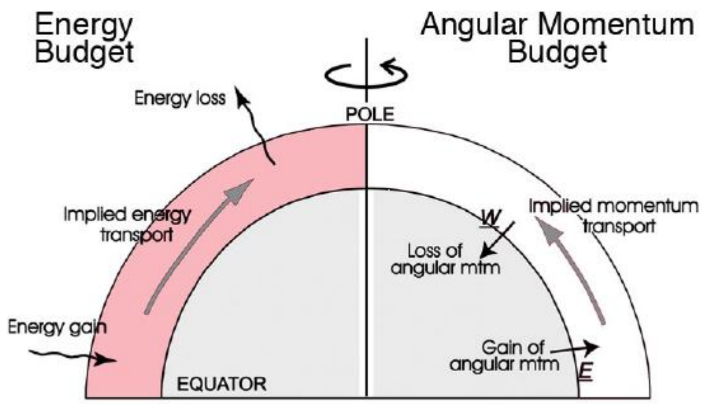
report 4:
GENERAL CIRCULATION

tank experiments hadley cell eddie transfer
atmospheric data tropic extra-tropic

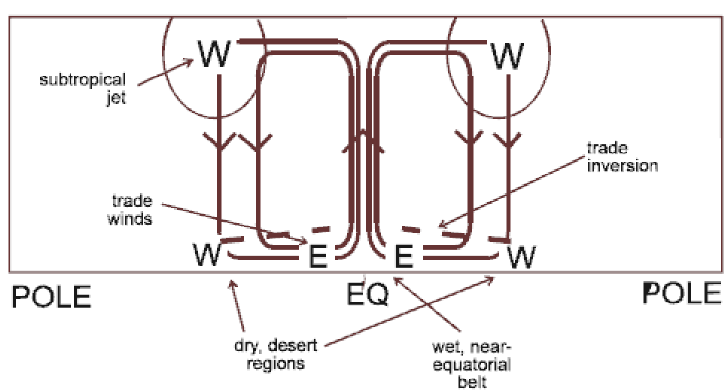
Bill McKenna
12.307
Spring 2010

hadley cell



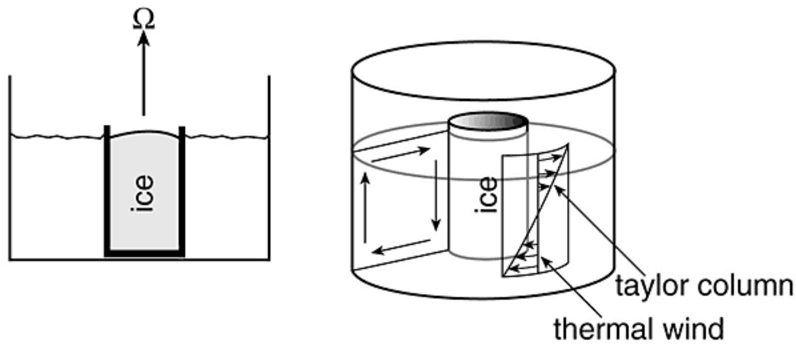
Earth's warm tropical equator and cold polar regions implies a basic pattern of heat gain and loss.

Matching this with common sense knowledge of "warm air rising" and "cold air sinking" due to density differences, a circuit of airflow can be correspondingly imagined as air rising in the tropics and sinking at the pole.



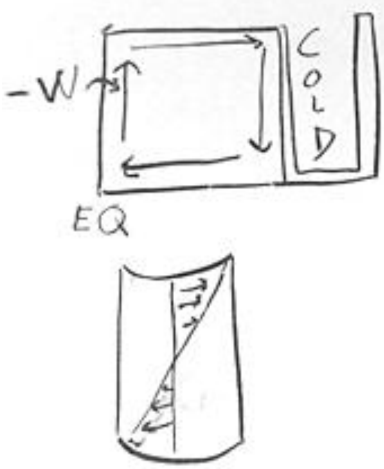
One atmospheric scientist, Hadley, advanced the understanding and theory underlying this supposed circulation pattern. The pattern does not apply globally, but works well to describe the behavior of air within the tropical band itself (where the inward gravity vector is approaches perpendicularity with the axis of rotation)

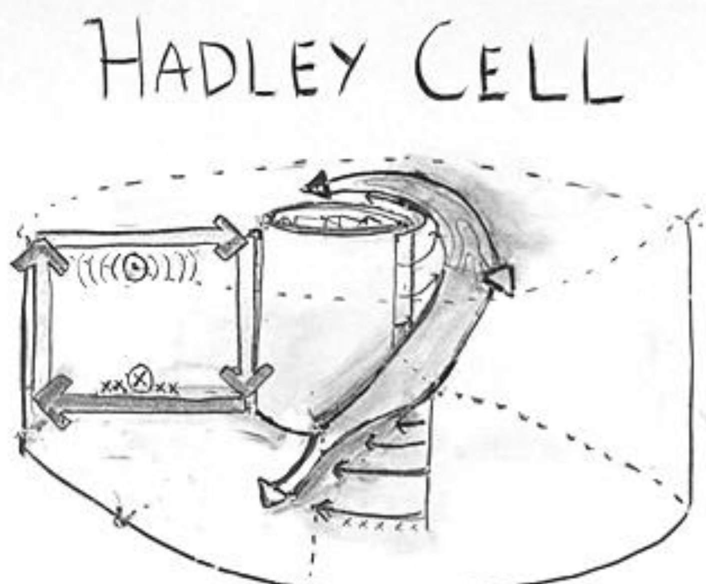
To model this atmospheric behavior in a tank environment, rotation must be present but not extreme.

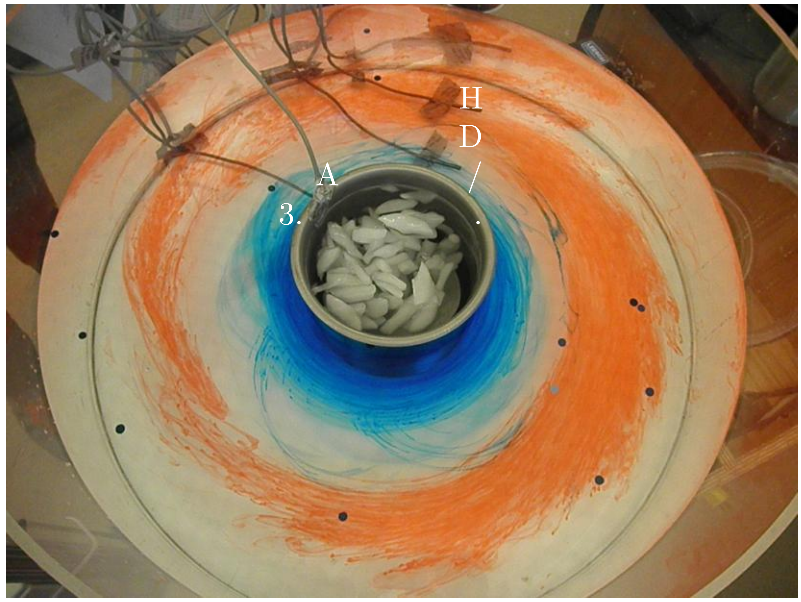


This overturning is amplified in a rotating system by conservation of momentum atop [project 1's radial inflow: "currents increase in speed as they move towards center"] & by overall fluid density separation causing different directions of flow. [project 2's polar dome: "rotating fluid interfaces along a front with a slope density gradients

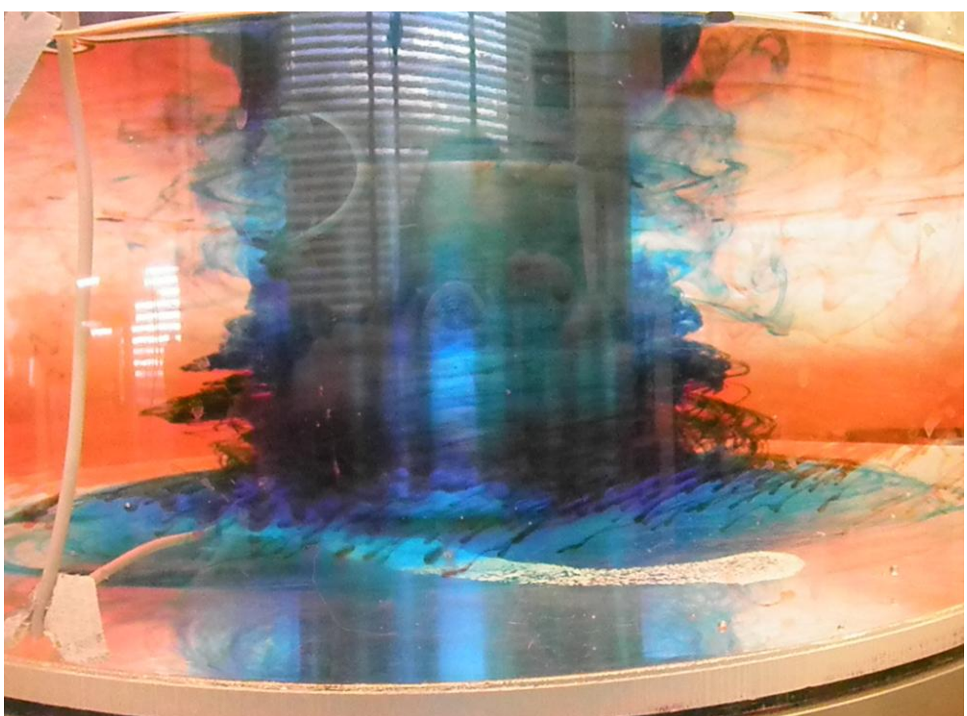
Here the in-tank behaviors shown in their dominant sectional and circumferential components. When composed, these predict a corkscrewing behavior forming what is known as a Hadley Cell.



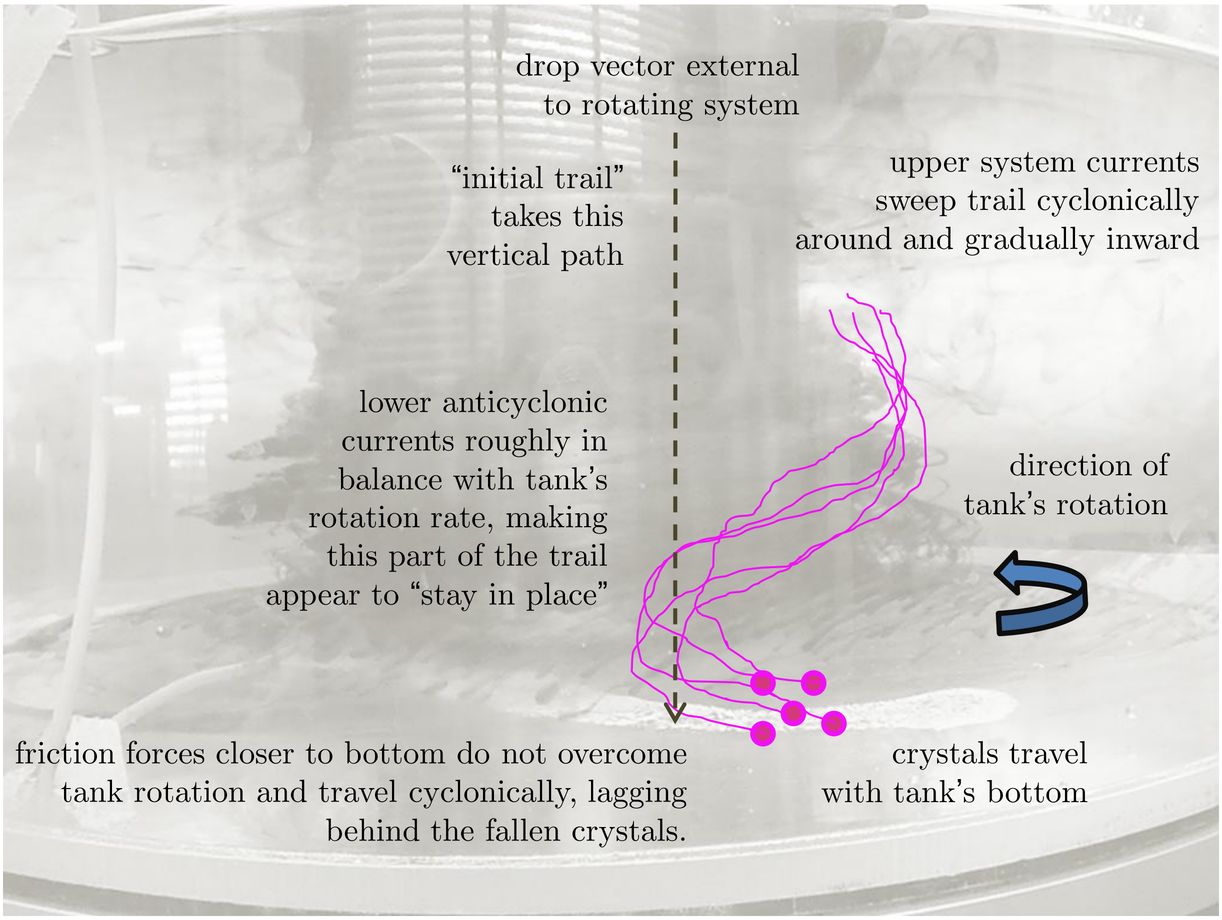




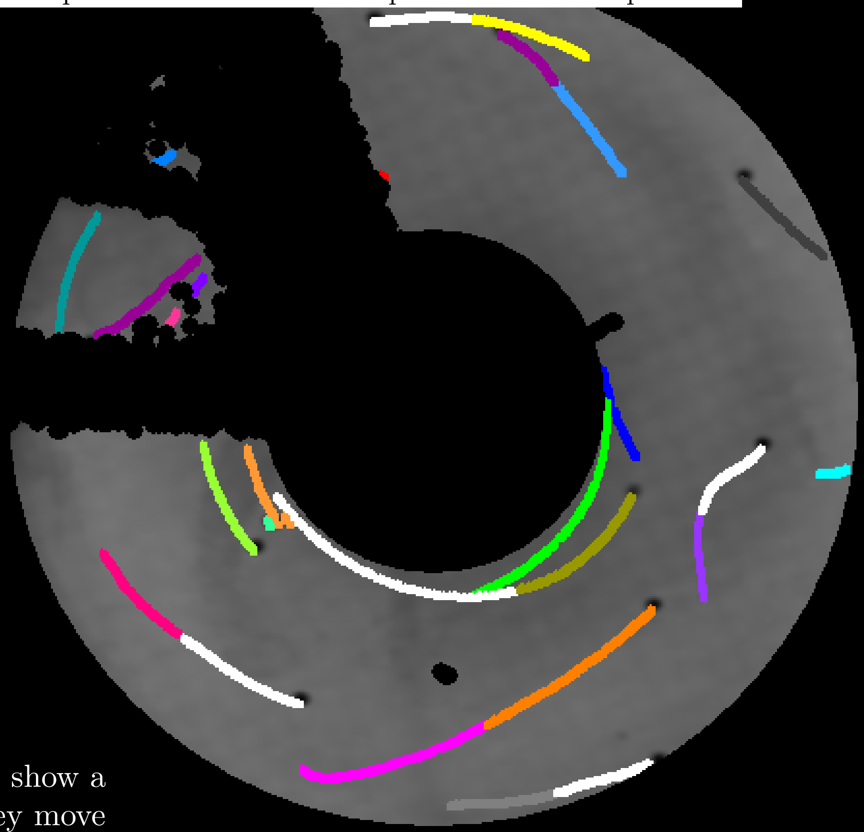
Dye is deployed to track current paths.
Red dye placed in ambient/warm water – visible cyclonic motion shown above.
Blue dye placed closest to cold source/heat sink.



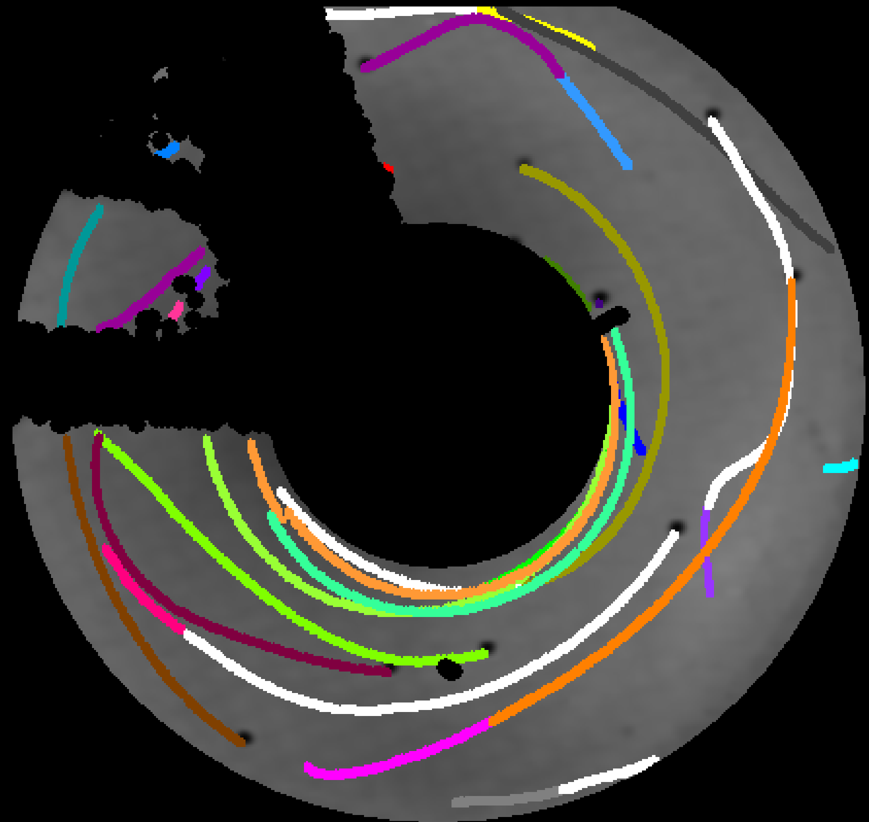
Anticyclonic corkscrewing near tanks bottom surface
pulls cold currents into a shape beginning to visually approximate a ‘cold dome.’



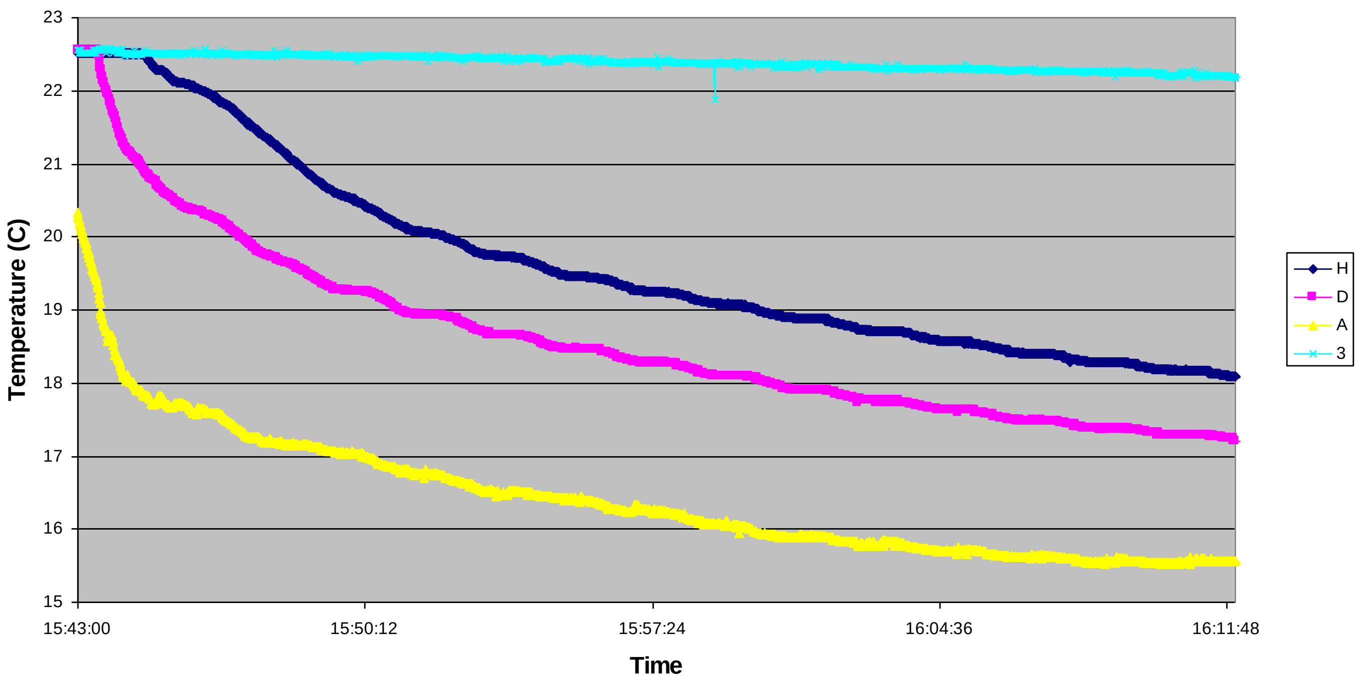
Recreated visual representation of permanganate dropped into tank.



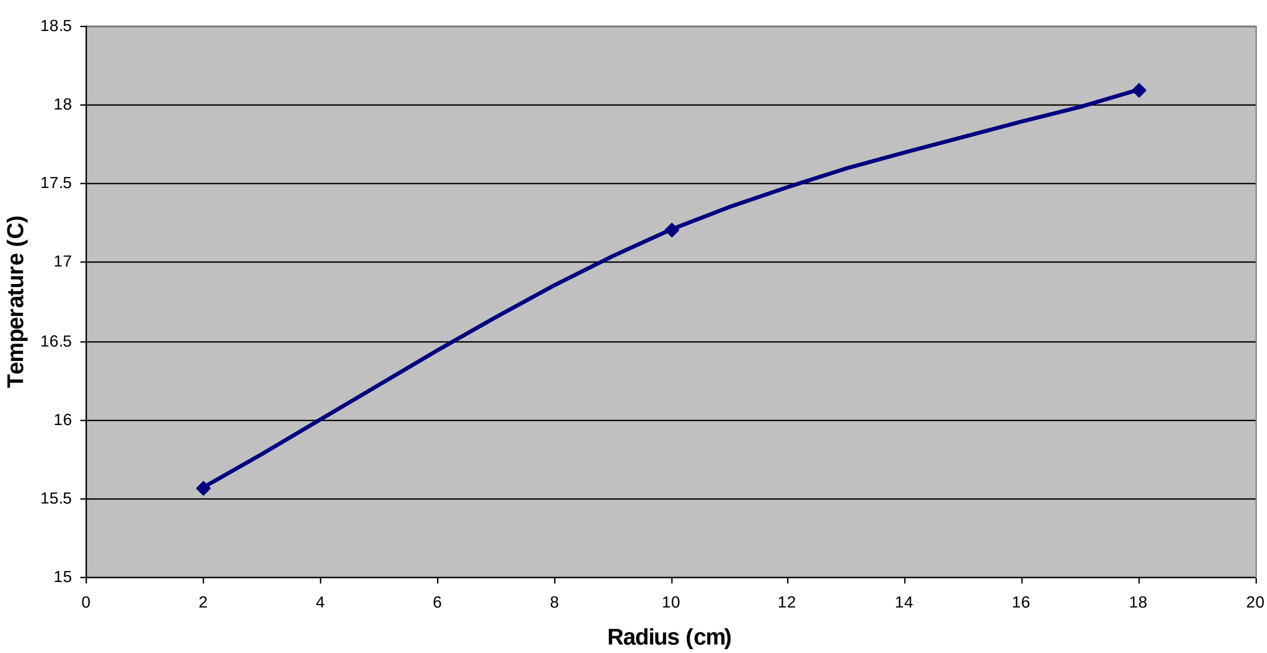
Particle tracker captures could show a simple speeding up of currents as they move inward, if soon after the introduction of ice, or if the cell is very developed, a maximizal speed may occur near the middle ring, slowing down near the center.



Temperature Over Time



Temperature Gradient, dT/dr



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$$\frac{\partial u}{\partial z} = -\frac{g\alpha}{2\Omega}\frac{\partial T}{\partial r}$$

Calculating Thermal Wind Balance

$u_{top} = 0.01\ ms^{-1}$ (*?)

$u_{bottom} = \tilde{}0.0\ ms^{-1}$

$du = \tilde{}0.01\ ms^{-1}$

$dz = 0.10\ m$

[tank depth]

*? – group member measurement

$g = 9.8\ ms^{-2}$

[gravity]

$\alpha = \tilde{}\ 2x10^{-4}\ K^{-1}$

[thermal expansion coefficient of water]

$g\,\alpha = .00196\ ms^{-2}\,K^{-1}$

$\Omega = .5\ rpm * \frac{2pi\ rad/r}{60\ s/m} = .052\ rads^{-1}$

$2\Omega = .104\ rads^{-1}$

$dT = 18.1^oC - 15.6^oC = 2.5\ K$

$dr = 18.5\ cm - 2\ cm = 16.5cm$

$\frac{du}{dz} = \frac{0.01\ ms^{-1}}{0.10\ m} = .1\ s^{-1}$

$\frac{g\,\alpha}{2\Omega} = .0188\ ms^{-1}K^{-1}$ [rad]

$\frac{dT}{dr} = \frac{2.5\ K}{.165\ m} = 15.15\ Km^{-1}$

$$\frac{\partial u}{\partial z} = -\frac{g\alpha}{2\Omega}\frac{\partial T}{\partial r}$$

$.0188\ ms^{-1}K^{-1} * 15.15\ Km^{-1} = .28\ s^{-1}$

Assuming

$u_{top} = 0.01\ ms^{-1} \rightarrow .1\ s^{-1} = .28\ s^{-1}$

Close! [same order of magnitude], but what would $\mathbf{u_{top}}$ on the left be if we assume veracity on the right?

$\frac{du}{dz} = \frac{\mathbf{u}\ ms^{-1}}{0.10\ m} = .28\ s^{-1}$

$u_{top} = 0.028\ ms^{-1} \leftarrow$ This is over twice the measured speed. Not a ridiculous measurement, depending on where our 1 cm/s measurement was taken from.

In class we discussed decreasing the considered **z** height of the thermal wind behavior to correspond with the region it's acting over, that is, less than the water height, 10 cm. Again, assuming veracity of the right, and this time assuming our 1 cm/s measure was correct, what percentage of the total height does thermal wind balance occur?

$u_{top} = 0.01\ ms^{-1} \rightarrow \frac{du}{dz} = \frac{0.01\ ms^{-1}}{\mathbf{z}\ m} = .28\ s^{-1}$

$3.5\ cm \leftarrow \mathbf{z} = .035\ m = 3.5\ cm$

$3.5/10\ cm = \mathbf{35\%}$

[tank depth]

$\leftarrow$ Thermal wind dominance in the bottom third of the tank? Maybe. What if we try **50%, or 5cm**, as the behavior diagram on the preceding pages depict.

$\frac{du}{dz} = \frac{\mathbf{u}\ ms^{-1}}{\mathbf{.05}\ m} = .28\ s^{-1}$

$\rightarrow u_{top} = 0.014\ ms^{-1}$

0.014 predicted/ .01 measured = 1.4

less than 1.5 could be considered within reasonable bounds of measurement errors or velocity variations within tank-radius

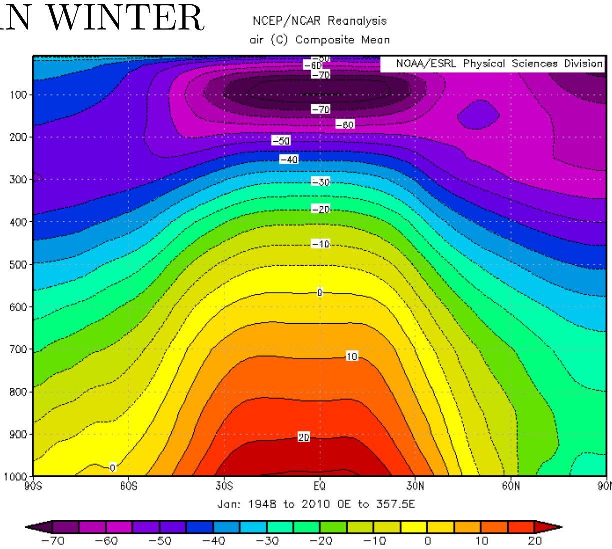
tropic

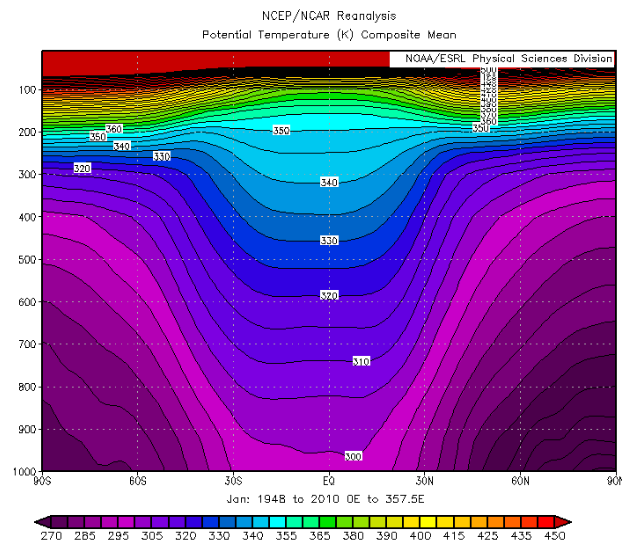
Hadley circulation predominates in a band around Earth's equator. Average temperature graphs imply that this circulation method very effectively maintains consistent temperatures across this band.

Potential temperature graphs show the underlying tendency of air's gathering into "polar domes". Potential temperatures steep slopes at the middle latitudes give us an indication of the area where front-like behavior and windshear phenomenas arise, marking a regime change displayed in the next section.

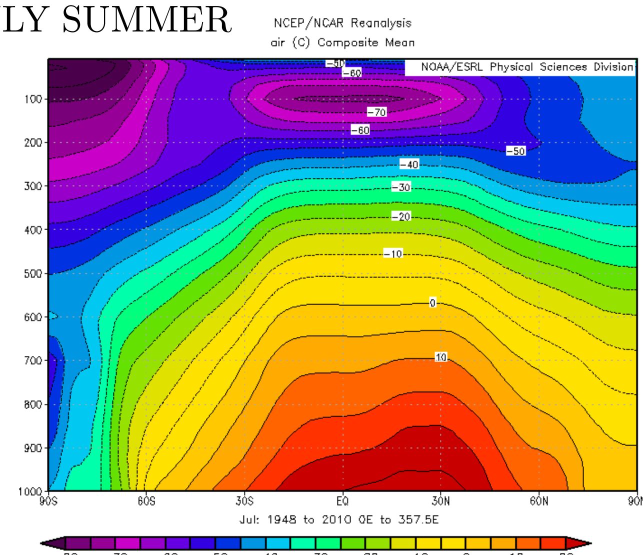
Coriolis forces become relevant / dominant around 30 degrees latitude. This determines a relevant band of interest for studying the complex directional flows occurring in Hadley cell's expression on the earth's surface.

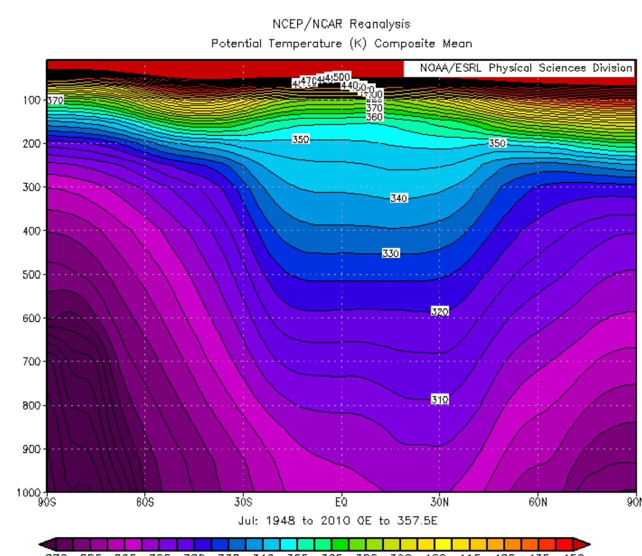
JAN WINTER





JULY SUMMER

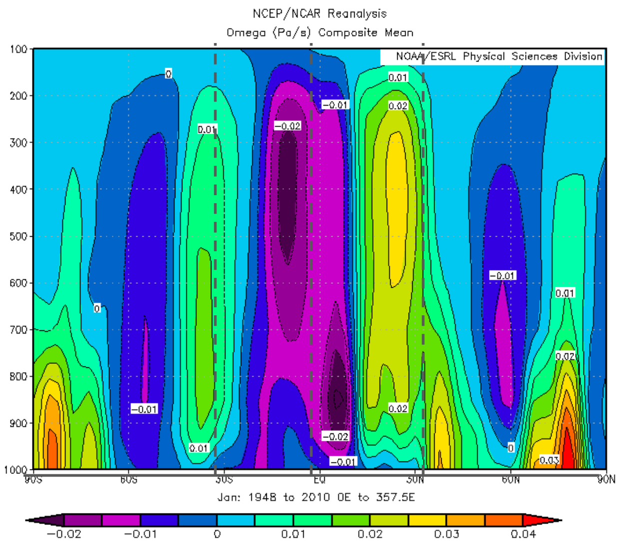




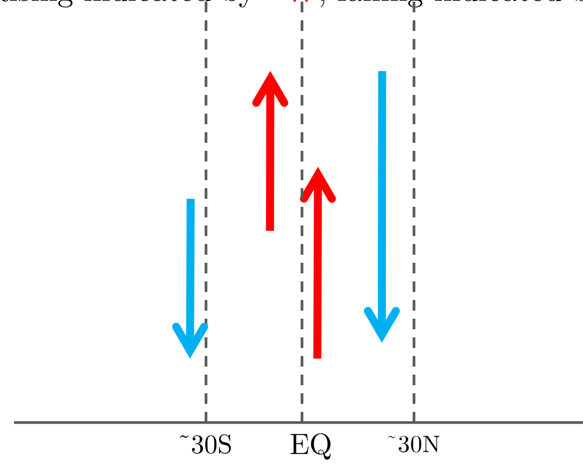
Summer months show a net/sum differential heating concentrated in the Norther Hemisphere. This would suggest a shift in the incoming solar radiation vector that agrees with understandings of Earth axis tilt relation to seasonal weather variation.

The impact on the potential energy field is a Northern polar dome of decreased size, meaning a less steep rise in the Nhem middle latitudes. This then would correposnd to less drastic differences in windspeed/shears—fronts of lessened intensity correlating to decreased storm activity.

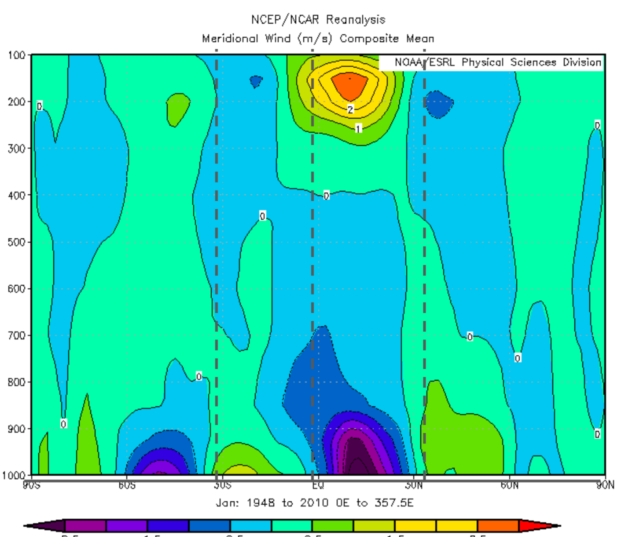
JANUARY / "WINTER" in N_{hem}



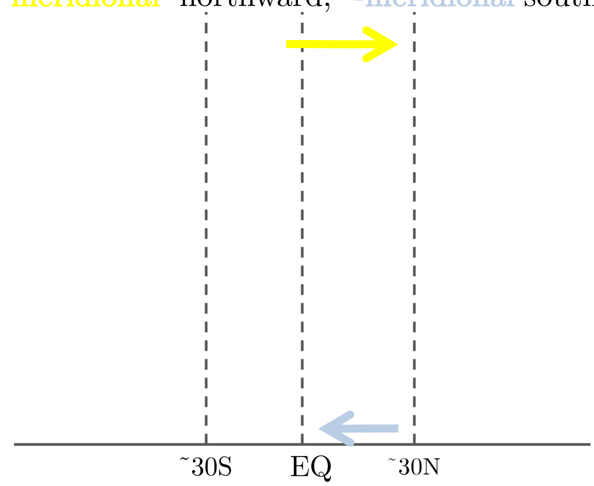
Omega cues us in to the rising and falling of air
Rising indicated by −W, falling indicated by +W

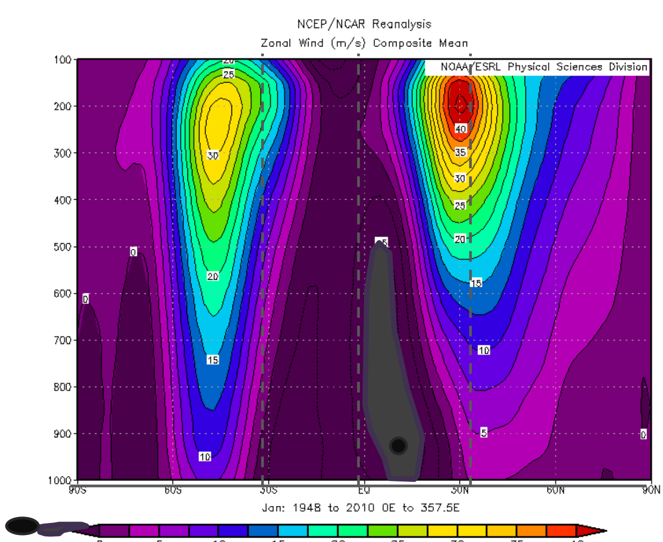


~band of interest

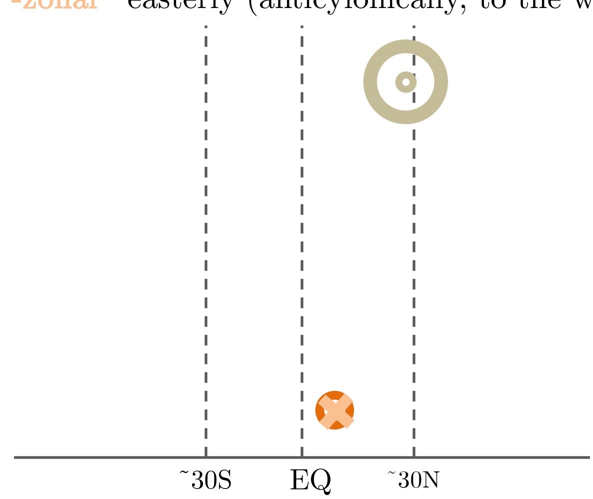


Meridional winds are winds running longitudinally
+meridional northward, -meridional southward





Zonal winds run latitudinally
+zonal westerly (cyclonically, to the east),
-zonal easterly (anticyclonically, to the west)



tank experiments atmospheric data	hadley cell / tropic	eddie transfer extra-tropic

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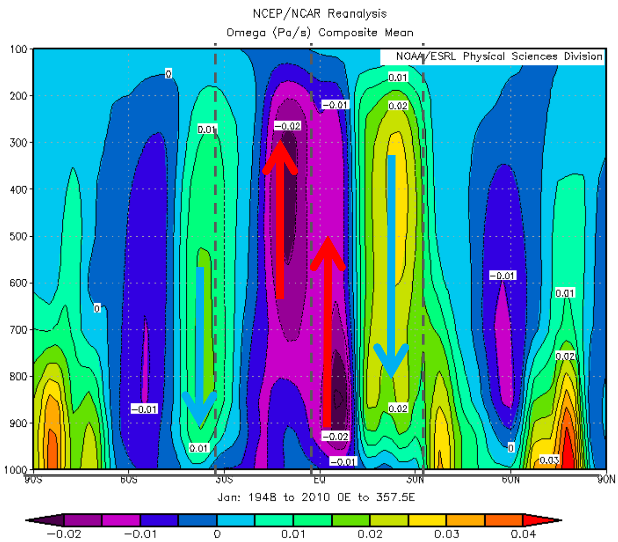
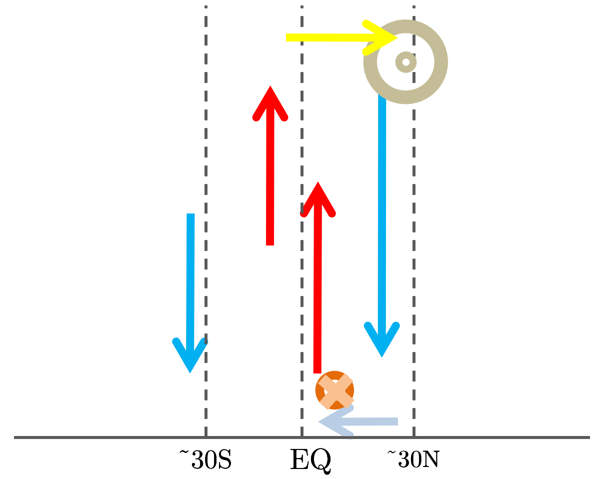
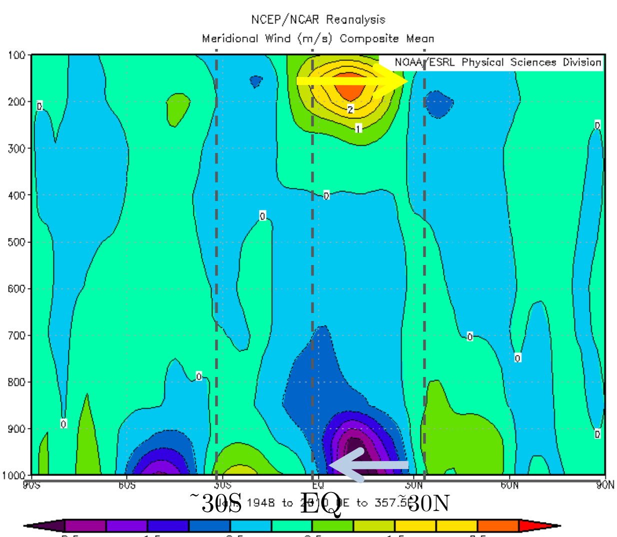
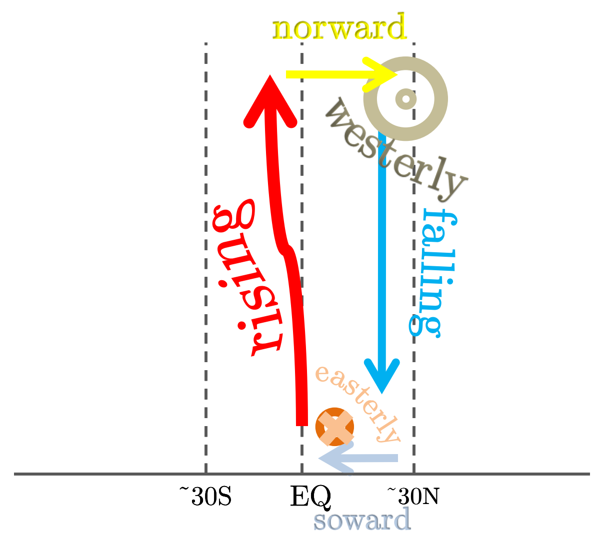


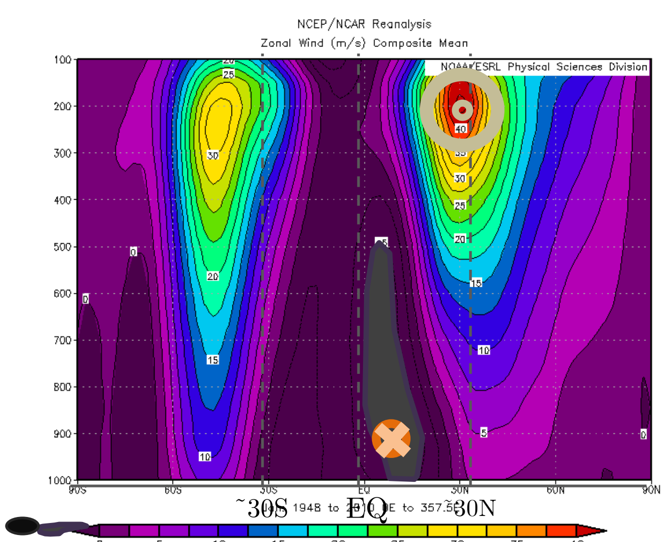


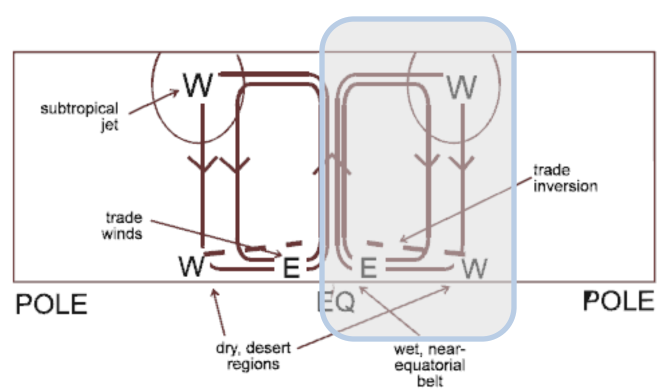
JANUARY / WINTER in N_{hem}





Dominant mode





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atmospheric data

hadley cell

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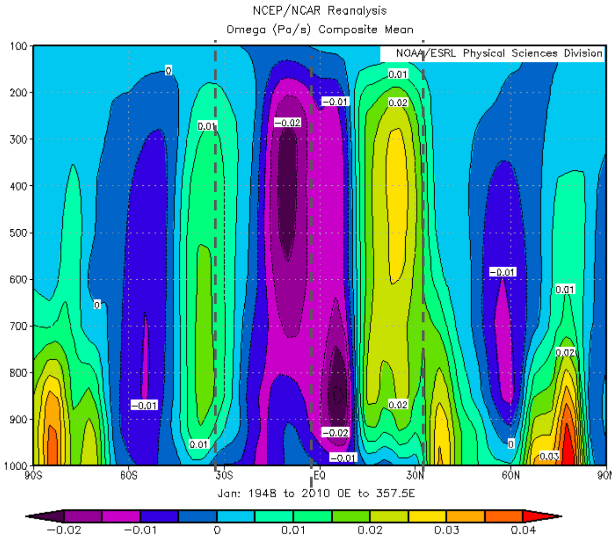
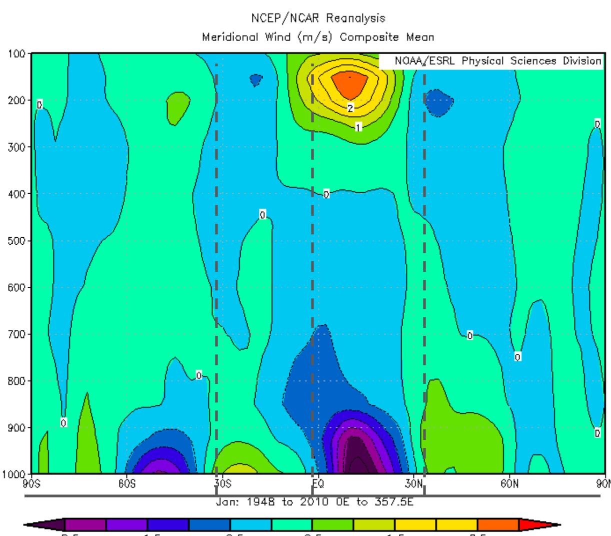
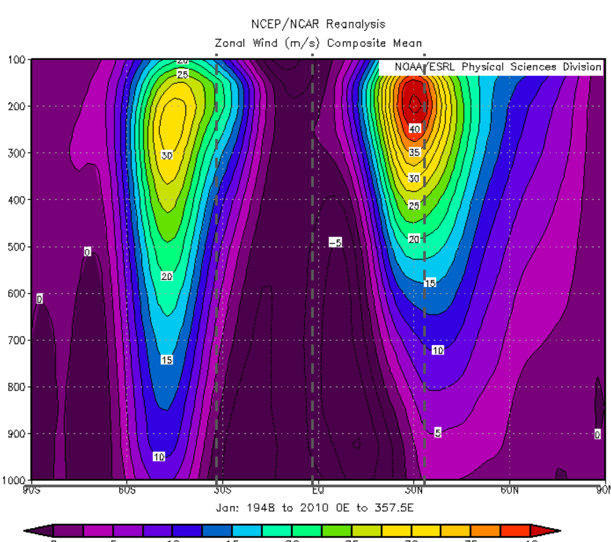
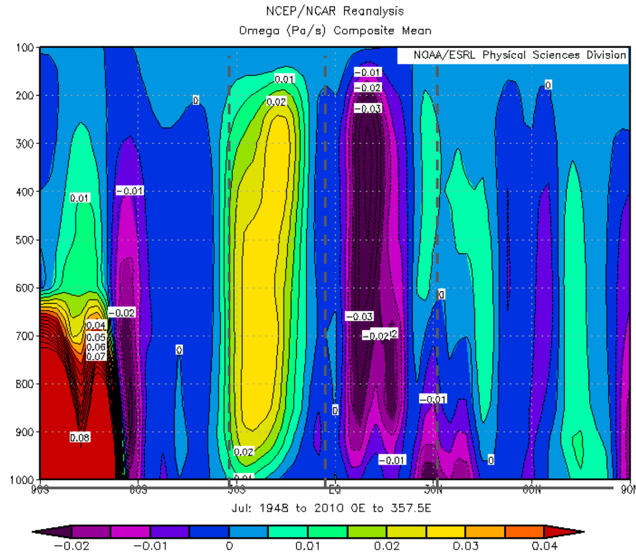
JANUARY / “WINTER” in N_{hem}

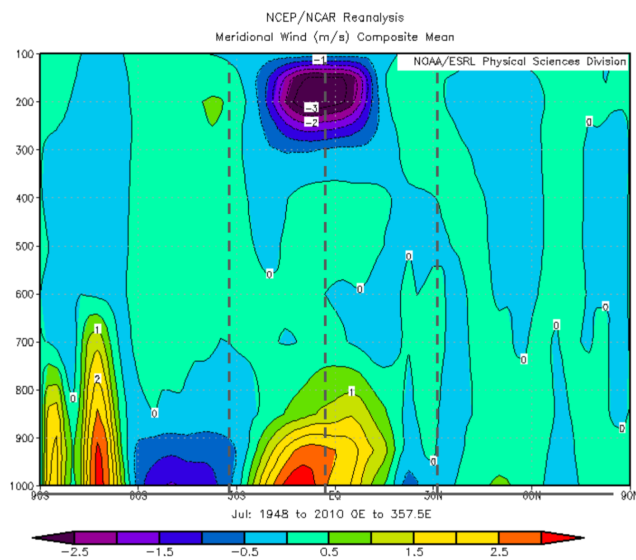


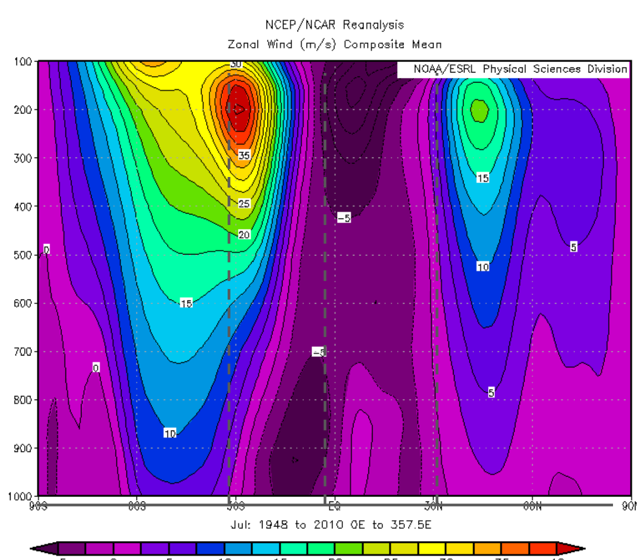




JULY / “SUMMER” in N_{hem}







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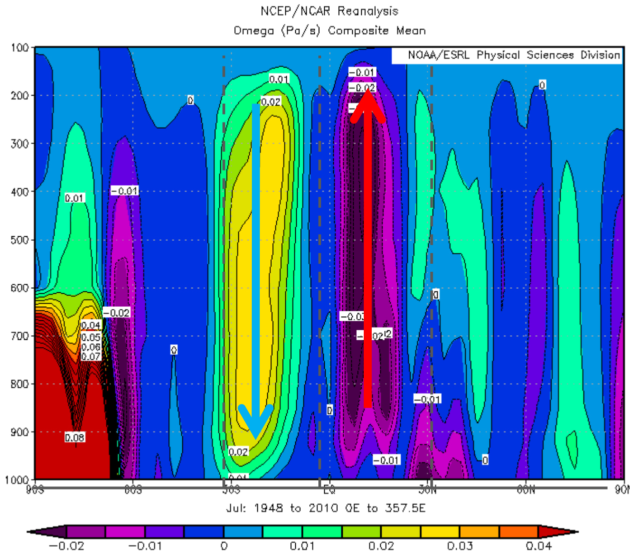
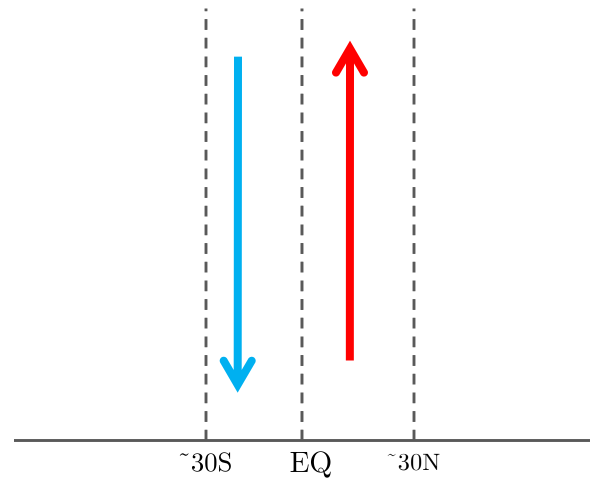
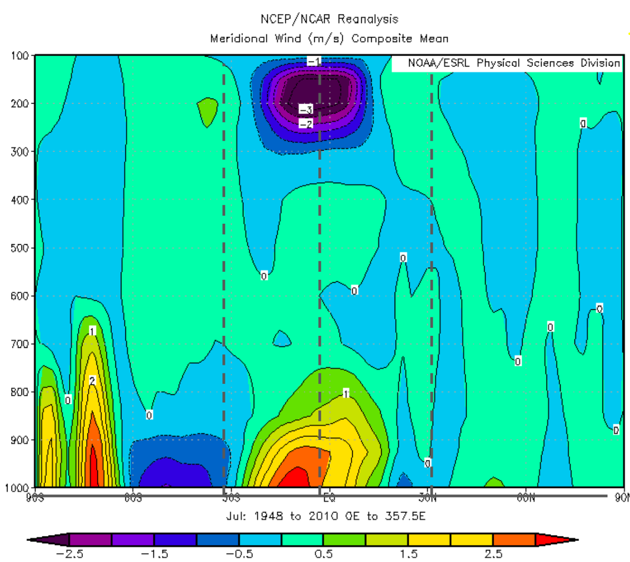


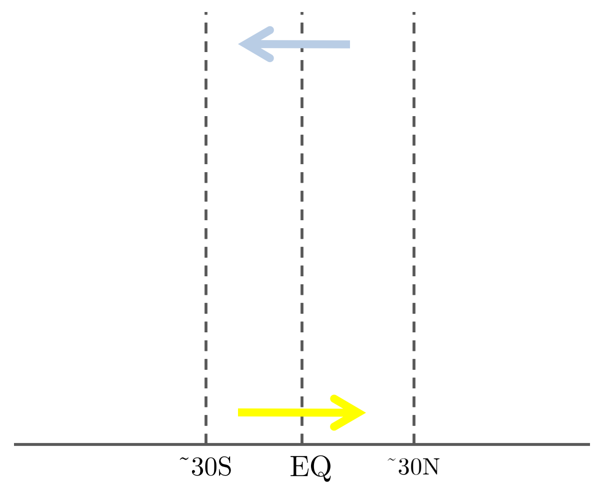
Rising indicated by −W, falling indicated by +W



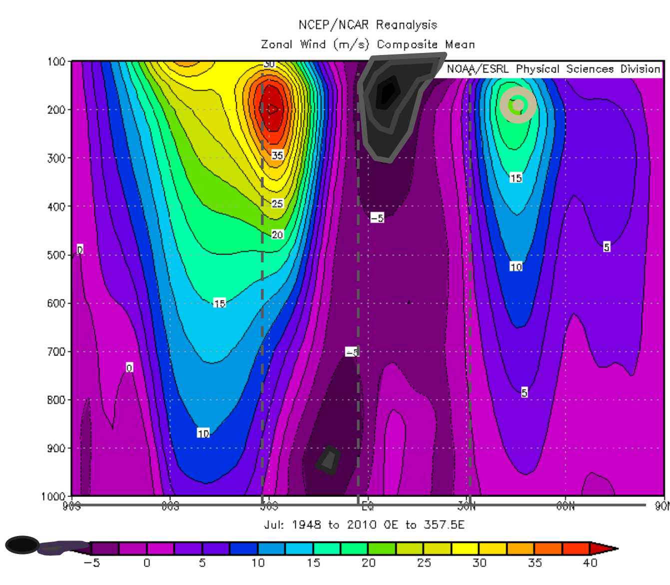
~band of interest

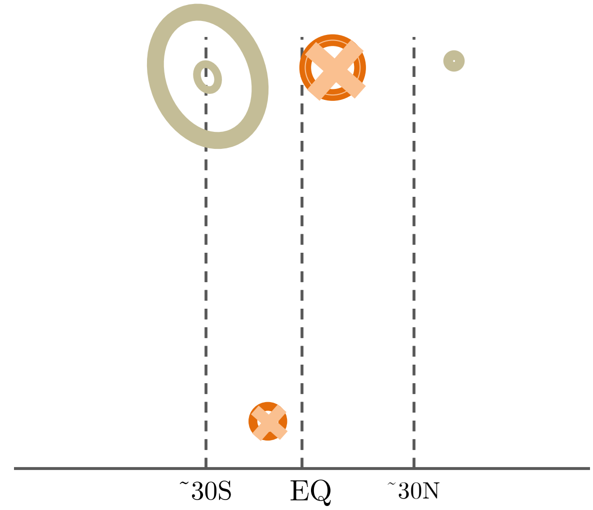


+meridional northward, -meridional southward



+zonal westerly (cyclonically, to the east)
-zonal easterly (anticyclonically, to the west)





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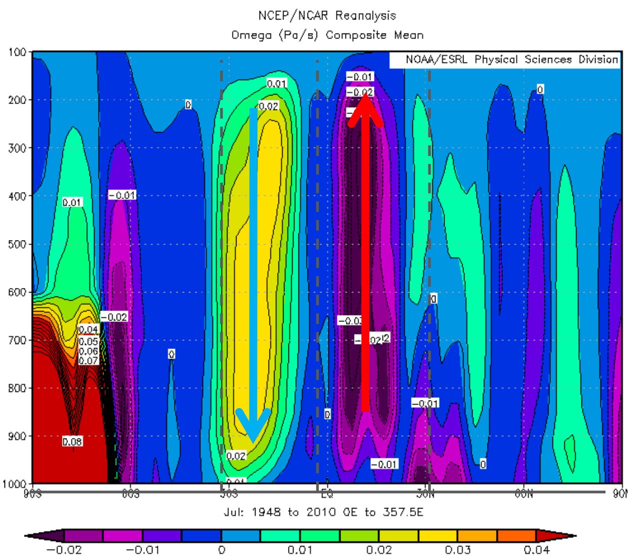
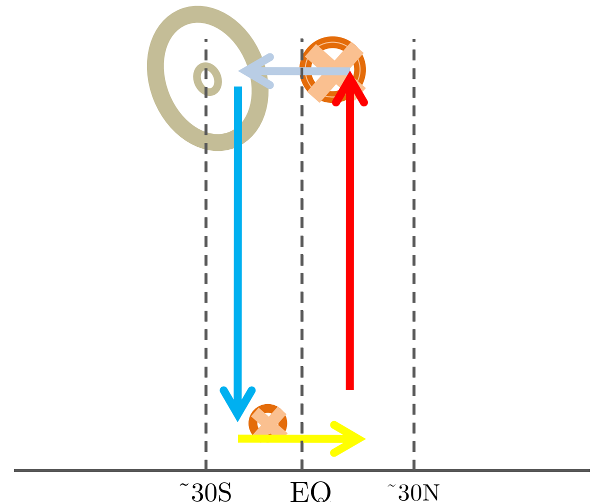
JULY / “SUMMER” in N_{hem}





~band of interest

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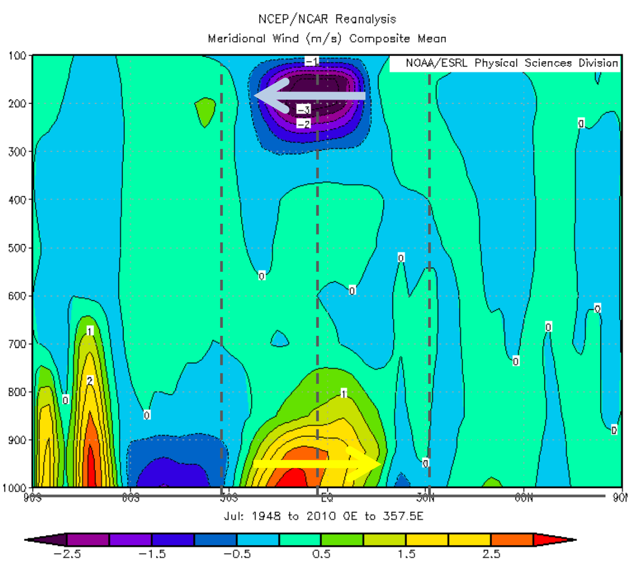
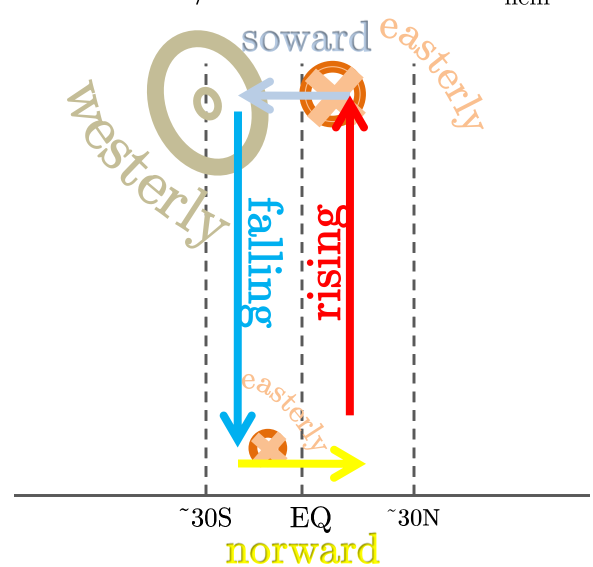
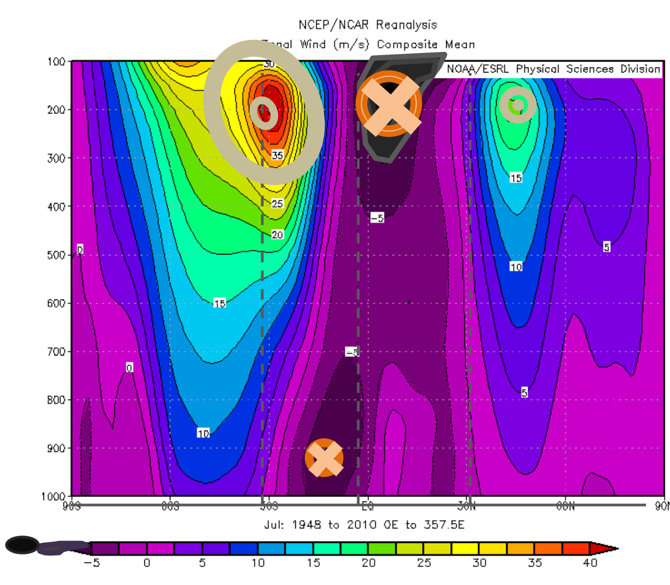
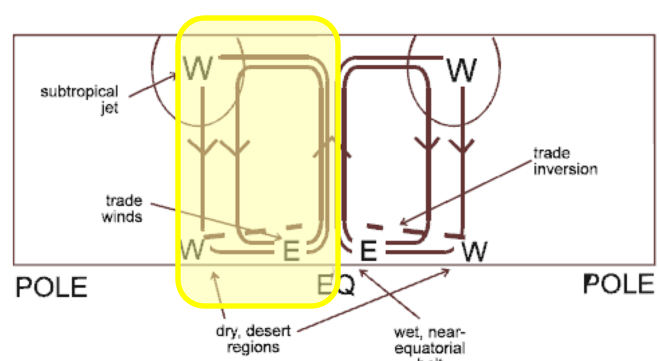
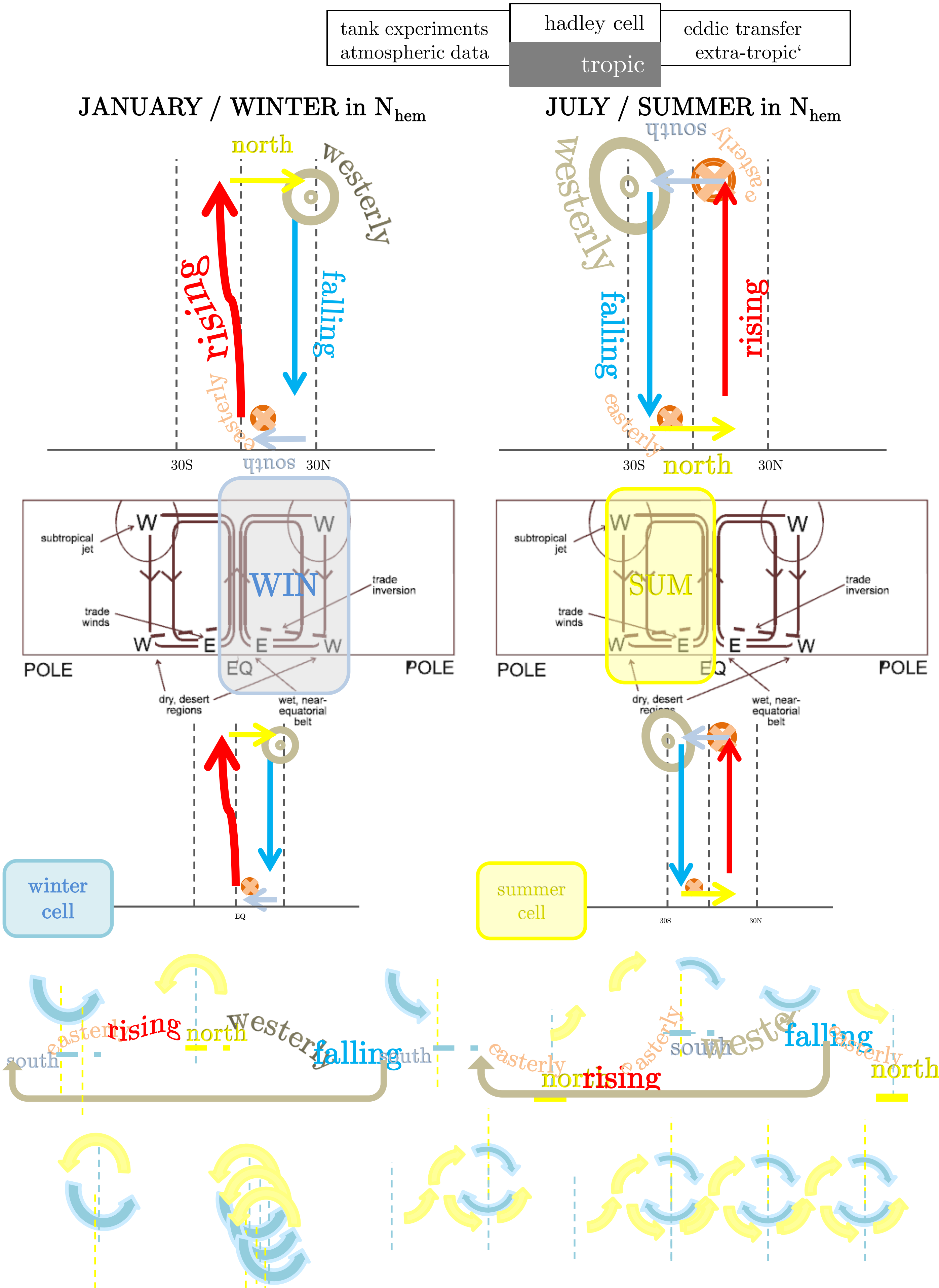






Dominant mode





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JANUARY / WINTER in N_hem
JULY / SUMMER in N_hem
north
westerly
rising
falling
easterly
south
30S
30N
subtropical jet
trade winds
trade inversion
W
E
EQ
POLE
WIN
SUM
dry, desert regions
wet, near-equatorial belt
winter cell
summer cell
EQ
30S
30N

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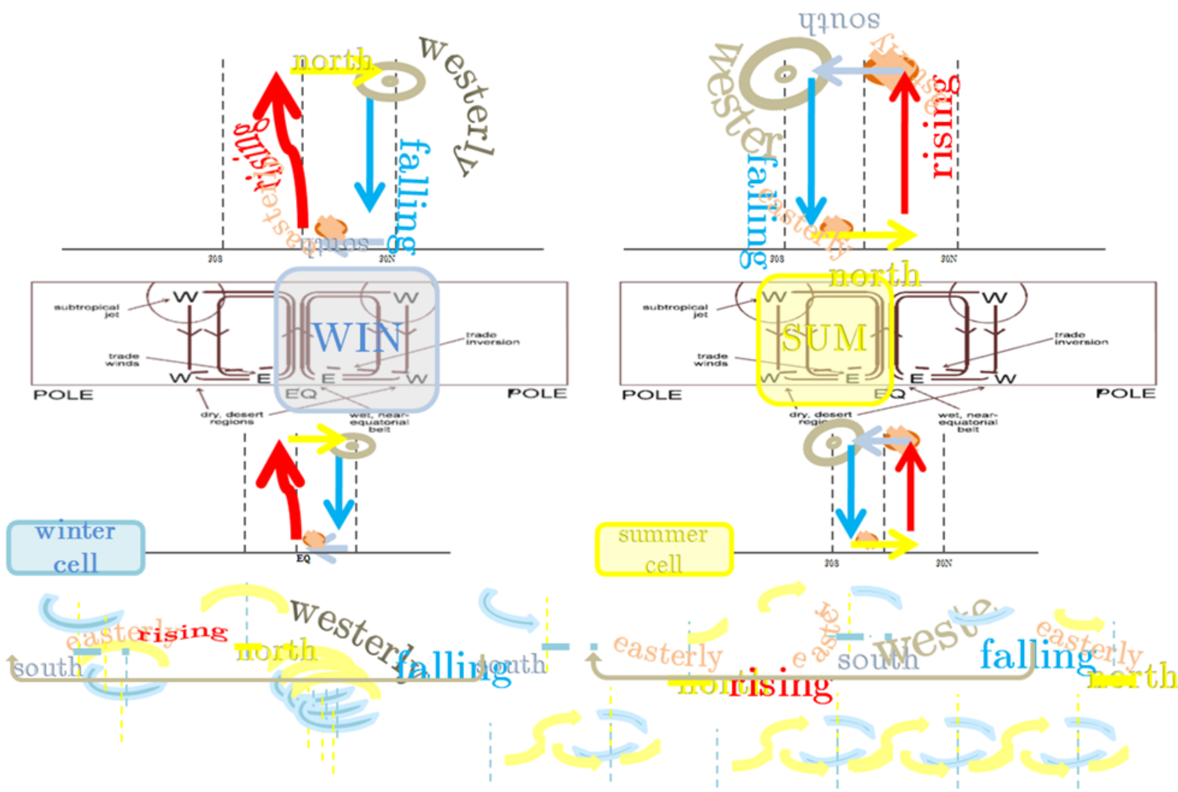
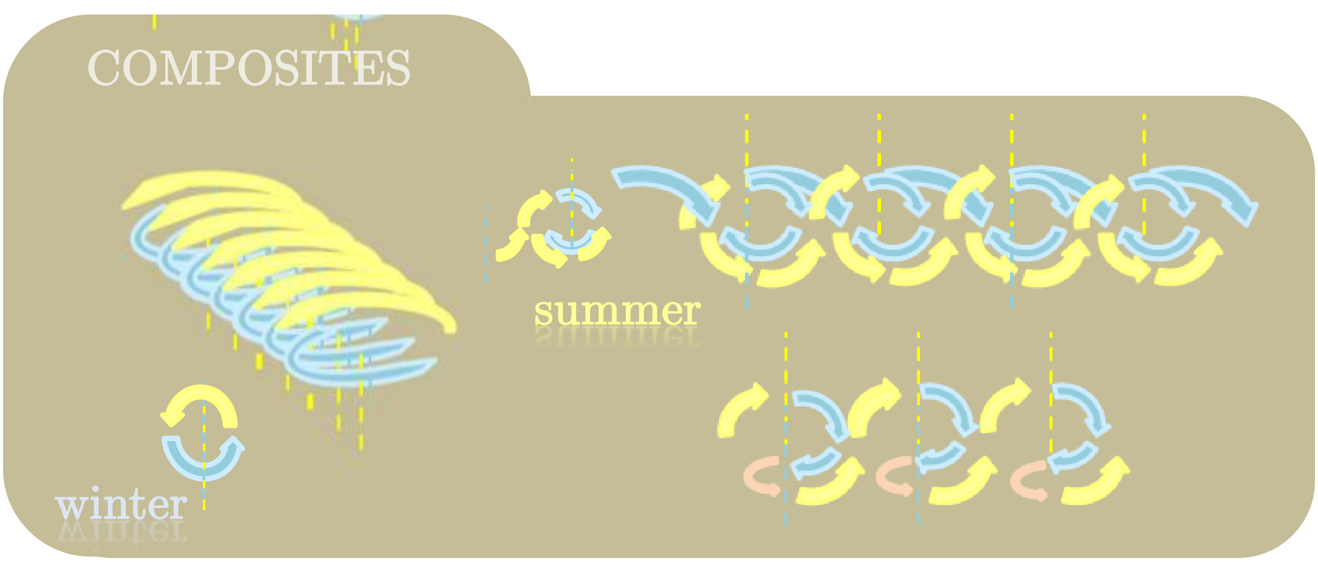
	tropic	

JANUARY / WINTER in N_{hem} **JULY / SUMMER in N_{hem}**





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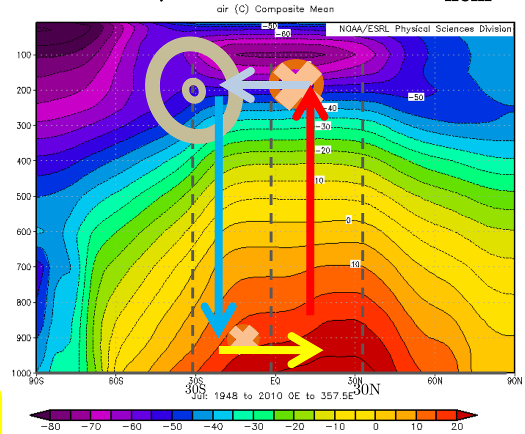
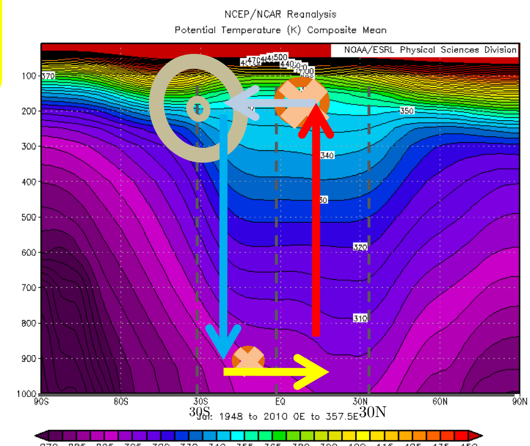


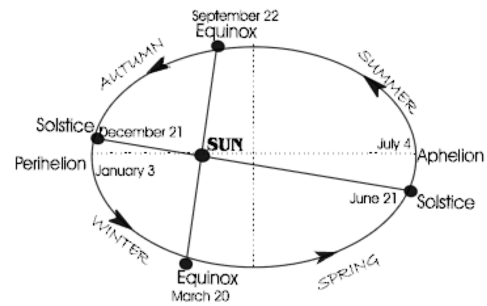
Avg Temp
1948 -2010

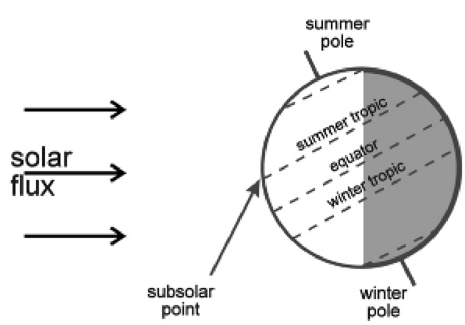
JUN
summer
cell



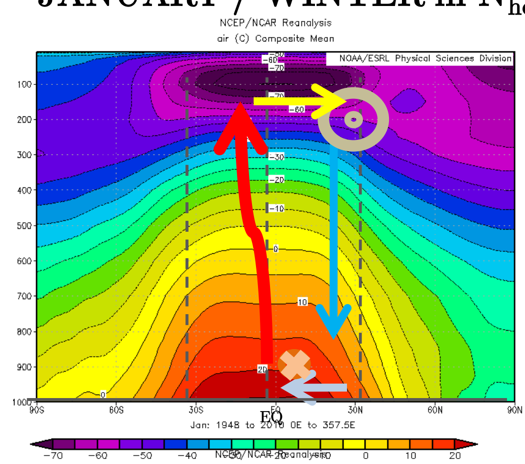
Pot. Temp
1948 -2010

Summer: Incoming solar radiation occurs at a latitude north of the equator, thus we observe the most significant upwelling occurring north of equator. Because the Hadley regime appearance in the equatorial latitudes is dependent on gravity's relation to axis of rotation, the Hadley cell will still occur within this band. One reason we get the cell pictured at left, loosely worded (and probably "backwards" in terms of cause & effect), is that there doesn't seem to be enough room between the upwelling's location and the 30N latitude for a complete "sectionally clockwise" cell, that is, a northward meridional jet would quickly enter the (I believe, higher pressure?) latitudes of the eddy regime, thus we have air traveling south, generating strong westerlies in the southern hemisphere, giving them their "winter."



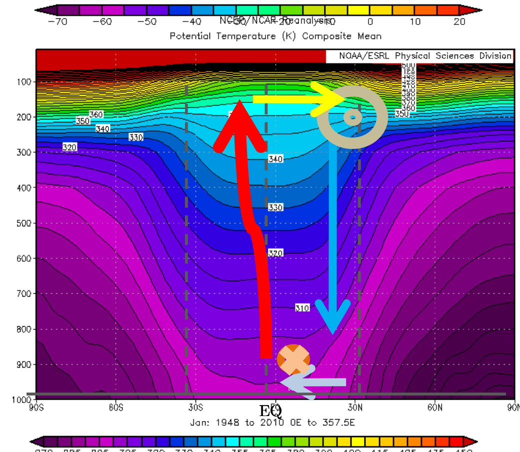


JANUARY / WINTER in N_{hem}



Avg Temp
1948 -2010

JAN
winter
cell



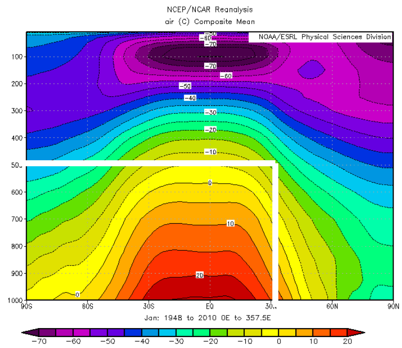
Pot. Temp
1948 -2010

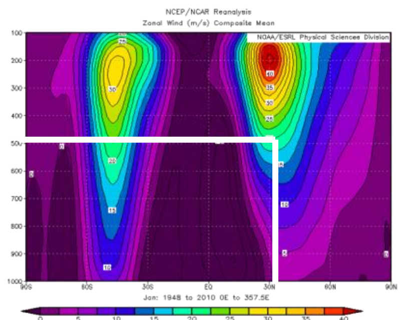
Winter: Rising action occurs on or below equator, since the winter pole is closer to the sun during this part of earth's orbit--incoming solar flux is focused more on the winter tropic. Northward meridional flows generate strong westerlies in the northern hemisphere, here these westerlies are interfacing with the eddy regime to do further heat transport. Downward flow also occurs here around 30N, from air that has cooled in the process (and also from cold air that enters the westerly flow from the eddy exchange?) Further analysis is enabled by graphics overlaying composite flows onto earlier temperature graphs, which I've done "roughly" scaled appropriately to pressure levels that vary between plots.

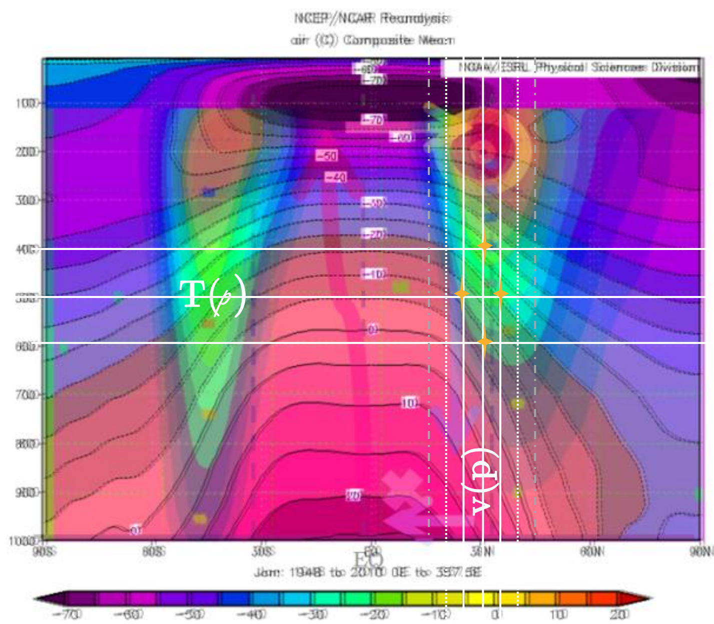
------------------------- *air current to air temperature relations* ----------------

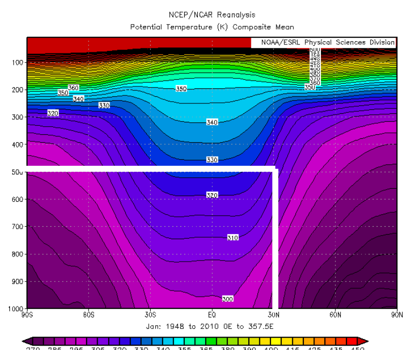
After a brief analysis, one interesting feature found is that the location of the westerly jet aligns extraordinarily close with the convergence of Potential Temperature gradient lines of both positive and negative slopes. This would correspond with the "surface" of the water in our fronts experiment—particles on the surface move the fastest where the inclide of the front surface is most steep. You can also view how the downwelling aligns very closely with the end of the average temperature's uniform zone and the beginning of the potential temperature's steep rise.

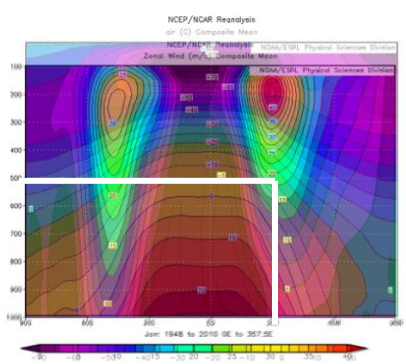
tank experiments atmospheric data	hadley cell	eddie transfer extra-tropic
	tropic	











$$\frac{du}{dp} = \frac{R}{f\,p}\,\frac{dT}{dy} \quad \downarrow \ 500\text{mb}$$

$du = v(400\text{mb}) - v(600\text{mb})$

$R = 287$ gas constant

$dT = T(35^\circ) - T(25^\circ)$

$dy = 10^\circ$ lat $\times$ 110 km/lat $\times$ 1000 m/km

$dp = -200\text{mb}$

$p = 500\text{mb}$

$dy = 1100\,000$ m

$v(400^{\text{mb}}) = 26.5\ \text{ms}^{-1}$
$v(600^{\text{mb}}) = 14.5\ \text{ms}^{-1}$

$f = \cancel{2}\,\Omega\,\cancel{\sin\varphi} = \Omega$, $\varphi = 30^\circ$

$T(35^\circ) = -20^\circ\text{C}$
$T(25^\circ) = -10^\circ\text{C}$

$du = 12\ \text{ms}^{-1}$

$f = 7.27\text{x}10^{-5}\ \text{rads}^{-1}$

$dT = -10^\circ\text{K}$

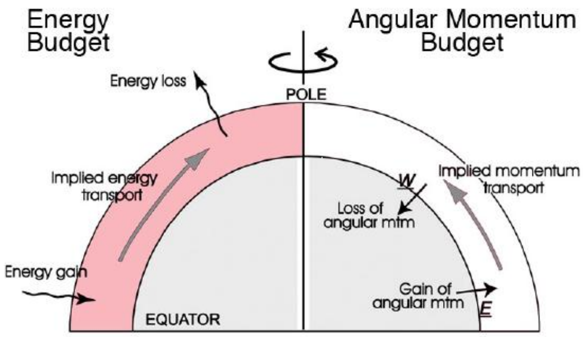
$$\frac{12}{-200} = \frac{287}{(7.27 \times 10^{-5})\ {}^{*}500}\ \frac{-10}{1,100,000}$$

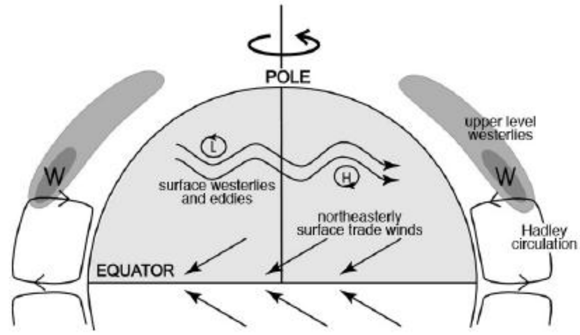
$$-.06 = 7895.5\ \frac{dT}{dy}$$

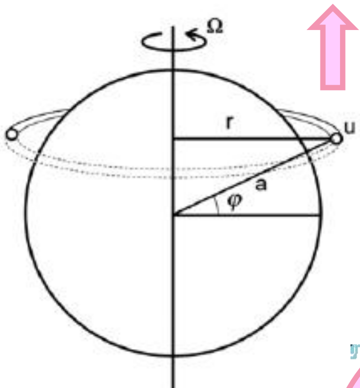
$$\frac{dT}{dy} = -9.09\text{x}10^{-6}$$

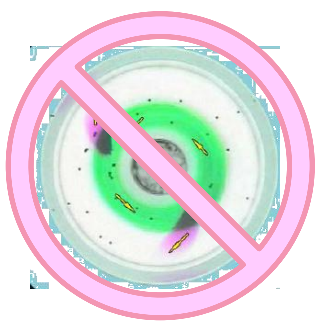
$$.06 \cong .0718$$

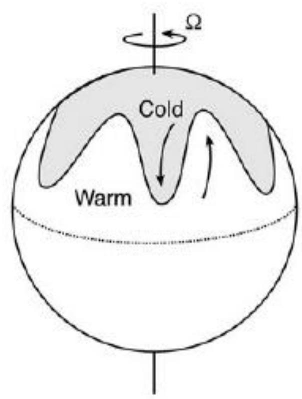
eddy transfer

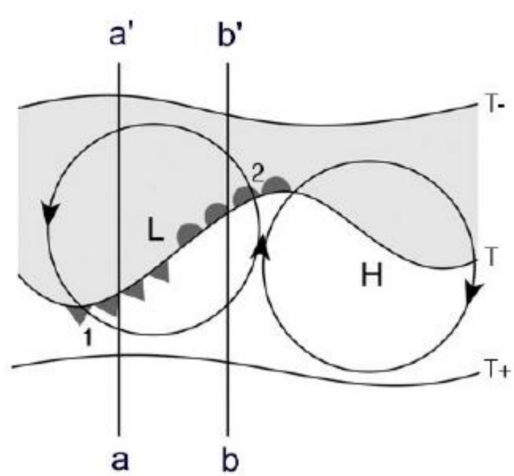


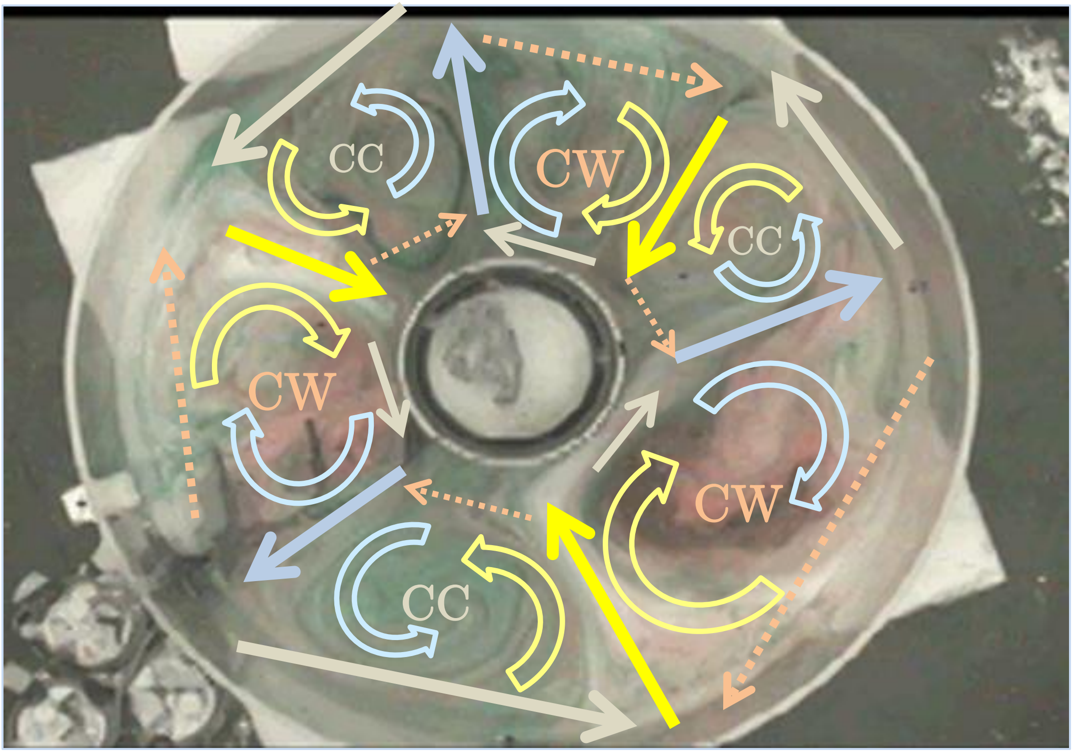








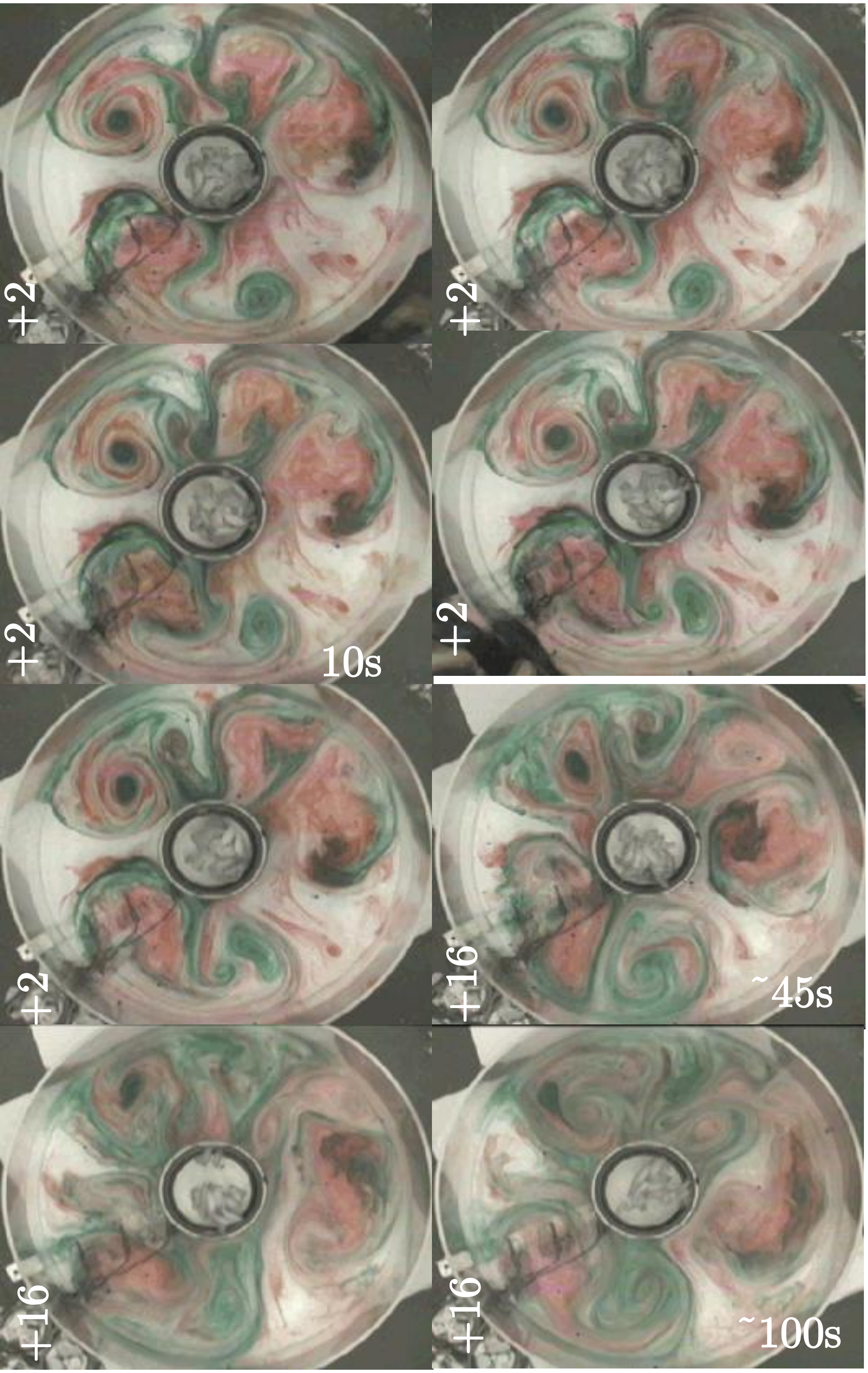




yellow & blue tracks correspond to
rapid N & S meridional transit

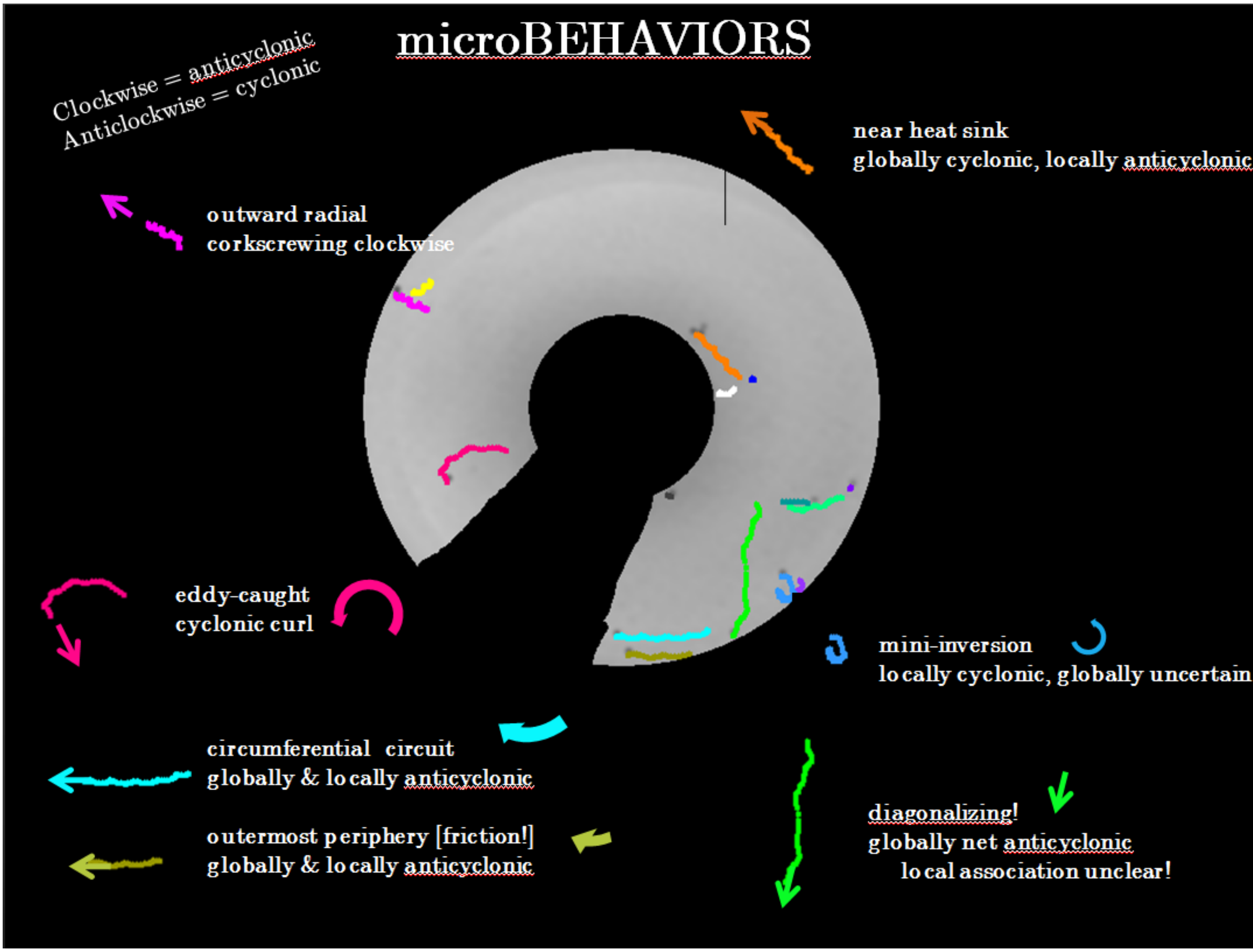
when these tracks are composed together, eddies form

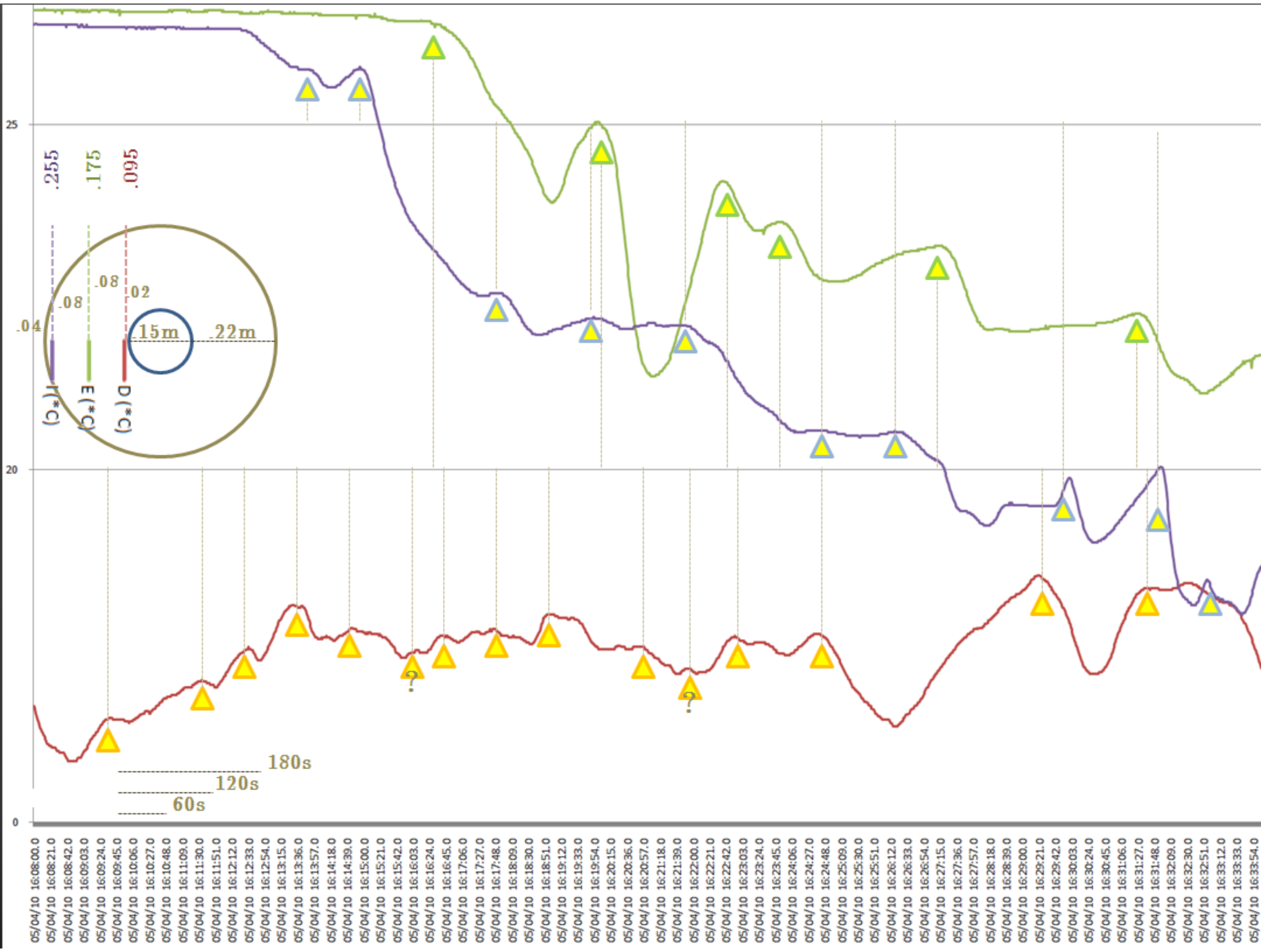
tank experiments	hadley cell	eddy transfer
atmospheric data	tropic	extra-tropic



10x speed, 6fps

tank experiments	hadley cell	eddie transfer
atmospheric data	tropic	extra-tropic





Tracing fluctuation of sensor E, the green line above.

-2.5 +1 -3.5 + 2.5 -.75 +.25 -1 +.5 -1.5 +.25 -1.33 +.66

Net episodic = **-.903**

-1.5 -1 -.5 -.5 -1.25 -.66

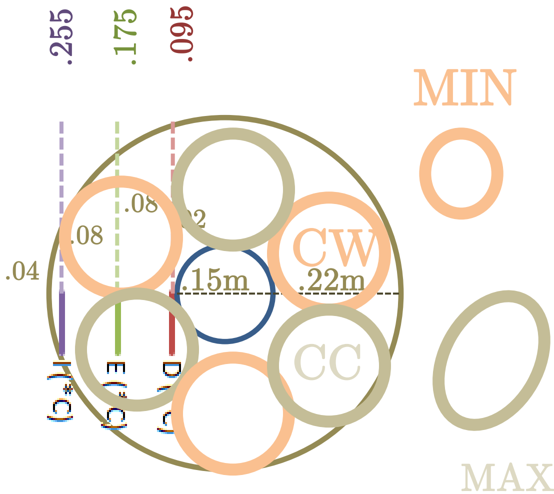
Average negative = -1.76

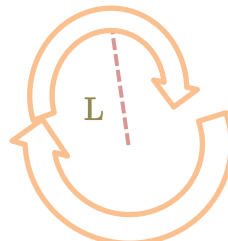
-2.5 -3.5 -.75 -1 -1.5 -1.33

Net average trend = **-.91**

Average positive = +.85

+1 + 2.5 +.25 +.5 +.25 +.66





L = eddy radius r = 1 / 2 distance between cold source & ext. env.

$L = .11\text{m}$

$f = 2\Omega = 2.01\ \text{s}^{-1}$

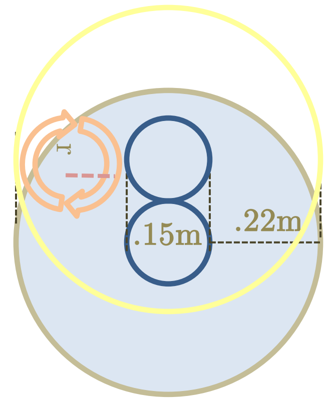
$Ro = u / 2\Omega L,$

rossby number on an eddy's scale

[accurate calculation dependent upon further visual data analysis]

radial heat flux

$$L\frac{\Delta m}{\Delta t} = \rho\, c_p \int \oint \overline{v'T'}\,dz$$



$L = 333\ kJ\ kg{-1}$

$z = .15m$

$1.07\ kg$ of ice @ $T_{start} = 2m\ 40s$

$c_p = 4.2\ kJ\ kg^{-1}\ K^{-1}$

$0.0\ kg$ of ice @ $T_{end} = 23m\ 06s$

$\rho = 1000\ kg/m^3$

$\Delta m_{ice} = -1.07\ kg$

$\oint = 2\ pi * r$

$r = .11m$

$\Delta T = 1226\ s$

$\oint = .6912\ m$

$L\frac{\Delta m}{\Delta t} = -.29\ kW$

$\rho\, c_p = 4200\ kJ\ K^{-1}\ m^{-3}$

[pending visual calculations assumption on correct order of → magnitude pulled from lab guide]

$T' = -.91\ ^oK$

$v' = 6 \times 10^{-4}\ m\ s^{-1} = .6\ mm\ s^{-1}$

$\oint v'T' = -5.46 \times 10^{-4}\ ms^{-1}K \quad * .6912\ m$

$\int \oint v'T'\,dz = -3.77 \times 10^{-4}\ m^2s^{-1}K \quad * .15\ m$

$\int \oint v'T'\,dz = -5.66 \times 10^{-1}\ m^3s^{-1}K$

outwardly for 1226s

$-.29\ kW = 4200\ kJ\ K^{-1}m^{-3} * -5.66 \times 10^{-1}\ m^3s^{-1}K$

$$\boxed{.29\ kW \cong .238\ kJ/s}$$

outwardly for 1226s

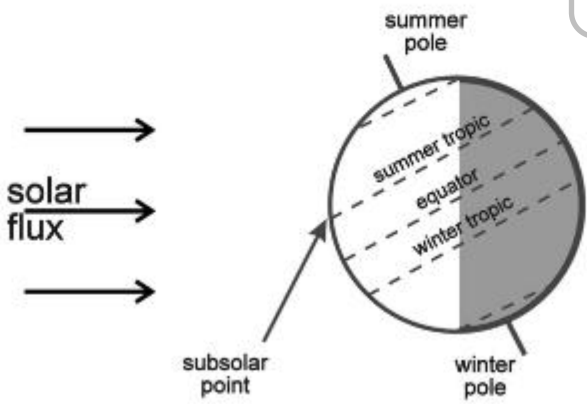
$.29\ /\ .238 = 1.22$
acceptable amount of error

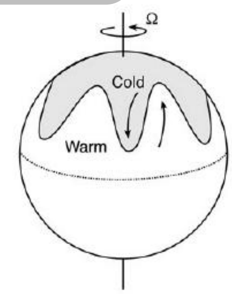
using leftside #, we could calculate a likely v' average

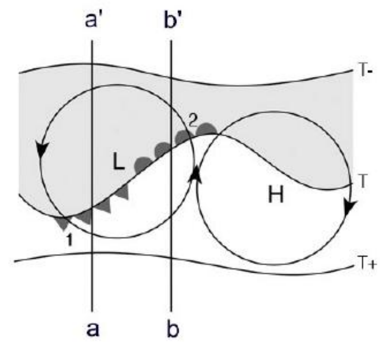
rightside rate would melt .88 kg of ice in this # of sec

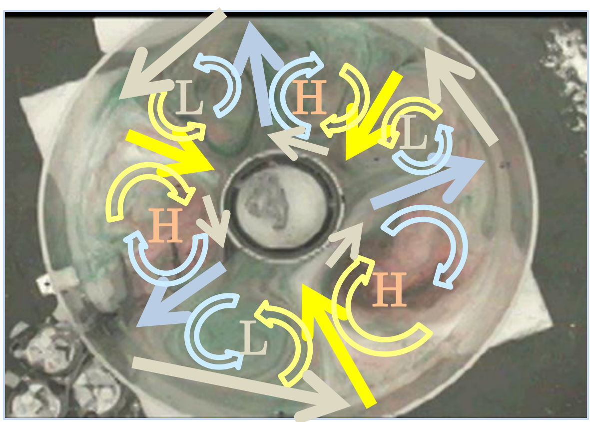
extra-tropic

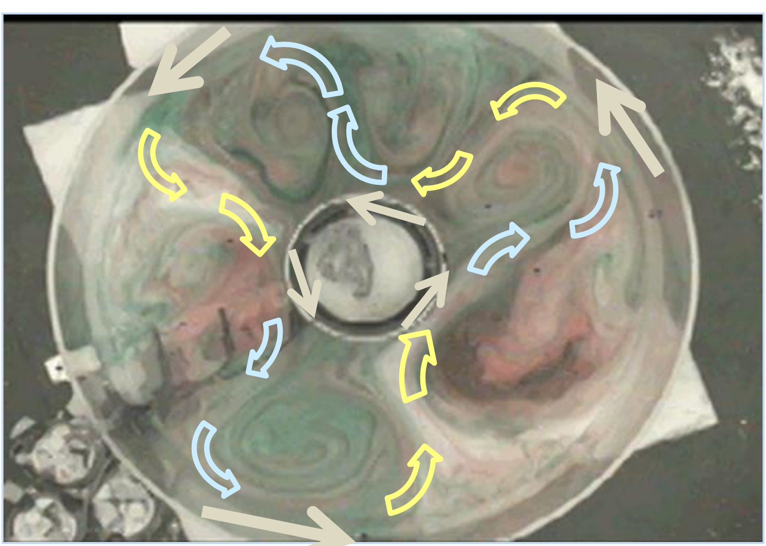
what on Earth is “meridional flow”?!

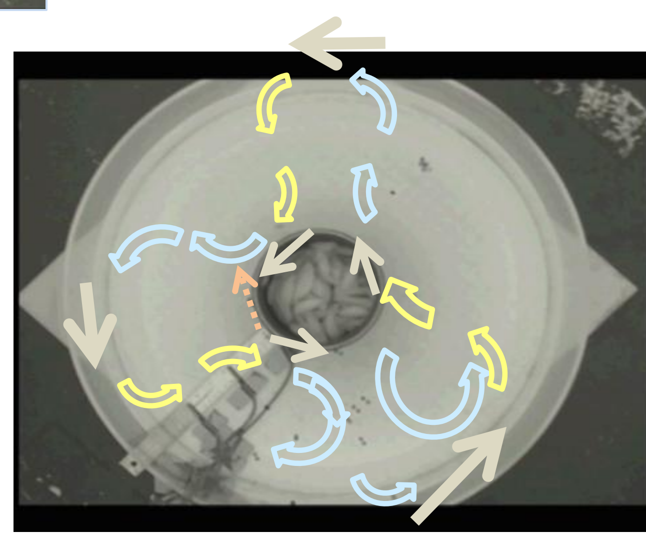










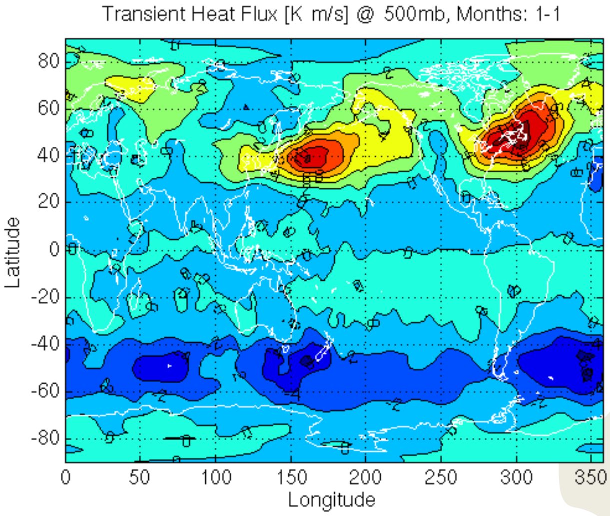


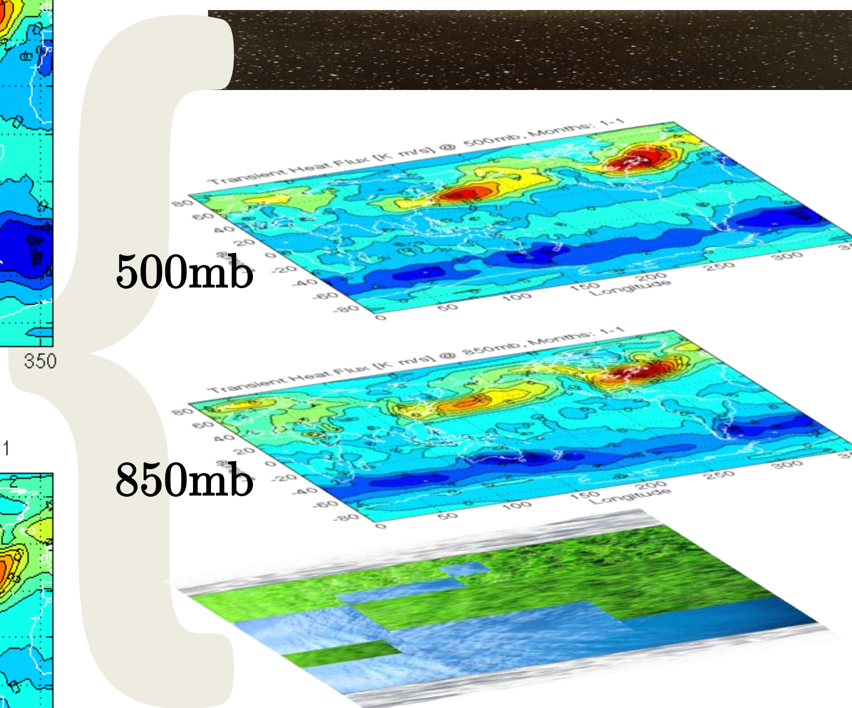
*overhead view preferences flow of surface currents
** from this, into the tank & out of the tank vectors could be proposed, bottom of the tank currents guessed, and interior eddy structure further explored

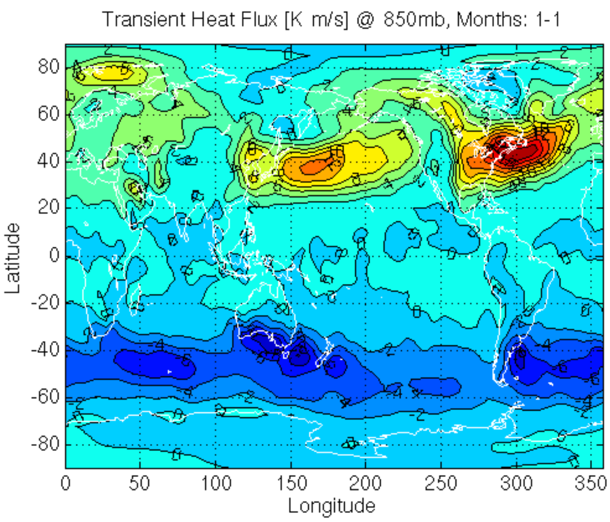
**reorientation of general circulation wave pattern. Pink vector shows at least one cluster of particles' path that flows with westerly currents near heat sink, before rejoining with southward meridional flow.

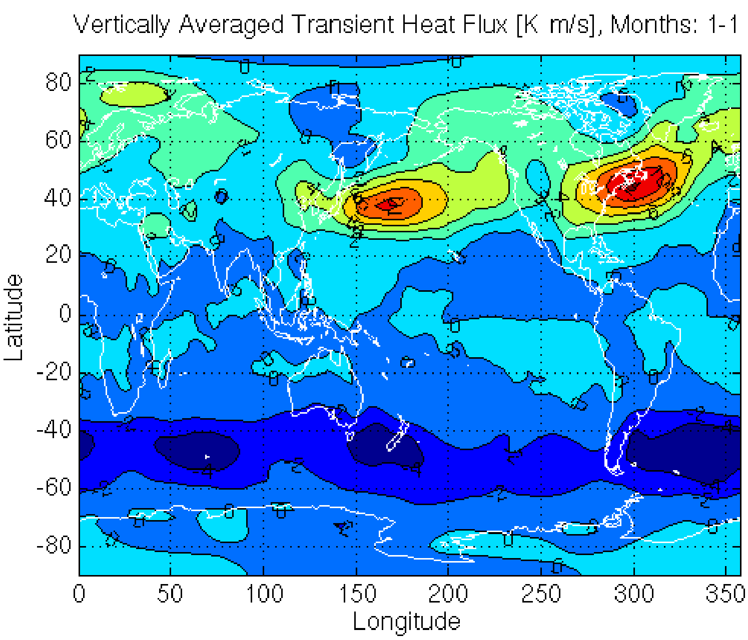
JANUARY

tank experiments — atmospheric data | hadley cell — tropic | eddie transfer — **extra-tropic**



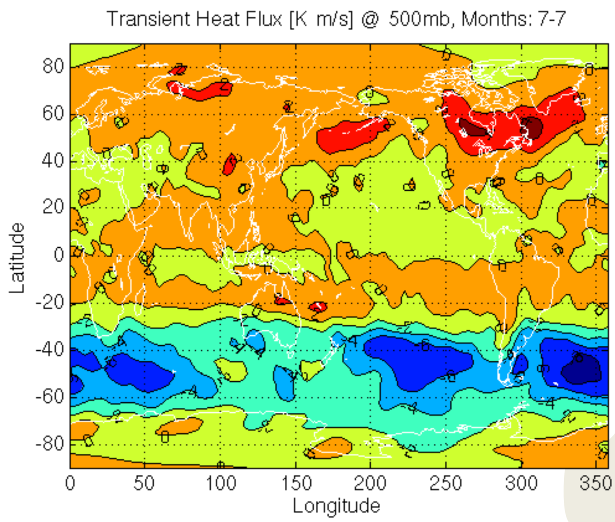


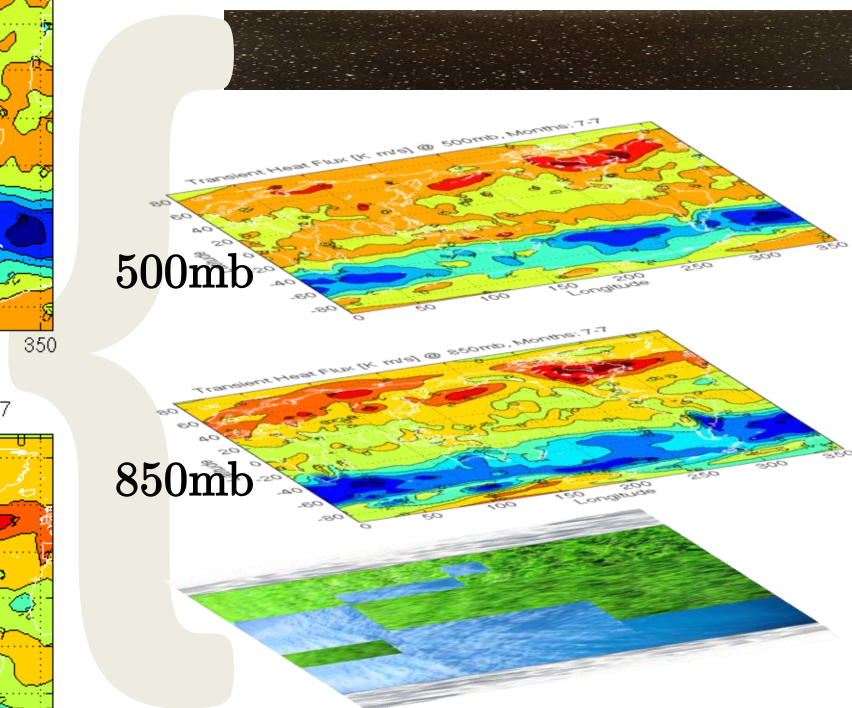


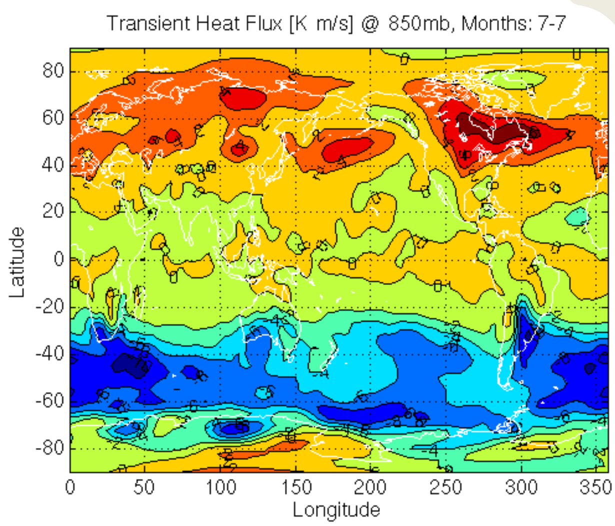


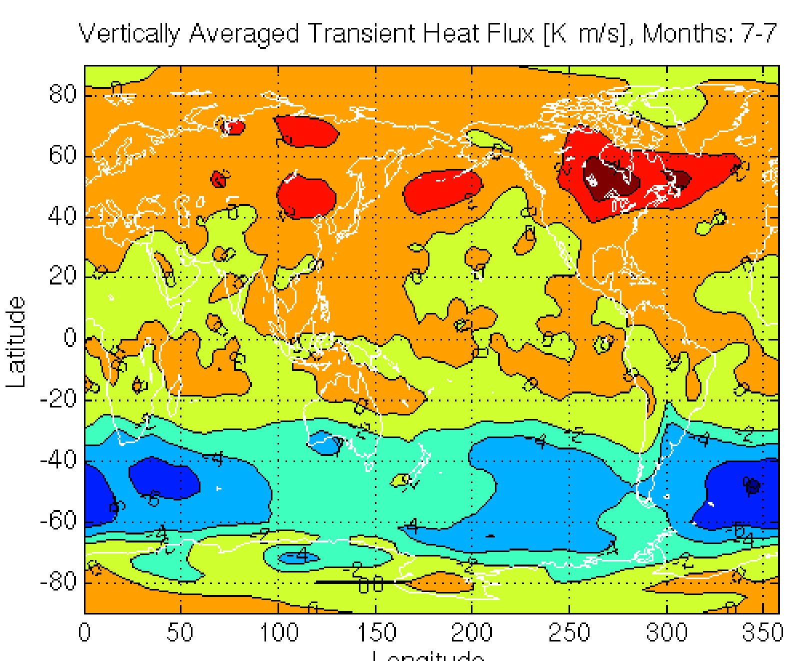
JULY

tank experiments | atmospheric data | hadley cell | tropic | eddie transfer | extra-tropic

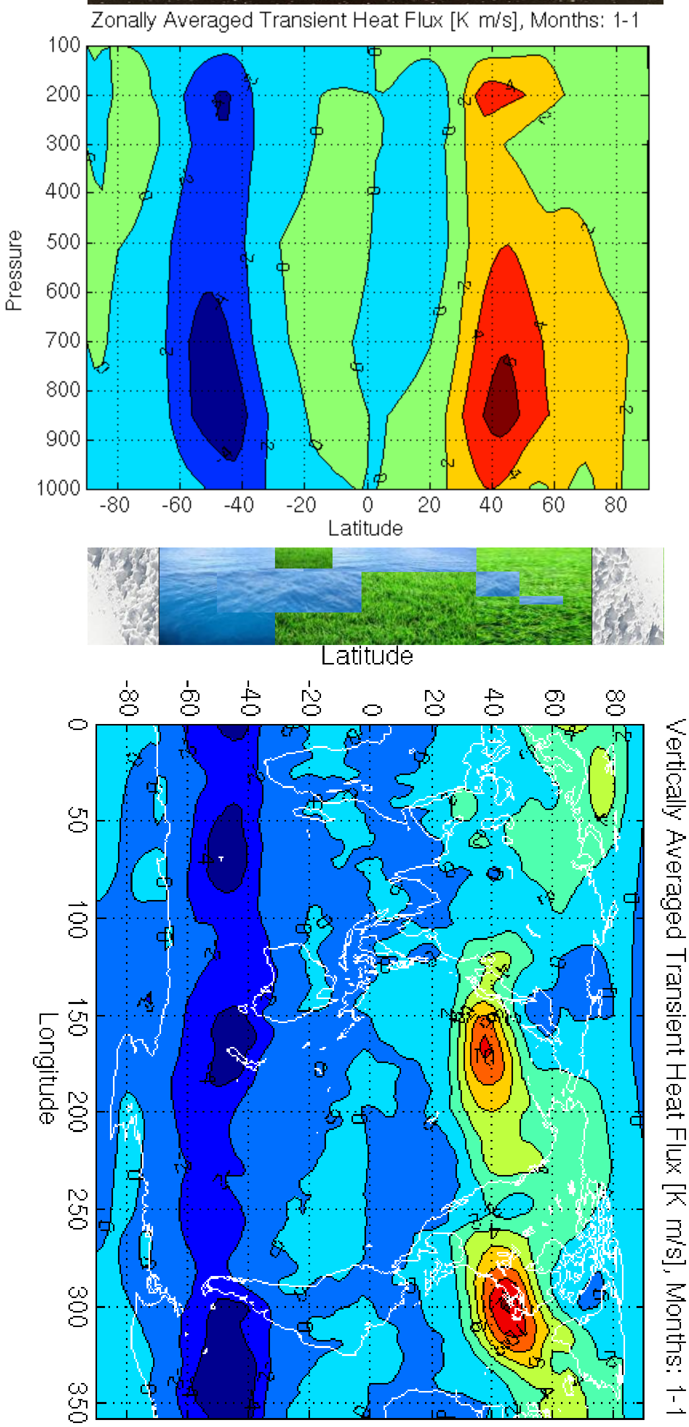




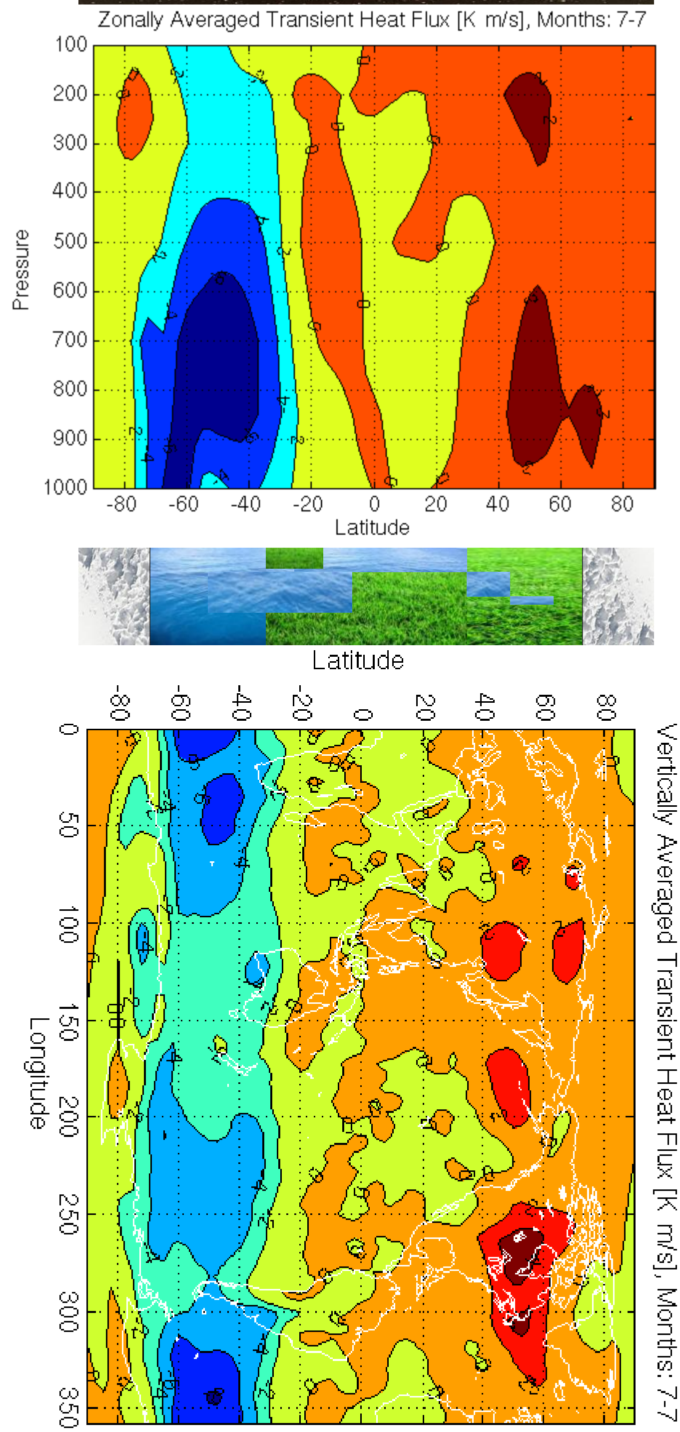




JANUARY

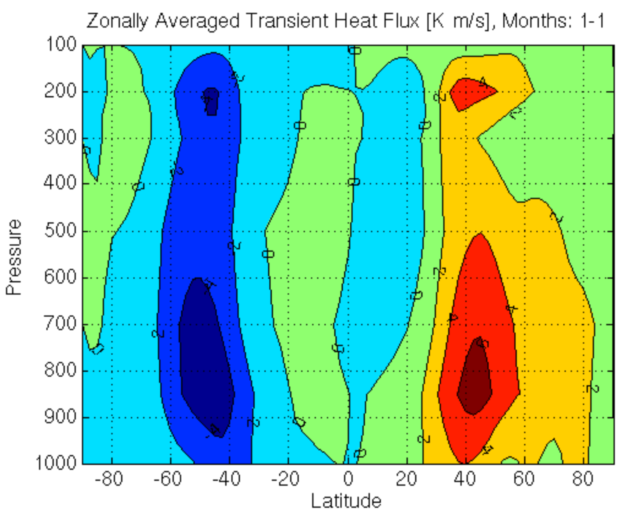


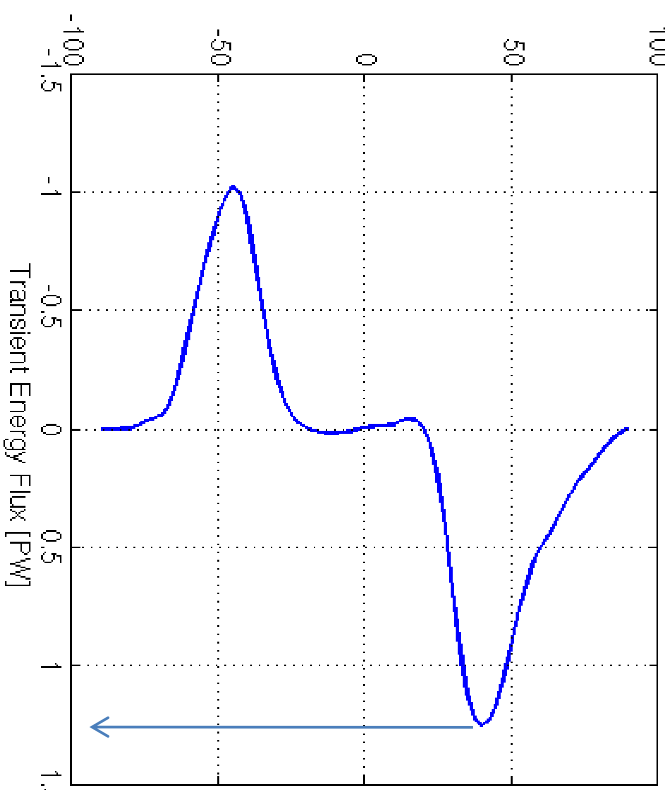
JULY



tank experiments | hadley cell | eddie transfer
atmospheric data | tropic | extra-tropic

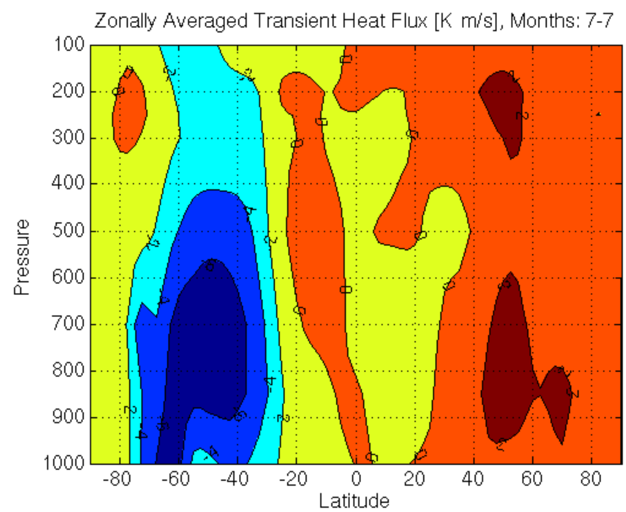
JANUARY

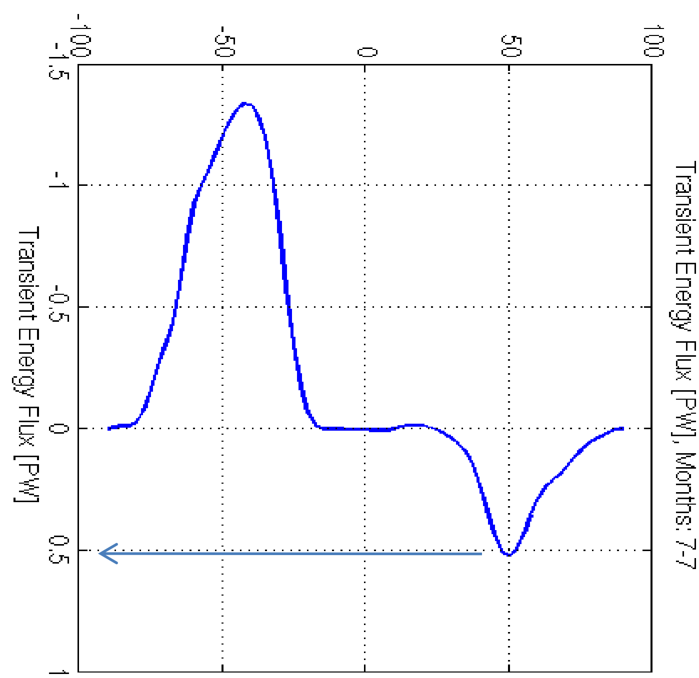




$$\mathrm{FLUX}_{\mathrm{jan}} = 1.25\ \mathrm{PW}\ /\ \mathrm{mo}$$

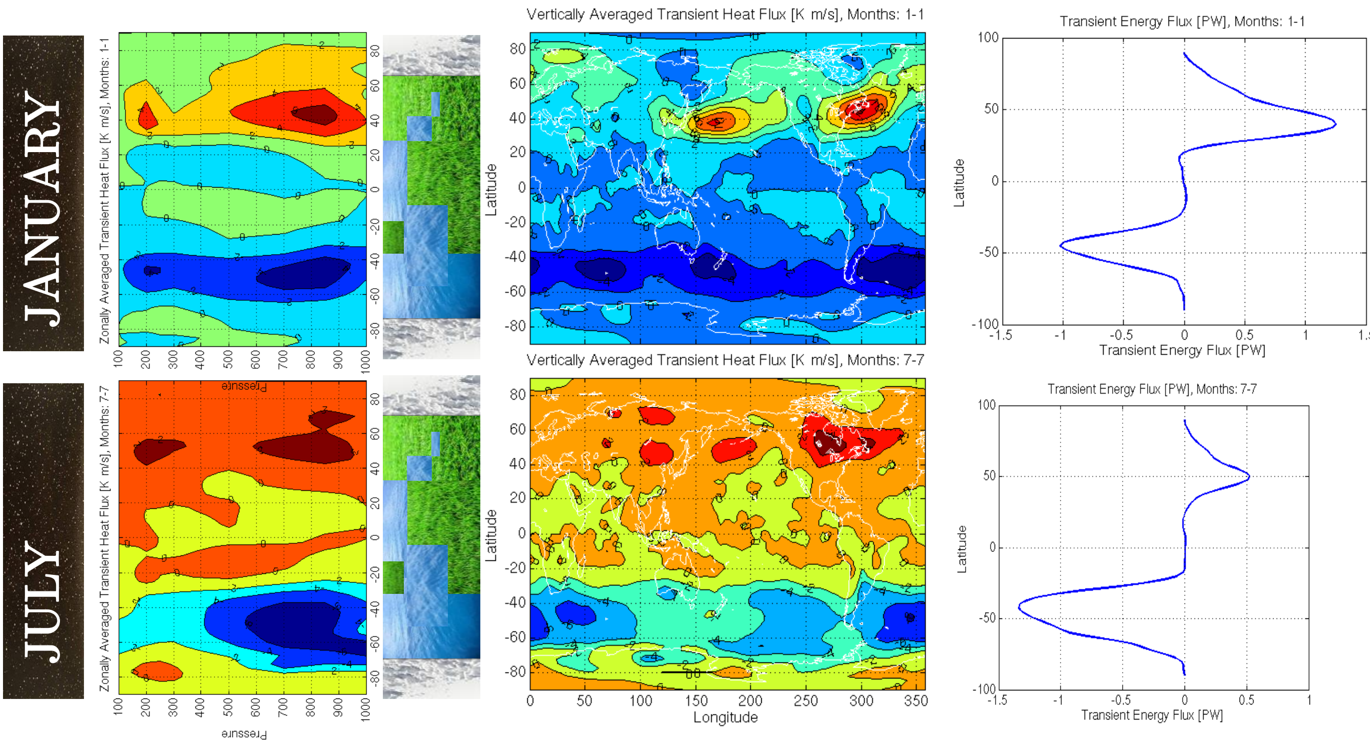
JULY





$$\mathrm{FLUX}_{\mathrm{july}} = .5\ \mathrm{PW}\ /\ \mathrm{mo}$$

tank experiments | hadley cell | eddie transfer
atmospheric data | tropic | extra-tropic



ATMOS

$\mathrm{FLUX}_{\mathrm{jan}} = 1.25$ PW [for 1 mo]

$\mathrm{FLUX}_{\mathrm{july}} = .5$ PW [for 1 mo]

PW = petawatt = 10^{15} W

TANK

.29 kW ≅ .238 kJ/s
outwardly [for 1226s]

1.25 PW * 1226s = 1532.5 PJ

.5 PW * 1226s = 613 PJ

.29 kW * 1226s = 355 J

1532.5×10^{15} / 355 J = 4.3×10^{15} times greater in winter

613×10^{15} / 355 J = 1.7×10^{15} times greater in summer

2592000 seconds in a month
* .29 kW = 751680 J

In order to match the heat transferred by the earth in one second
665 million tanks running for 1 month (earth Nhem summer)
1.66 billion tanks running for 1 month (earth Nhem winter)

the latter number translates to 1 tank for all the world's human population in 1900.