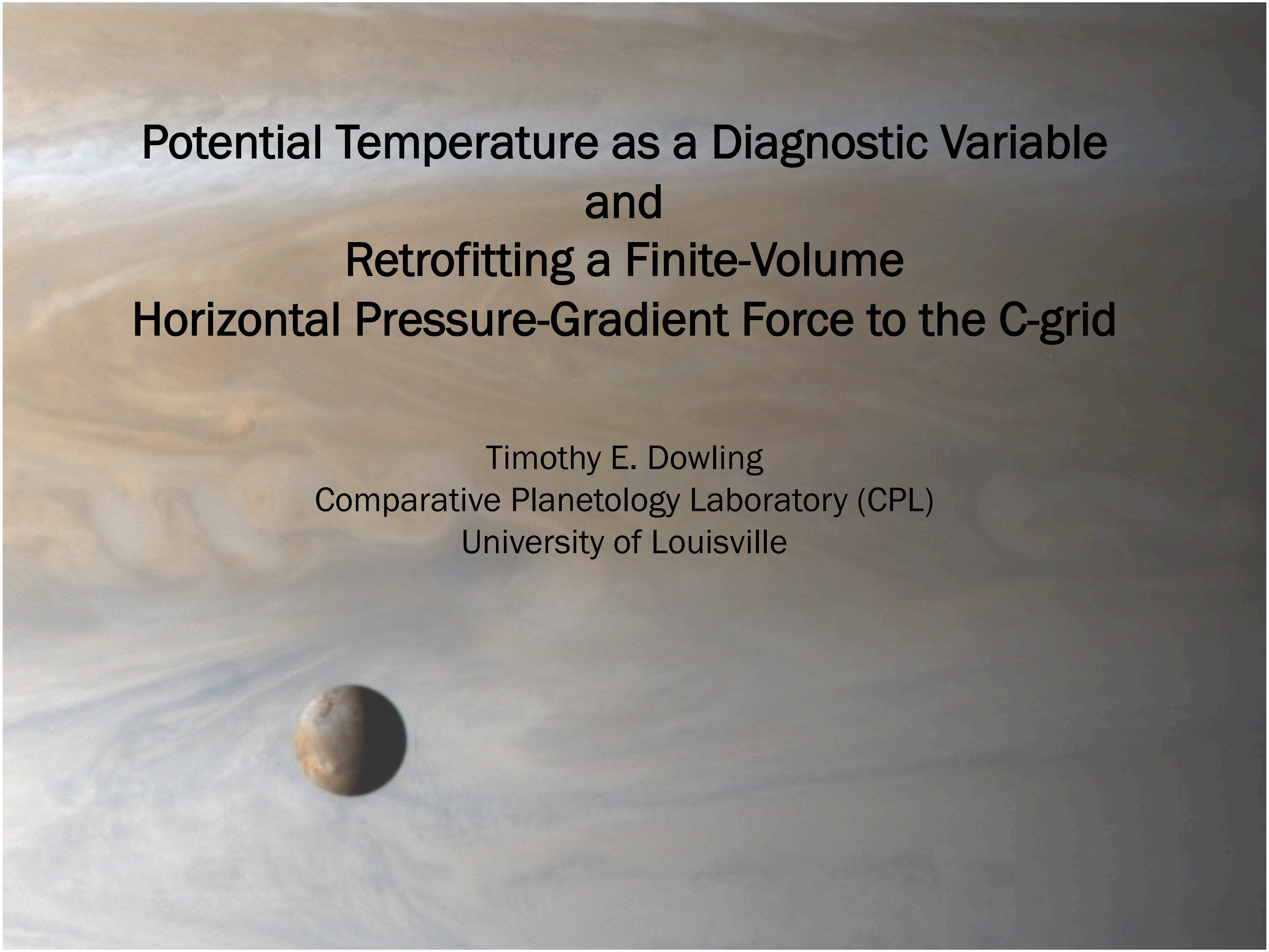

Potential Temperature as a Diagnostic Variable and Retrofitting a Finite-Volume Horizontal Pressure-Gradient Force to the C-grid

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Comparative Planetology Laboratory (CPL)
University of Louisville

Hierarchy of a Variable Set

θ

P

Altitude ↑

Pure Isentropic Coordinate

> Set and forget

> No worse than its inputs

> Must solve a PDE in time

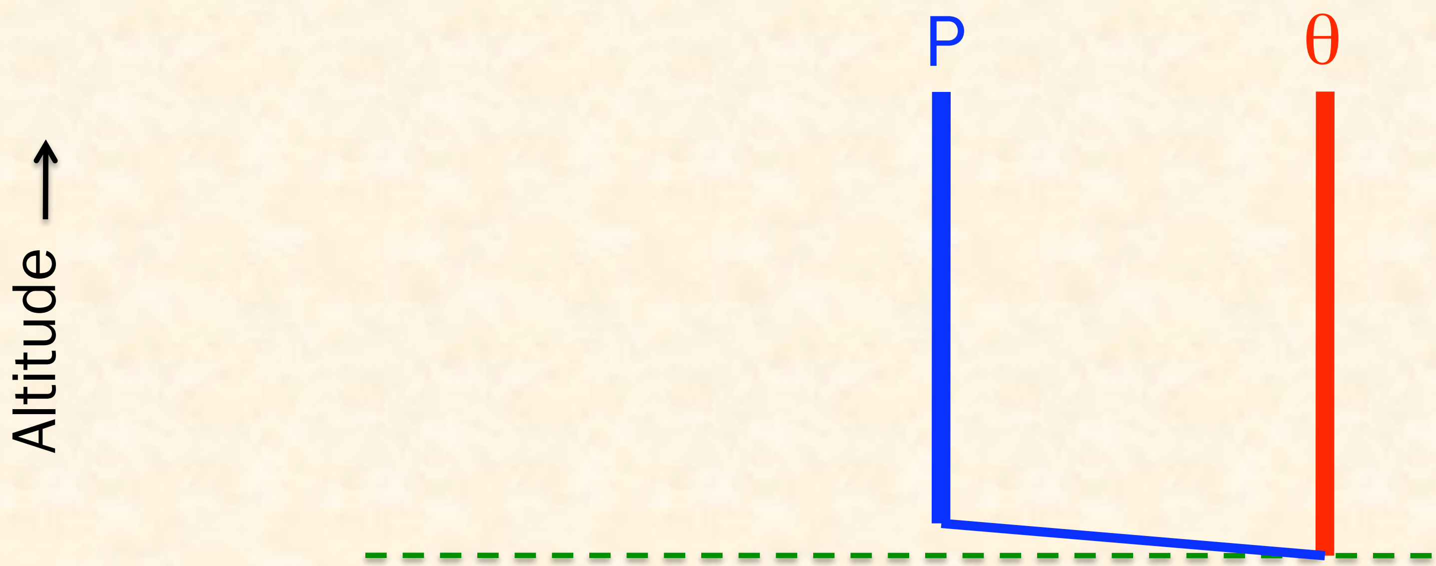
> Can be noisy, can blow up

Coordinate Variable

Diagnostic Variable

Prognostic Variable

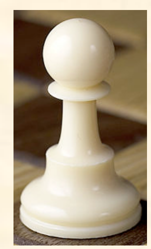
Hierarchy of a Variable Set



Pure Sigma Coordinate

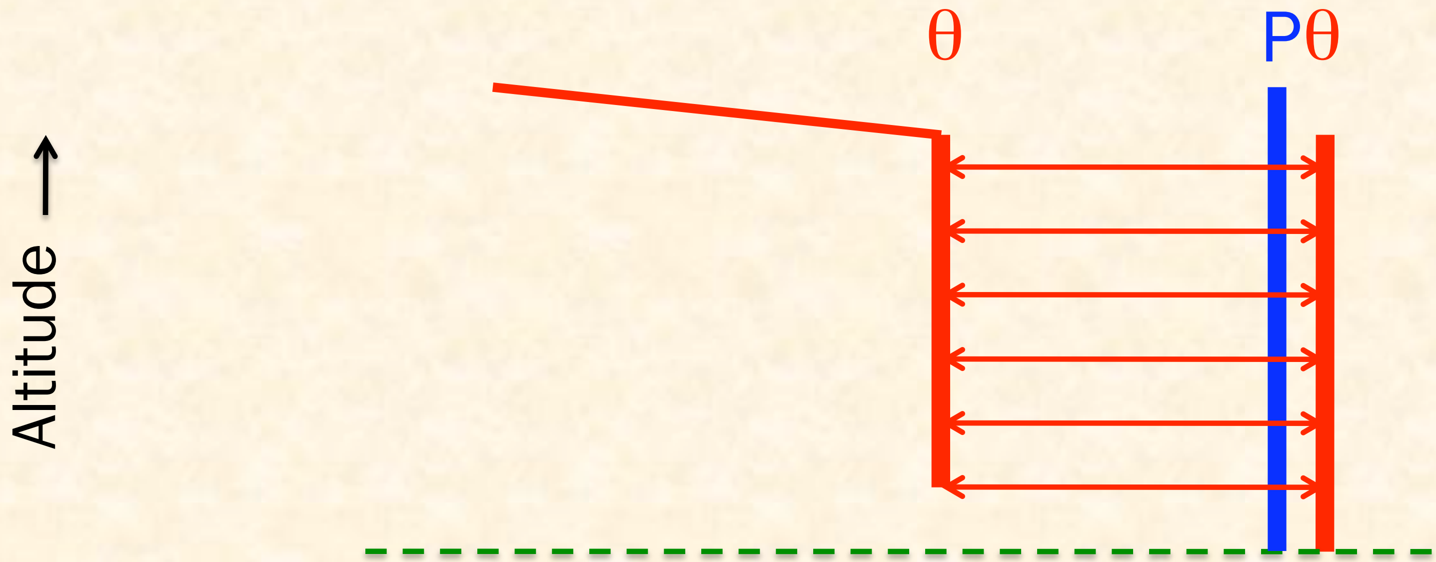
Coordinate Variable

Diagnostic Variable



Prognostic Variable

Hierarchy of a Variable Set



Hybrid Sigma-Theta Coordinate: Style 1
(Konor & Arakawa 1997)

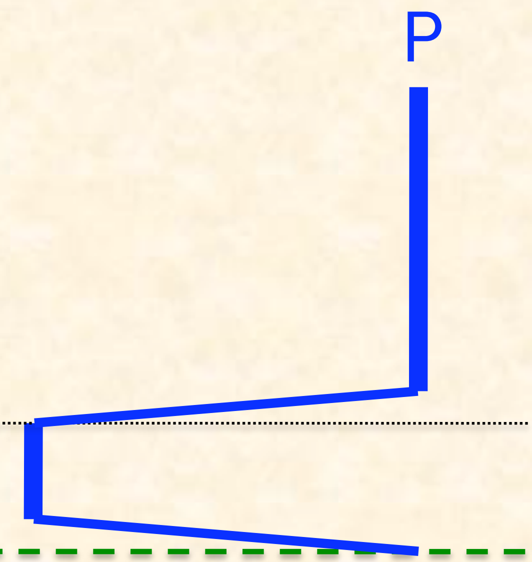
Coordinate Variable

Diagnostic Variable

Prognostic Variable

Hierarchy of a Variable Set

Altitude ↑



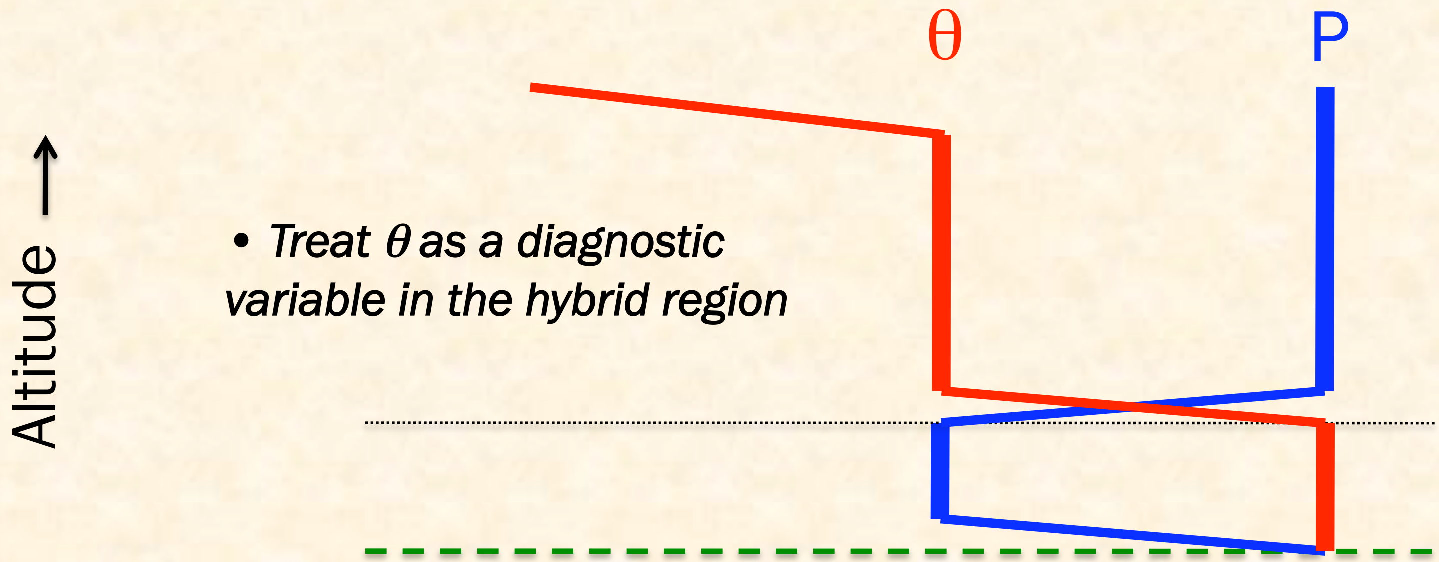
- *Introduce a pure-sigma region*

Coordinate Variable

Diagnostic Variable

Prognostic Variable

Hierarchy of a Variable Set



- *Treat θ as a diagnostic variable in the hybrid region*

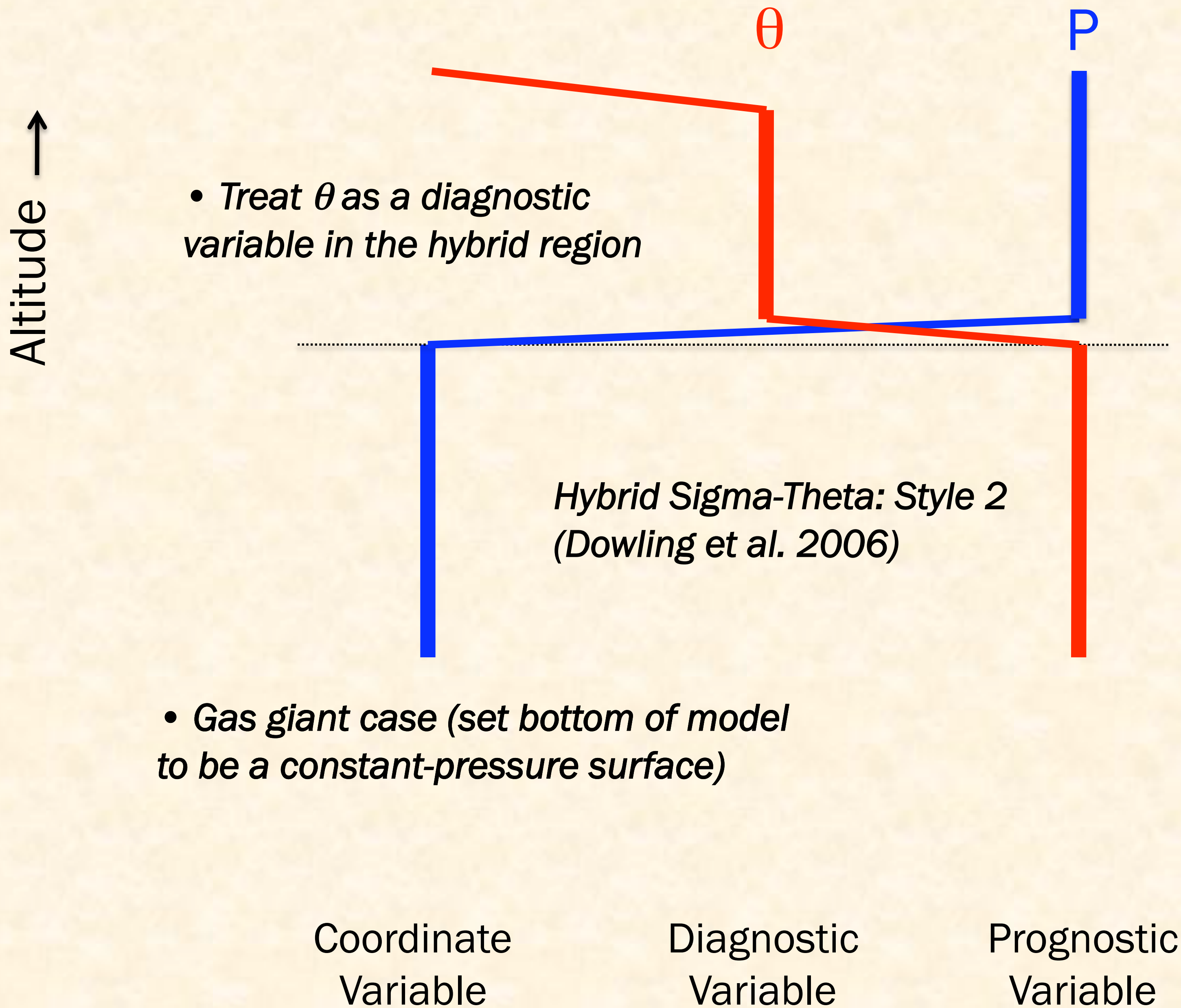
Hybrid Sigma-Theta: Style 2 (Dowling et al. 2006)

Coordinate Variable

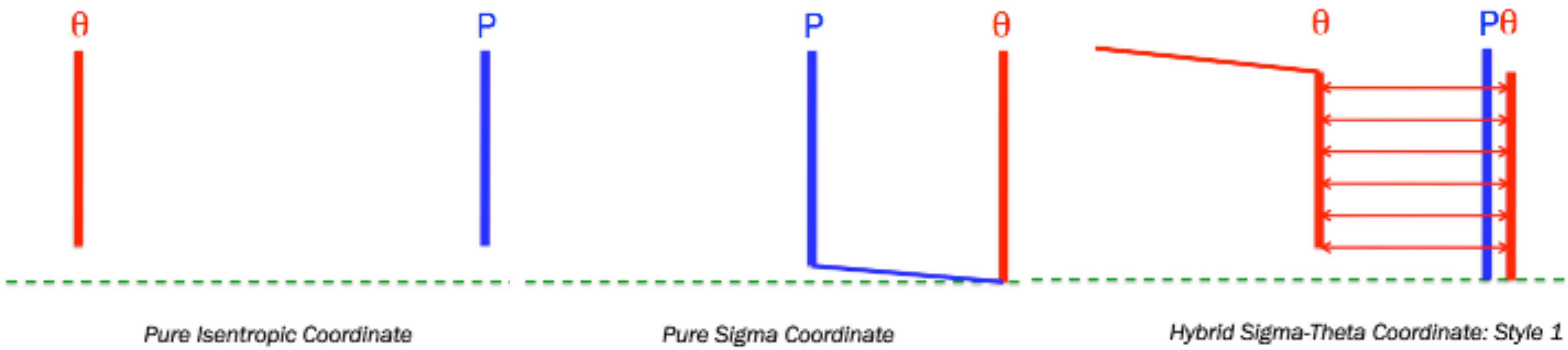
Diagnostic Variable

Prognostic Variable

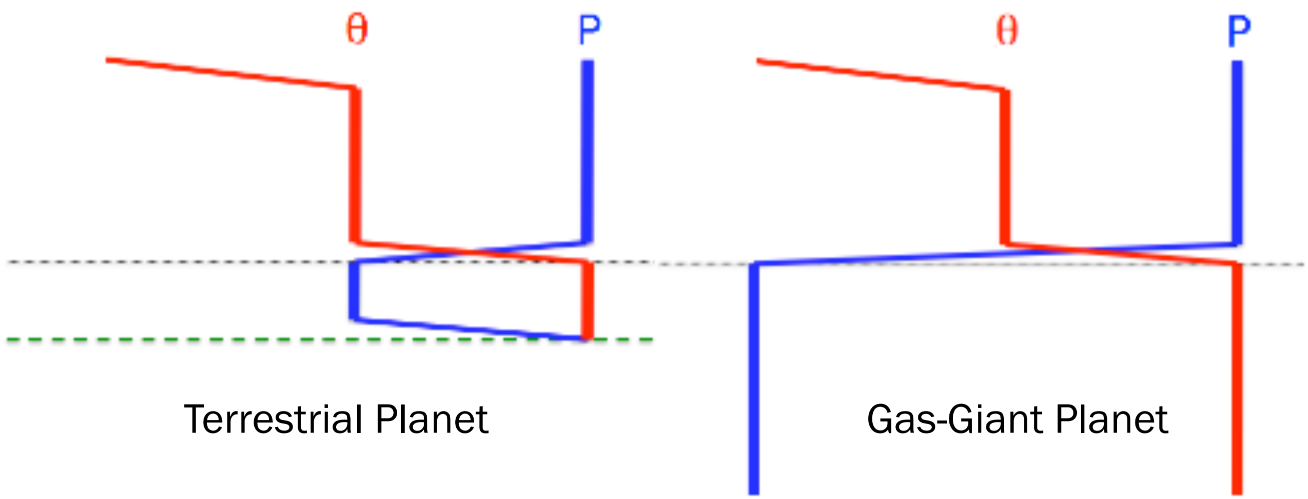
Hierarchy of a Variable Set



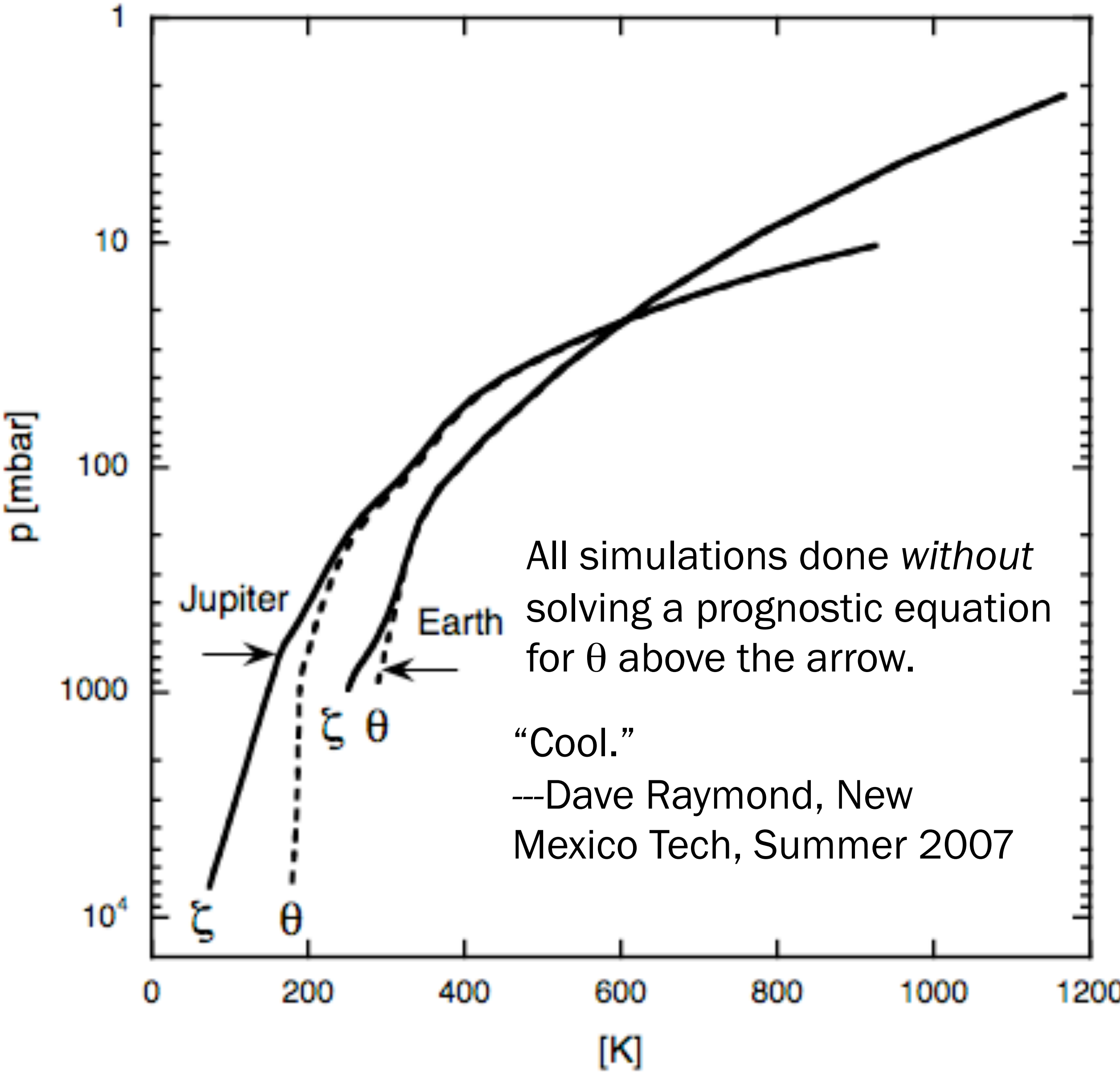
Summary: θ and P Hierarchy



EPIC Model (Dowling et al. 2006)



Q: What do the other models represented at this workshop look like in these terms?



All simulations done *without* solving a prognostic equation for θ above the arrow.

"Cool."
---Dave Raymond, New Mexico Tech, Summer 2007

Hybrid Vertical Coordinate
$\zeta = f[\sigma] + g[\sigma]\theta$

$0 < g(\sigma) \leq 1$ above arrow, such that we can use $\theta = \theta_{diag} = (\zeta - f[\sigma])/g[\sigma]$

$g[\sigma] = 0$ below arrow, forming a pure-σ region

Hybrid Vertical Velocity

$\zeta = F(\theta, p, pbot) = f[\sigma] + g[\sigma]\theta$

$$\dot{\zeta}_{k+1/2} = \tilde{g}(\sigma_{k+1/2}) \frac{\dot{Q}_{k+1/2}}{\Pi_{k+1/2}} - F_p \sum_{m=1}^{k} g h_m D_m \Delta\zeta_m - F_{p_{\rm bot}} \sum_{m=1}^{nk} g h_m D_m \Delta\zeta_m$$

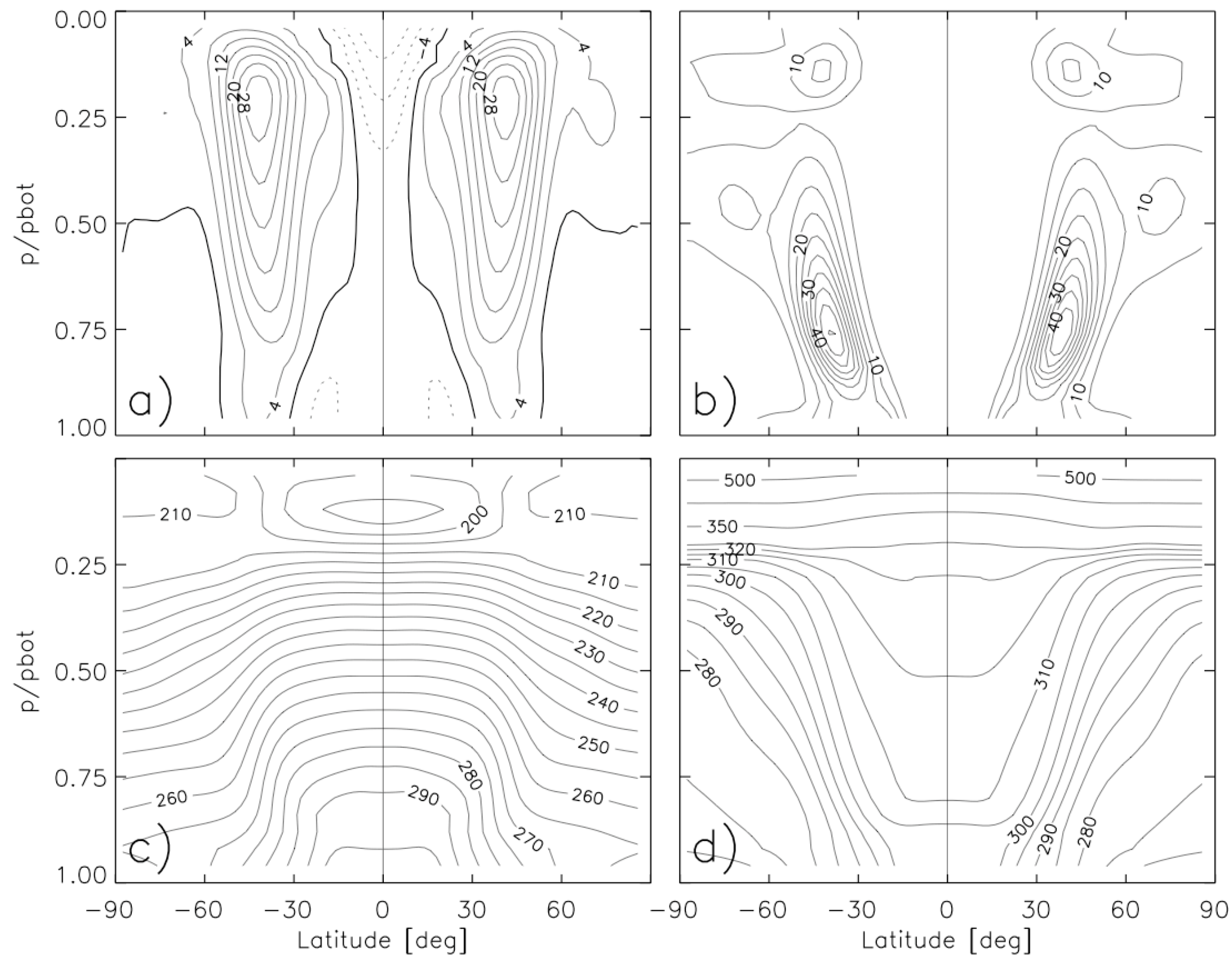
$D_k \equiv (\vec{\nabla} \cdot \vec{v})|_\zeta$ is the horizontal divergence

$$h = -(1/g)\partial p / \partial \zeta$$

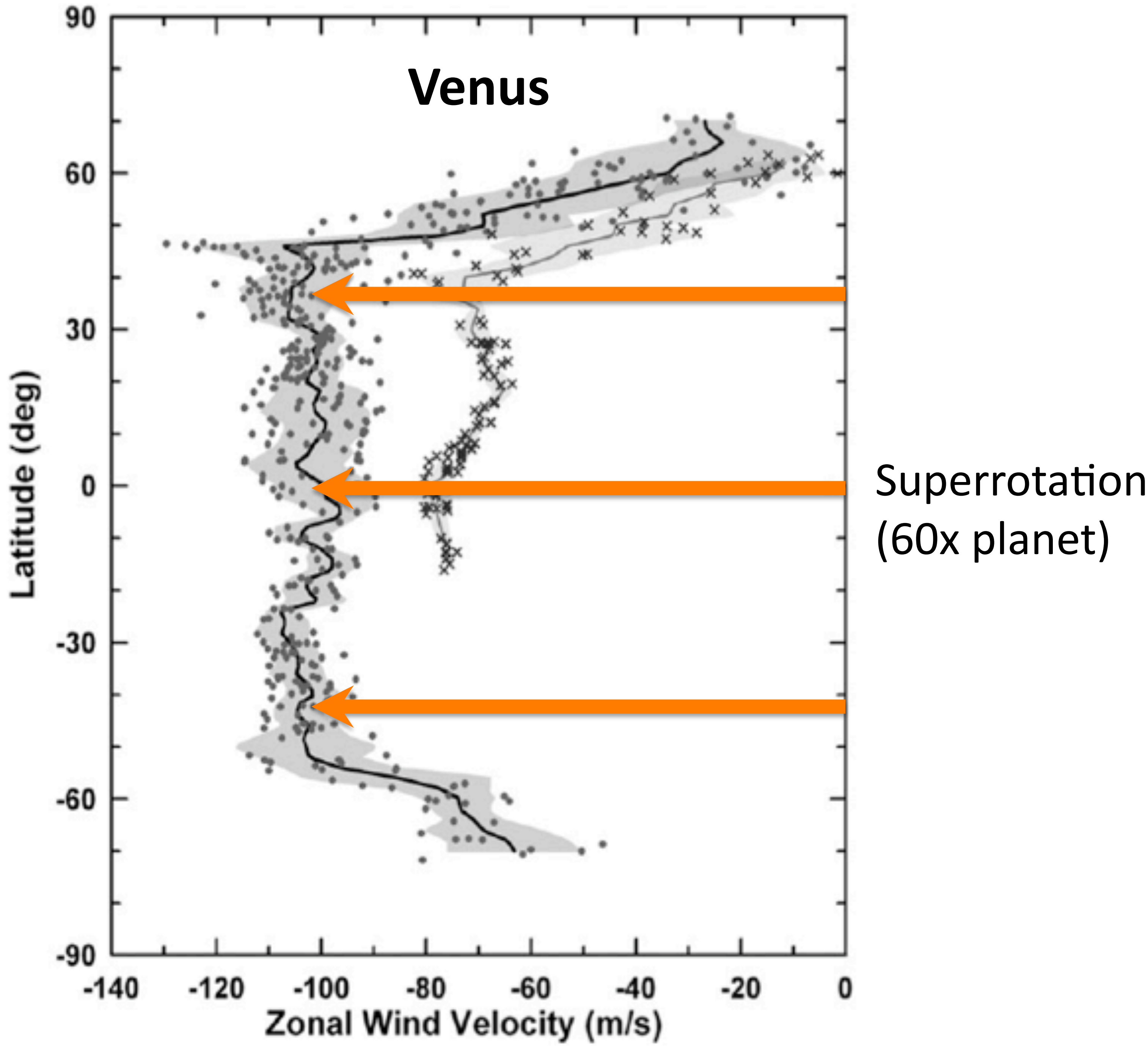
Heating enters the model through the hybrid vertical velocity, just as in a pure-θ model.

Example Results

Earth: Held Suarez

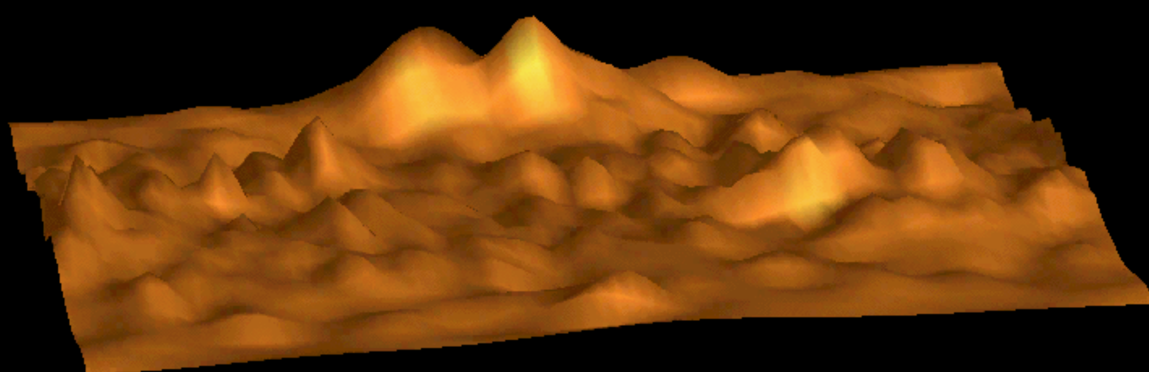


EPIC model results for Earth Held-Suarez benchmark. a) Mean zonal wind [m/s]; b) Mean square temperature eddies [K^2]; c) Mean temperature [K]; Mean potential temperature [K]. From Dowling et al. (2006)


Venus
90
60
30
0
-30
-60
-90
Latitude (deg)
-140
-120
-100
-80
-60
-40
-20
0
Zonal Wind Velocity (m/s)
Superrotation
(60x planet)

Example Results

Venus



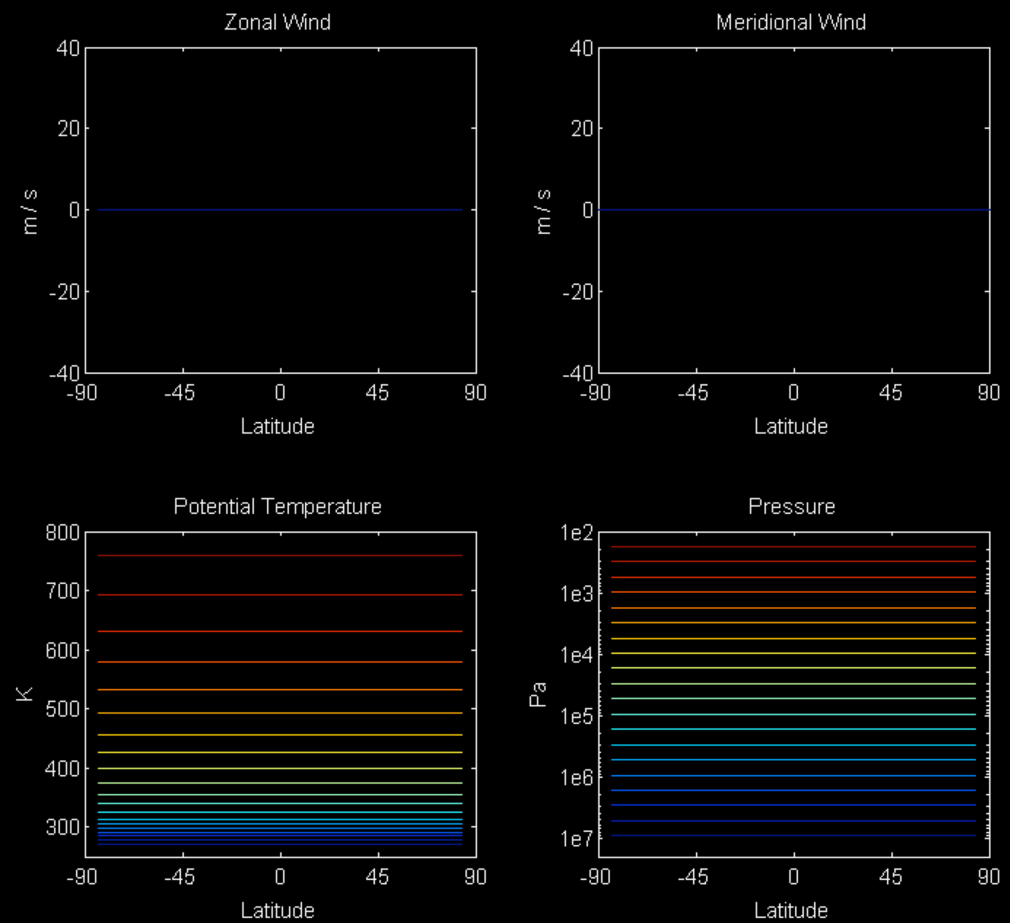
32x64
20 layers
90 bar to
.001 bar

- Venus rotation period is 243 (Earth) days, retrograde
- Atmosphere superrotates at 100 m/s (4-day wind)
- Hide's Theorem (1969) rules out superrotation for axisymmetric flow. Transient, 3D eddies are required.

Venus Superrotation

Flat topography case

Herrnstein and Dowling, 2007



P predicted

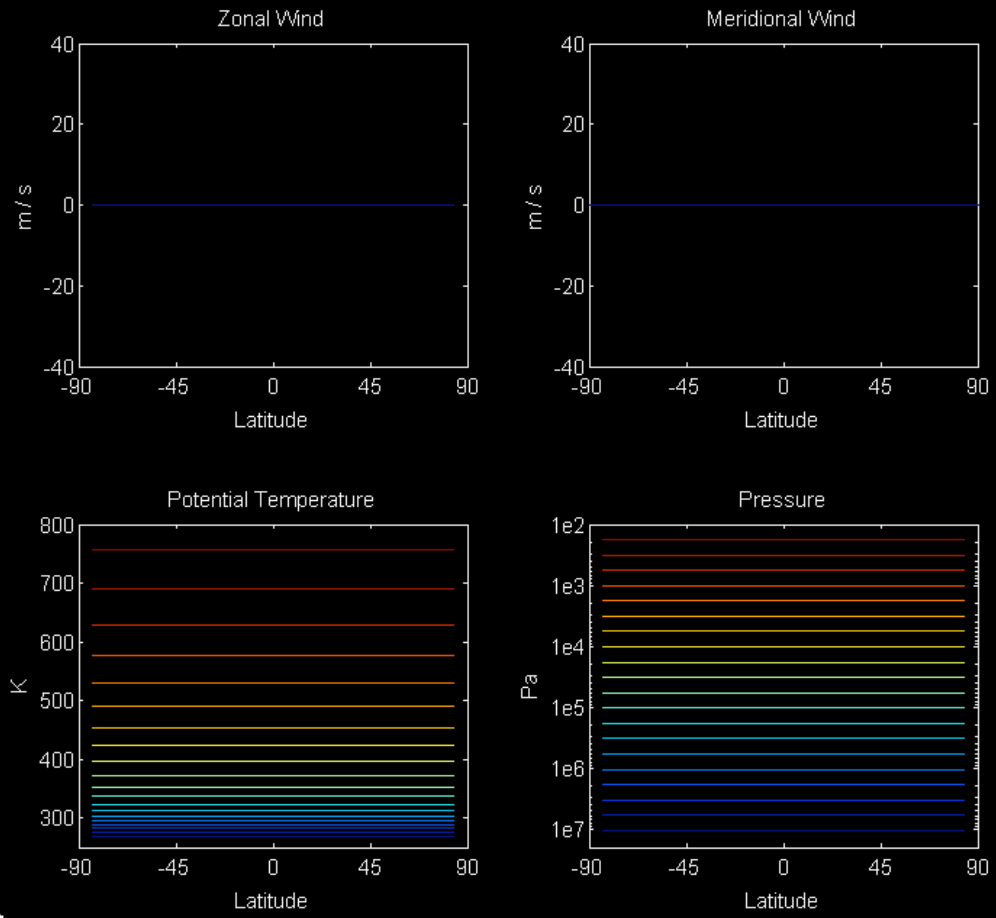
θ predicted

t = 0 yrs

- Simple Newtonian forcing (Lee, Lewis, Read 2005)
- Equator-to-pole Hadley cell rapidly forms polar jets
- Eddies mix zonal momentum towards equator

Venus Superrotation

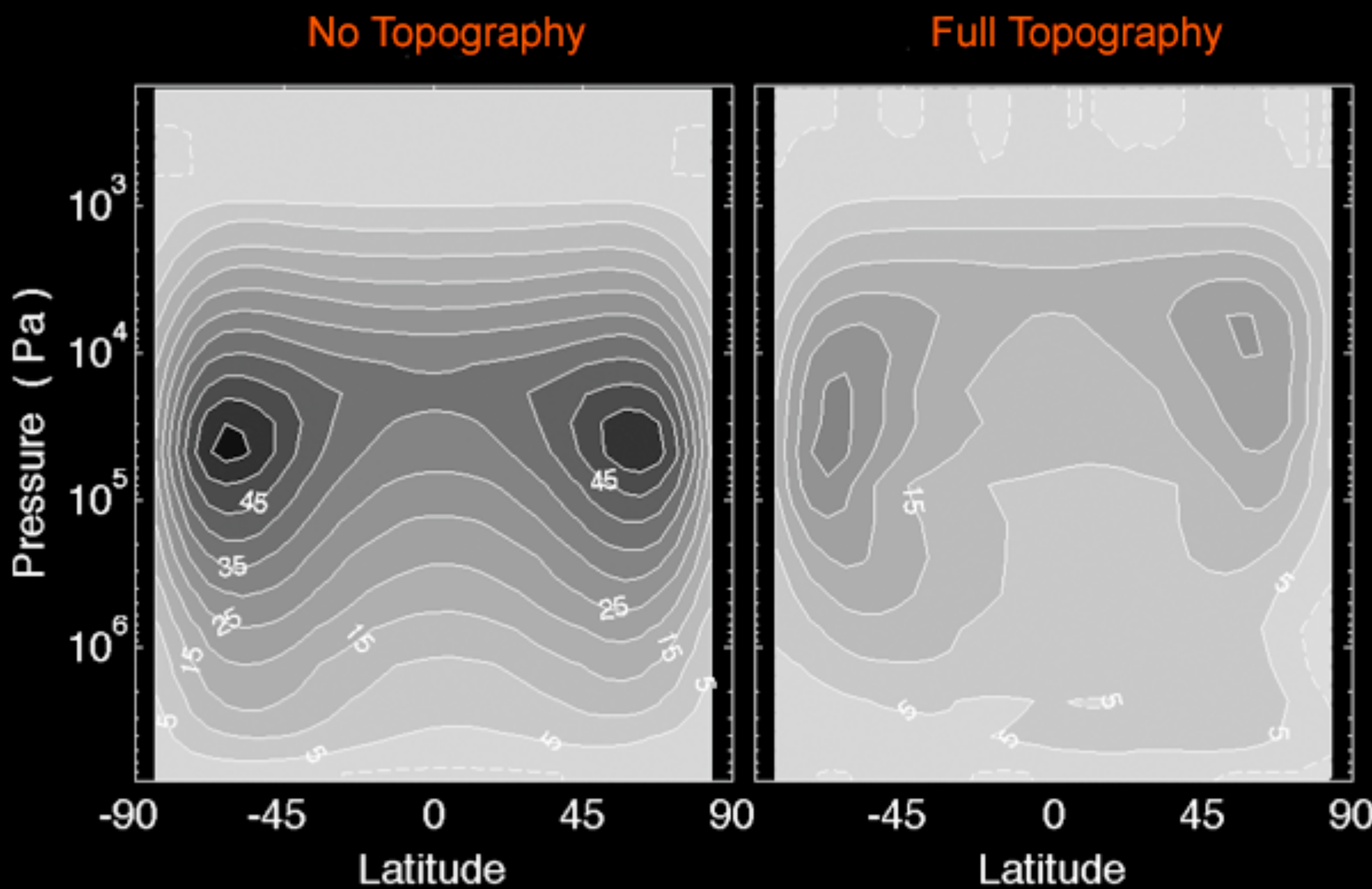
Full topography case



t = 0 yrs

Herrnstein and Dowling, 2007

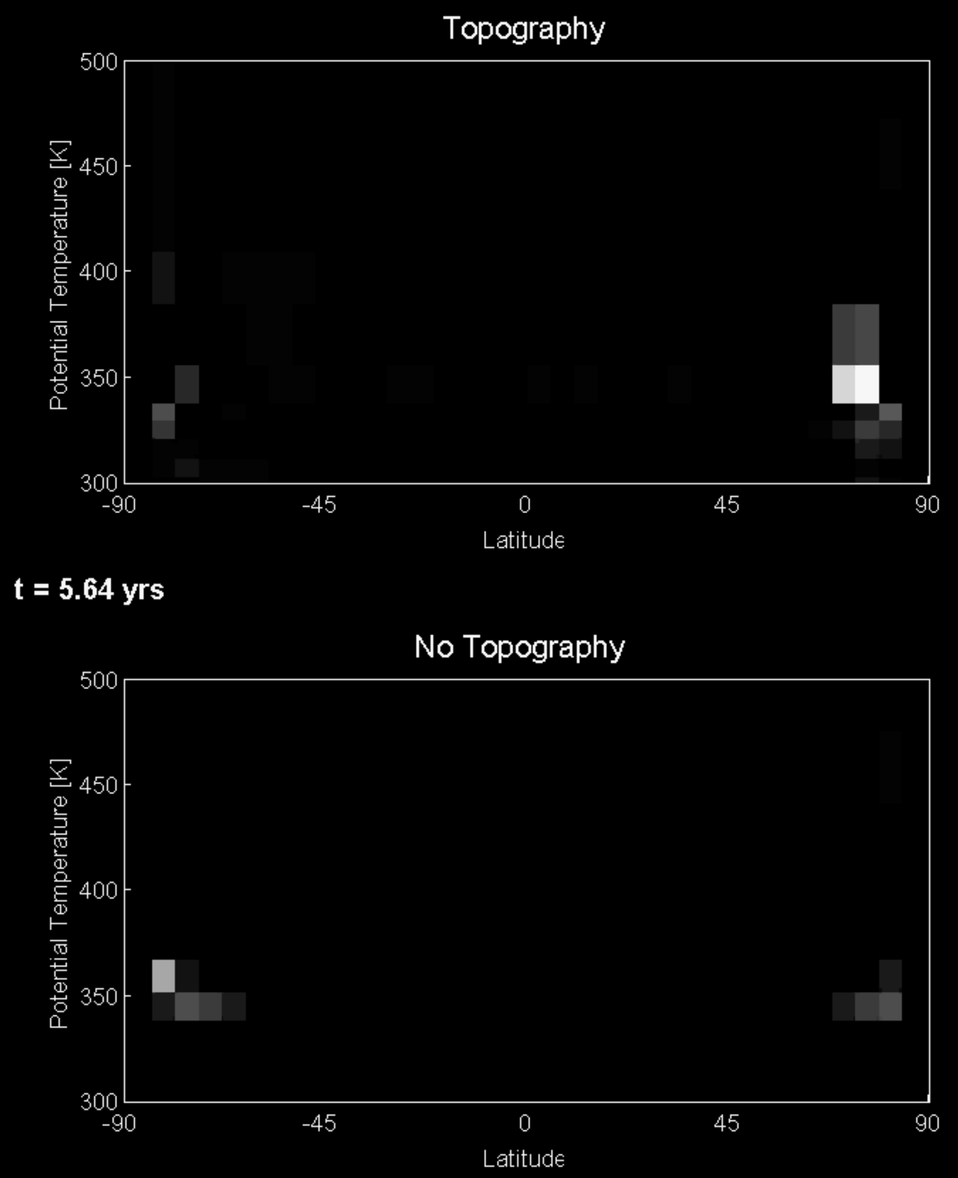
Venus Superrotation



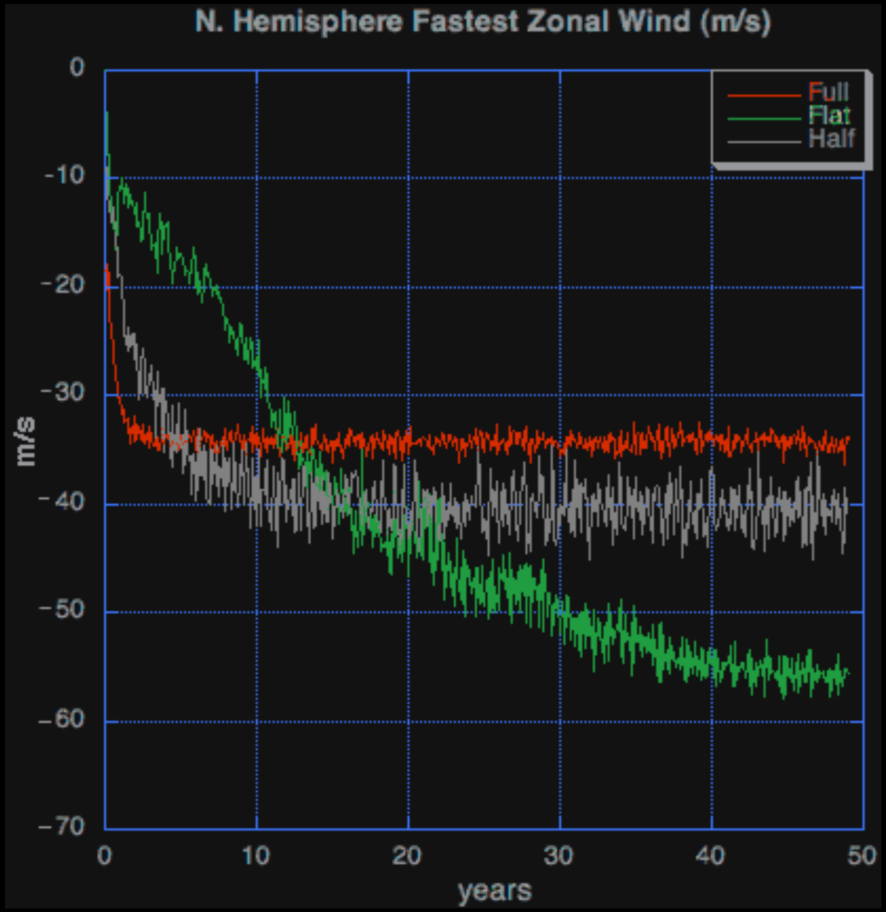
Venus Superrotation

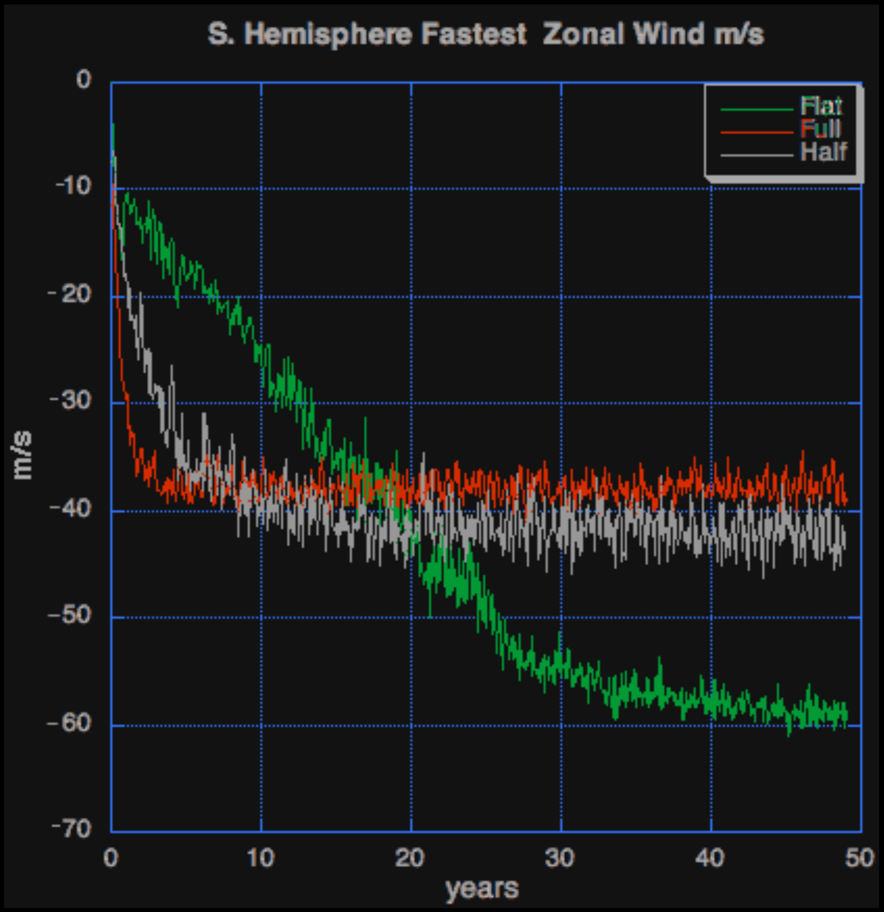
EP Flux Div

Herrnstein and Dowling, 2007



Venus Superrotation



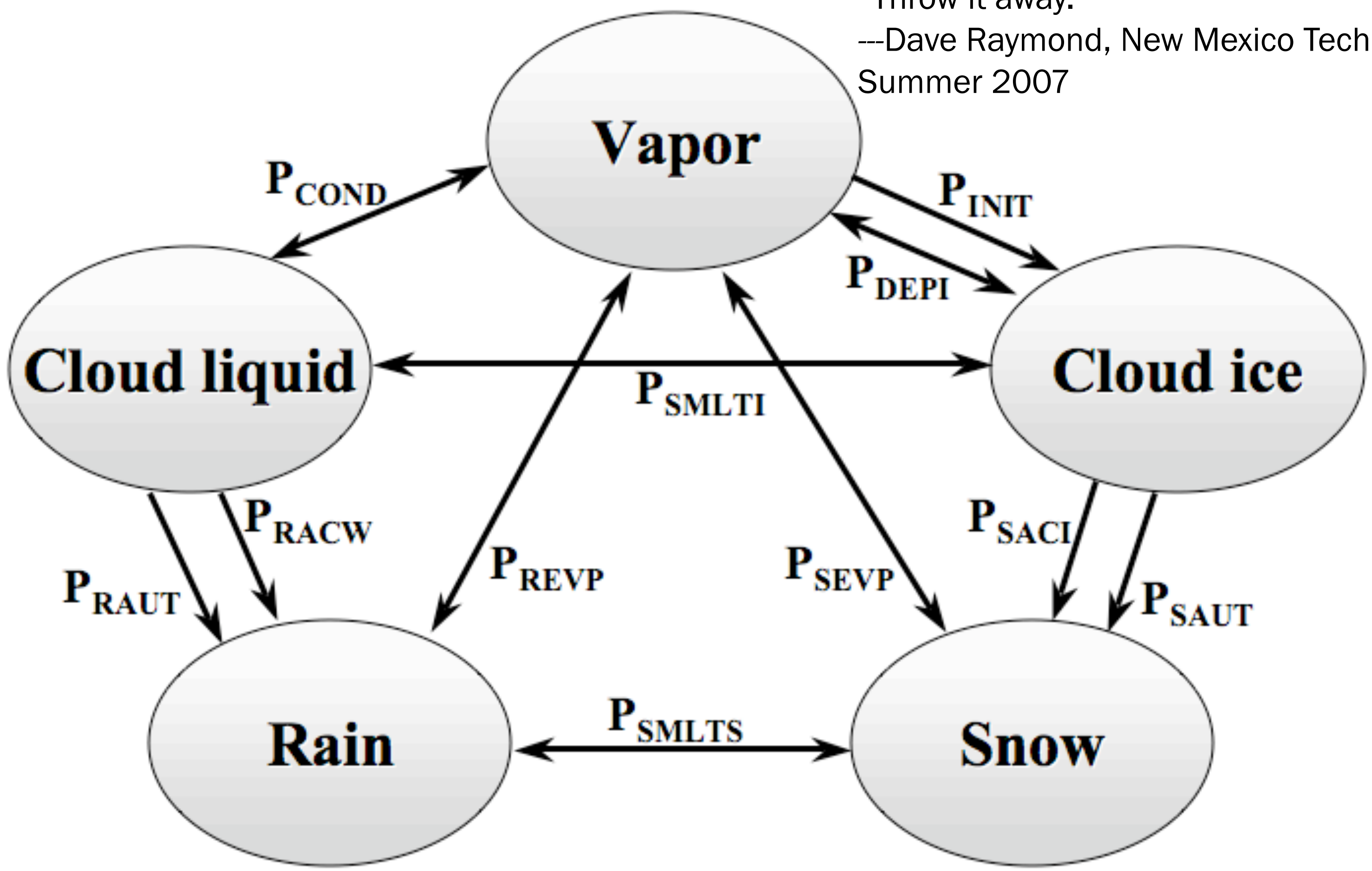


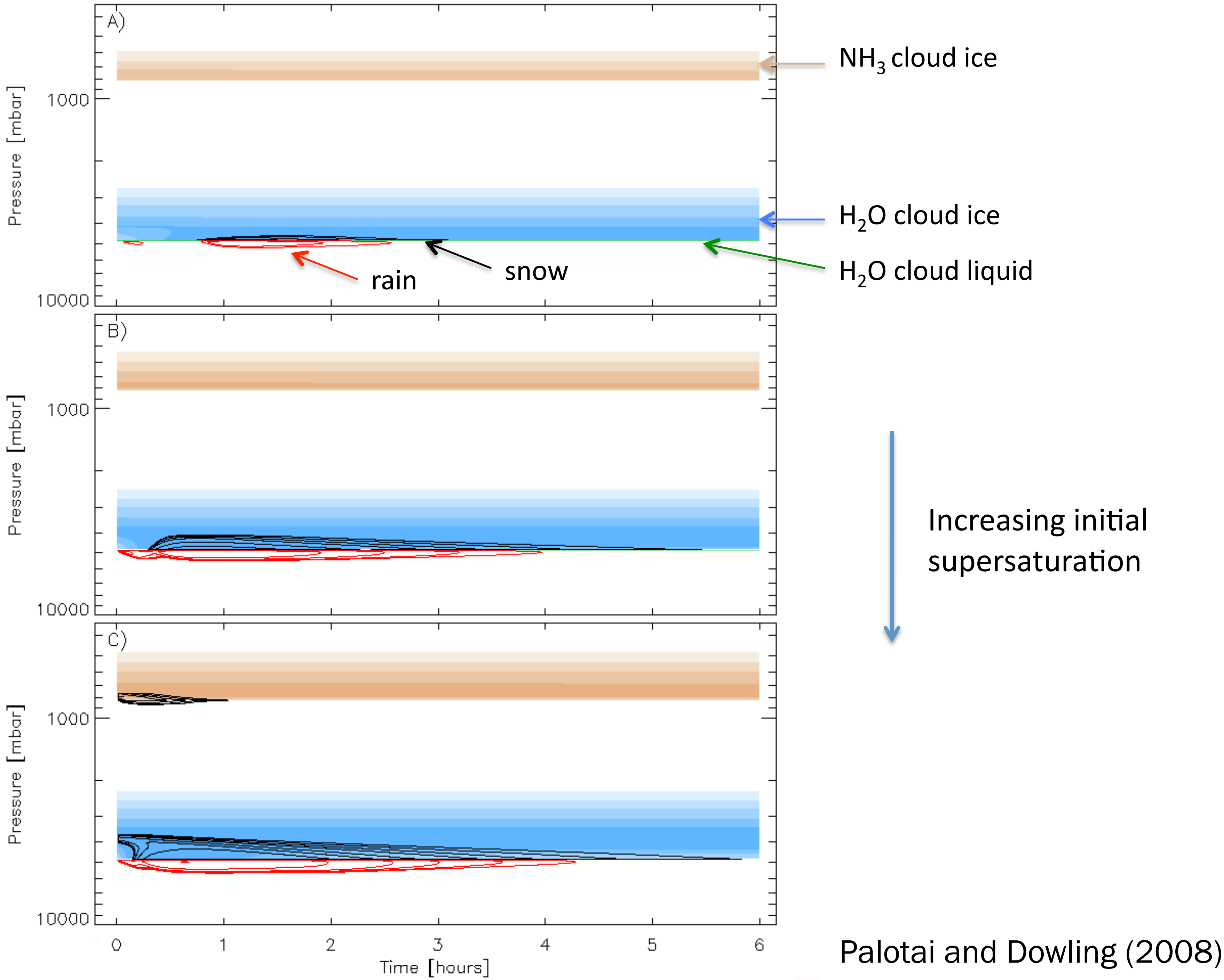
- Mountains provide a template for eddies: much faster spinup
- Mountain wave drag: max winds drop from 1/2 to 1/3 goal

Jupiter: Cloud Microphysics

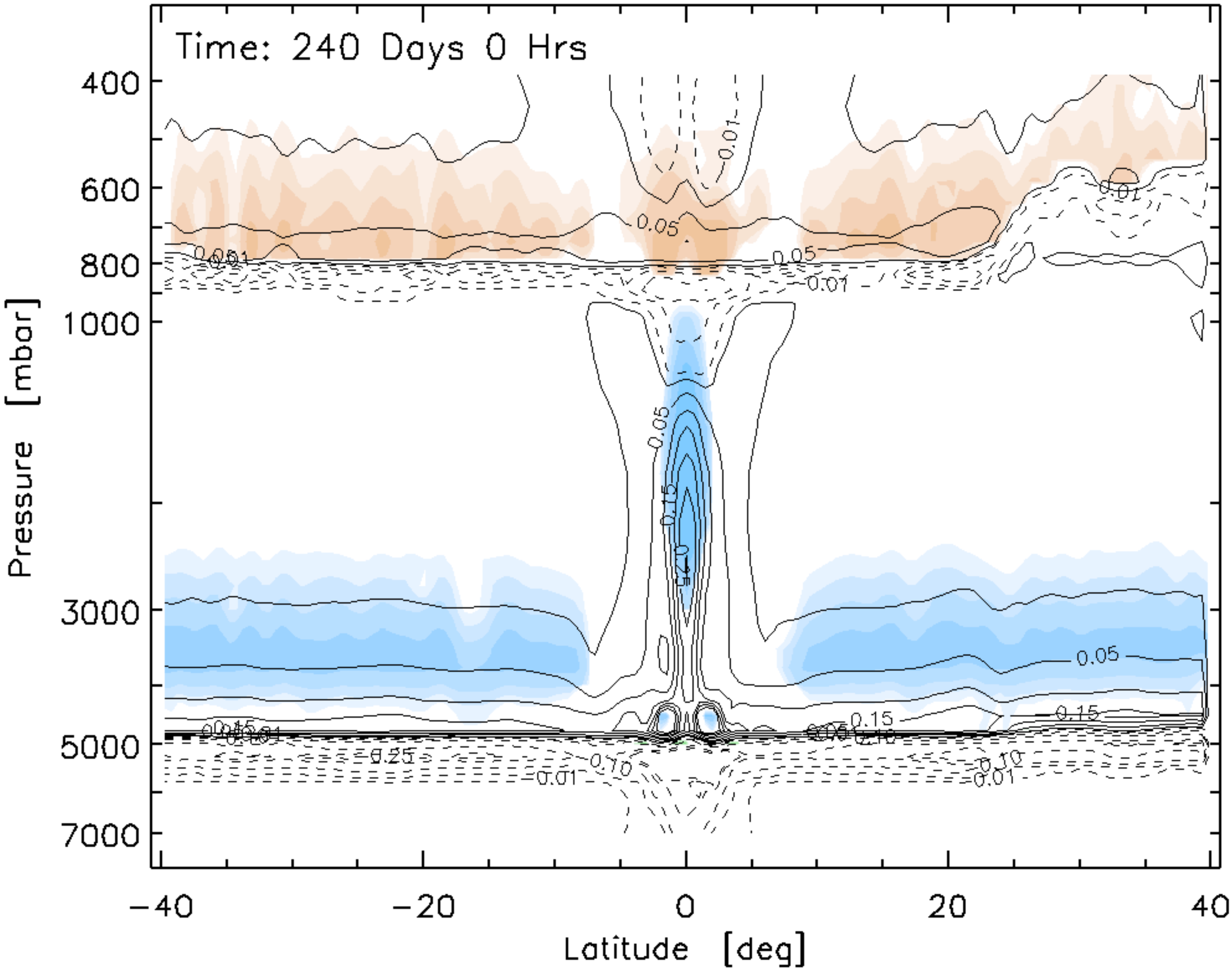
- 5-phase, 11 process cloud microphysics scheme adapted to Jupiter (Palotai and Dowling 2008)

"Throw it away."
---Dave Raymond, New Mexico Tech, Summer 2007

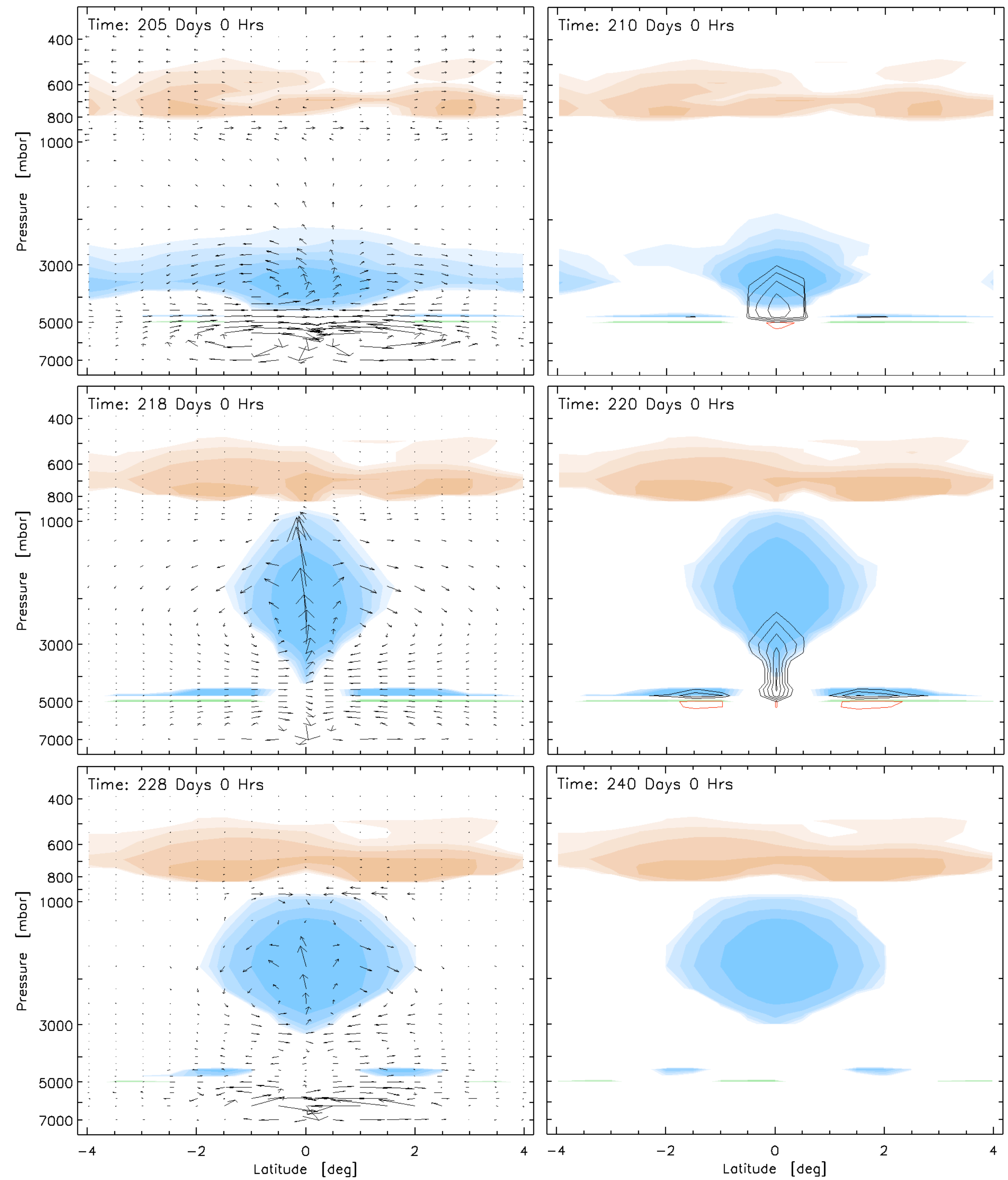




Palotai and Dowling (2008)

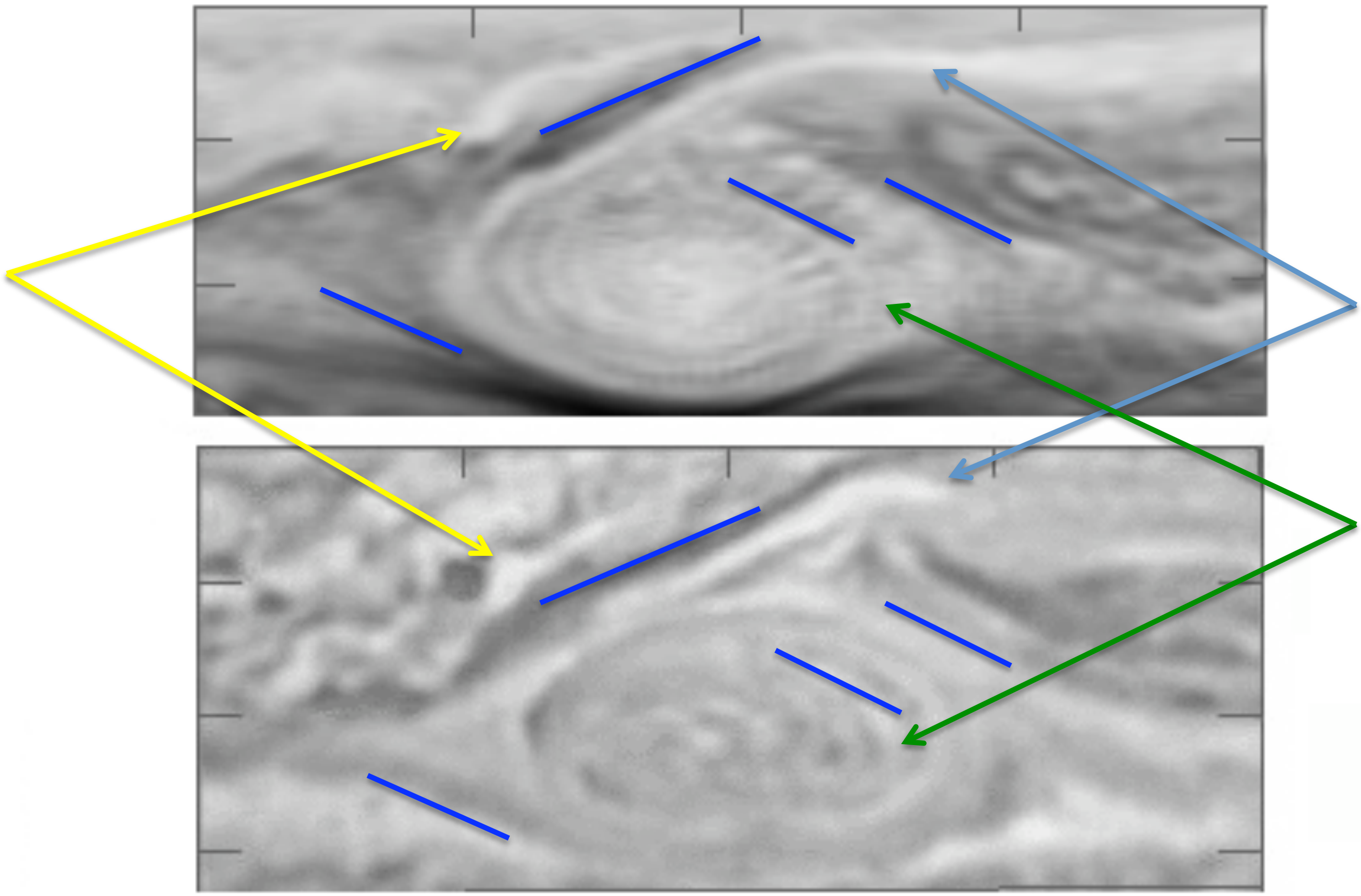


Time: 240 Days 0 Hrs
Pressure [mbar]
400
600
800
1000
3000
5000
7000
Latitude [deg]
−40
−20
0
20
40
0.01
0.05
0.15
0.10
0.25



Time: 205 Days 0 Hrs
Time: 210 Days 0 Hrs
Time: 218 Days 0 Hrs
Time: 220 Days 0 Hrs
Time: 228 Days 0 Hrs
Time: 240 Days 0 Hrs
Pressure [mbar]
400
600
800
1000
3000
5000
7000
Latitude [deg]
−4
−2
0
2
4

Consistency of Great Red Spot: Cassini vs. HST

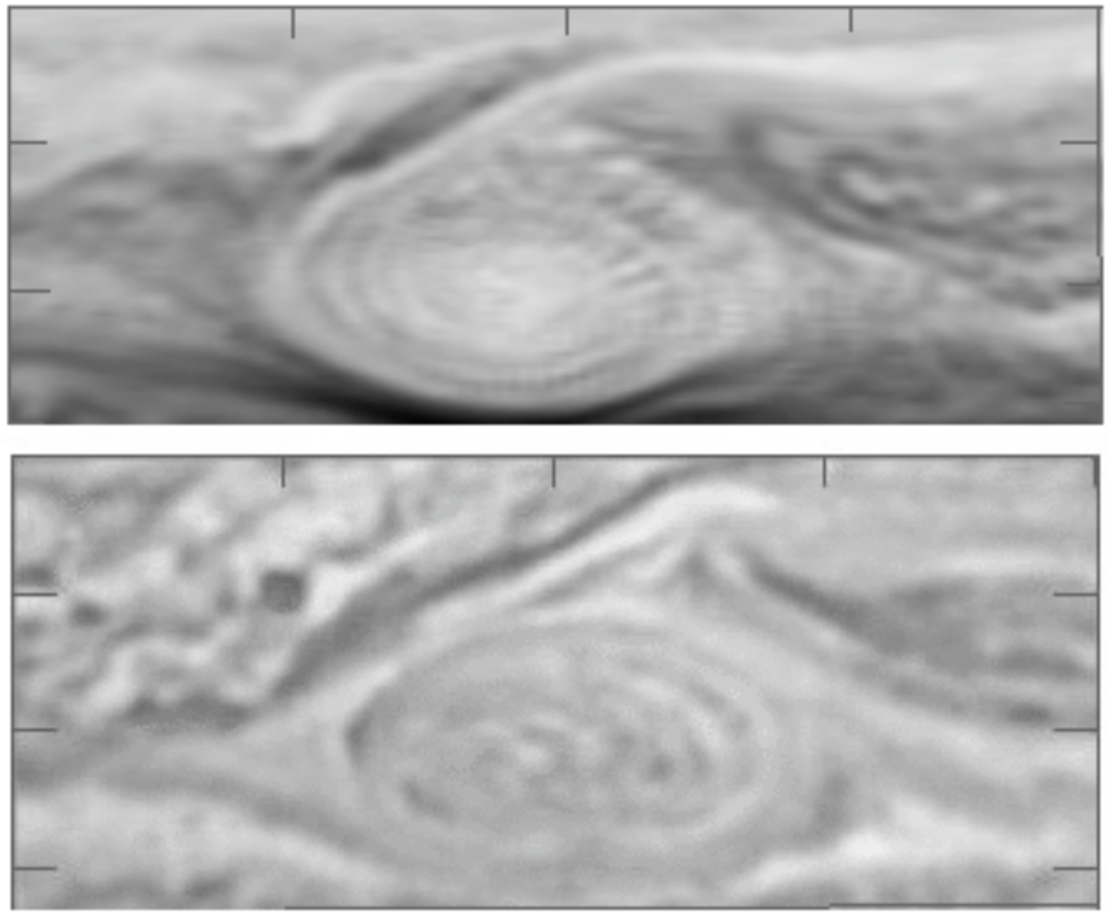


Only one of these is an observation

Top: EPIC model absolute vorticity at 8 bar

Bottom: HST visible image of GRS cloud tops = 0.7 bar

Missing from model: clouds, thunderstorms, radiative heating and cooling



Top: EPIC model absolute vorticity at 8 bar
Bottom: HST visible image of GRS cloud tops = 0.7 bar
Missing from model: clouds, thunderstorms, radiative heating and cooling

Summary, Part 1

Switching to $\theta = \theta_{diag}$ in the hybrid region, the EPIC model:

a. runs faster

b. is more robust

c. generates the same results

Remaining issues, Part 1

a. need to optimize bottom of transition, where θ_{diag} is touchy (e.g. division by vanishingly small $g[\sigma]$)

b. need to talk more people into trying hybrid-coordinate runs using the unprognosticated θ

Part 2. Retrofitting a Finite-Volume Horizontal Pressure-Gradient Force to the C-grid

Strong formulation: the horizontal pressure gradient force (PGF) splits into two terms in σ-θ coordinates

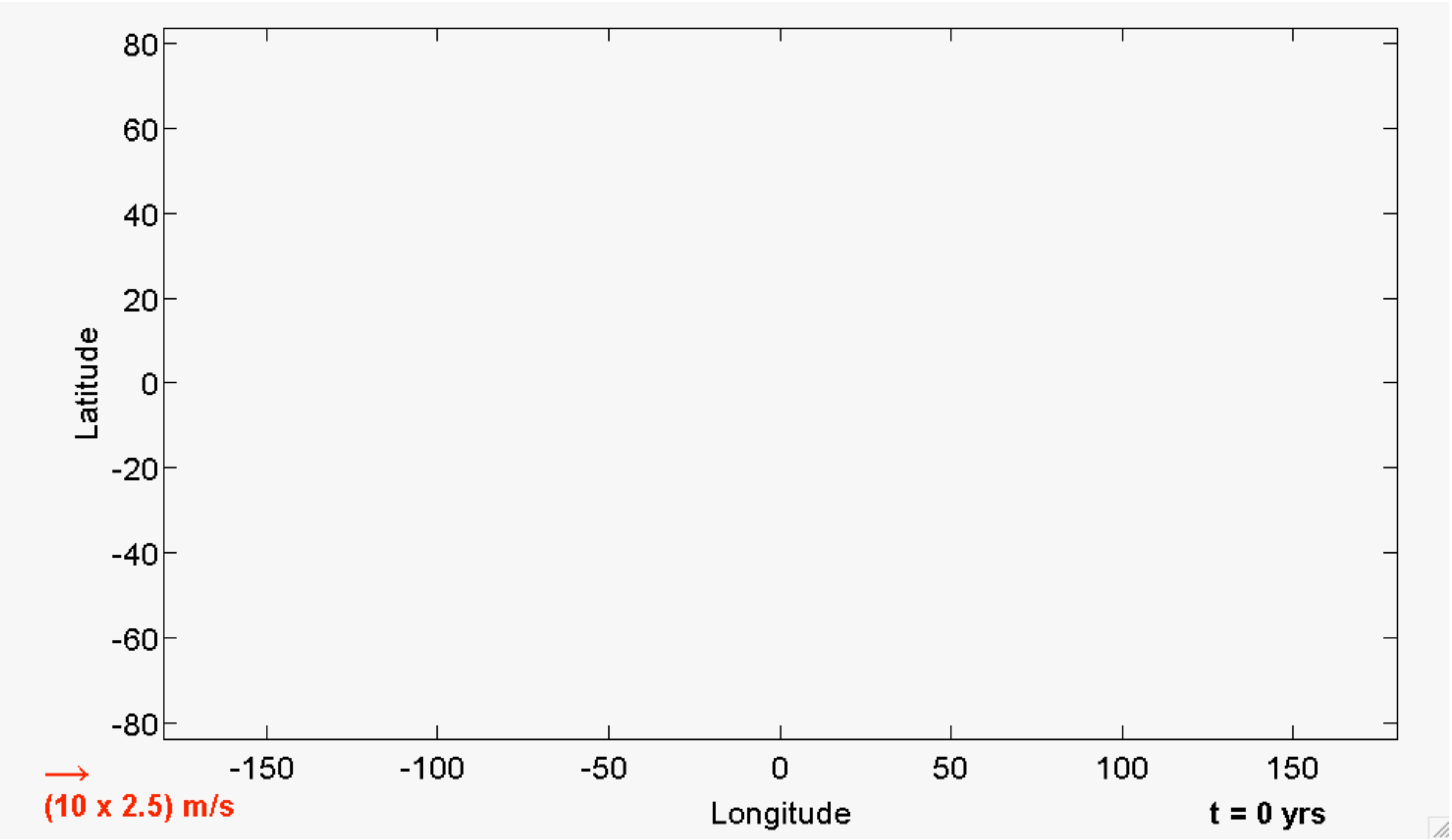
$$-\frac{1}{\rho}\nabla_z p = -\nabla_\zeta M + \Pi \nabla_\zeta \theta$$

As is well known, in steep terrain, the truncation errors for the two terms do not properly cancel, leading to an inaccurate PGF and spurious winds.

It gets worse---dry air on gas giants is a mixture of ortho and para H_2; fundamentally a two-component system described by the fraction of para-hydrogen, f_{para}. This splits the PGF again:

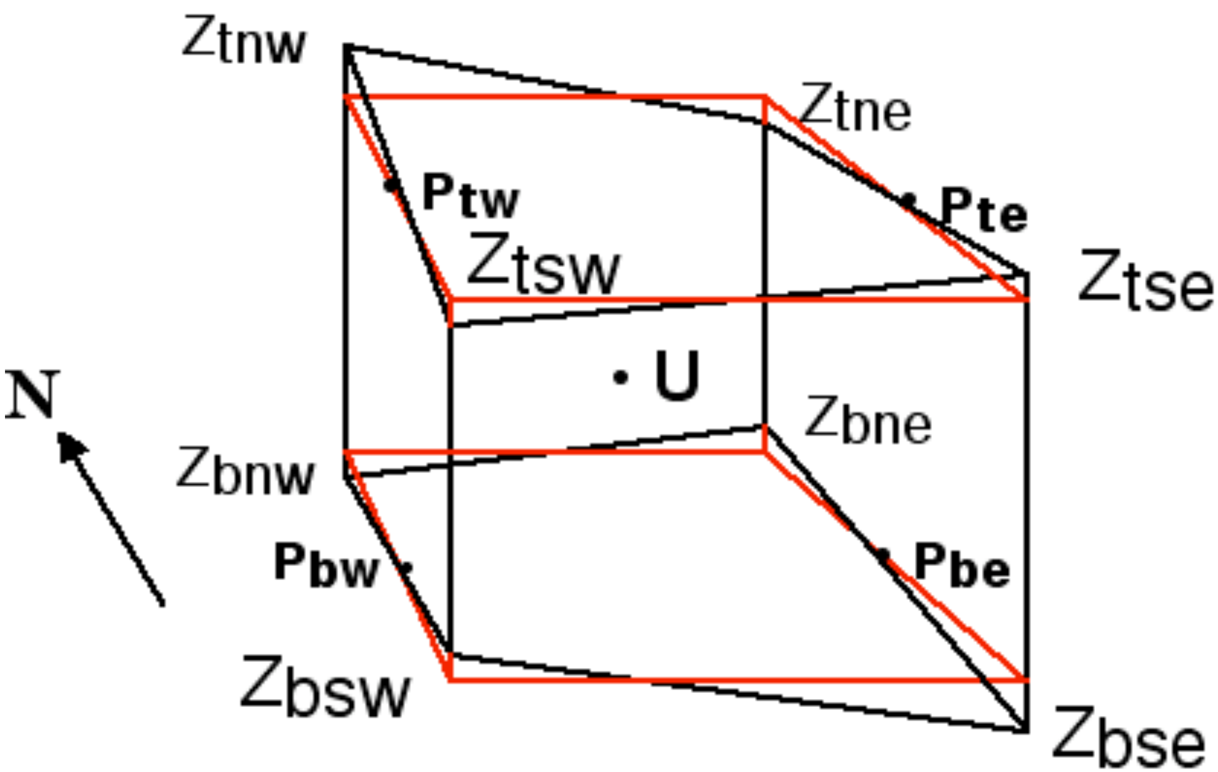
$$-\frac{1}{\rho}\nabla_z p = -\nabla_\zeta M - F_{gibb}(T)\nabla_\zeta f_{para} + \Pi \nabla_\zeta \theta$$

We are encountering spurious surface winds in our Venus spinup experiments using the strong-formulation PGF.



Weak formulation PGF:
Compute component pressure force on six sides, divide by mass.

Can apply this without switching rest of GCM to finite volume (delaying the inevitable…)



Assumptions:

1. Latitude map factors are linear across cell
2. 4 P values used to set pressure
3. P = a*z+b on each face
4. Arbitrary heights, z, on 8 corners

$$-\frac{1}{\rho}\frac{\partial p}{\partial x}\Big|_z = -\frac{1}{\rho}\frac{1}{r}\frac{\partial p}{\partial \phi}\Big|_z = \frac{1}{\bar{\rho}}\frac{1}{\Delta\phi}\frac{top - bottom + west - east}{r_s(\delta z_s + {}^1\!/_2\,\delta z_n) + r_n(\delta z_n + {}^1\!/_2\,\delta z_s)} ,$$

where

$$top = \begin{cases} 0\,, & z_{\rm te} = z_{\rm tw}\,; \\ \dfrac{-t_1(p_{\rm tw} - p_{\rm te}) + t_2(z_{\rm te}p_{\rm tw} - z_{\rm tw}p_{\rm te})}{z_{\rm te} - z_{\rm tw}}\,, & z_{\rm te} \neq z_{\rm tw} \end{cases}$$

$$t_1 = (z_{\rm tne} + z_{\rm tse})^2 - z_{\rm tne}z_{\rm tse} - (z_{\rm tnw} + z_{\rm tsw})^2 + z_{\rm tnw}z_{\rm tsw}\,,$$

$$t_2 = 3(z_{\rm tne} + z_{\rm tse} - z_{\rm tnw} - z_{\rm tsw})\,,$$

$$bottom = \begin{cases} 0\,, & z_{\rm be} = z_{\rm bw}\,; \\ \dfrac{-b_1(p_{\rm bw} - p_{\rm be}) + b_2(z_{\rm be}p_{\rm bw} - z_{\rm bw}p_{\rm be})}{z_{\rm be} - z_{\rm bw}}\,, & z_{\rm be} \neq z_{\rm bw} \end{cases}$$

$$b_1 = (z_{\rm bne} + z_{\rm bse})^2 - z_{\rm bne}z_{\rm bse} - (z_{\rm bnw} + z_{\rm bsw})^2 + z_{\rm bnw}z_{\rm bsw}\,,$$

$$b_2 = 3(z_{\rm bne} + z_{\rm bse} - z_{\rm bnw} - z_{\rm bsw})\,,$$

$$west = east(I-1)\,,$$

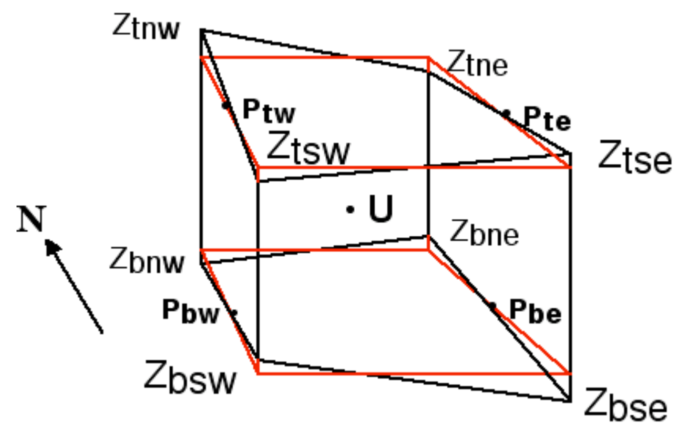
$$east = \frac{-e_1(p_{\rm be} - p_{\rm te}) + e_2(z_{\rm te}p_{\rm be} - z_{\rm be}p_{\rm te})}{z_{\rm te} - z_{\rm be}}\,,$$

$$e_1 = (z_{\rm tne} + z_{\rm tse})^2 - z_{\rm tne}z_{\rm tse} - (z_{\rm bne} + z_{\rm bse})^2 + z_{\rm bne}z_{\rm bse}\,,$$

$$e_2 = 3(z_{\rm tne} + z_{\rm tse} - z_{\rm bne} - z_{\rm bse})\,,$$

$$\delta z_n = z_{\rm tne} - z_{\rm bne} + z_{\rm tnw} - z_{\rm bnw}\,,$$

$$\delta z_s = z_{\rm tse} - z_{\rm bse} + z_{\rm tsw} - z_{\rm bsw}\,.$$



Given 8 arbitrary corner altitudes and p = a z + b, yields PGF = 0 exactly.

Current task: Non-trivial problem of constructing a static initial condition with p = p(z).

(Mathematica-supplied fortitude)

Summary, Part 2

Switching to weak-formulation for the horizontal pressure gradient force:

a. Eliminates two-term split in PGF and their misaligned truncation errors in steep topography

b. Eliminates two-term split in PGF for ortho-para hydrogen

EPIC now has a finite-volume PGF that yields zero for 8 arbitrary corners when $p = a z + b$ across the cell

Remaining issues, Part 2

a. Constructing a static (u, v = 0) initial condition that precisely satisfies $p_{k+½} = p_{dat}(z_{k+½}[p,\theta])$ on the grid, which is implicit in pressure, poses a challenge in hybrid coordinates