PV is conserved is our strongest statement to explain weather

But then where does PV come from?

ATM 405/561

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Outline

- Read this brief review of our journey from not-at-all-conserved *momentum*, to sorta-conserved *relative vorticity*, to more-conserved *absolute* vorticity, to most-conserved *potential* vorticity.
  - https://www.notion.so/miamimapes/Horizontal-vorticity-and-PV-as-explanations-for-cyclones-anticyclones-2e6d2c075dba44699dc822ca5748e2e8

Questions about it: write answers

- 1. Using the concepts from the reading, and earlier homework, explain how patches or elements of **relative vorticity** advect other patches of **relative vorticity**, under the assumption that **relative vorticity** is sorta almost conserved.
- 2. Using the concepts from the reading, and earlier homework, explain how **planetary vorticity** is converted to **relative vorticity,** so that their sum, the **absolute vorticity,** is almost conserved. Consider a loop of air moving in latitude, and explain how the different Coriolis force felt by its northern and southern edges acts as a torque on the fluid loop.
- 3. Using the concepts from the reading, and the reading, explain how **static stability** is converted to **absolute vorticity,** so that **potential vorticity,** their **product,** arguably the truest essence of vortices (cyclones and anticyclones) is really really almost conserved.
- 4. Based on the end of the reading, what you will look for in vertically resolved data about diabatic heating rate in the atmosphere to explain the ultimate source of PV?

Using the concepts from the reading, and earlier homework, explain how patches or elements of **relative vorticity** advect other patches of **relative vorticity**, under the assumption that **relative vorticity** is sorta almost conserved

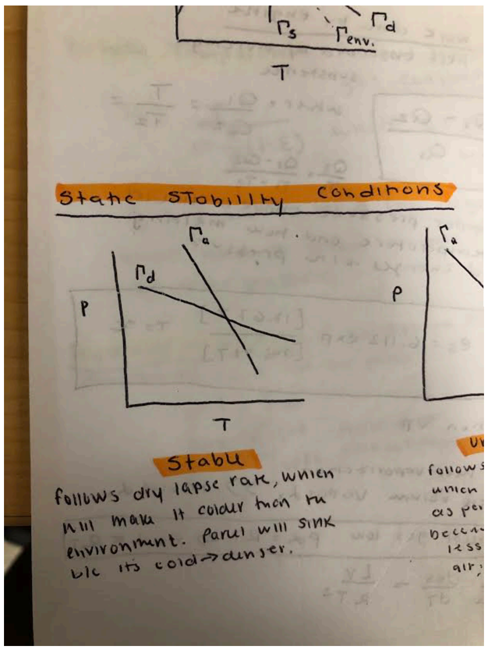
From my understanding relative vorticity is due to curved wind flow and wind shear. Patches of relative vorticity can advect patches of relative vorticity is because it's not perfectly conserved. RV does not take into account Earth's rotation. So even if the winds are balanced without considering potential temperature differences or corilolis effect changes in the air velocity field may not be conserved.

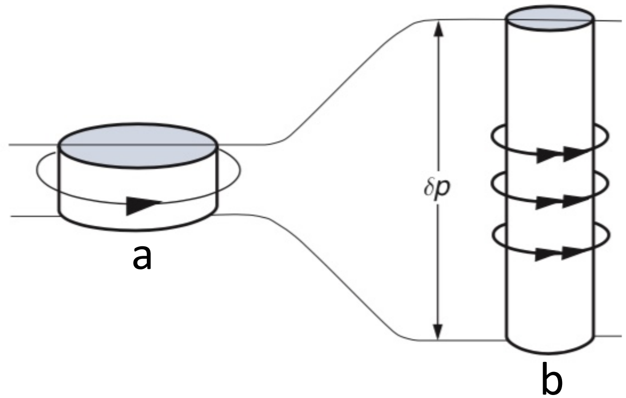
Using the concepts from the reading, and earlier homework, explain how **planetary vorticity** is converted to **relative vorticity,** so that their sum, the **absolute vorticity,** is almost conserved. Consider a loop of air moving in latitude, and explain how the different Coriolis force felt by its northern and southern edges acts as a torque on the fluid loop.

Planetary vorticity is the spin imparted to the air by the rotating earth and is dependent on latitude. Maximum spin at the poles. Planetary Vorticity is usually much greater than relative at extratropical latitudes, but in tropical latitudes they're of similar magnitude (planet spin vs parcel spin) $f=2\Omega\sin\theta$ so at north pole f is at a maximum. Planetary vorticity is converted to relative vorticity by Stokes' theorem? A loop of air moving in latitude would feel greater (+) effects in the northern latitudes but in the southern latitudes there would be a (-) effect on the loop thus giving us clockwise / anticlockwise rotation since f will dominate at polar latitudes?

Using the concepts from the reading, and the reading, explain how **static stability** is converted to **absolute vorticity,** so that **potential vorticity,** their **product,** arguably the truest essence of vortices (cyclones and anticyclones) is really really almost conserved.

When an air parcel is statically stable the adiabatic lapse rate is cooler than the environmental lapse rate so the air parcel will not rise because it is cooler.





Difference in potential temperature between the top and bottom is the same for the two cylinders. If PV is conserved and the cylinder is stretched (b) then static stability is decreasing and absolute vorticity must increase. if one goes from (b) to (a), then static stability is increasing and absolute vorticity must decrease. This makes total sense with the figure on the left (I think) because if you have a statically stable environment the air wont rise hence low PV since it has a heating term. BUT if static stability is low, approaching unstable conditions you will have PV and warm air will rise.

Based on the end of the reading, what you will look for in vertically resolved data about diabatic heating rate in the atmosphere to explain the ultimate source of PV?

PV tendency is positive where heating rate increases with height so I think that is what we are looking for. When PV is positive = cyclonic and dominated by f since absolute is dominated by f (most of the time). Heating rates are due to diabatic processes meaning an external source or sink of heat (i.e radiation from the sun or long wave cooling). Next slide says be careful of “cyclonic” and I’m not 100% why.

PV is conserved -- almost

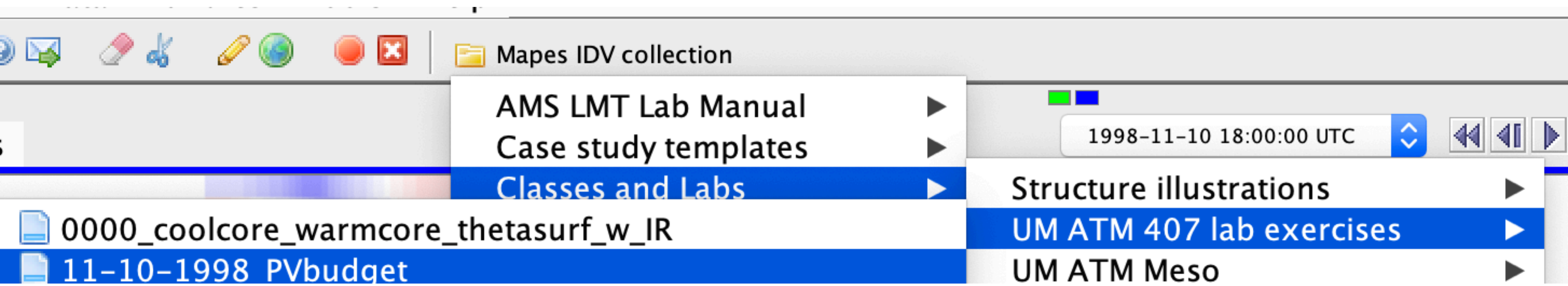
APPROXIMATE term that generates PV on the Earth

$$\frac{D}{Dt}(PV) = 0 \boxed{- g\zeta_a \frac{\partial \dot{T}_{diab}}{\partial p}}$$

Mostly, you are looking for WHERE THE DIABATIC OR PHYSICAL HEATING RATE INCREASES OR DECREASES WITH HEIGHT, weighted by (f+ζ). In both hemispheres... so be careful with ”cyclonic”.

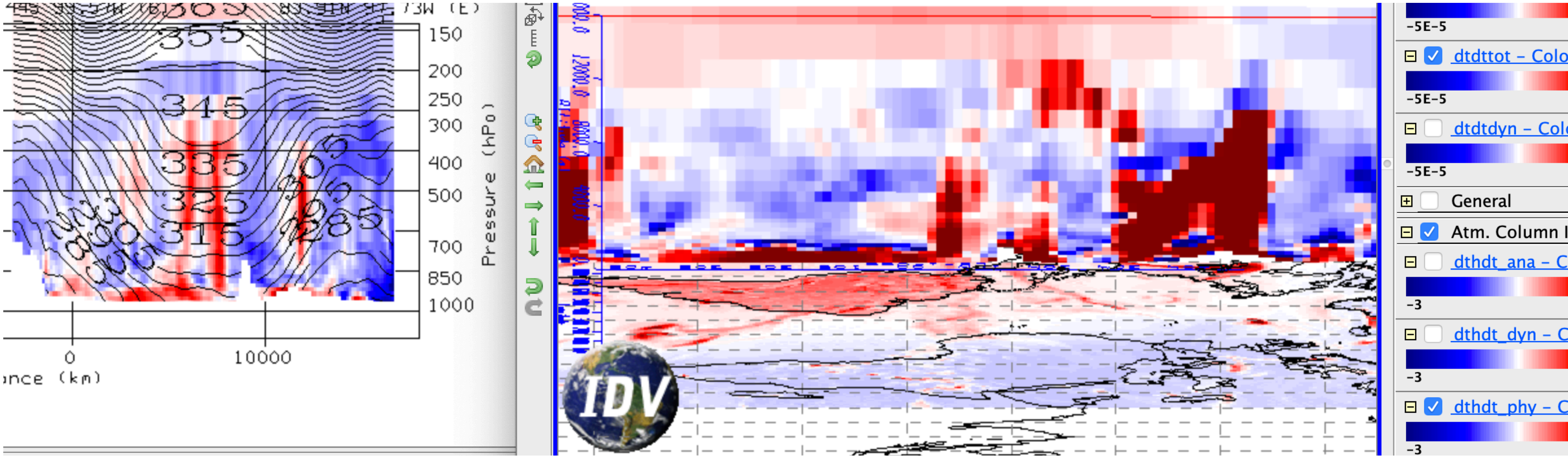
Assignment part 1: global view

- Open the bundle 11-10-98 PV budget



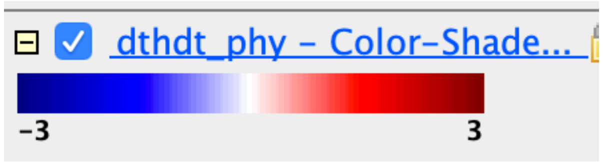
- Orient yourself to its displays, in **both windows**
  - a **pole-to-pole transect** of the **zonal mean** heating rates (averaged around the whole Earth)
  - A map view with many displays (including **movable cross sections**).

transect of *zonal mean* diab. heating, cross section of total diab. heating, map of column integral diab. heating



Assignment part 1: global view

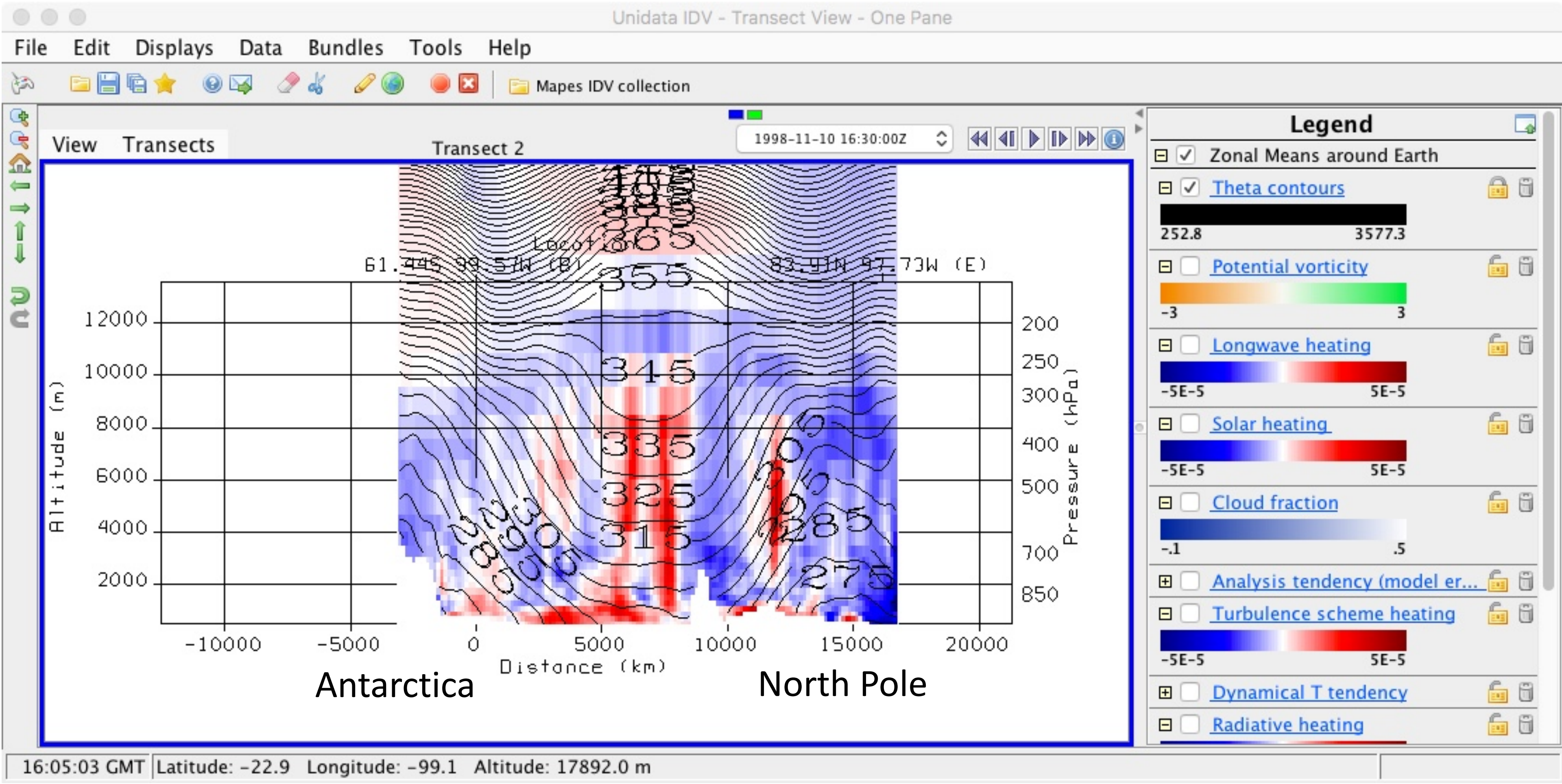
1. What time of year is it? How can you see that in the column-integrated heating rate map dthdt_phy, or other radiative heating rates?



Winter – it is November. Much higher heating rates in the southern hemisphere

Assignment part 1: global view

- Now turn to the Transect View window, showing average cross sections all around the Earth. Create a slide showing the transect of total diabatic heating. Label it: where is the south pole, the north pole? Hint: Antarctica is mountainous.
- The units of all heating rates are are K/s. What is the color range in K/day?



The units of all heating rates are are K/s. What is the color range in K/day – I don't know how to change this

Assignment part 1: global view

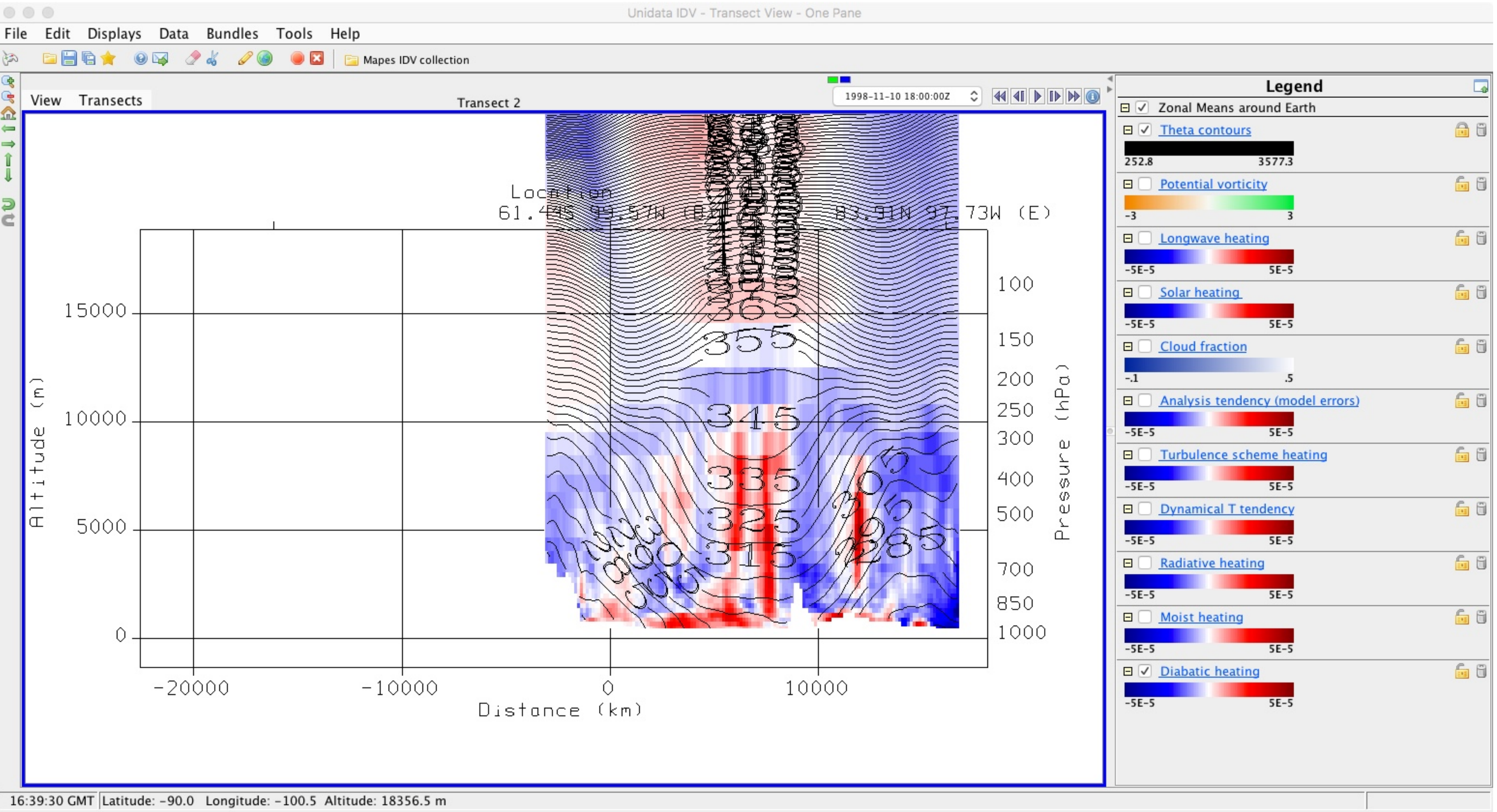
- Create slides with transect images showing individual terms of the zonal mean heat budget.
- Use that imagery to explain the nature of all the main features in your total diabatic heating slide.
  - for instance, slides might have the total heating image repeated in one corner, and individual terms one per slide.
  - Write enough narrative words that a reader can see the sense of your work and

- These equations relate all the terms displayed there:

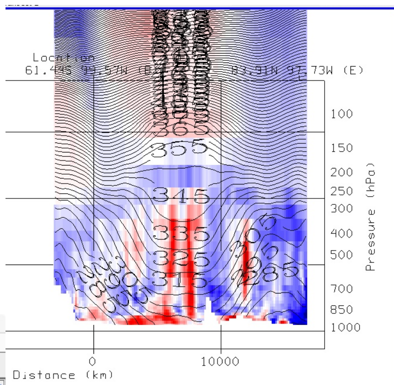
  $\partial T/\partial t$ = dynamical + diabatic + analysis

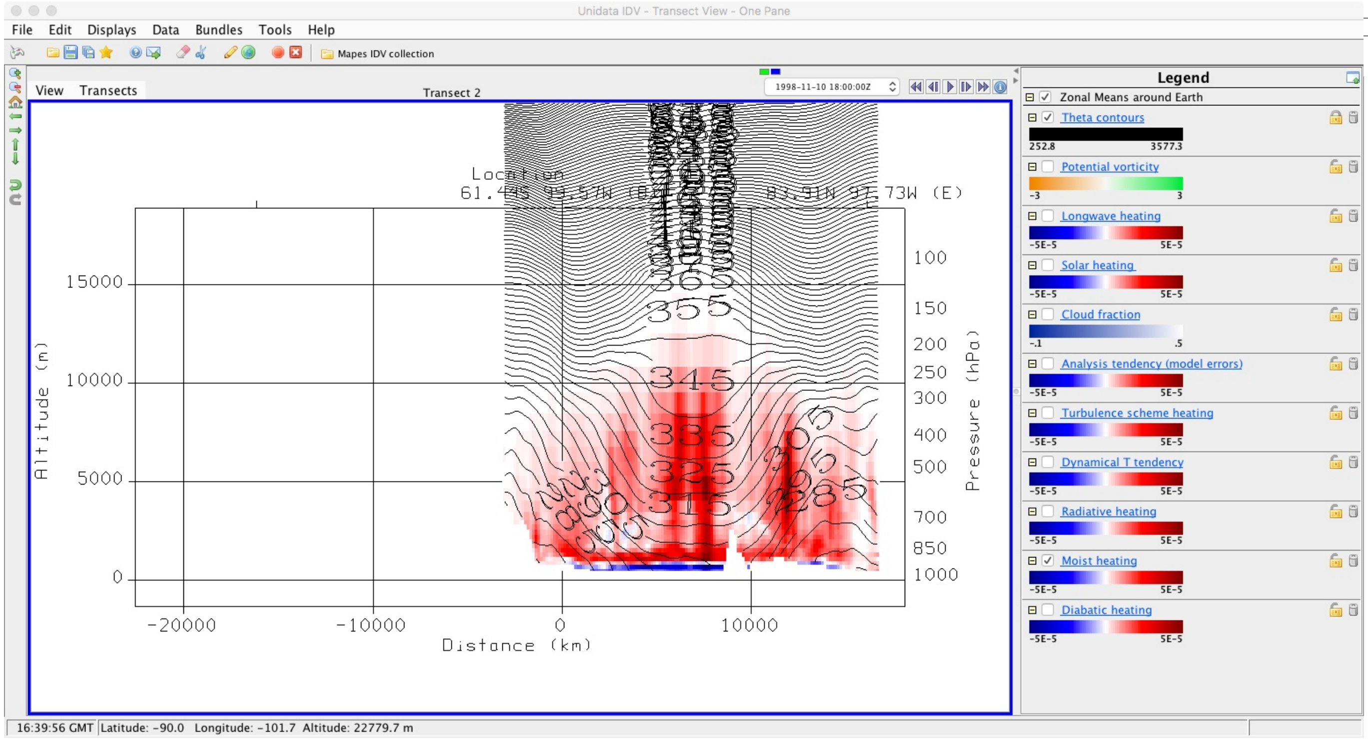
  diabatic = moist + radiative + turbulence

  radiative = longwave + solar

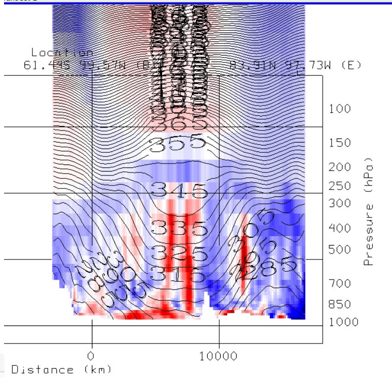


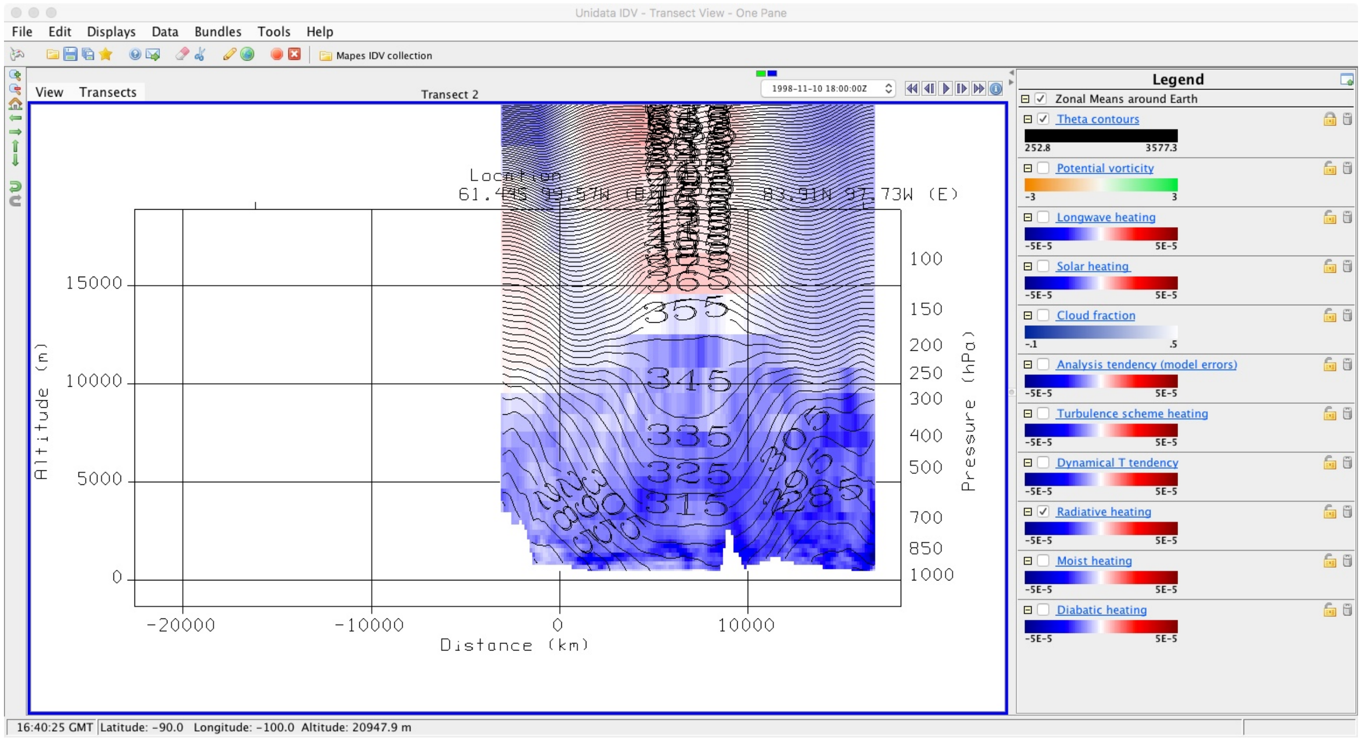
Diabatic terms which are the total heating terms. Positive heating in southern hemisphere / tropics (LHS) where it's the summer. Less warming in the northern hemisphere (RHS). In southern hemisphere positive heating up through higher altitudes most likely due to the moist terms which would include latent heating terms.



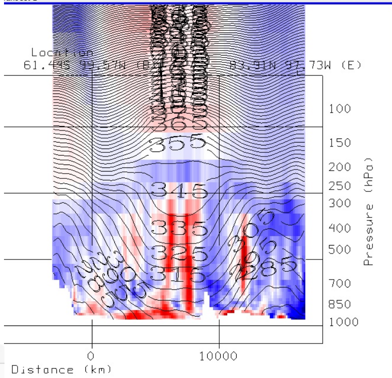


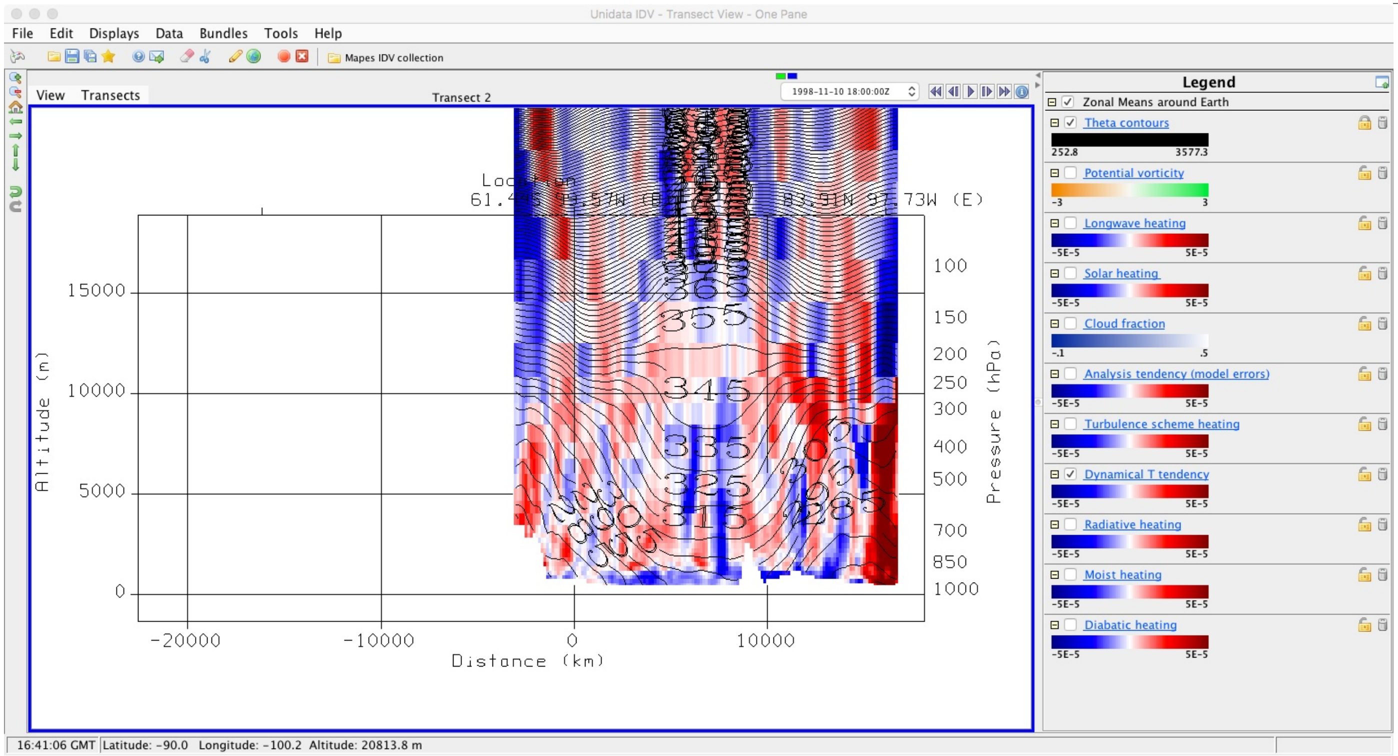
Moist heating terms- composed of latent heat terms of condensation and evaporation, and freezing/melting. Latent heat release through evaporation and from melting. It's actually pretty strong throughout the whole transect, but strongest in southern hemisphere and tropics. Also based on the isentropes it looks like warm core.



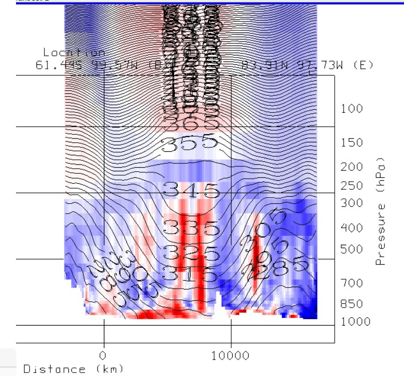


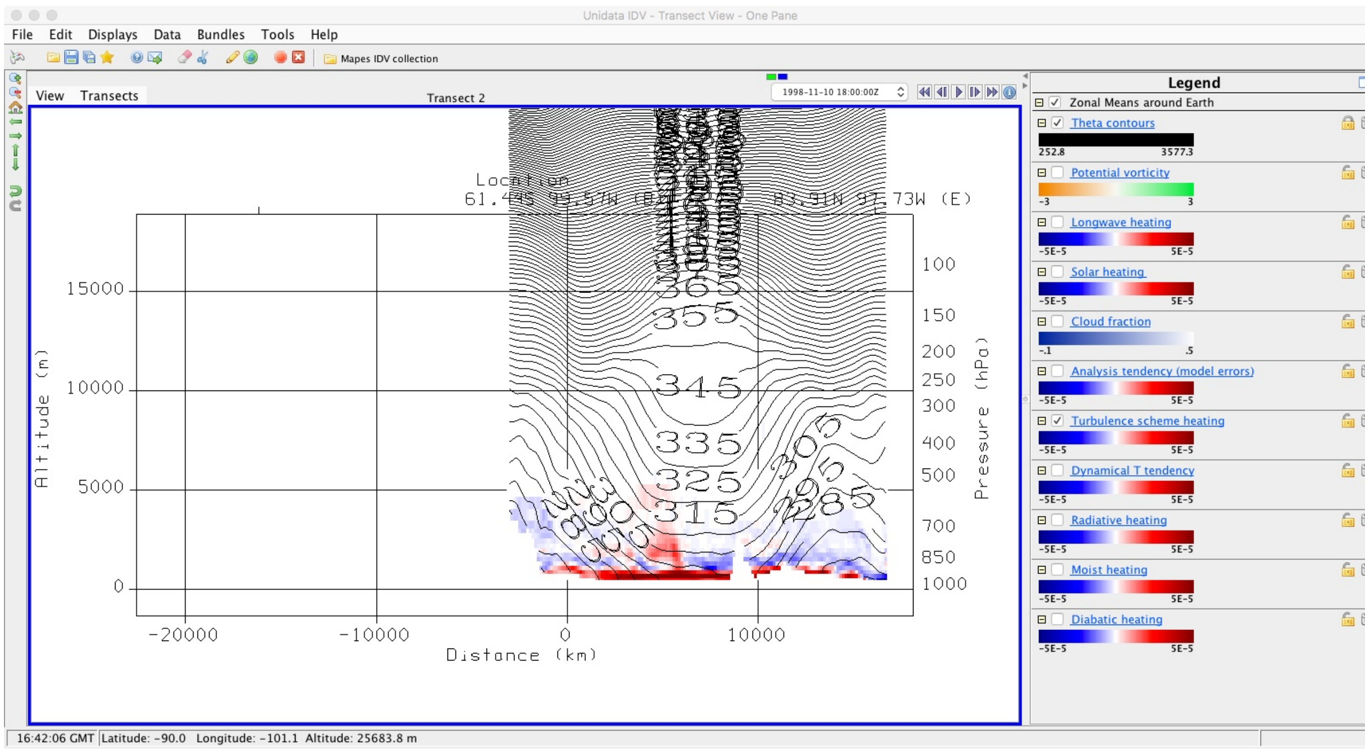
Radiation terms - which is a combination of long wave and short wave radiation. Because this is mostly blue (cooling) I expect this to be long wave cooling. Lighter blue near the south pole, but I thought there would more short wave warming? I'm not 100% sure why I though that, but that was my first instinct.



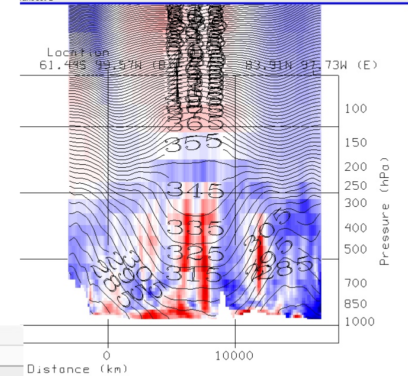


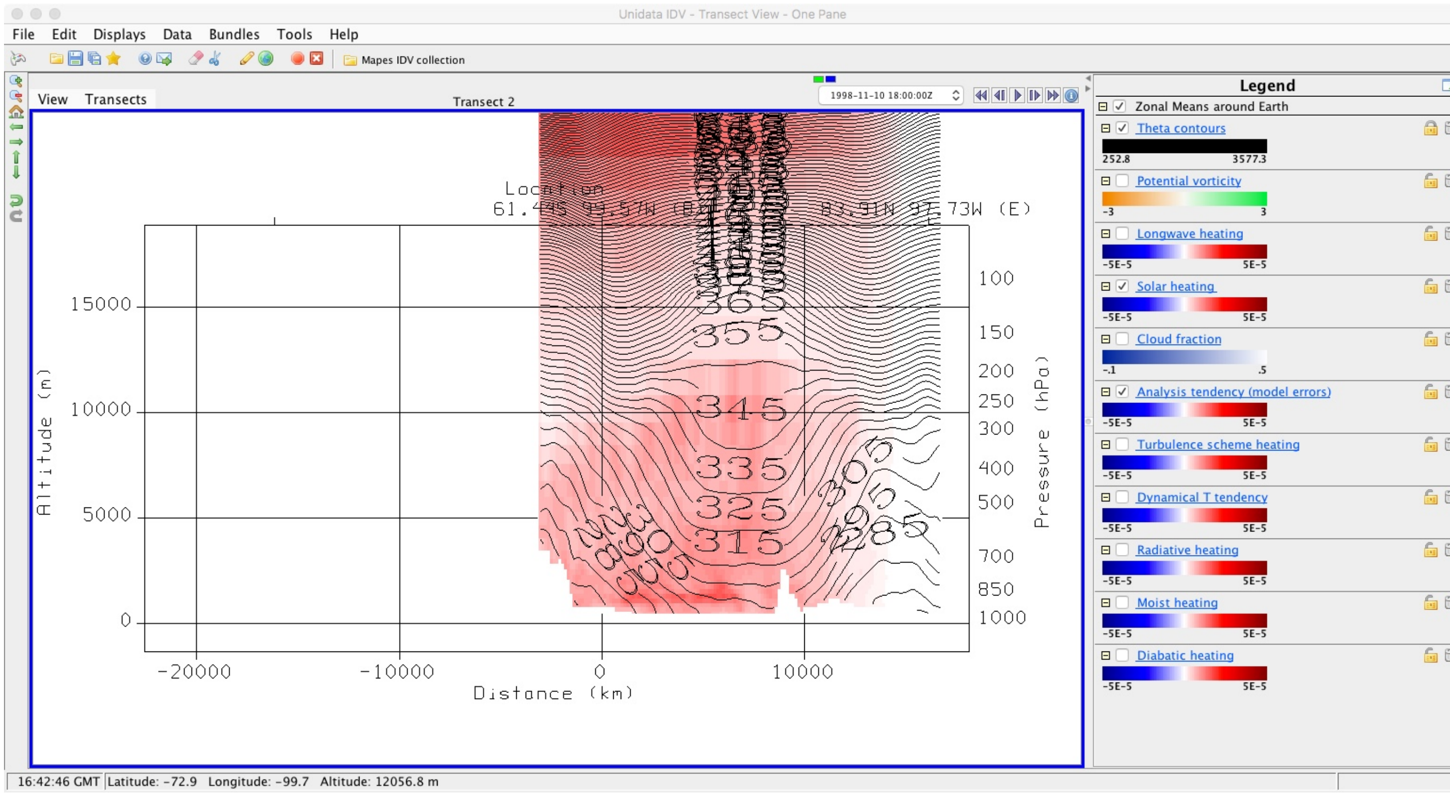
This is the dynamic terms of the heating rate- This term includes winds and temperature gradient along with static stability. So the dynamic terms are pretty mixed. Higher heating at the north pole. However, I don't know which term would dominate – static stability (which if this is red that'd be instability? Bc it's a warming??) Some strong cooling where the total terms shows strong warming. I think this one is the most confusing one to interpret.



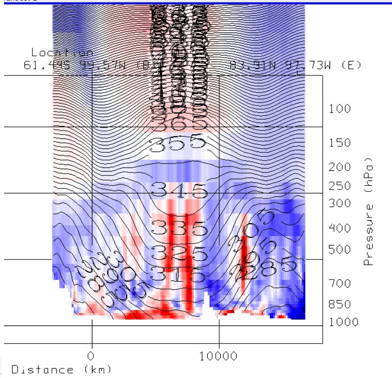


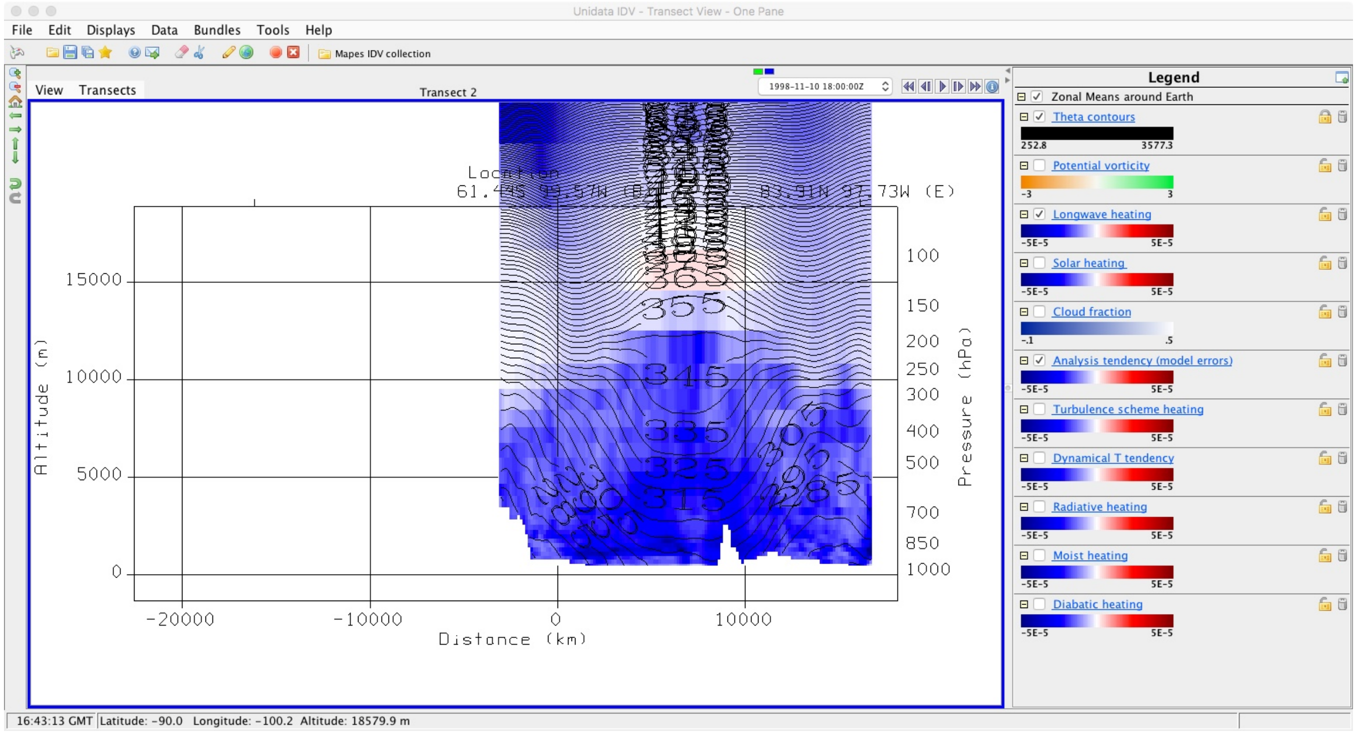
Heating rate due to turbulence- mainly at the surface. Highest heating due to turbulence again in southern hemisphere. Which you'd expect the solar radiation figure to correspond with higher solar radiation at those similar latitudes to create boundary layer turbulence.





Weak short wave warming. Strongest SW heating where highest turbulence heating is. Makes sense I think. Less short wave warming at the north pole.

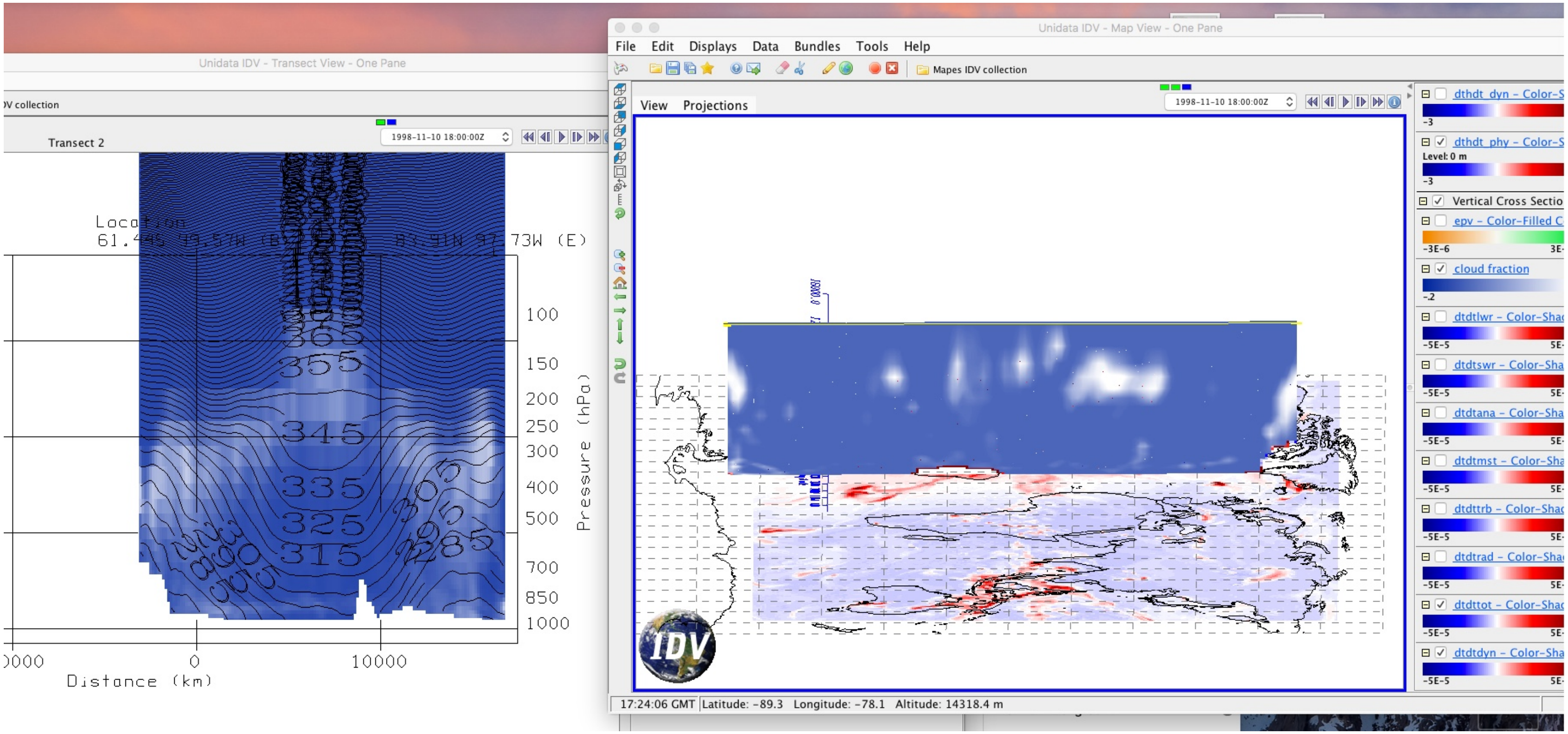




Long wave radiation terms which is almost all cooling. Definitely way stronger than the shortwave cooling all over.

Assignment part 1: global view

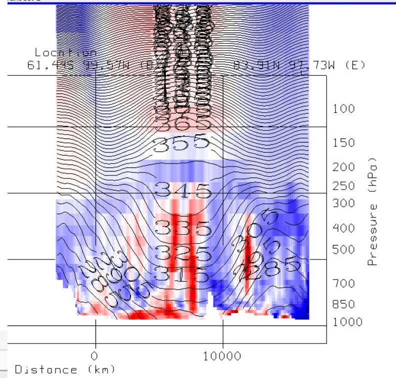
- Radiation and clouds:
  - Toggle the cloud fraction display with the radiative heating rate displays. Can you see any features that clearly indicate how clouds affect radiation?
    - clouds scatter solar photons, which are absorbed by vapor, especially at low levels.
    - clouds cool by emitting longwave from their tops
    - clouds absorb upwelling longwave from the surface at their bases (hard to see in the zonal mean, clearer in individual cross sections in Part 2)

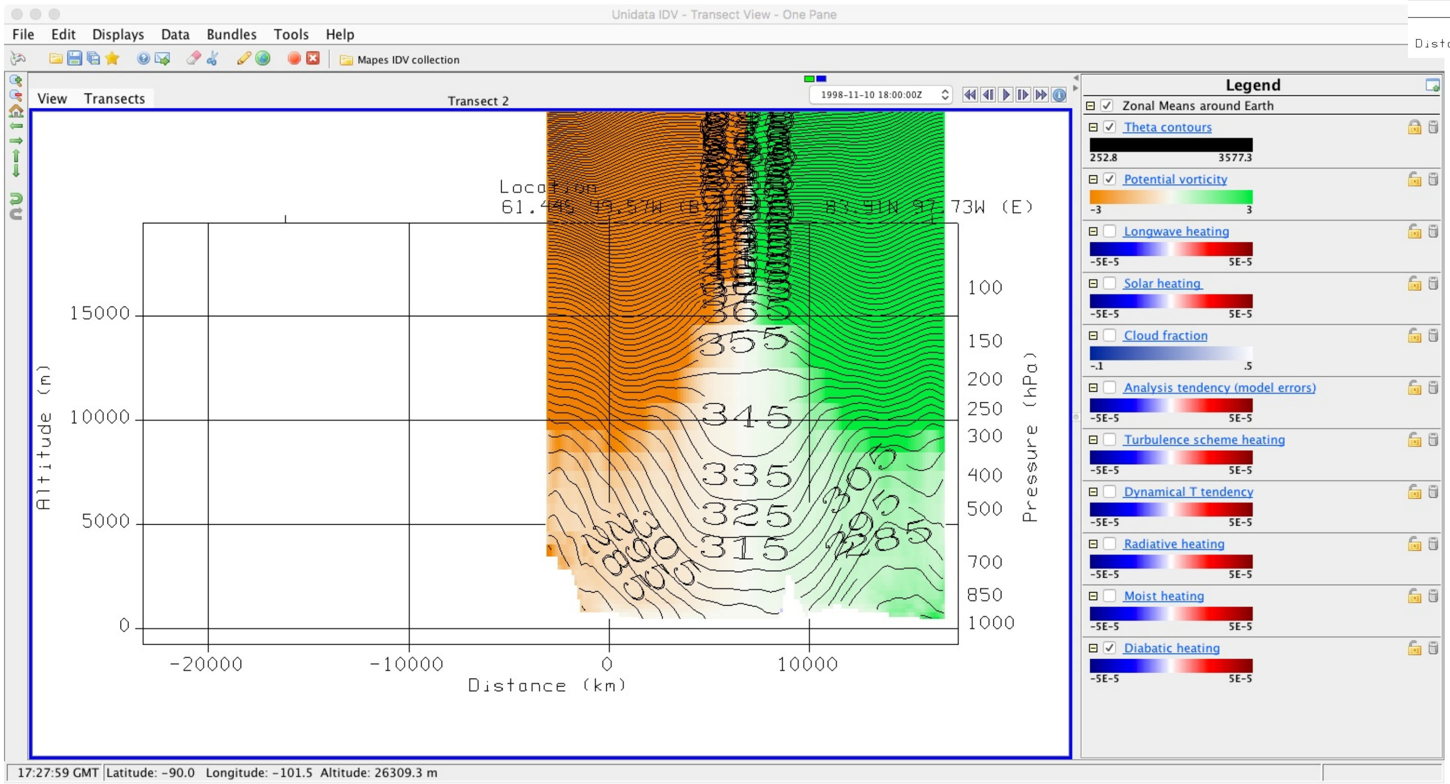


I think this is wrong – You showed this in class and mine doesn't look like this

Assignment part 1: global view

- From your total diabatic heating, indicate areas where PV tendency is positive and negative. Also label these areas as cyclonic or anticyclonic tendencies.
- Does the zonal mean PV transect resemble areas where your PV *tendency* is strong? It's not so simple: PV has a long lifetime in the stratosphere, so a large source is not required to explain a large value.
- How does this zonal-mean PV show the imprint of both its vorticity factor and its static stability factor? Label an image to explain your answer.





This is very interesting. It's almost split perfectly in half. Southern Hemisphere has negative PV and Northern Hemisphere has positive PV. I didn't expect this to be an even split – I understand PV is "mostly" conserved but I thought it'd be more mixed than this. I thought PV would be strongest where we have red contours above blue ones, but that doesn't seem to be the case.

Assignment part 2: Local sections

- Now explore the *cross section displays in the Map View window.*
- You can drag the cross section around to storms or other features. Drag them to north-south positions that slice through tropical and higher latitude weather features that interest you (perhaps guided by other displays).

Legend explanation for cross sections

$\partial T/\partial t$ = dtdt_tot (physics) + dtdt_dyn (advection) + dtdy_ana

(ana is *analysis*; a "missing" tendency needed to make the tendencies add up to the observed evolution $\frac{\partial T}{\partial t}$; indicative of the sum of all model errors)

diabatic tot = moist (mst) + radiative (rad) + turbulence (trb)

rad = lwr + swr

longwave

shortwave

analysis (0 for perfect model)

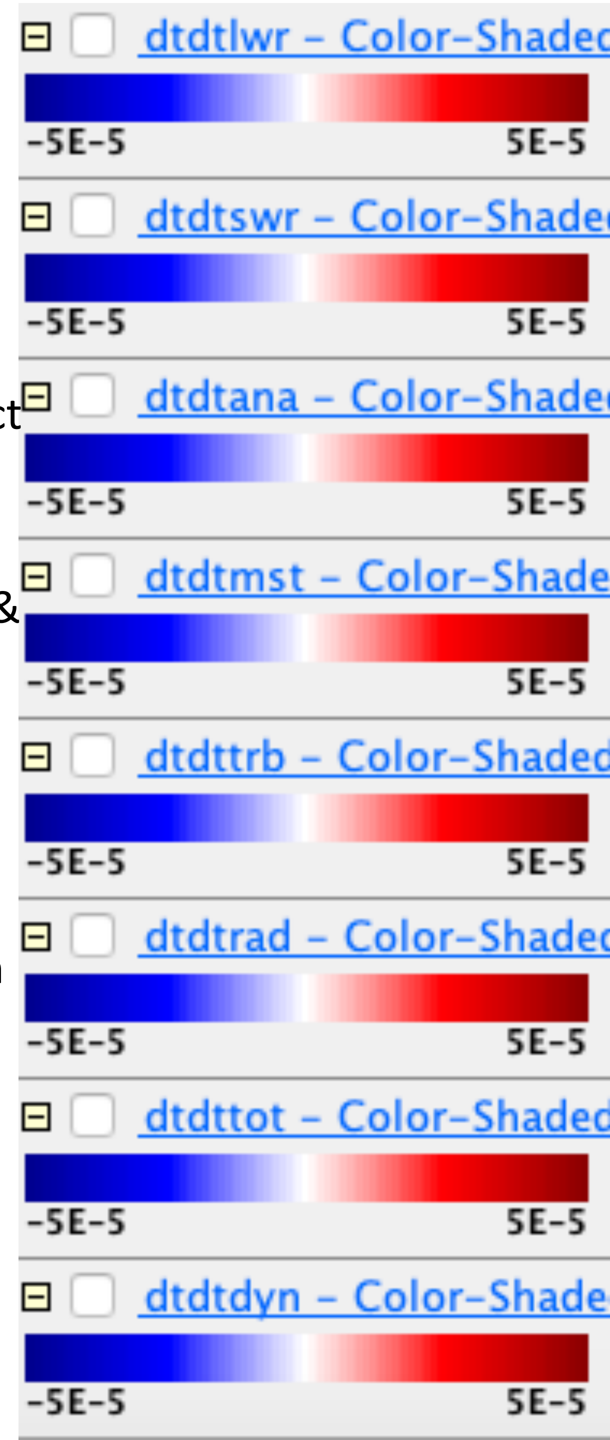
moist mst (convection & cloud cond.)

turbulence (PBL)

SW+LW radiation

total physics ("diabatic")

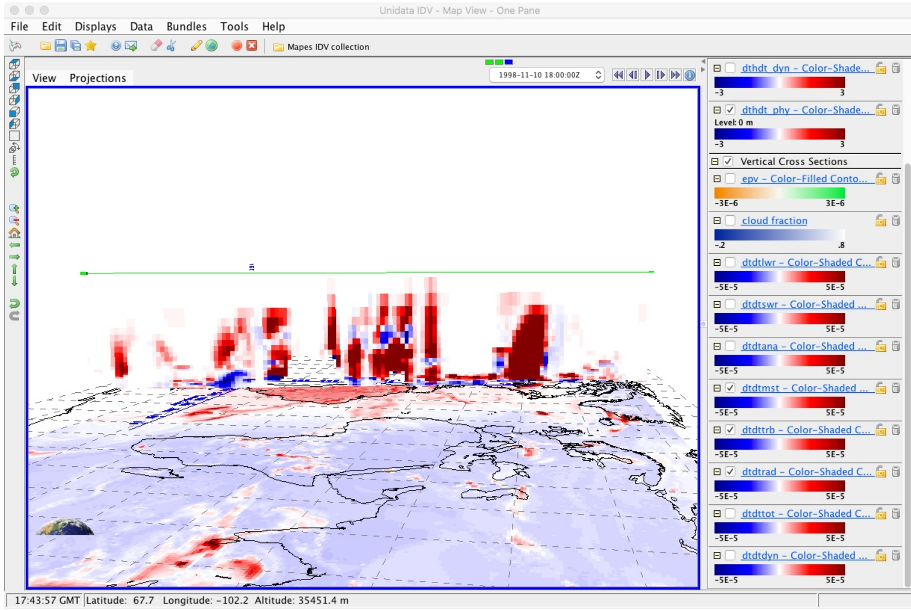
dynamic (advective)

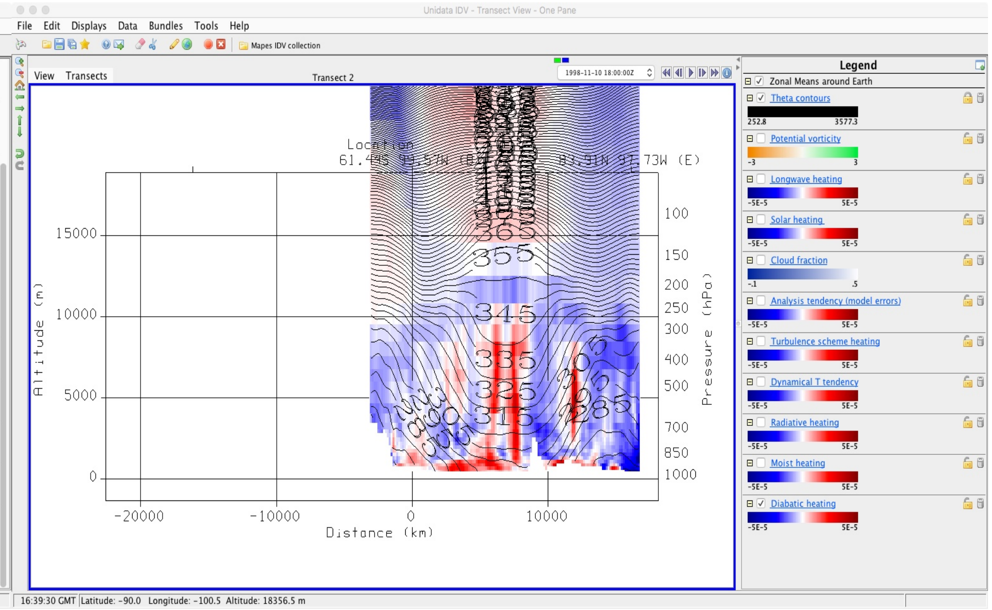


Assignment part 2: Local view

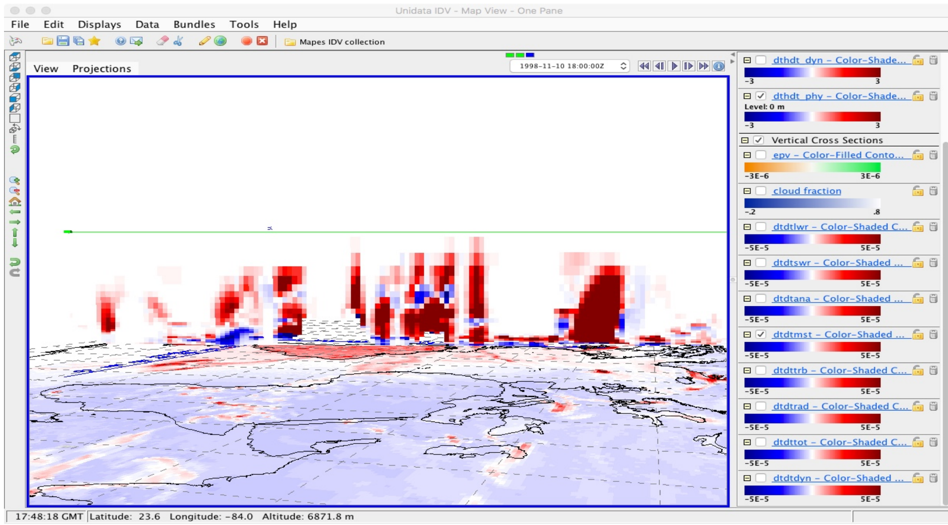
- Make comparison slides juxtaposing the zonal-mean transects and your local cross-sections, like in slide 6 above.
- Toggle the various terms making up the total diabatic heating, in order to explain
  - Which is more variable (more spatially concentrated): radiative or moist heating? Illustrate your answer with images.

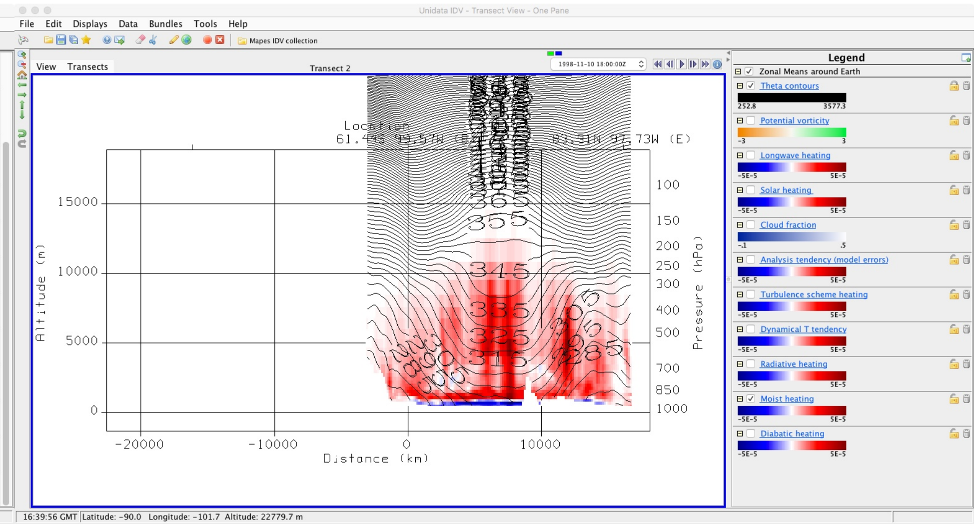
diabatic tot = moist (mst) + radiative (rad) + turbulence (trb)



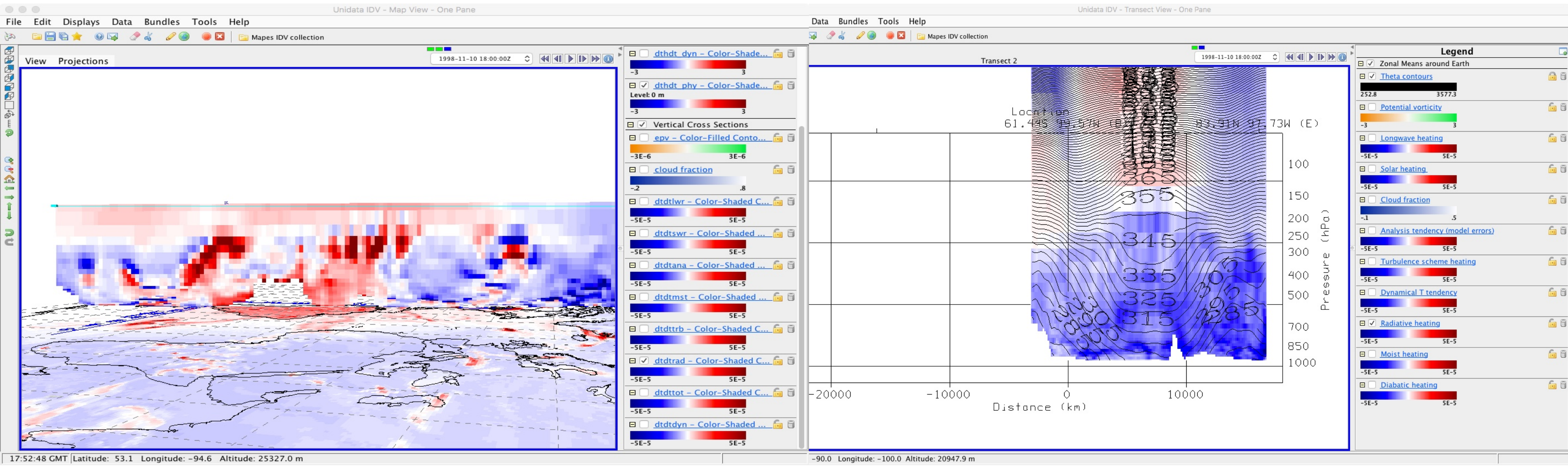


In this cross section there seems to be more heating in the northern hemisphere. Which is weird for the winter. But perhaps it's just the cross section I chose?

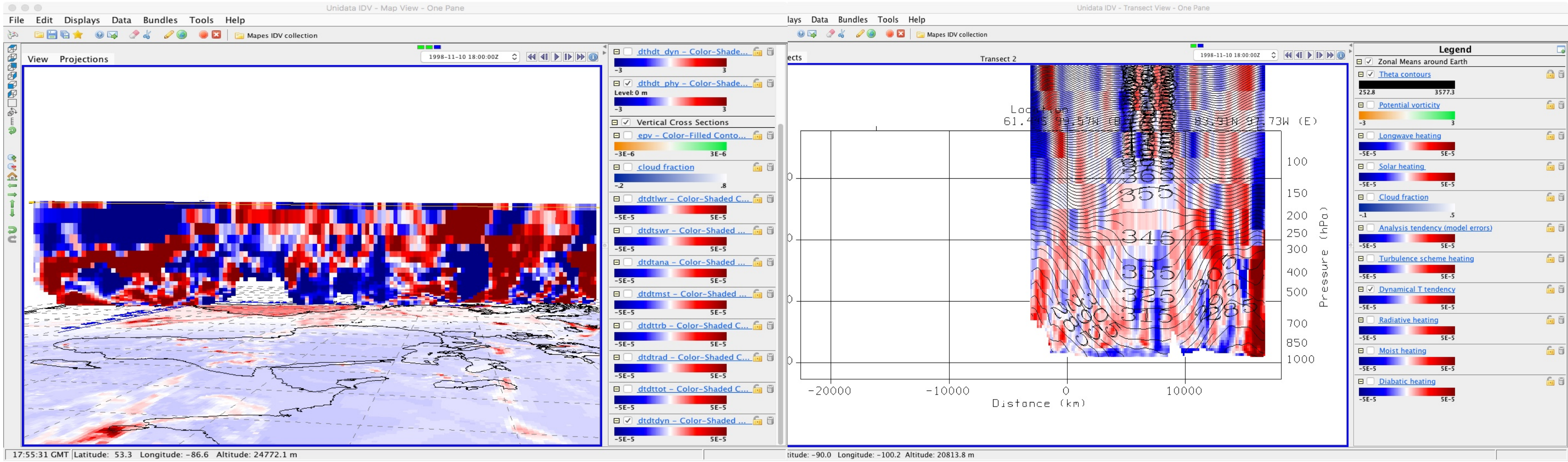




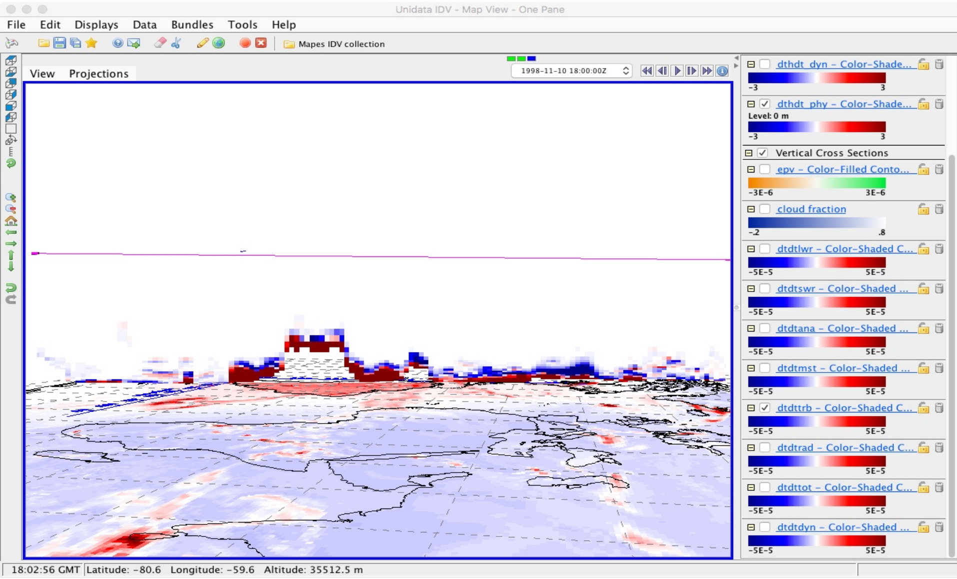
Looks like slide above was dominated by moist cross section so that makes me think that maybe my IDV isn't overlaying the variables correctly? Big blob of moist heating in northern hemisphere so I think that'd be due to evaporation since it's a release of latent heat? Can kind of see it in the transect. Definitely more prominent in the cross section image

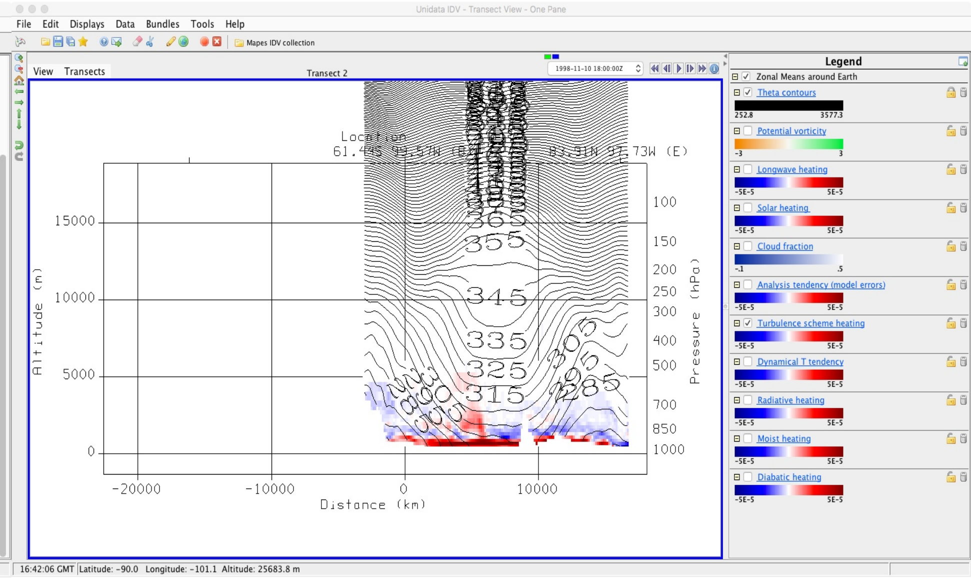


Definitely more local short wave warming since the total radiative term has quite a bit of red in it, as opposed to the transect image. So maybe short wave warming from aerosol? But overall long wave cooling dominates the zonal average.



Cross section definitely has darker colors Which imagine over the zonal mean transect the drastic difference between heating and cooling with dynamics eventually smooths out. The zonal mean one looks like it pretty much balances. Again, I can't really explain why there's no geographical dependence. Not as obvious as some of the other terms.

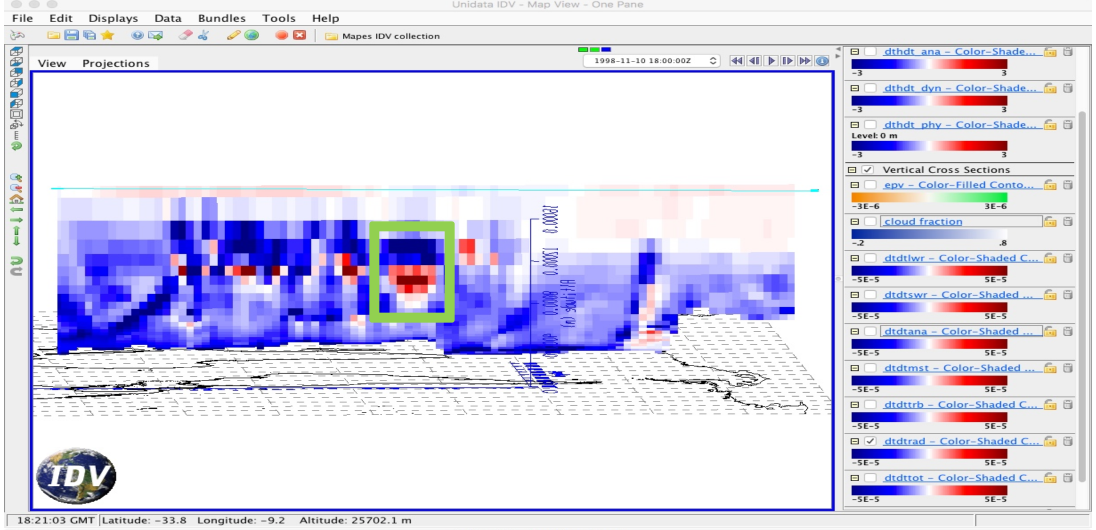


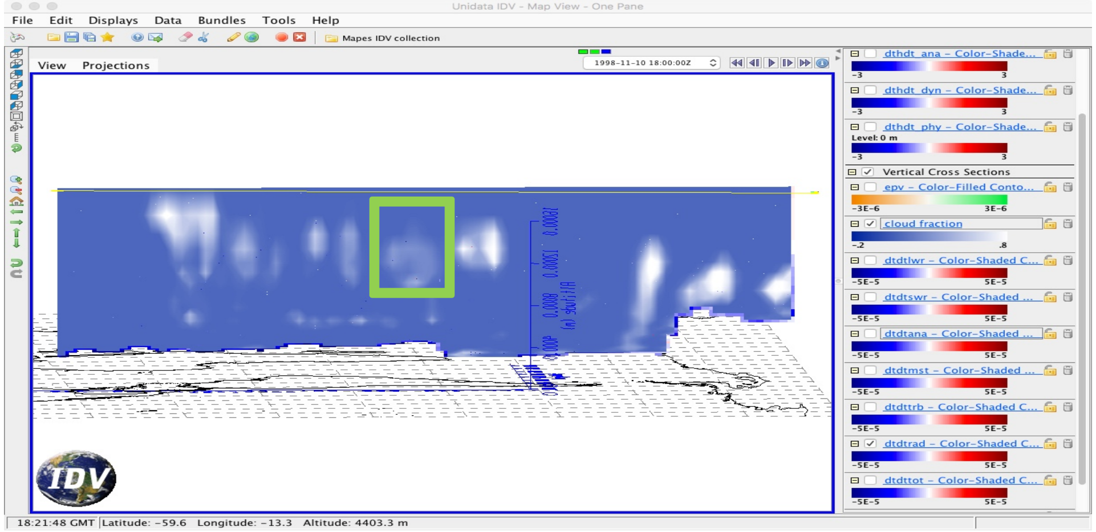


Seems to make sense. More turbulence over mountain ranges thus a heating. Both figures show this. I'd like to learn more about the cold layer right above the warm layer.

Assignment part 2: Local view

- Revisit cloud-radiative interactions
  - LW radiation can be understood as water vapor cooling, cloud top cooling, and cloud base warming. Toggle the layers to find a good example, then juxtapose cloud fraction and radiative heating cross-section images to show an example of a place where cloud effects are dominant



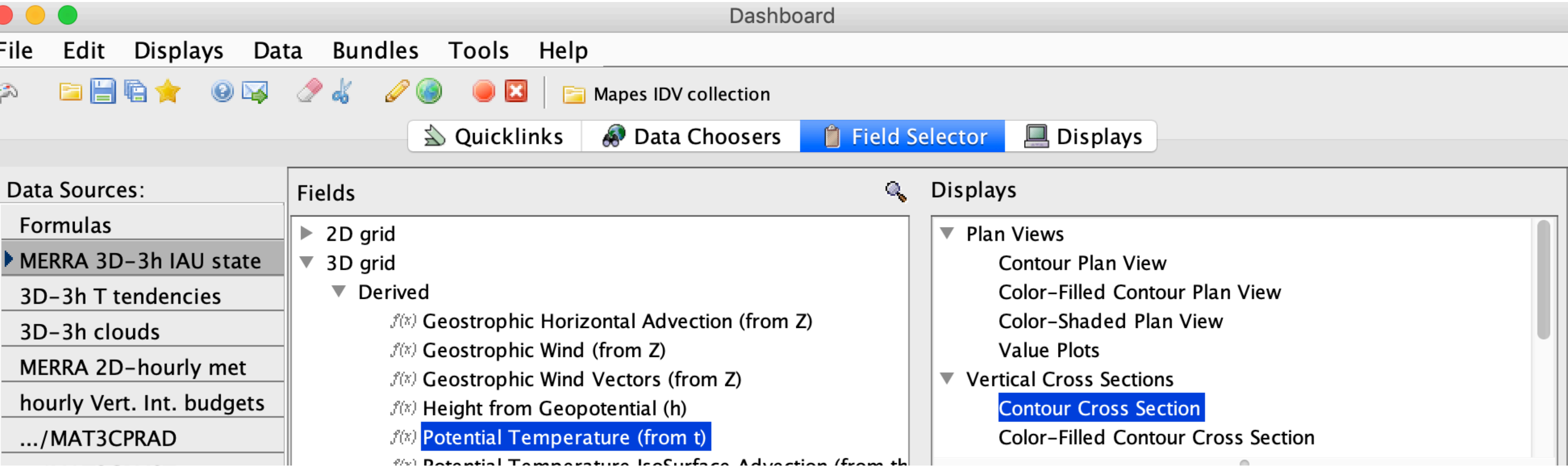


If I look at them separately I can see where the clouds correspond to a warming where cloud bottom is and a cooling where cloud top is.

Assignment part 2: Local view

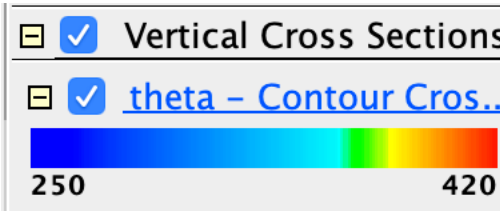
- Consider the PV source term motivating this exploration.
  - Where does the vertical gradient of heating imply large PV sources? Use arrows to annotate a couple positive and negative source regions.
  - Can you find a weather situation where this source term is a positive feedback on PV?

Create a new cross section of potential temperature contours

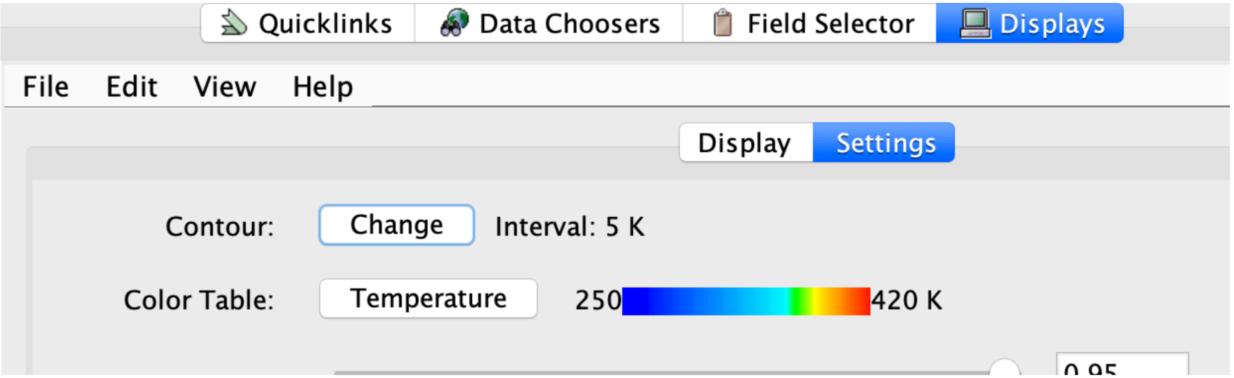


Create a new cross section of potential temperature contours

- Now click its Legend entry to pop up its Display Controls.

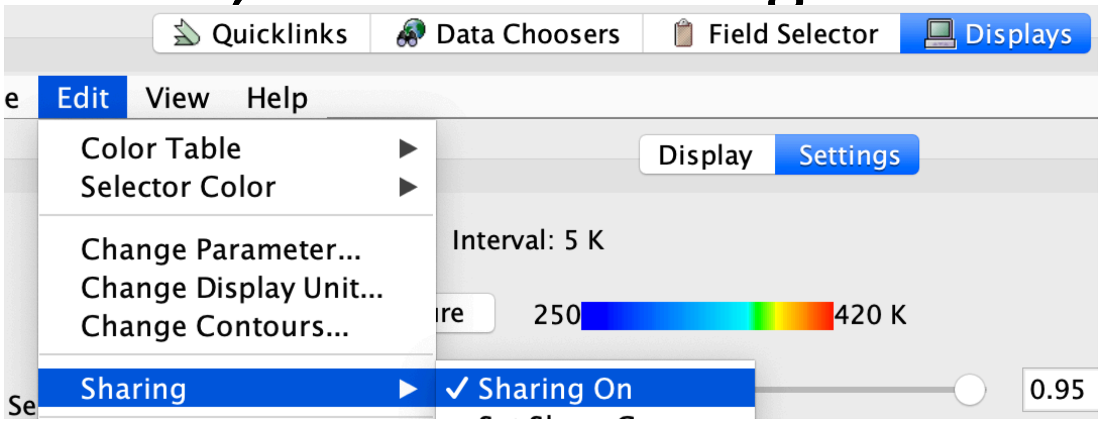


- Change the contour interval to 5K. Change the Color to Black. Change their label size to 20.



Create a new cross section of potential temperature contours

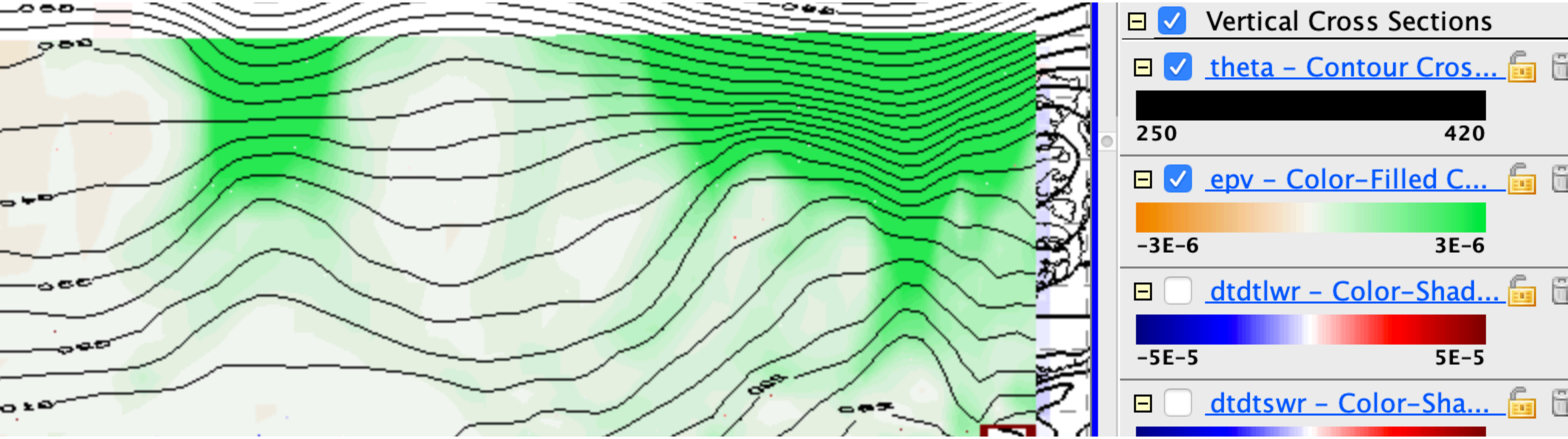
- Again click the Legend entry to pop up the Display Controls.
- Under the Edit menu, turn on Sharing



- Move the main north-south cross section slightly. This will make your new theta contour section snap into place with it.

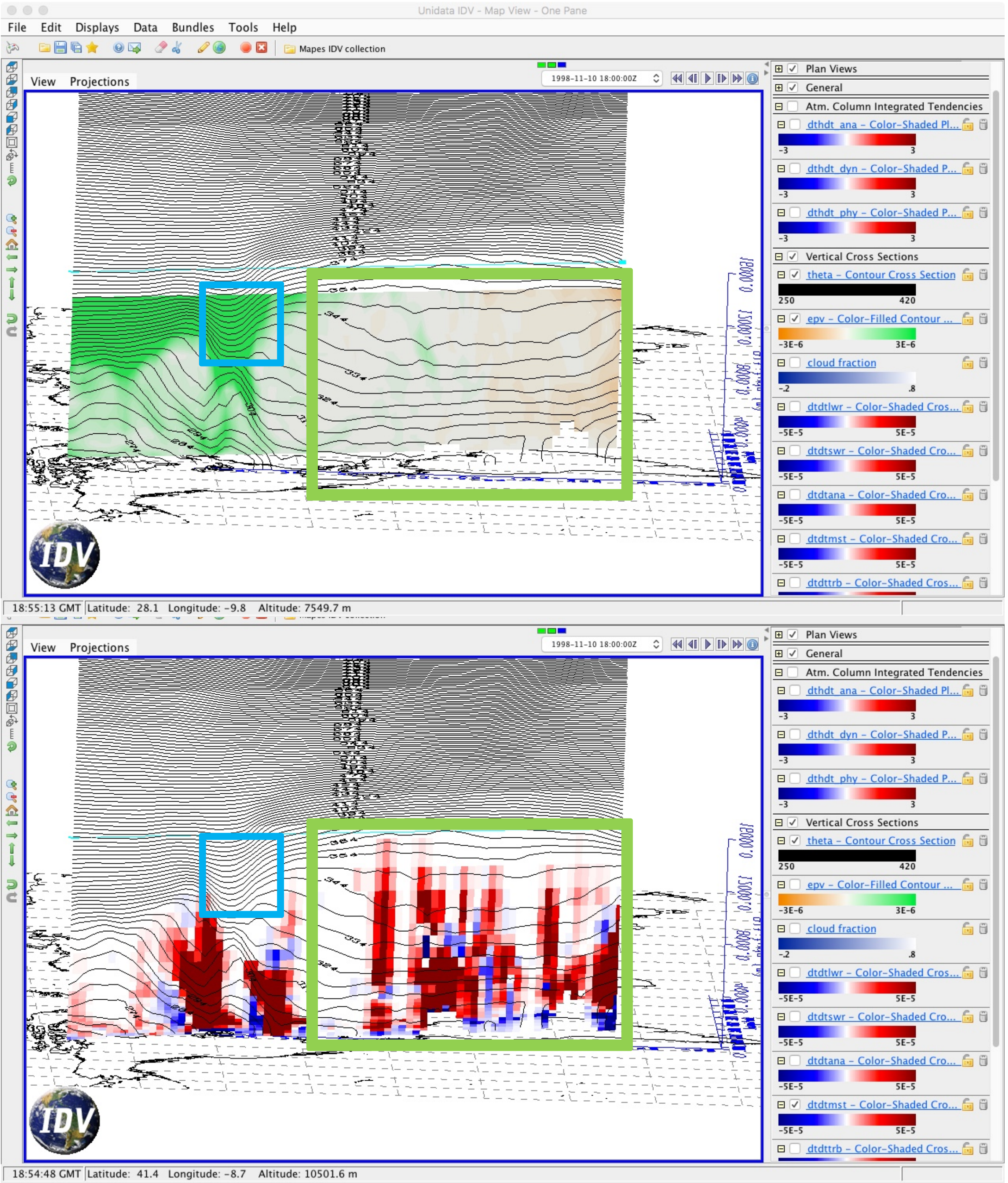
Create a new cross section of potential temperature contours

- You should see our familiar relation between theta surfaces and (most clearly) upper-level cool core cyclones:



Warm and cool cores & condensation heating

- Use the cross section with theta contours and the moist-processes heating rate (dtdtmst) to find an example
  - with the condensation heating in a warm core storm, like the one halfway to Ireland
  - how does the PV source term from latent heating feed back on such a warm core storm?

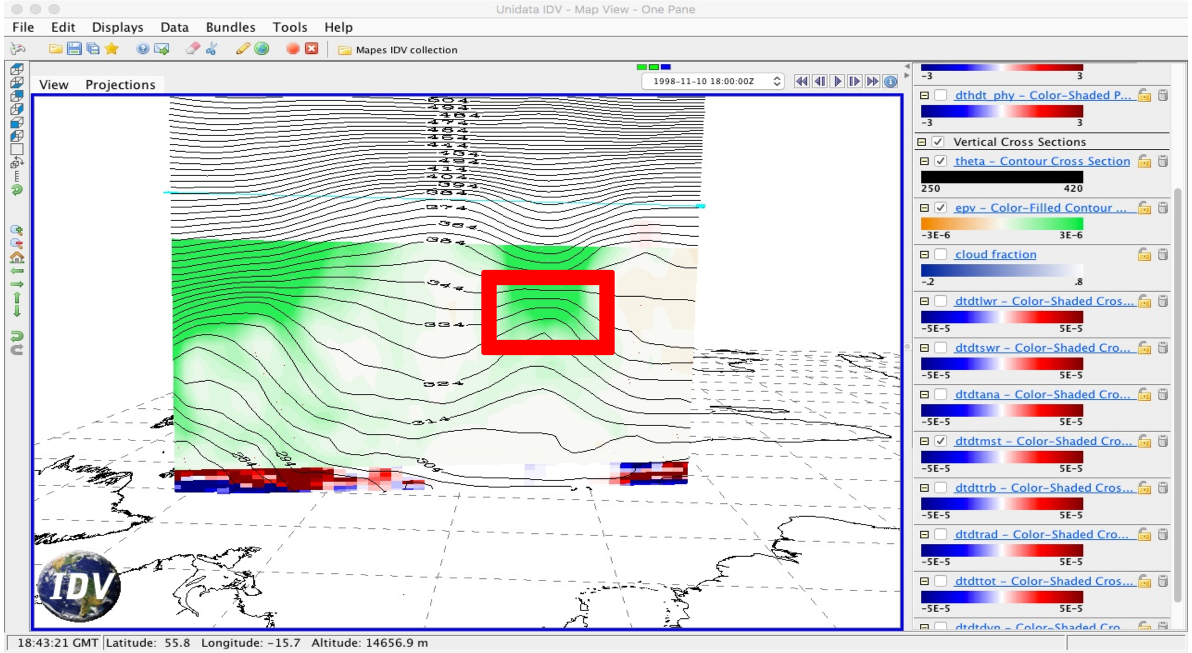


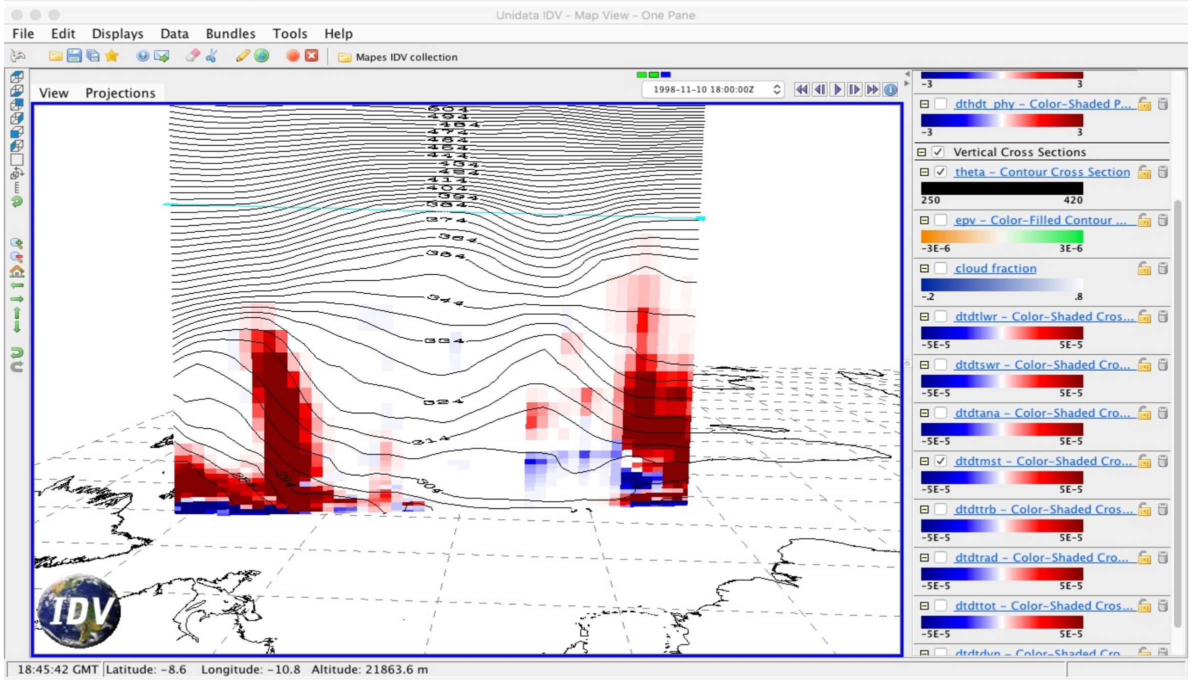
I believe this is a warm core anti-cyclone actually? Depressed isentropes with slightly negative PV. In this example there's a lot of moist heating under the depressed isentropes.

But have warm core cyclone in same example in the blue box. I think depressed isentropes and positive P. vorticity.

Warm and cool cores & condensation heating

- Use the cross section with theta contours and the moist-processes heating rate (dtdtmst) to find an example
  - where a cool core cyclone (lifted isentropes, cyclonic PV aloft; a tentacle of the polar vortex) may be gently lifting air to its condensation level, releasing some latent heating
  - how does the PV source term from latent heating feed back on such a cool core storm?





Positive PV in upper atmosphere lifted isentropes to indicate cool core cyclone.

Not sure if this is a great example bc not a lot of moist heating data where we have high pv

"The Primitive Equations" (meaning elemental, fundamental)

$$\frac{D}{Dt}\vec{V}_h = -f\hat{k} \times \vec{V}_h - \vec{\nabla}_p \Phi + \vec{F}_r$$

F=MA in the HORIZONTAL

$$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p}$$

HYDROSTATIC
(w/ ideal gas law to eliminate ρ)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

MASS CONSERVATION

$$\frac{\partial T}{\partial t} = -\vec{V} \cdot \vec{\nabla}_p T - \omega S_p + \frac{J}{C_p}$$

FIRST LAW OF THERMO

How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

1. Warmed column of air gets **thicker**

2. Air accelerates due to PGF

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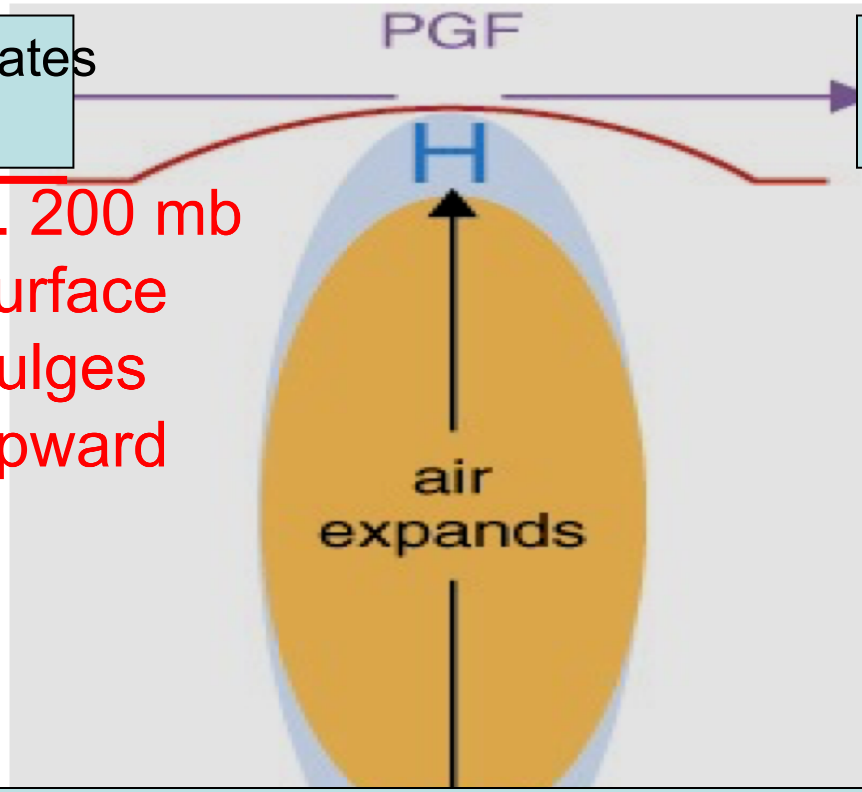

1. 200 mb surface bulges upward

0. Heating (maybe latent heating by condensation in a patch of convection over warm water someplace)

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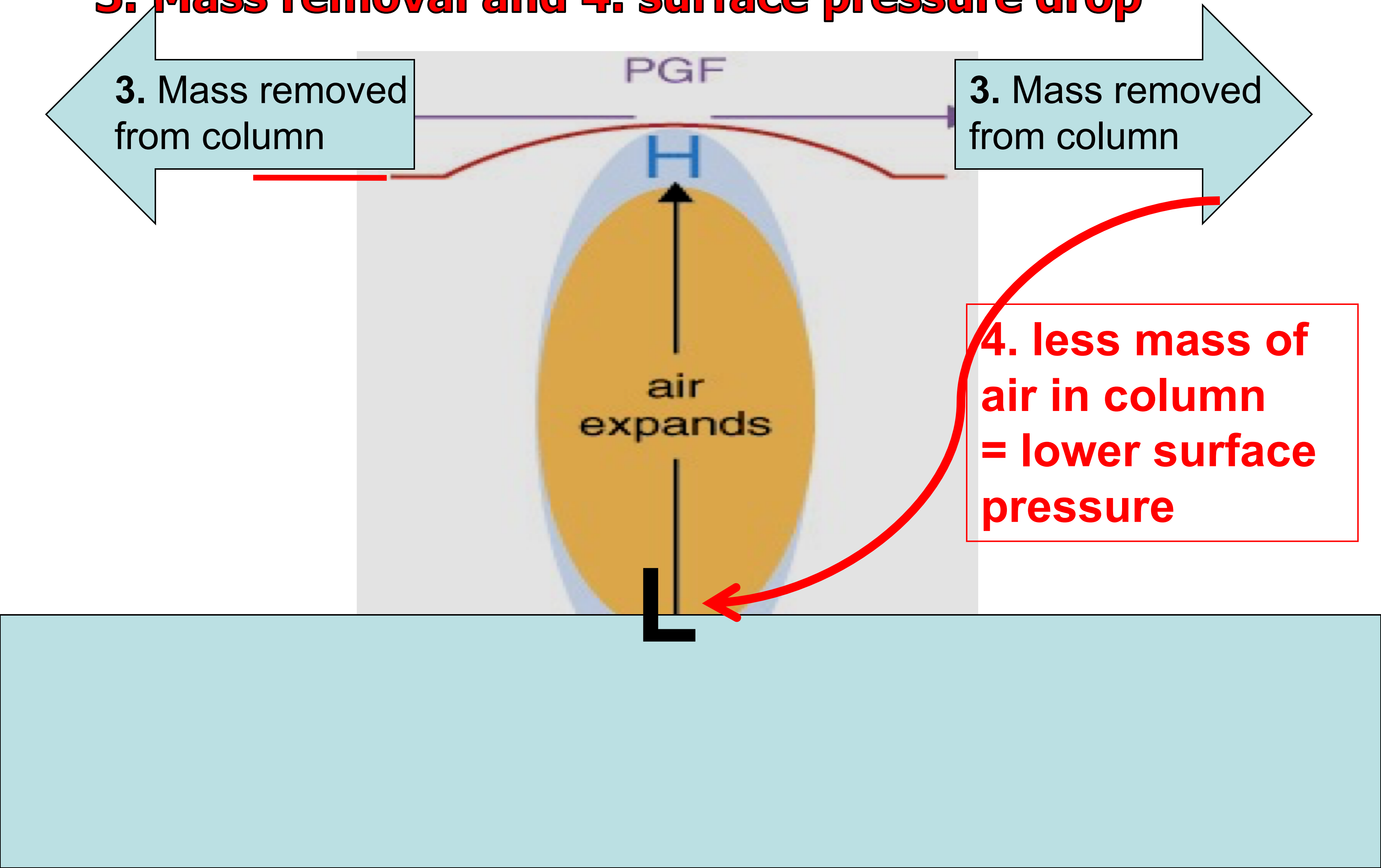
3. Mass removal and 4. surface pressure drop



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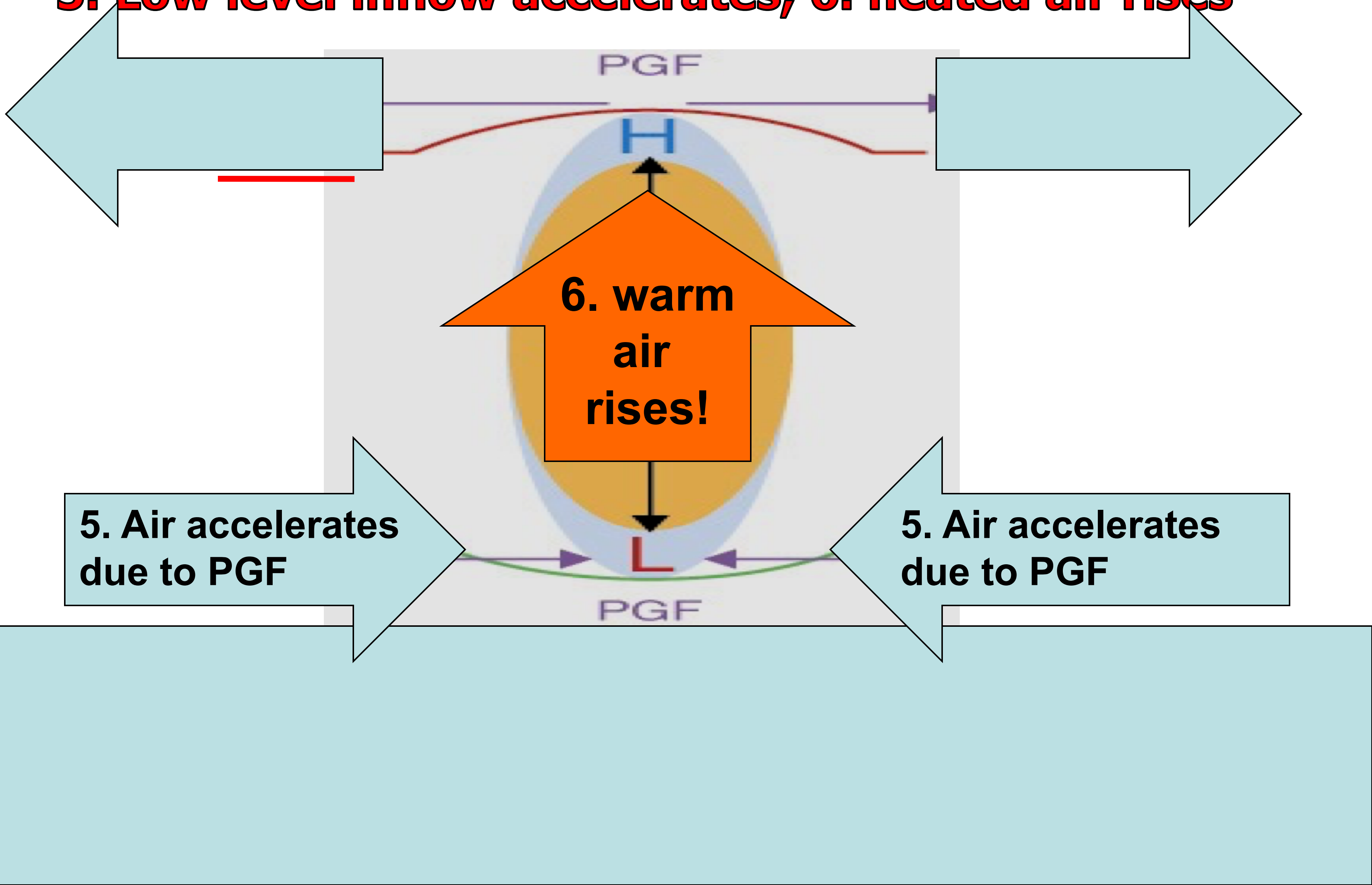
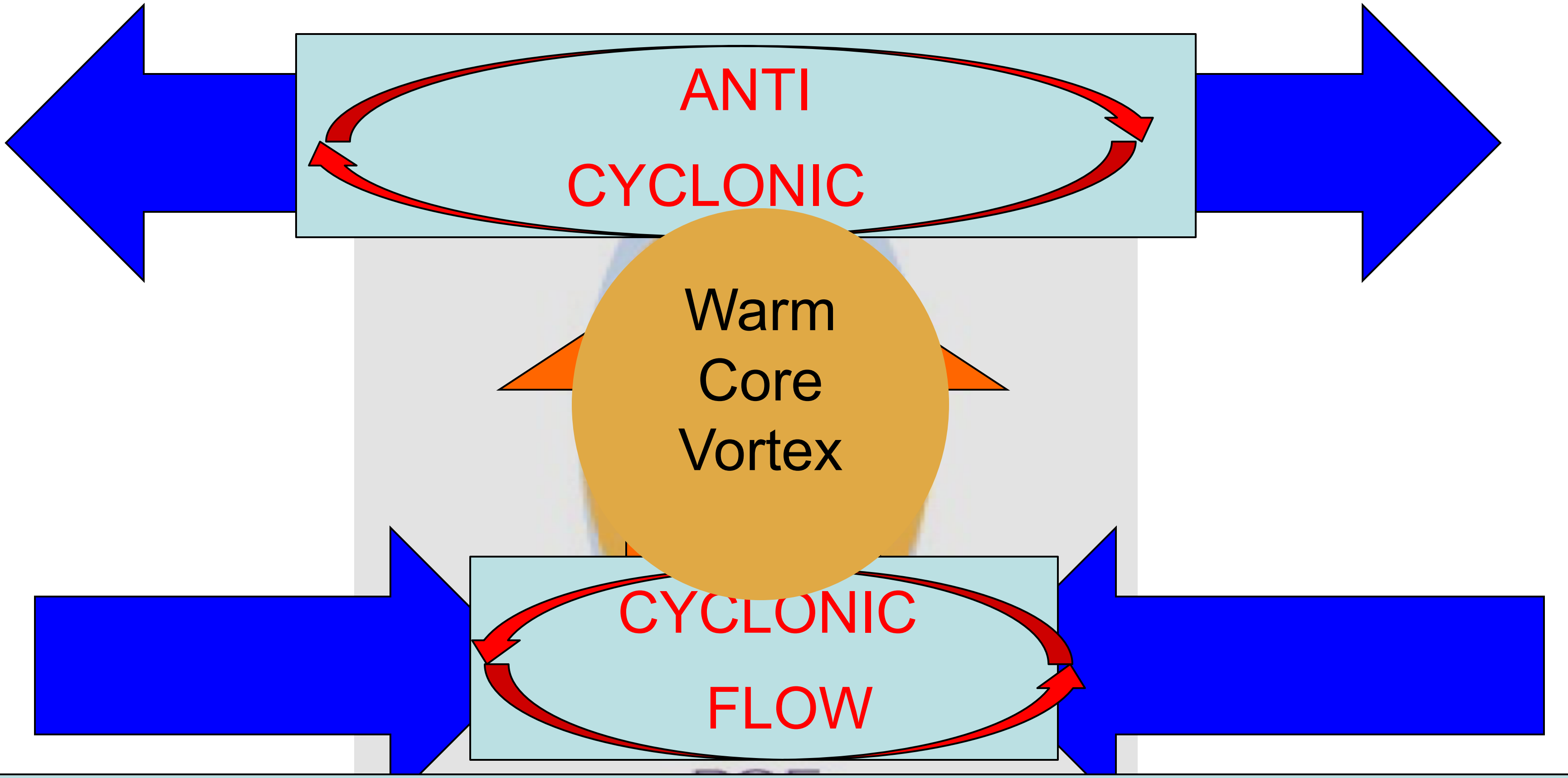
5. Low level inflow accelerates, 6. heated air rises



How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps



7. Coriolis turns flow to right

HW: use The Primitive Equations to compute how a local heating J drives flow in an initially motionless atmosphere

$$\frac{D_h T}{Dt} \boxed{(kT/p)\omega} = J/C_p$$

1. J causes T to increase

net change of T =
amount of heat added/Cp

$$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p}$$

2. Warmer **T causes increased thickness** of the heated column

$$\frac{D}{Dt}\vec{V}_h = \boxed{-fk \times V} - \vec{\nabla}_p \Phi$$

3. High Φ over hot column pushes wind outward

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

4. Surface pressure drops

(remember, omega = Dp/Dt; Holton eq. 3.44)

HW: use The Primitive Equations to compute how a local heating J drives flow in an initially motionless atmosphere

$$\frac{D}{Dt}\vec{V}_h = \boxed{\text{-fk x V}} - \vec{\nabla}_p \Phi$$

5. Low Φ under hot column pulls wind inward

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0$$

6. Hot air rises (finally!)

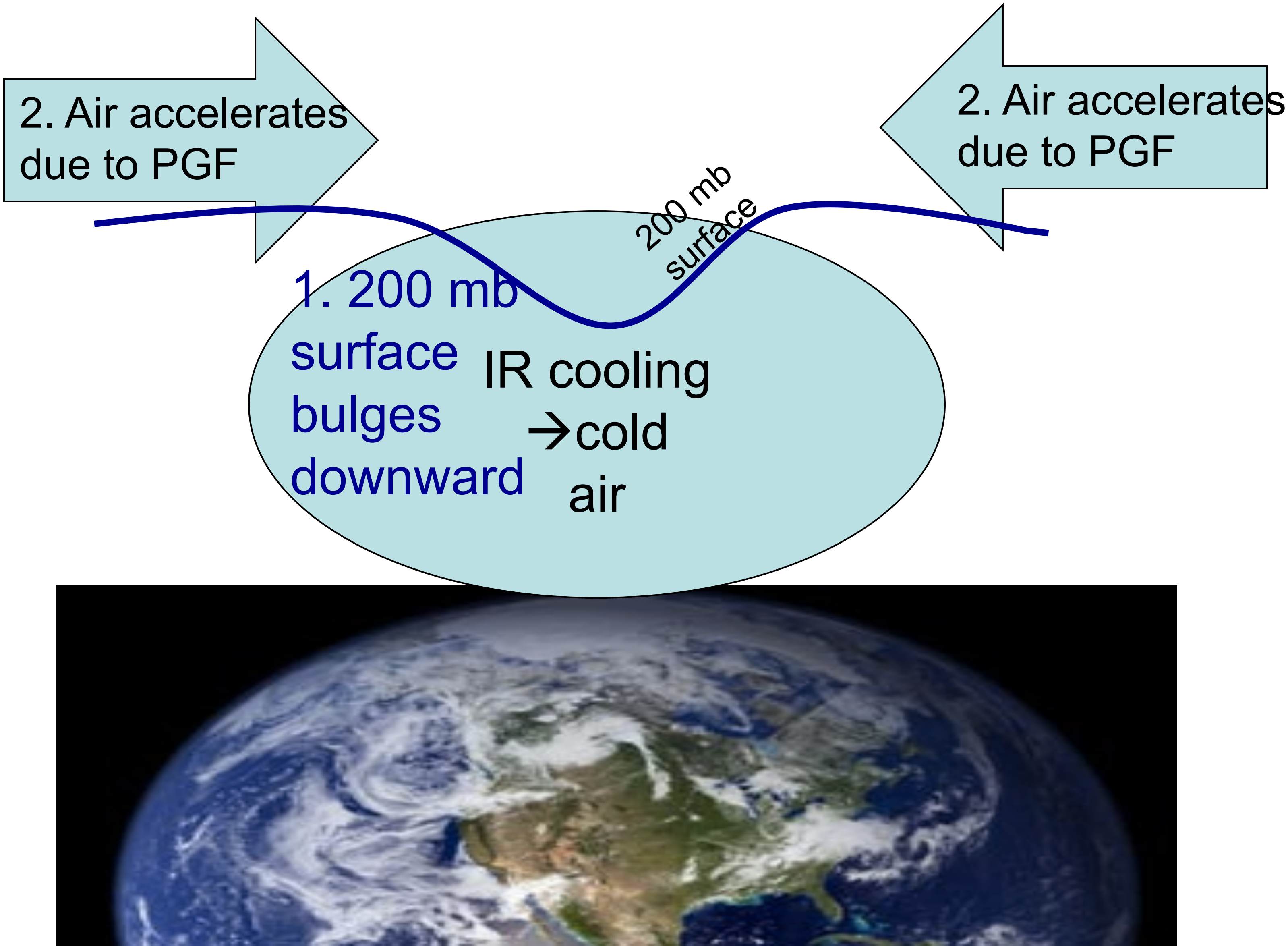
ω =~ ρgw

$$\frac{D}{Dt}\vec{V}_h = -f\hat{k} \times \vec{V}_h \boxed{-\nabla p\ \Phi}$$

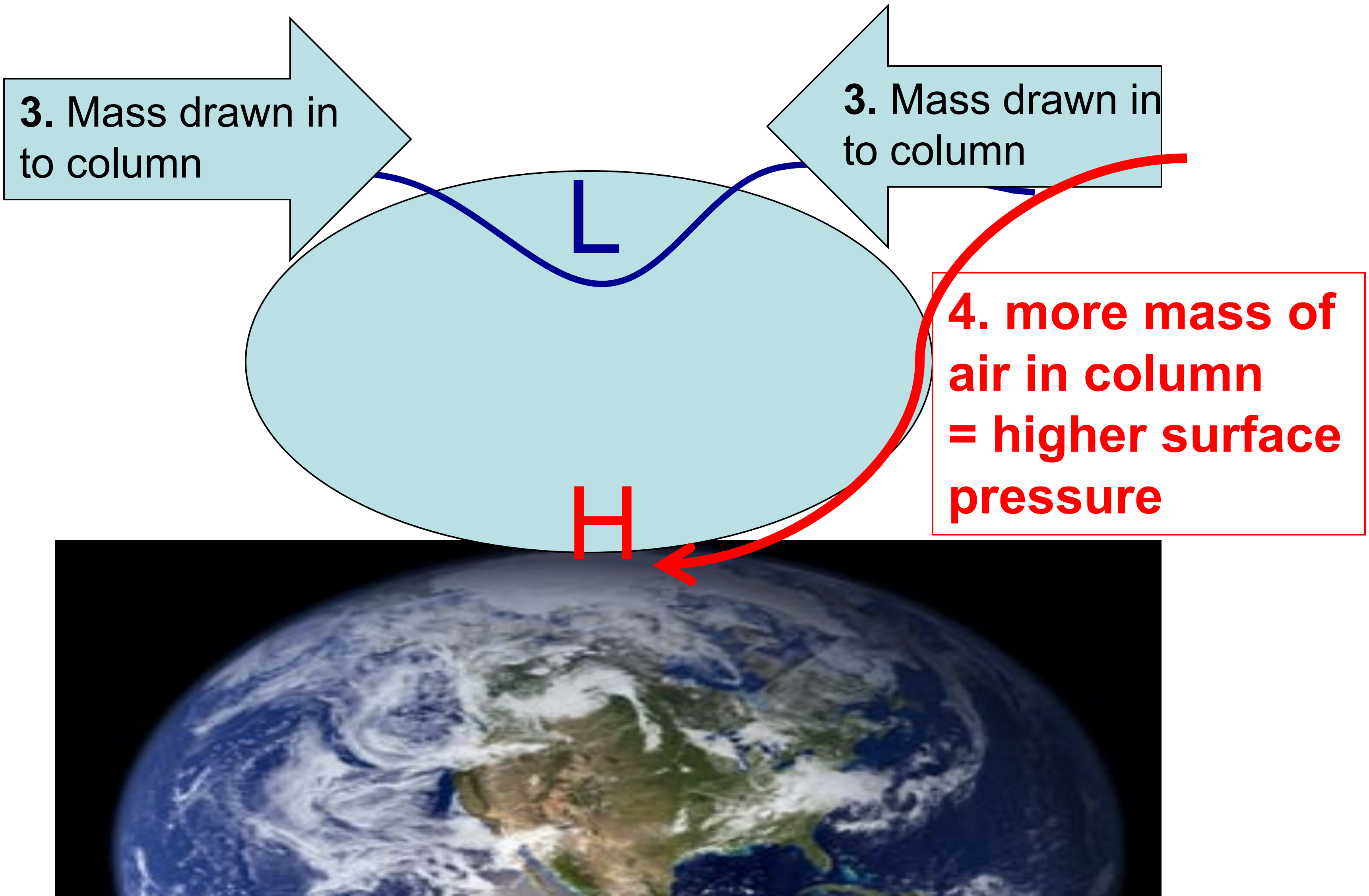
7. Coriolis force turns inflowing and outflowing air to make round-and-round flow

How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

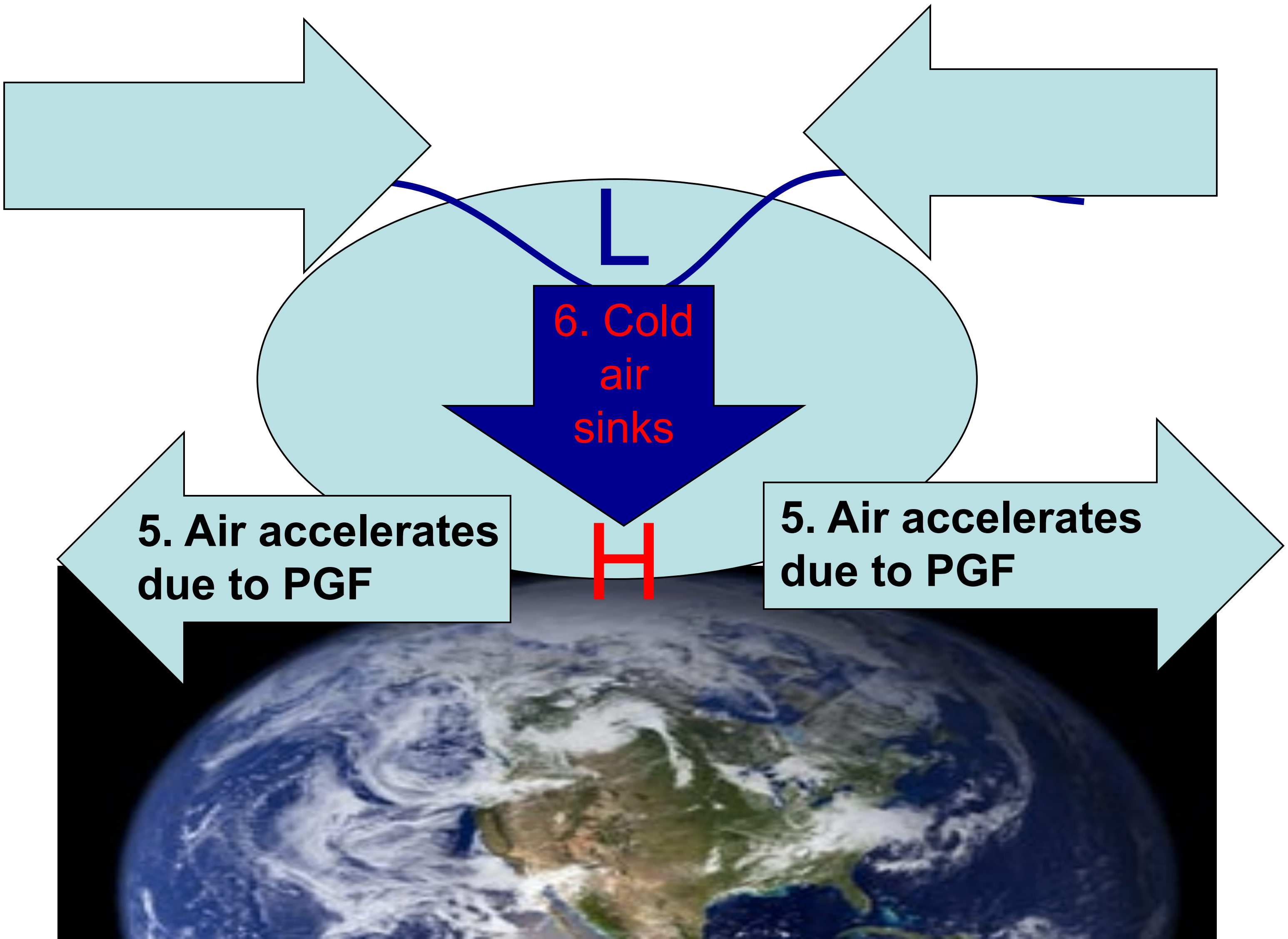
1. Cooled column of air gets **thinner**



How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

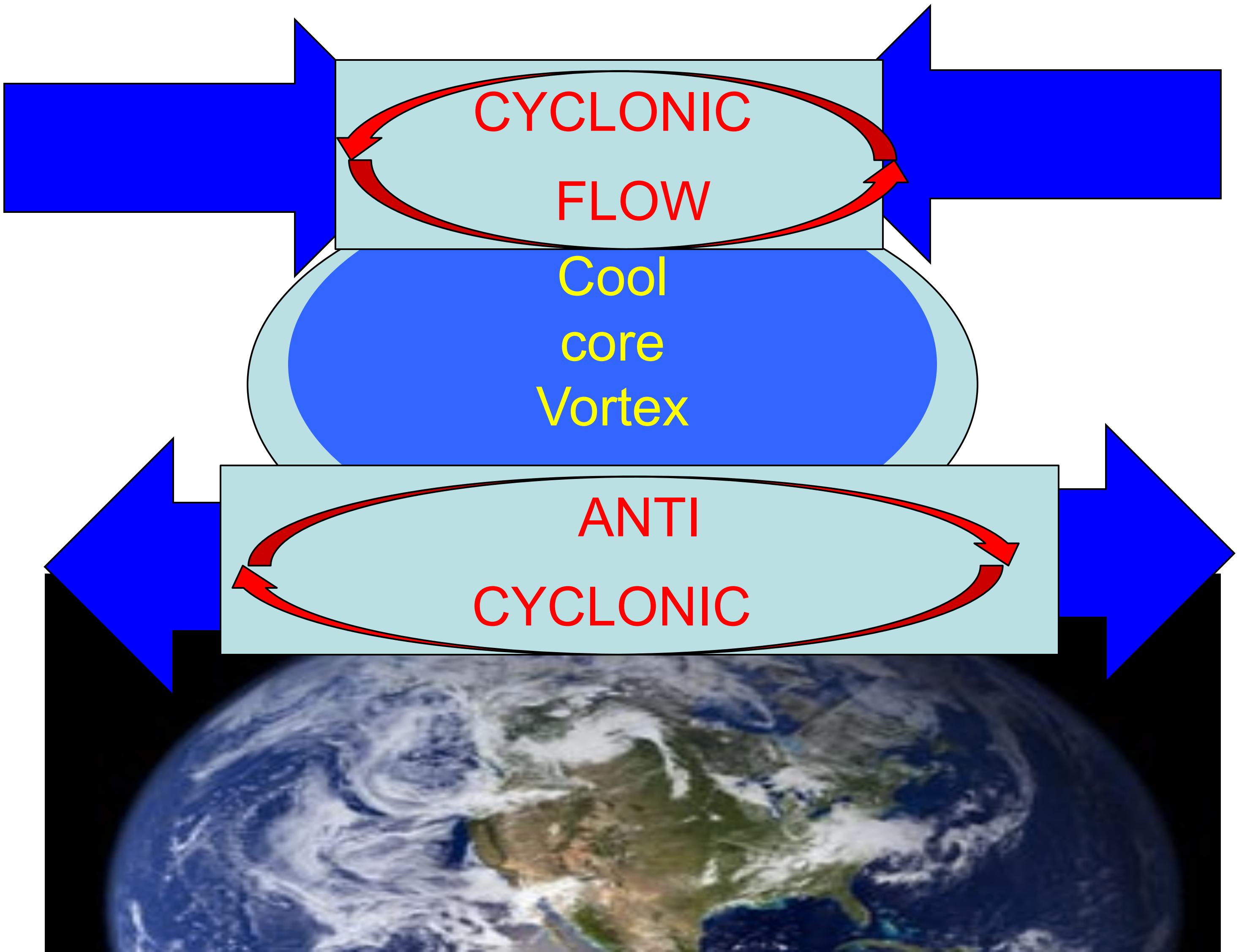


How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

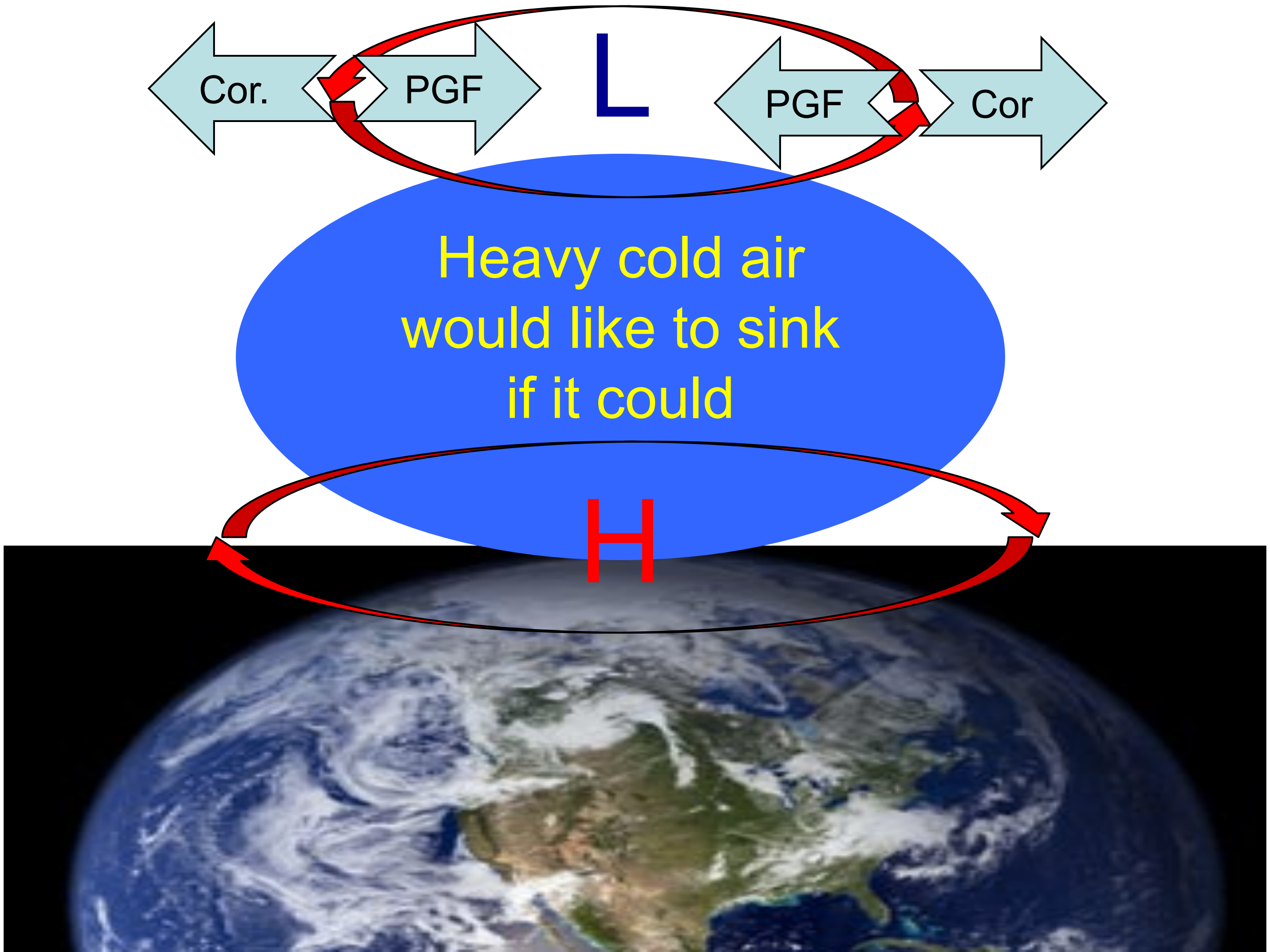


How cooled air sinks and a cool core vortex develops:

7. Coriolis force turns the winds



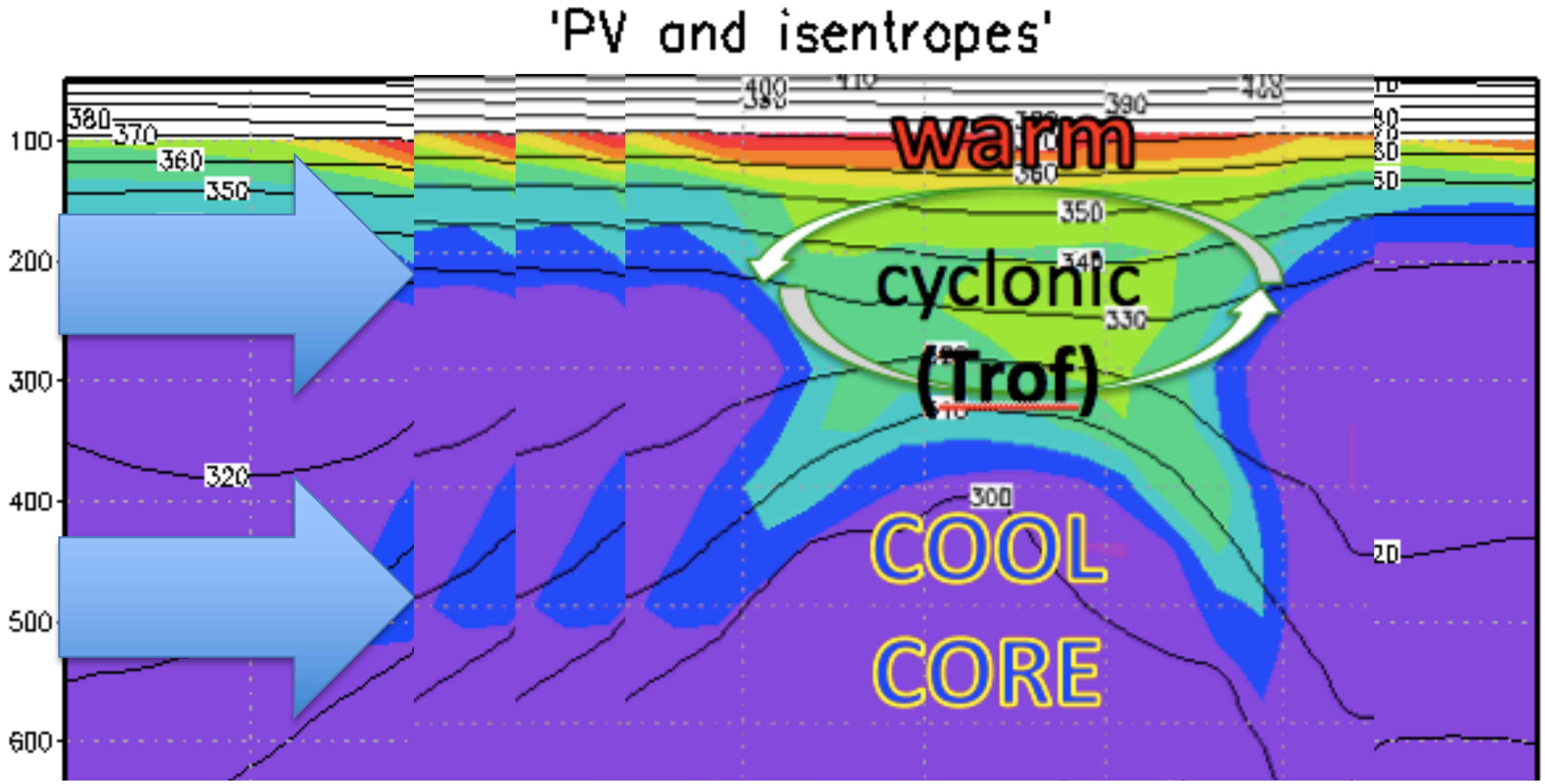
The geostrophically balanced polar vortex: The Coriolis force on the westerly jet stream prevents cold pool of Arctic air from sinking down and covering the whole Northern Hemisphere



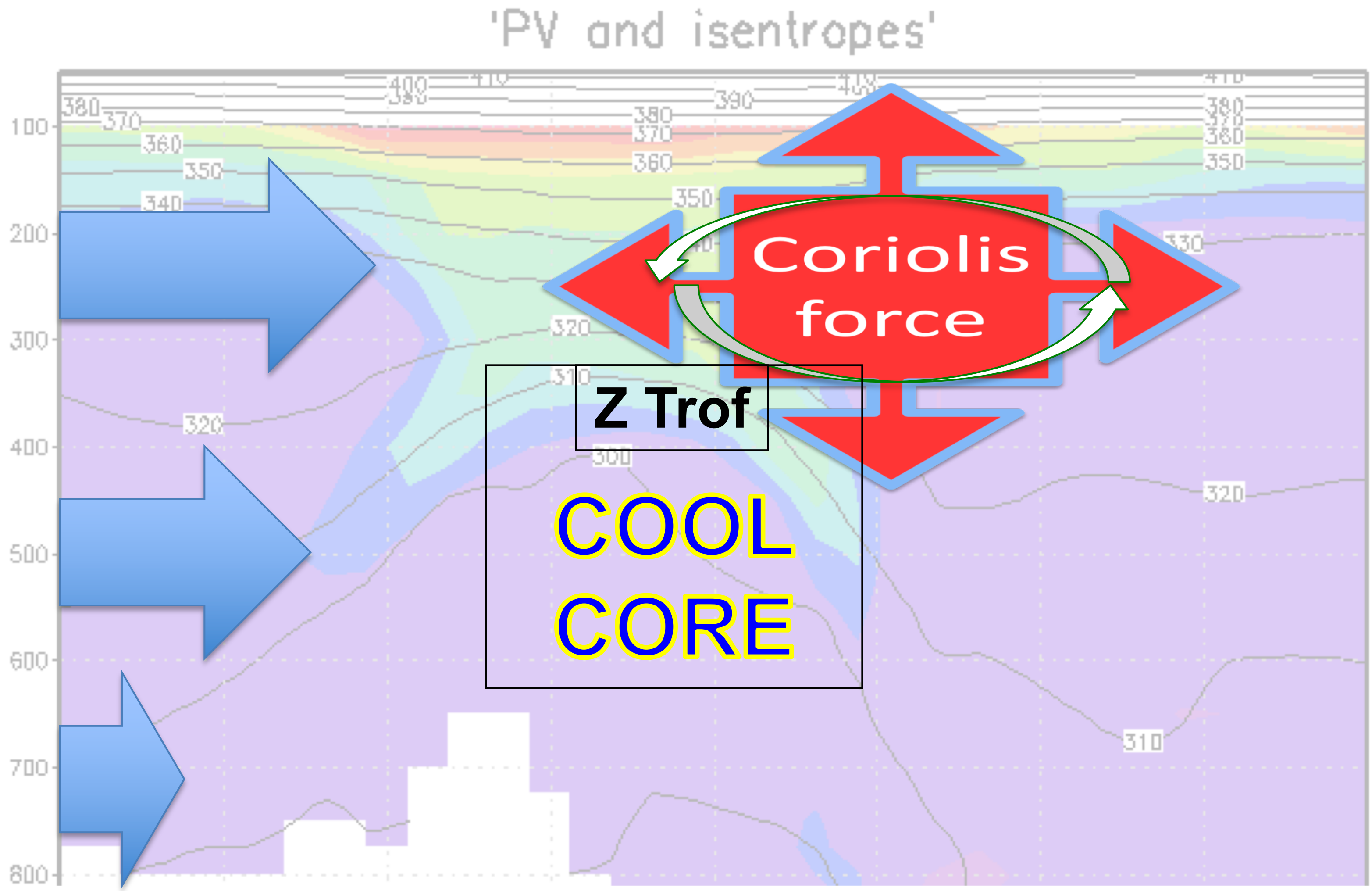
Polar and stratospheric "Reservoirs" of ζ_a or PV

- Potential vorticity: $\mathbf{PV = -g\,\zeta_a\,(\partial\theta/\partial p)}$
  - The polar latitudes, where f is large, are a "reservoir" of high PV even when there is no wind!
  - The stratosphere where $(\partial\theta/\partial p)$ is large is a "reservoir" of PV even when there is no wind!
  - When tentacles or pieces of the polar & stratospheric **PIZZA or OCTOPUS of PV** stretch or break off into the midlatitudes, they become our upper-tropospheric synoptic cyclones.

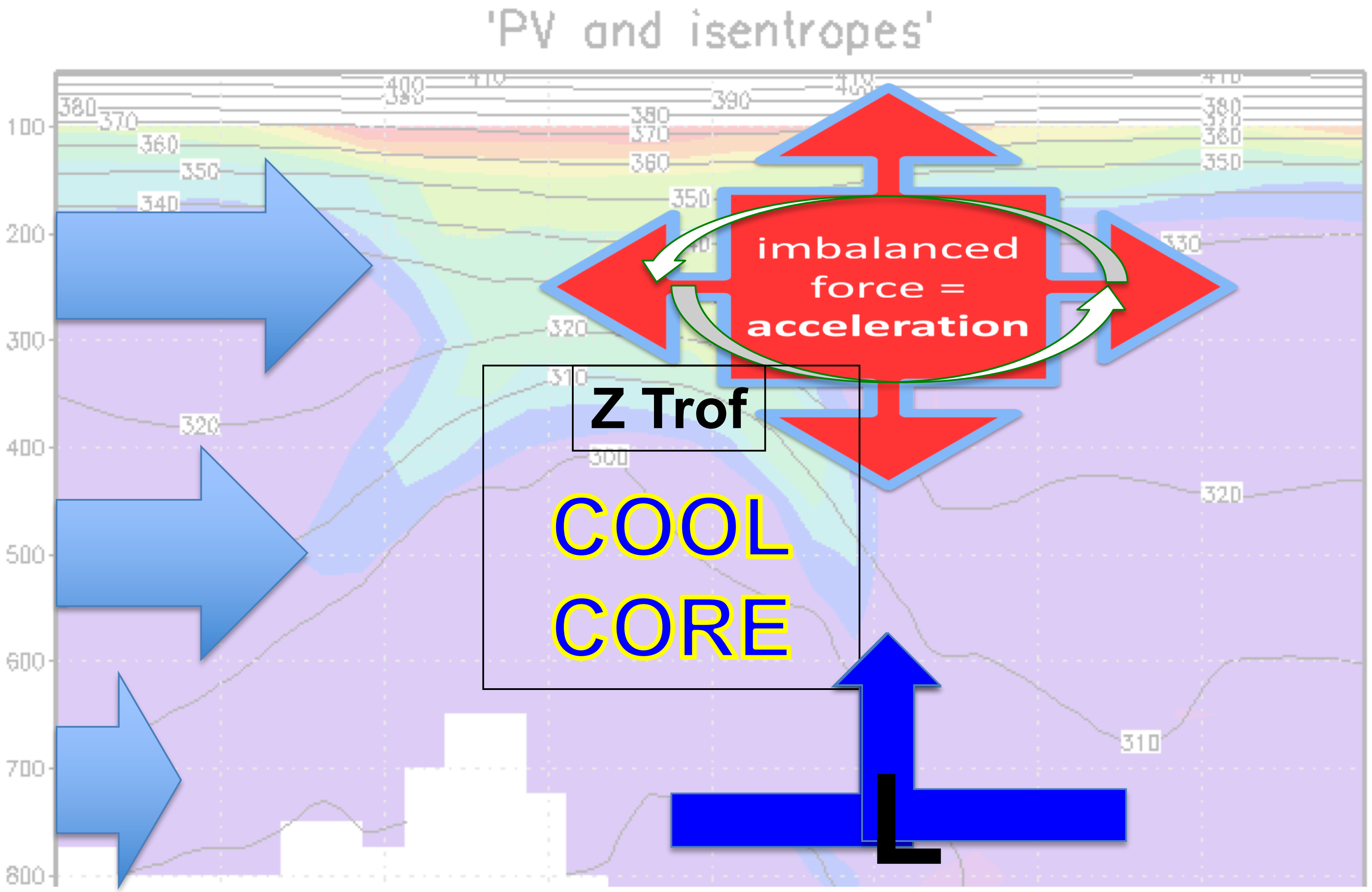
Unsheared advection of T, u, v, vort, PV: no breaking of balance



Sheared advection breaks thermal wind balance



Sheared advection breaks thermal wind balance



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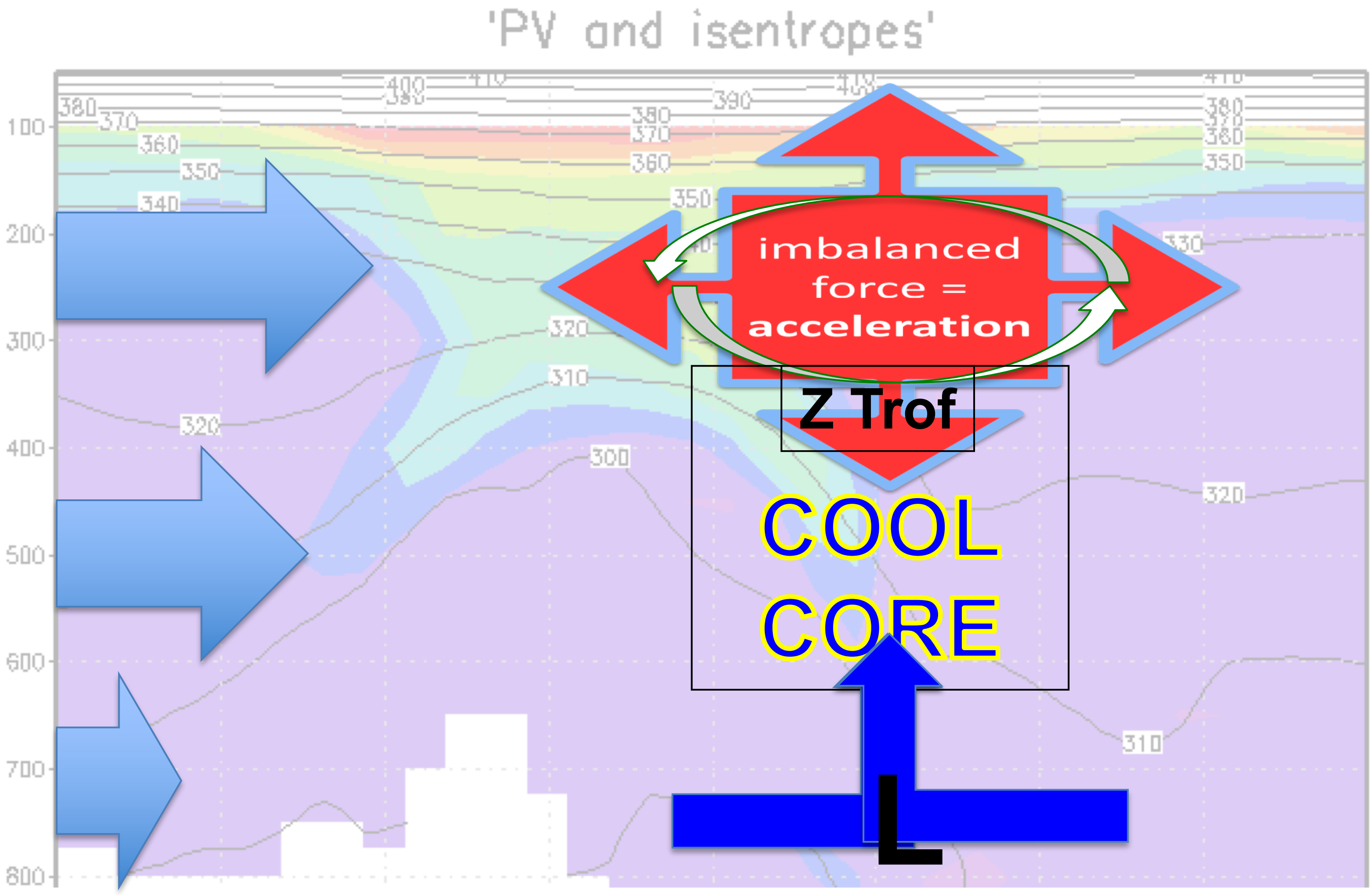
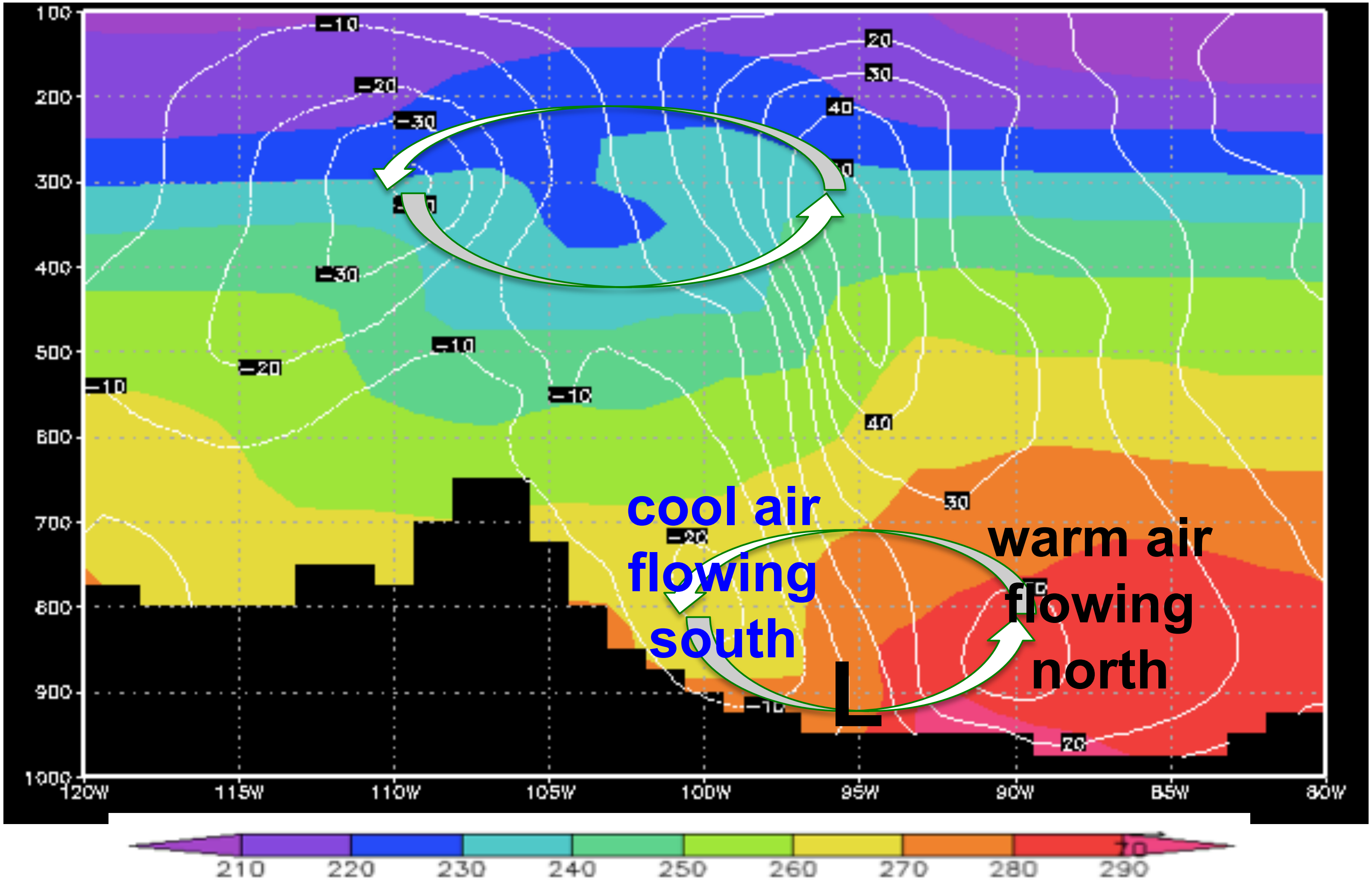


But there is some T advection too



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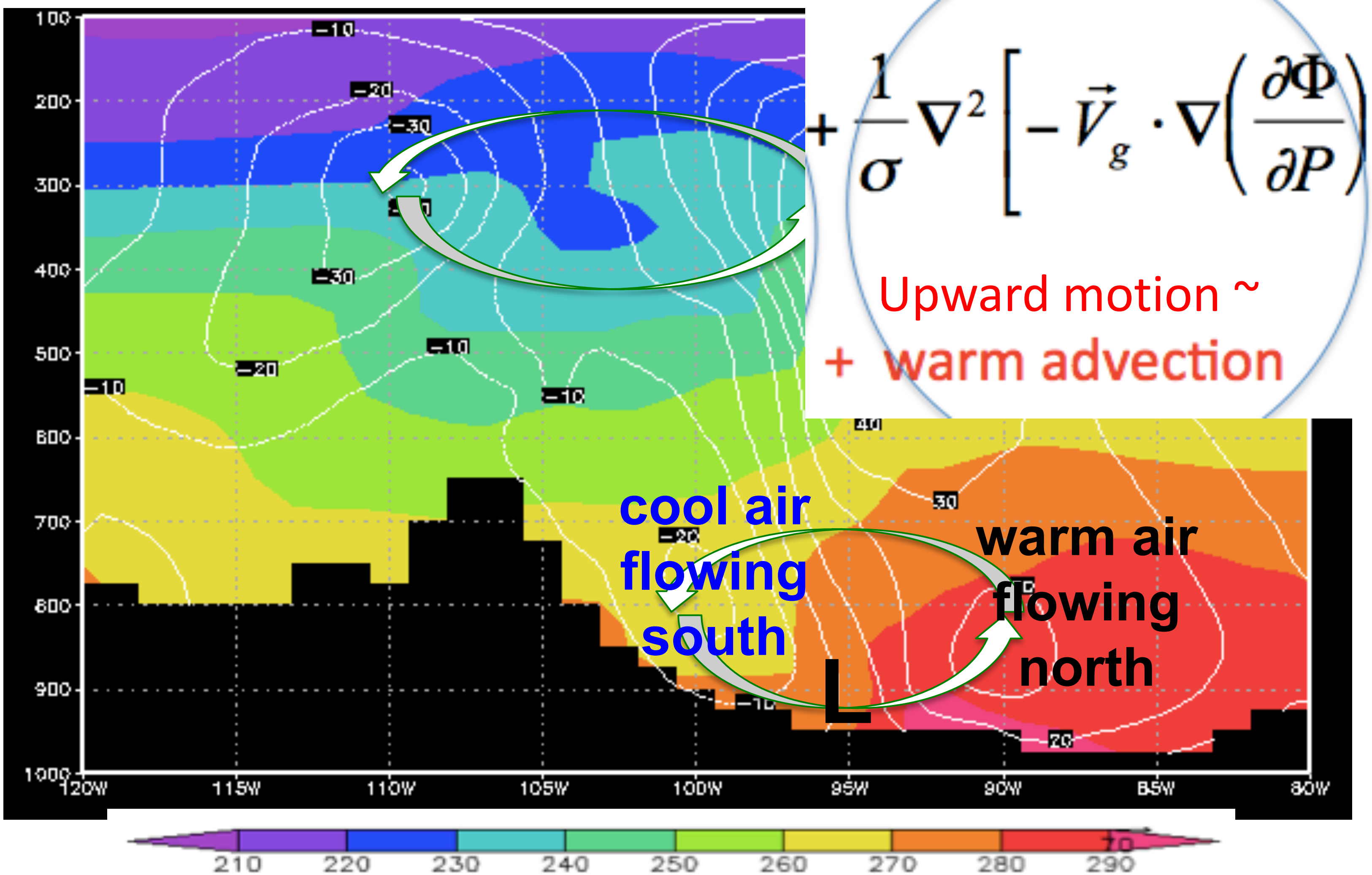

$$+\frac{1}{\sigma}\nabla^2\left[-\vec{V}_g\cdot\nabla\left(\frac{\partial\Phi}{\partial P}\right)\right]$$

East-west section: omega