

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?

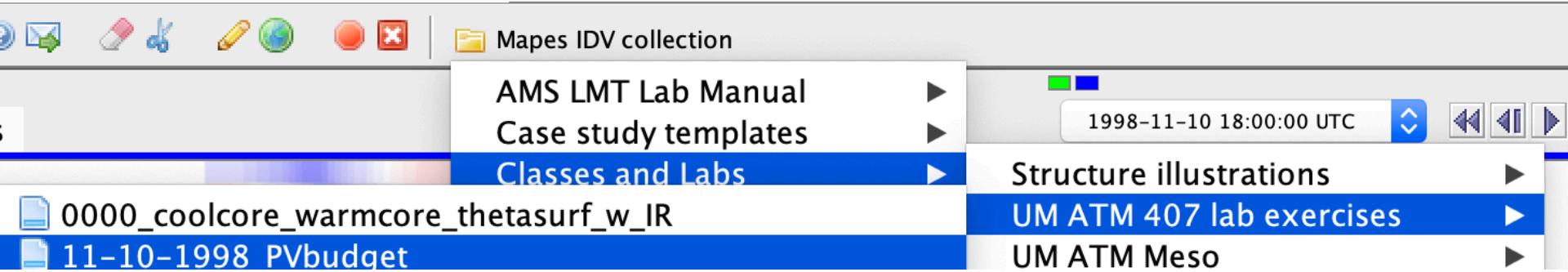
PV is conserved -- almost  
APPROXIMATE term that generates PV on the Earth

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

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

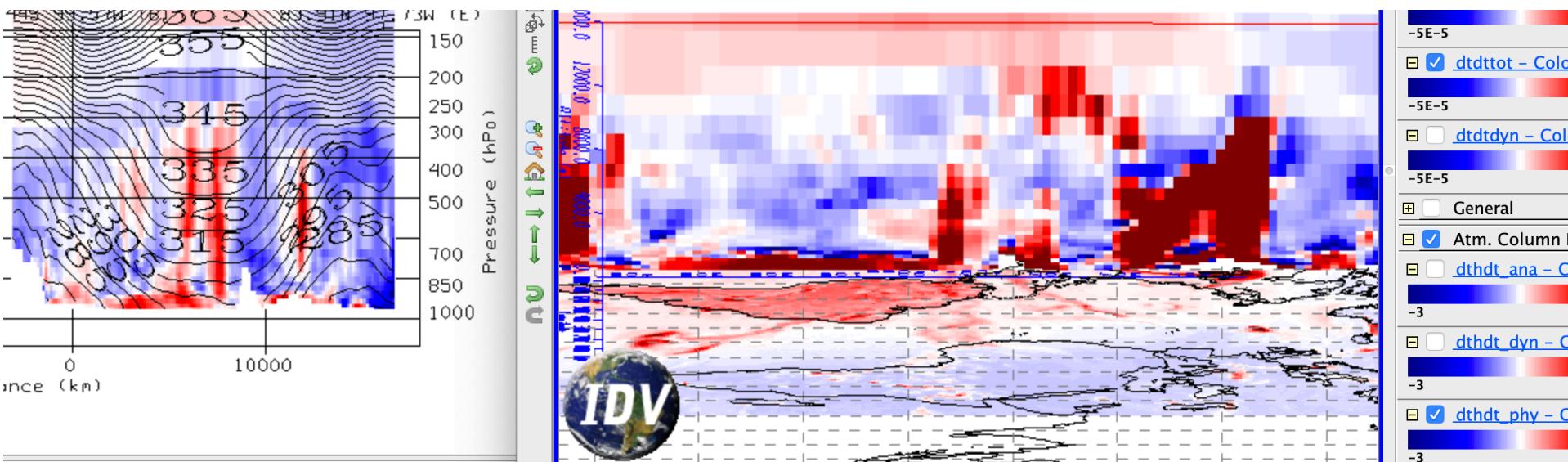
# Assignment part 1: global view

- Open the bundle **11-10-98 PV budget**



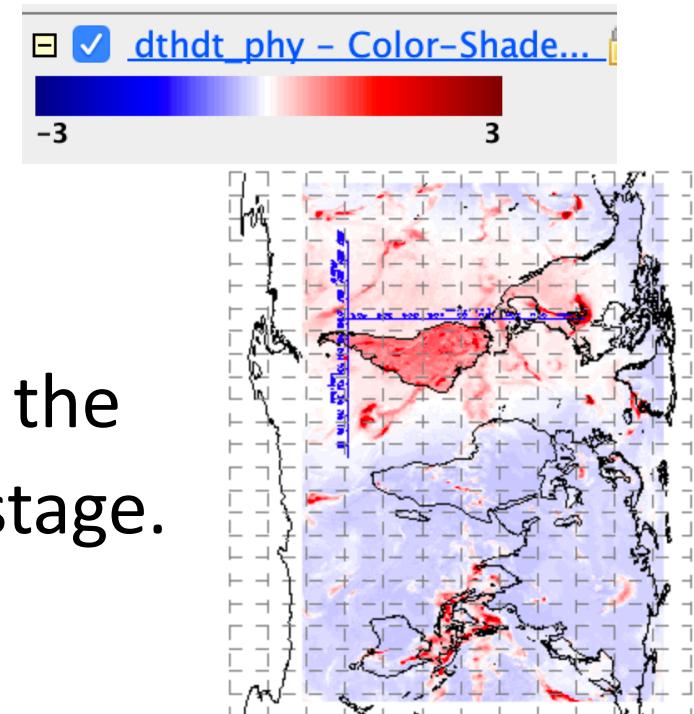
- Orient yourself to its displays, in **both windows**
  - a **pole-to-pole transect** of the **zonal mean** heating rates (averaged around the whole Earth)
  - A map view with many displays (including **movable cross sections**).

**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?



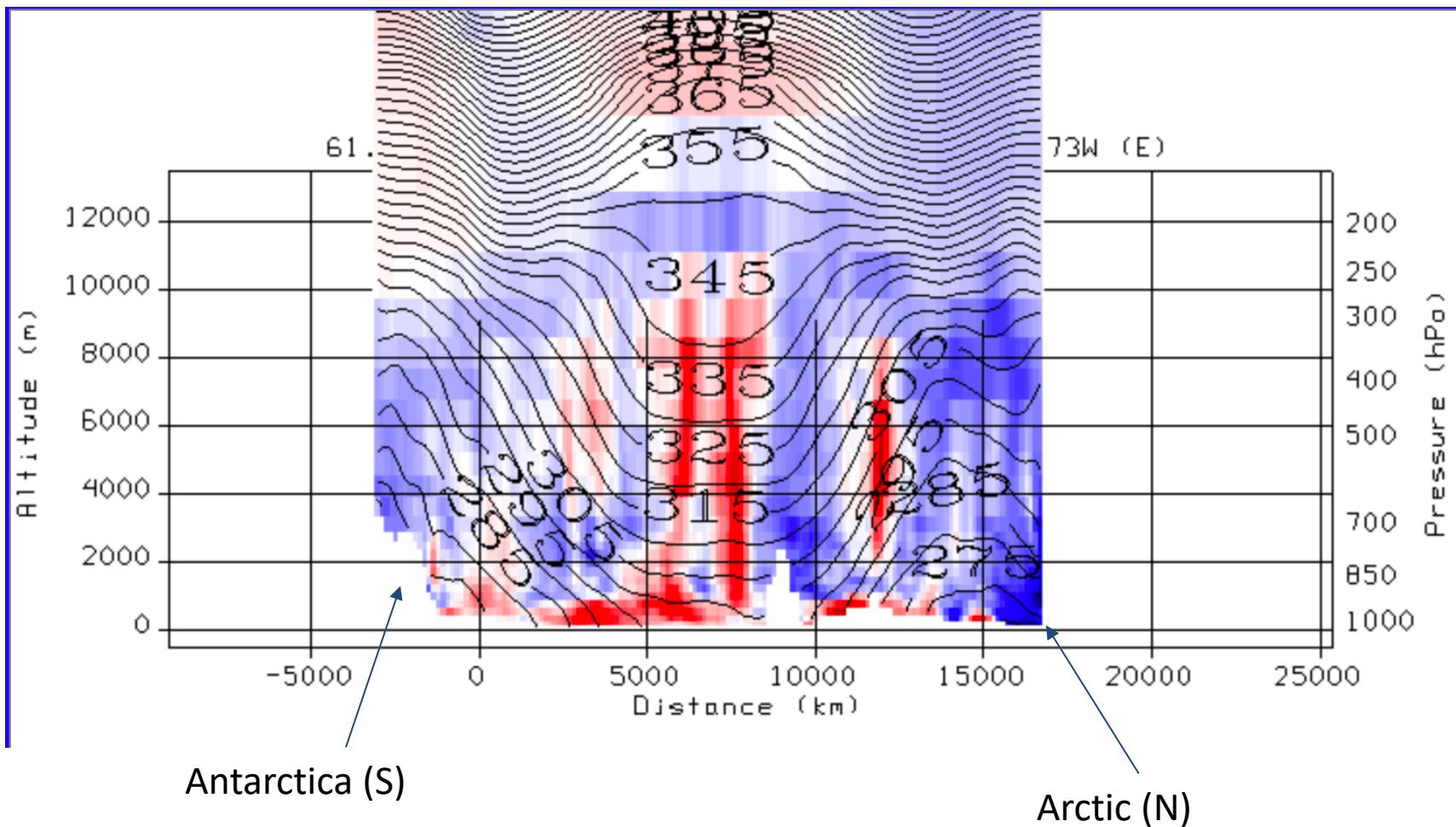
It is autumn- November 1998

This is seen in heating focused  
slightly below the equator with the  
Northern pole in a net cooling stage.

# 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 K/s. What is the color range in K/day?

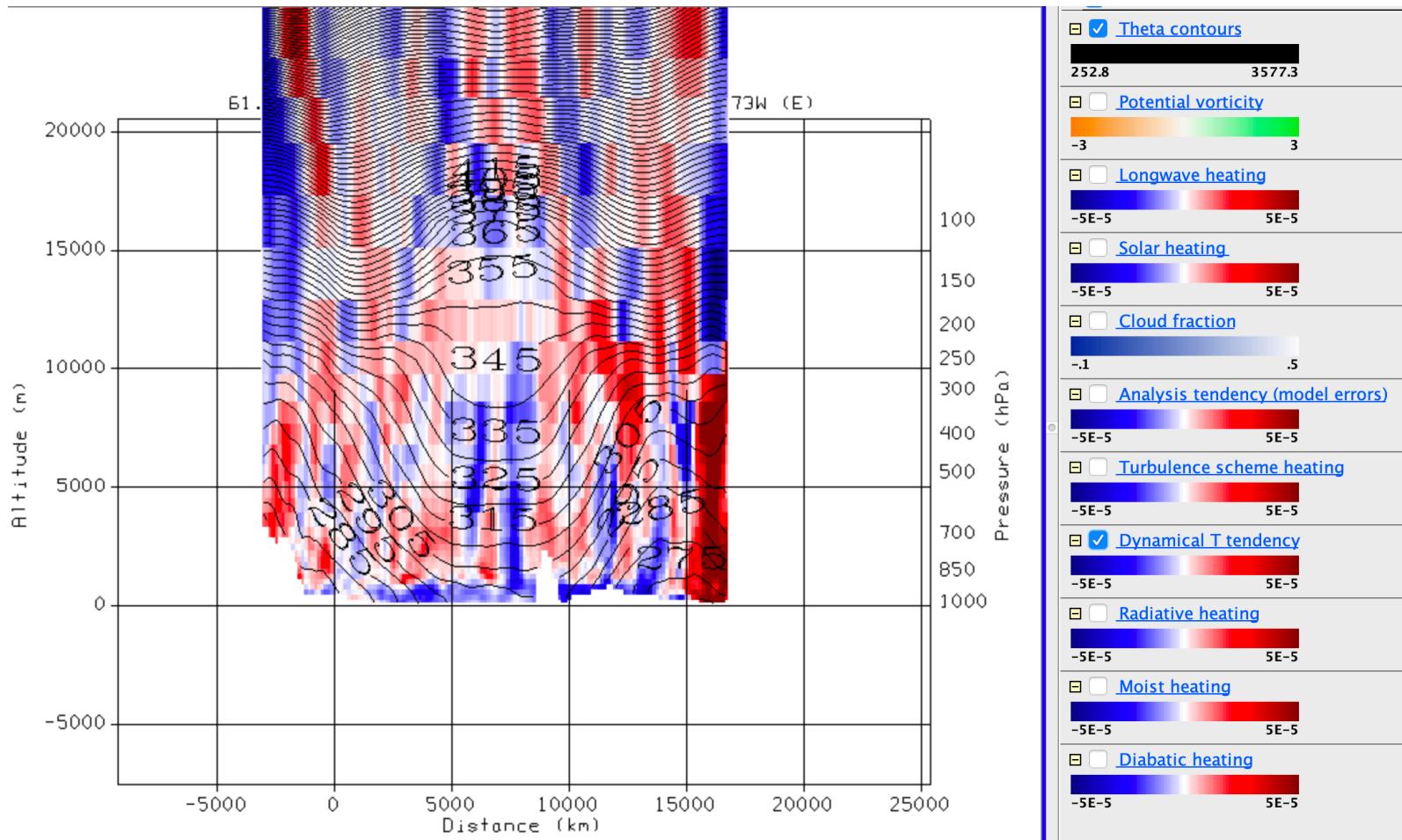
$$5e-5 \text{K/s} * (3600 \text{s/hr}) * (24 \text{hr/day}) = \\ +/- 4.32 \text{K/day}$$



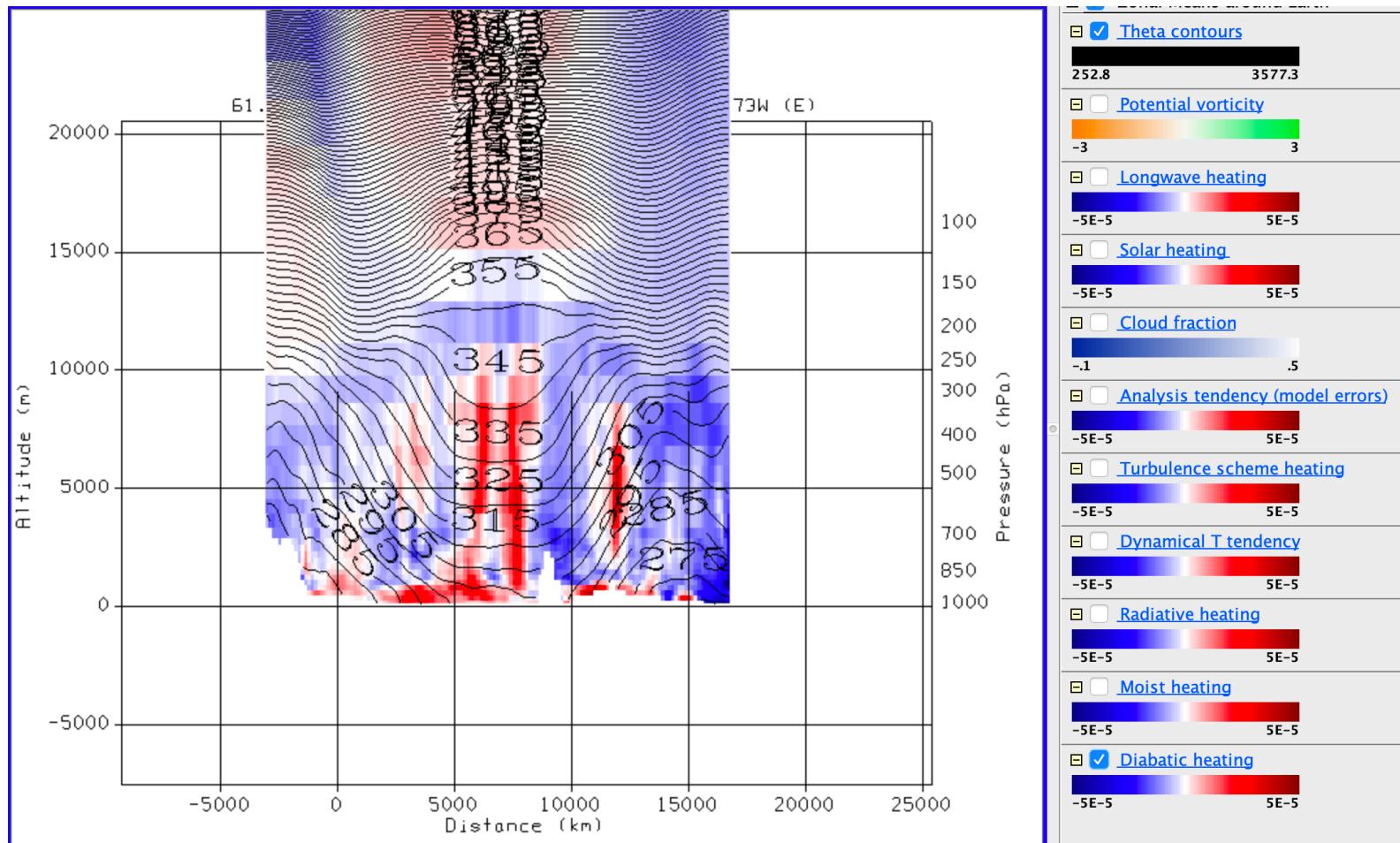
# Assignment part 1: global view

- 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:  
 $\partial T / \partial t = \text{dynamical} + \text{diabatic} + \text{analysis}$   
 $\text{diabatic} = \text{moist} + \text{radiative} + \text{turbulence}$   
 $\text{radiative} = \text{longwave} + \text{solar}$

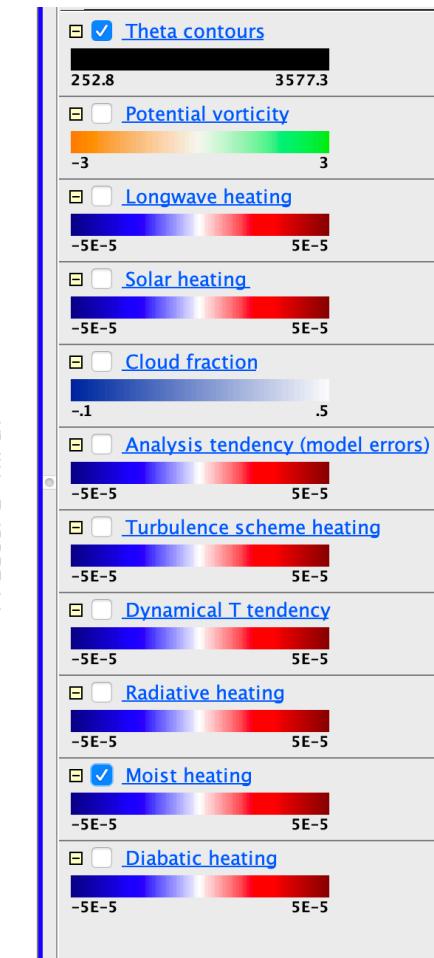
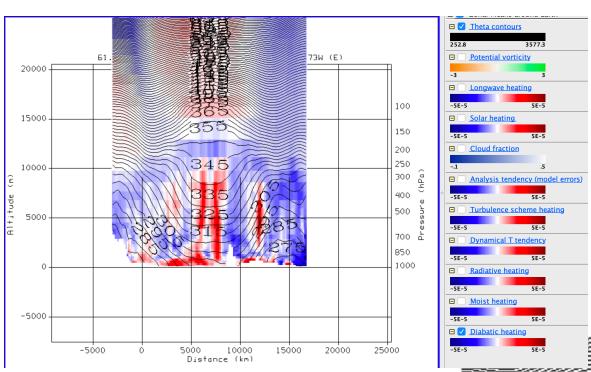
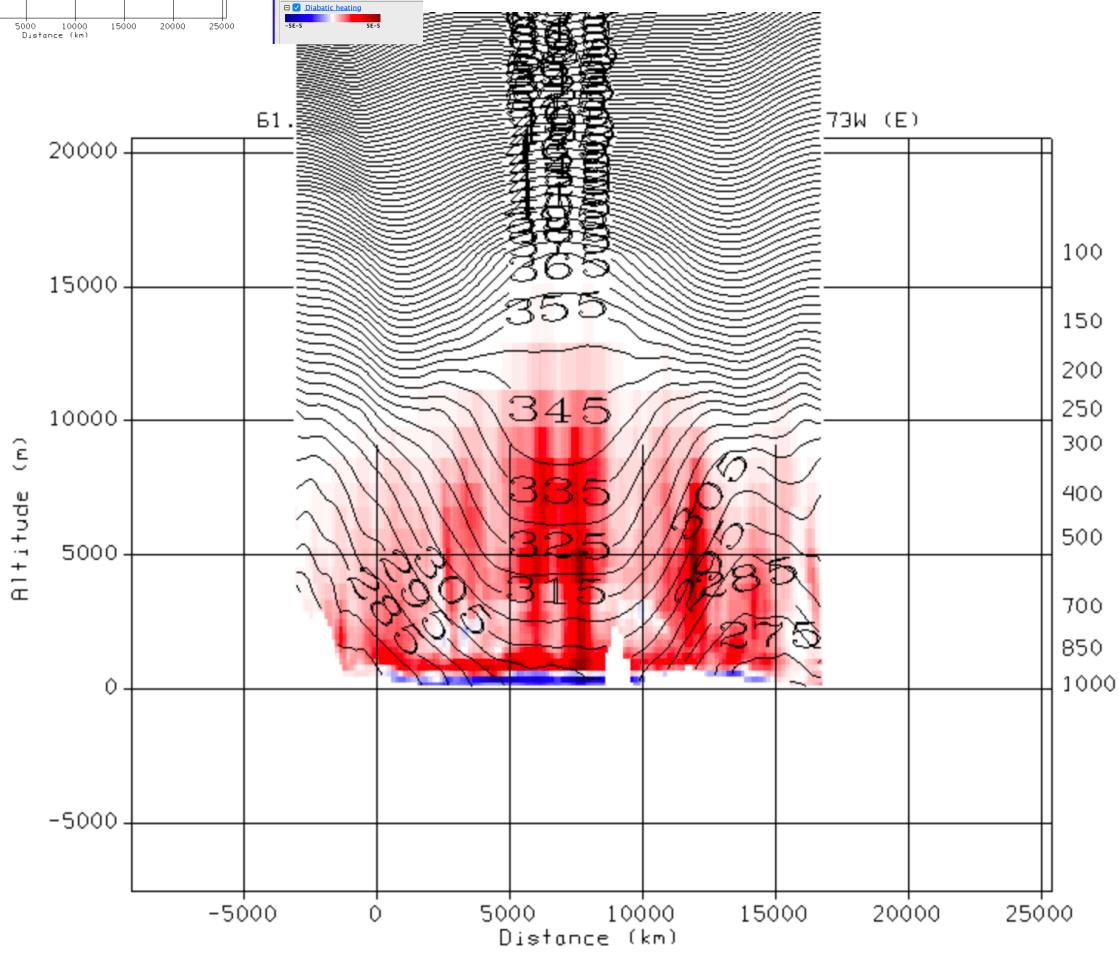
# Dynamical Heating



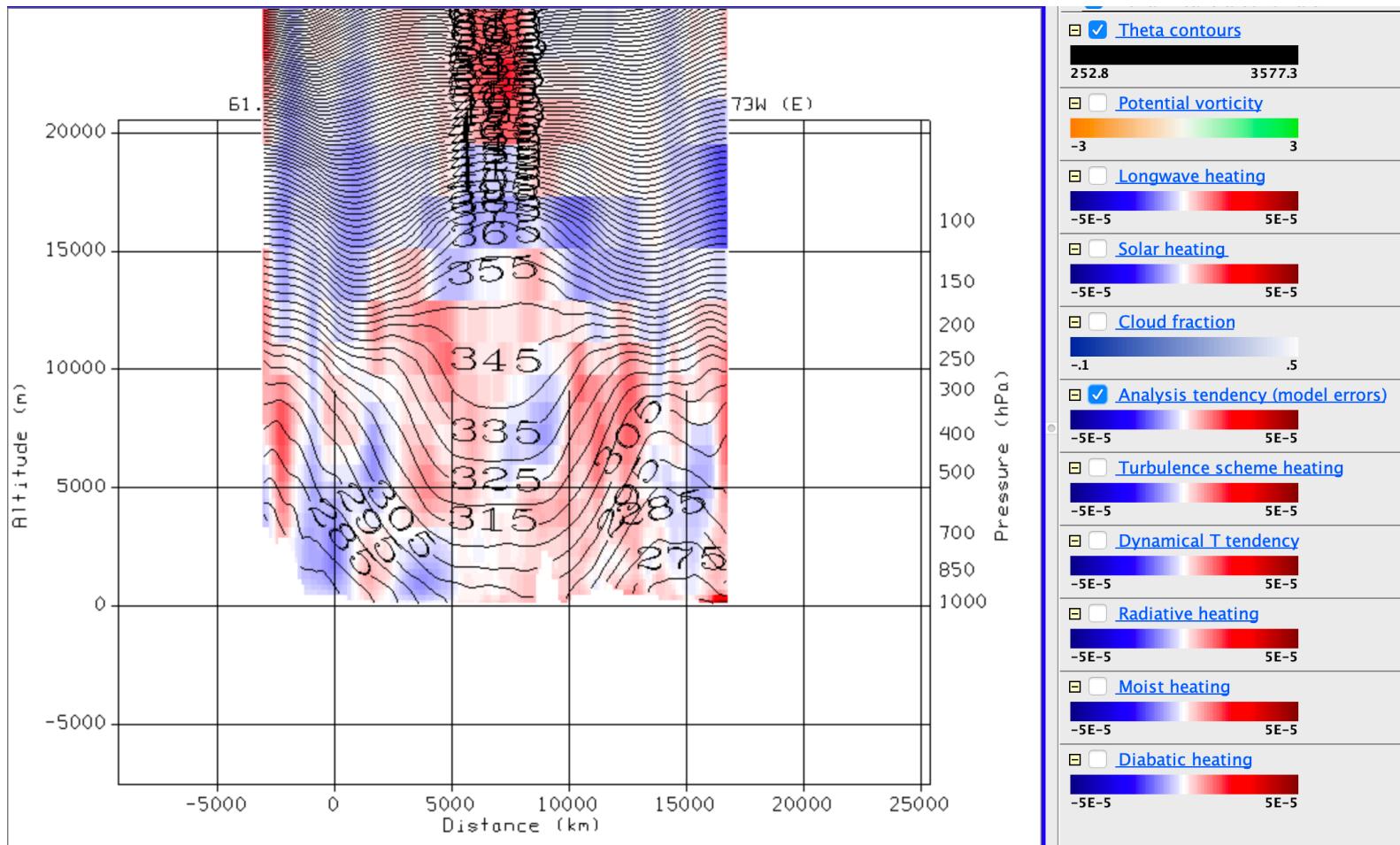
# Diabatic Heating



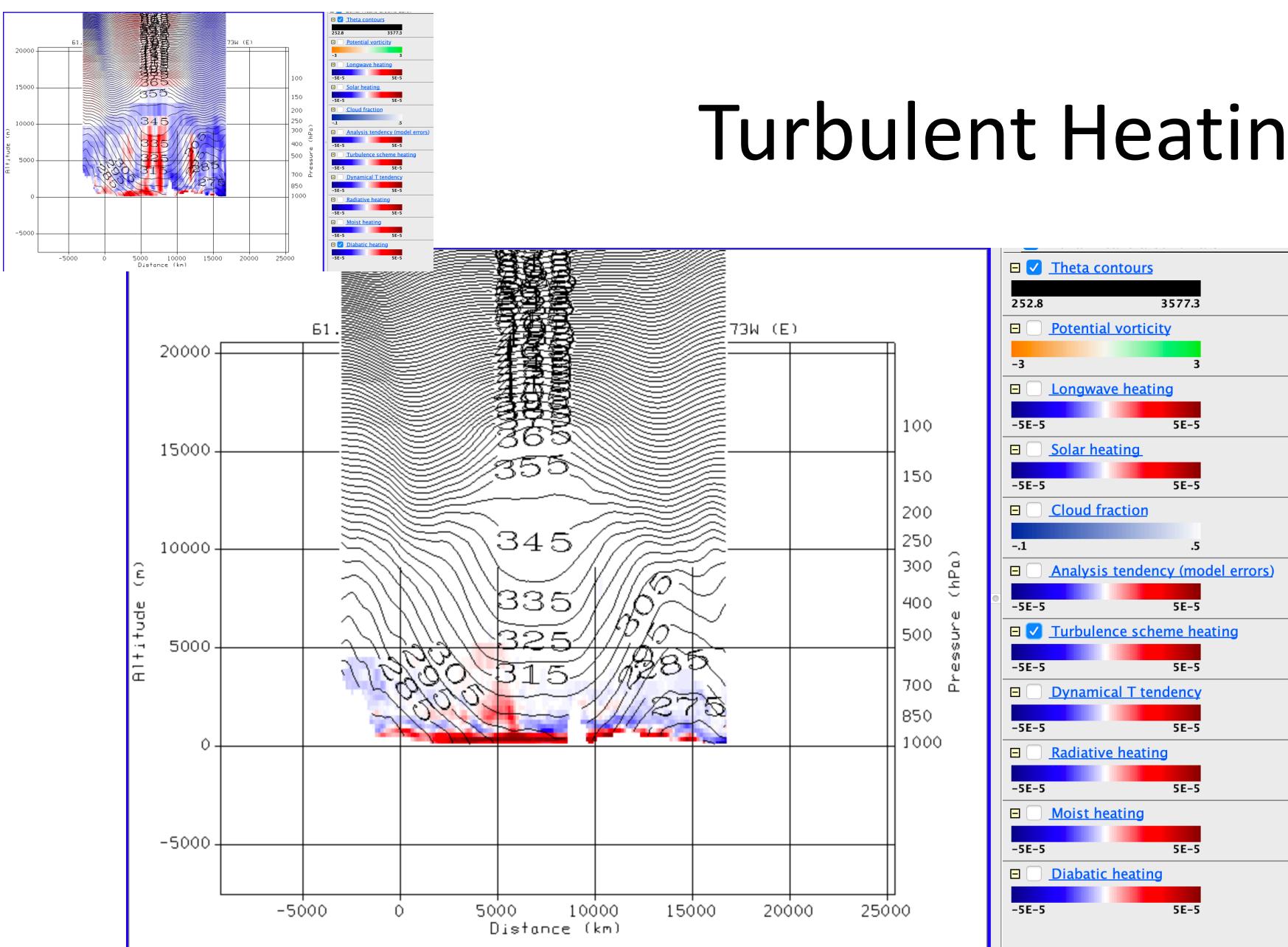
# Moist Heating



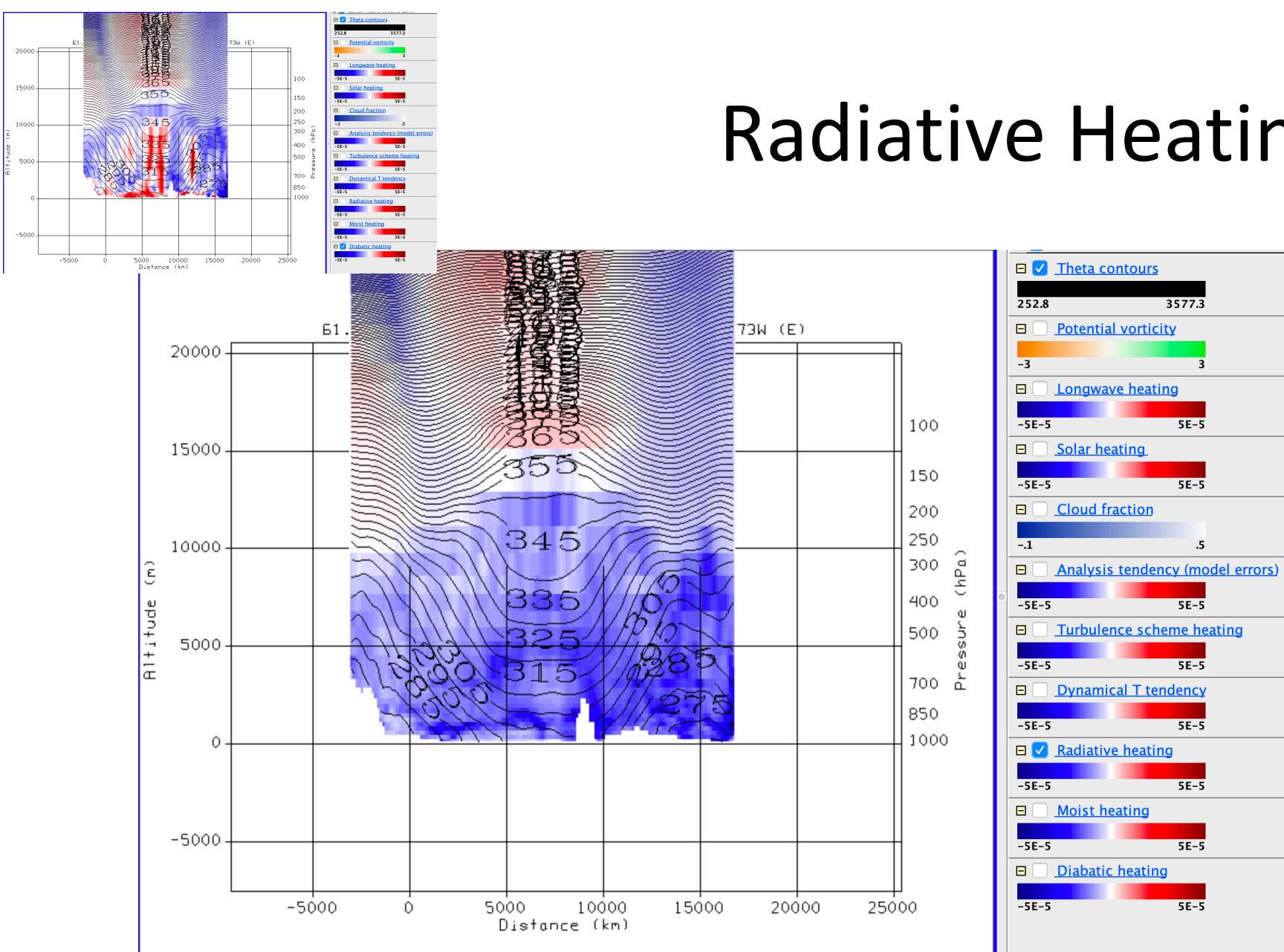
# Analysis Heating



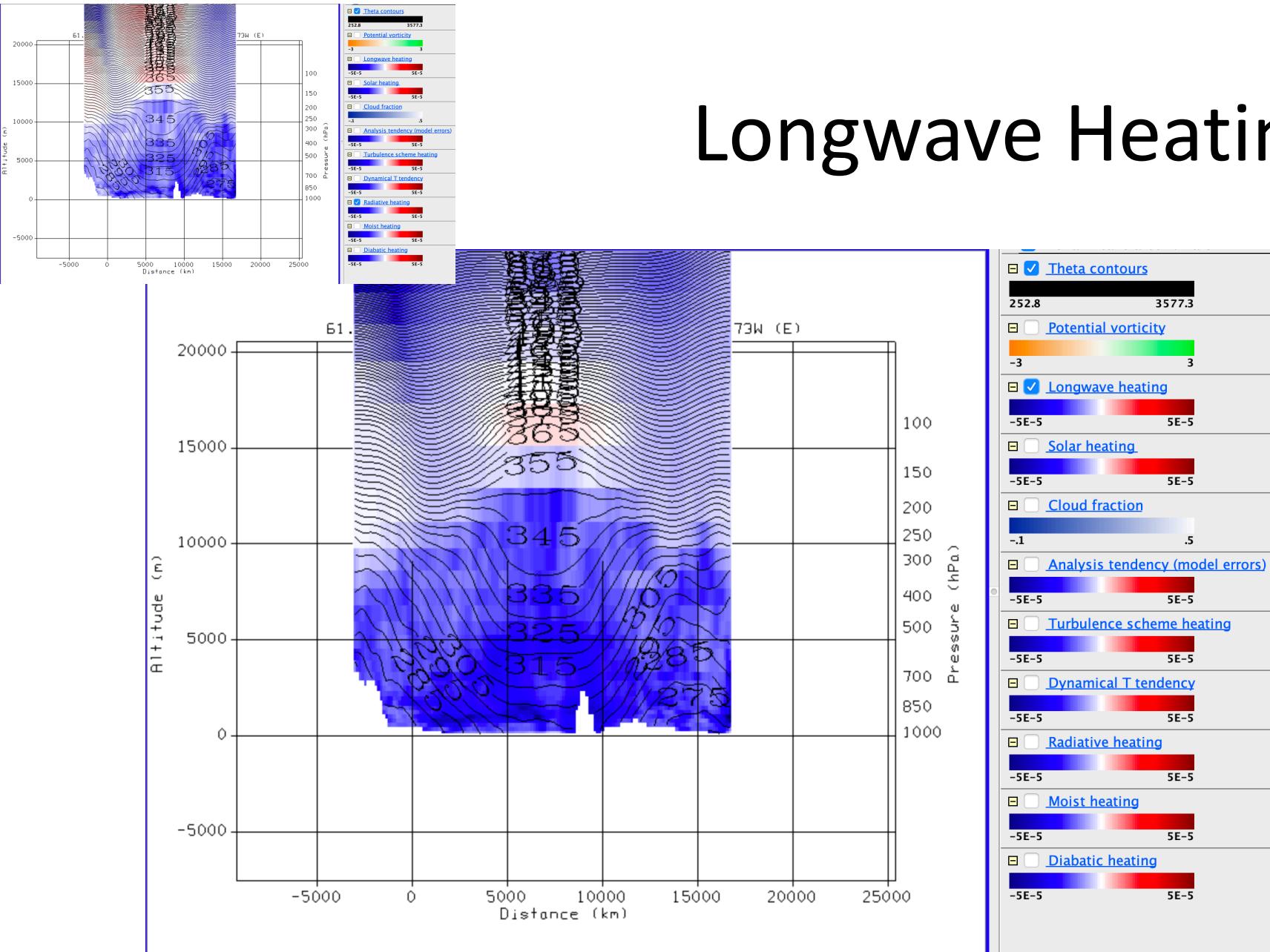
# Turbulent Heating



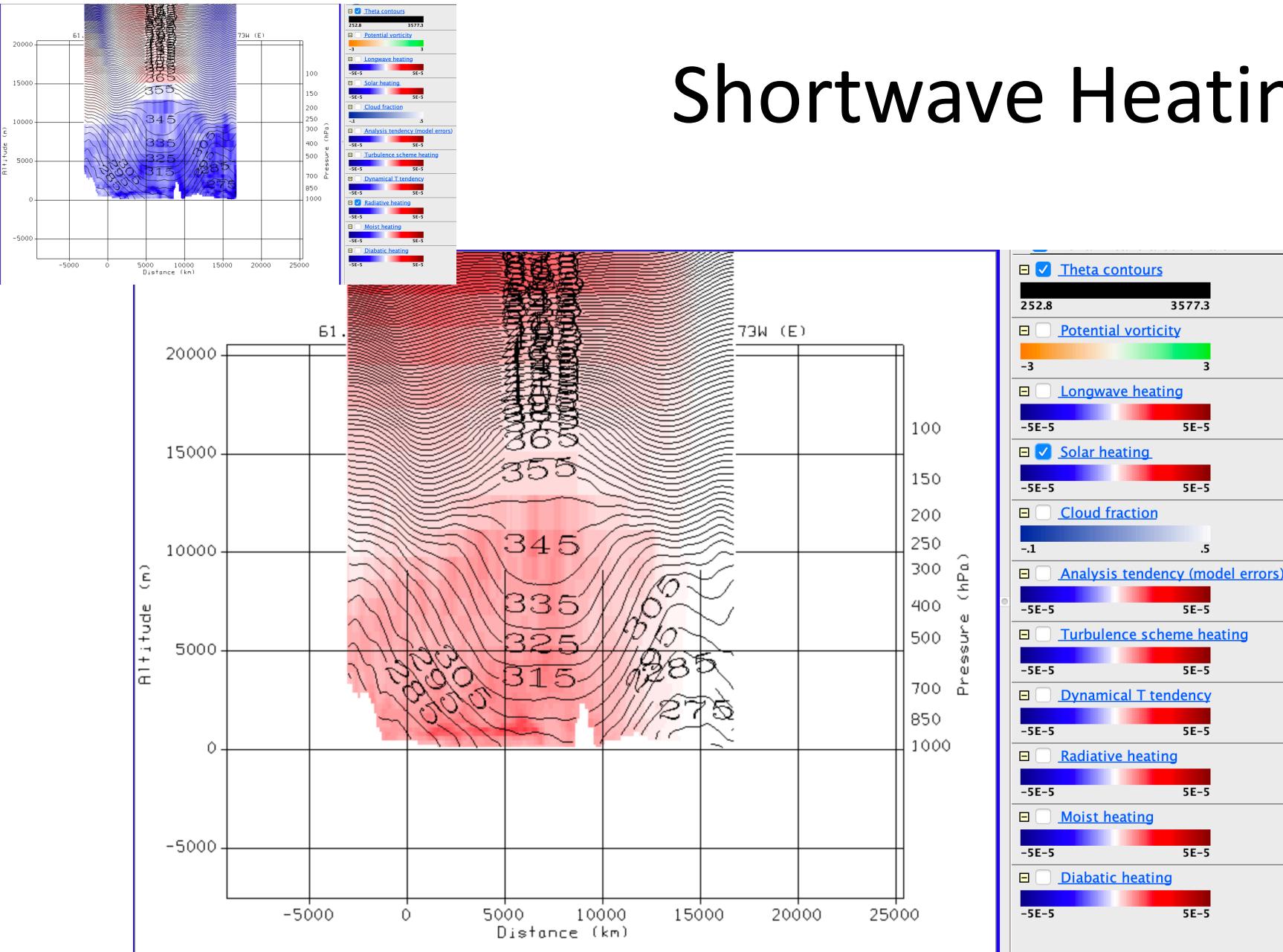
# Radiative Heating



# Longwave Heating



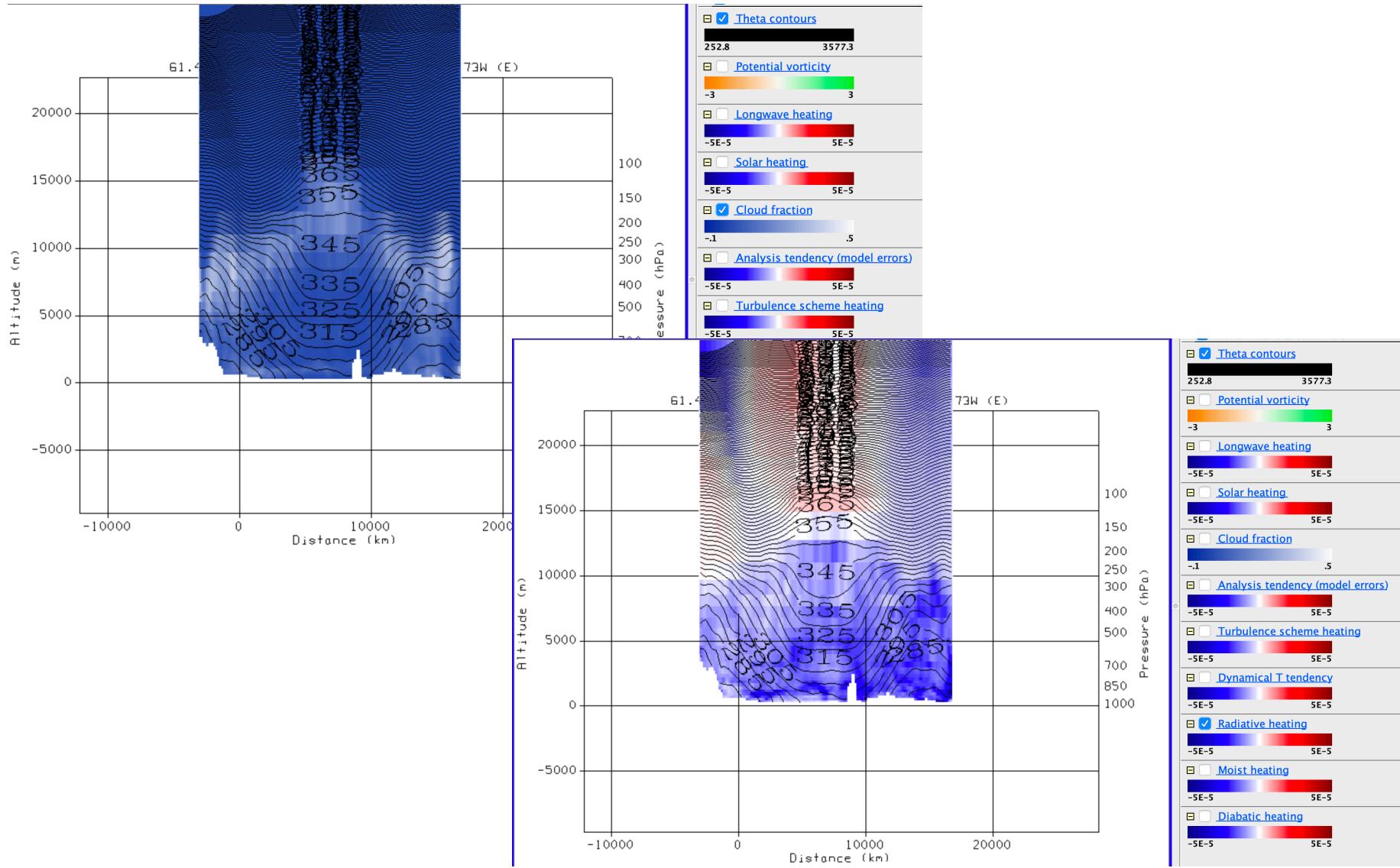
# Shortwave Heating



# 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)

# Clouds and Radiative Forcing



# 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 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).

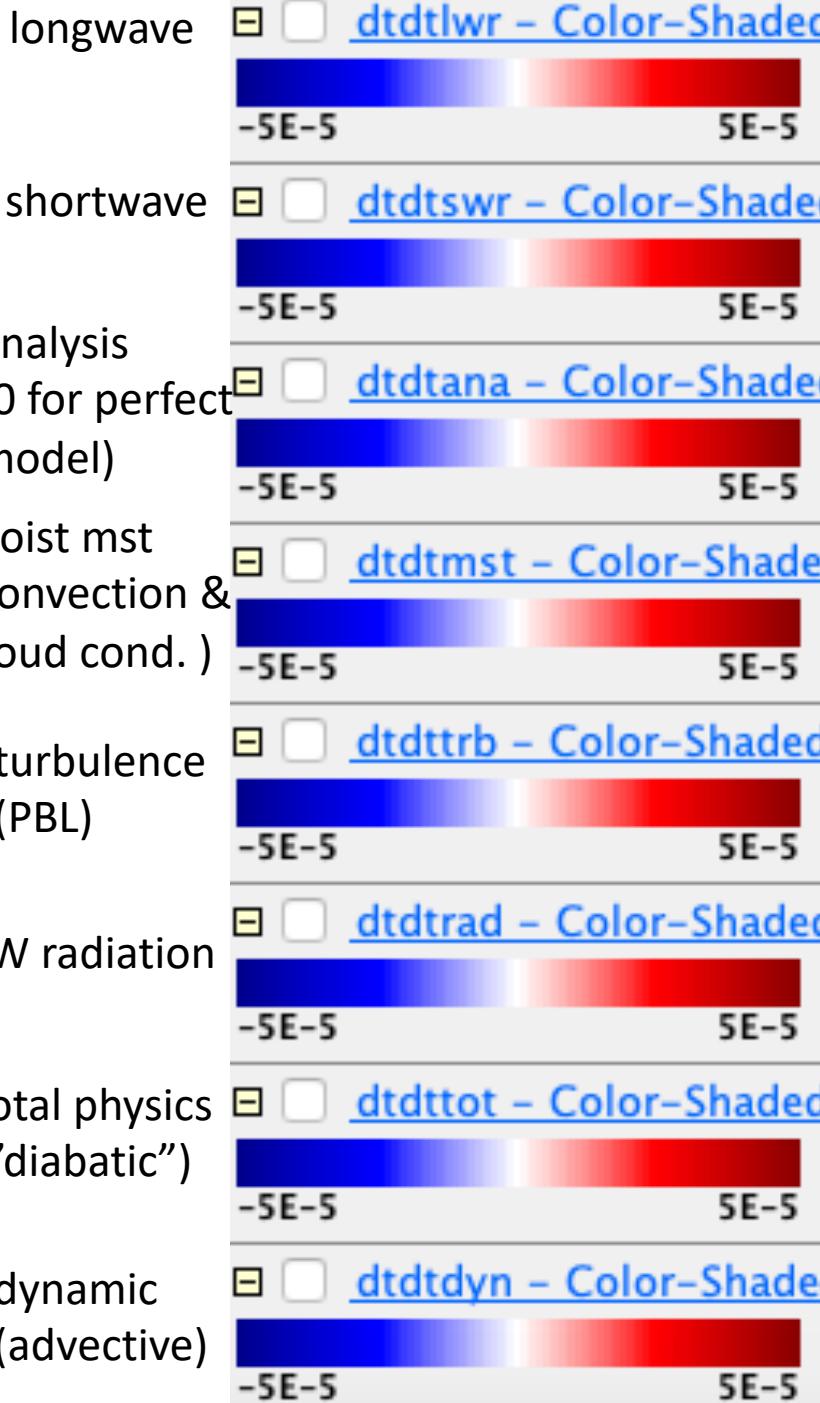
# Legend explanation for cross sections

$$\partial T / \partial t = \text{dtdt\_tot} \text{ (physics)} + \text{dtdt\_dyn} \text{ (advection)} + \text{dtdy\_ana}$$

(**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)

$$\text{diabatic tot} = \text{moist (mst)} + \text{radiative (rad)} + \text{turbulence (trb)}$$

$$\text{rad} = \text{lwr} + \text{swr}$$

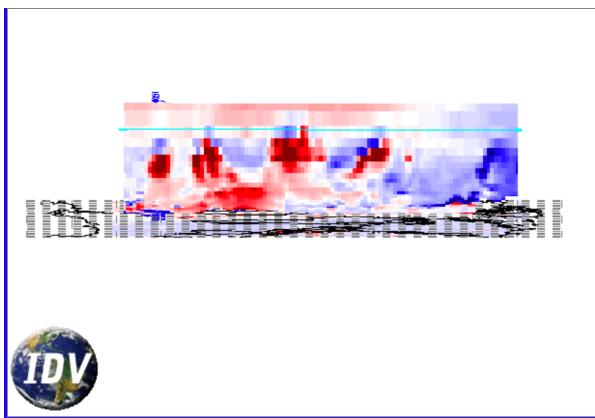


# Assignment part 2: Local view

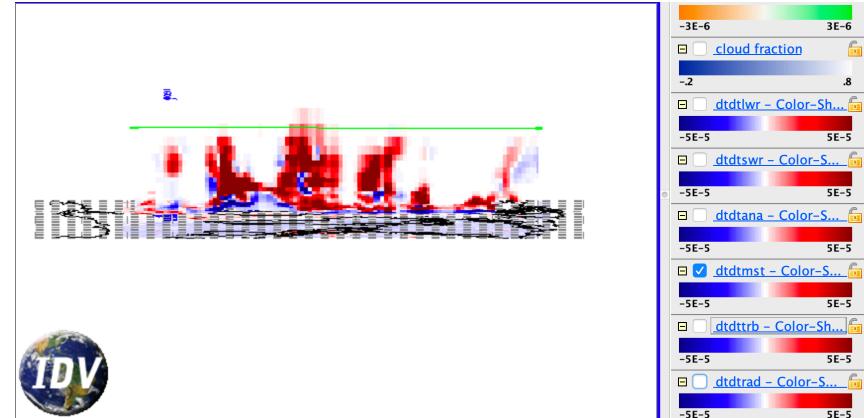
- Make comparison slides juxtaposing the zonal-mean transects and your local cross-sections, like in slide 6 above.
- Toggle the various terms making up the total diabatic heating, in order to explain
  - Which is more variable (more spatially concentrated): radiative or moist heating? Illustrate your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

# Radiative heating has more variability and spatial concentration

**Radiative**



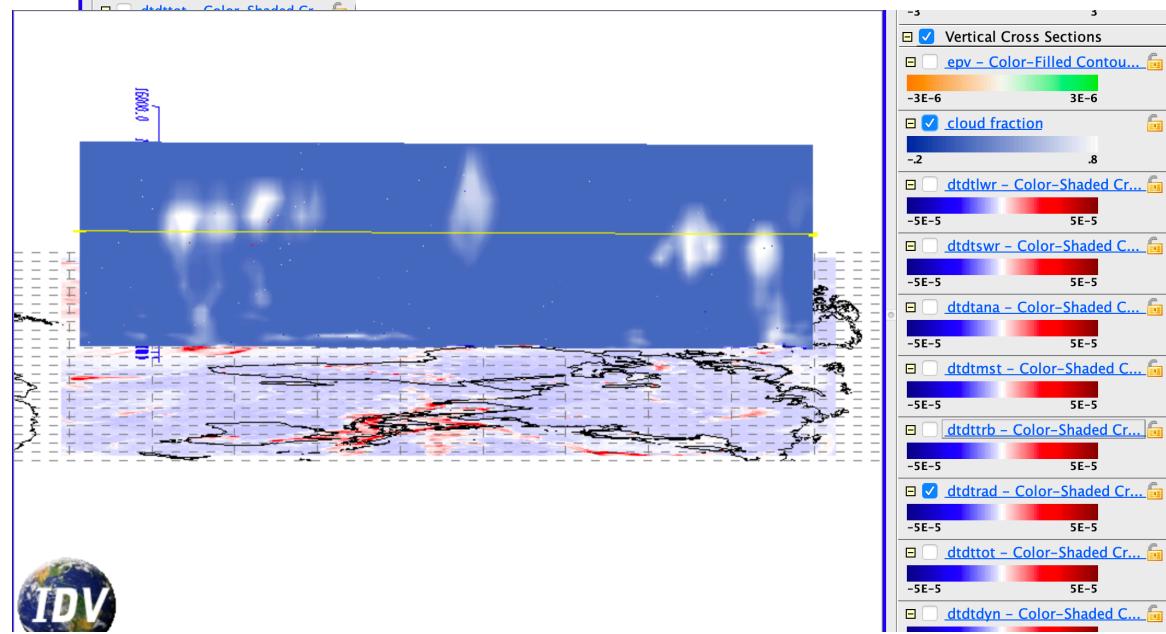
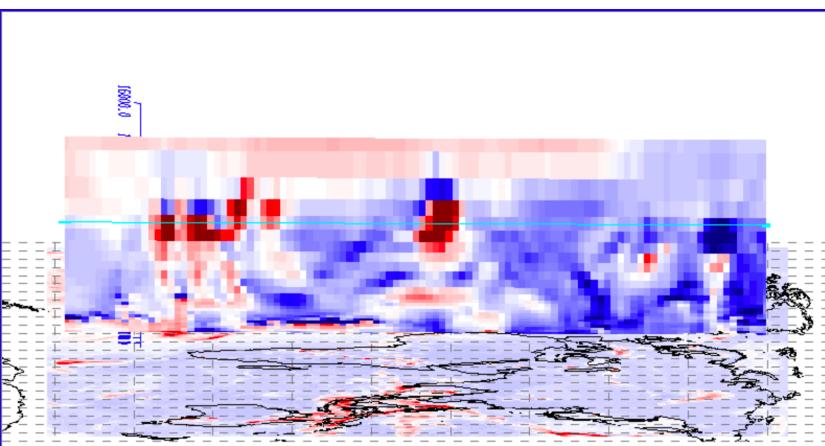
**Moist**



# 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

# Clouds are shown in radiation 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?

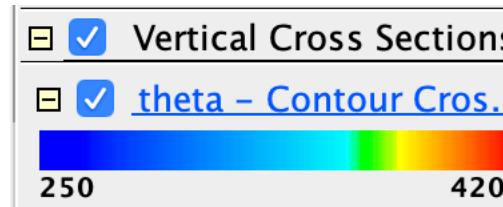
# Create a new cross section of potential temperature contours

The screenshot shows the IDV software interface with the following details:

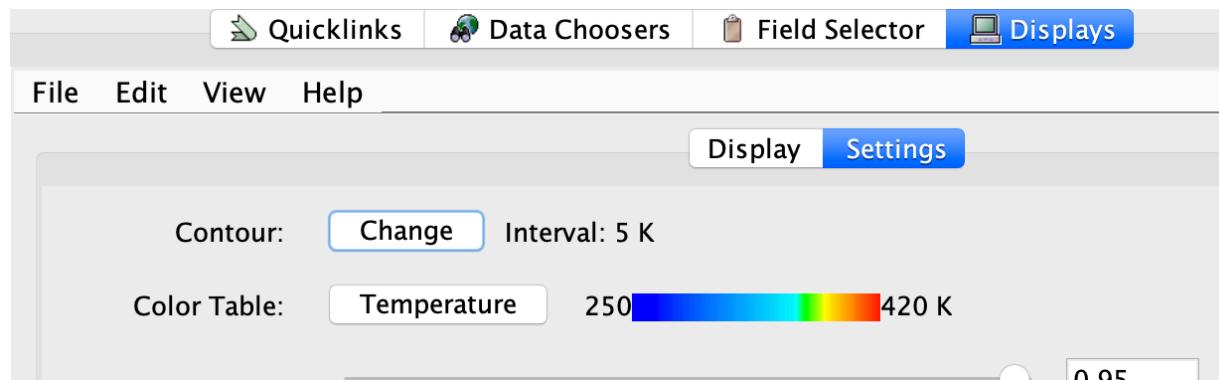
- Top Bar:** Dashboard, File, Edit, Displays, Data, Bundles, Tools, Help.
- Toolbar:** Includes icons for Save, Open, Print, Copy, Paste, Undo, Redo, and various display options.
- Mapes IDV collection:** A folder icon labeled "Mapes IDV collection".
- Tab Bar:** Quicklinks, Data Choosers, Field Selector (highlighted in blue), Displays.
- Data Sources:** A list of available data sources:
  - Formulas
  - MERRA 3D-3h IAU state (selected)
  - 3D-3h T tendencies
  - 3D-3h clouds
  - MERRA 2D-hourly met
  - hourly Vert. Int. budgets
  - .../MAT3CPRAD
- Fields Panel:** Shows categories: 2D grid, 3D grid, Derived. Under Derived, several items are listed:
  - f(h) Geostrophic Horizontal Advection (from Z)
  - f(h) Geostrophic Wind (from Z)
  - f(h) Geostrophic Wind Vectors (from Z)
  - f(h) Height from Geopotential (h)
  - f(h) Potential Temperature (from t) (highlighted in blue)
  - f(h) Potential Temperature IsoSurface Advection (from th)
- Displays Panel:** Shows categories: Plan Views, Vertical Cross Sections. Under Plan Views, several items are listed:
  - Contour Plan View
  - Color-Filled Contour Plan View
  - Color-Shaded Plan View
  - Value PlotsUnder Vertical Cross Sections, two items are listed:
  - Contour Cross Section (highlighted in blue)
  - Color-Filled Contour Cross Section

# Create a new cross section of potential temperature contours

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

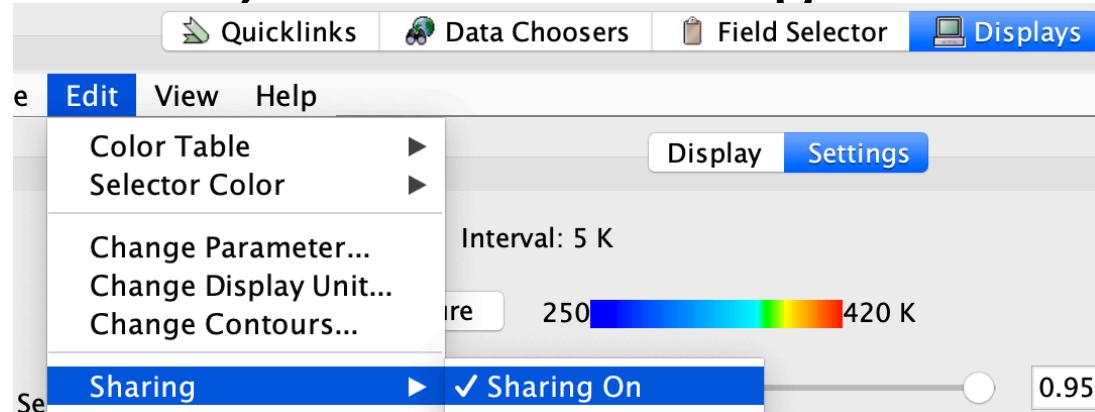


- Change the contour interval to 5K. Change the Color to Black. Change their label size to 20.



# Create a new cross section of potential temperature contours

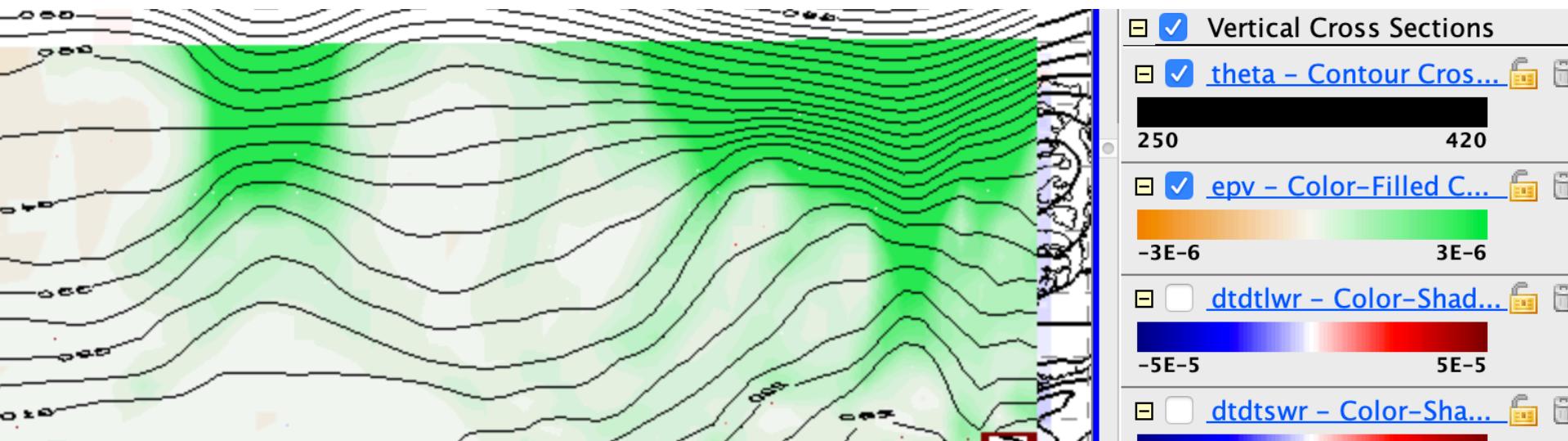
- Again click the Legend entry to pop up the Display Controls.
- Under the Edit menu, turn on Sharing



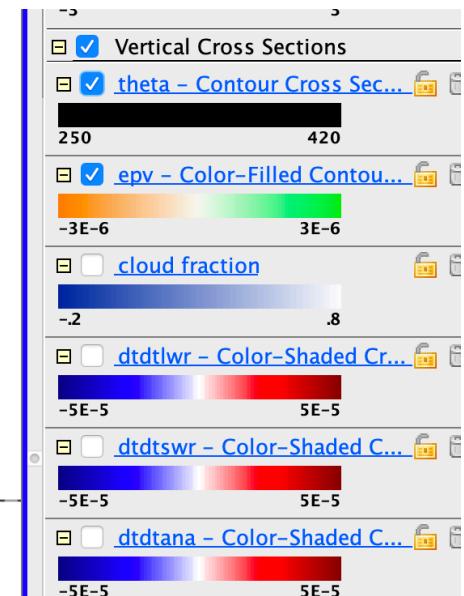
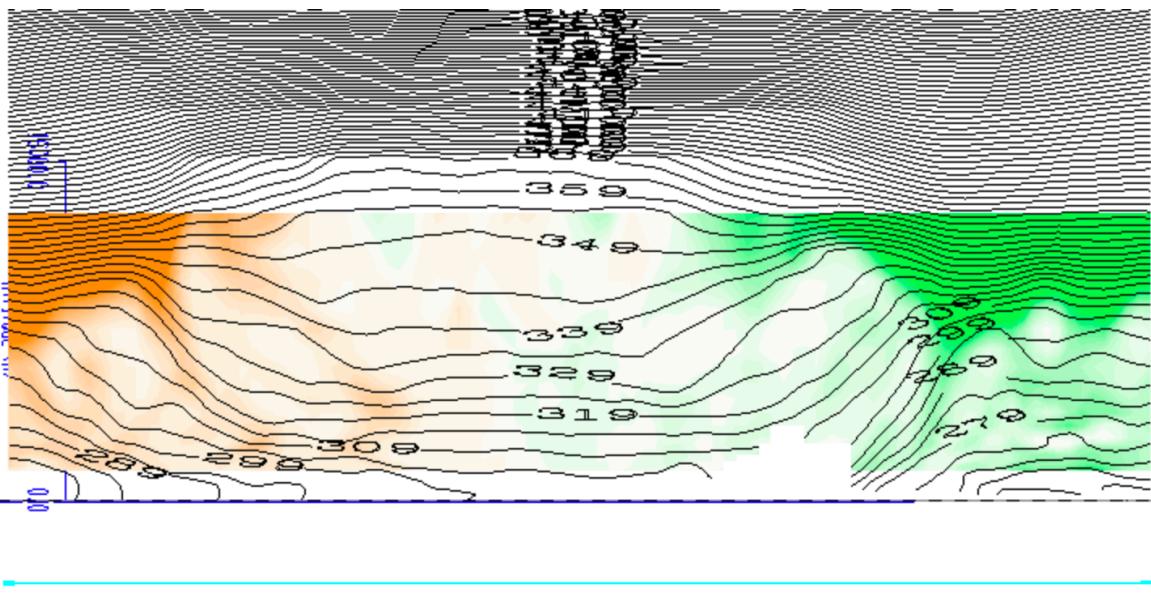
- Move the main north-south cross section slightly. This will make your new theta contour section snap into place with it.

# 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:



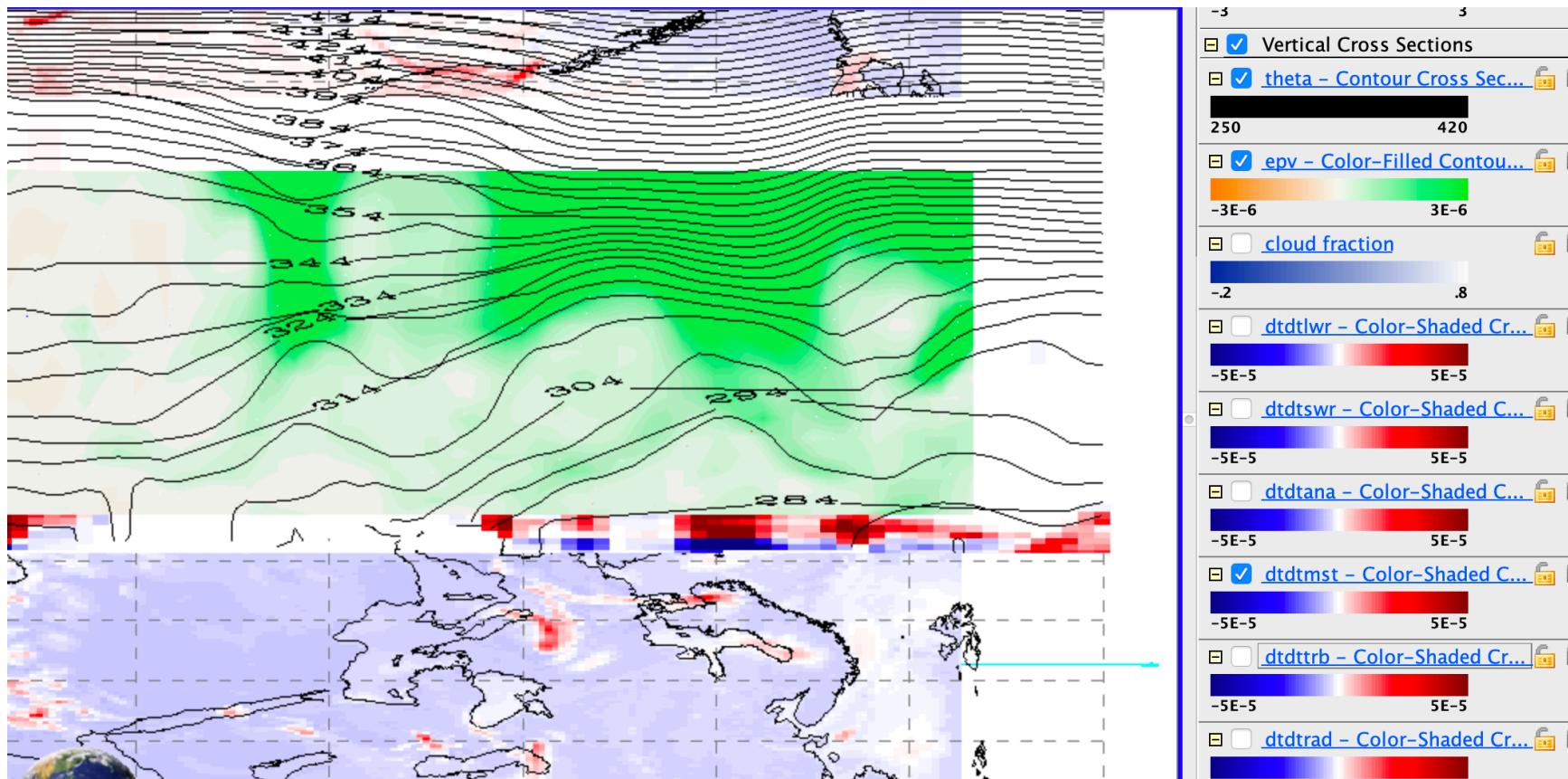
# New Theta contours with Vorticity



# Warm and cool cores & condensation heating

- Use the cross section with theta contours and the moist-processes heating rate ( $dtdtmst$ ) to find an example
  - 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?

# Moist condensation near Ireland



# 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)

$$\frac{D}{Dt} \vec{V}_h = -f \hat{k} \times \vec{V}_h - \vec{\nabla}_p \Phi + \vec{F}_r \quad \begin{matrix} \text{F=MA} \\ \text{in the} \\ \text{HORIZONTAL} \end{matrix}$$

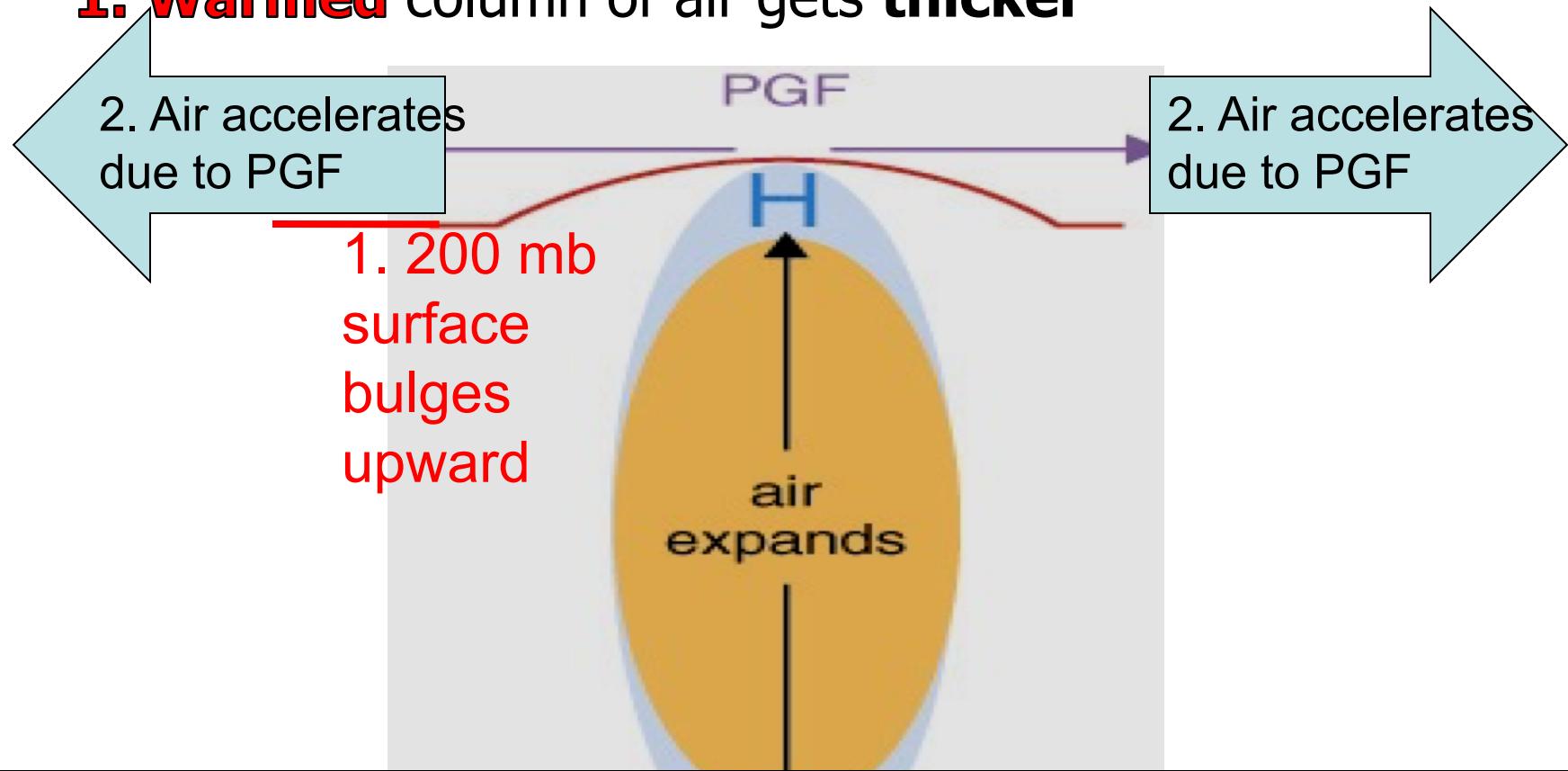
$$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p} \quad \begin{matrix} \text{HYDROSTATIC} \\ (\text{w/ ideal gas law to} \\ \text{eliminate } \rho) \end{matrix}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \quad \text{MASS CONSERVATION}$$

$$\frac{\partial T}{\partial t} = -\vec{V} \cdot \vec{\nabla}_p T - \omega S_p + \frac{J}{C_p} \quad \text{FIRST LAW OF THERMO}$$

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

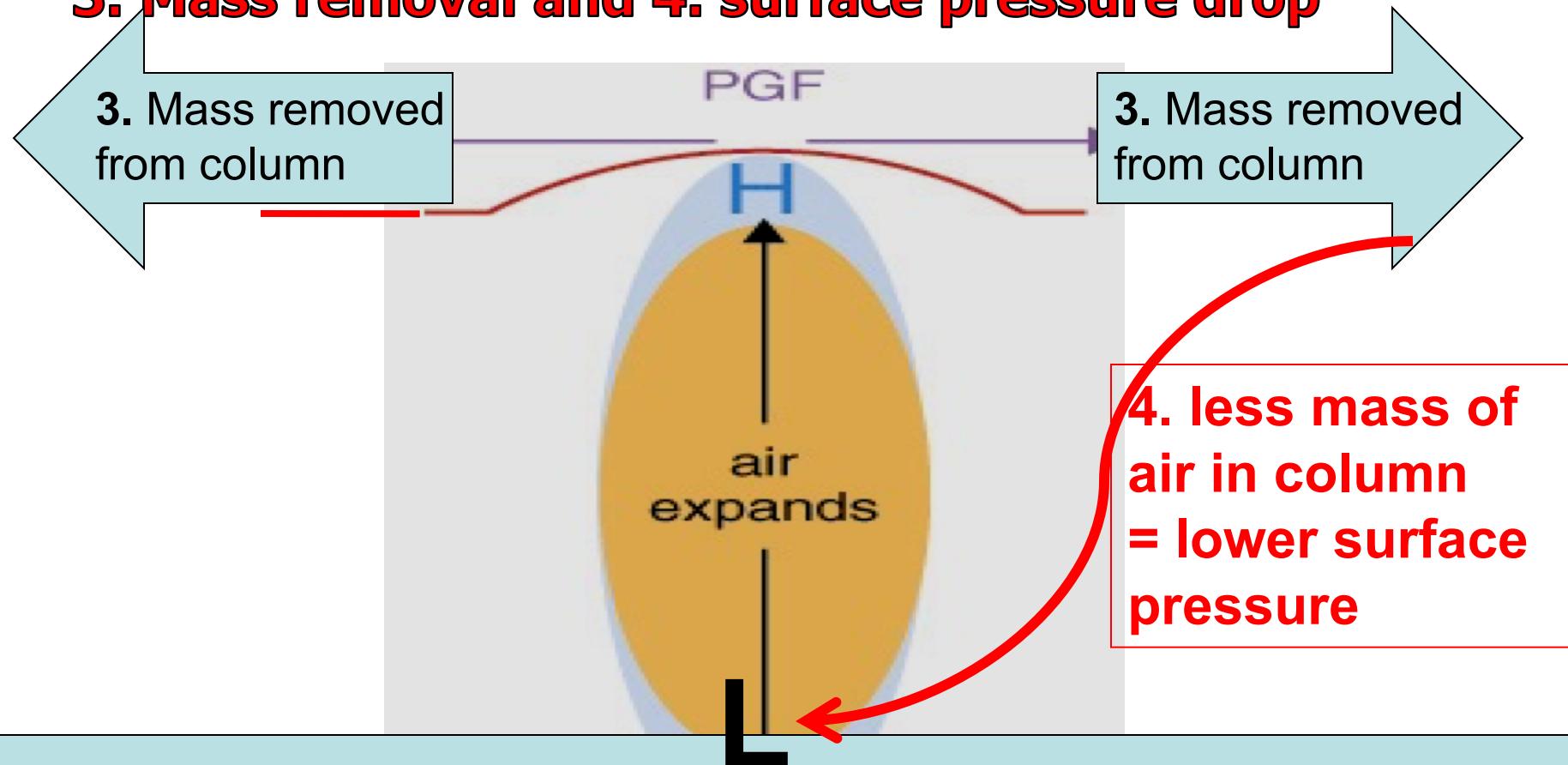
**1. Warmed** column of air gets **thicker**



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

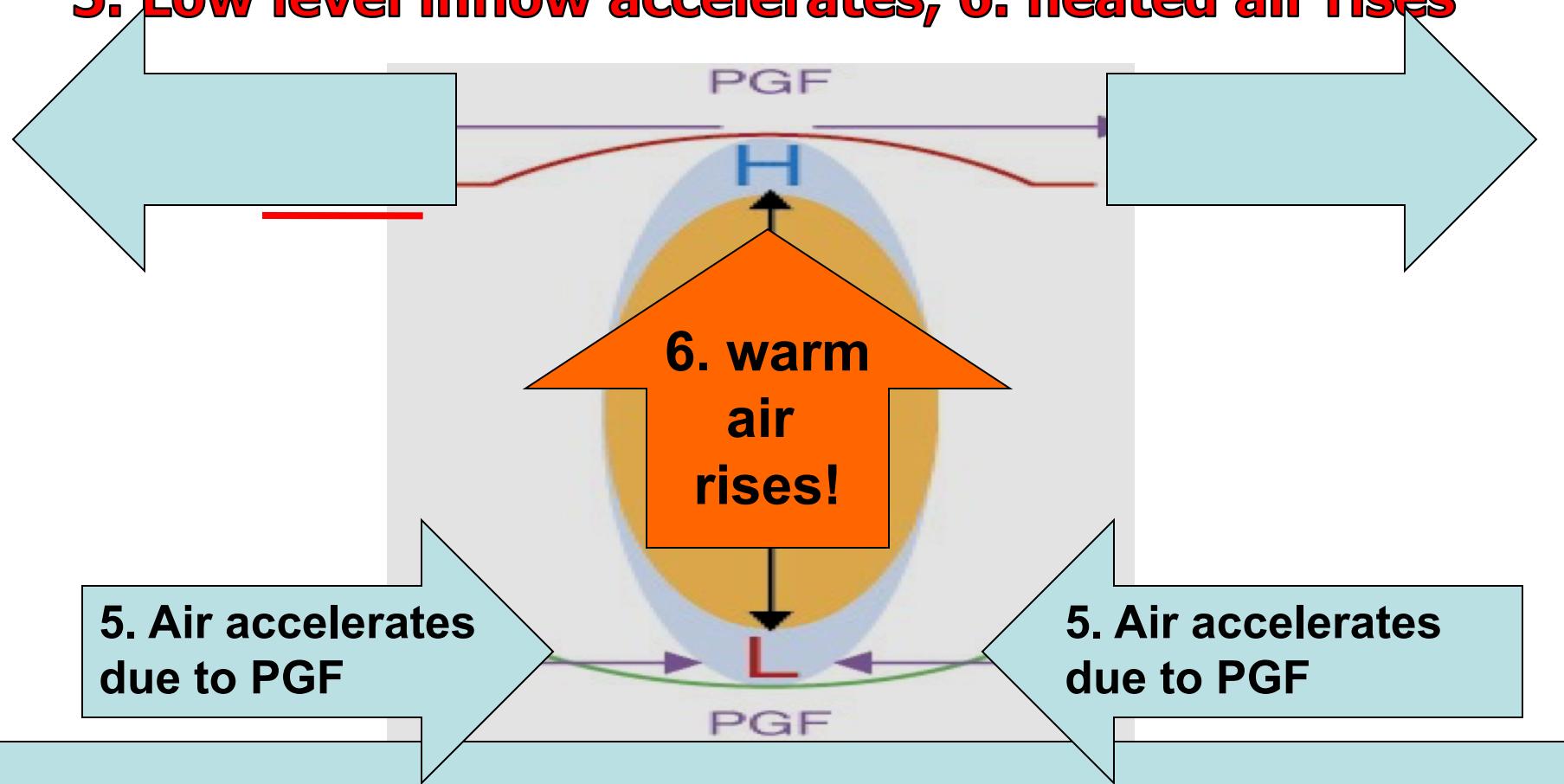
# How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

## 3. Mass removal and 4. surface pressure drop

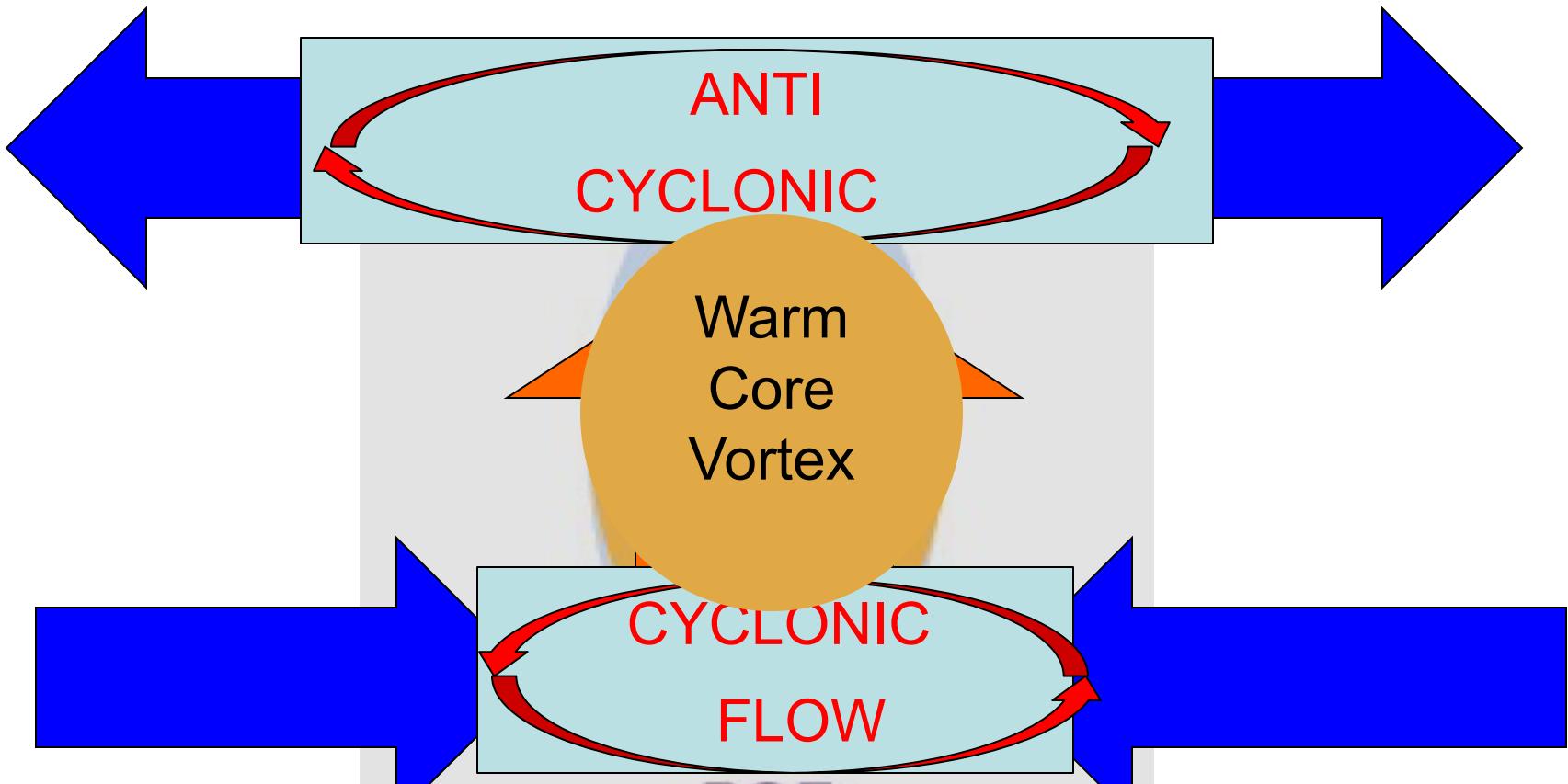


# How heated air rises and a warm core vortex develops: the Primitive Equation view. 7 logical steps

**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

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

**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

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

**3. High  $\Phi$  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

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

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

**5. Low  $\Phi$  under hot column pulls wind inward**

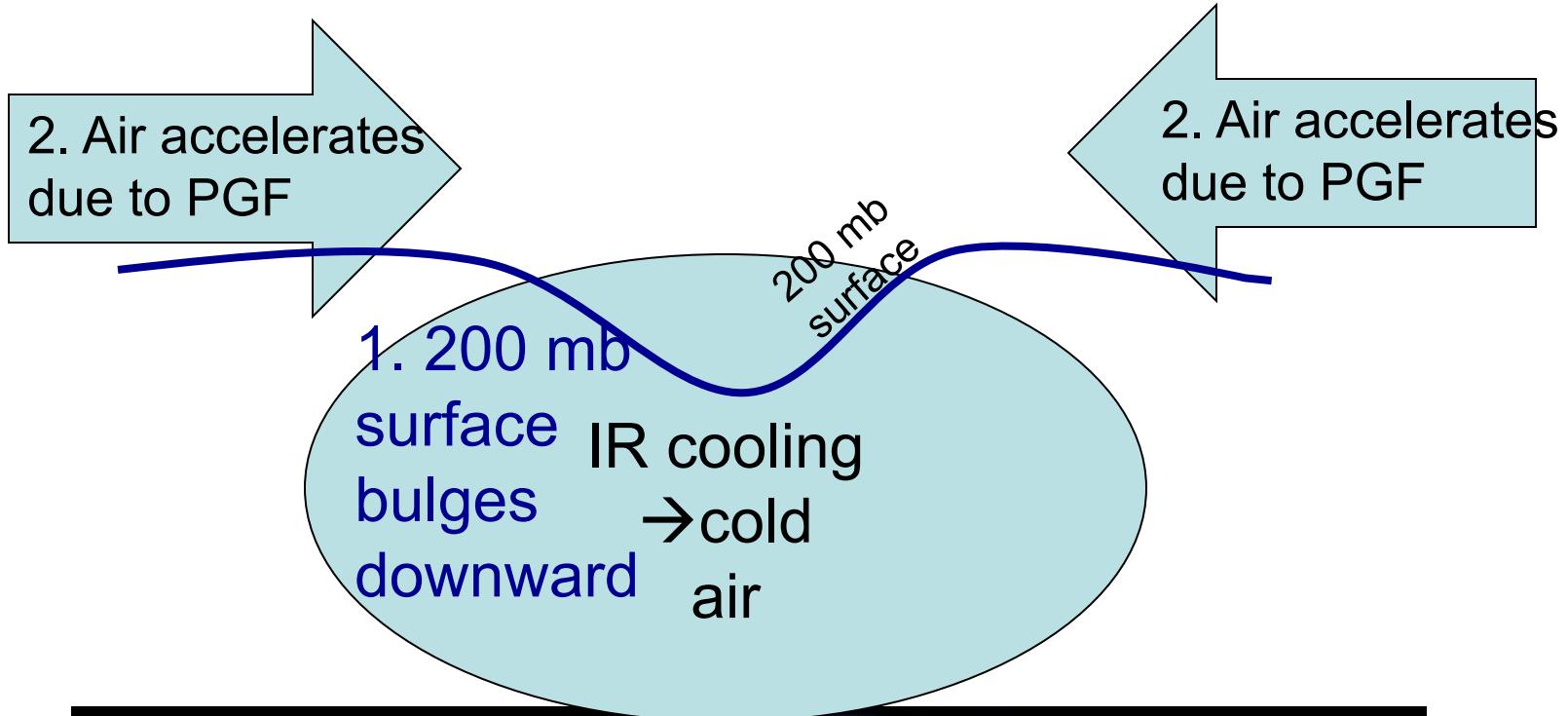
**6. Hot air rises (finally!)**  
 $\omega \approx \rho g w$

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

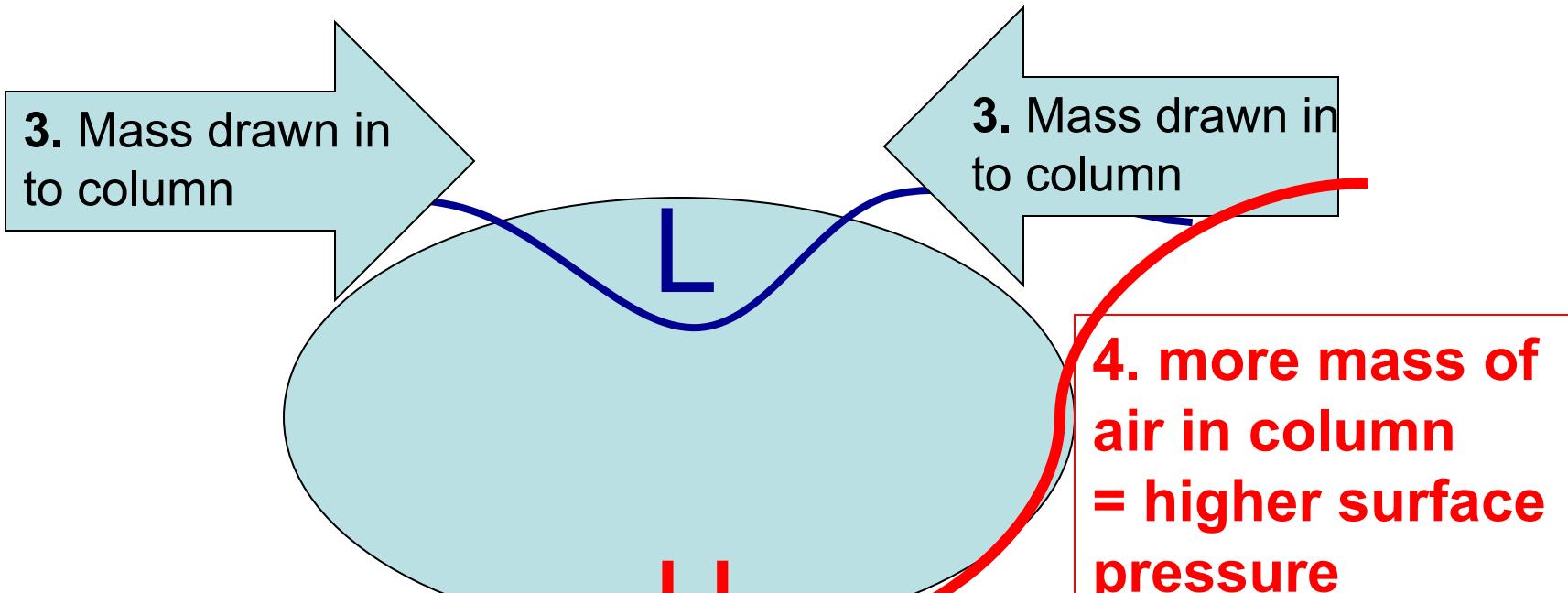
**7. Coriolis force turns inflowing and outflowing air to make round-and-round flow**

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

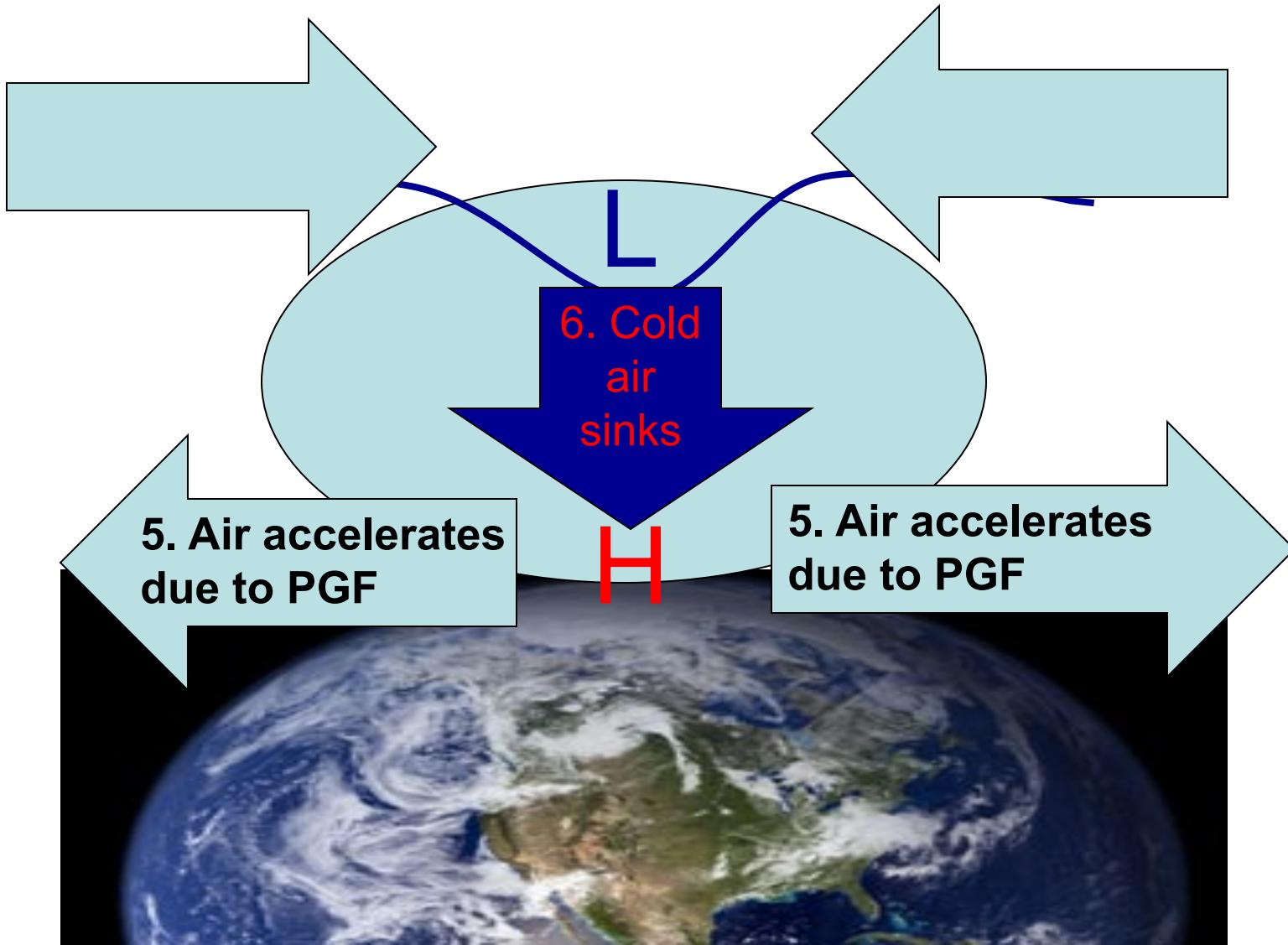
## 1. Cooled column of air gets thinner



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

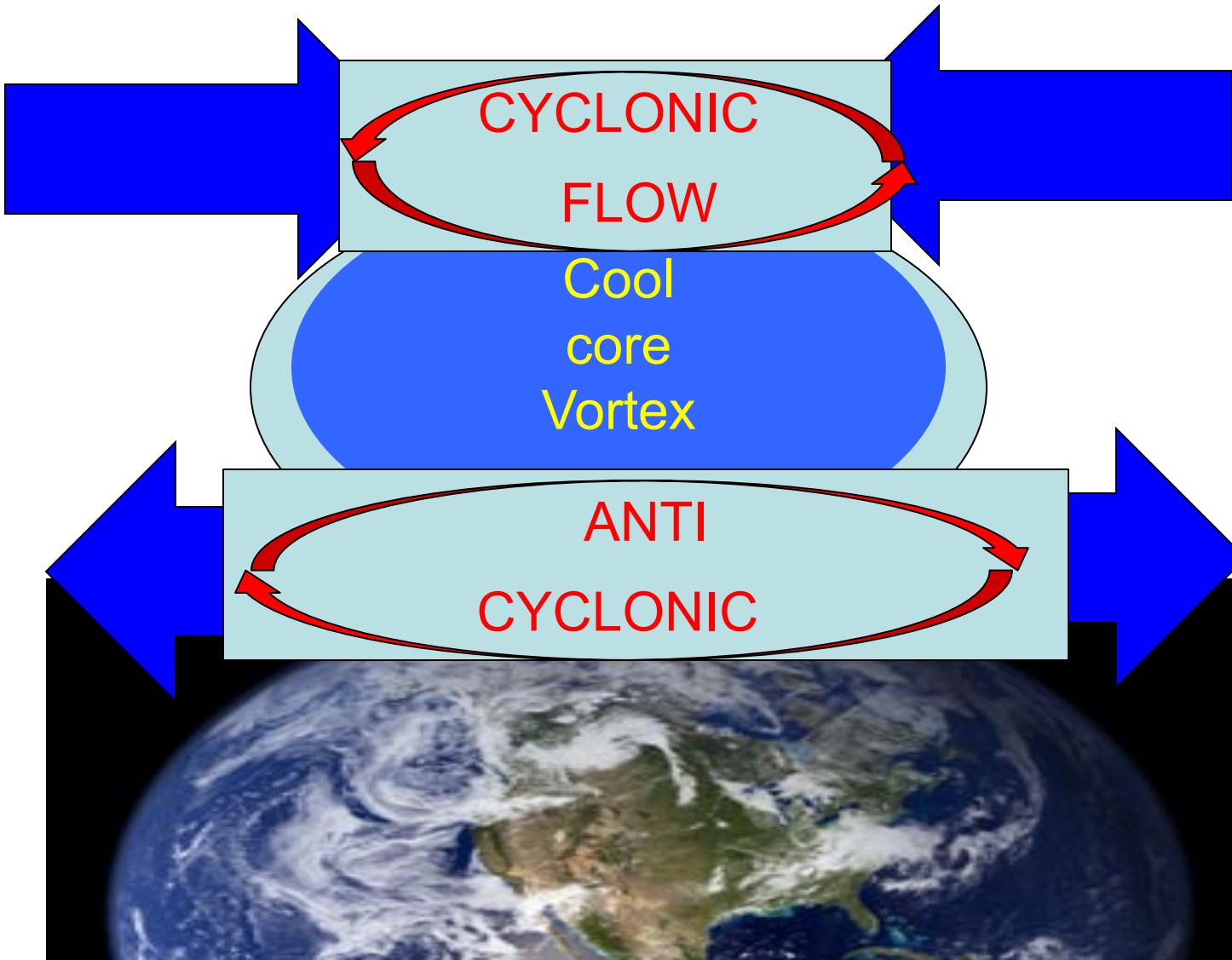


# How cooled air sinks and a cool core vortex develops: the Primitive Equation view. 7 logical steps

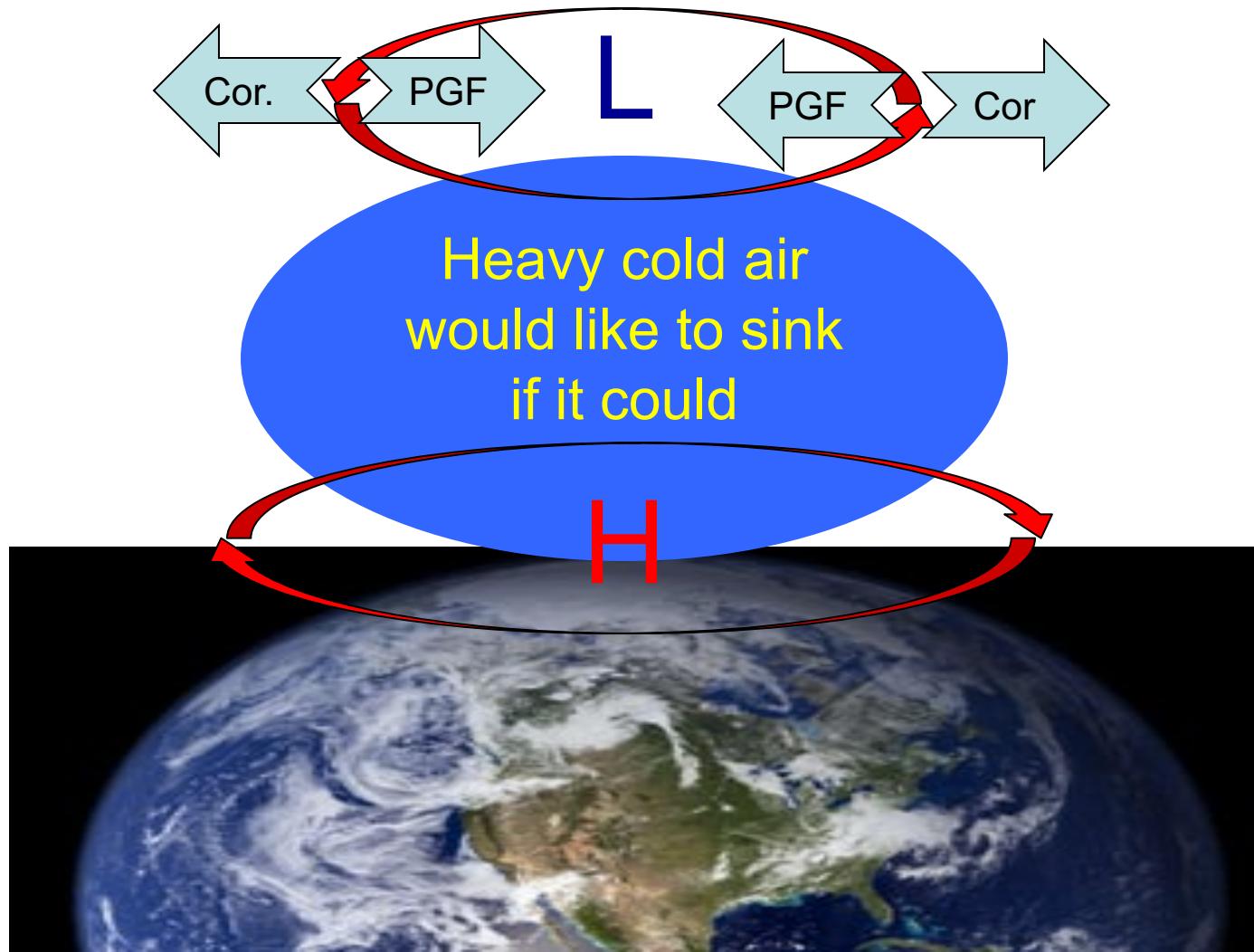


# How cooled air sinks and a cool core vortex develops:

## 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



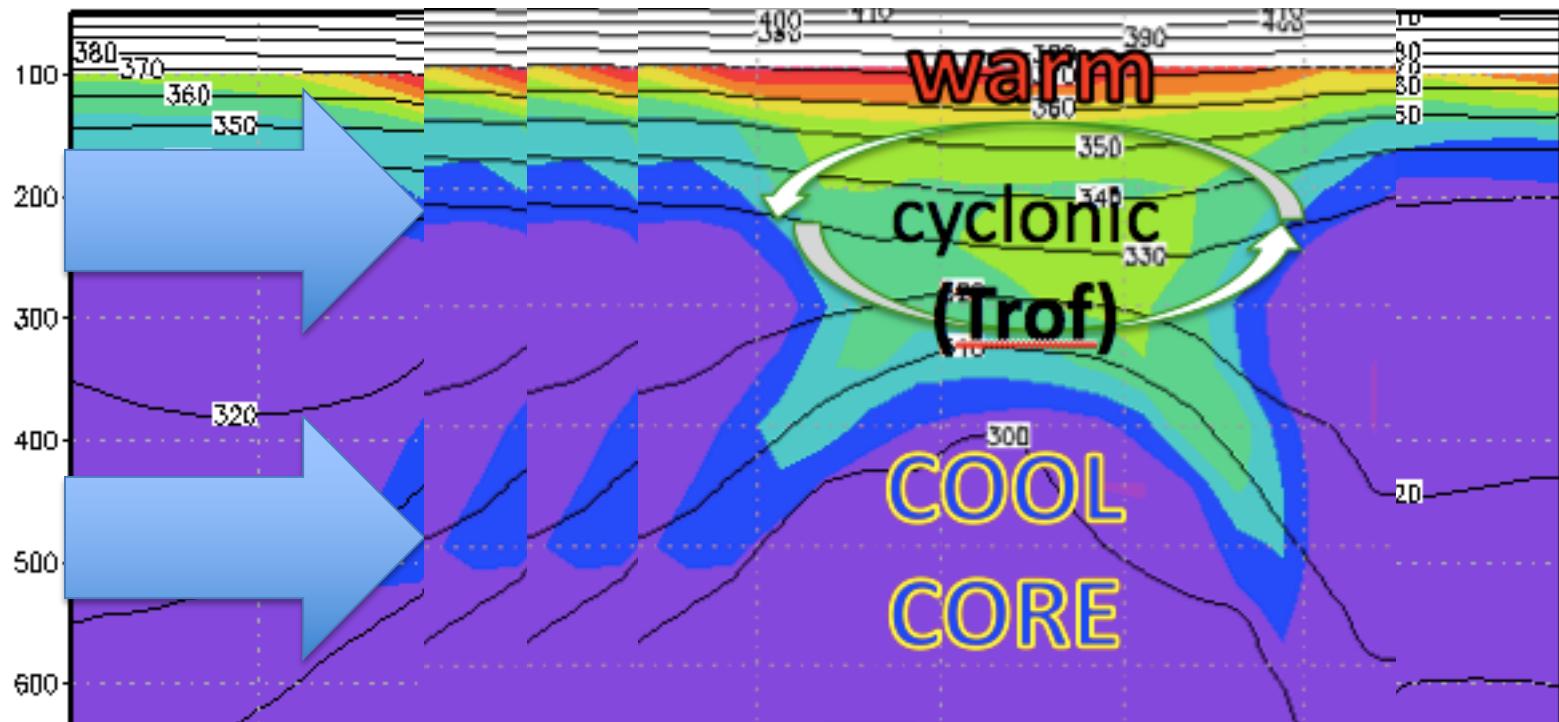
# Polar and stratospheric "Reservoirs" of $\zeta_a$ or PV

- Potential vorticity:  $PV = -g \zeta_a (\partial\theta/\partial p)$ 
  - 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.

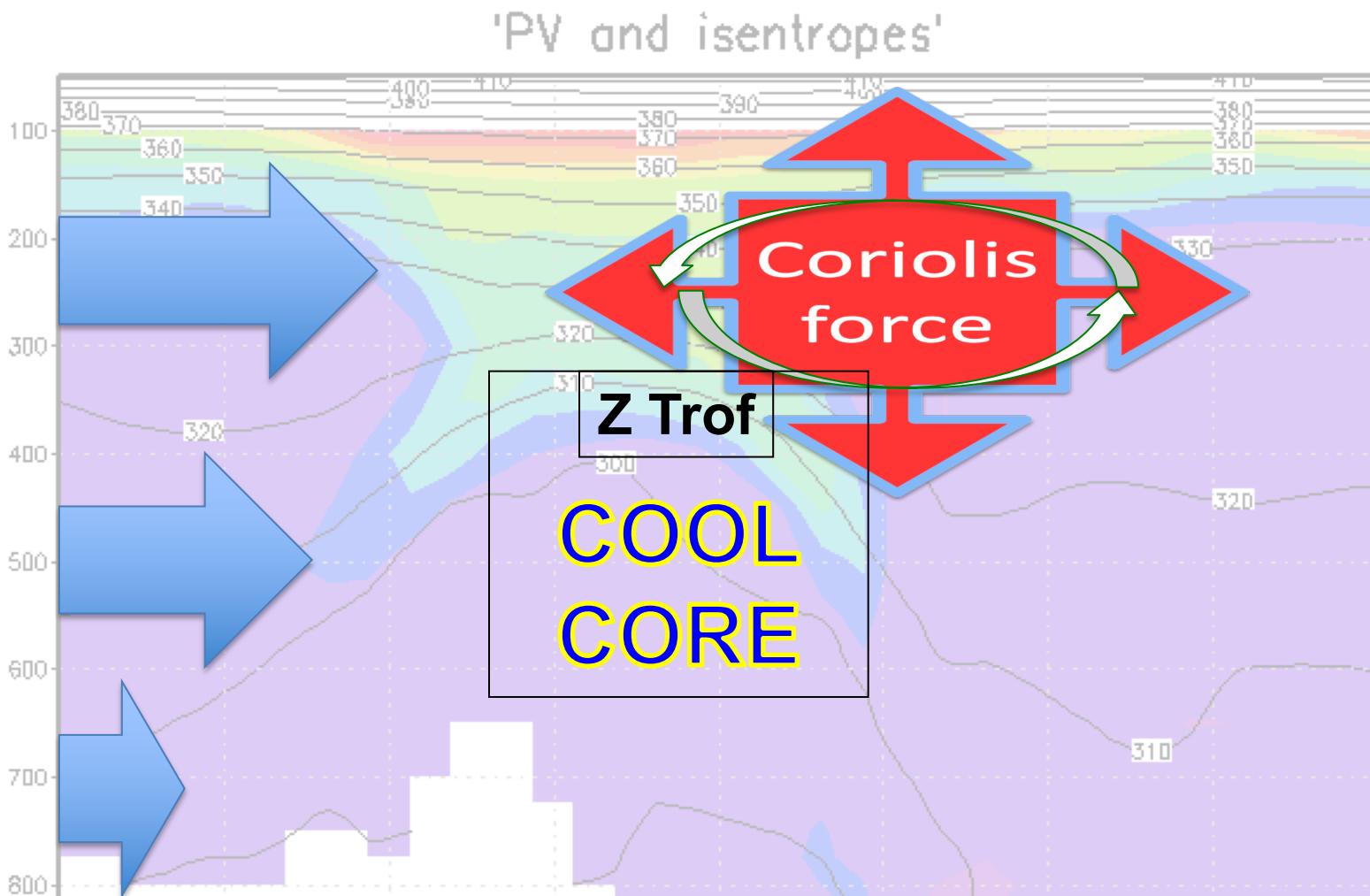


# Unsheared advection of T, u, v, vort, PV: no breaking of balance

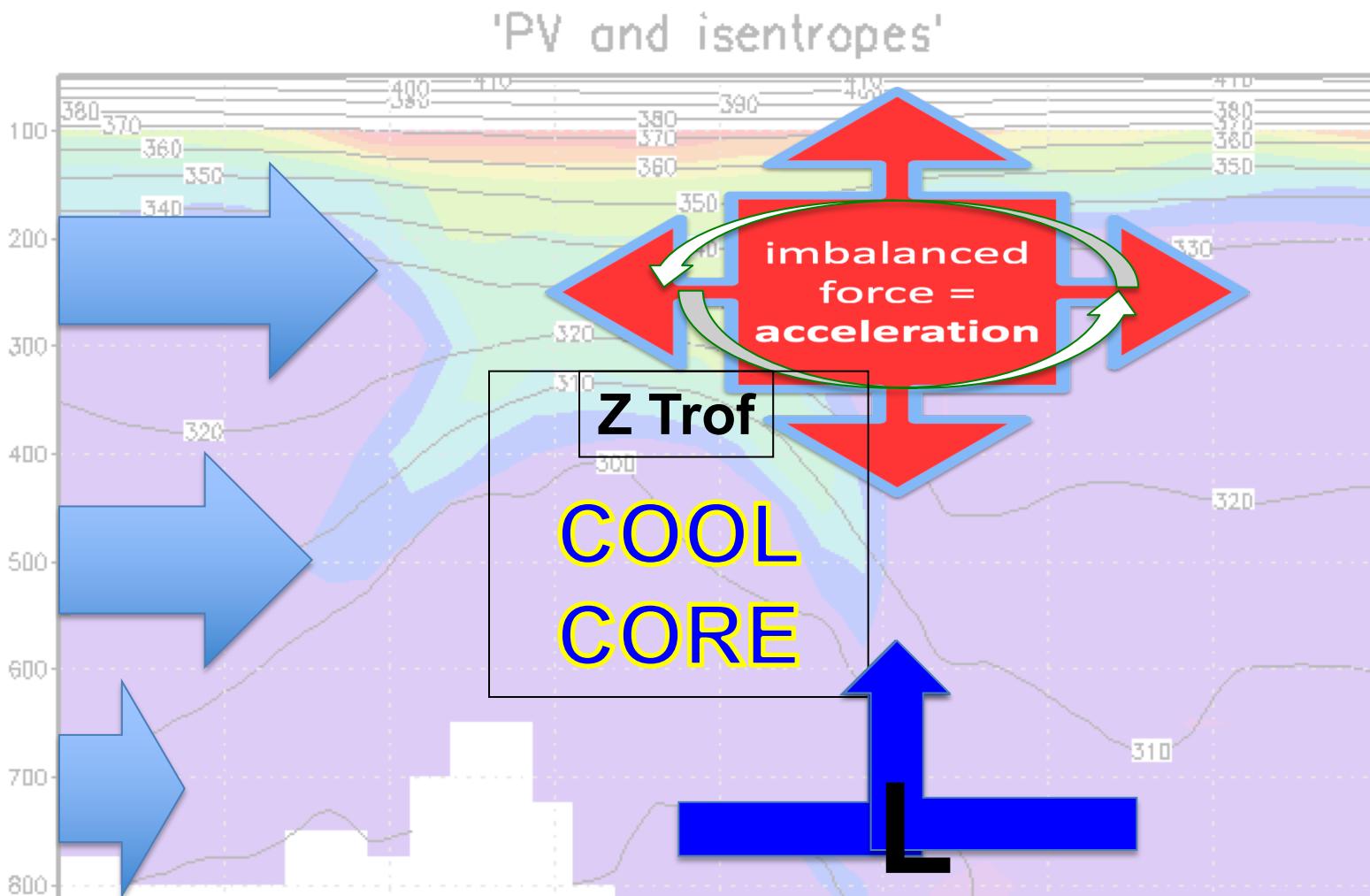
'PV and isentropes'



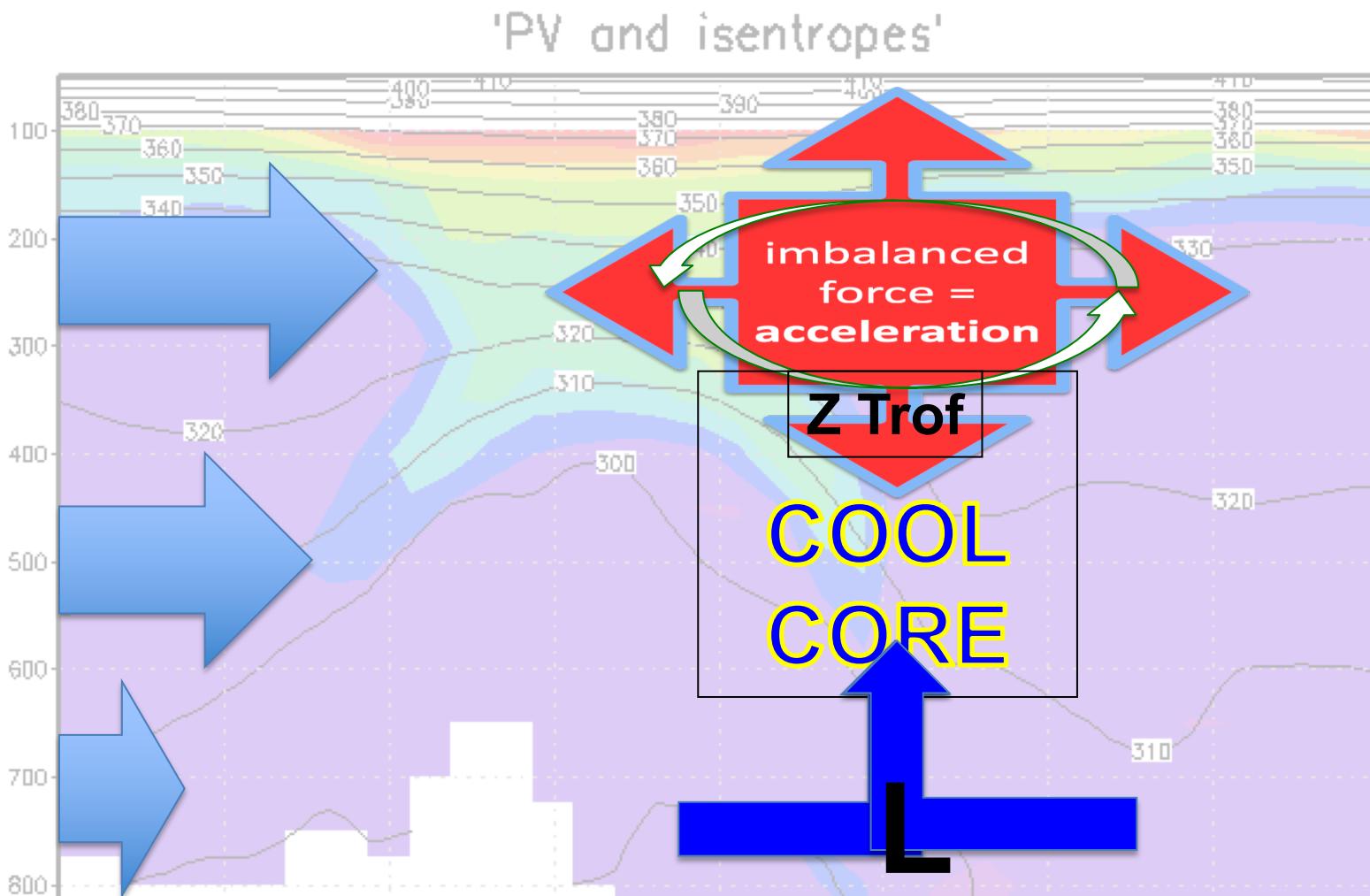
# Sheared advection breaks thermal wind balance



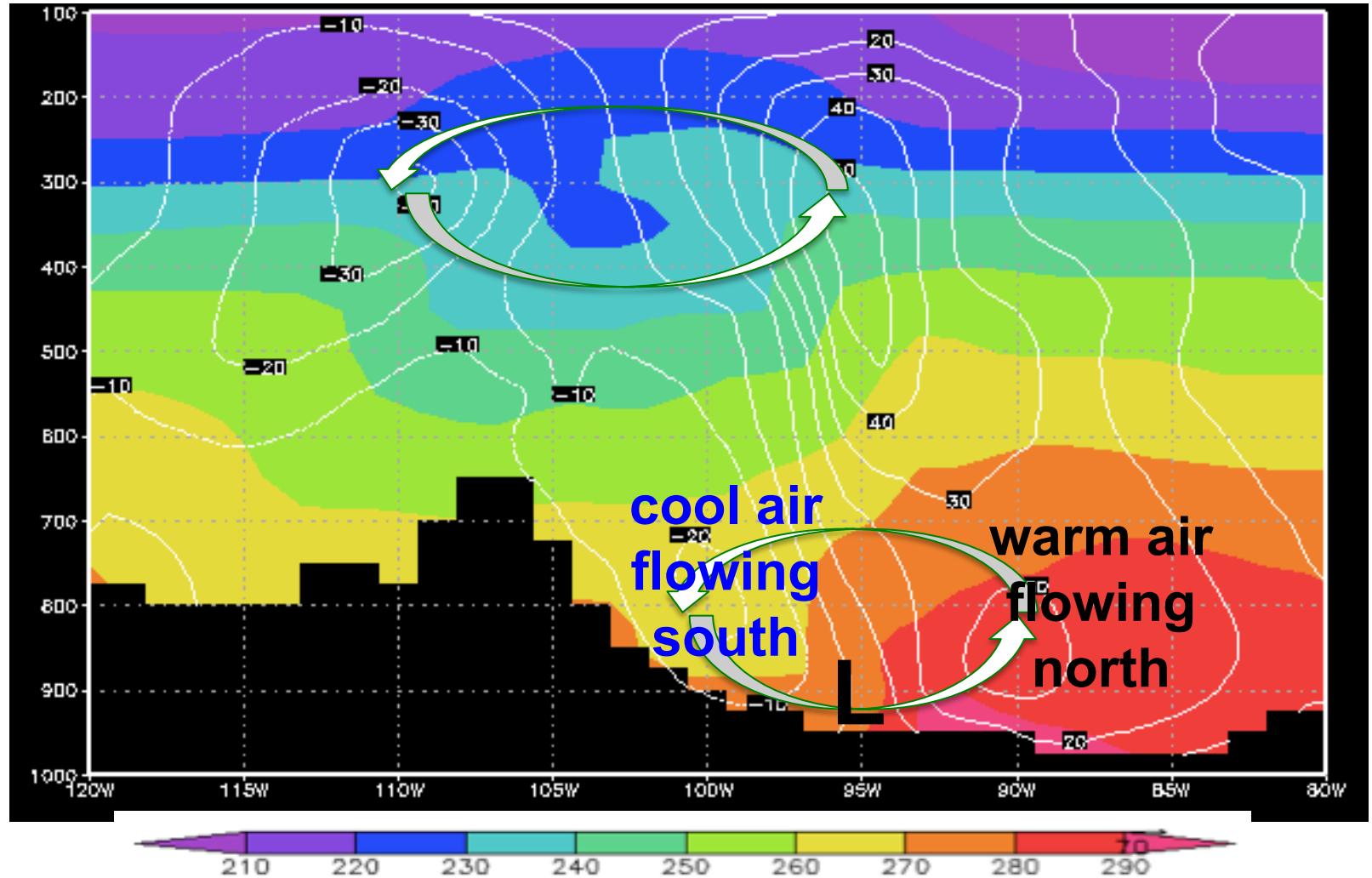
# Sheared advection breaks thermal wind balance



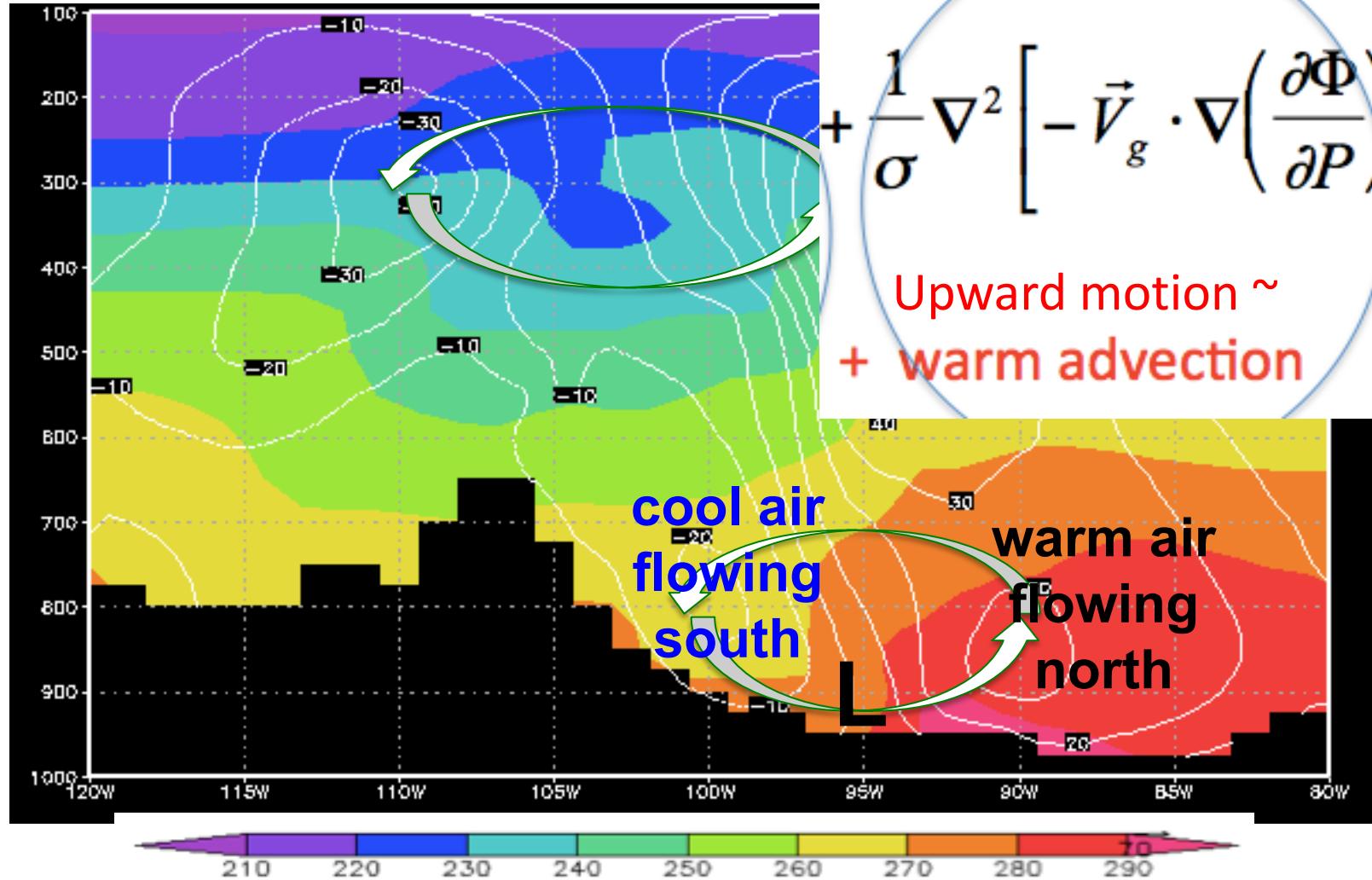
# Sheared advection breaks thermal wind balance



# But there is some T advection too



# But there is some T advection too



# East-west section: omega

