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?

PV is conserved -- almost

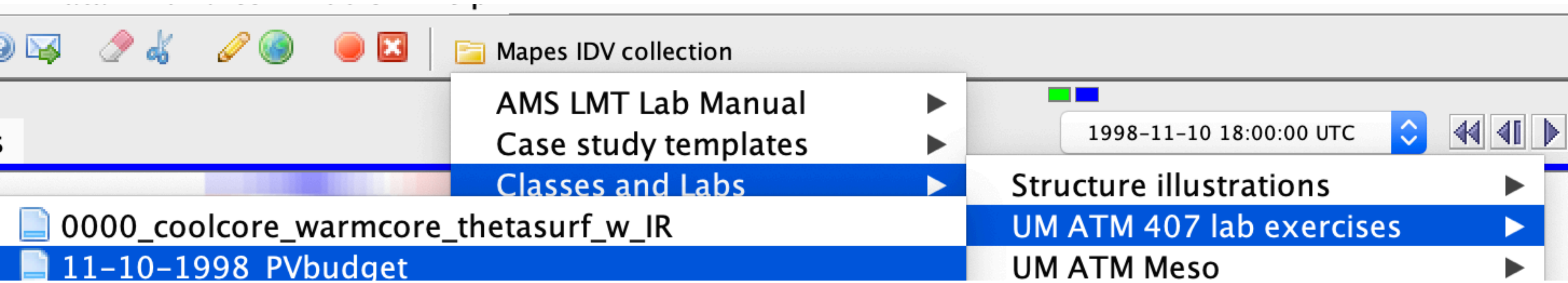
APPROXIMATE term that generates PV on the Earth

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

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”.

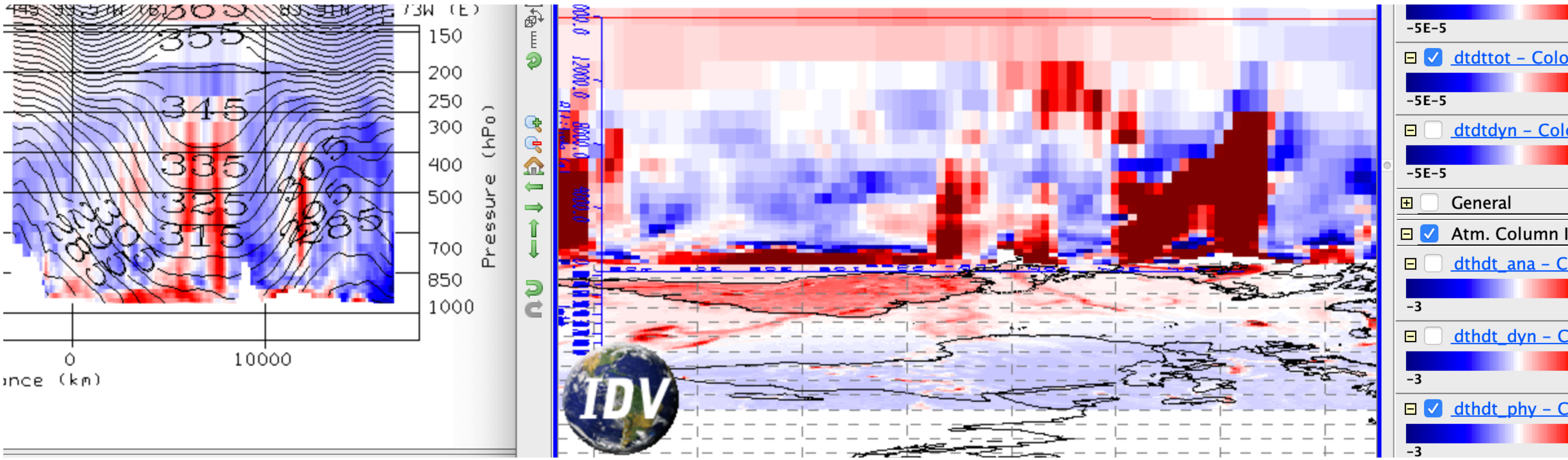
Assignment part 1: global view

- Open the bundle 11-10-98 PV budget



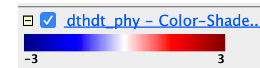
- Orient yourself to its displays, in **both windows**
  - a **pole-to-pole transect** of the **zonal mean** heating rates (averaged around the whole Earth)
  - A map view with many displays (including **movable cross sections**).

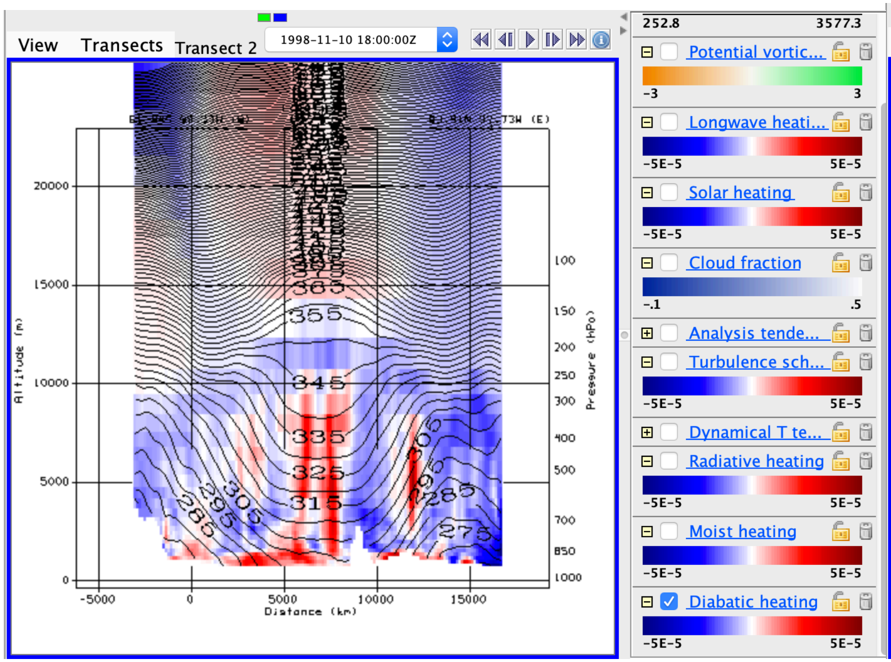
transect of *zonal mean* diab. heating, cross section of total diab. heating, map of column integral diab. heating

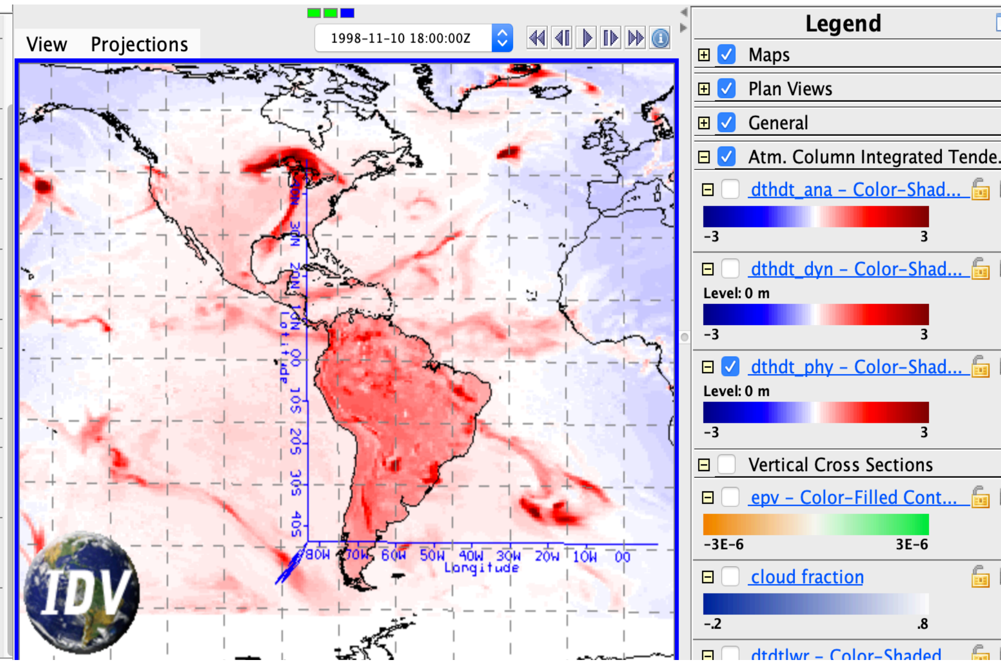


Assignment part 1: global view

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?







Above is the pole-to-pole transect of the zonal mean diabatic heating rate. You can see that in the northern hemisphere the heating rates are less than those in the southern hemisphere.

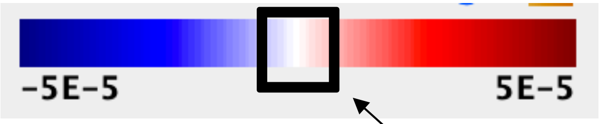
Above is the column-integrated heating rate map dthdt_phy which shows larger heating rates in the Southern hemisphere in comparison to the Northern hemisphere.

The time of year is northern hemisphere fall/winter and southern hemisphere spring/summer

Assignment part 1: global view

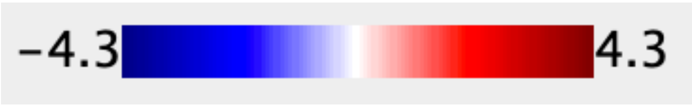
- Now turn to the Transect View window, showing average cross sections all around the Earth. Create a slide showing the transect of total diabatic heating. Label it: where is the south pole, the north pole? Hint: Antarctica is mountainous.
- **The units of all heating rates are are K/s. What is the color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

- If the units of all heating rates was changed to K/day from K/sec you would multiply the range of the scale by 86,400 to account for the amount of seconds in a day. The color range would be the same if you changed the bounds, but if you kept the bounds the same you would notice a range of colors in the white section of the K/sec color bar.



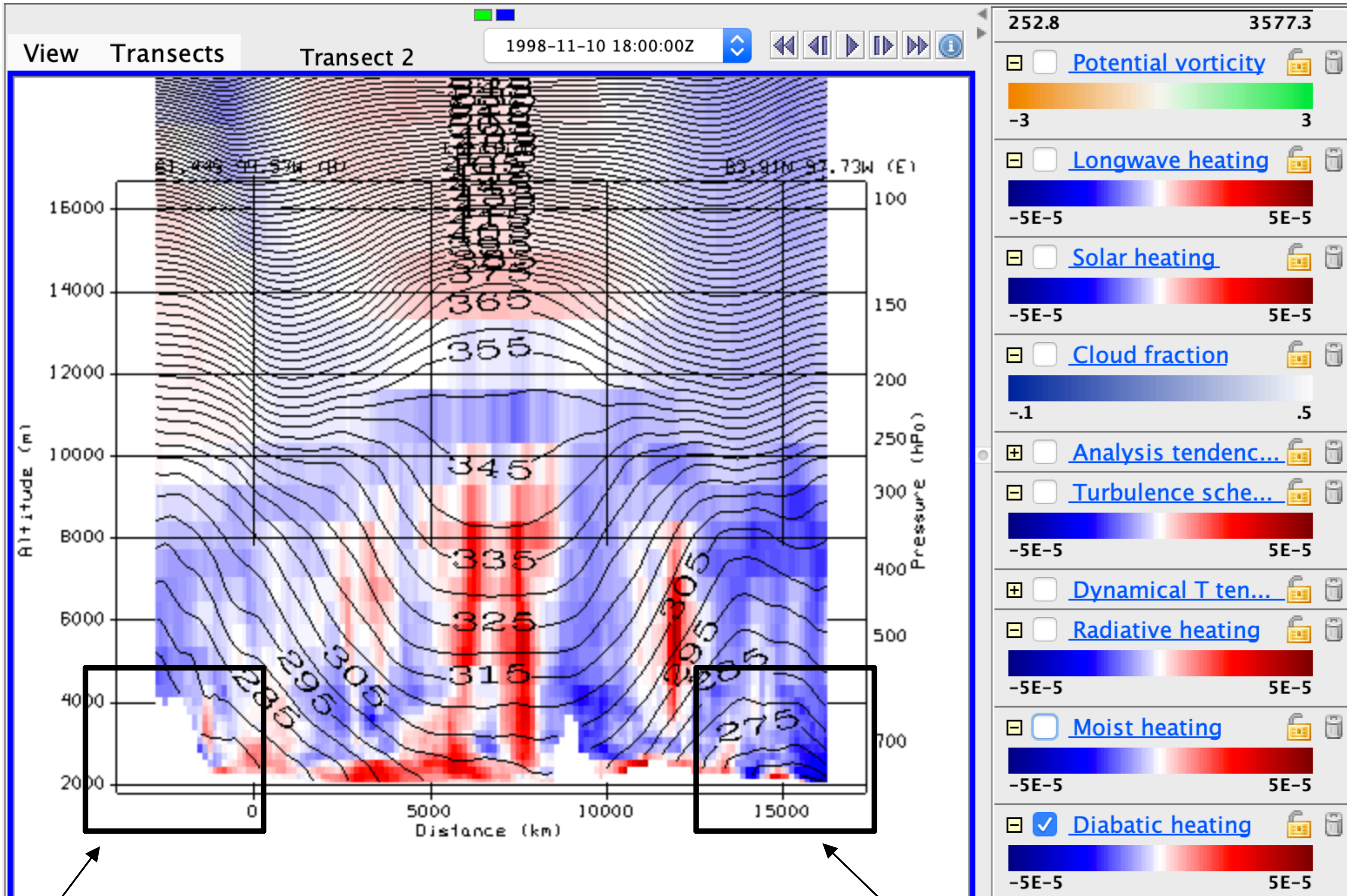
K/sec color bar

K/day color range if scale bounds went unchanged



K/sec color bar multiplied by 86,400

The transect of total diabatic heating.



South Pole

North Pole

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:

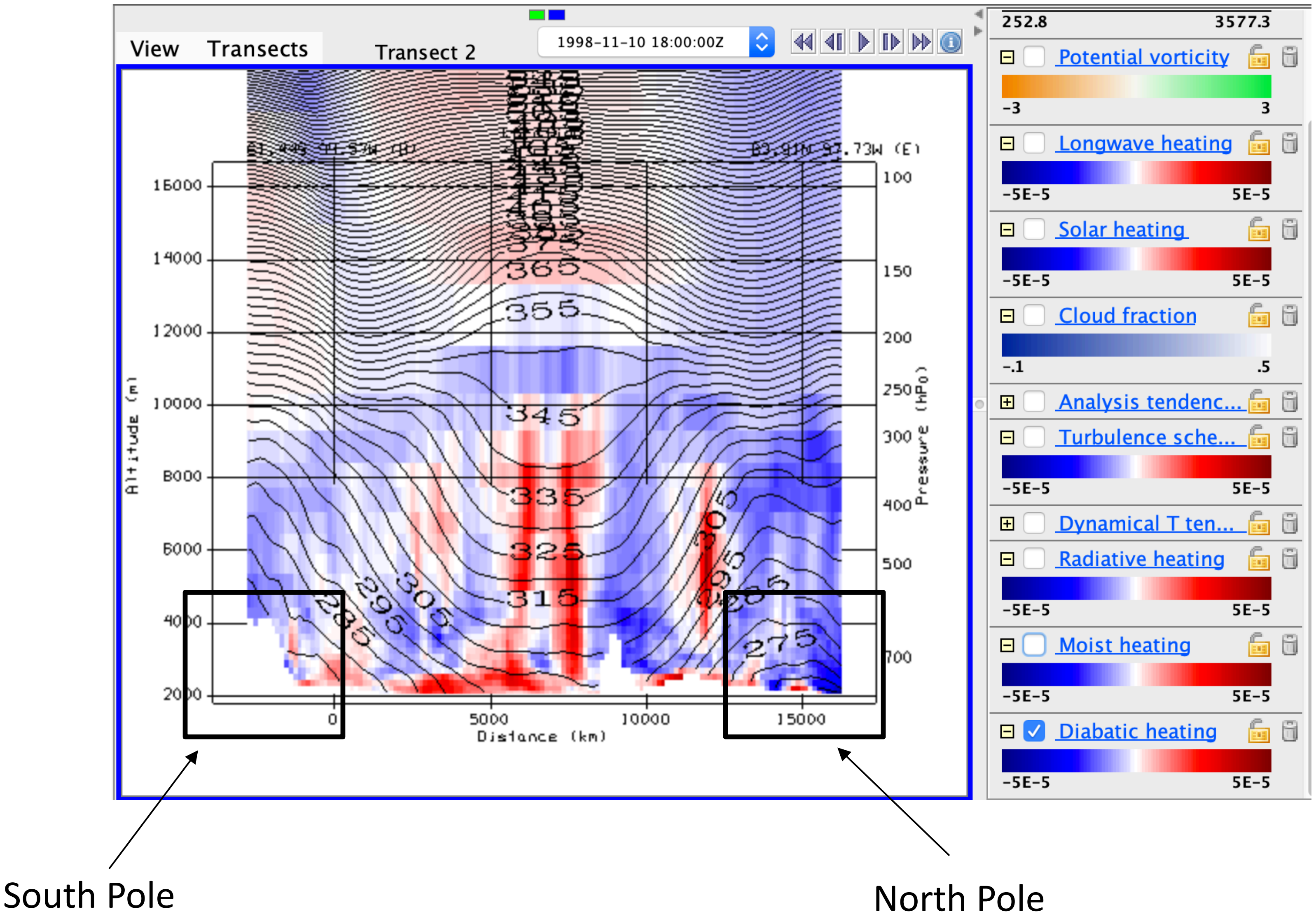
  $\partial T/\partial t$ = dynamical + diabatic + analysis

  diabatic = moist + radiative + turbulence

  radiative = longwave + solar

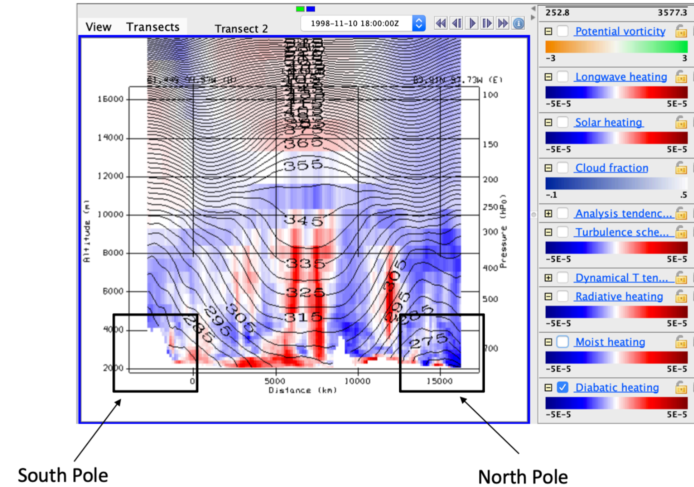
The transect of total diabatic heating.

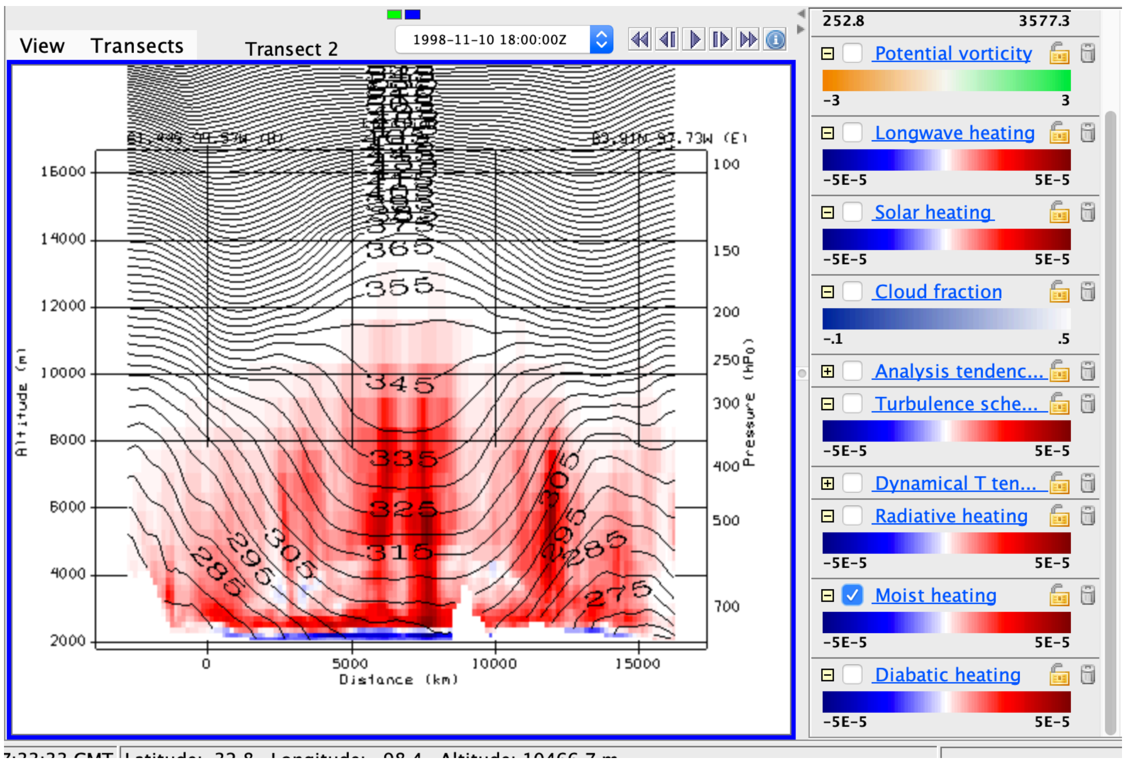
diabatic = moist + radiative + turbulence



Moist Heating

diabatic = moist + radiative + turbulence

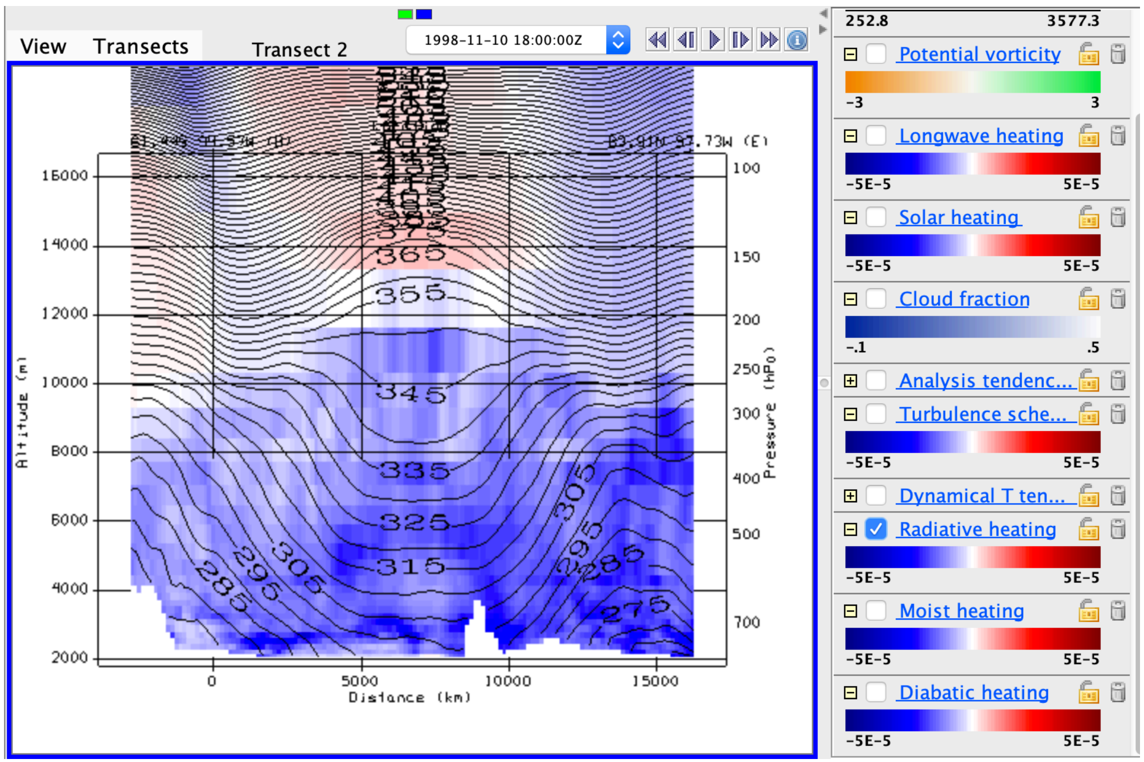


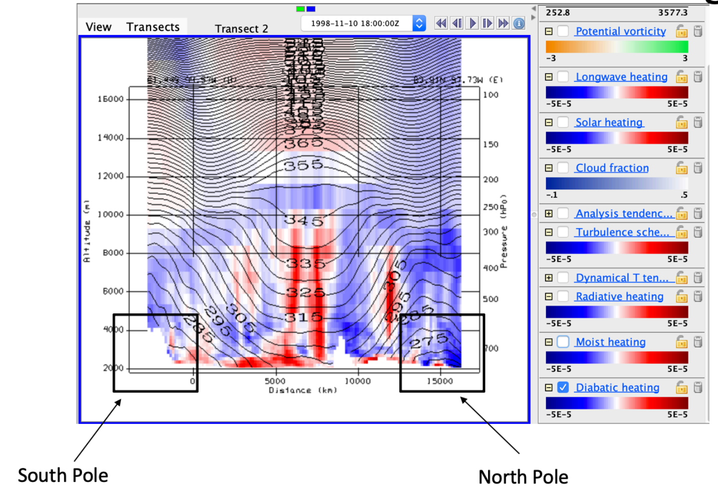


- Moisture is a factor in the diabatic heating term and it can be seen here that in the northern hemisphere there seems to be a weaker signature of moisture heating above the surface than in the southern hemisphere and the tropics. The heating term isn't strong.

Radiative Heating

diabatic = moist + radiative + turbulence

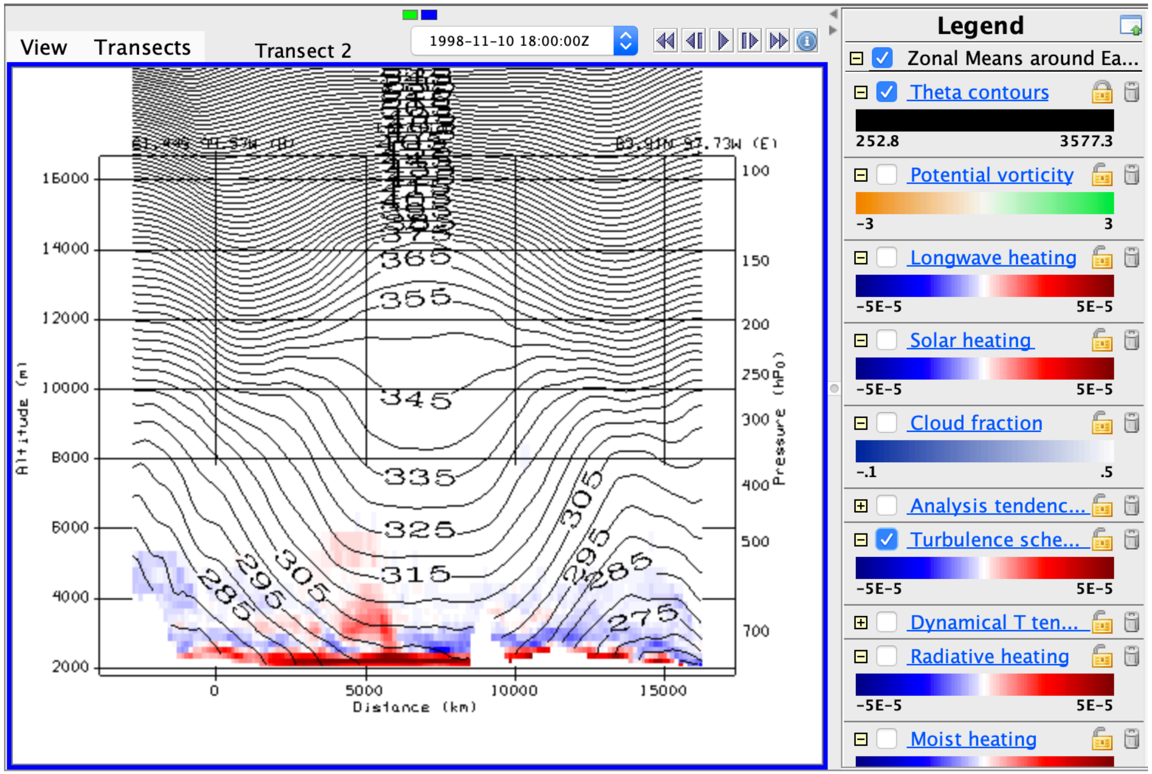


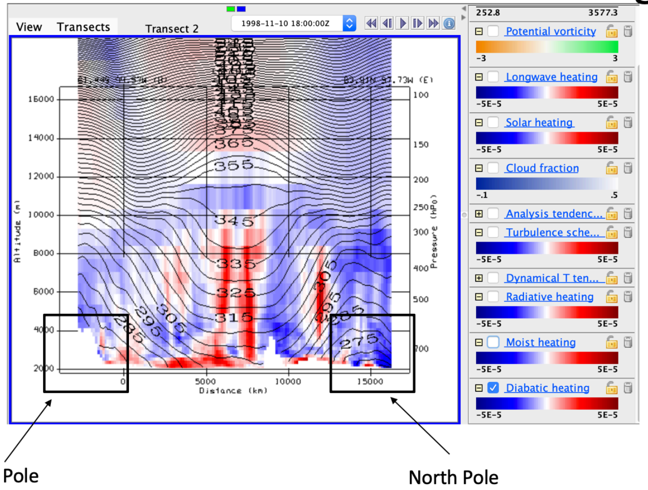


- Strong negative radiative heating is occurring in the northern hemisphere troposphere. This means that there is more radiative heating leaving the atmosphere then is coming in.
- You would expect this to be more negative in the northern hemisphere during the transition from Fall to Winter.

Turbulence Scheme Heating

diabatic = moist + radiative + turbulence



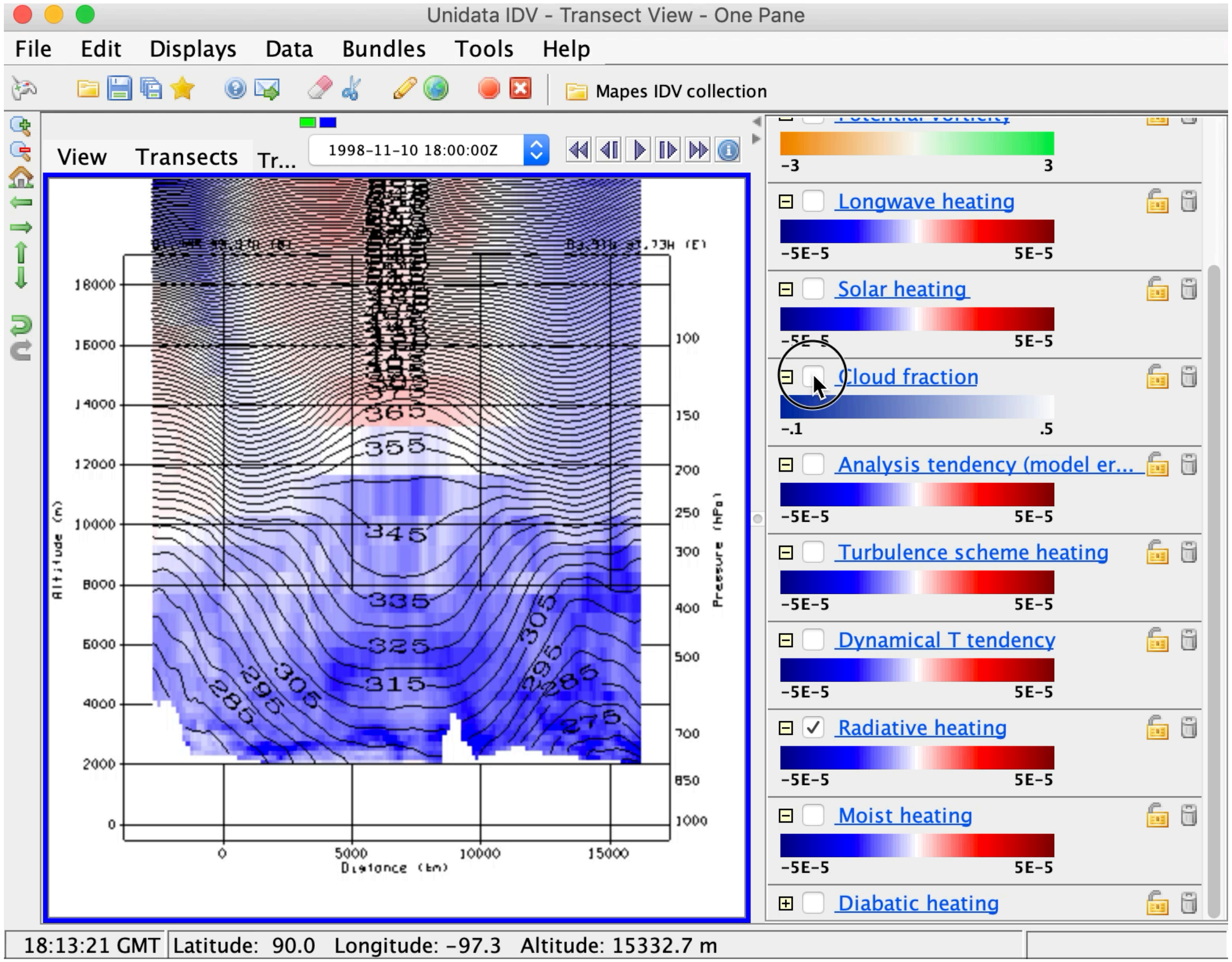


- Towards the North Pole, you will notice that there is a slight negative turbulence heating rate near the surface. While in the southern hemisphere you can see a positive turbulence heating rate near the surface.

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)

Can you see any features that clearly indicate how clouds affect radiation?

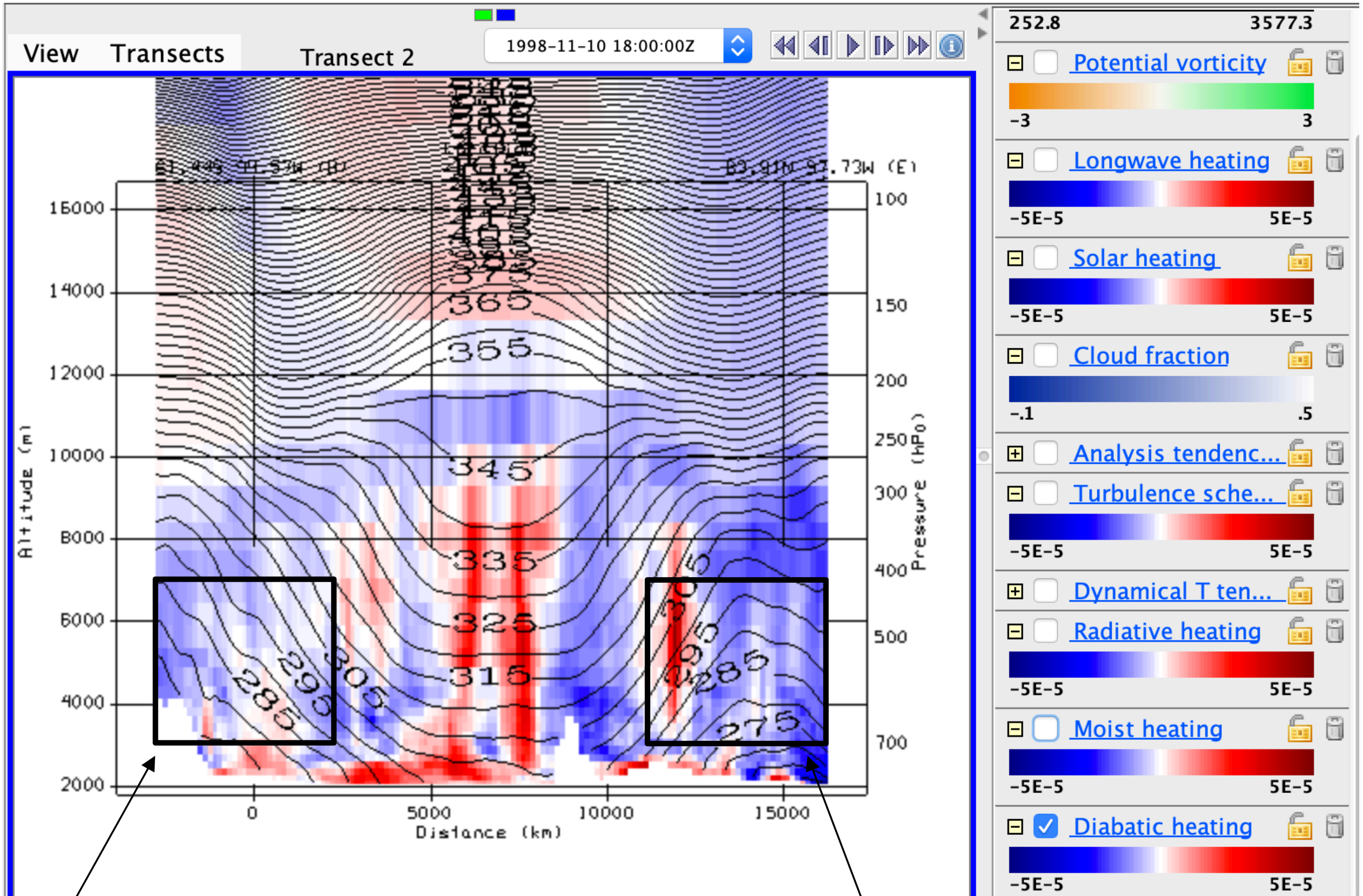


- To the left I have included a video of the cloud fraction being shown and then turned off leaving the radiative heating profile.
- You can see that where cloud fraction begins increasing, you begin to see a shift from positive to negative radiative heating.
- It's obvious that a higher cloud fraction leads to a negative change in radiative heating and therefore a cooling of the atmosphere.
- The clouds likely act as a reflector of incoming radiation

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.

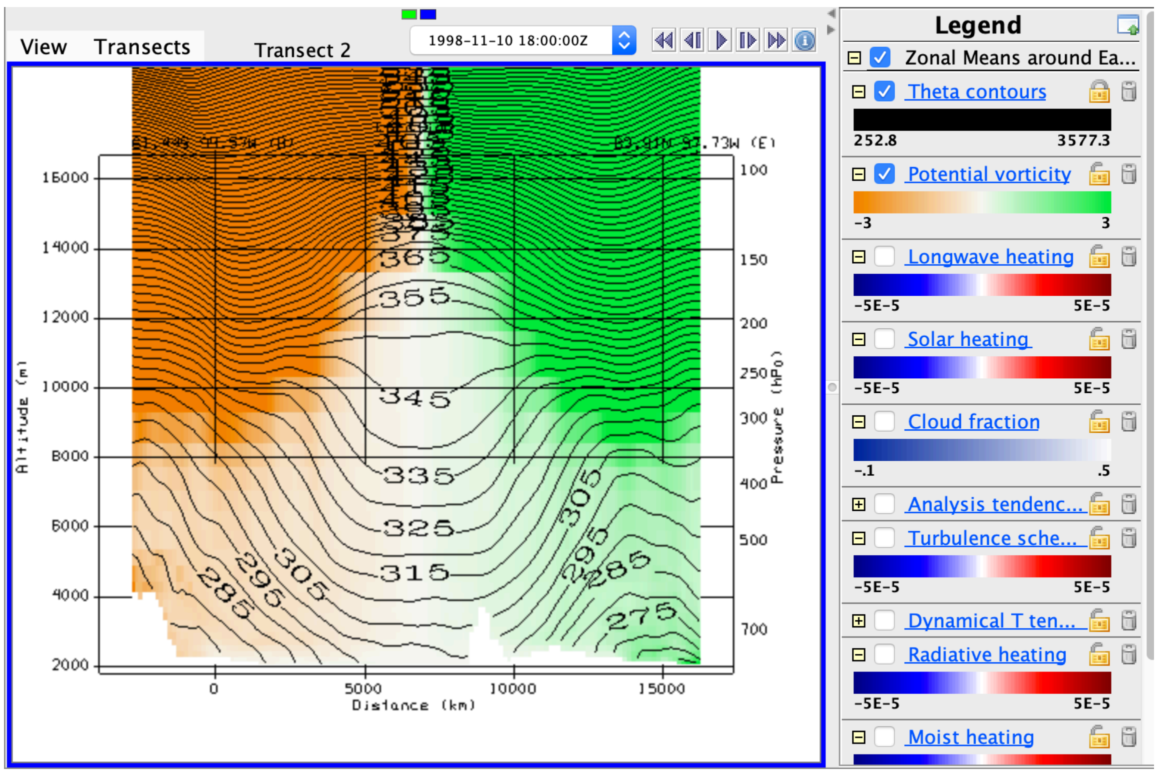
The transect of total diabatic heating.

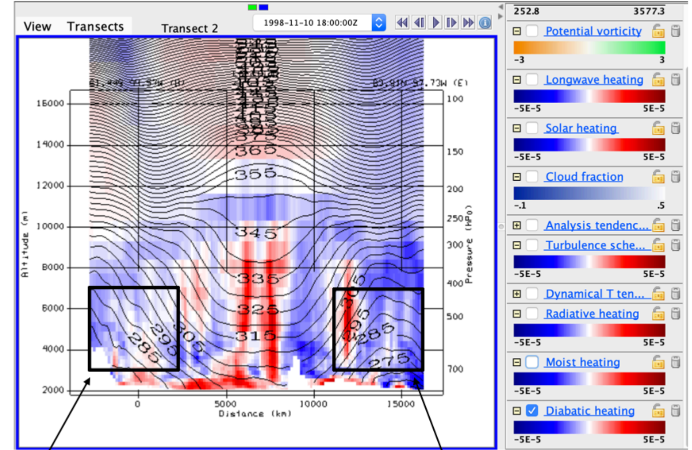


Positive PV tendency occurs when isentropic surfaces bow down…. Cyclonic tendency

Negative PV tendency occurs when isentropic surfaces bow up… anticyclonic tendency

Potential Vorticity



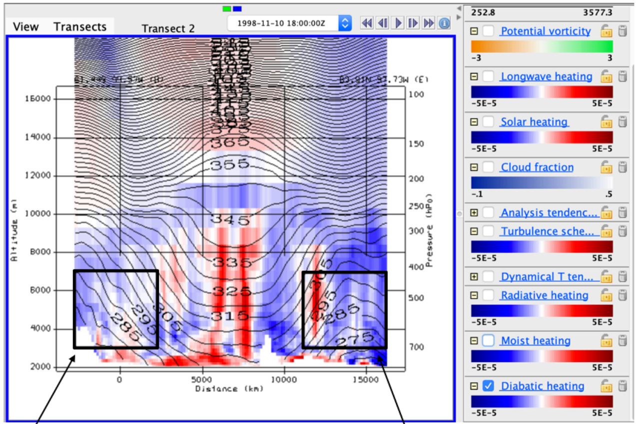


Positive PV tendency occurs when isentropic surfaces bow down.... Cyclonic tendency

Negative PV tendency occurs when isentropic surfaces bow up... anticyclonic tendency

- Does the zonal mean PV transect resemble areas where your PV *tendency* is strong?

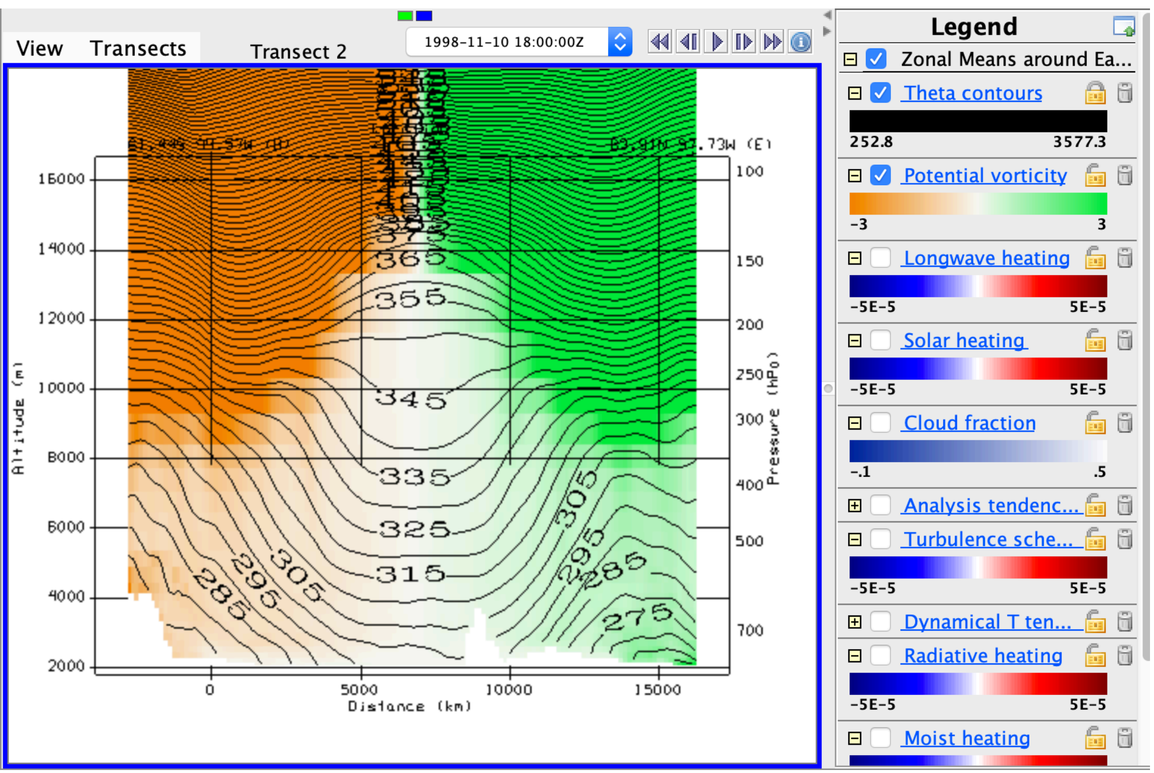
- The zonal mean PV transect shows that there is actually positive potential vorticity where I believed there to be negative PV tendency.
- It's possibly that the planetary vorticity dominates and is therefore not showing PV tendencies because it's so strong.



Positive PV tendency occurs when isentropic surfaces bow down.... Cyclonic tendency

Negative PV tendency occurs when isentropic surfaces bow up... anticyclonic tendency

Potential Vorticity



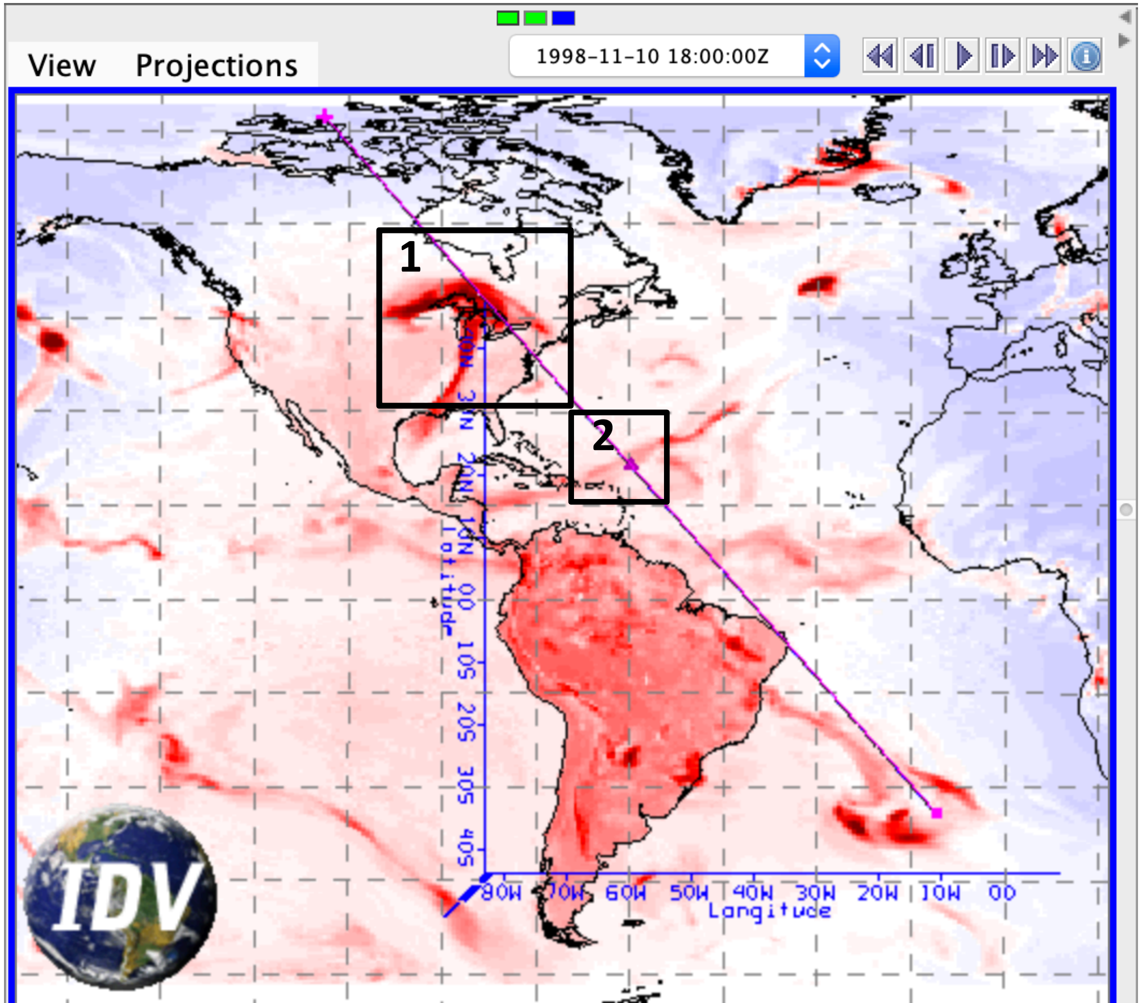
- How does this zonal-mean PV show the imprint of both its vorticity factor and its static stability factor?

- This view of the zonal-mean PV shows that there is +PV in the northern hemisphere and this also shows that the static stability is larger than average in the area of +PV…
- The opposite could be said for –PV… there would be a decrease in static stability

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).

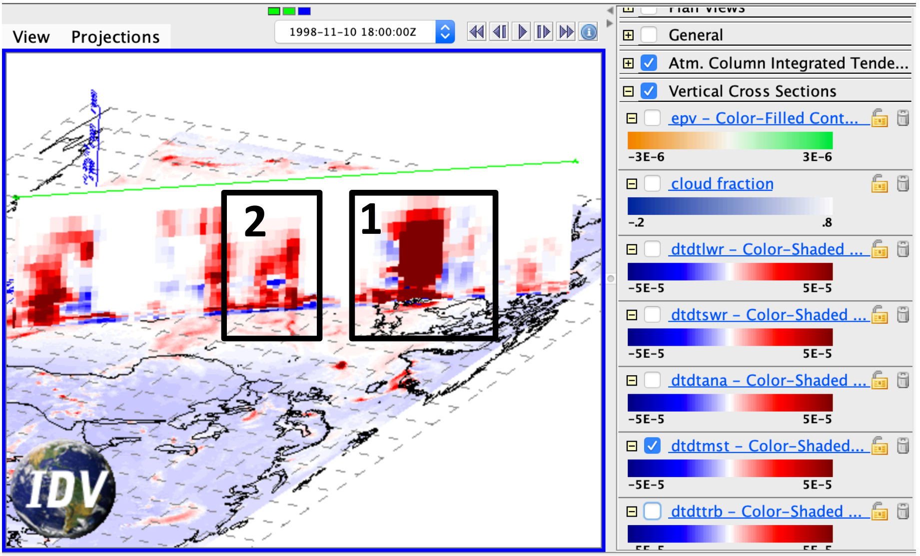
Interesting Weather event: *cross section display in the Map View window*



- Two areas of interest will be looked at further.
- Larger box, 1, shows a disturbance moving over the Eastern United States.
- Smaller box, 2, shows some waves of disturbance over the tropics
- Cross sections of different factors will be analyzed

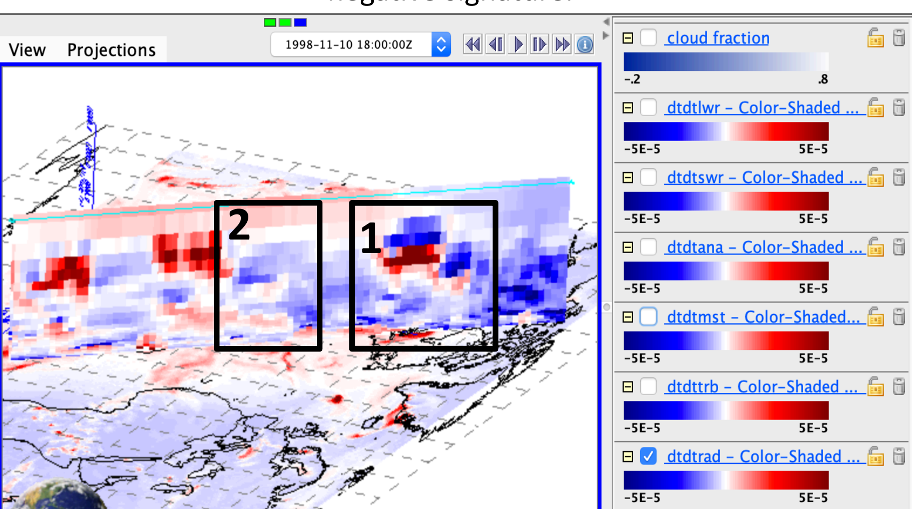
moist mst (convection & cloud cond.):

You can see that in box 1 there is strong convection with increased moisture which correlates to the disturbance noted in the previous slide. Box 2 shows increased moisture over the tropics with an interesting negative moisture heating rate



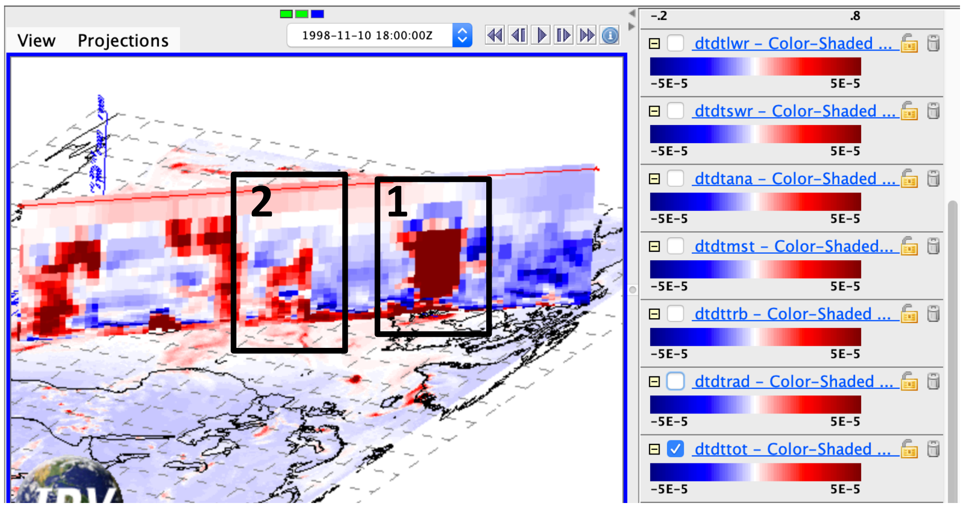
SW+LW radiation:

Radiation in box 1 shows that there is a mostly negative SW+LW radiation rate meaning cooling, except for in the mid-troposphere. Radiation in box 2 shows some positive SW+LW, but overall a negative signature.



total physics ("diabatic"):

strong diabatic heating in the troposphere in box 1 where there is the disturbance over the eastern US. Not as strong… but mild diabatic heating in box 2 as well. You can see that the moisture heating rate is a large factor in the diabatic heating rate.



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)

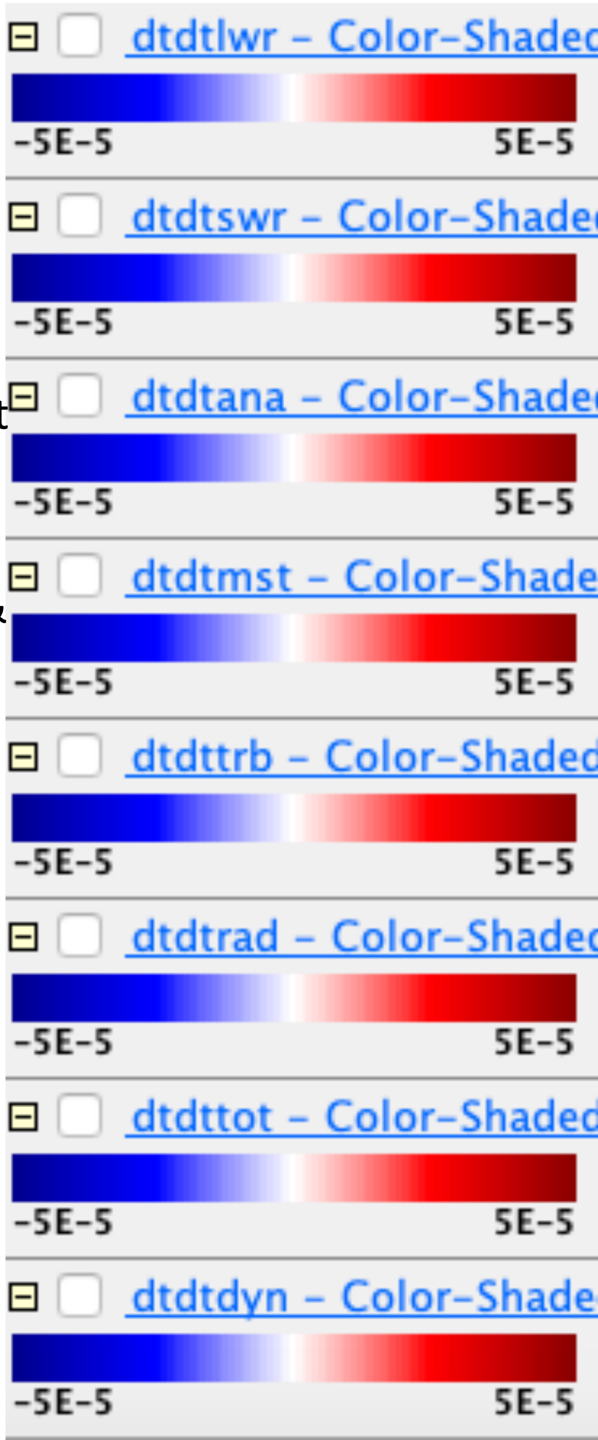
moist mst (convection & cloud cond.)

turbulence (PBL)

SW+LW radiation

total physics ("diabatic")

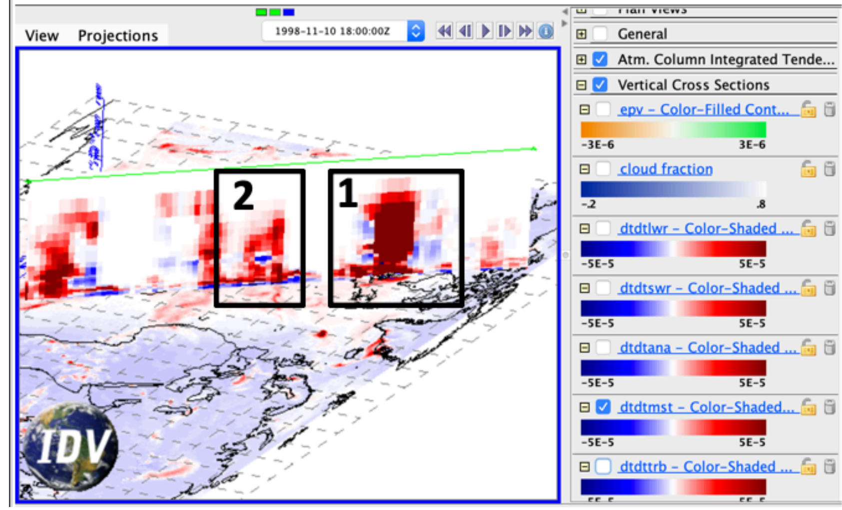
dynamic (advective)

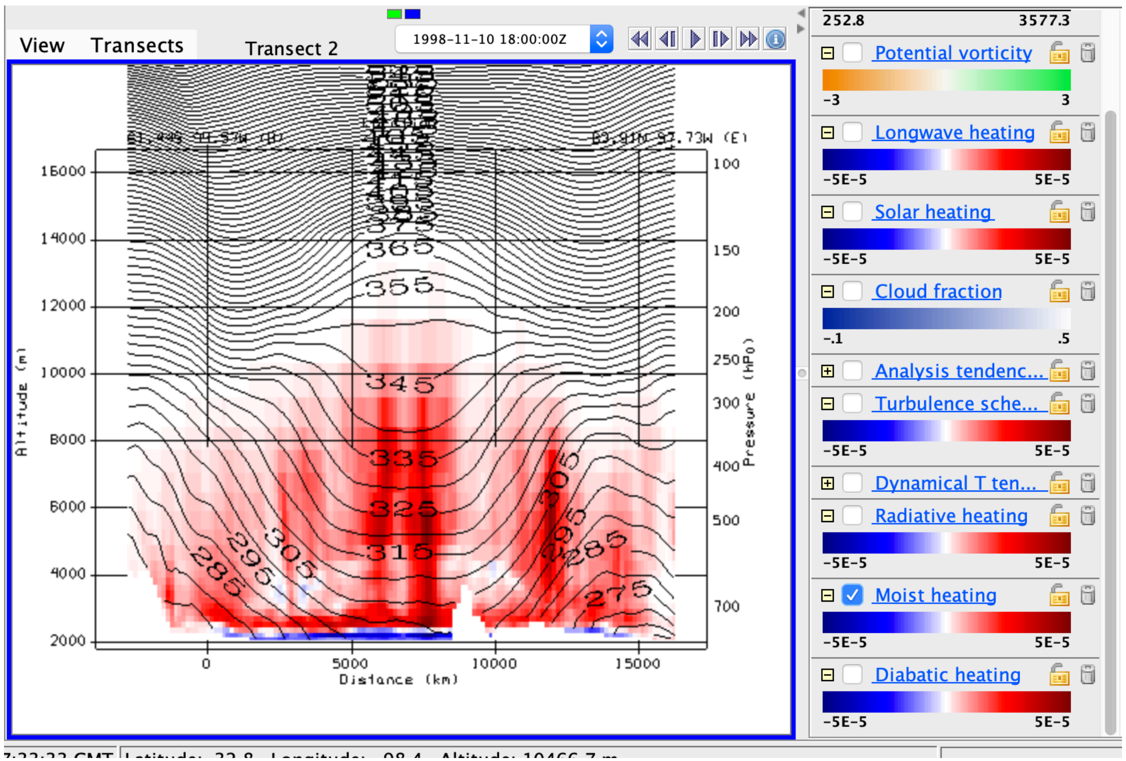


Assignment part 2: Local view

- 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.

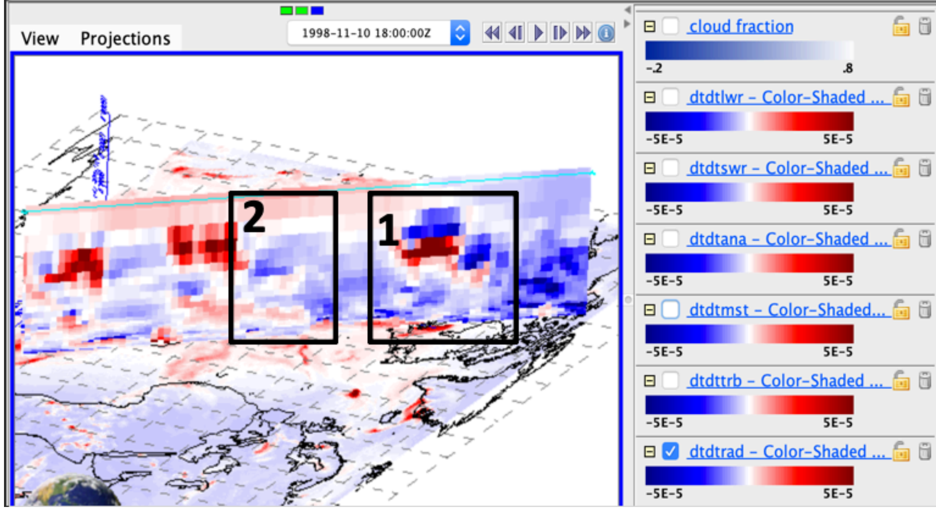
Moist Heating

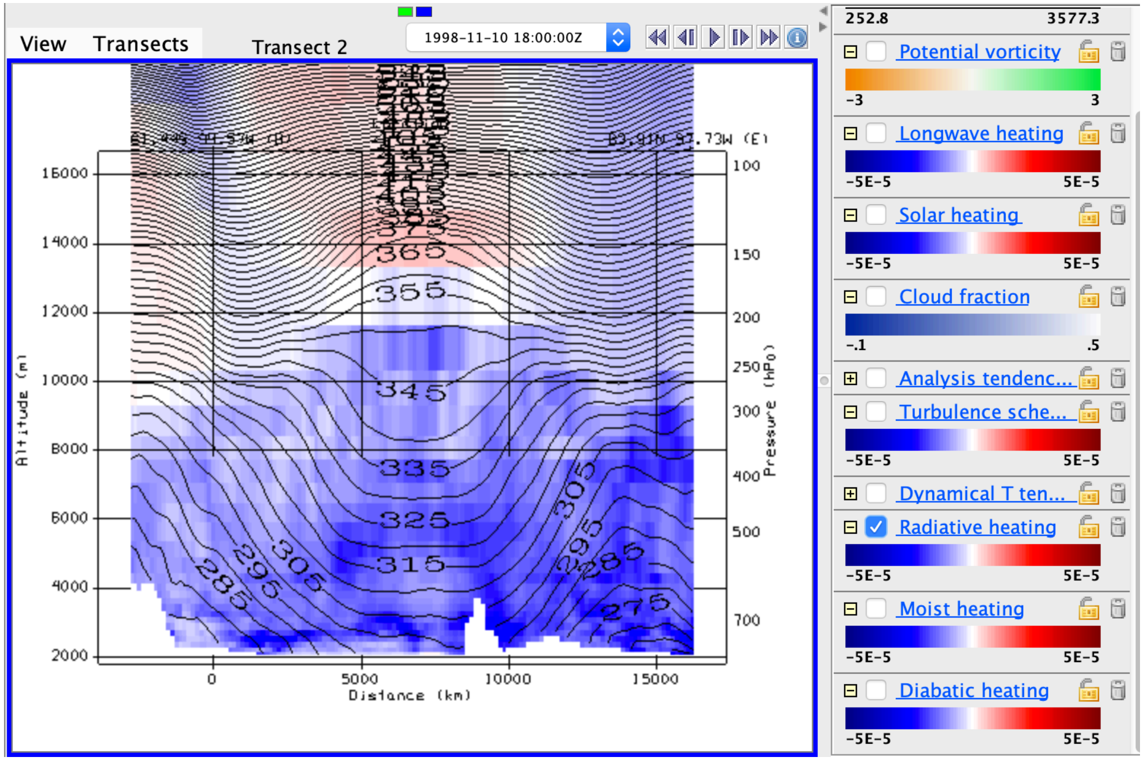




- Which is more variable (more spatially concentrated)?:
- moist heating. Areas of heating/cooling aren't widespread.

Radiative Heating

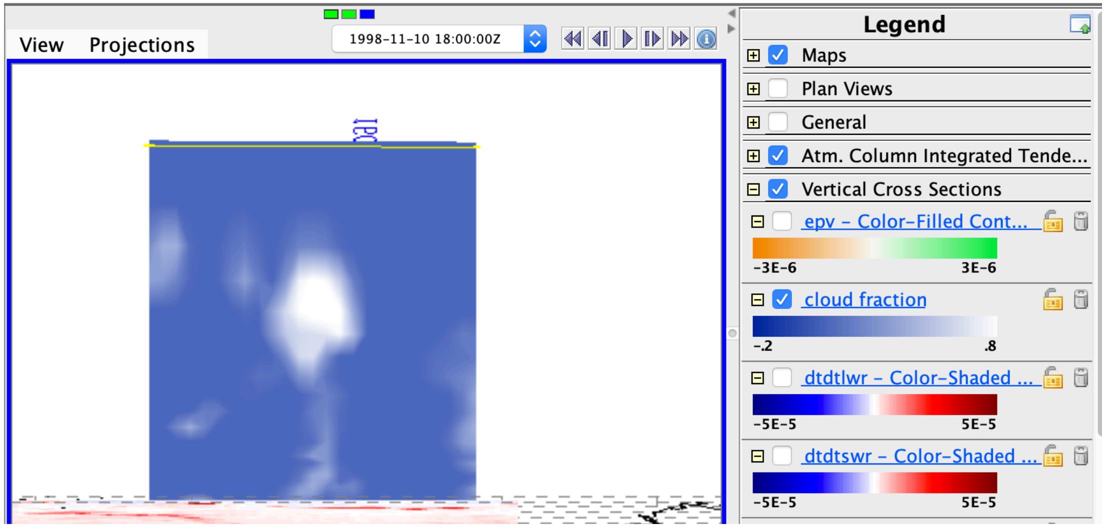




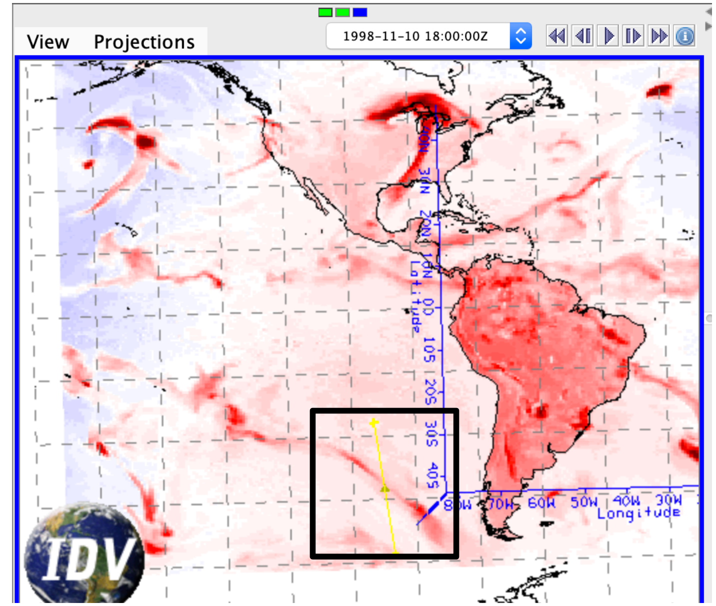
- Which is more variable (more spatially concentrated)?:
- Radiative Heating is not more spatially concentrated than moisture heating. Radiative heating is more broadly distributed

Assignment part 2: Local view

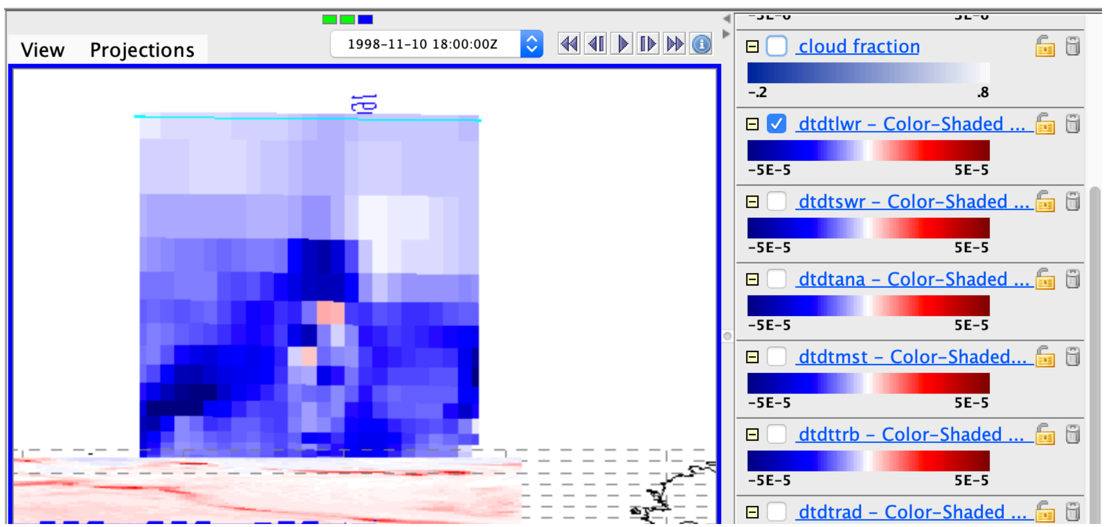
- Revisit cloud-radiative interactions
  - LW radiation can be understood as water vapor cooling, cloud top cooling, and cloud base warming. Toggle the layers to find a good example, then juxtapose cloud fraction and radiative heating cross-section images to show an example of a place where cloud effects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



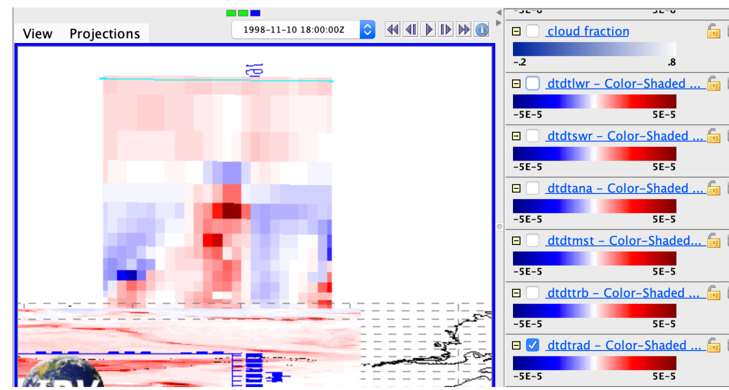
Above is the cloud fraction which shows the deep cloud in the location over the ocean



Above in the boxed region is the region of cloud cover I will be analyzing.



Above is the longwave heat rate of change, which is negative surrounding the cloud – but positive where the core of the cloud is. This could mean that the cloud is thick which allows for a negative longwave heat rate of change – cooling at the top of the cloud and relative warming at the base.

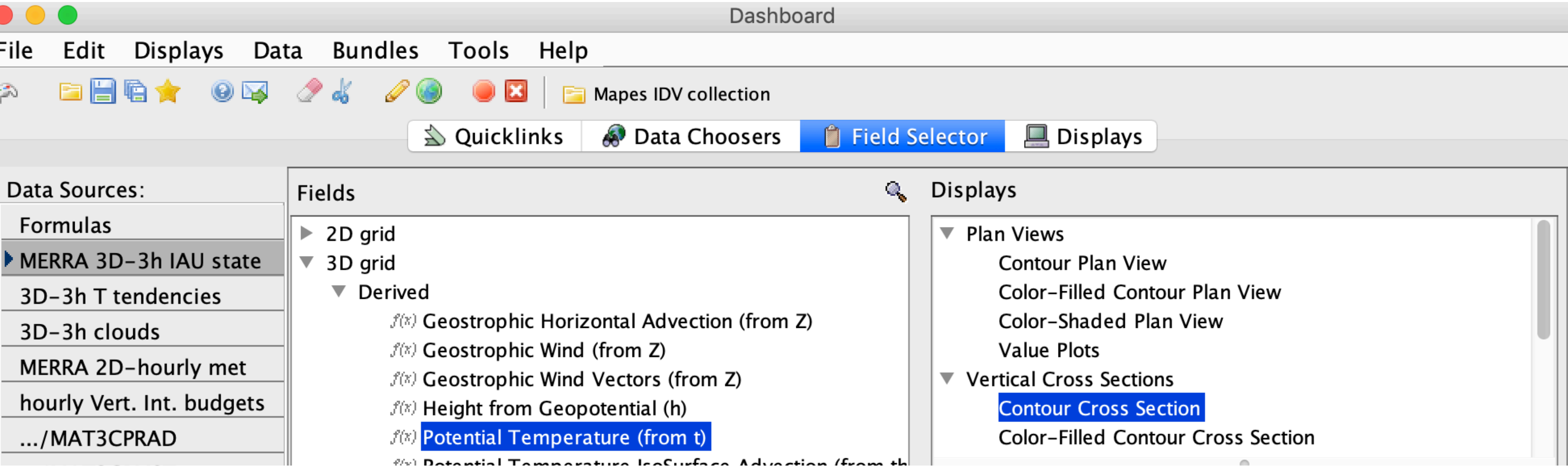


Above is the total SW+LW radiation which where the cloud is, is positive. This could mean that the cloud is a high cloud- which are typical factors of increasing atmospheric heat because they trap outgoing longwave radiation. Overall cooling at top of the cloud and warming at the base.

Assignment part 2: Local view

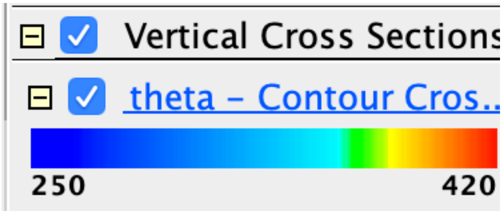
- Consider the PV source term motivating this exploration.
  - Where does the vertical gradient of heating imply large PV sources? Use arrows to annotate a couple positive and negative source regions.
  - Can you find a weather situation where this source term is a positive feedback on PV?
- **Unsure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

Create a new cross section of potential temperature contours

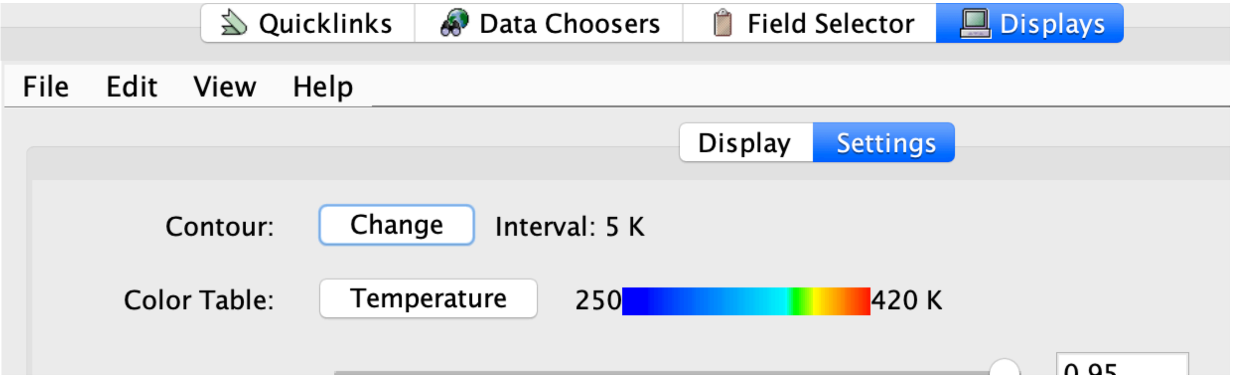


Create a new cross section of potential temperature contours

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

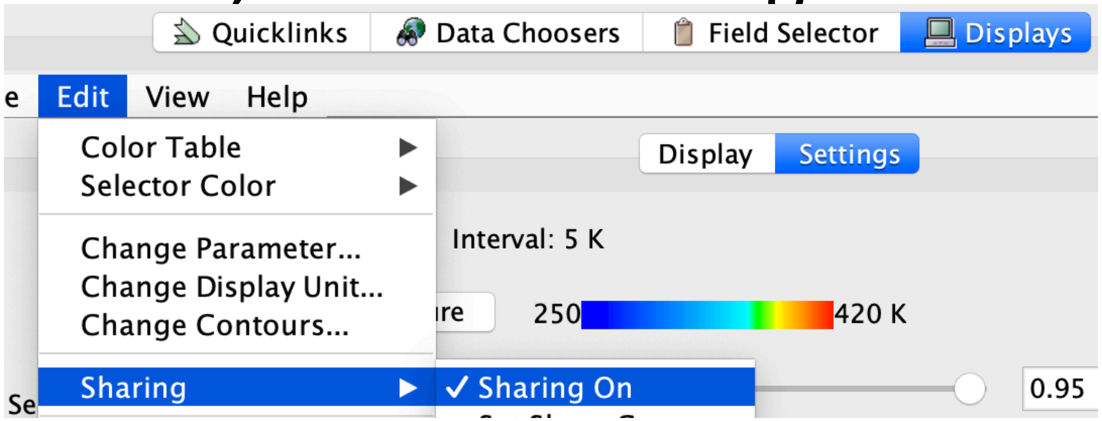


- Change the contour interval to 5K. Change the Color to Black. Change their label size to 20.



Create a new cross section of potential temperature contours

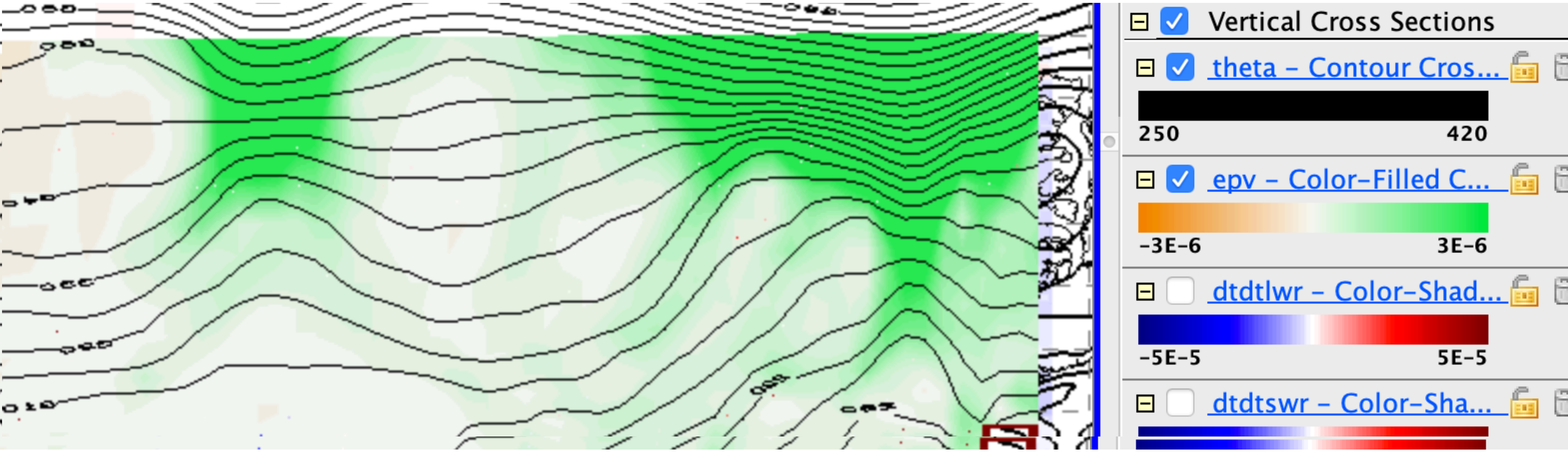
- Again click the Legend entry to pop up the Display Controls.
- Under the Edit menu, turn on Sharing



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

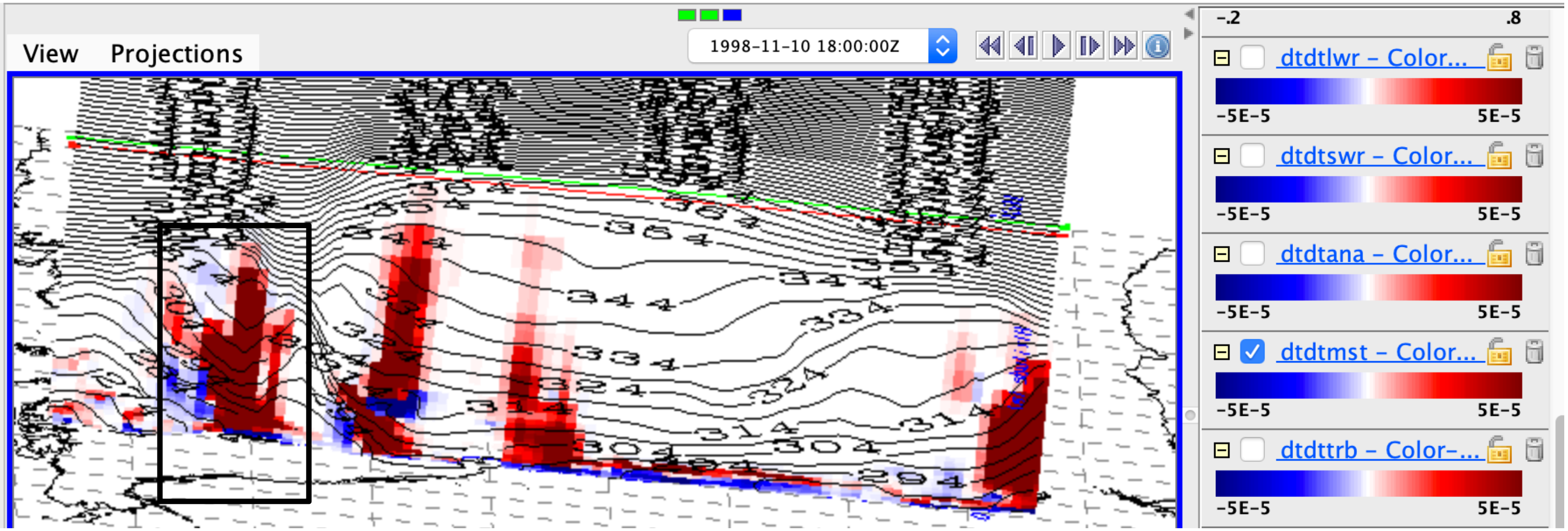
Create a new cross section of potential temperature contours

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



Warm and cool cores & condensation heating

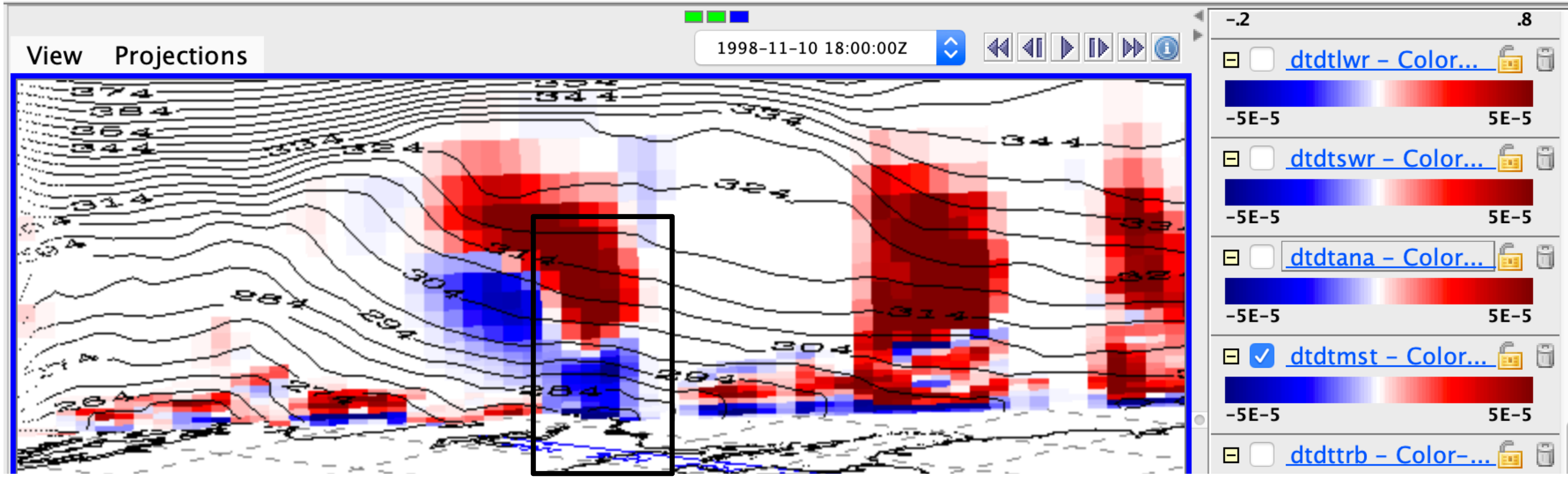
- Use the cross section with theta contours and the moist-processes heating rate (dtdtmst) to find an example
  - with the condensation heating in a warm core storm, like the one halfway to Ireland
  - how does the PV source term from latent heating feed back on such a warm core storm?



- There is condensation heating in a warm core storm, like the one boxed off in the image above.
- The image above has the theta surfaces overlaid on the moist-processes heating rate
- how does the PV source term from latent heating feed back on such a warm core storm?
- The PV source term from latent heating results in a wet potential vorticity, this is because of the abundance of moisture in this warm core storm. The PV will be negative here.

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?



- The image above has the theta surfaces overlaid on the moist-processes heating rate.
- The location of the boxed area is over the northeastern US, with its border to Canada.
- This is where a cool core cyclone may be gently lifting air to its condensation level, releasing some latent heating.
- With a cool core storm, the PV will be dry potential vorticity with less amount of moisture..

“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

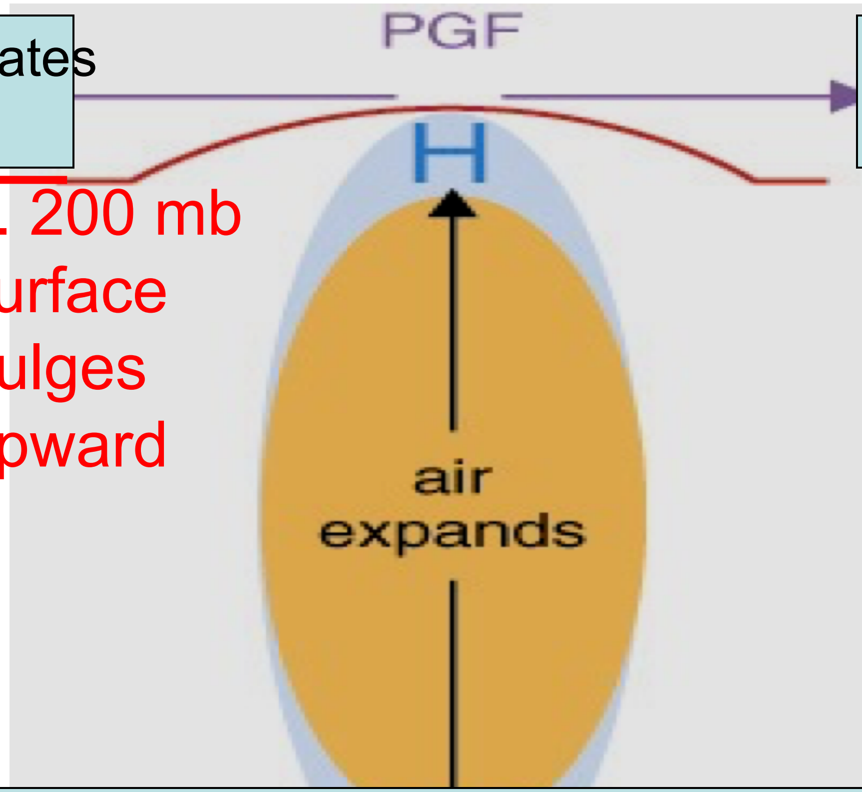
How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

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

2. Air accelerates due to PGF

2. Air accelerates due to PGF

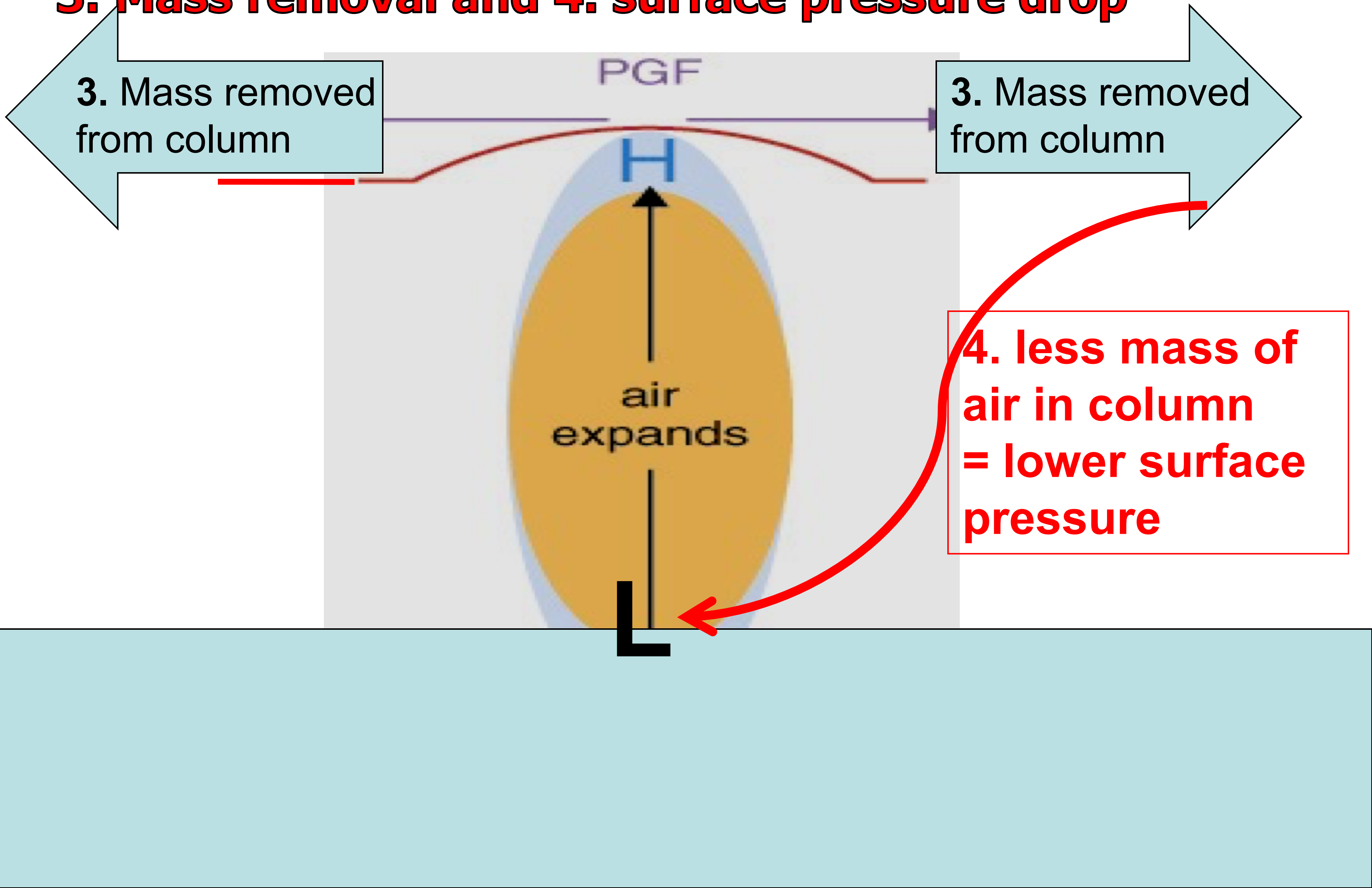
1. 200 mb surface bulges upward



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

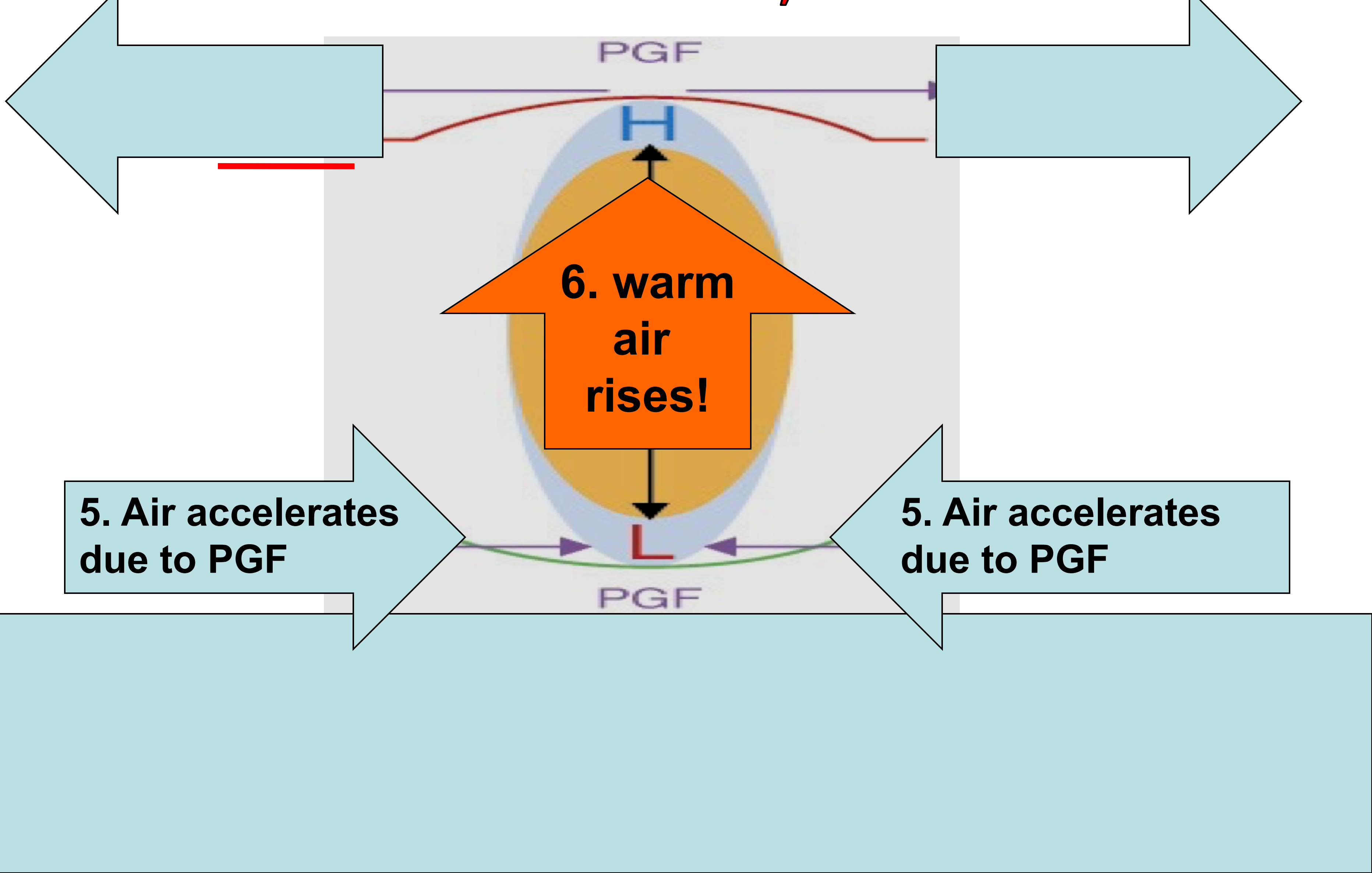
How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

3. Mass removal and 4. surface pressure drop

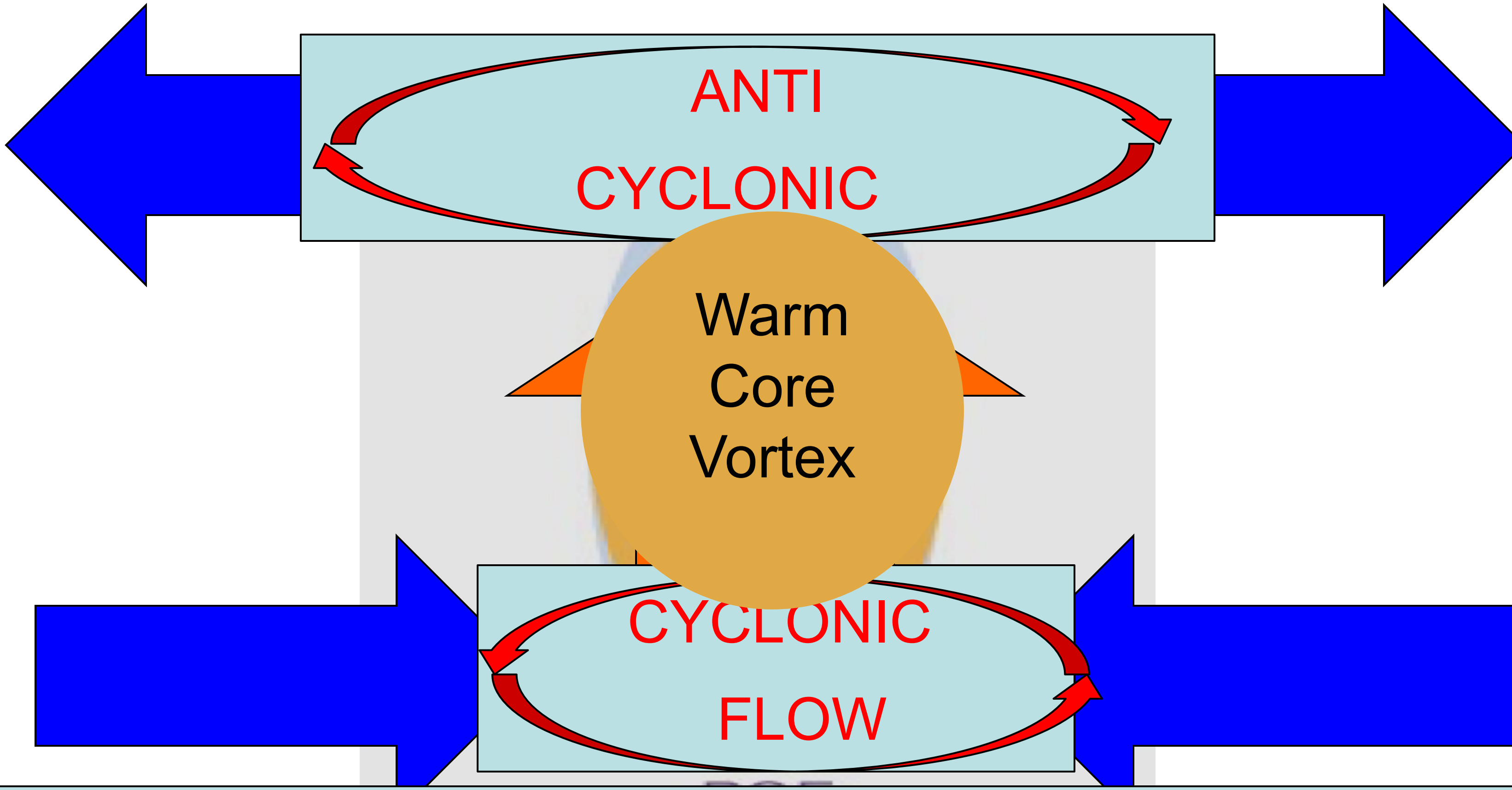


How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

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

$$\frac{D_h T}{Dt} \boxed{} = J/C_p$$

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

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

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

$$\frac{D}{Dt}\vec{V}_h = - \qquad - \vec{\nabla}_p \Phi$$

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!)

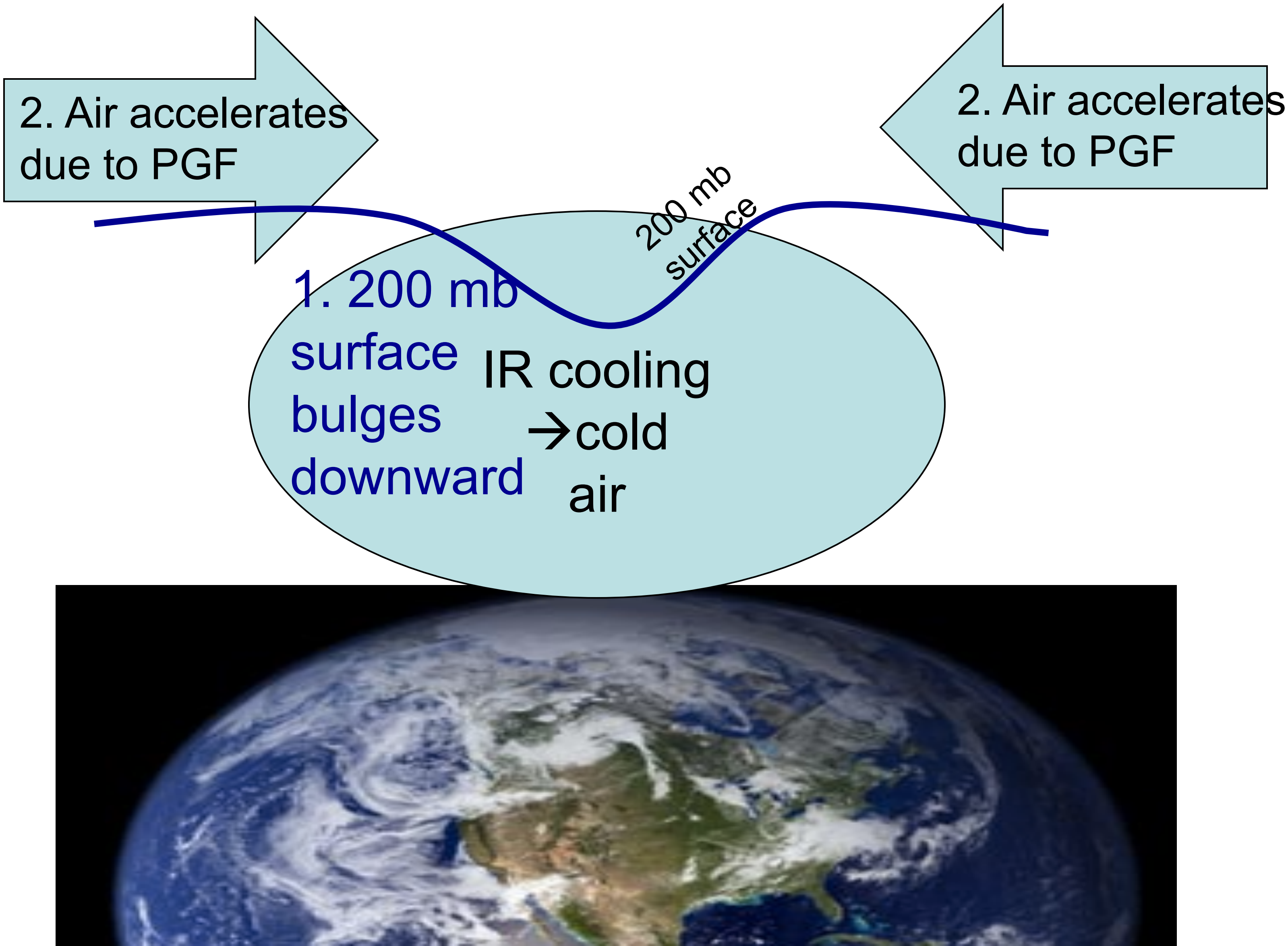
$\omega =\sim \rho g w$

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

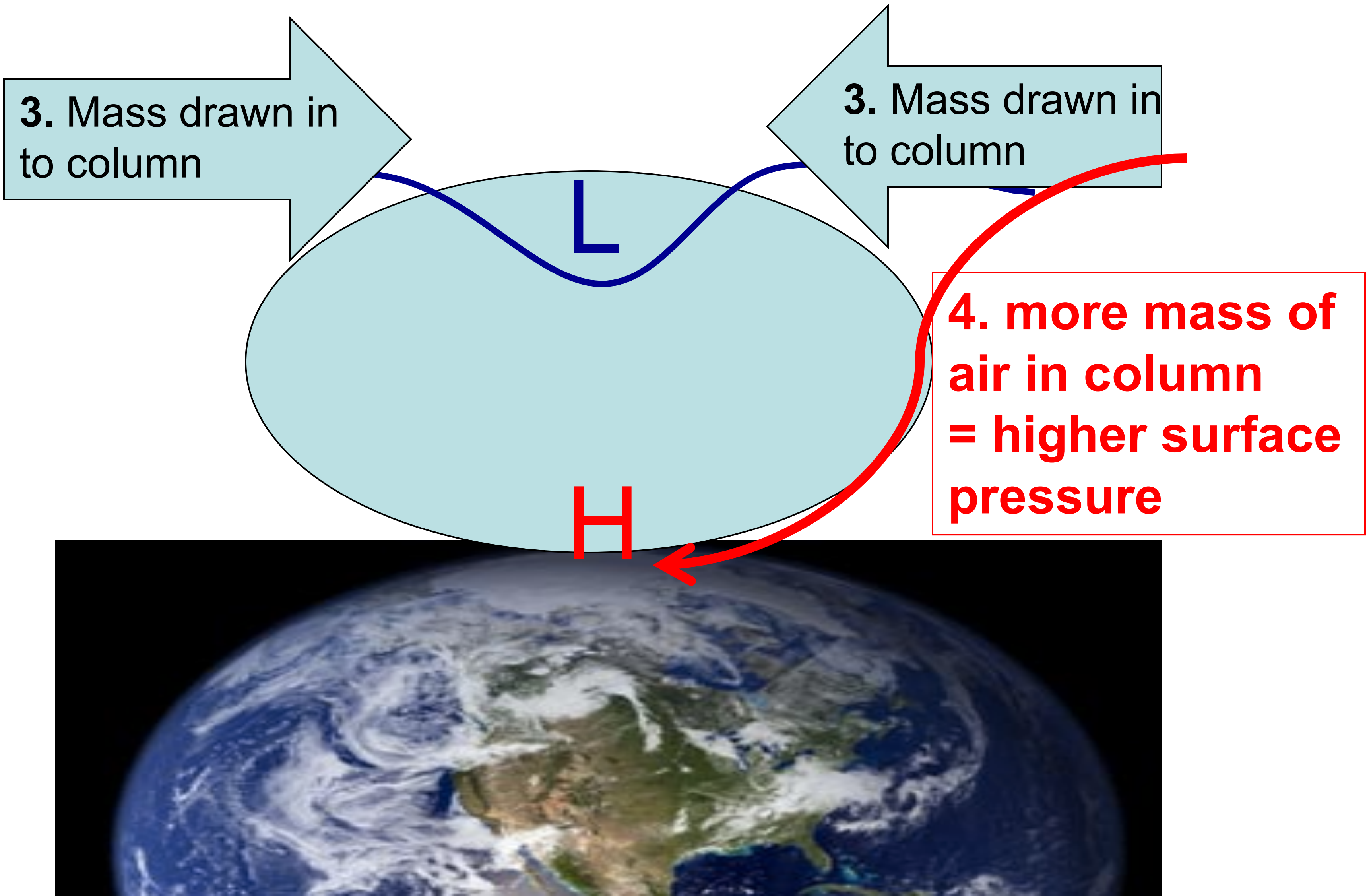
7. Coriolis force turns inflowing and outflowing air to make round-and-round flow

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

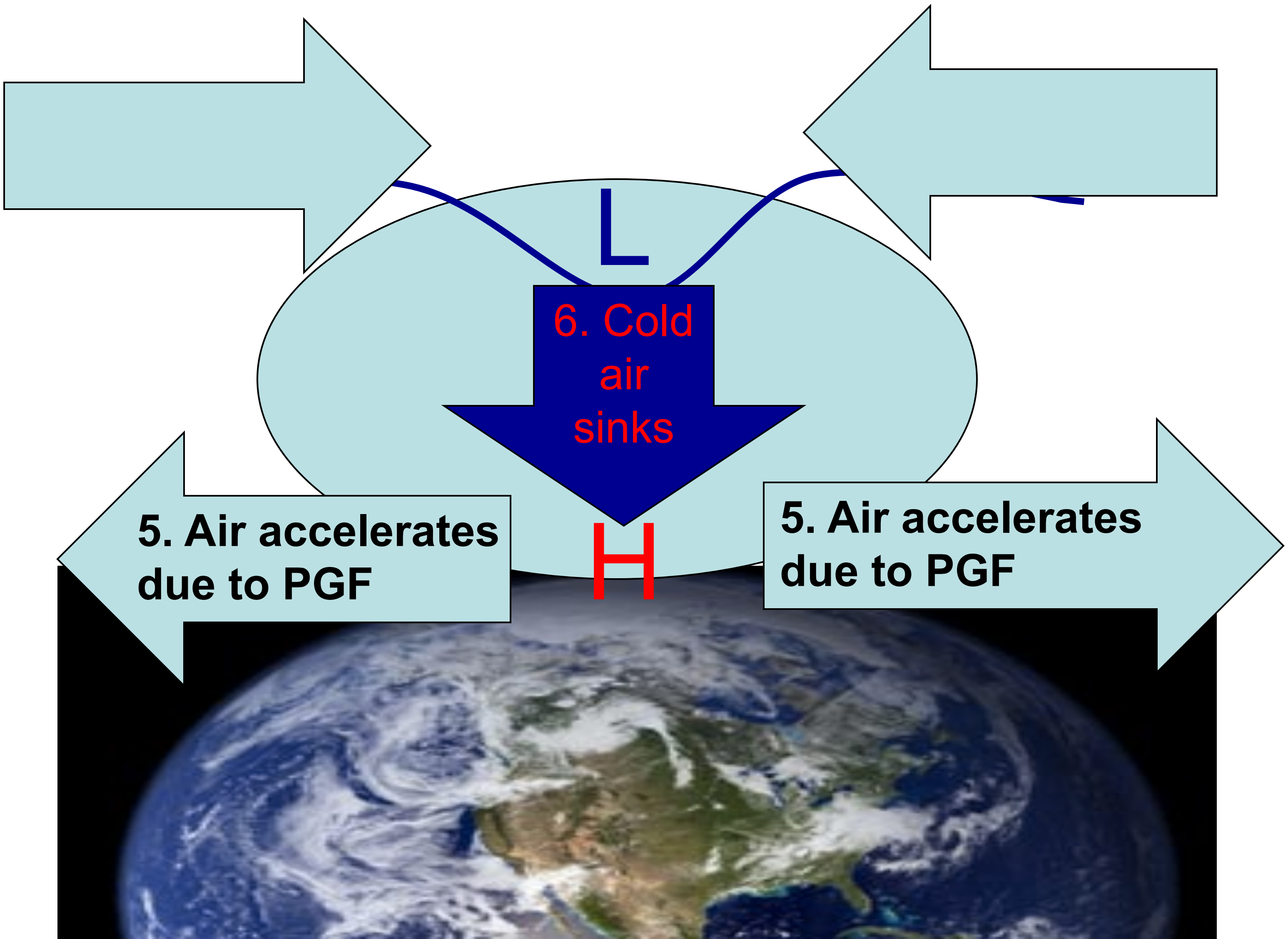
1. Cooled column of air gets **thinner**



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

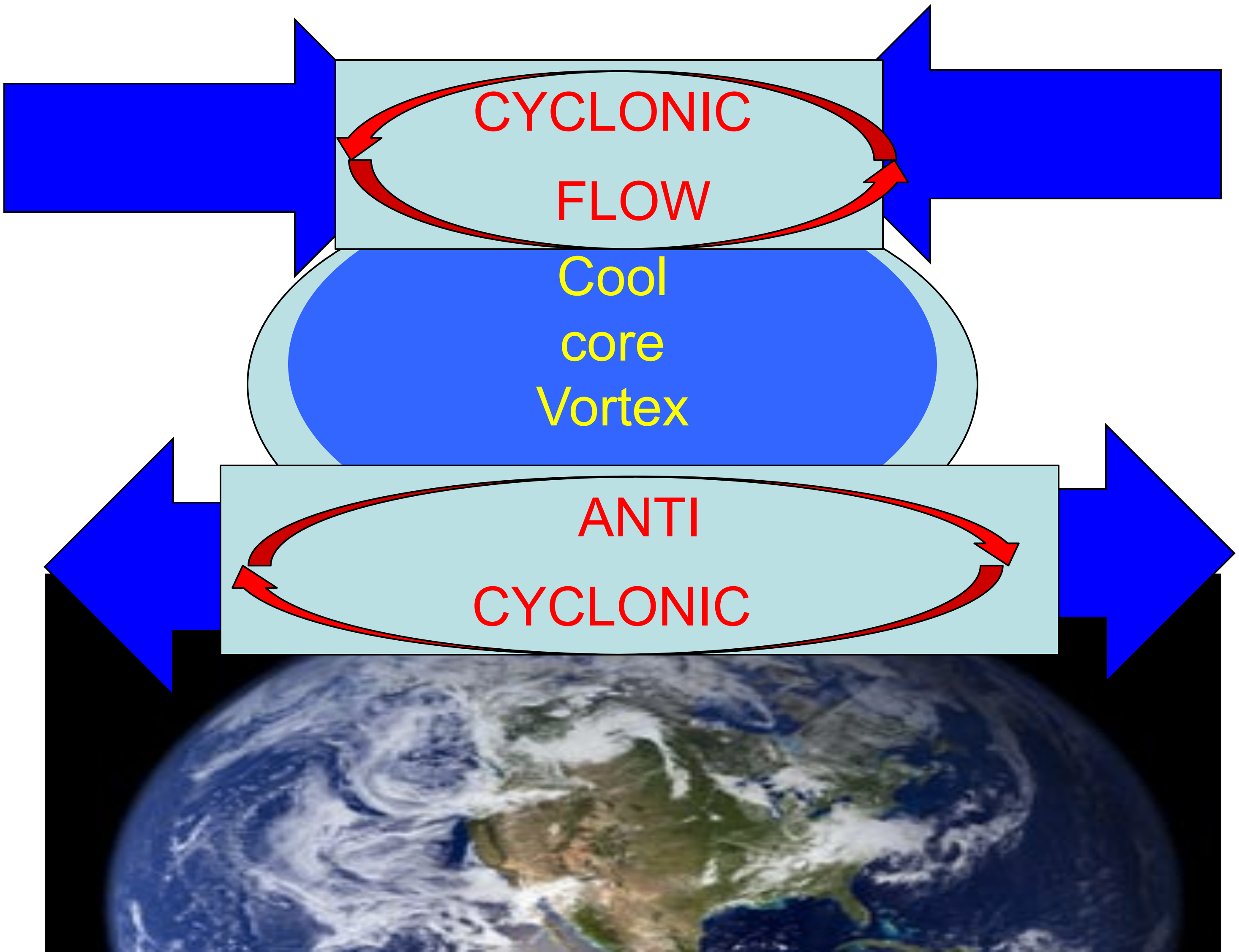


How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps



How cooled air sinks and a cool core vortex develops:

7. Coriolis force turns the winds

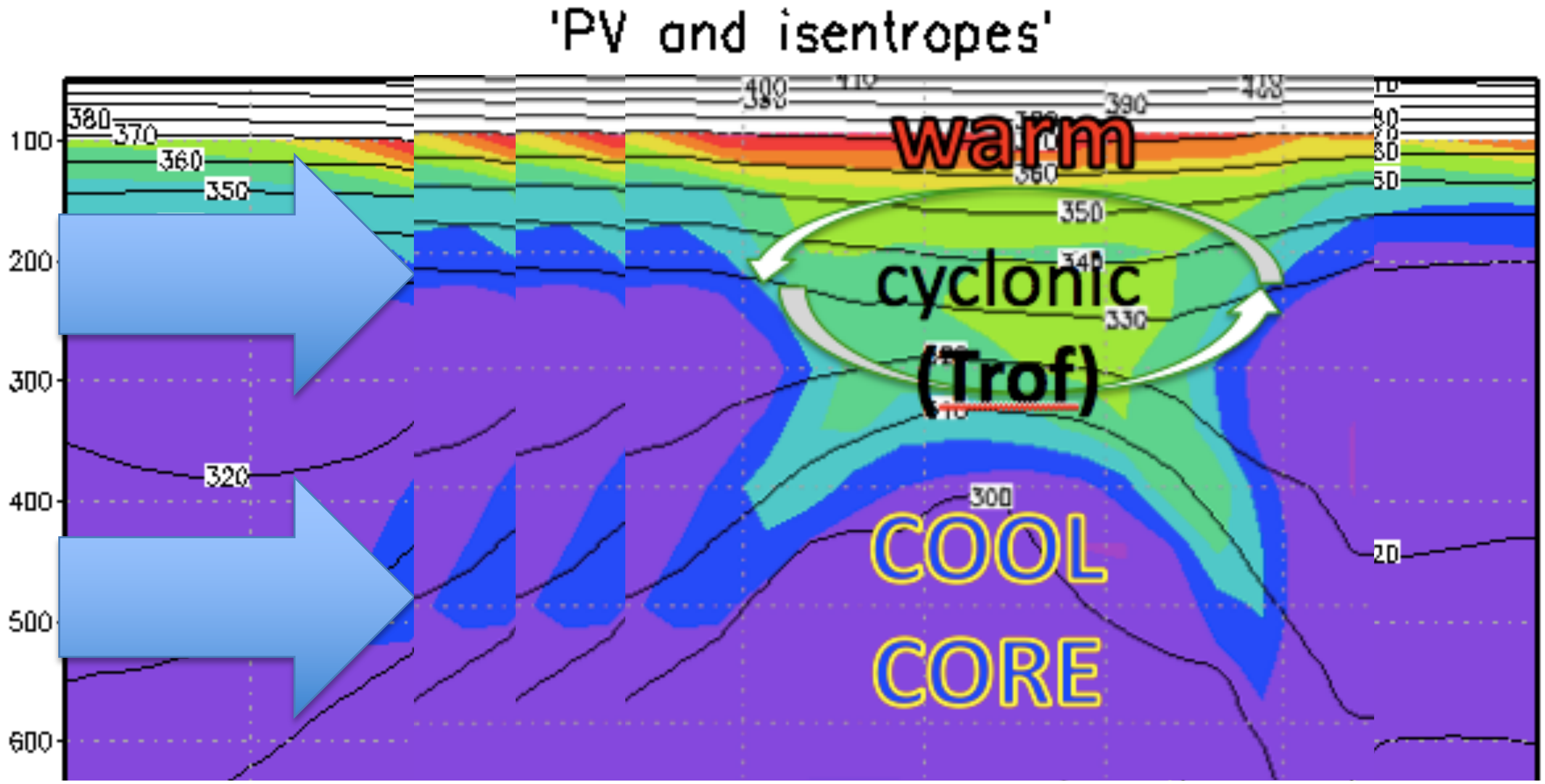


The geostrophically balanced polar vortex: The Coriolis force on the westerly jet stream prevents cold pool of Arctic air from sinking down and covering the whole Northern Hemisphere

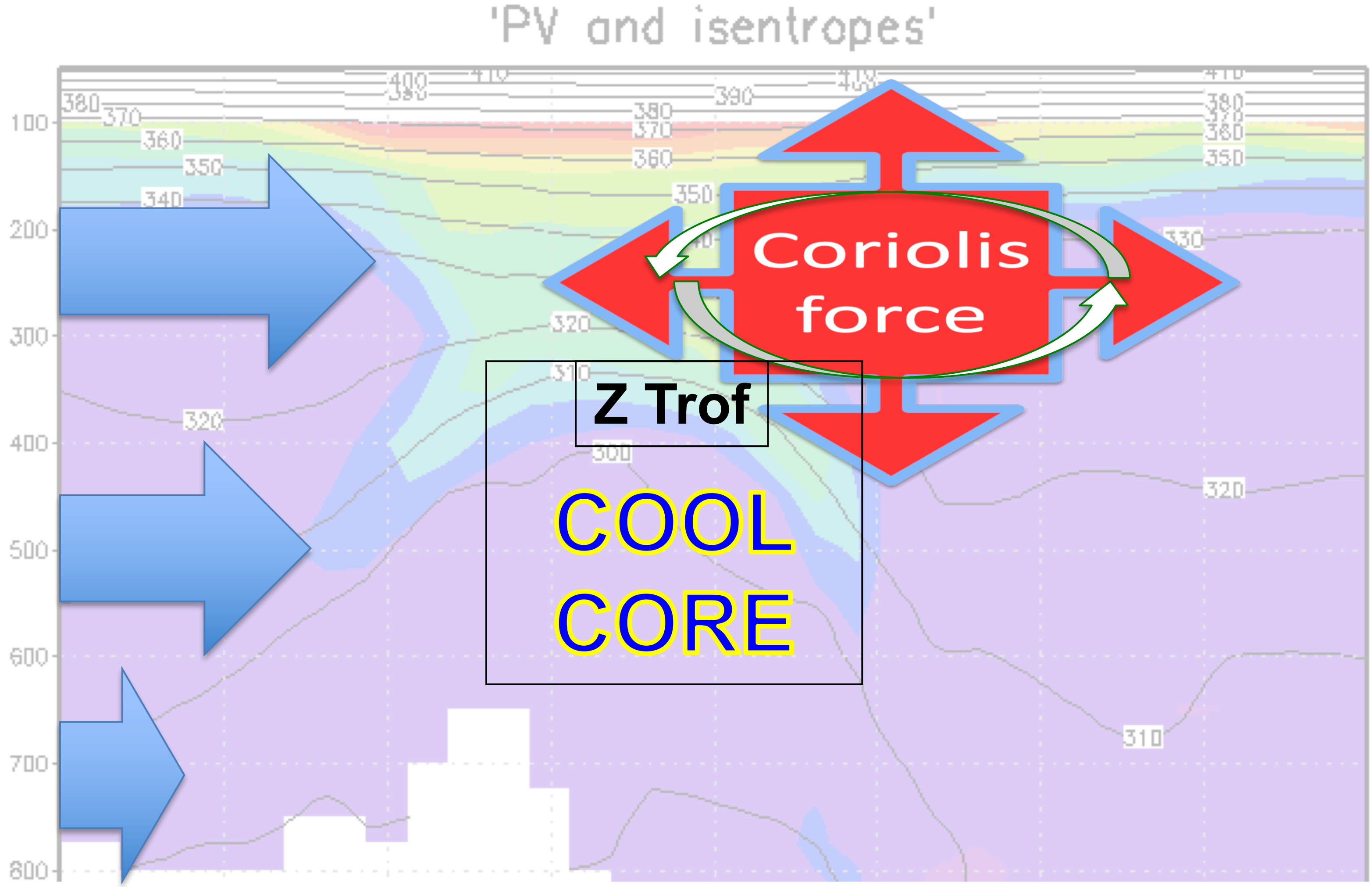
Polar and stratospheric "Reservoirs" of ζ_a or PV

- Potential vorticity: **PV = -g ζ_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.

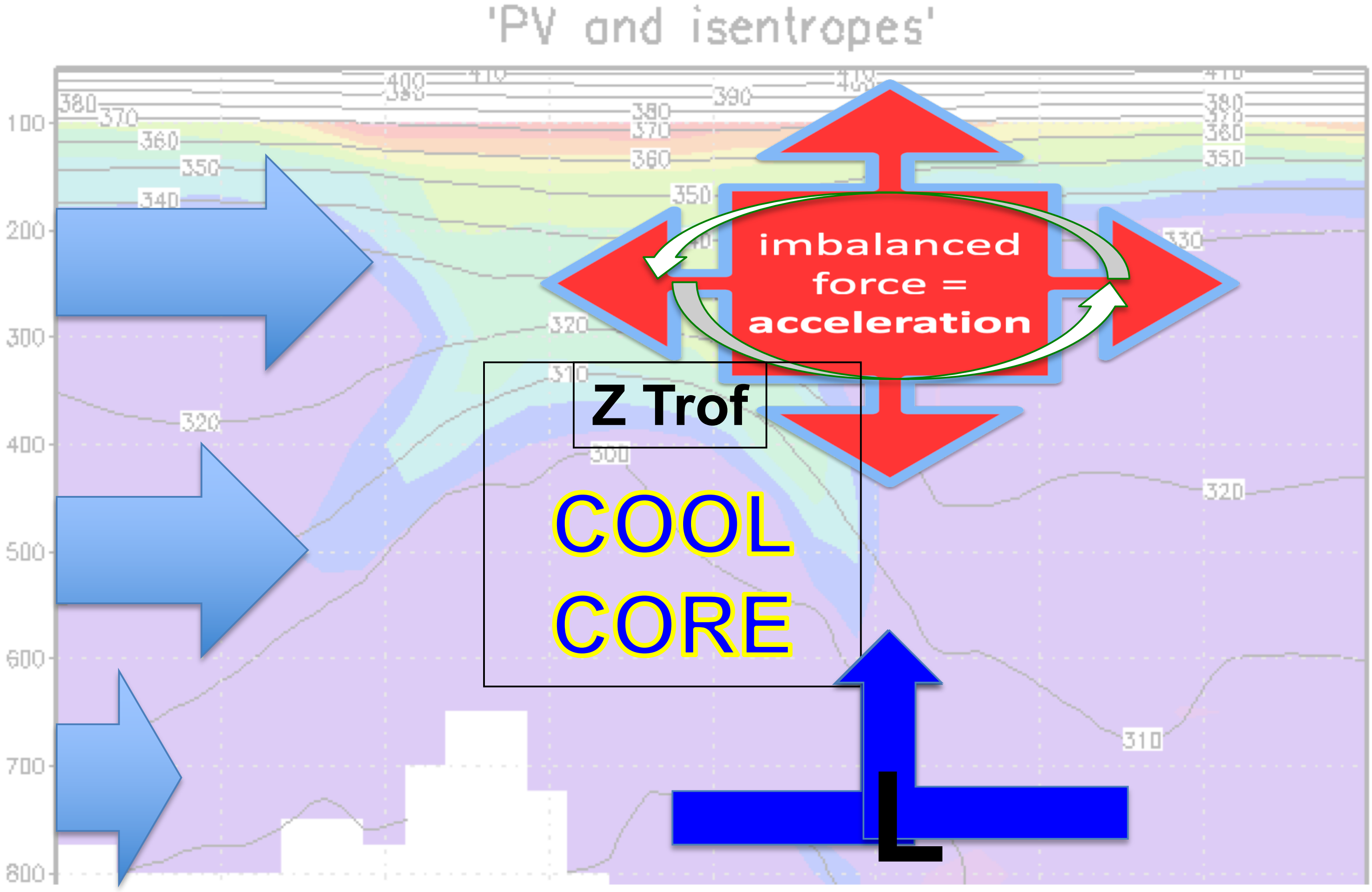
Unsheared advection of T, u, v, vort, PV: no breaking of balance



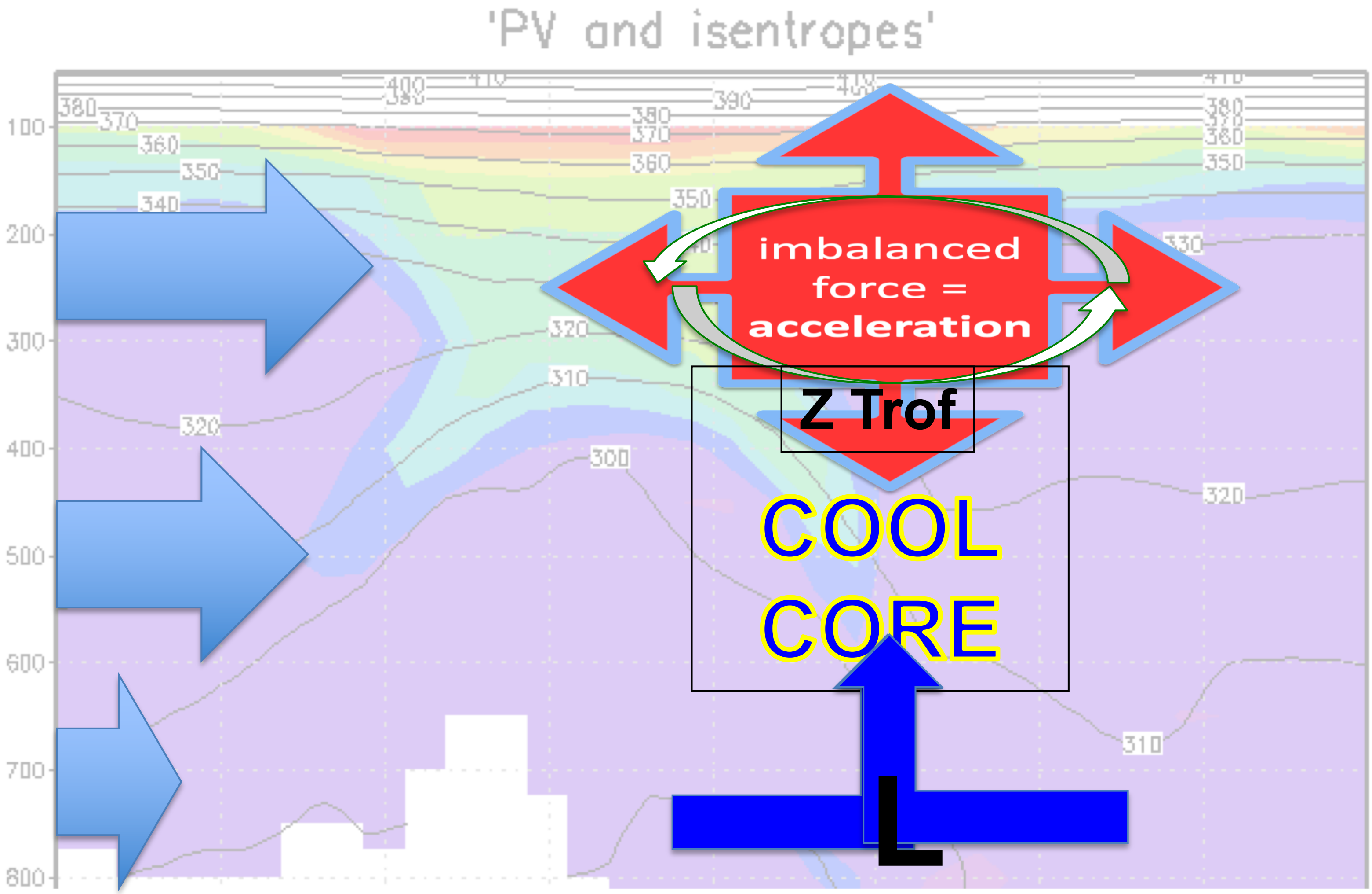
Sheared advection breaks thermal wind balance



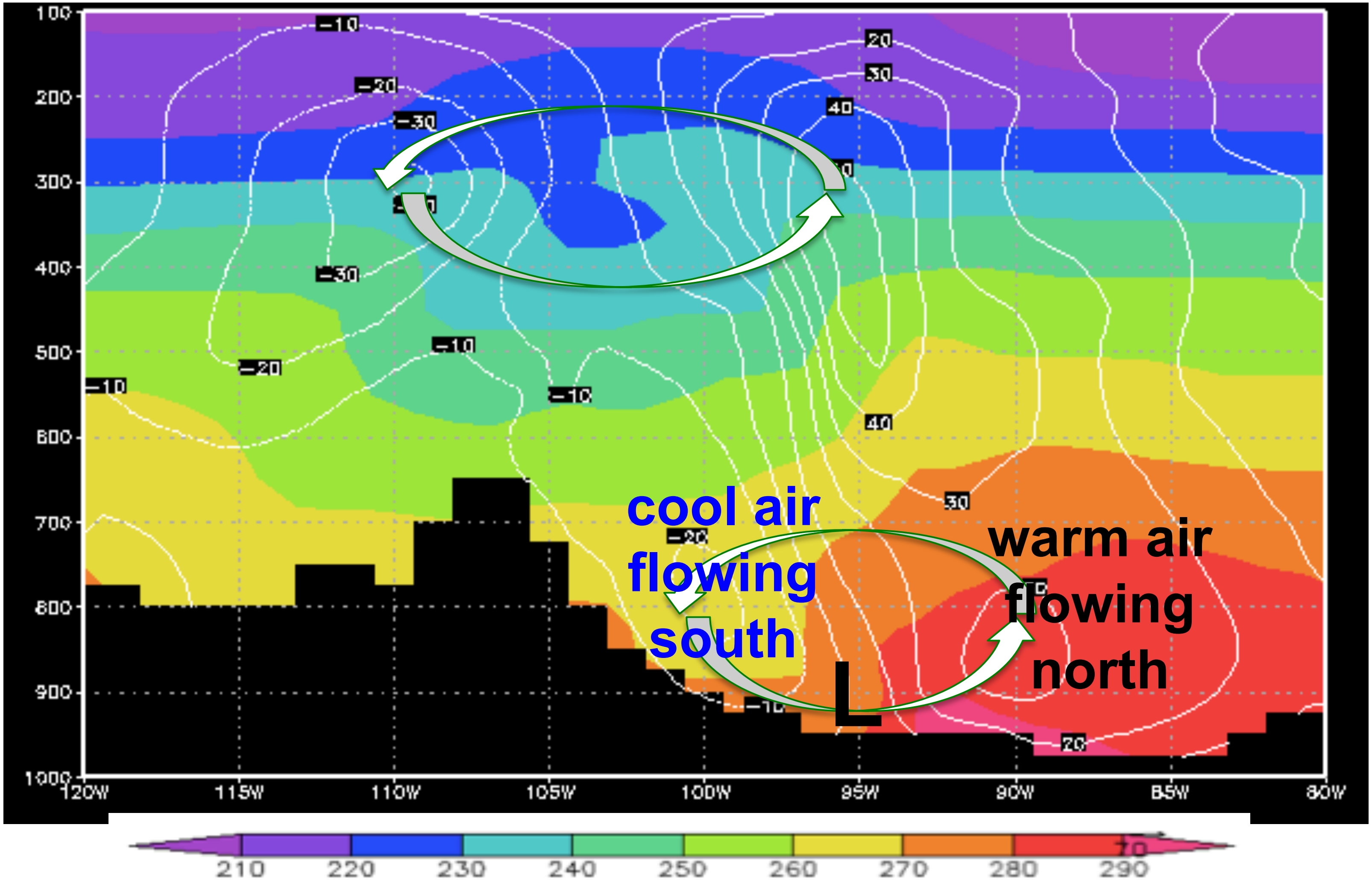
Sheared advection breaks thermal wind balance



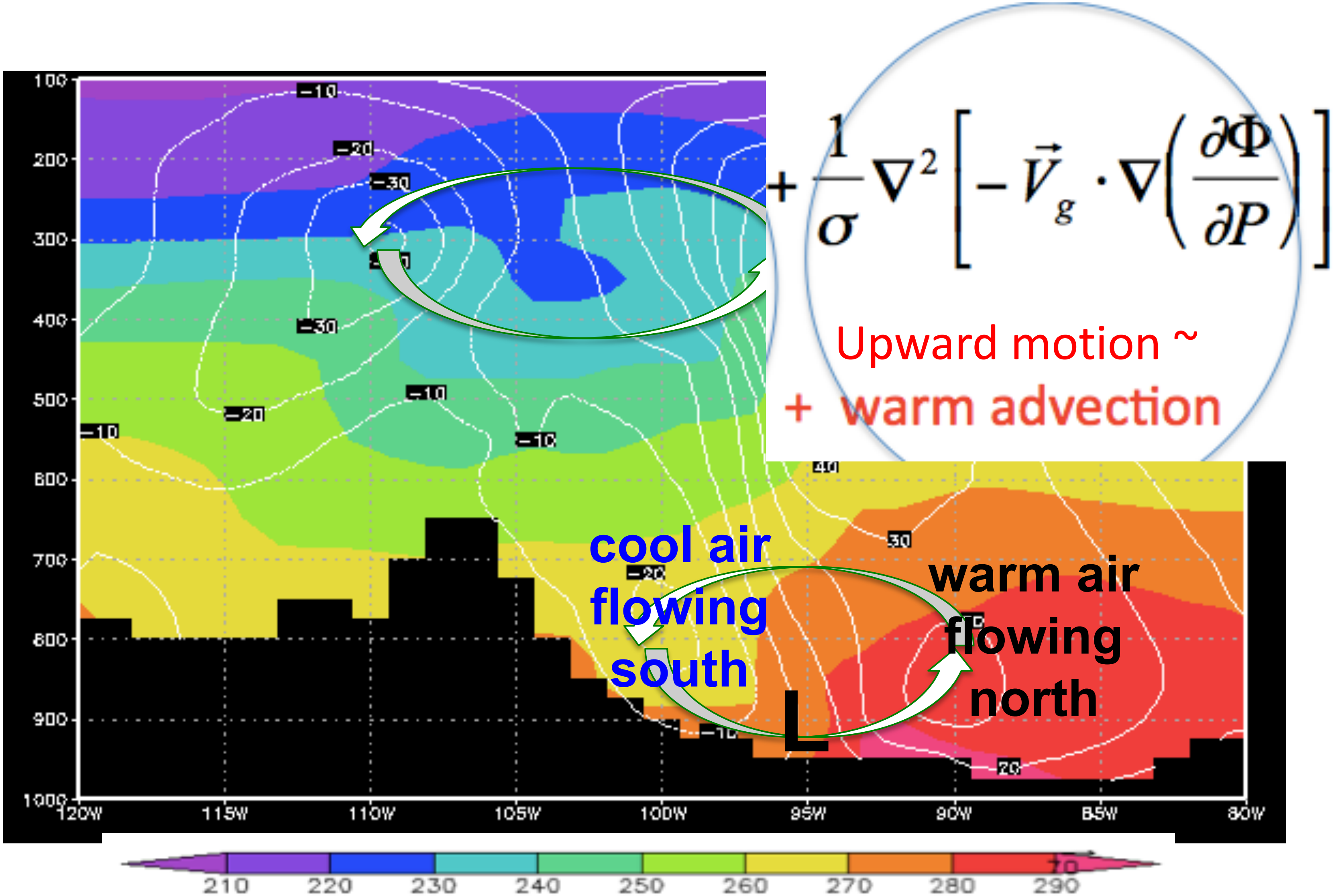
Sheared advection breaks thermal wind balance



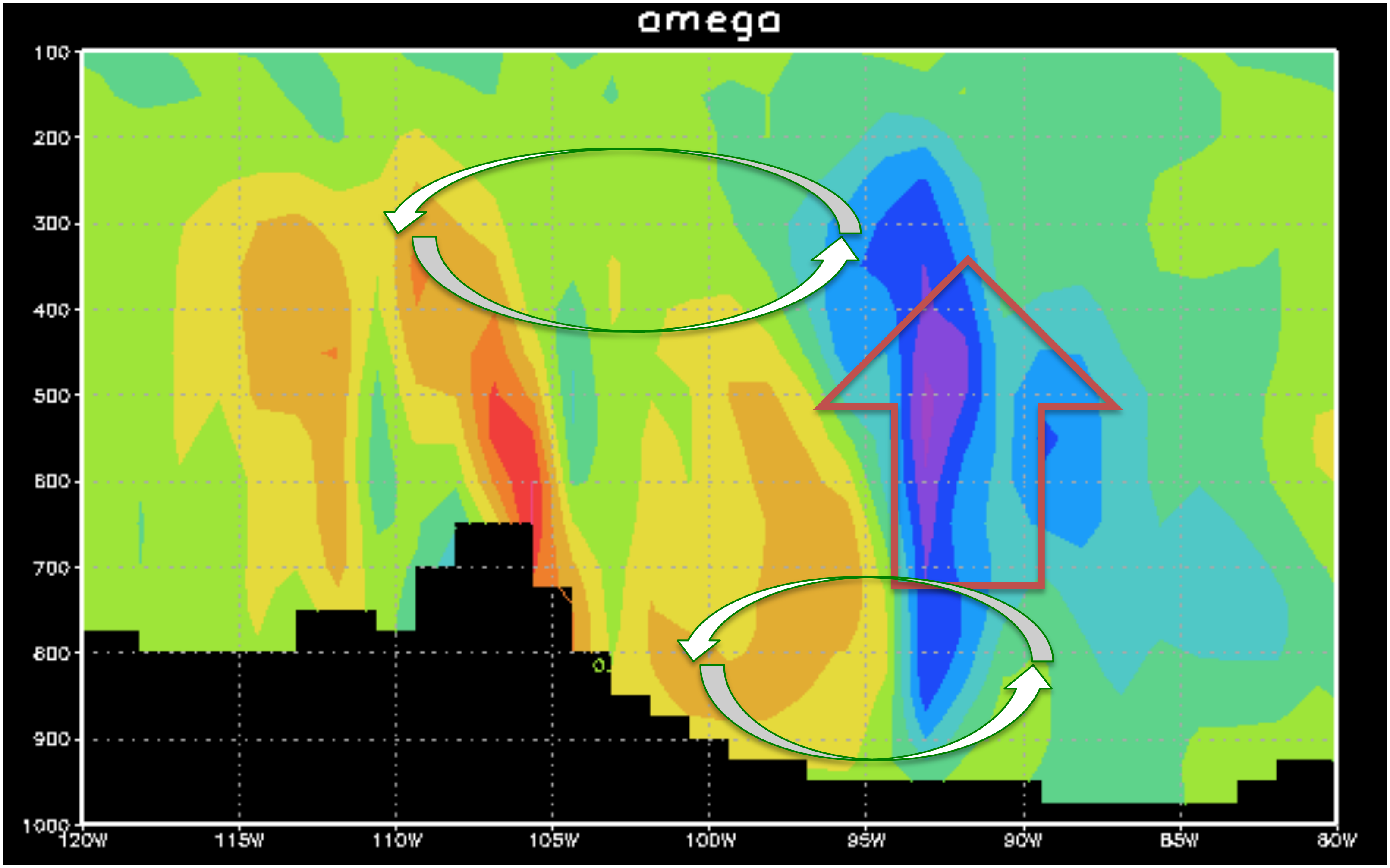
But there is some T advection too



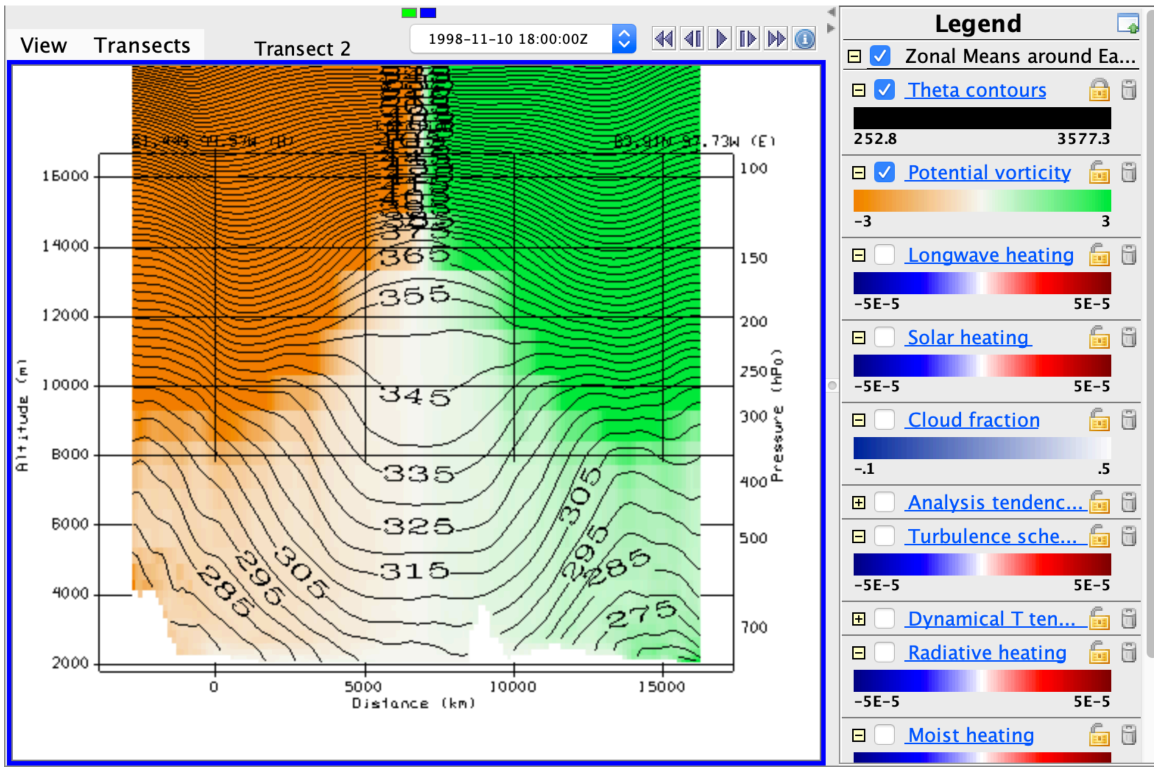
But there is some T advection too

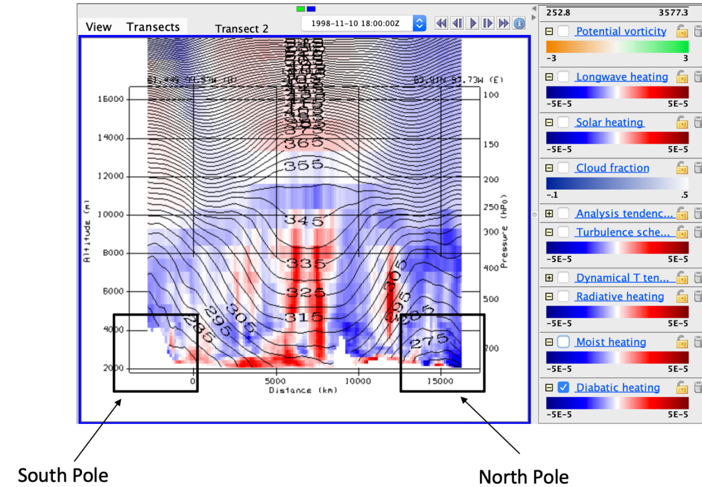


East-west section: omega

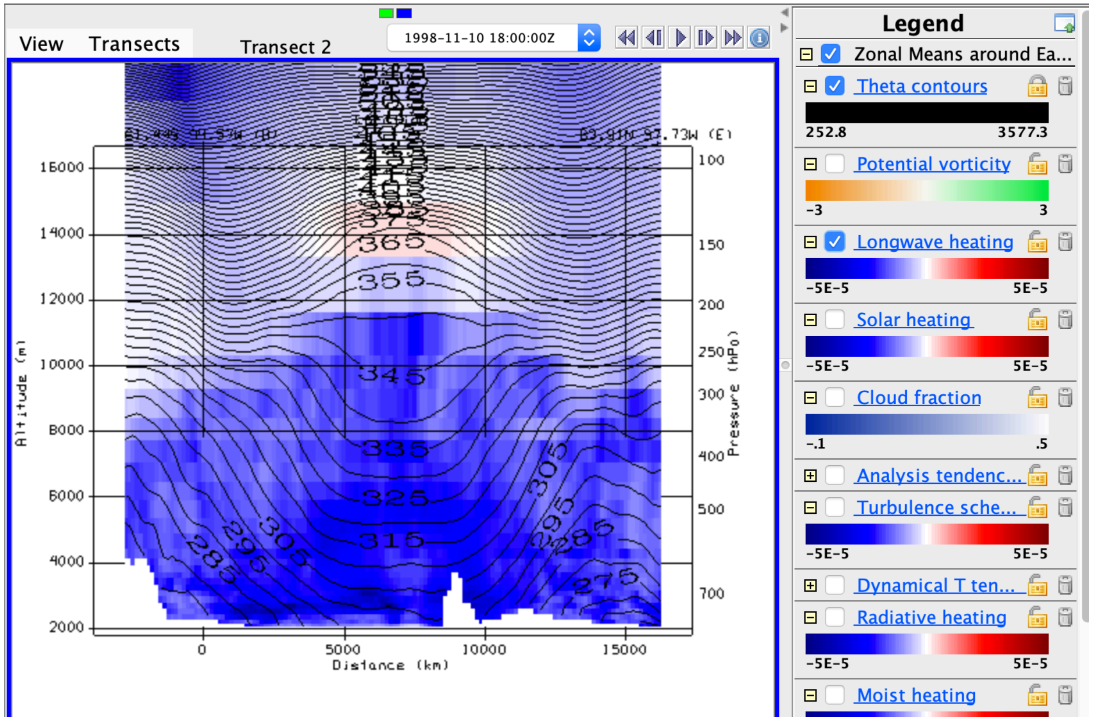


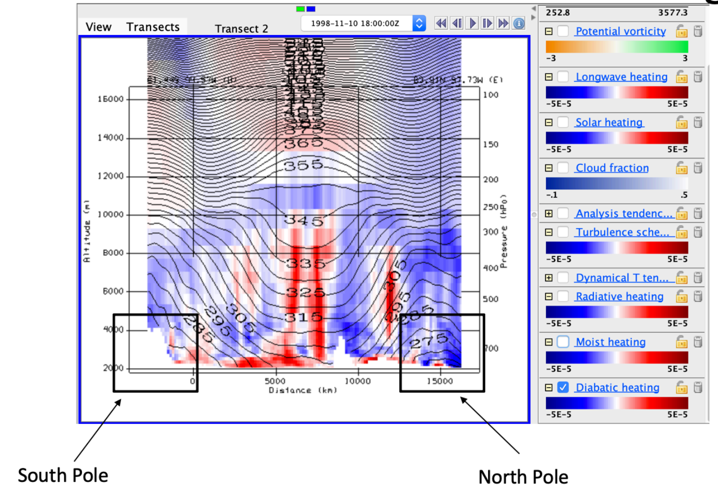
Potential Vorticity



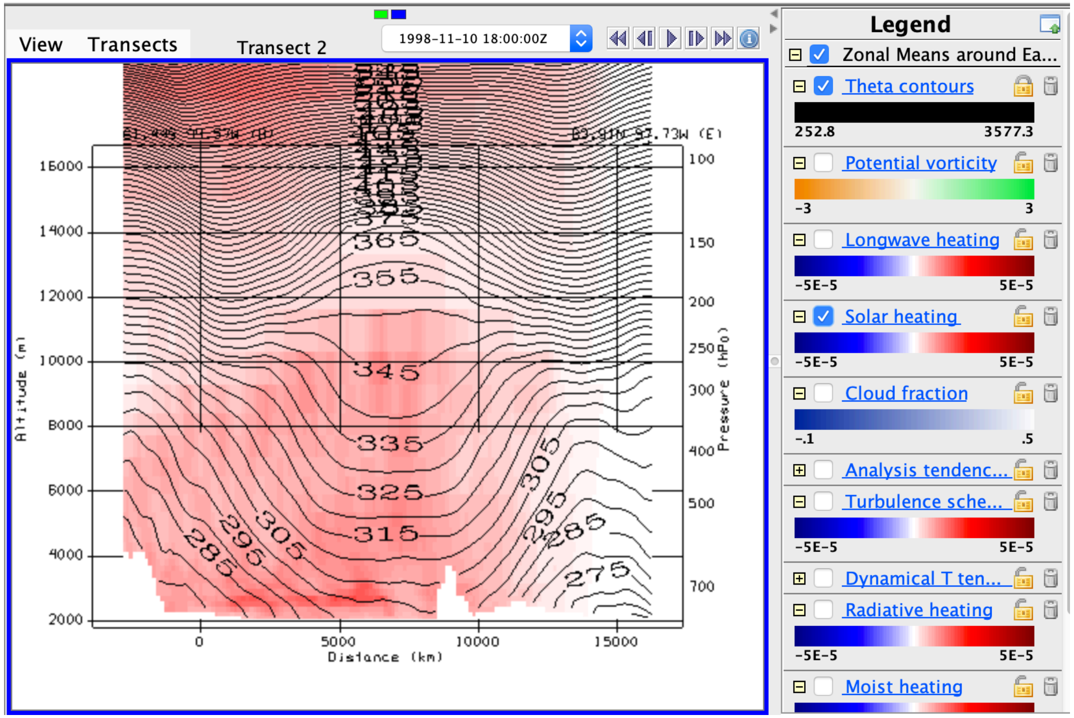


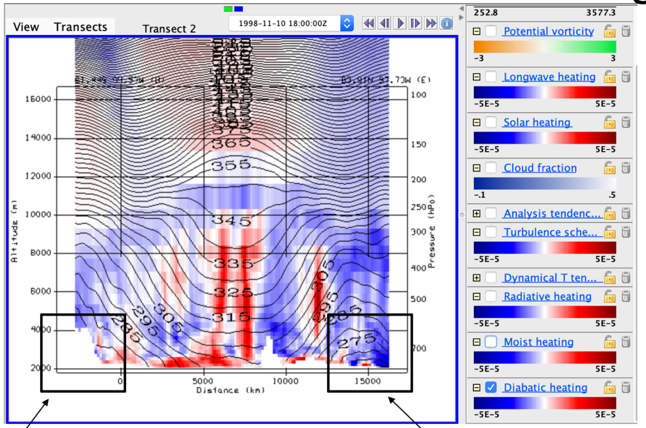
Longwave Heating





Solar Heating

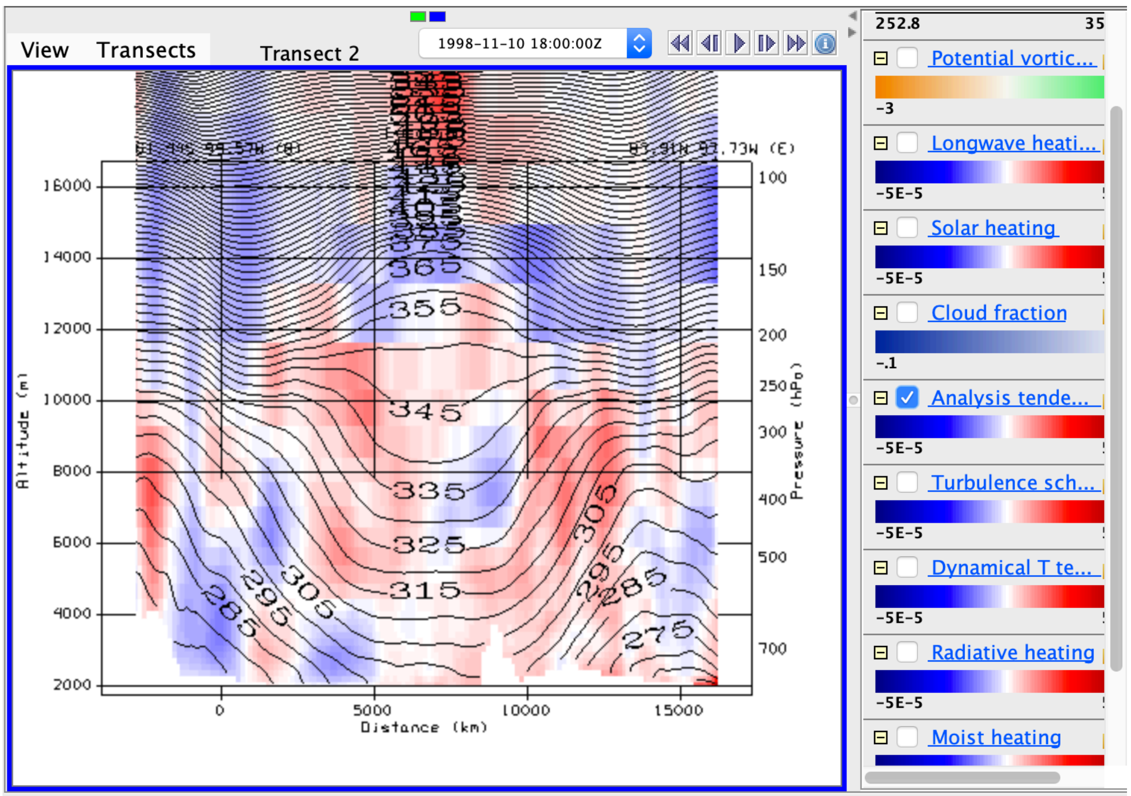


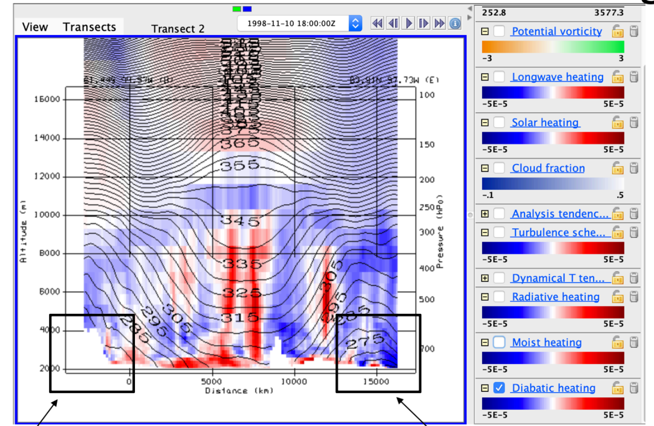


South Pole

North Pole

Analysis tendency (model errors)





South Pole

North Pole

Dynamical T tendency