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.

Relative vorticity advects other patches with the help of the divergent term.

$$d/dt(\zeta) = 0$$

$$+vf_y - (\zeta + f)(u_x + v_y)$$

- 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.

As we change latitude, planetary vorticity is converted on relative vorticity by stretching the vortex tube.

Questions about it: write answers

- 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 tendency is positive where heating rate increases with height.

PV is conserved -- almost

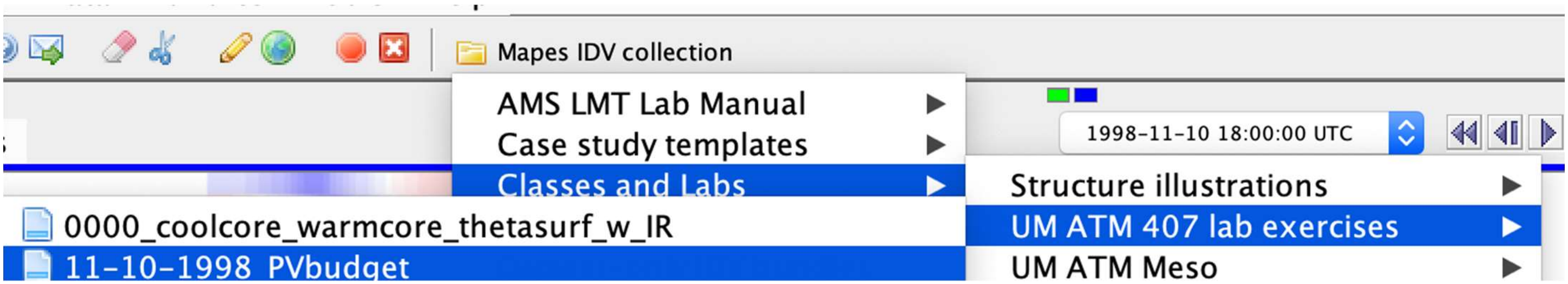
APPROXIMATE term that generates PV on the Earth

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

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”.

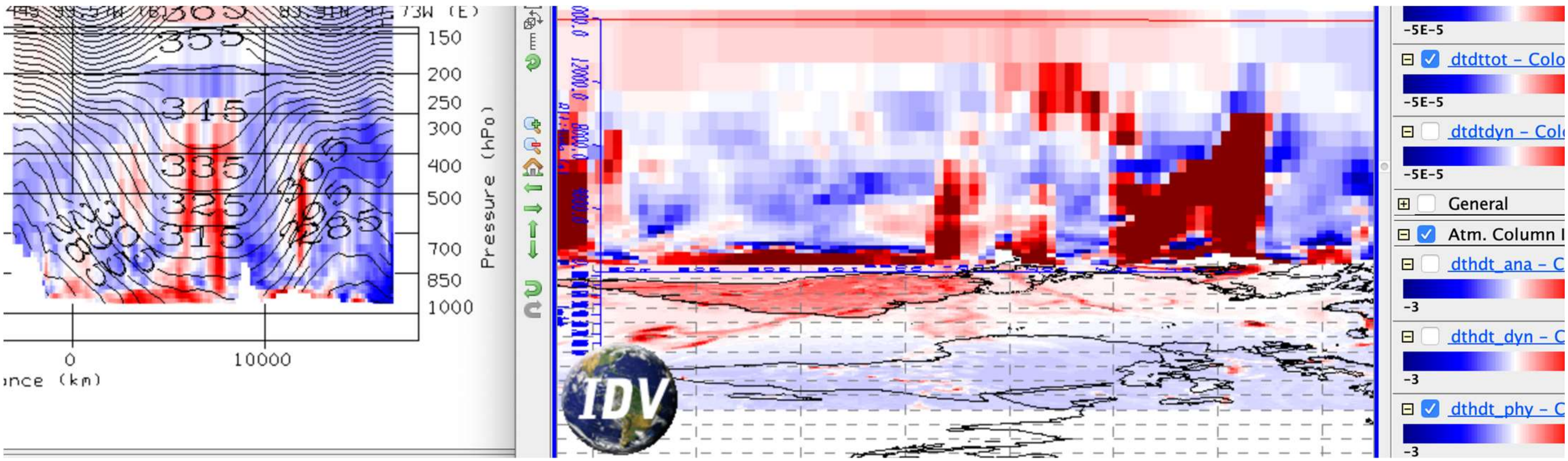
Assignment part 1: global view

- Open the bundle 11-10-98 PV budget



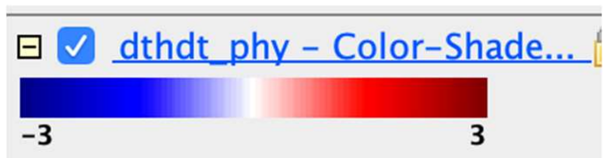
- Orient yourself to its displays, in **both windows**
  - a **pole-to-pole transect** of the **zonal mean** heating rates (averaged around the whole Earth)
  - A map view with many displays (including **movable cross sections**).

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

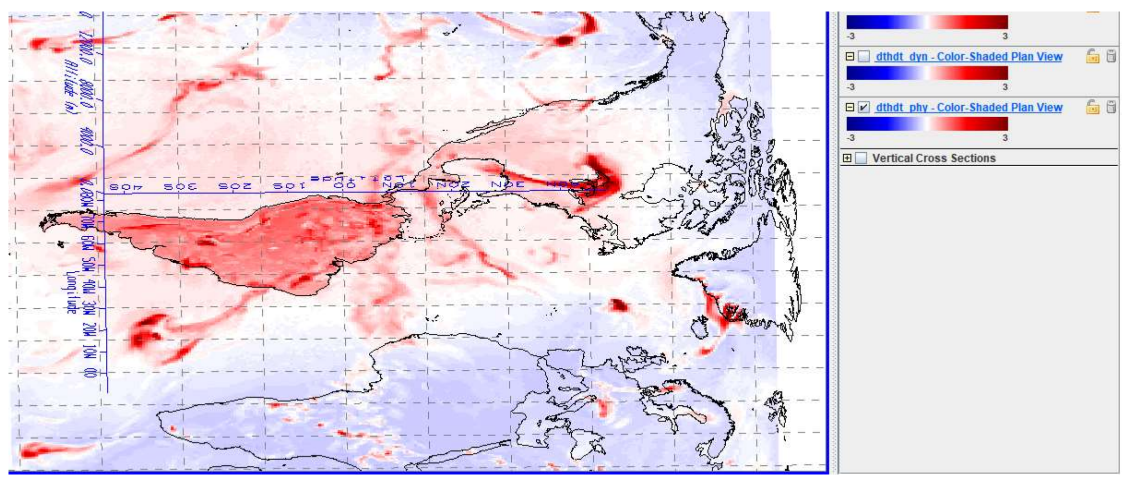


Assignment part 1: global view

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?



- It’s winter in the northern hemisphere
- SH receives more radiation heat than NH

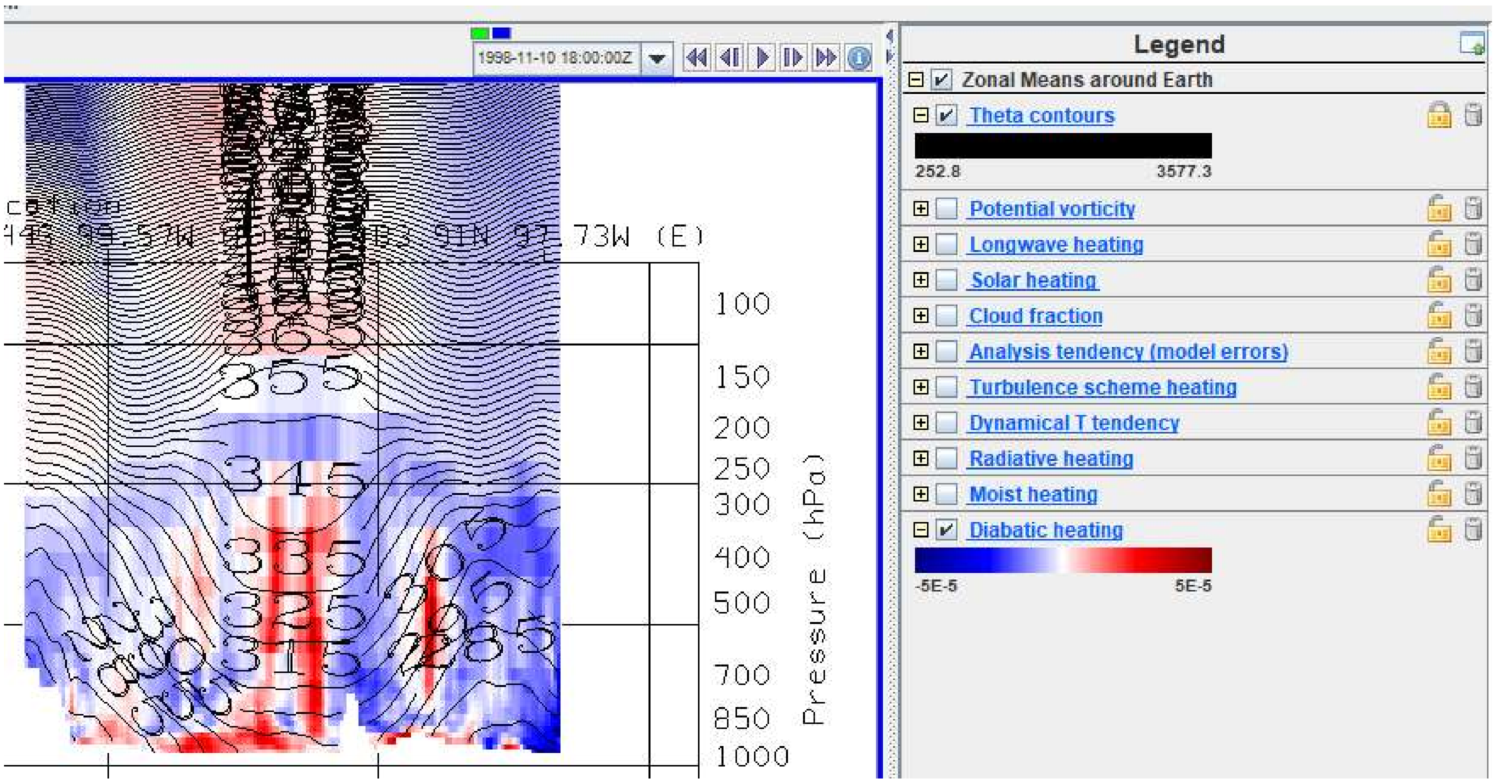


Assignment part 1: global view

- 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?

Assignment part 1: global view

- The colorbar goes from -5e-5 to 5e-5 K/s or -4.32 to 4.32 K/day
- SH NH



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

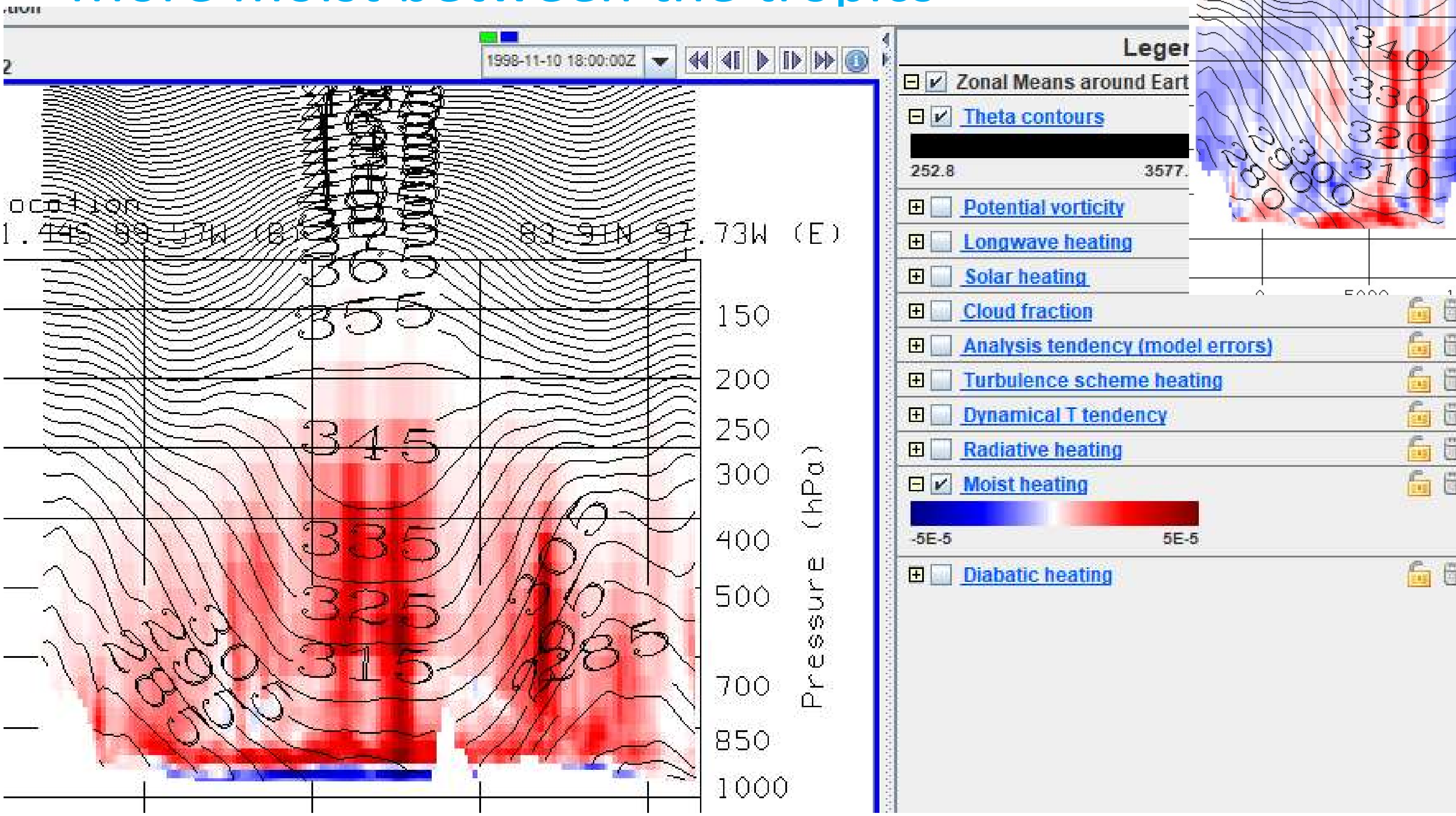
  diabatic = moist + radiative + turbulence

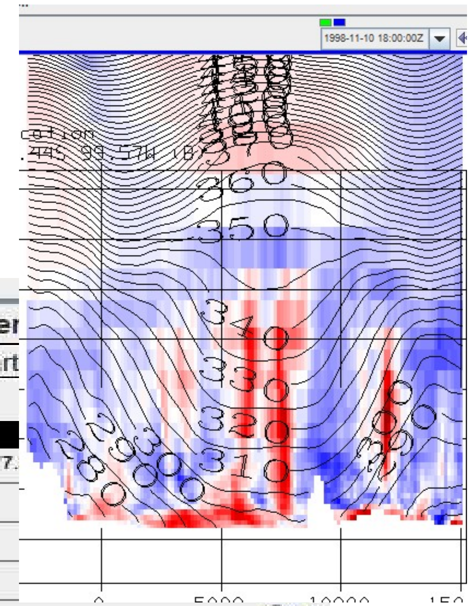
  radiative = longwave + solar

Assignment part 1: global view

Moist heating

More moist between the tropics

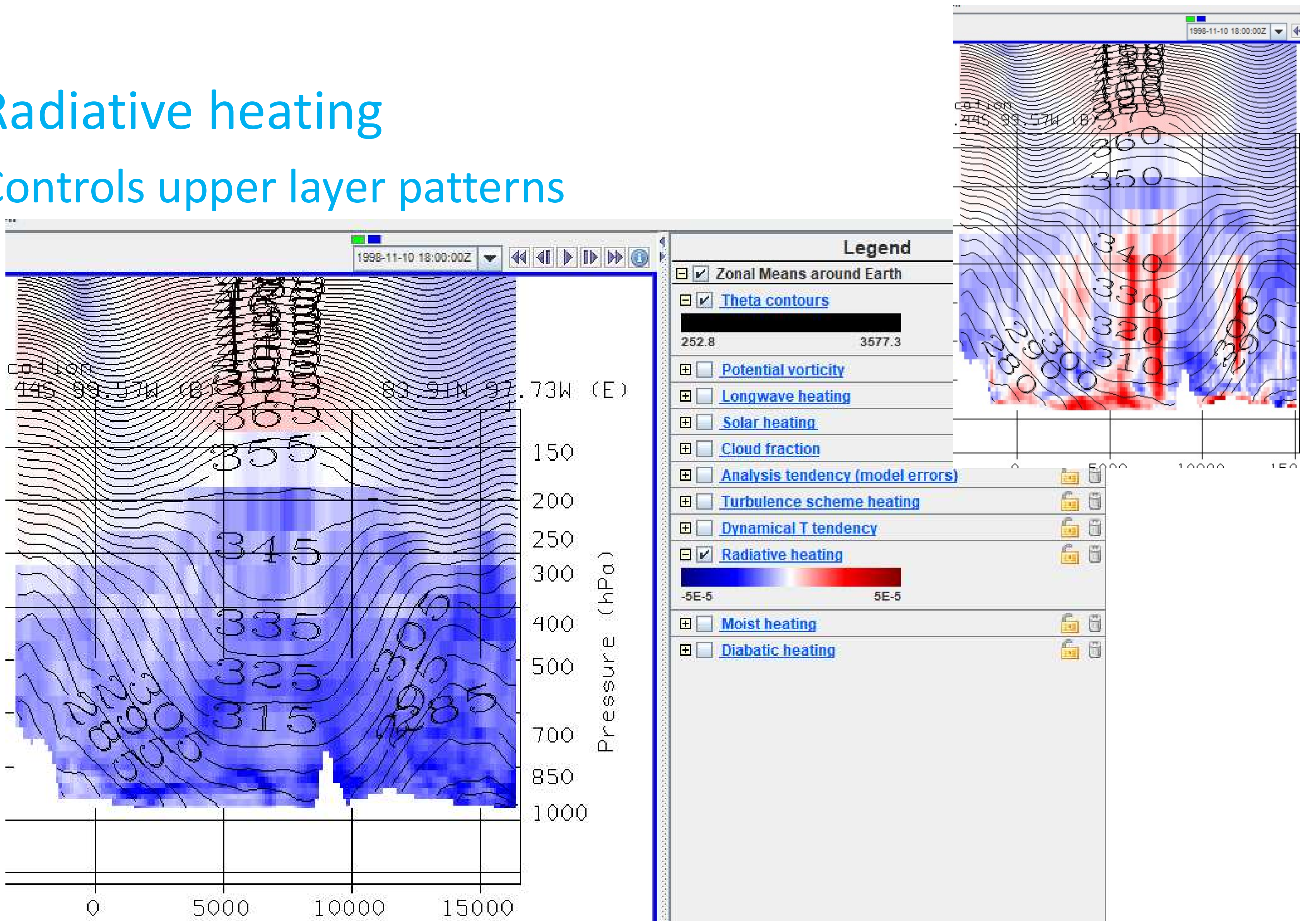




Assignment part 1: global view

Radiative heating

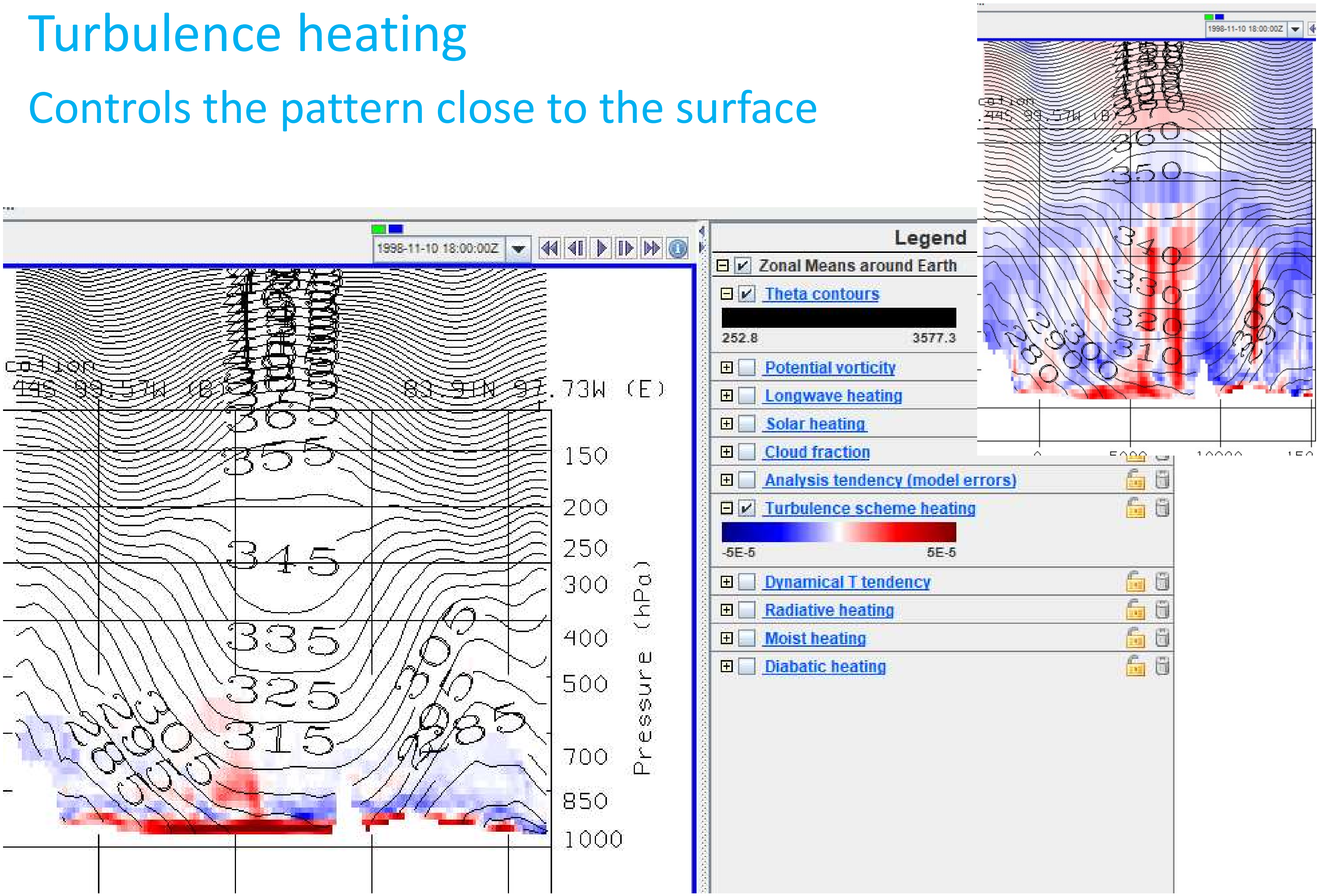
Controls upper layer patterns



Assignment part 1: global view

Turbulence heating

Controls the pattern close to the surface

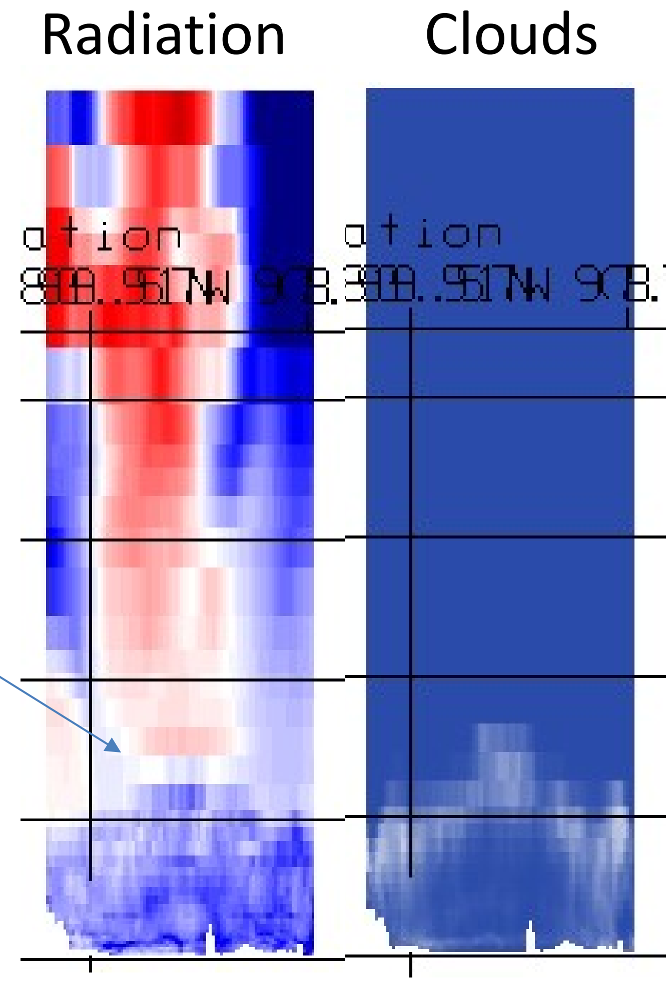


Assignment part 1: global view

- 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)

Assignment part 1: global view

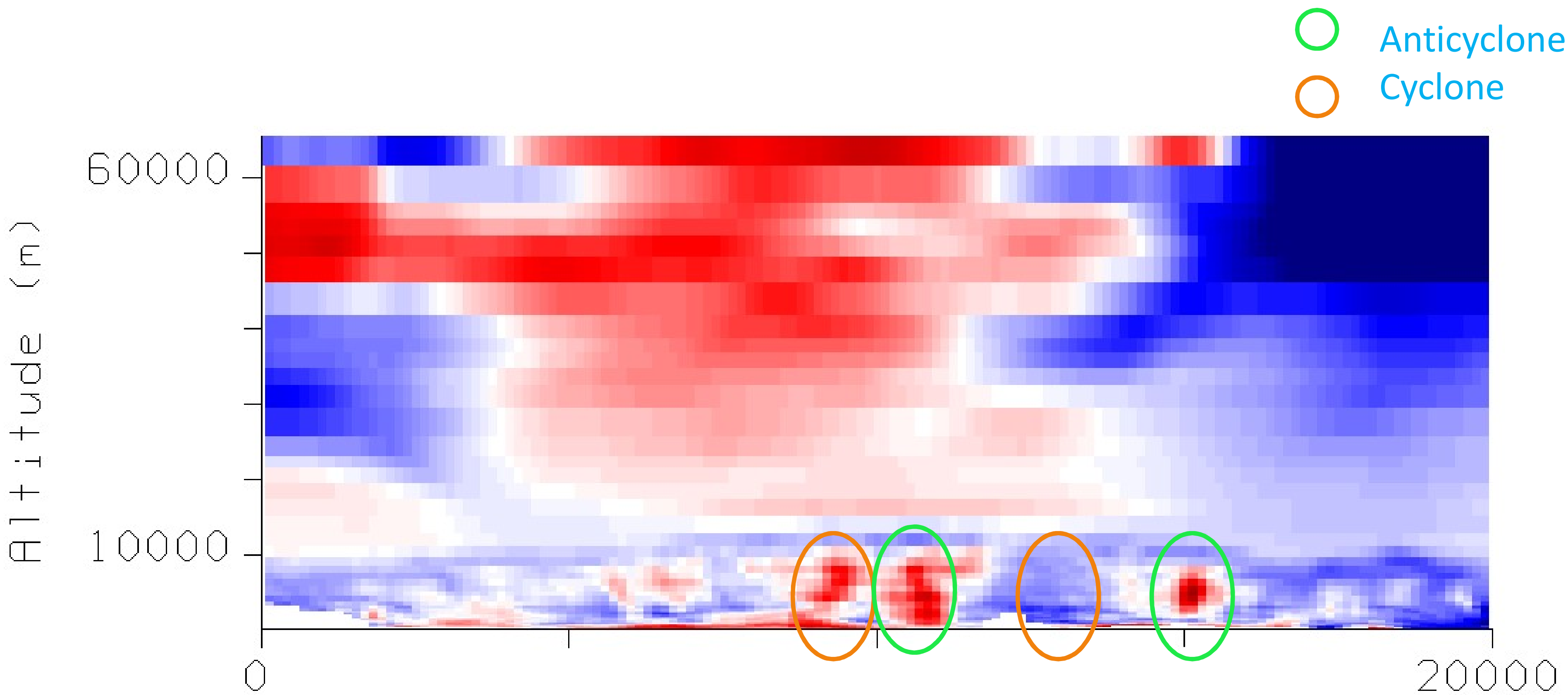
- Lower levels - ↑clouds, ↑ radiation reflected
- LW radiation emitted by clouds cools environment above top of them



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.

Assignment part 1: global view



$$d/dt(PV) = 0 - g(\zeta + f)\frac{\partial}{\partial p}\dot{\theta}_{diabatic} + curl(friction)\frac{\partial \theta}{\partial p}$$

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)

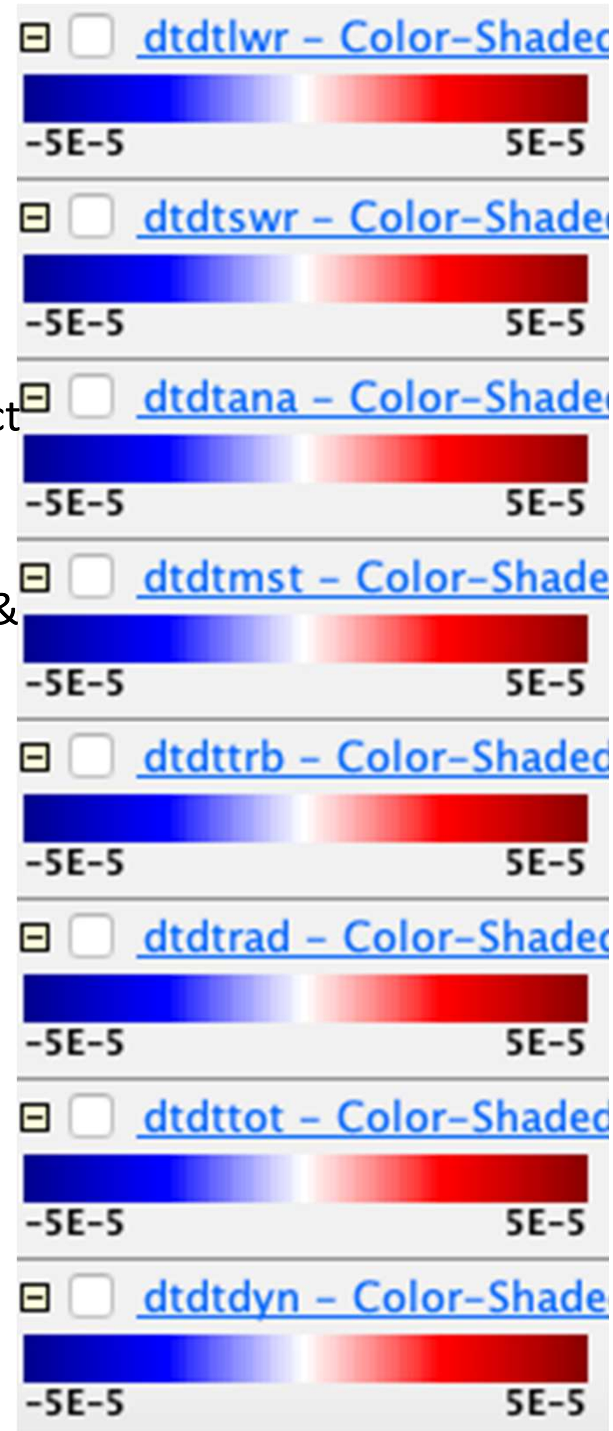
moist mst (convection & cloud cond.)

turbulence (PBL)

SW+LW radiation

total physics (”diabatic”)

dynamic (advective)

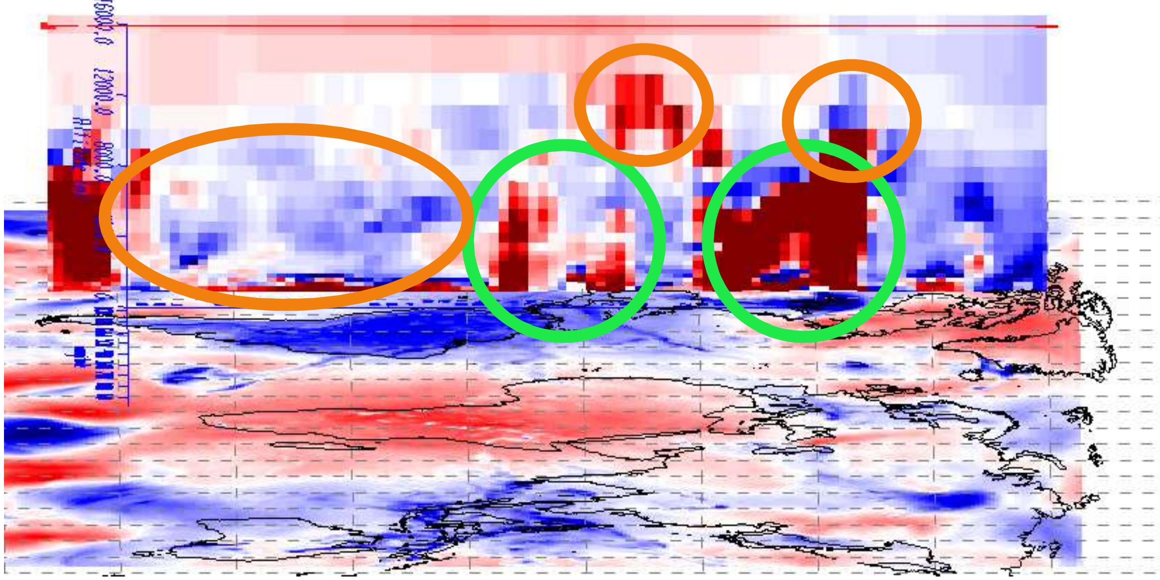


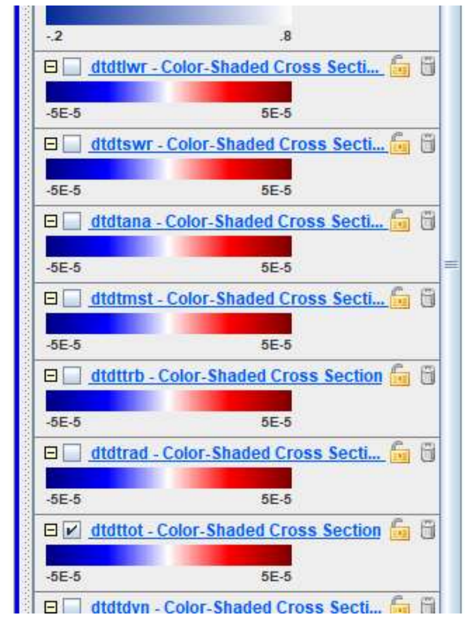
Assignment part 2: Local view

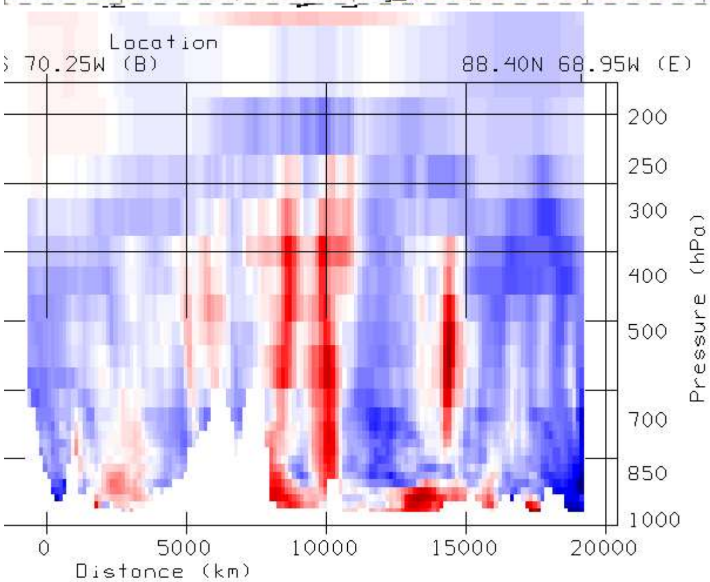
- Make comparison slides juxtaposing the zonal-mean transects and your local cross-sections, like in slide 6 above.
- Toggle the various terms making up the total diabatic heating, in order to explain
  - Which is more variable (more spatially concentrated): radiative or moist heating? Illustrate your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

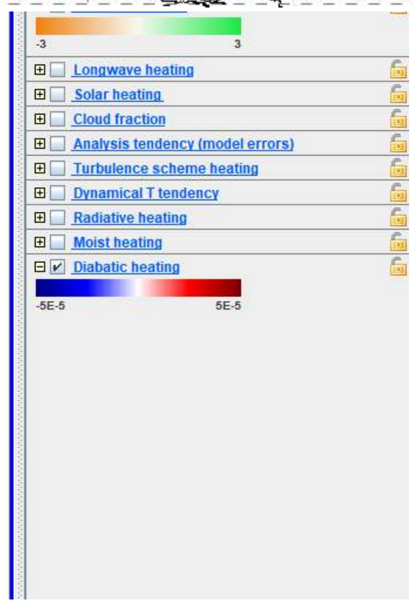
Assignment part 2: Local view

Diabatic Heating



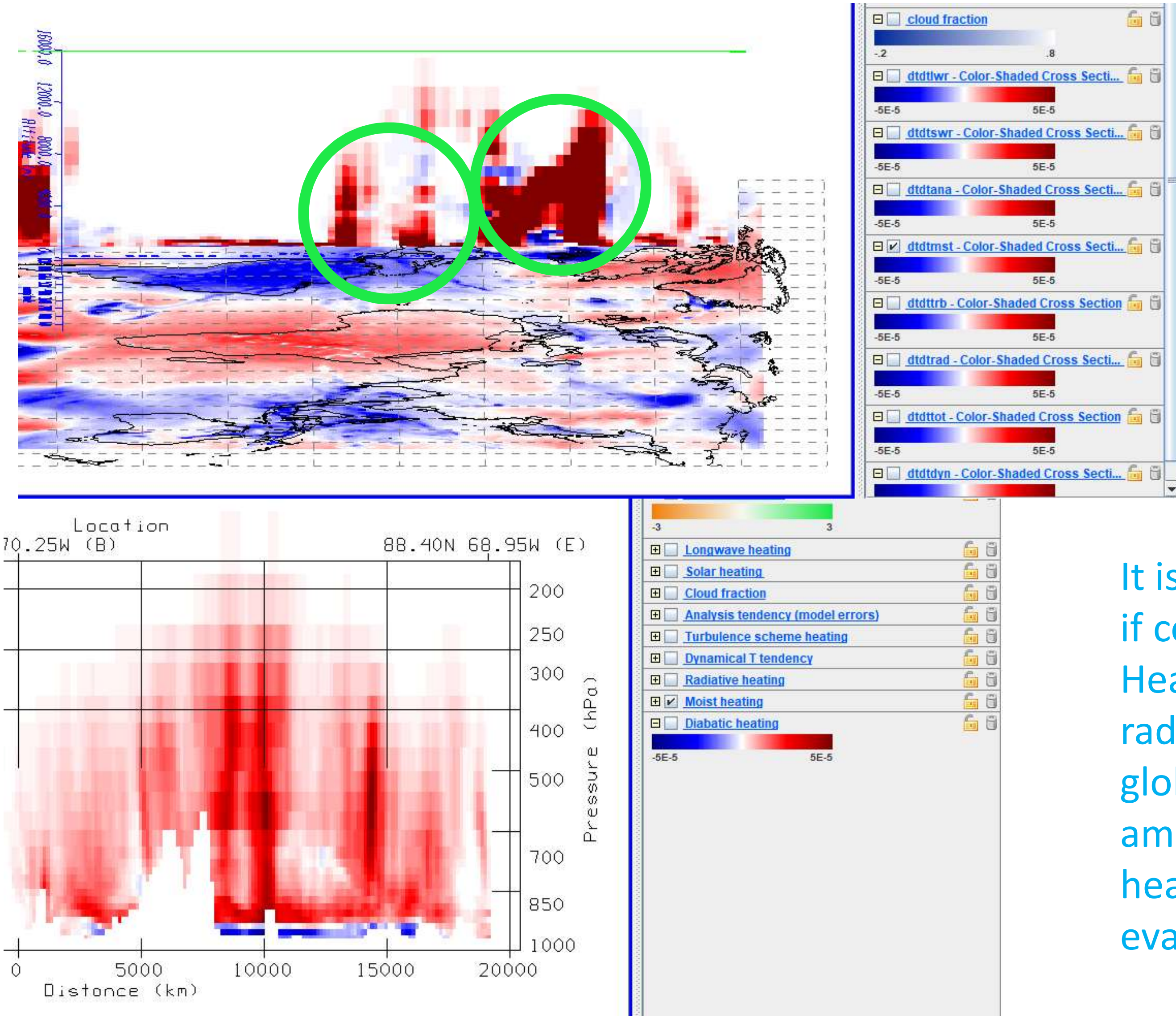






Assignment part 2: Local view

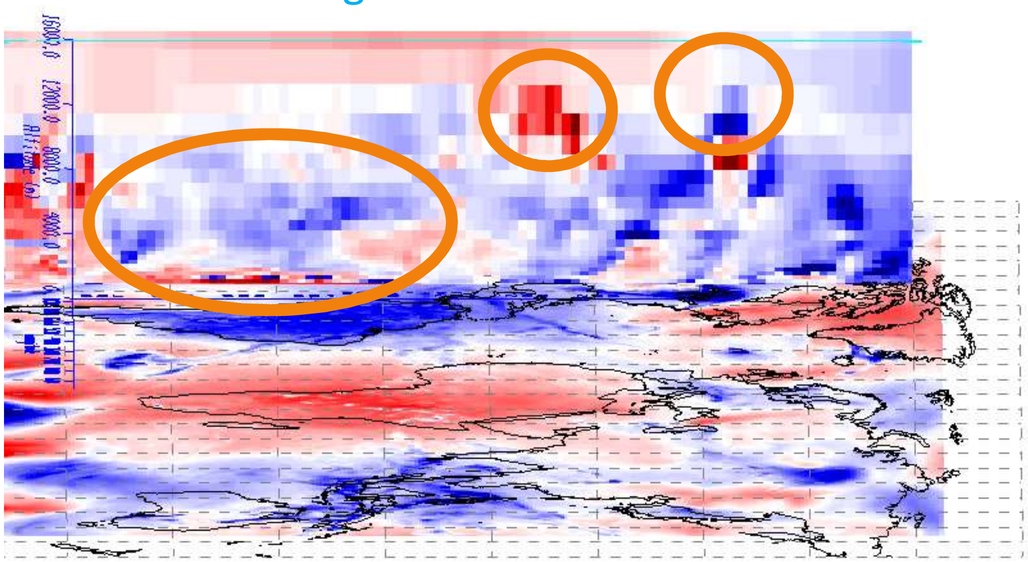
Moist Heating

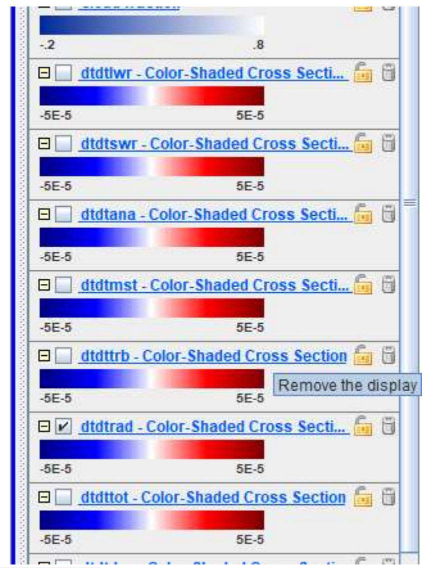


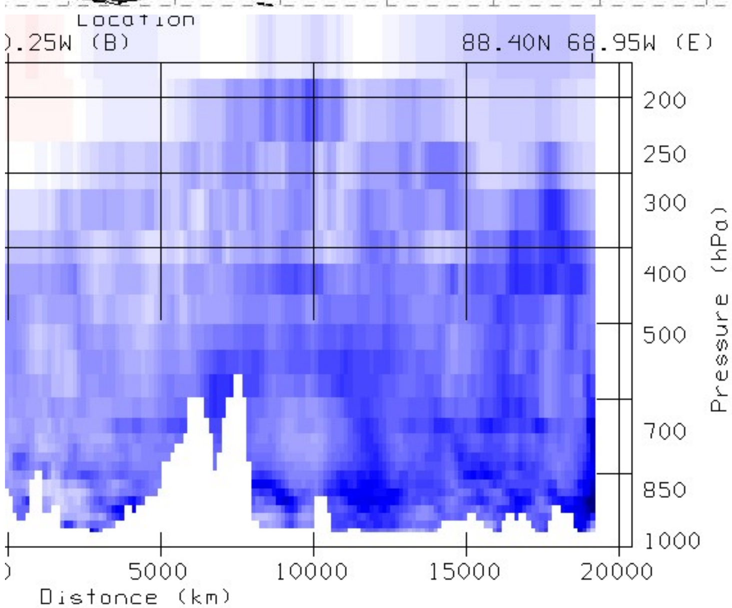
It is more concentrated if compared to Radiation Heating because radiation reaches all the globe (differen ammounts) and moist heating is related to evaporation rates.

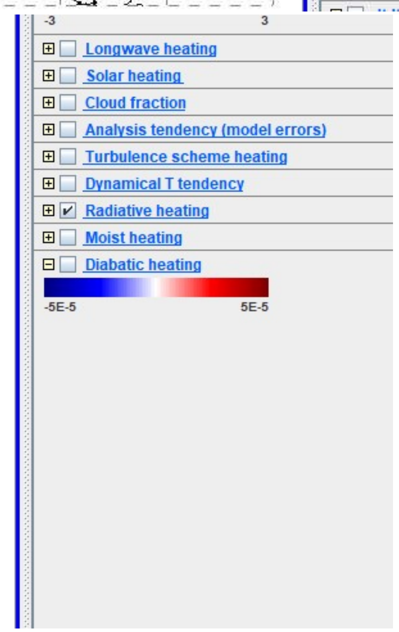
Assignment part 2: Local view

Radiative Heating







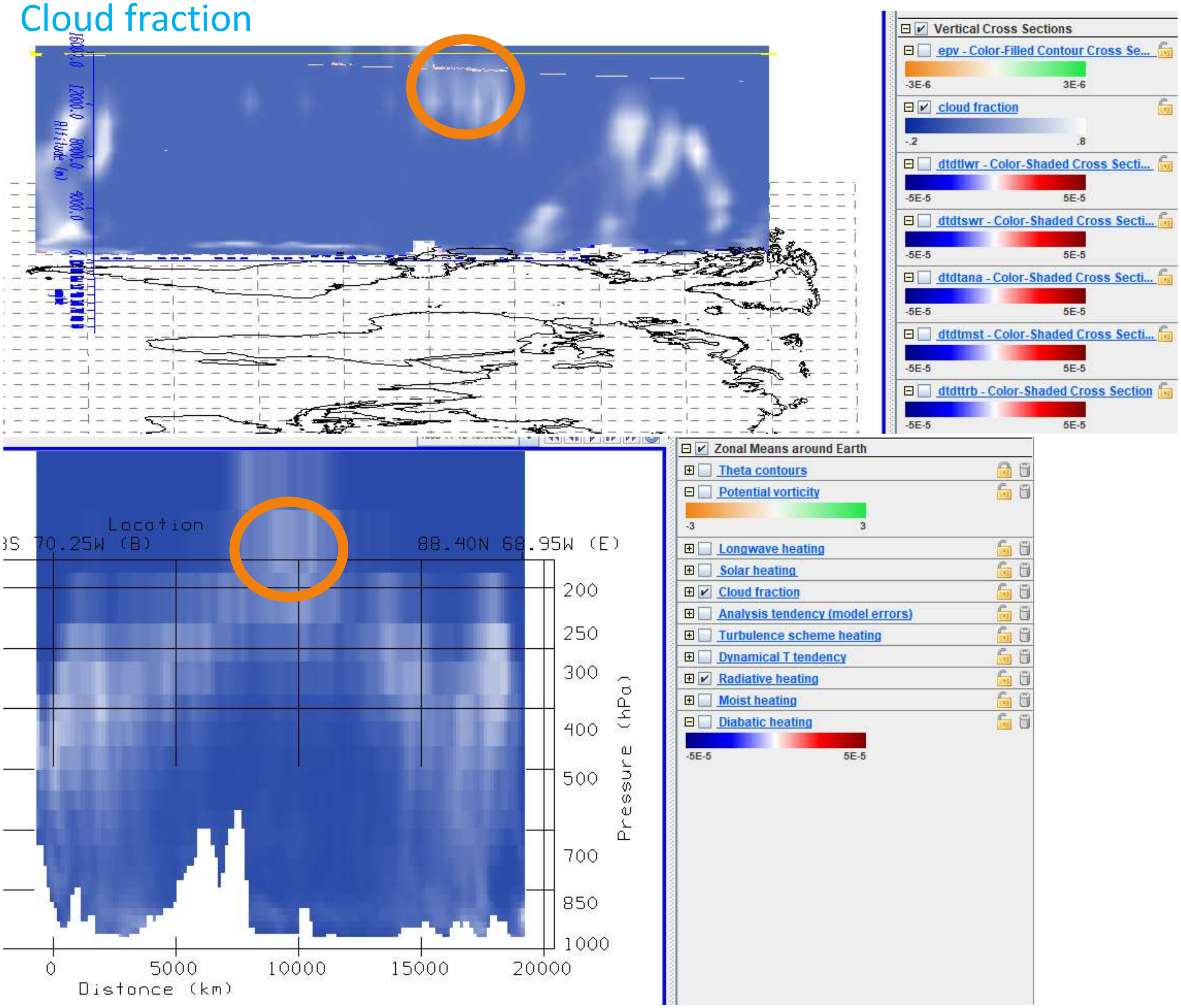


Assignment part 2: Local view

- 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

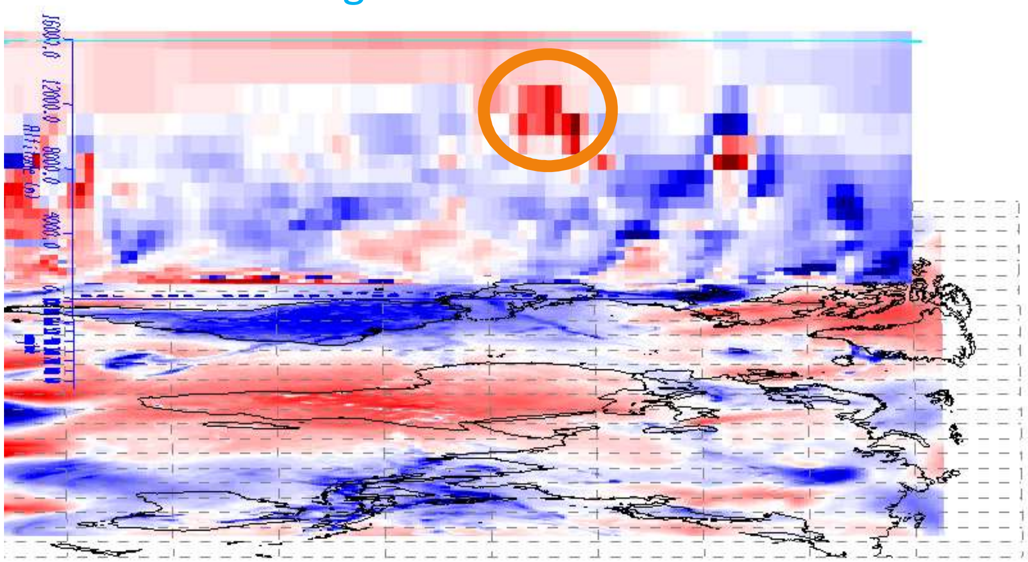
Assignment part 2: Local view

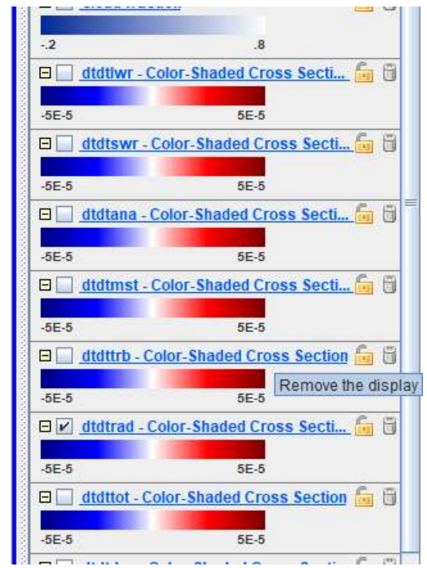
Cloud fraction

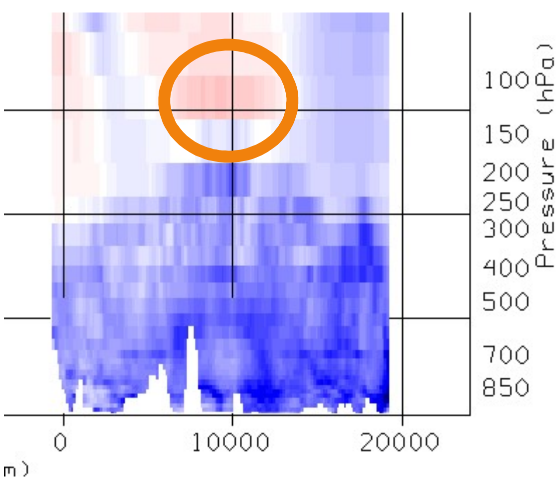


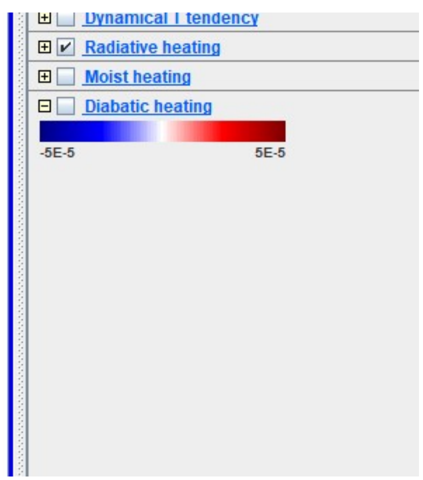
Assignment part 2: Local view

Radiative Heating





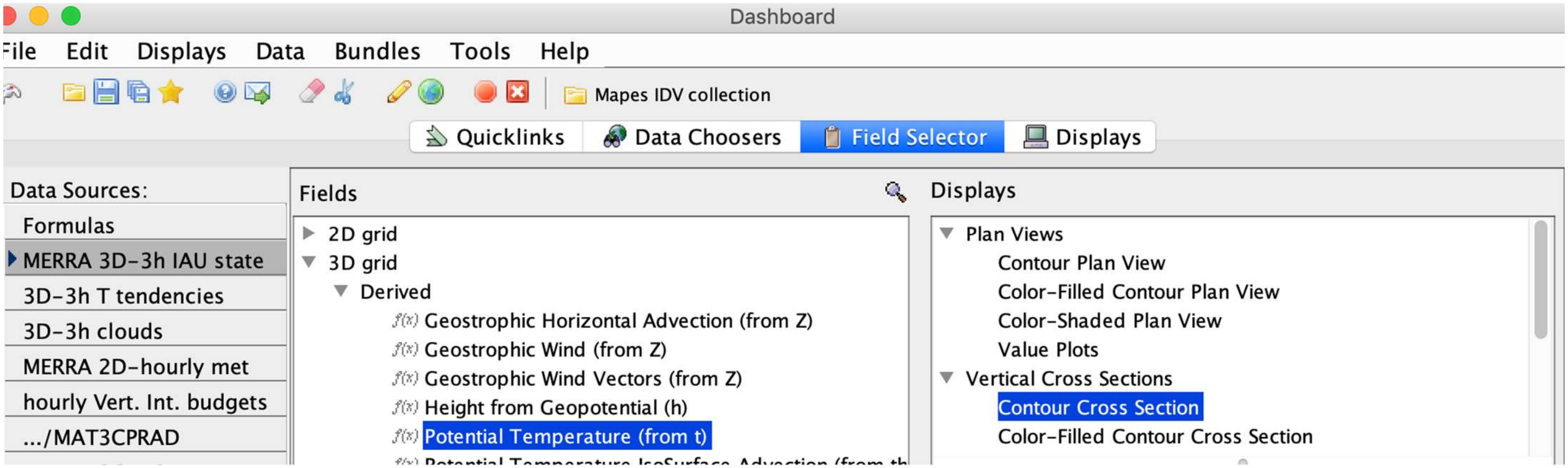




Assignment part 2: Local view

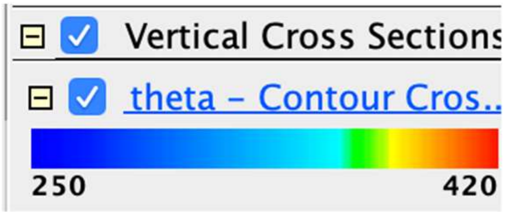
- Consider the PV source term motivating this exploration.
  - Where does the vertical gradient of heating imply large PV sources? Use arrows to annotate a couple positive and negative source regions.
  - Can you find a weather situation where this source term is a positive feedback on PV?

Create a new cross section of potential temperature contours

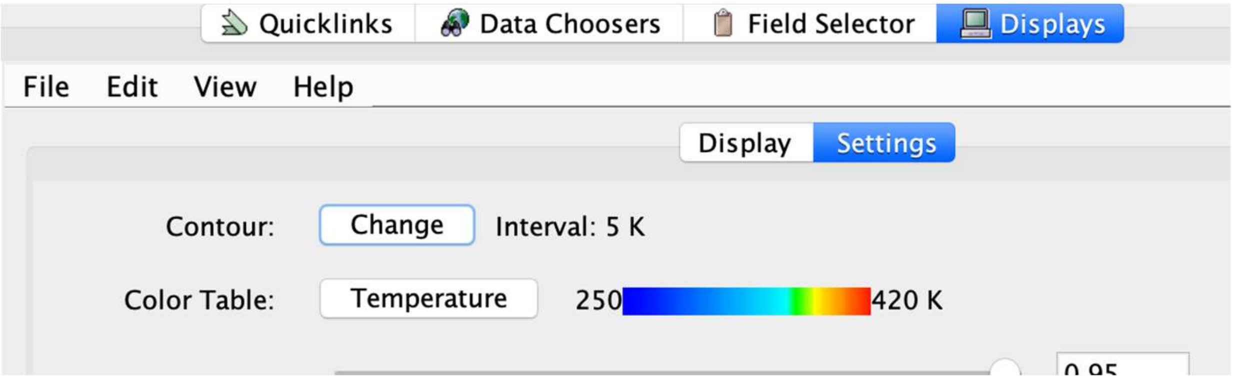


Create a new cross section of potential temperature contours

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

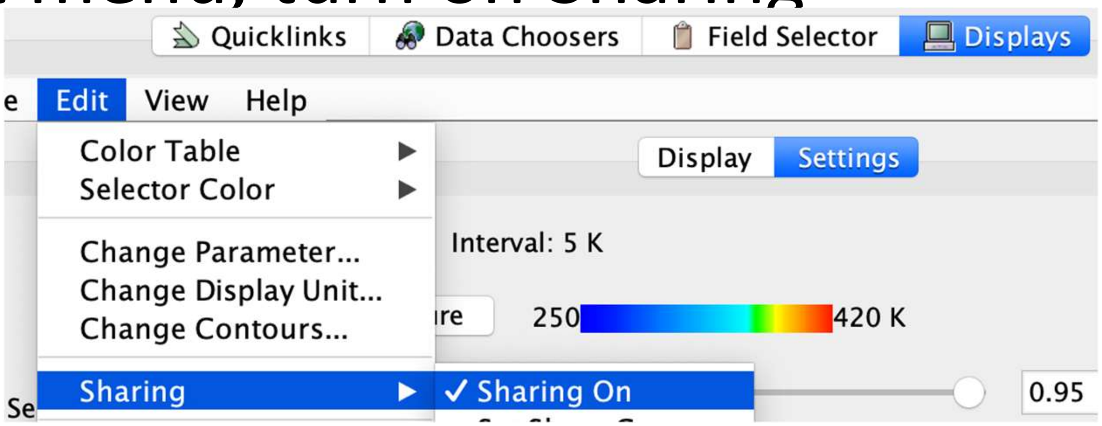


- Change the contour interval to 5K. Change the Color to Black. Change their label size to 20.



Create a new cross section of potential temperature contours

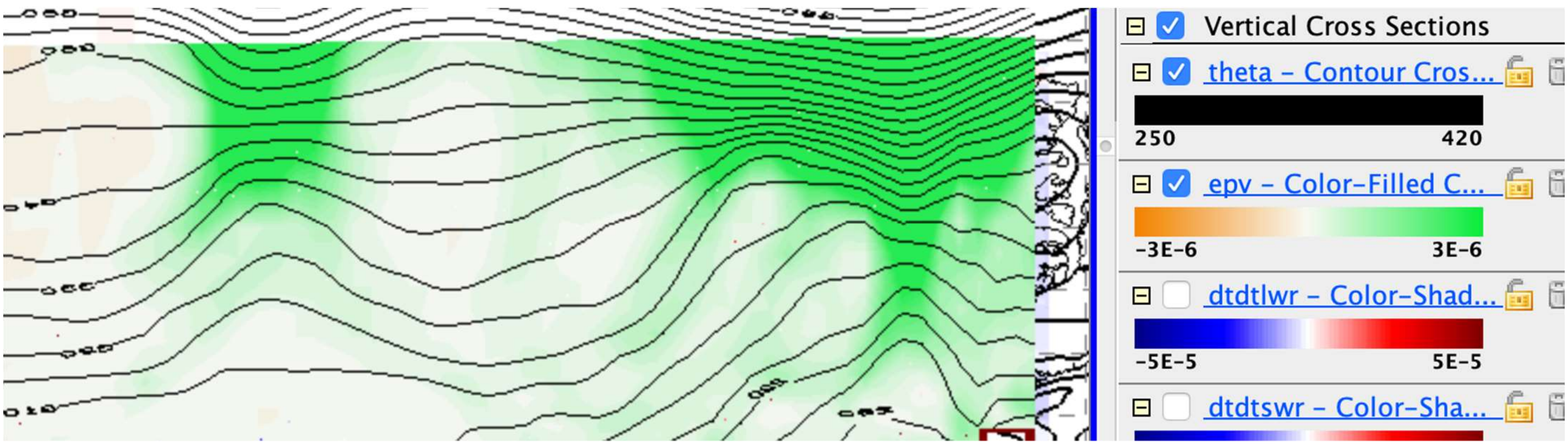
- Again click the Legend entry to pop up the Display Controls.
- Under the Edit menu, turn on Sharing



- 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?

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 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

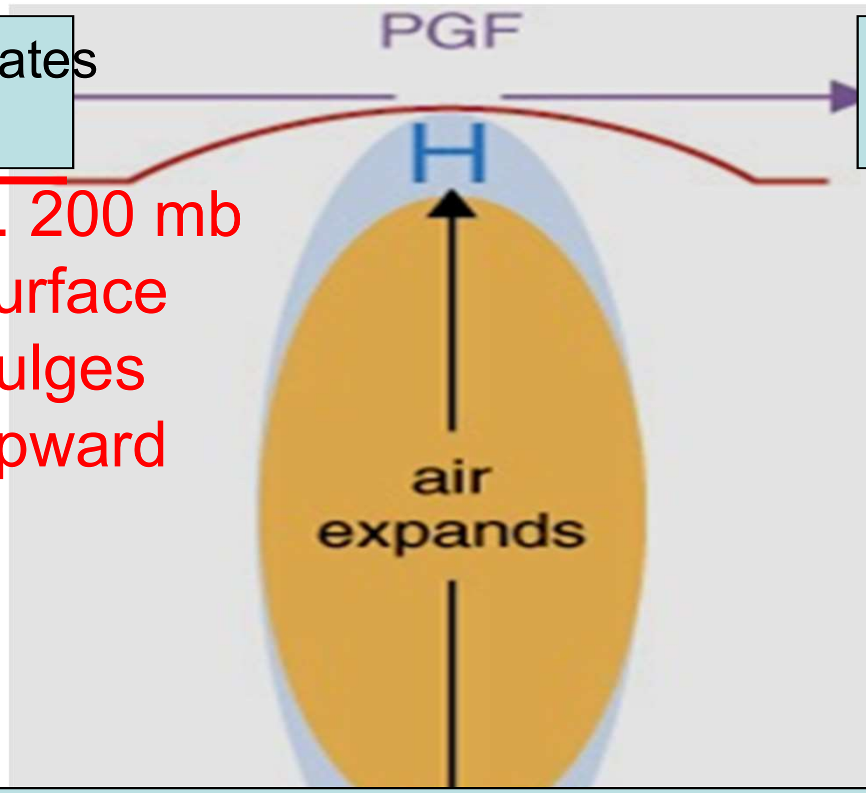
$$\frac{\partial T}{\partial t} = -\vec{V} \cdot \vec{\nabla}_p T - \omega S_p + \frac{J}{C_p}$$

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



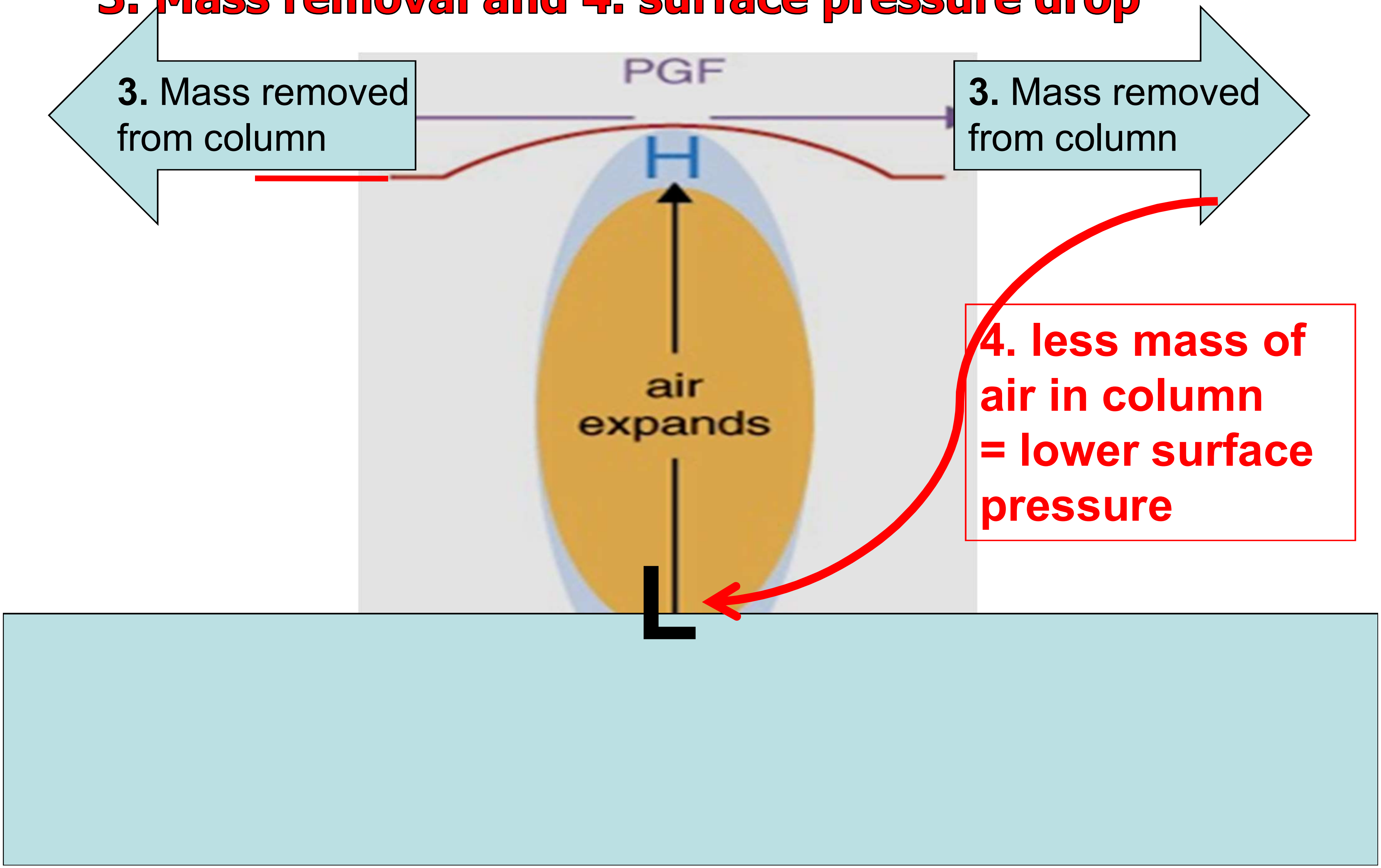
2. Air accelerates due to PGF

1. 200 mb surface bulges upward

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

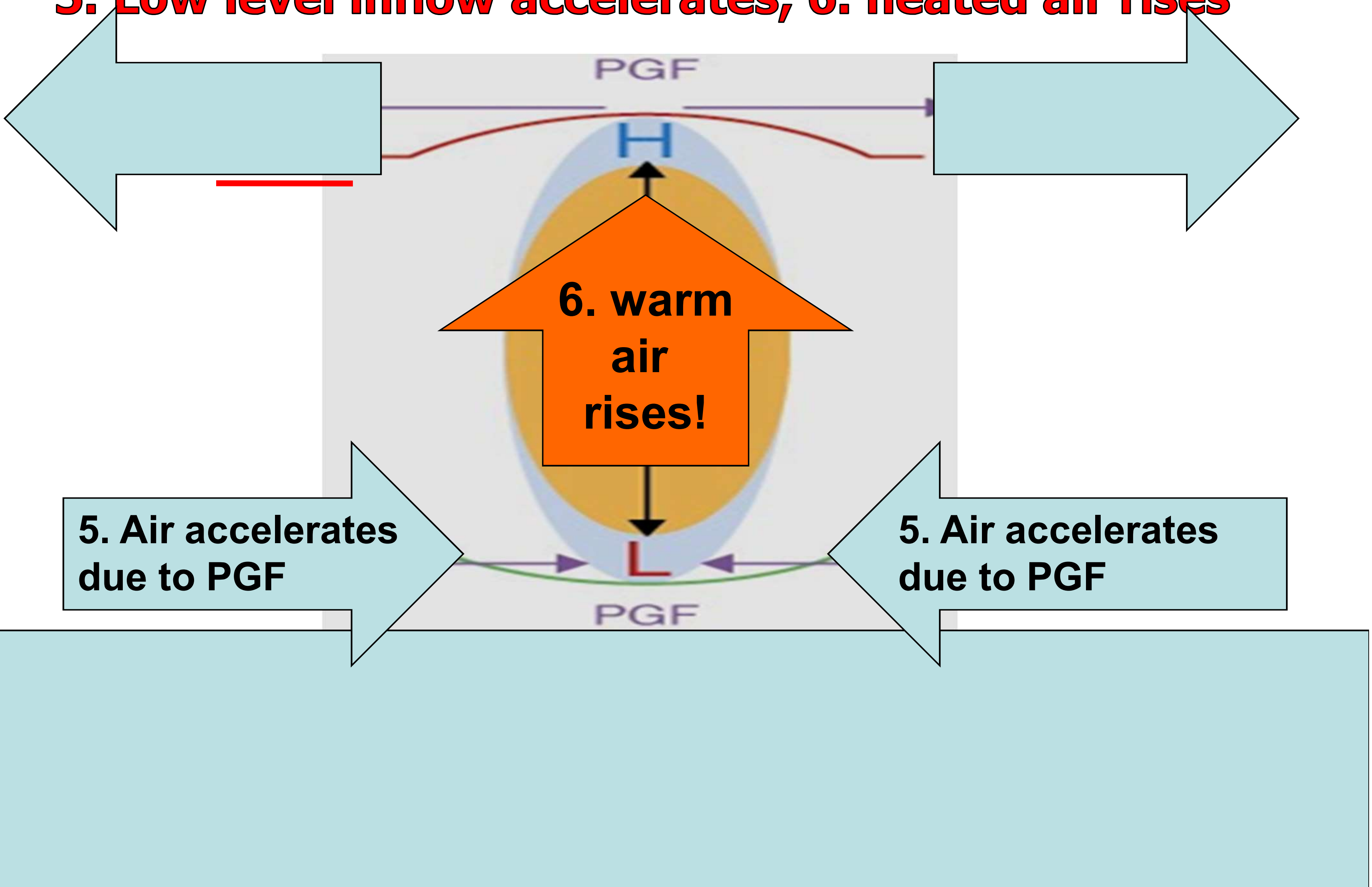
How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

3. Mass removal and 4. surface pressure drop

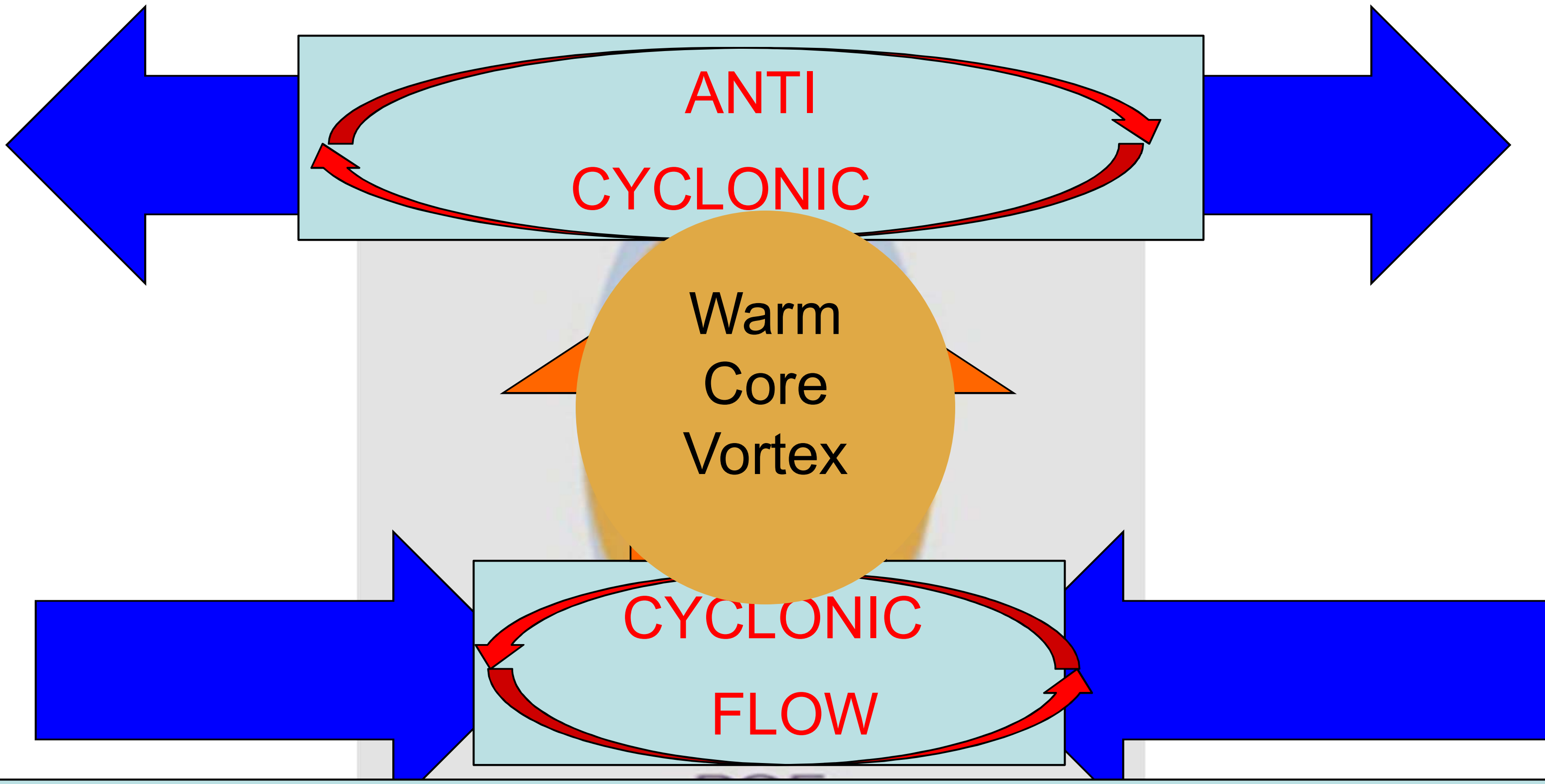


How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

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

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

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

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

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

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

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!)

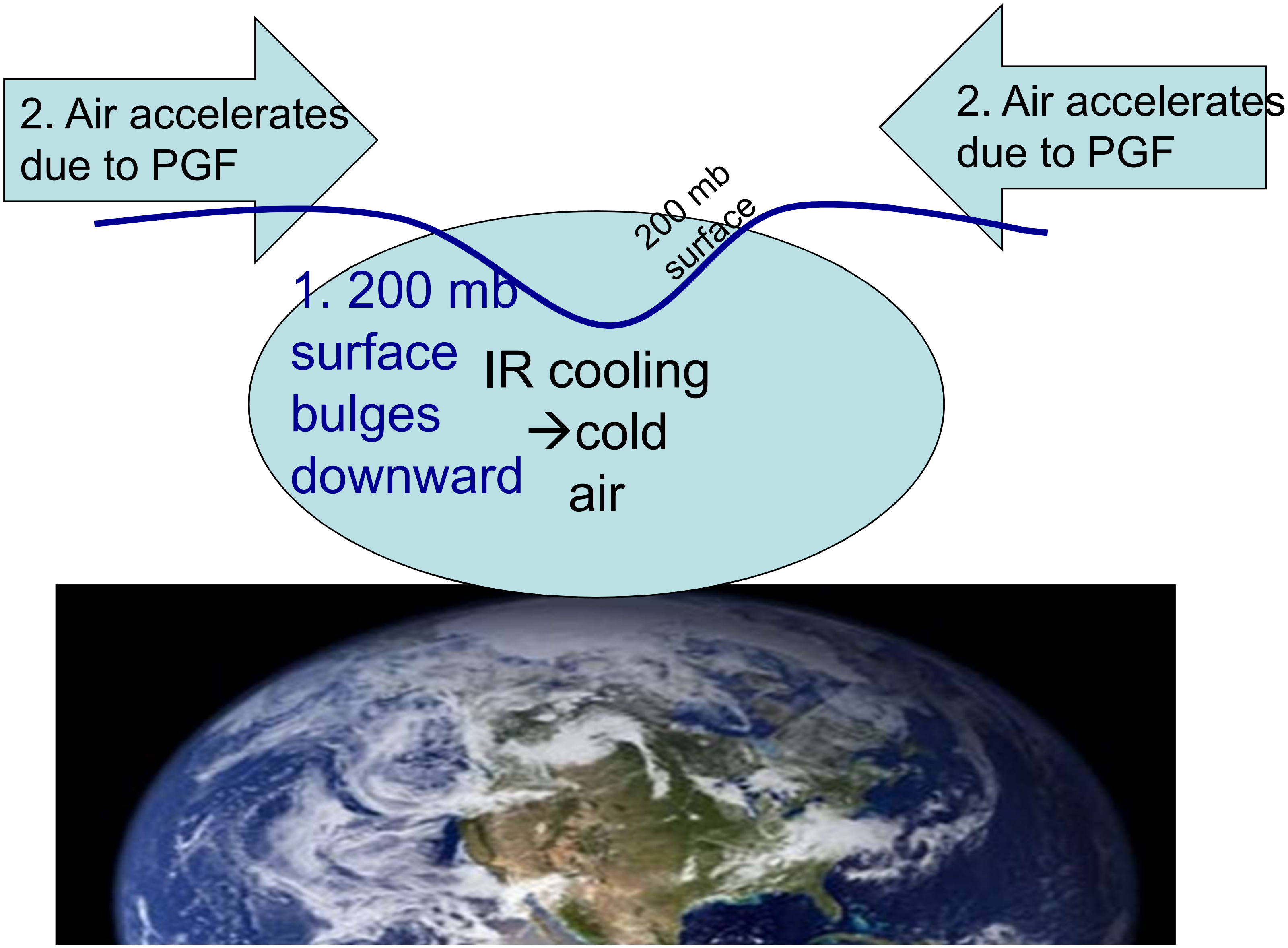
$\omega =\sim \rho g w$

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

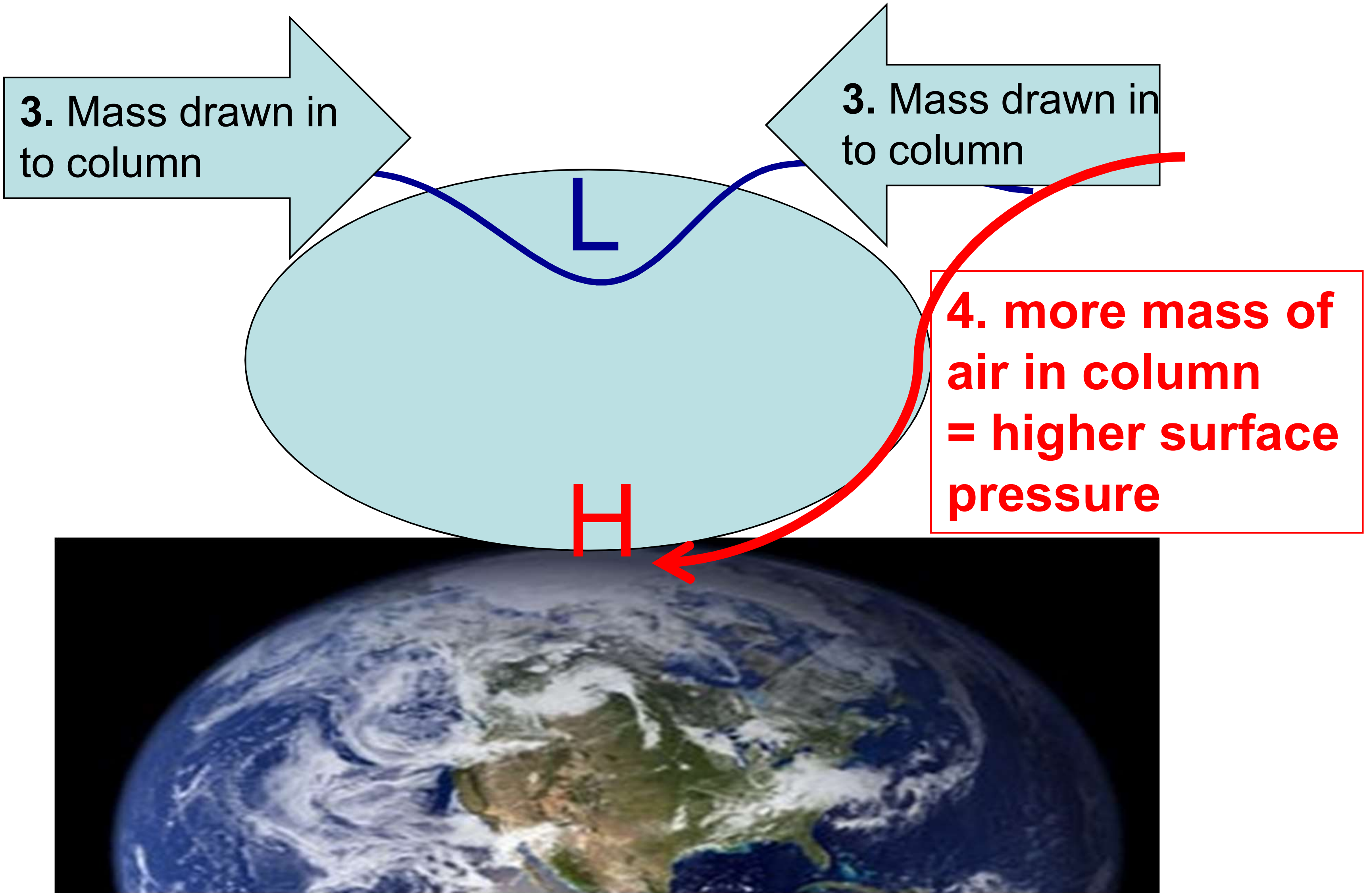
7. Coriolis force turns inflowing and outflowing air to make round-and-round flow

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

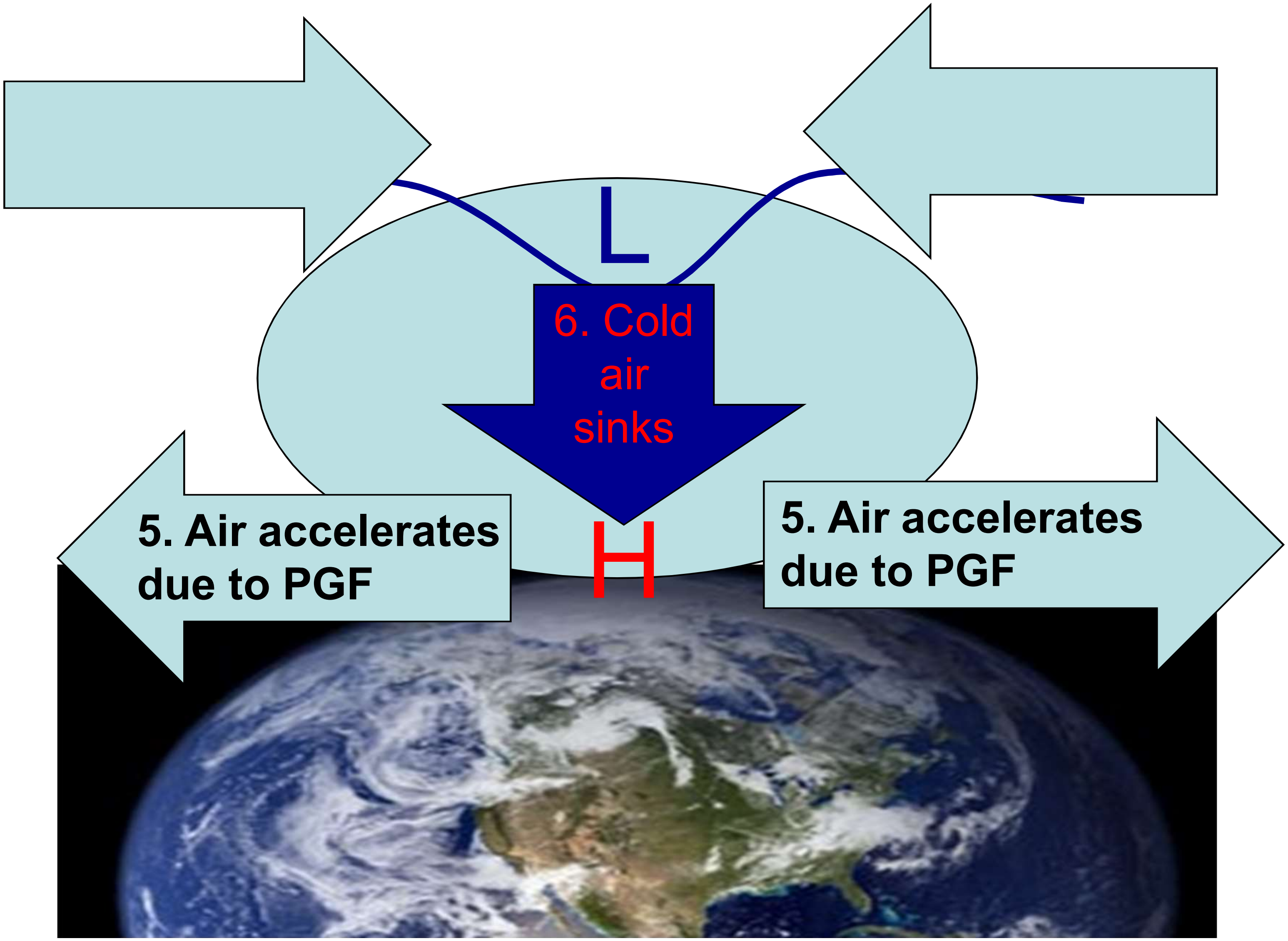
1. Cooled column of air gets **thinner**



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

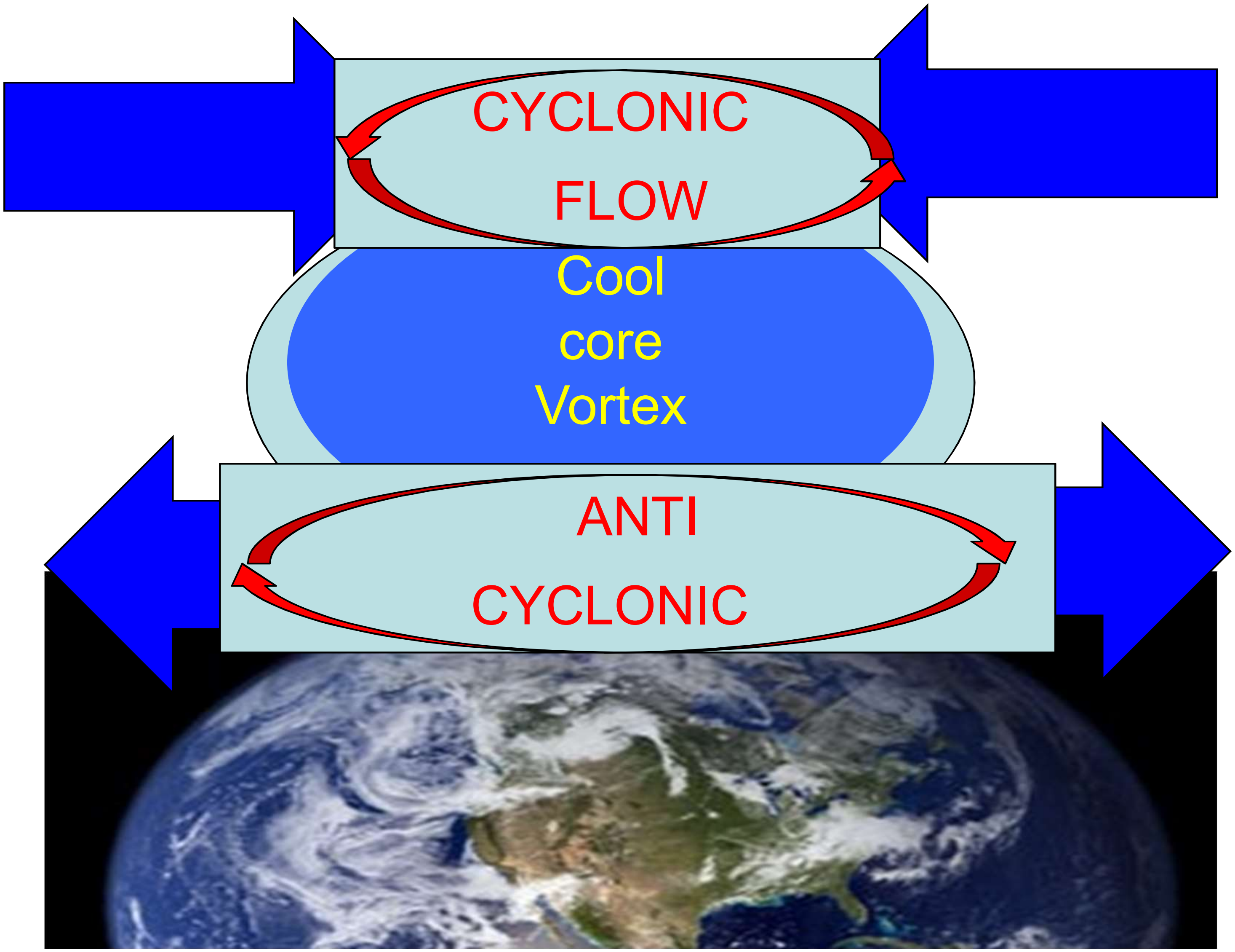


How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

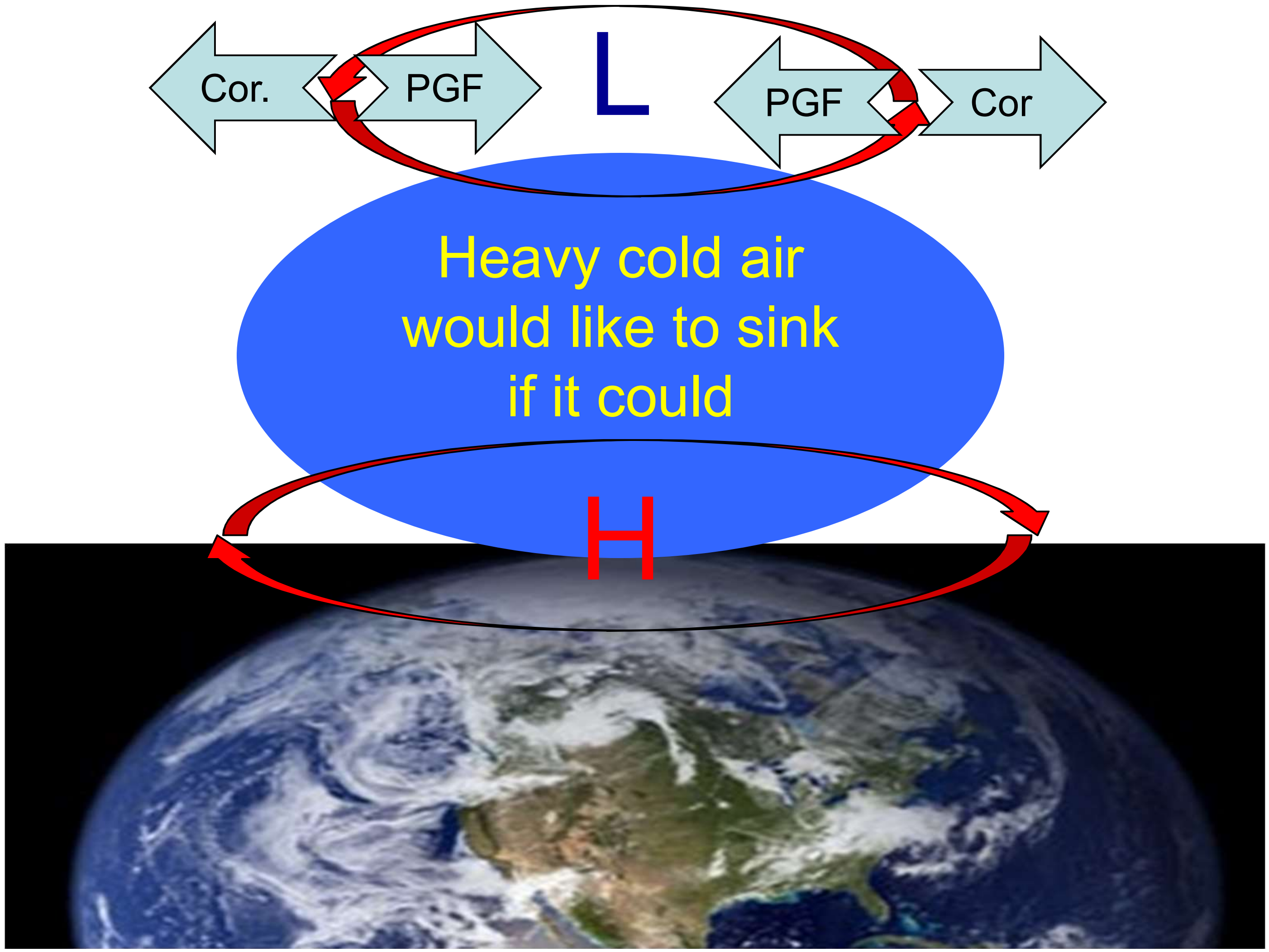


How cooled air sinks and a cool core vortex develops:

7. Coriolis force turns the winds



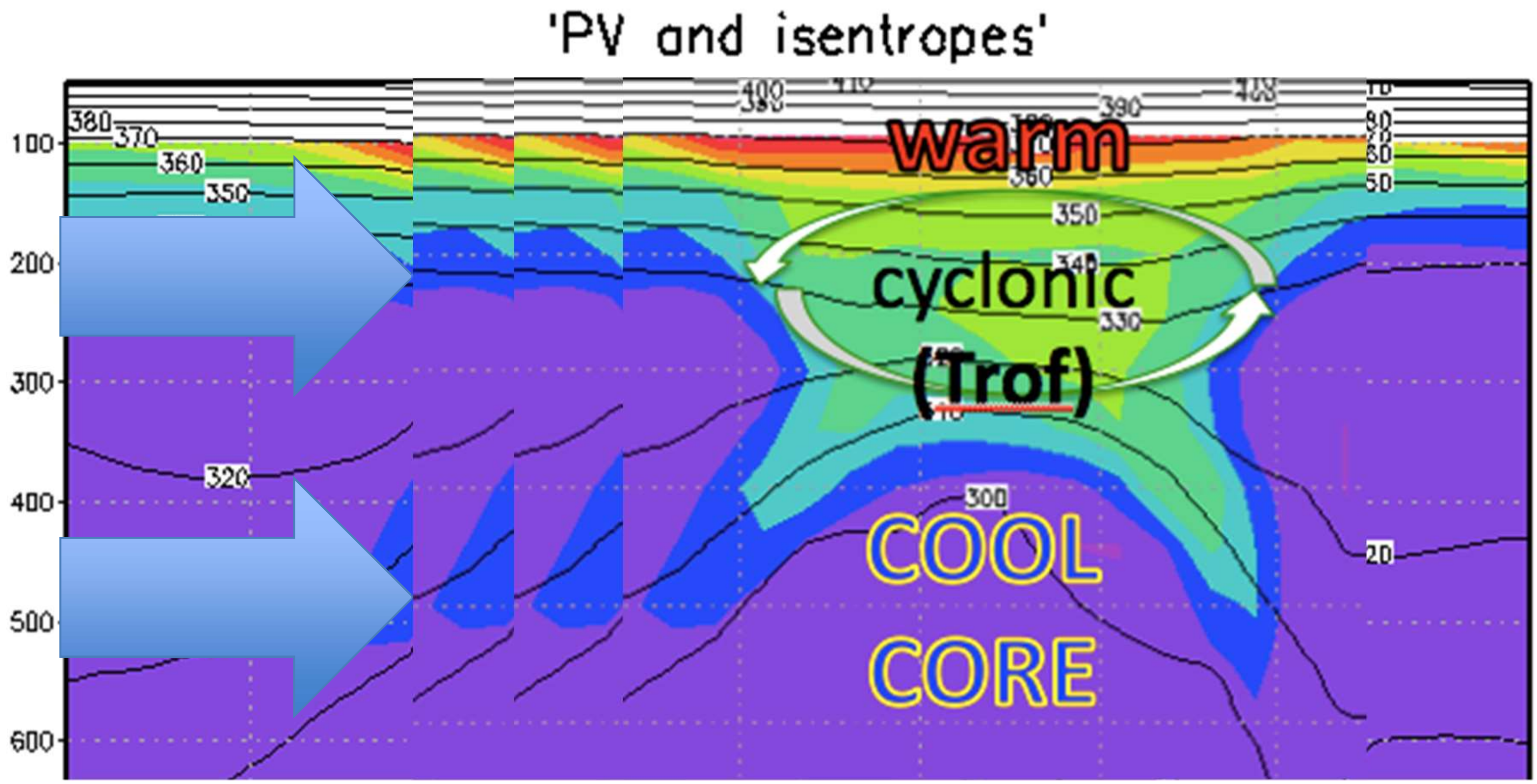
The geostrophically balanced polar vortex: The Coriolis force on the westerly jet stream prevents cold pool of Arctic air from sinking down and covering the whole Northern Hemisphere



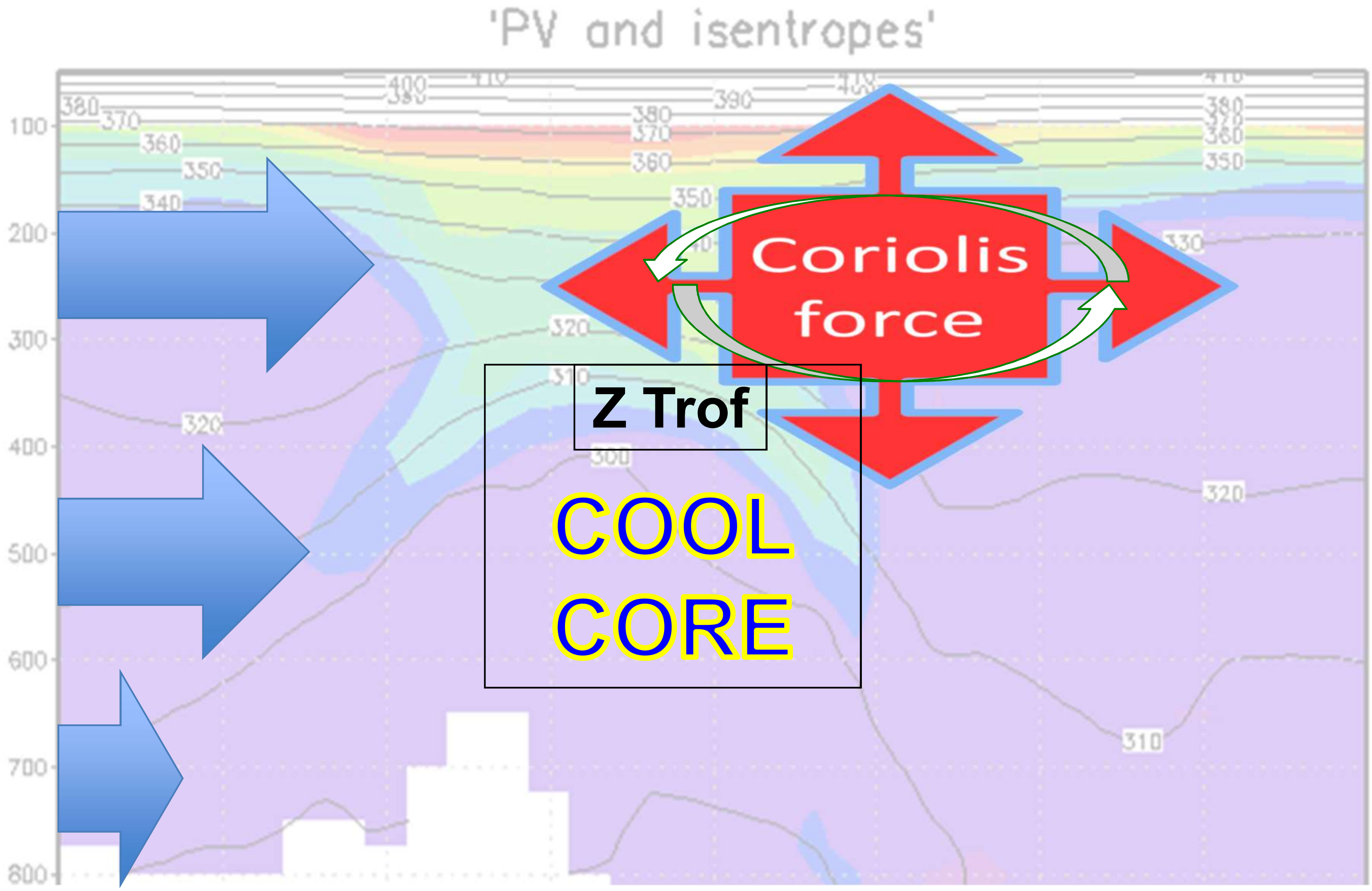
Polar and stratospheric "Reservoirs" of ζ_a or PV

- 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.

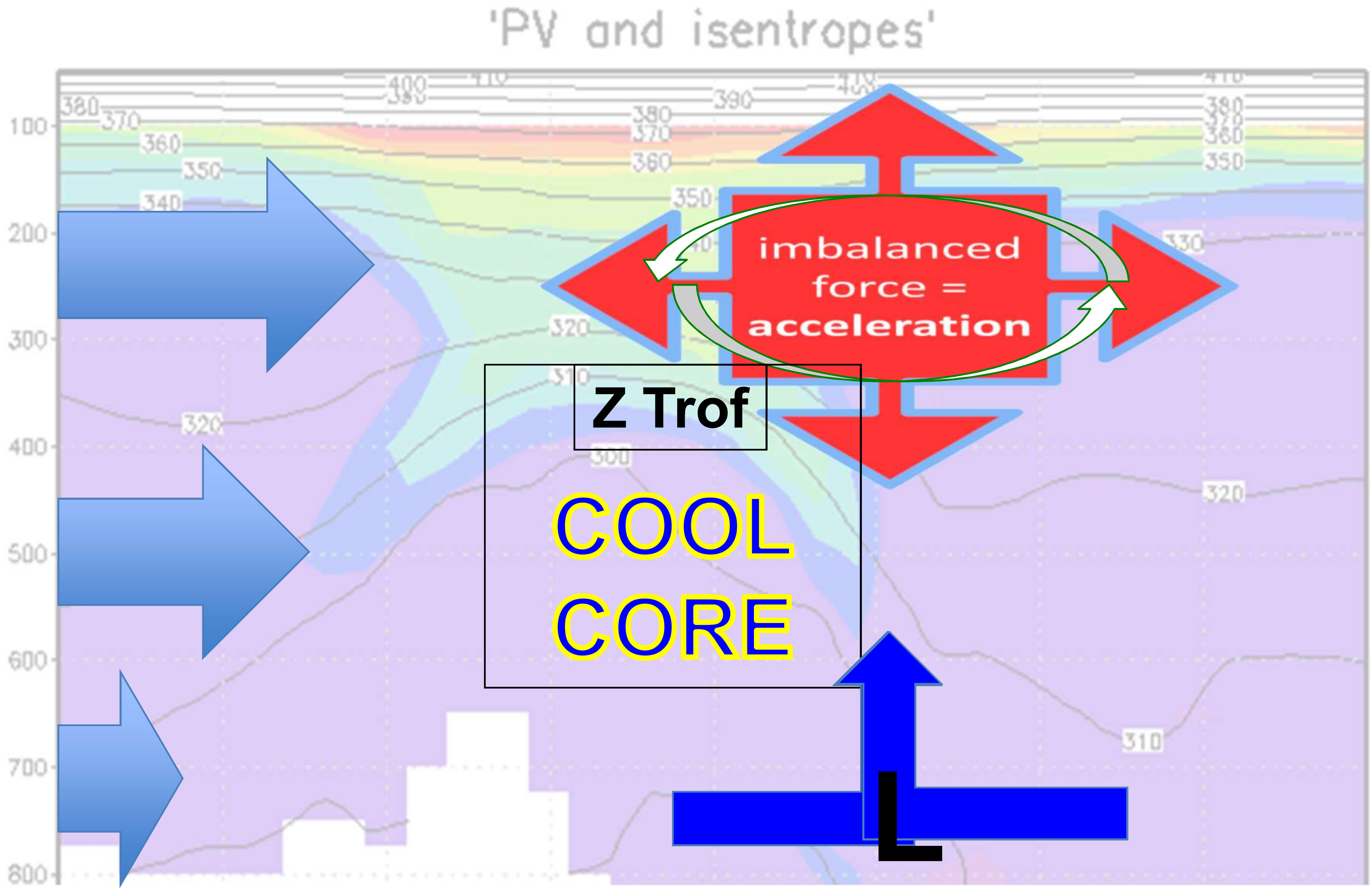
Unsheared advection of T, u, v, vort, PV: no breaking of balance



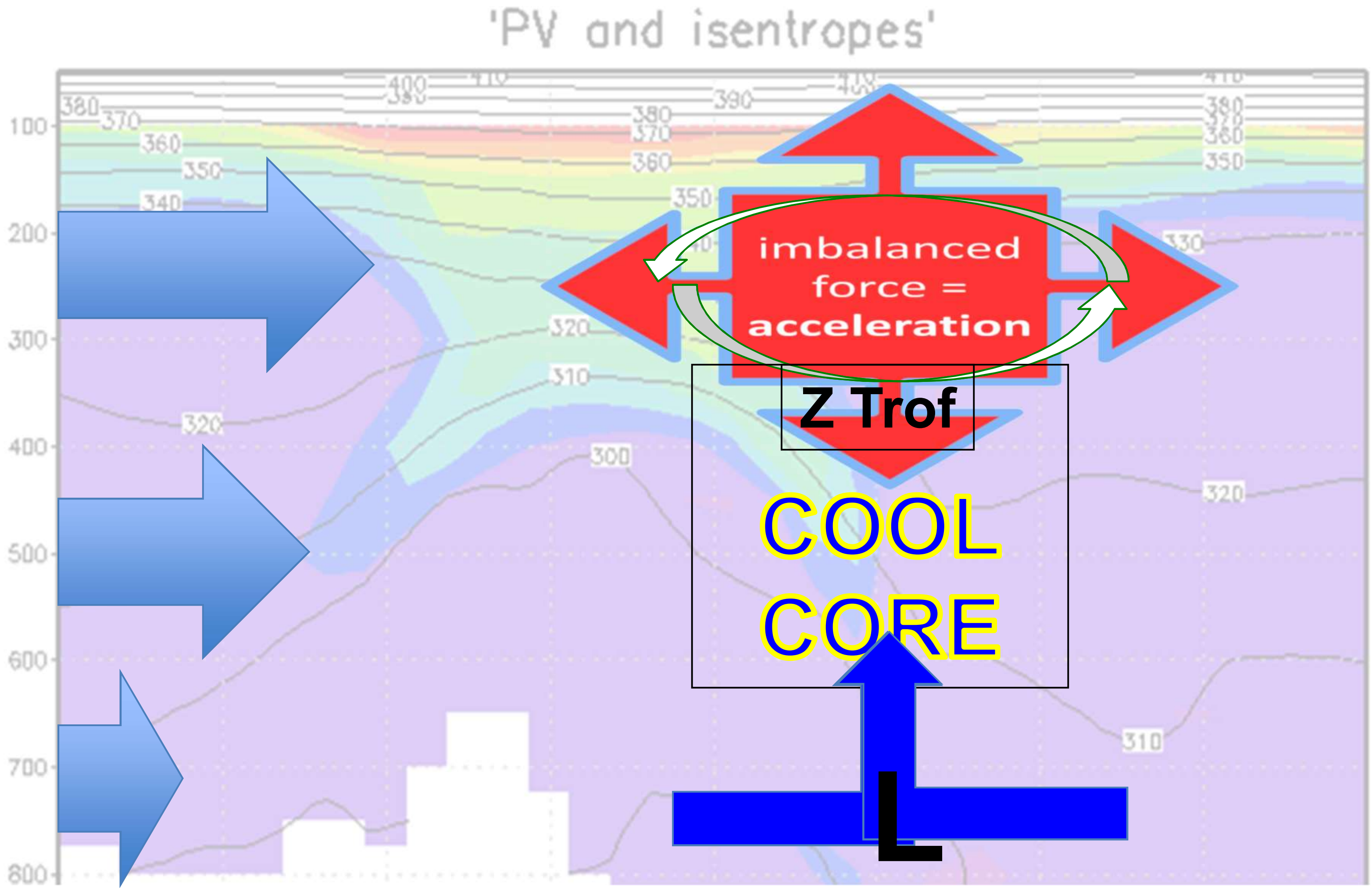
Sheared advection breaks thermal wind balance



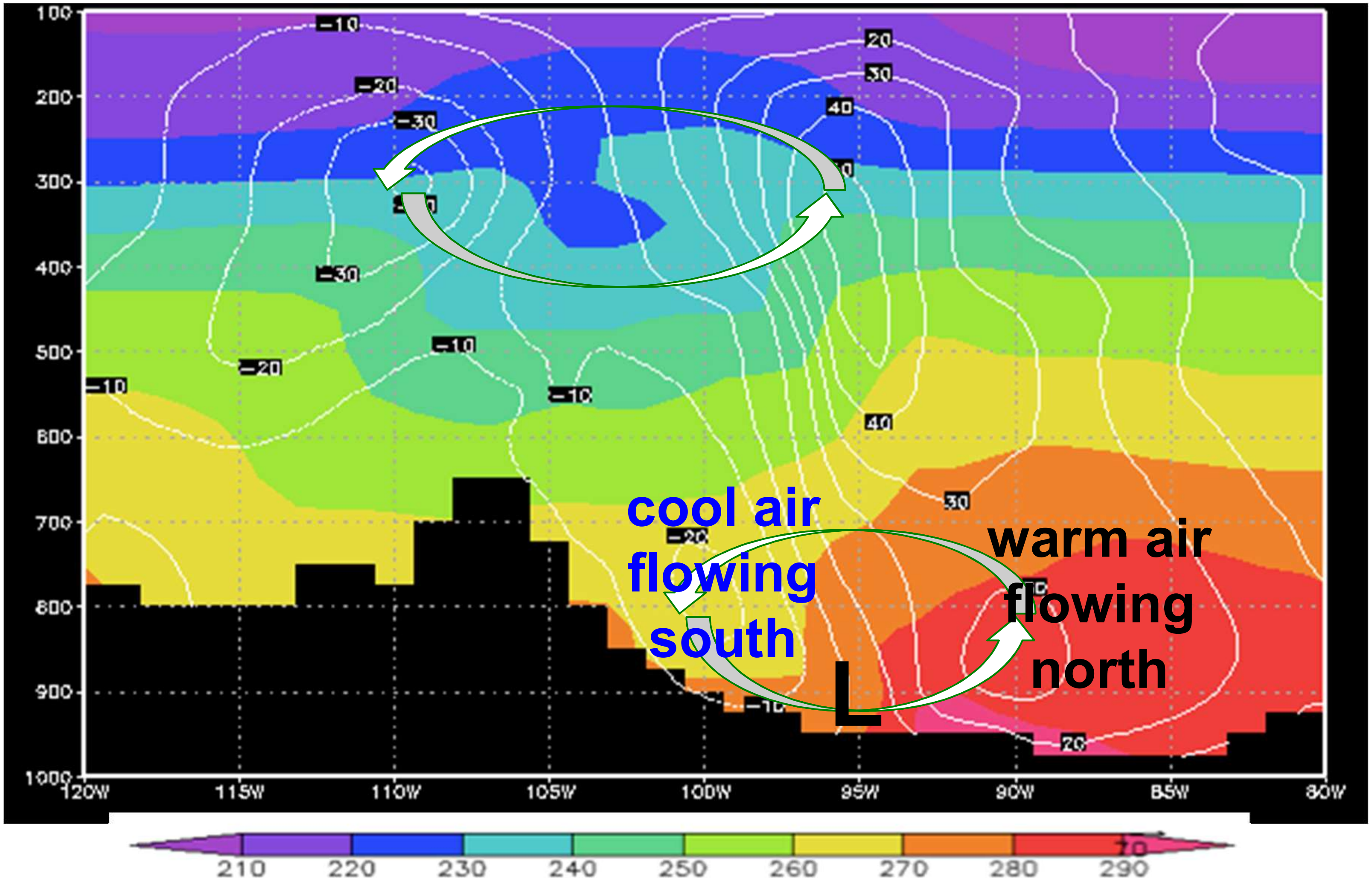
Sheared advection breaks thermal wind balance



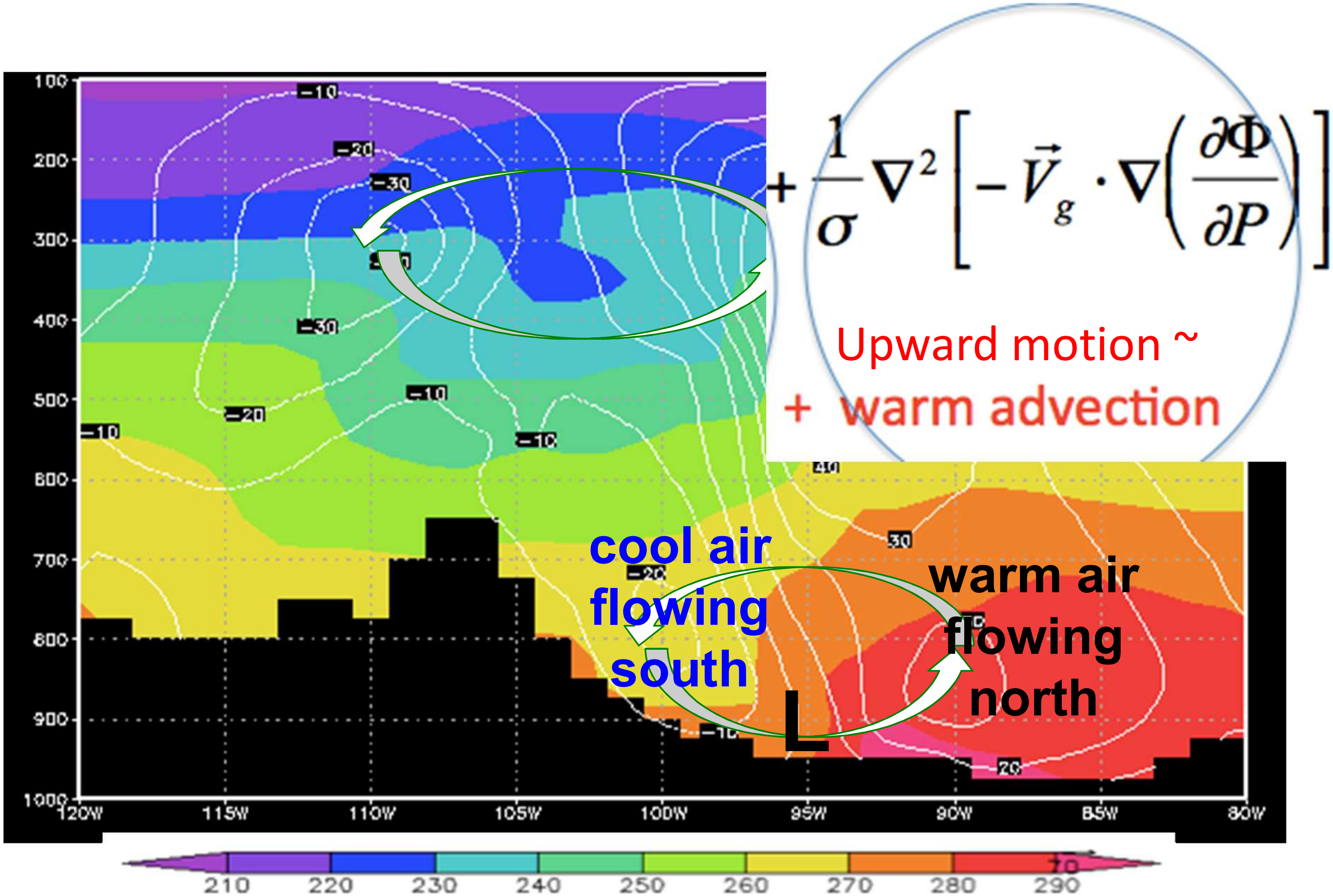
Sheared advection
breaks thermal wind balance



But there is some T advection too



But there is some T advection too



East-west section: omega