \rho c_p \int_0^\infty \oint \overline{v\vartheta} dx dz = \frac{c_p}{g} \int_0^{p_s} \oint \overline{v\vartheta} dx dp$$

$$= \frac{c_p}{g} \times 2\pi a \cos\varphi \int_0^{p_s} \left[\overline{v\vartheta}\right] dp$$

$$\int_0^{p_s} [\overline{v}][\overline{\vartheta}] dp = ([\overline{v}]_t [\overline{\vartheta}]_t + [\overline{v}]_b [\overline{\vartheta}]_b)\Delta p = [\overline{v}]_t ([\overline{\vartheta}]_t - [\overline{\vartheta}]_b)\Delta p.$$

$H \approx 6.5$ PW!

Compare our estimates to reanalysis estimates:

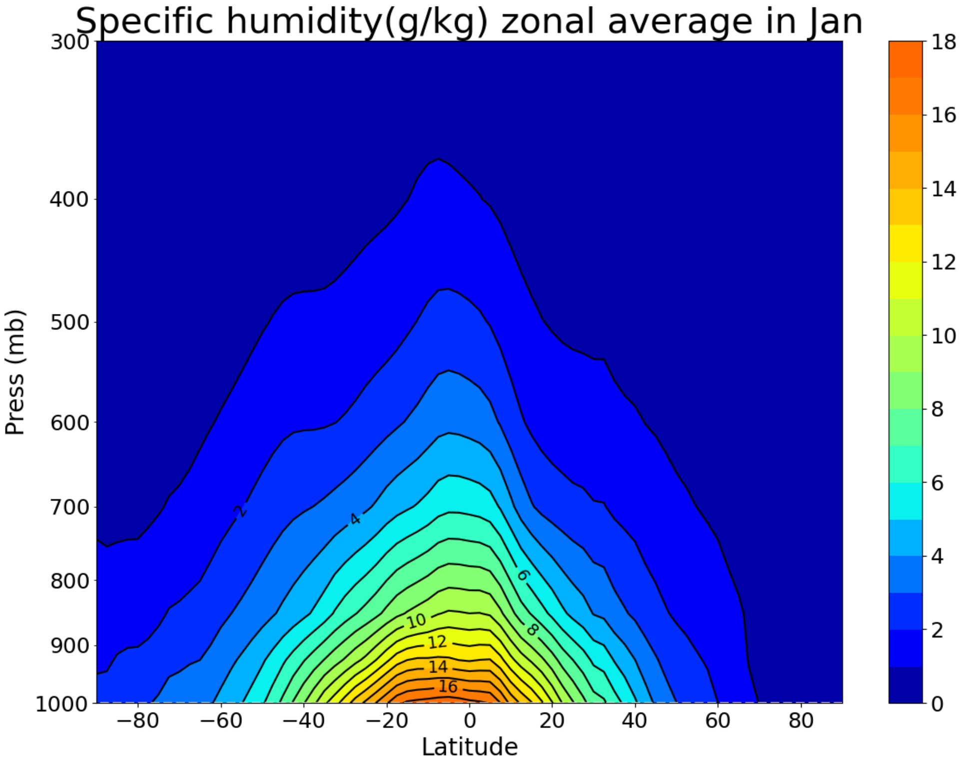


Why do we get 6.5 PW?? seems too high!

We need to consider also latent heating!

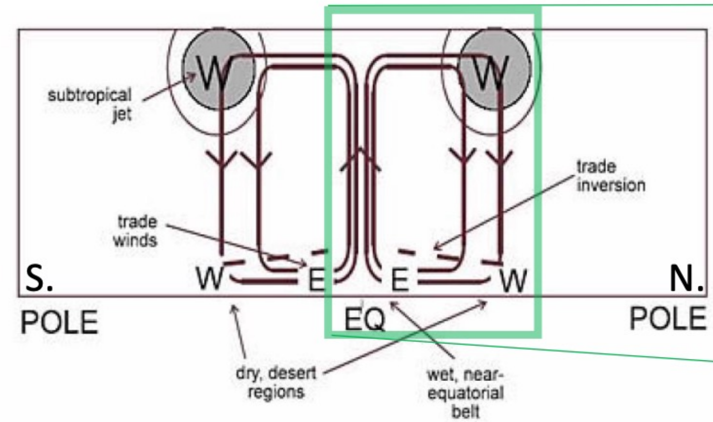
Moisture distribution

Plot zonally averaged field of specific humidity (g/kg)



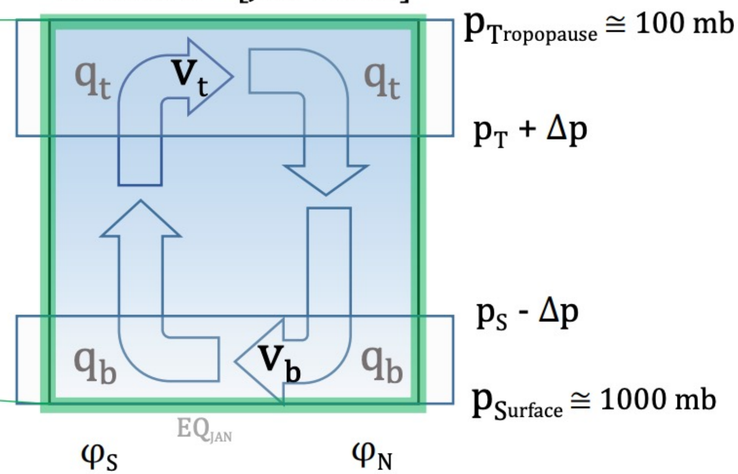
- Specific humidity= amount of water vapour (in grams) in 1kg of air
- Confined to low-levels (note max pressure is 300mb) higher in tropics

General circulation – Hadley cell



2-LAYER MODEL →

N. branch – [Jan. Mean]



Latent Heat Flux Contribution   Eqn. 10 [pg. 9]   If $q_t \cong 0$ then...

$$\mathcal{L} = \frac{L}{g} \times 2\pi a \cos\varphi \int_0^{p_s} \overline{vq}\,dp \simeq \frac{L}{g} \times 2\pi a \cos\varphi [\overline{v}]_b [\overline{q}]_b \Delta p.$$

Constants *(for atmospheric air)*

Latent heat of fusion

$L = 2.25 \times 10^6$ J/kg

$g = 9.8$ m/s^2

$a \cong 6.4 \times 10^6$ m
(^ Earth's radius)

Estimate values for:

Spec. humidity **q** is units of **g/kg**
Use MKS system for calculations.

1 millibar $=10^2$ Pascals

$[\overline{v}$elocities$]$	$[\overline{q}$: specific humidity$]$	φ : latitude	p : pressure
$\overline{v}_t =$	$\overline{q}_t =$	$\varphi_{avg} =$	$\Delta p =$
$\overline{v}_b =$	$\overline{q}_b =$		

Tip: convert specific humidity to kg/kg

→ Express $\mathcal{L}$ in Petawatts, PW$=10^{15}$ W.

Total Heat Flux $= \mathcal{H} + \mathcal{L}$

Meridional transport of moisture

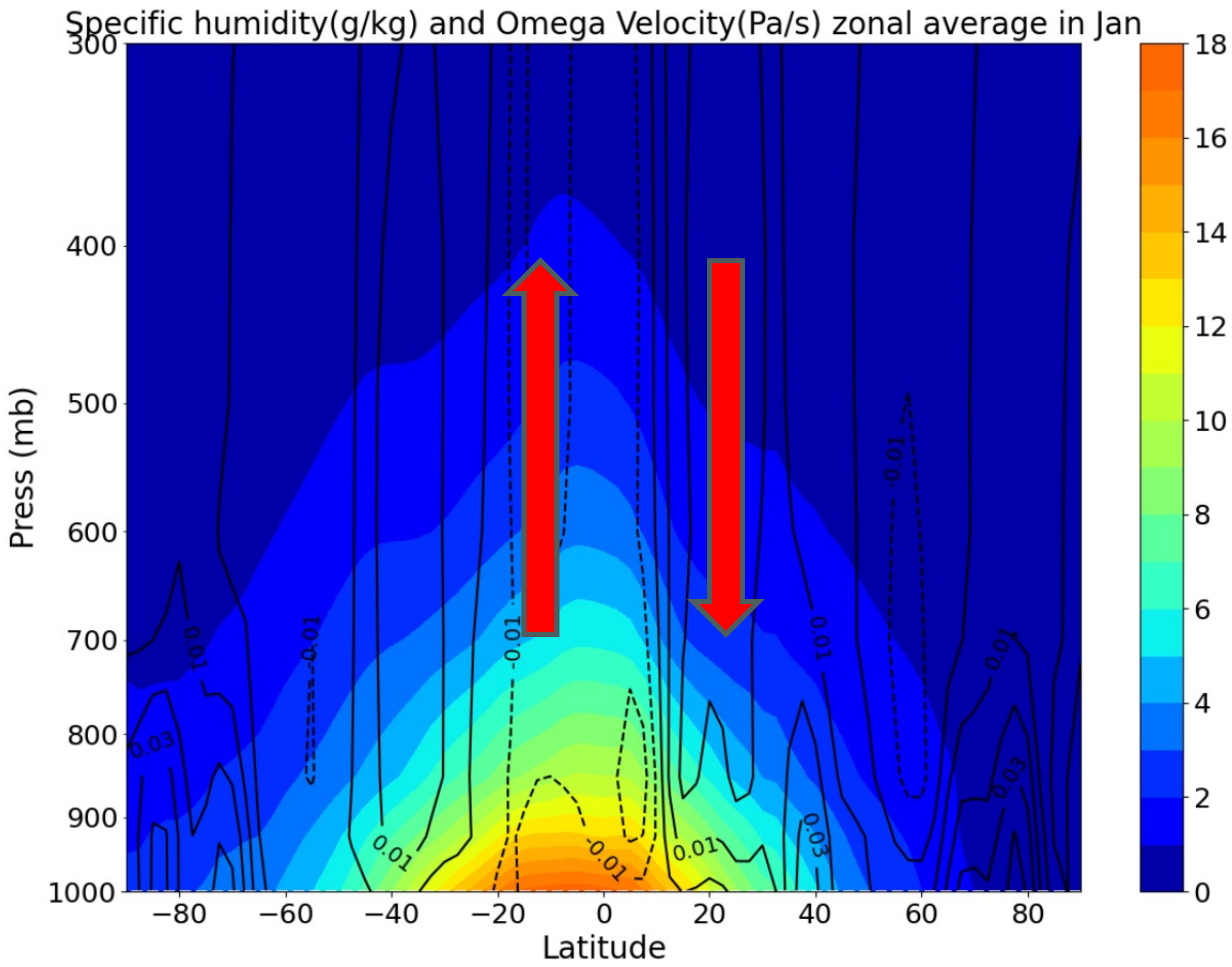
$$\mathcal{L} = \frac{L}{g} \times 2\pi a \cos\varphi \int_0^{p_s} \overline{vq}\, dp$$

Two layer approximation

$$\simeq \frac{L}{g} \times 2\pi a \cos\varphi [\overline{v}]_b [\overline{q}]_b \Delta p.$$

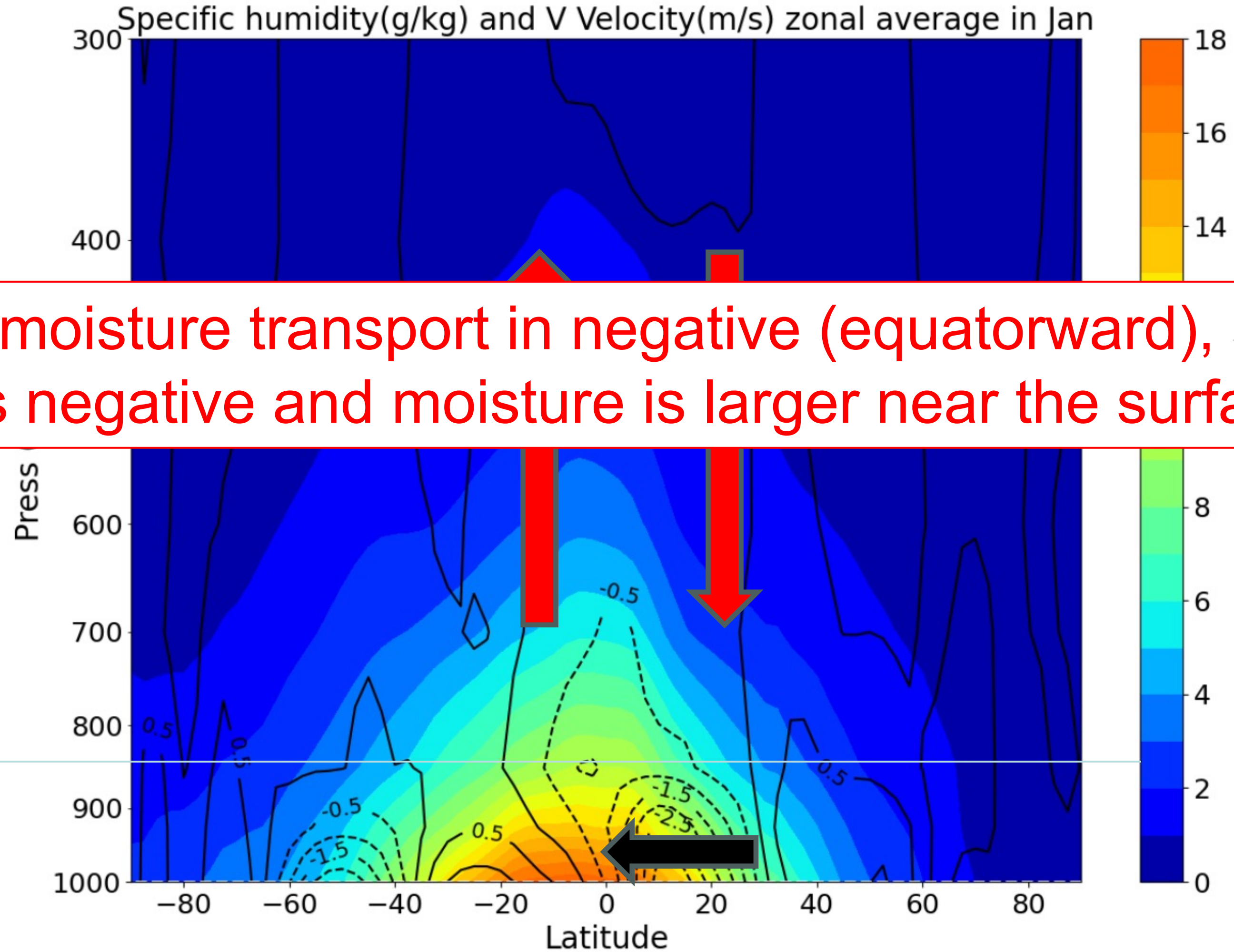
Meridional transport of moisture

$$\mathcal{L} \simeq \frac{L}{g} \times 2\pi a \cos\varphi [\overline{v}]_b [\overline{q}]_b \Delta p$$



Meridional transport of moisture

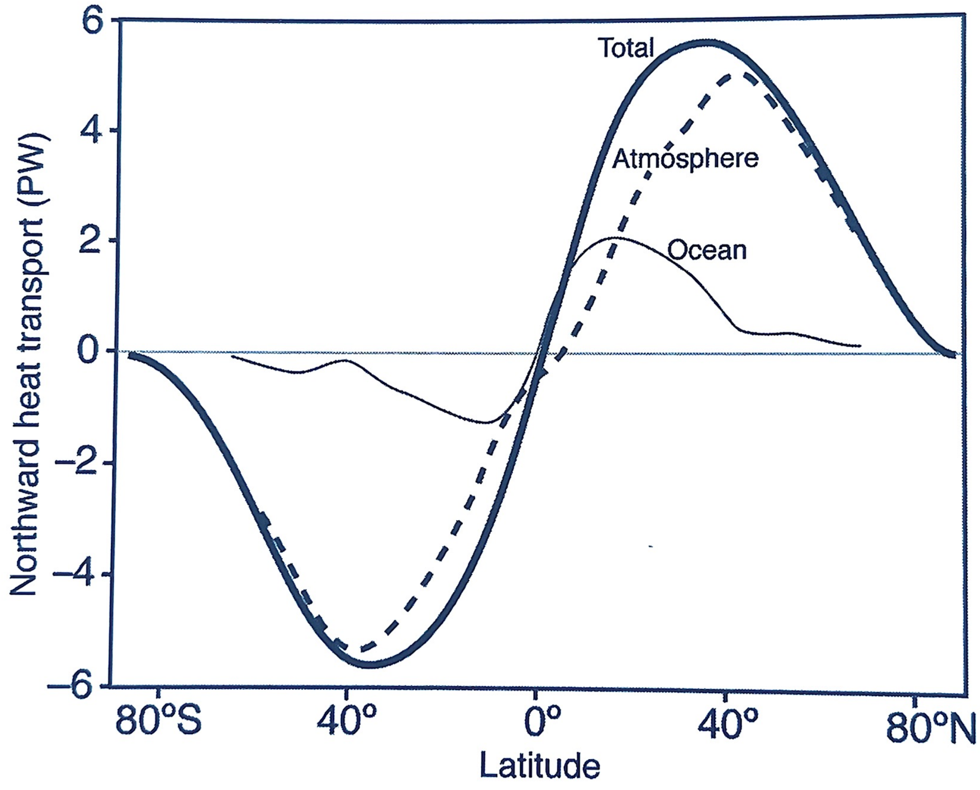
$$\mathcal{L} \simeq \frac{L}{g} \times 2\pi a \cos\varphi [\overline{v}]_b [\overline{q}]_b \Delta p$$



The moisture transport in negative (equatorward), since v is negative and moisture is larger near the surface!

L= [(2.25x10^6)/10] x (6x6x10^6) x1x (-2x13x10^-3) x (150x10^2)
= 5.4x10^15 W = -3 PW

Compare our estimates to reanalysis estimates:



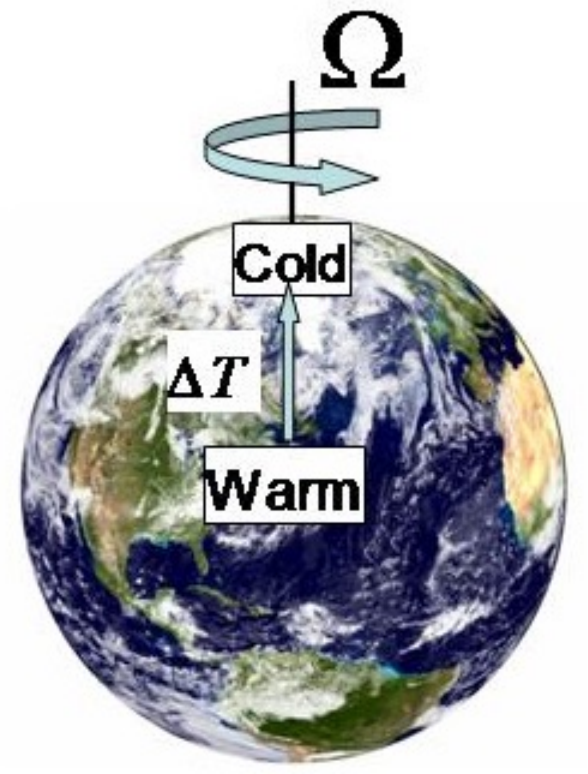
Total heat transport = H + L ~6.5-3=3.5 PW

→ Not a bad rough estimation!

What about the midlatitudes, where the “eddy regime” is dominating?

General Circulation of the atmosphere

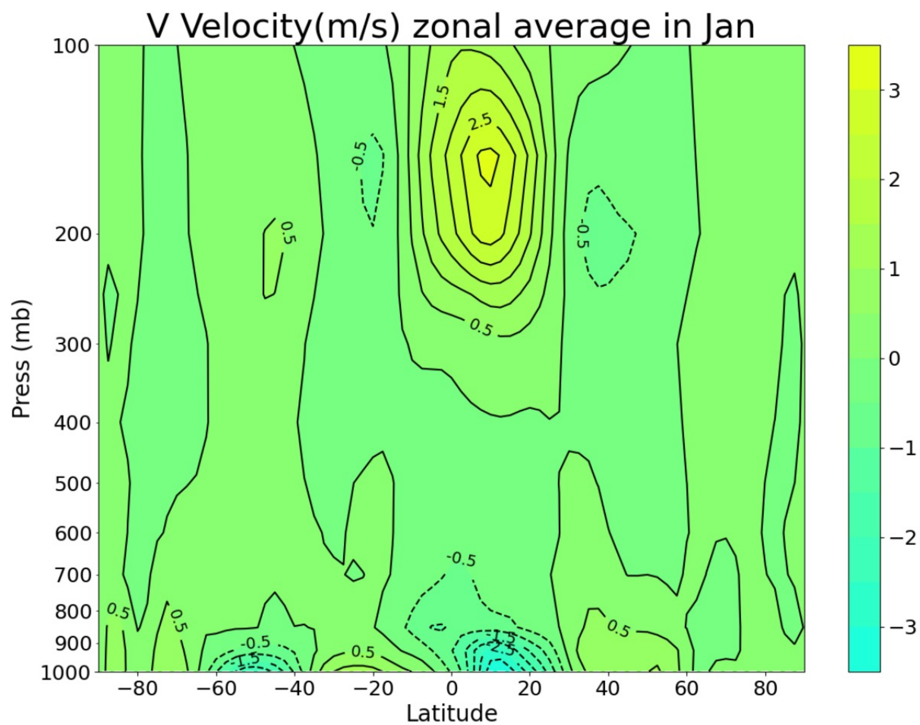
1. Pole – Equator Temperature Difference
2. Earth rotation



Two experiments	Two regimes
Ω = large ΔT = large →	Mid-latitude weather systems
Ω = small ΔT = large →	Tropical Hadley cell circulation

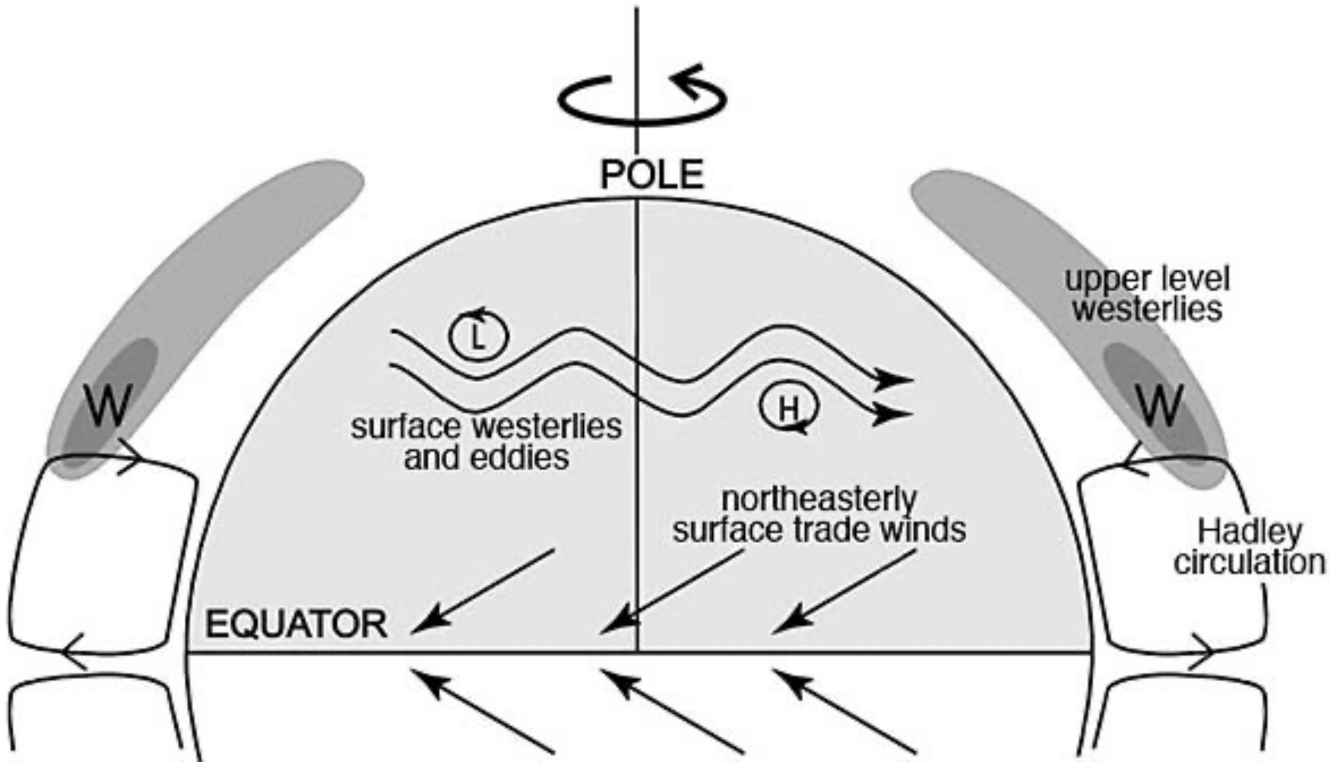
Laboratory abstraction of Earth's weather

Let's look again at the mean V structure:

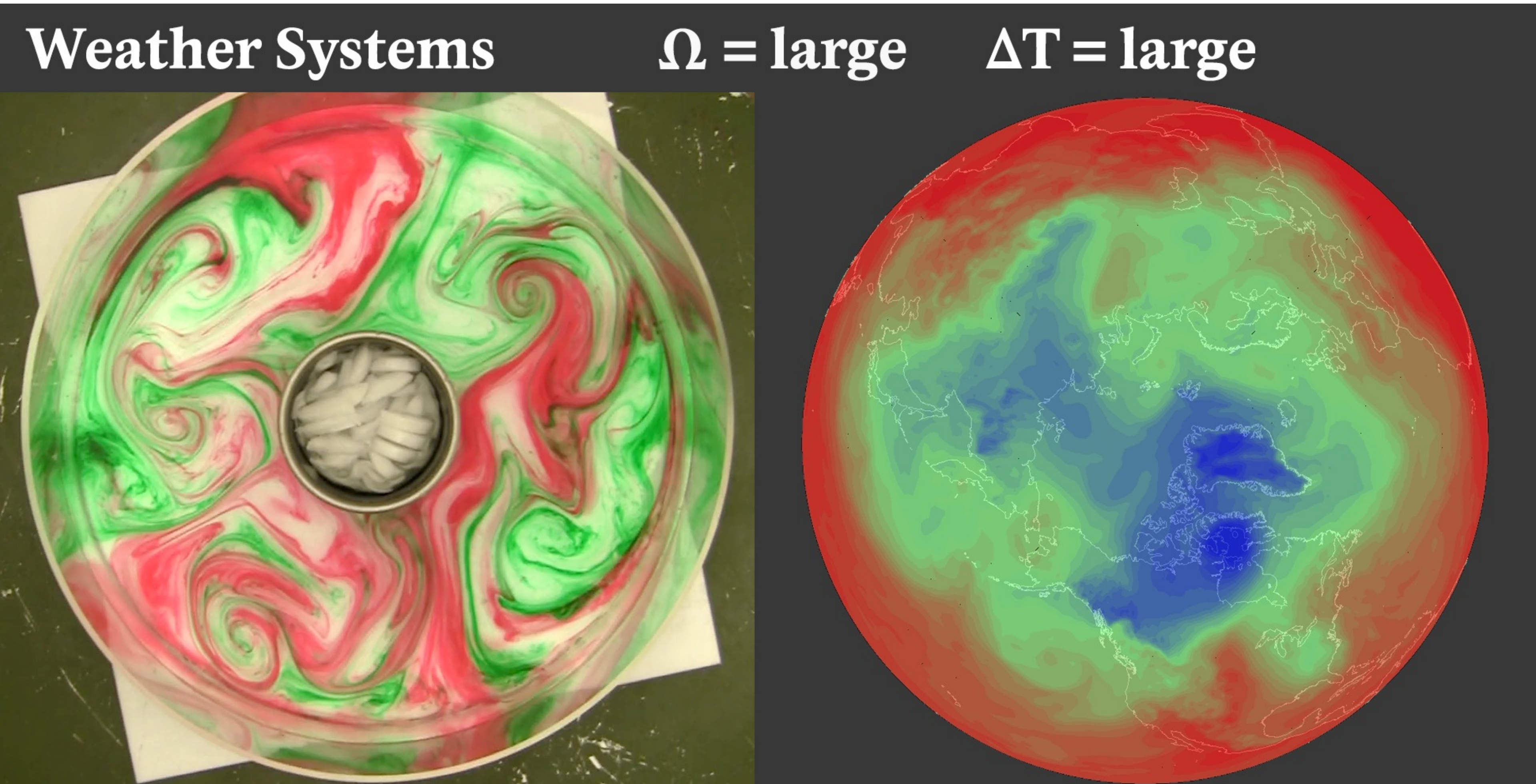


- V is mainly large in the tropics (in the two 'layers') but generally very small in the midlatitudes (weak 'Ferrel Cell')
- So how can heat be transported poleward??
- In the midlatitudes, $\overline{VT}$ is small since $\bar{V}$, but in fact $\overline{V'T'}$ is not!

Schematic of Earth's global circulation



Eddies regime



How do midlatitude eddies transfer heat poleward?

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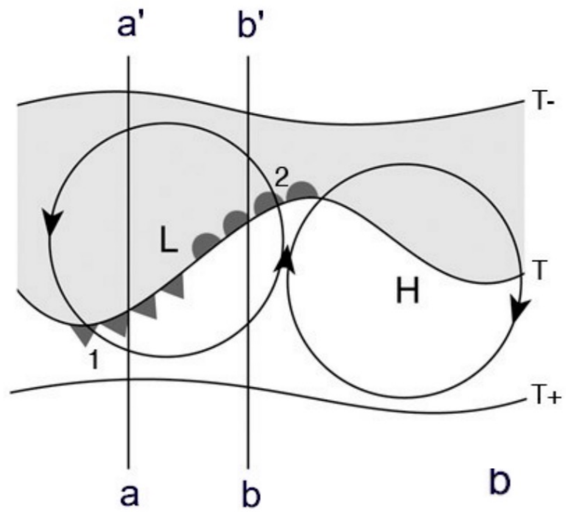
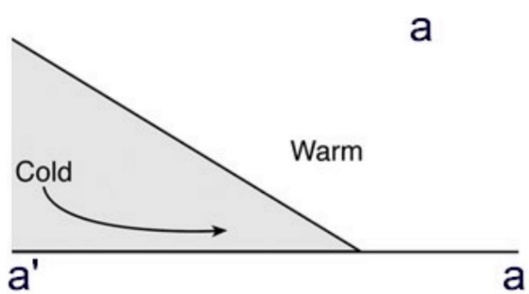
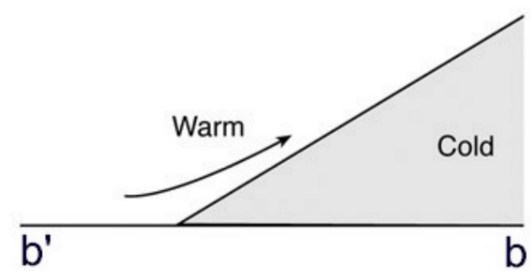


Cold front



Warm front



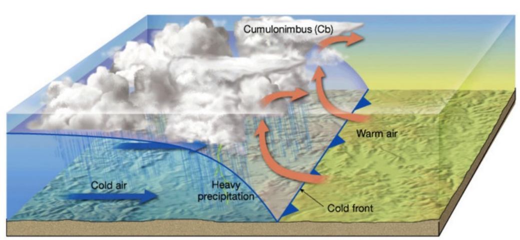


Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

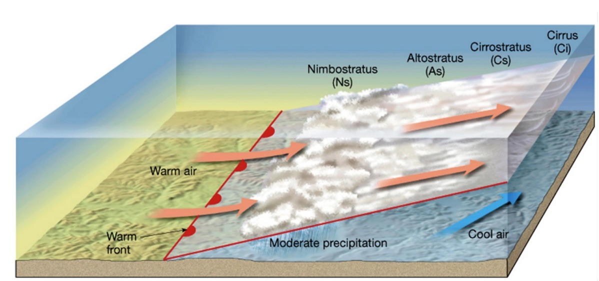
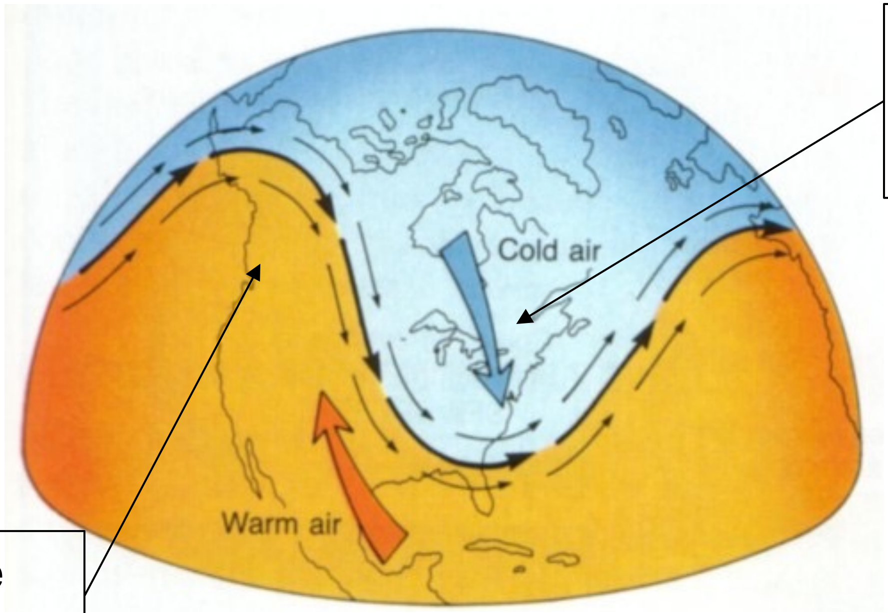


Figure 9.6 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

How do midlatitude eddies transfer heat poleward?



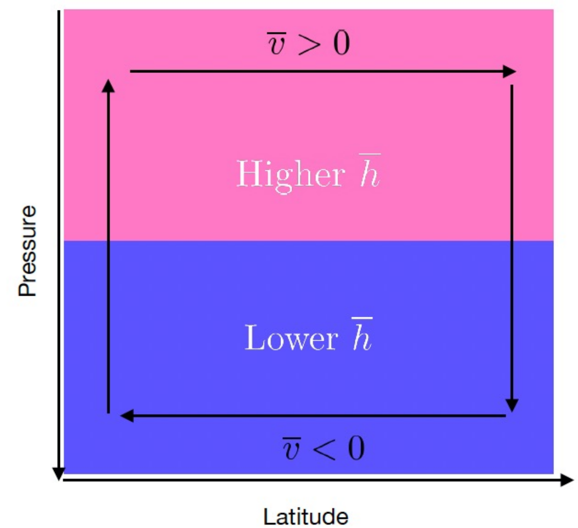
$v' < 0$ negative
$T' < 0$ negative
$v'T' > 0$ positive

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

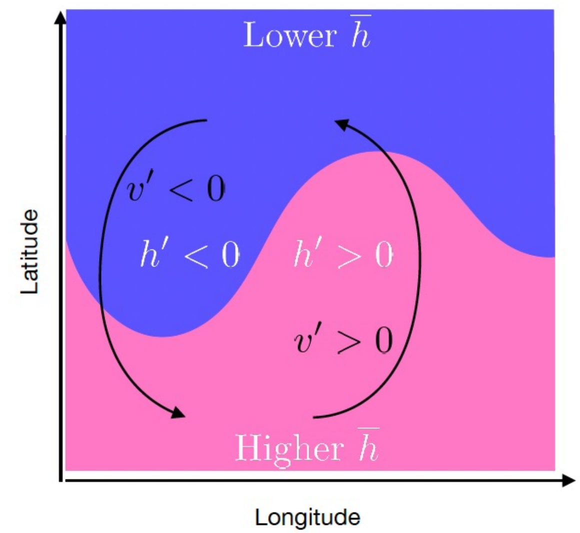
- Warm air is transported poleward, cold air is transported equatorward
- Hence, is both cases, the heat flux is positive (poleward), and acting to reduce the background temperature gradient

Mechanisms for poleward heat transport

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



Hadley overturning circulations



Midlatitude eddies

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

Energy transport in the atmosphere

Exercise

$$H = \rho \iint vhdA\, \rho \iint vh\, dzdx$$

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

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

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

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

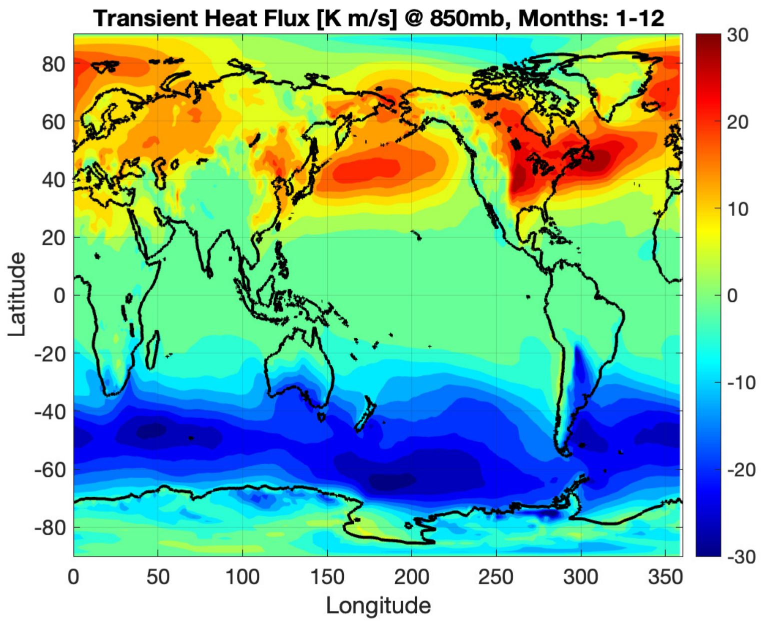
Transient energy transport in the atmosphere- *Exercise*

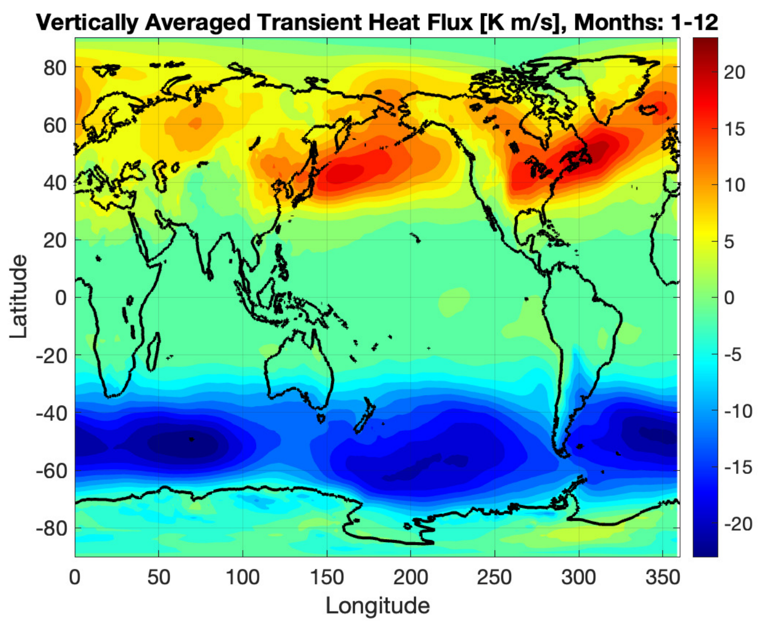
$$H = \frac{2\pi a}{g} \cos\varphi \int_0^{p_s} \left(c_p [\overline{v'\theta'}] + L_v [\overline{v'q'}] \right) dp$$

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

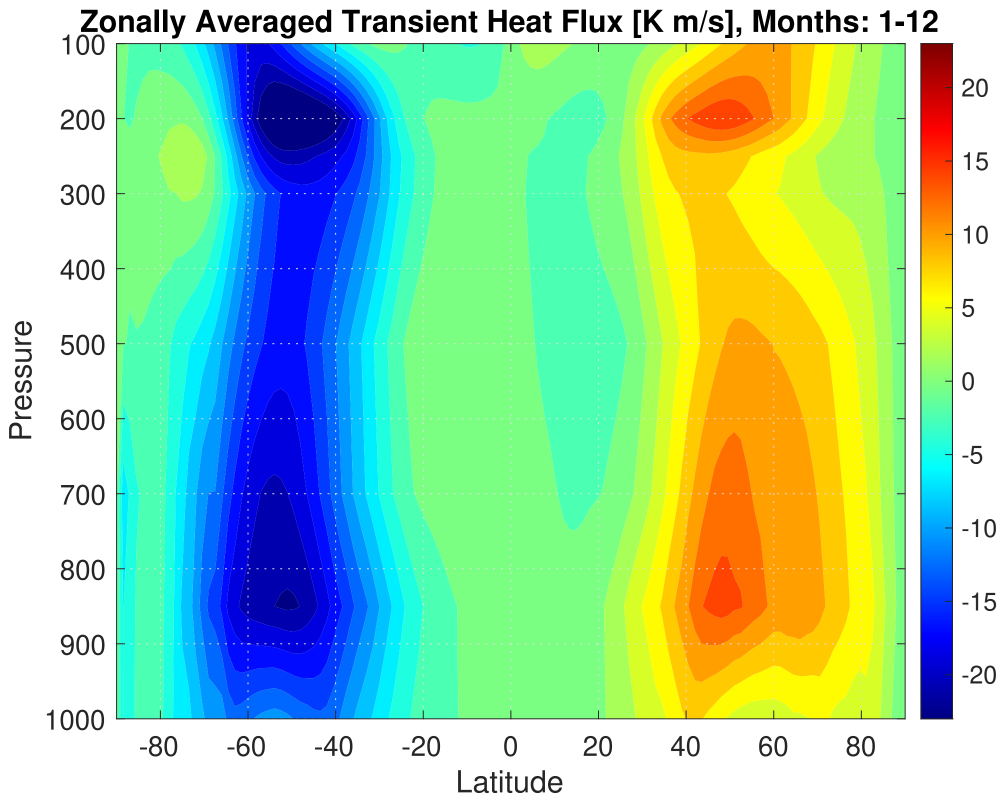
- The script should produce the transient heat flux [K m/s] at a chosen level (e.g., 850 mb below) and vertically averaged





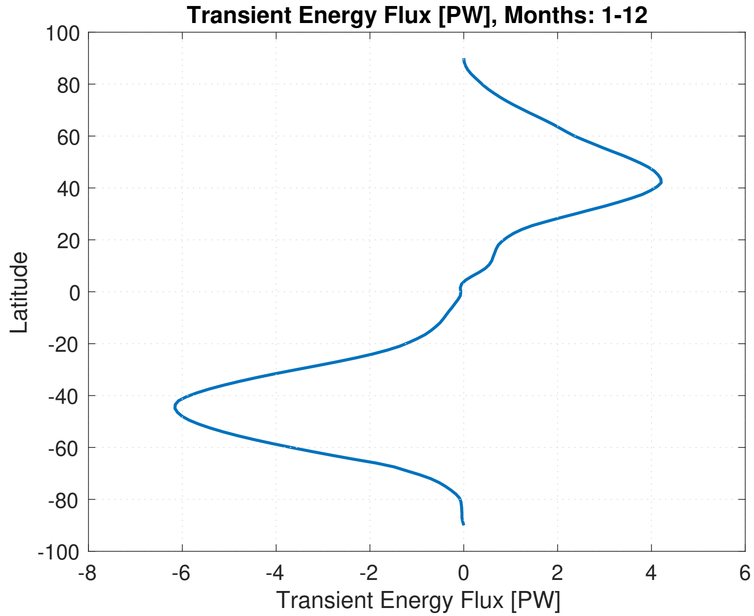
What you need to do:

- Calculate and plot the zonal mean transient heat flux



What you need to do:

- Calculate and plot the total transient poleward energy flux



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

Comments about reports

- No need to repeat all the theory in the notes!! Only the relevant equations that you actually use to calculate things

Report 2-

- Atmosphere: dust advection, front (optional), temperature variability (explain variance and gradient connection, explain why variance decreases)

Report 3-

- Hadley cell: proof of existence (figures from EsGlobe), heat transport in the Hadely cell and in the midlatitudes

Project 4- dig deeper!

- Go back and dig deeper into one of the projects, or come up with another project
- Should be short as there is not much time
- Next class we will brainstorm ideas for projects

Initial thoughts on the Dig Deeper project:

- Lab/observations data?
- Atmosphere/ocean/fluid dynamics more generally?
- Previous projects/new project?

Some ideas-

- Tornados (we have a dataset)
- Ocean currents
- New lab experiments (Weather in a Tank website for ideas, e.g., Fronts, Taylor-Proudman columns)
- CMIP6 climate change simulation data (temperature, model-to-model spread, year-to-year variability…)
- ERA5 reanalysis data (e.g., seasonal variation of poleward heat flux)
- Extratropical cyclones (dataset of storm tracks)
- Migration of the Hadley Cell
- …