Some Crucial Aspects of Atmospheric Dynamics

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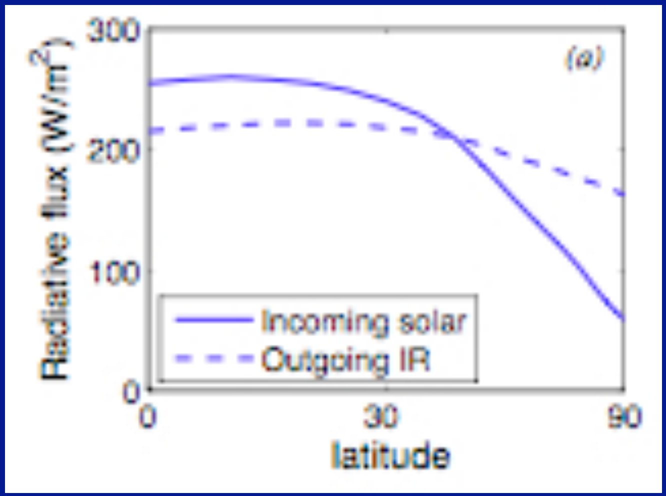
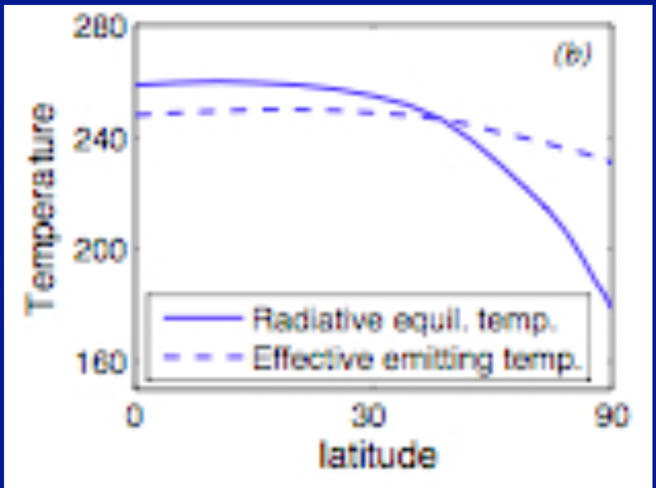
OUTLINE

- Some relevant fluid dynamics fundamentals
- Recent idealized, 3-D calculations
  (giant planets only in this talk)
- Numerical smell test
- An important missing physics
- Summary

RADIATIVE-DYNAMICAL INTERACTION





Incoming (SW) and outgoing (LW) radiation is NOT homogeneous over the planet

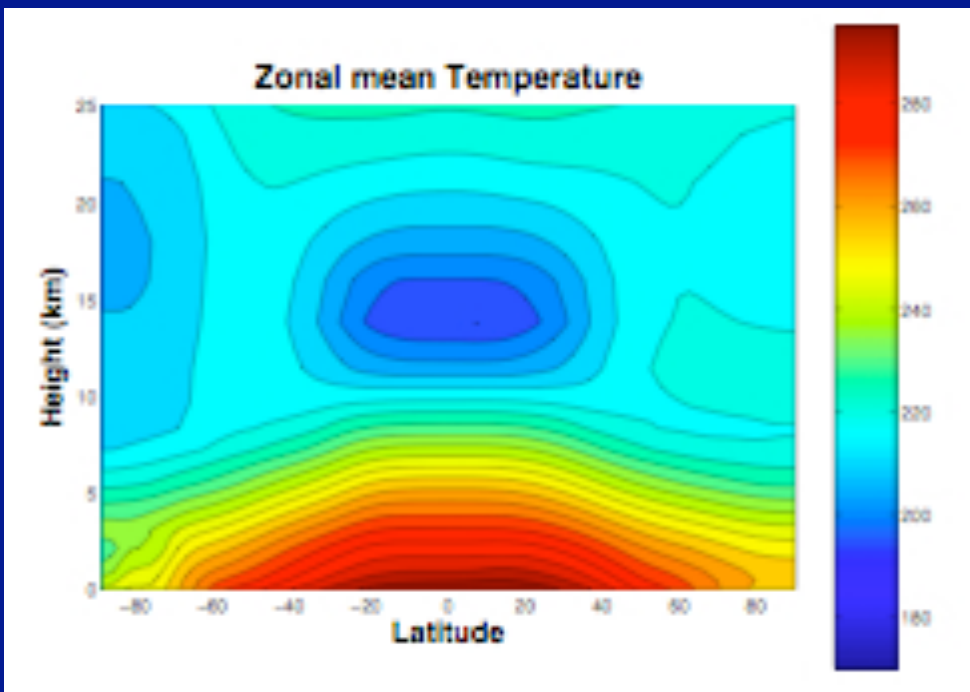
The atmosphere is NOT directly driven by stellar irradiation, particularly in the radiative layers (unless there are absorbers).

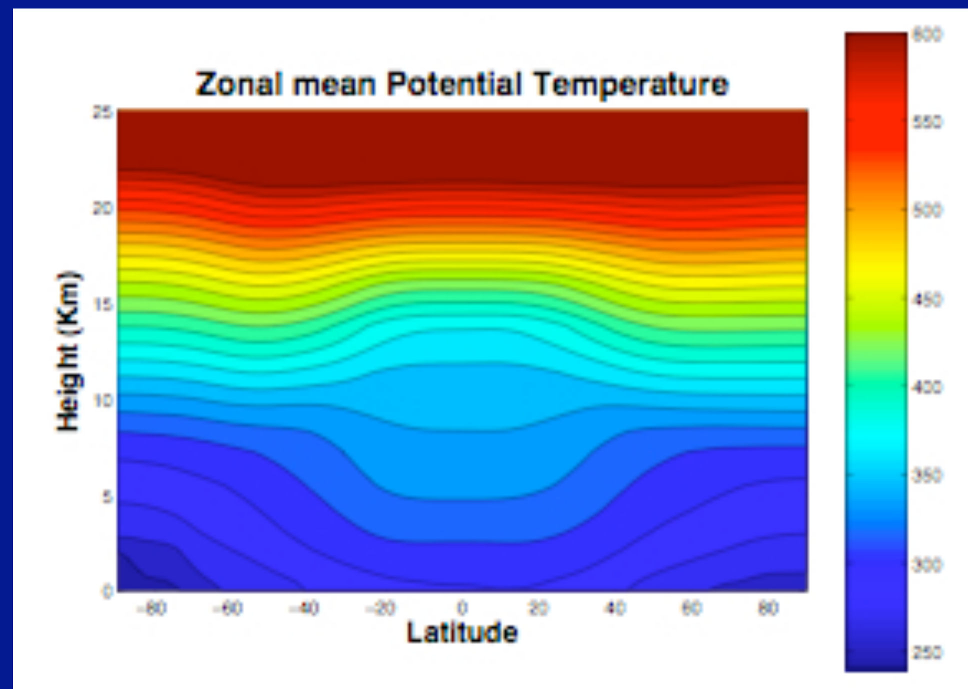
The gradient of the difference between radiative equilibrium temperature and effective emitted temperature drives the flow, BUT the flow changes both.

Most of the transport is not direct: eddies and waves do most of the work.

TEMPERATURE STRUCTURE IS COMPLEX!

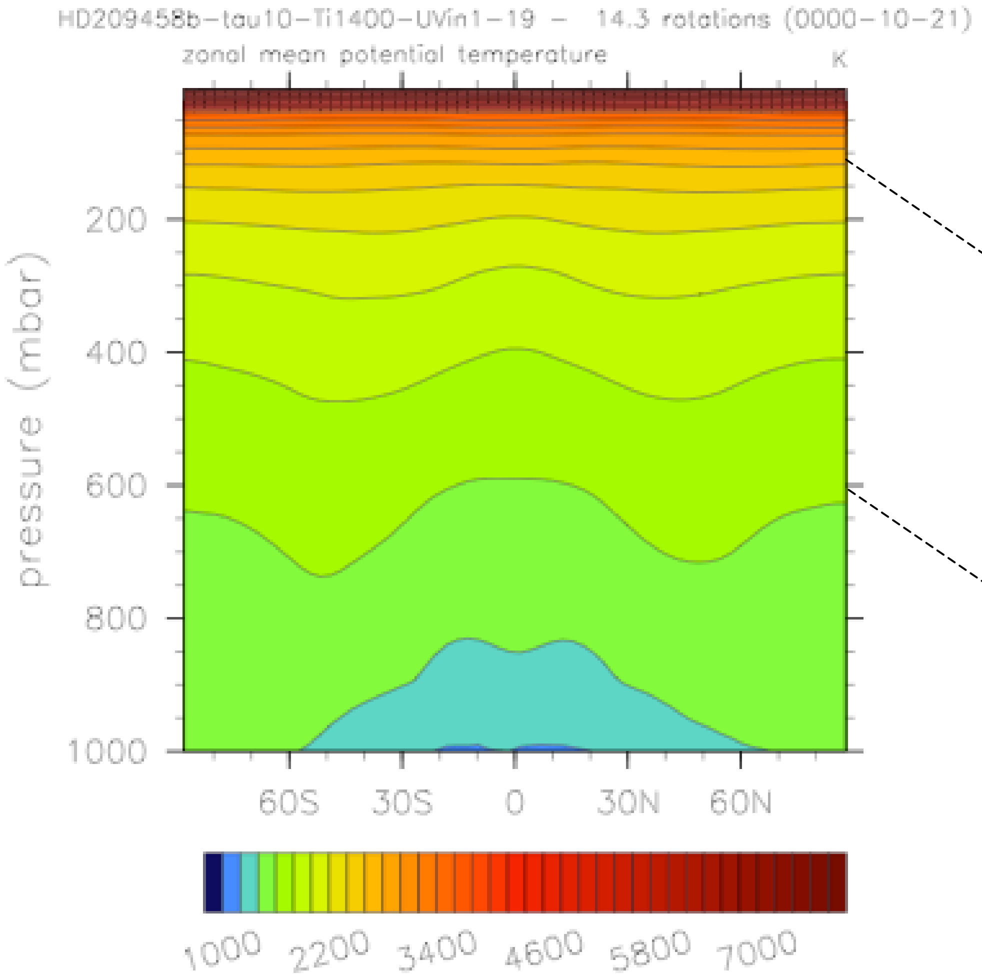
Earth but still very illustrative -- also, fairly well understood.

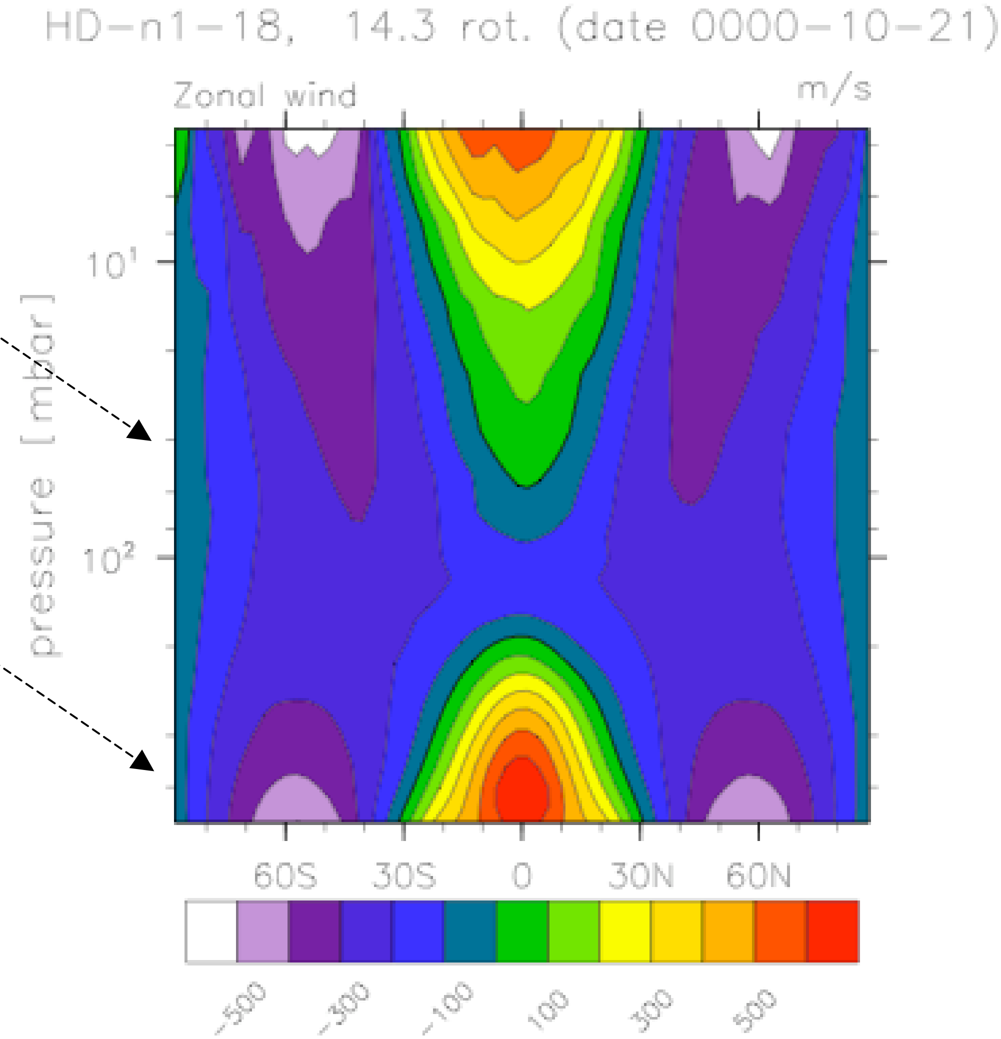




Clever transformations [e.g., potential temperature, $\theta = T(p_R/p)^K$] very useful.

MEAN ZONAL POTENTIAL TEMP. & WIND





PRIMITIVE EQUATIONS

- Fundamental set of equations in Geophysical Fluid Dynamics.

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} + w\frac{\partial \mathbf{v}}{\partial z} = -\frac{1}{\rho}\nabla p - f\hat{\mathbf{k}}\times\mathbf{v} + F_{\mathbf{v}} + D_{\mathbf{v}}$$

$$\frac{\partial p}{\partial z} = -\rho g$$

$$\frac{\partial \rho}{\partial t} + \mathbf{v}\cdot\nabla\rho + w\frac{\partial \rho}{\partial z} = -\rho\left(\nabla\cdot\mathbf{v} + \frac{\partial w}{\partial z}\right)$$

$$\frac{\partial \theta}{\partial t} + \mathbf{v}\cdot\nabla\theta + w\frac{\partial \theta}{\partial z} = F_\theta + D_\theta$$

$$p = \rho R T$$

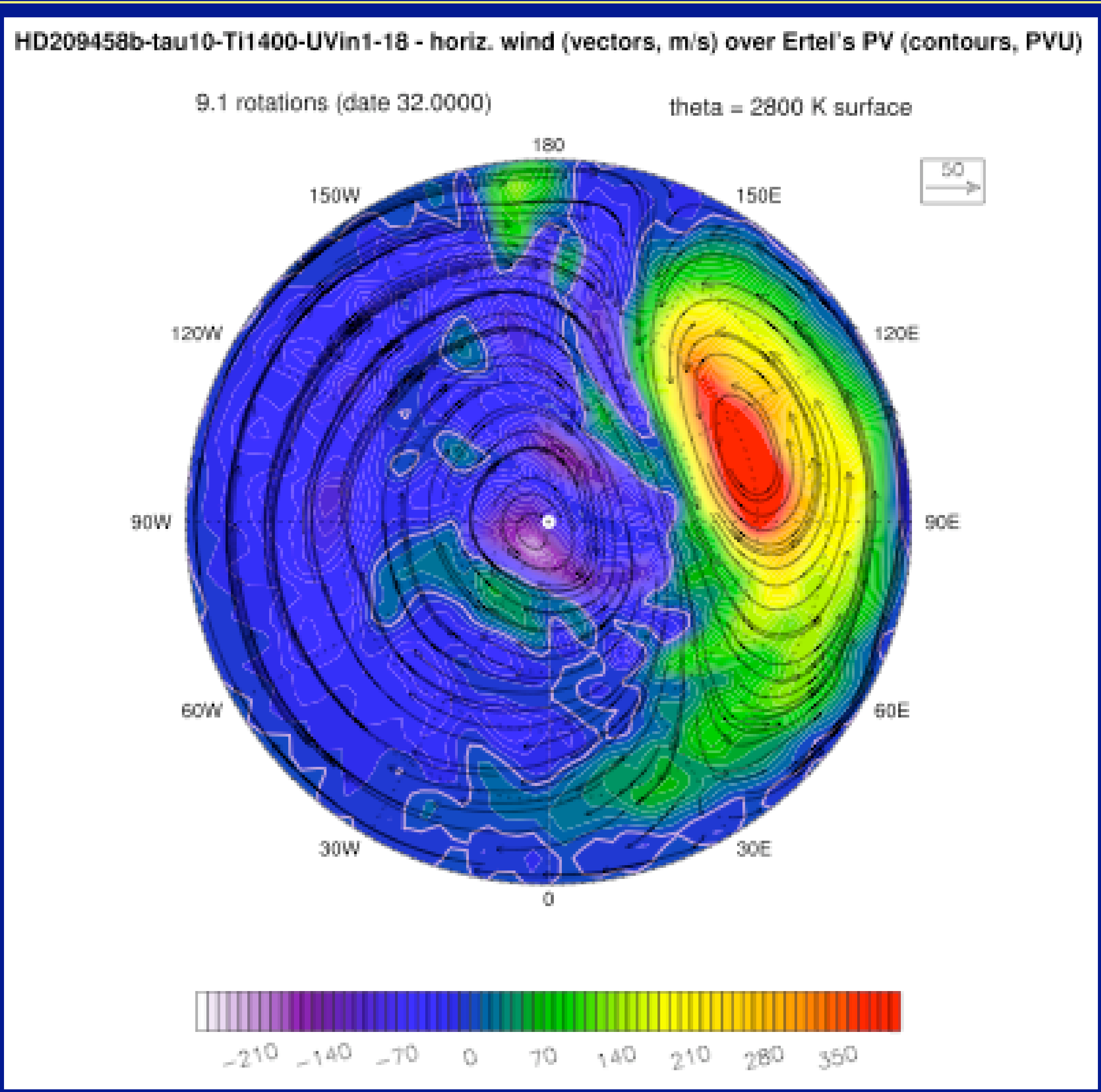
$\mathbf{v}$ = lateral winds
w = vertical wind
p = pressure
ρ = density
F = sources
D = sinks
f = Coriolis param.
g = gravity
θ = potential temp.
T = temperature
R = gas constant

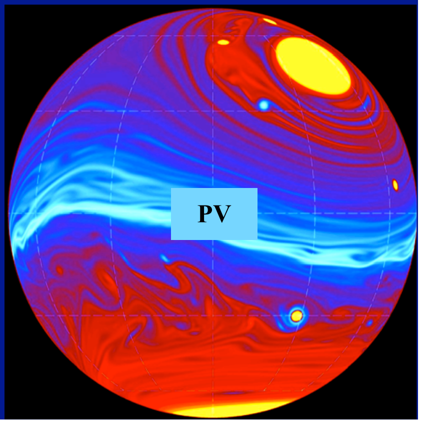
- Currently, equations only *APPROXIMATELY* solved: use them to gain physical insights and STUDY MECHANISMS AND NOT MAKE HARD “PREDICTIONS”.

3-D GENERAL CIRCULATION MODEL

- NCAR Community Atmospheric Model (CAM/CCM3)
- T21, T42, T85, T106 resolutions + L layers [26 here] (*pseudospectral* horizontal, finite difference vertical)
- Extensively tested, full global climate model
- Physics parameterizations (e.g., convective adjustment, radiation, gravity wave, H2O, O3, etc.)

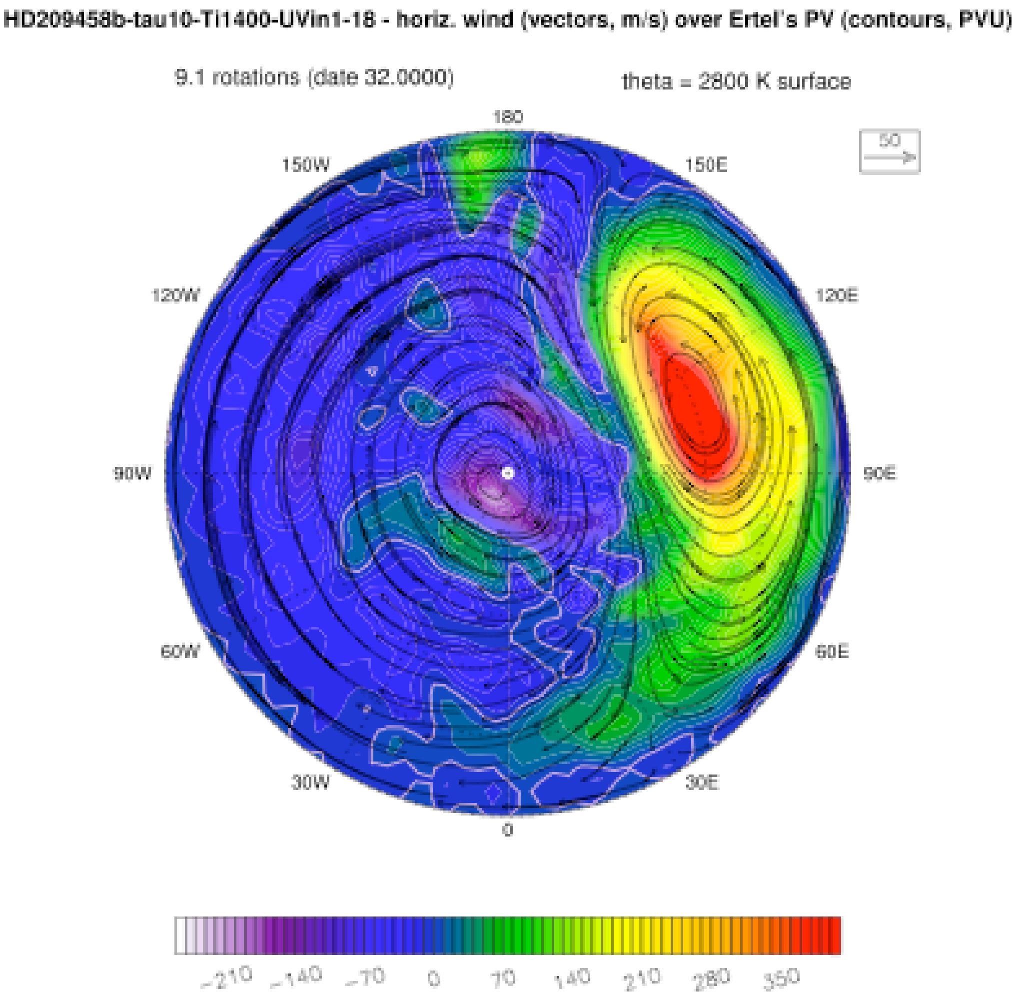
SPATIAL COMPLEXITY AND VARIABILITY

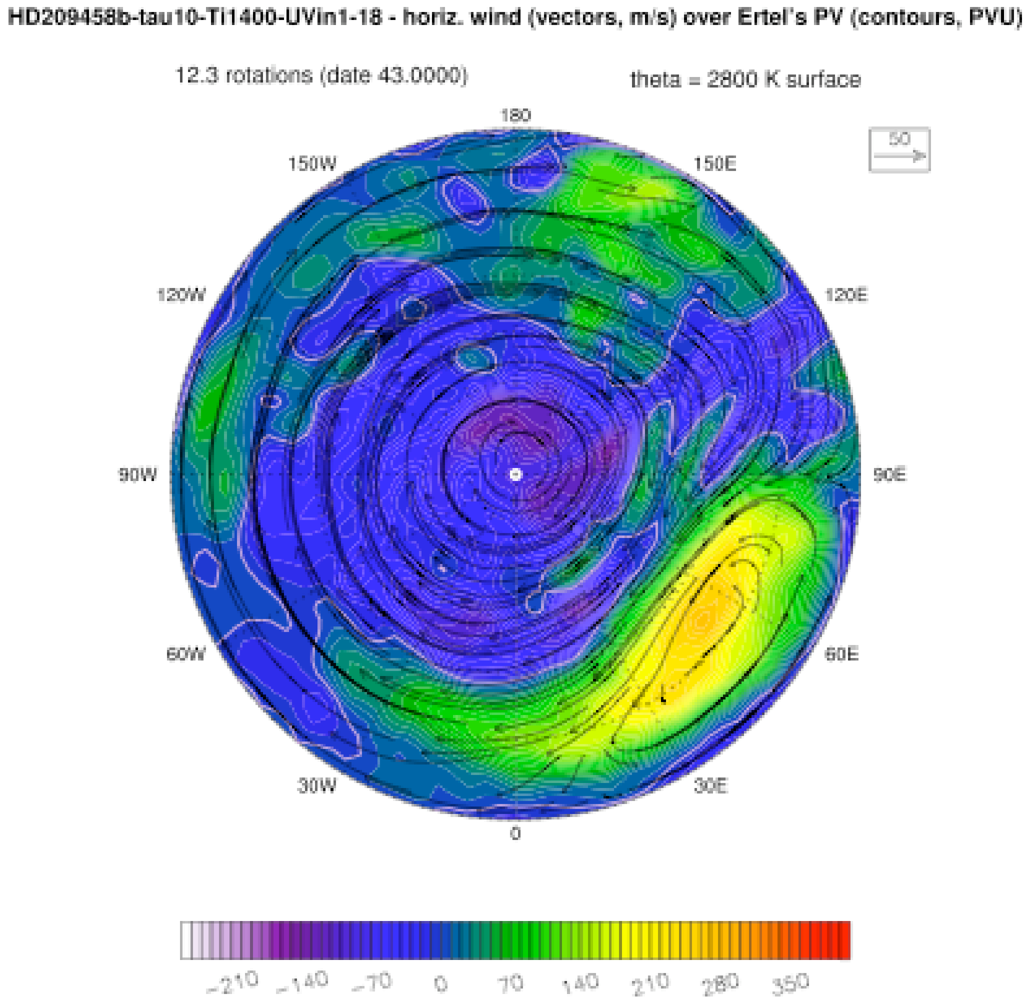




POTENTIAL VORTICITY (PV)

EXO-STORMS (TIME VARIABILITY)

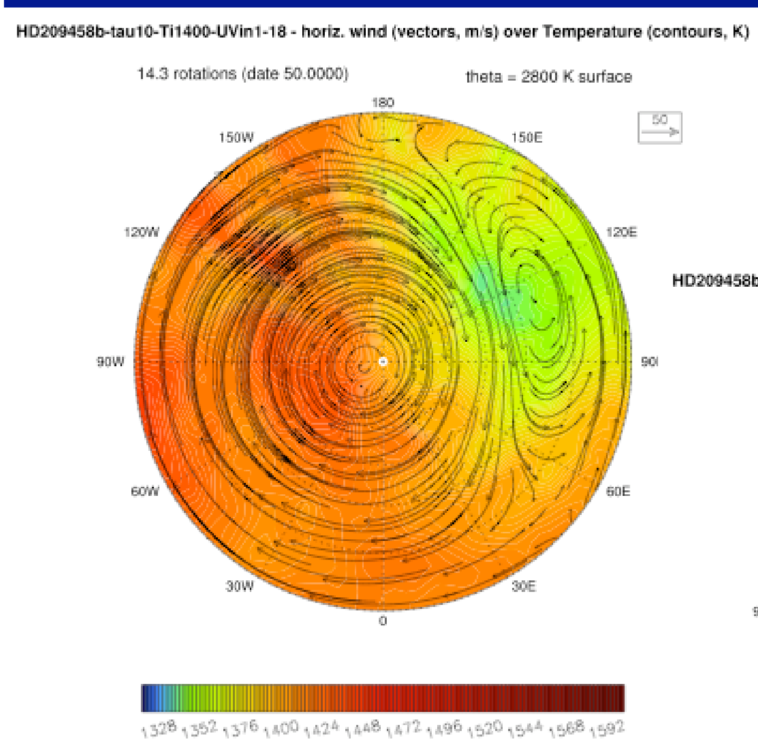




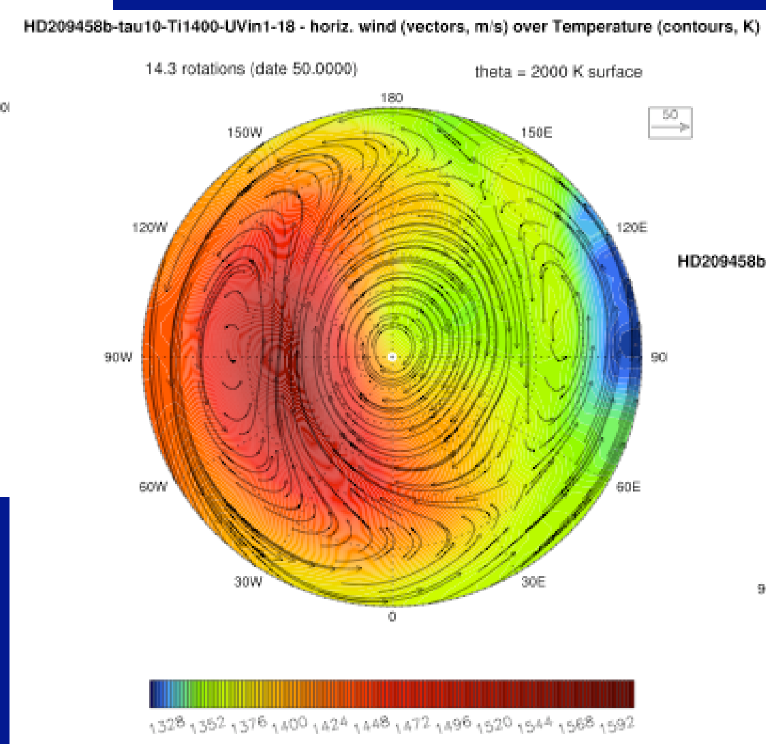
"Of course, there is a movie."

TEMPERATURE (3 HEIGHTS)

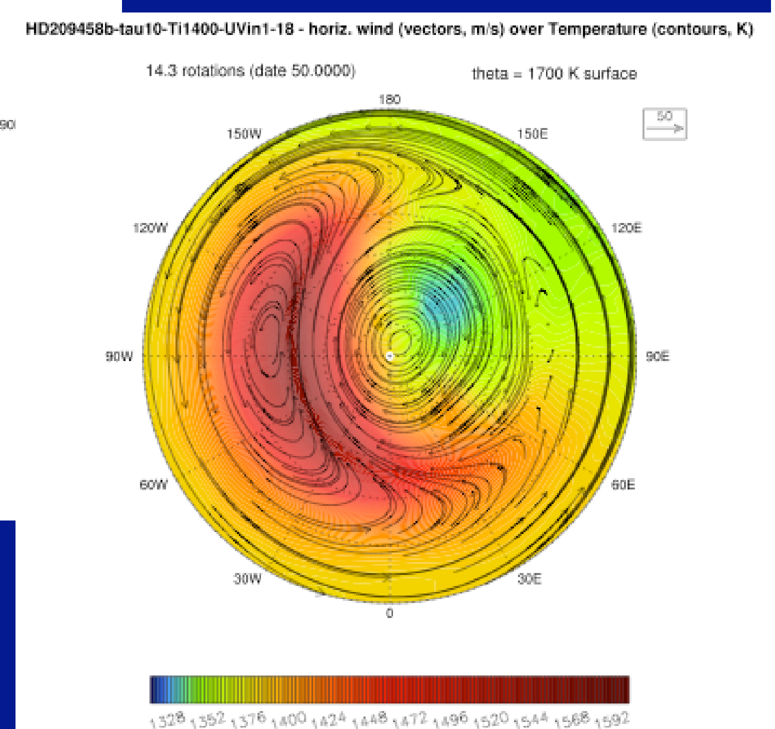
θ = 2800 (p ≈ 100mb)



θ = 2000 (p ~ 600mb)



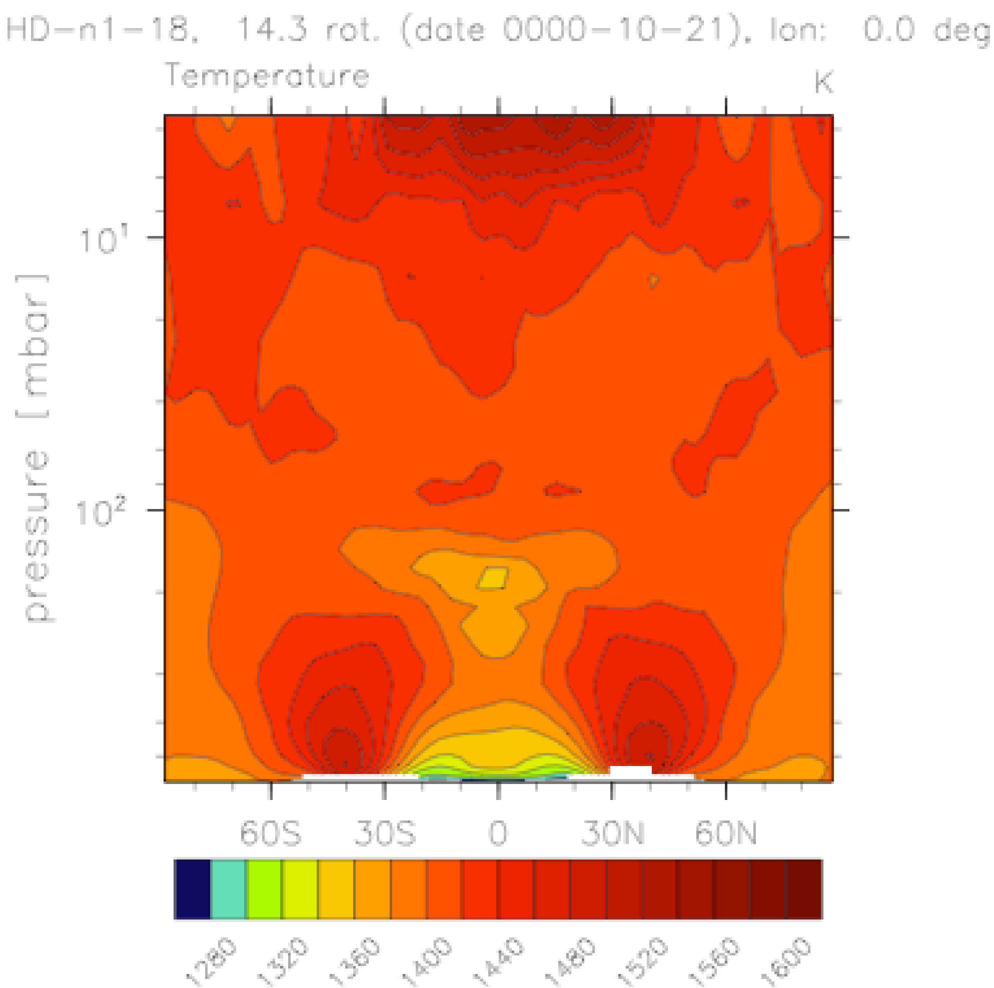
θ = 1700 (p ~ 900mb)



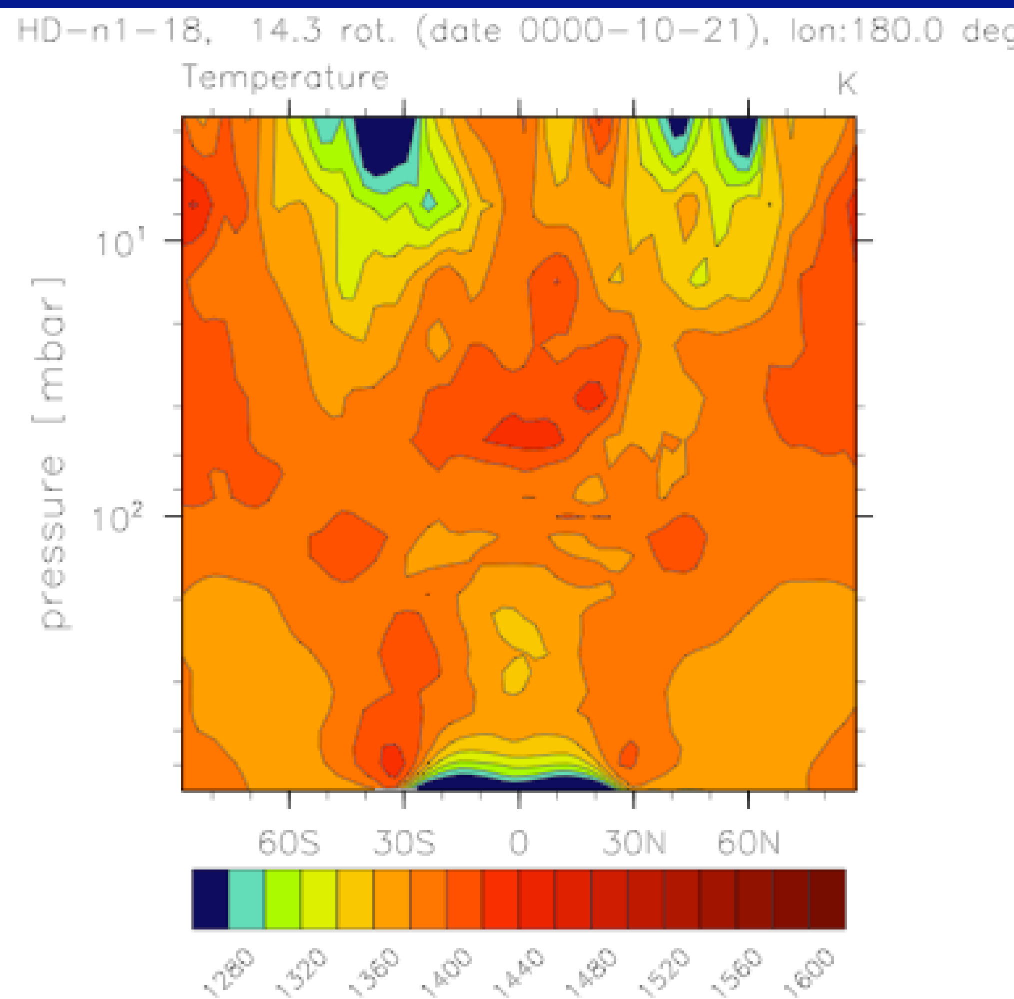
Mix of barotropic and baroclinic:
large areas are barotropic (vertically uniform)

TEMPERATURE (LATITUDE-HEIGHT)

Sub-stellar



Anti-stellar

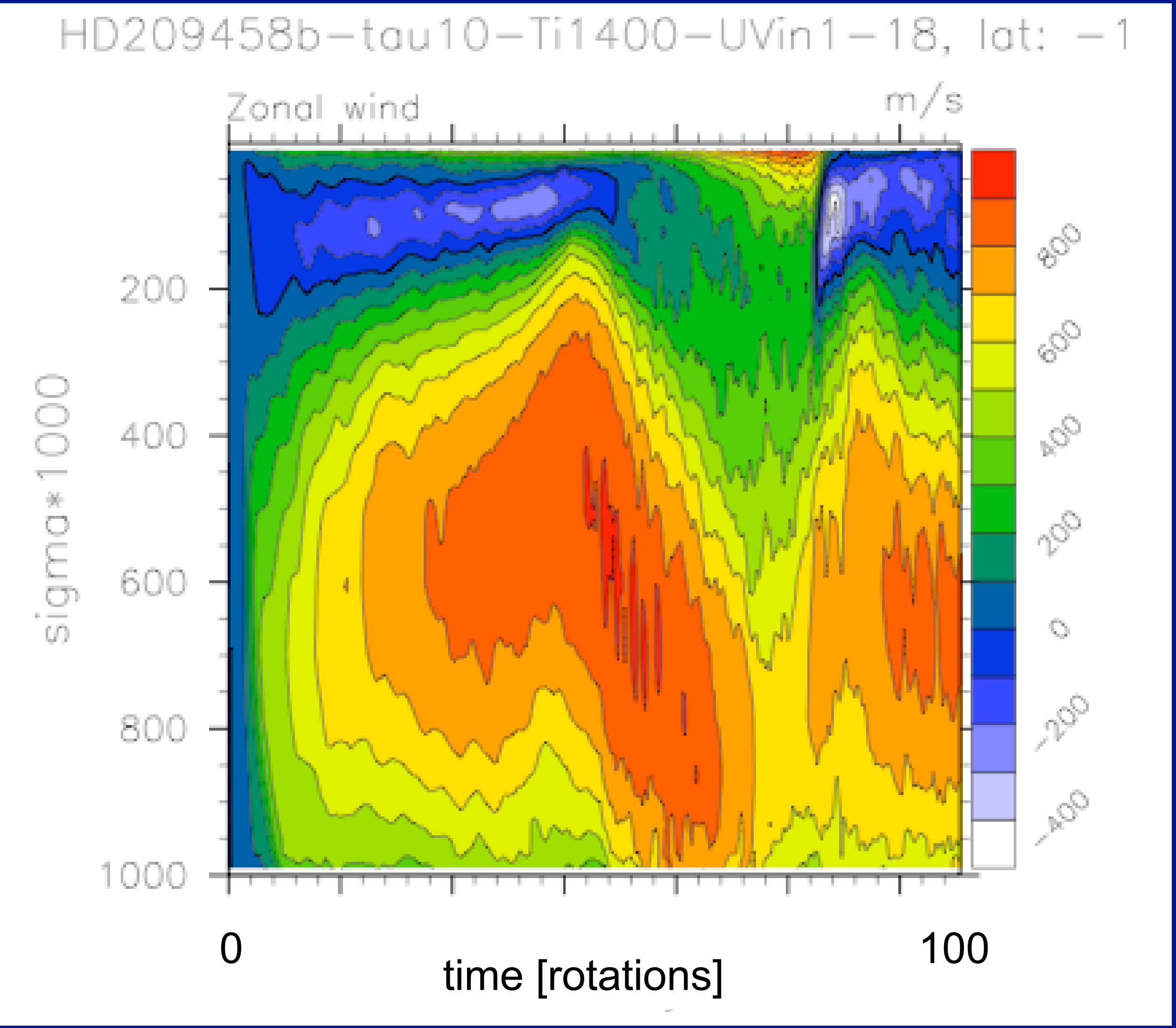


Large regions of constant temperature, but also prominent (multiple) inversions

"What typically happens
in long time integrations?"

“Another movie: it’s a double feature!”

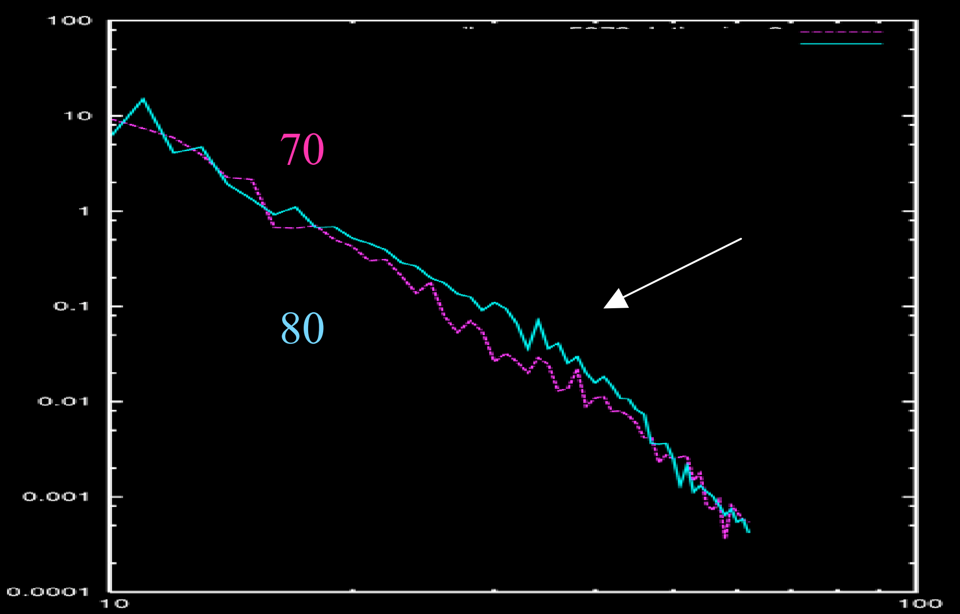
"THE BIG BOUNCE"

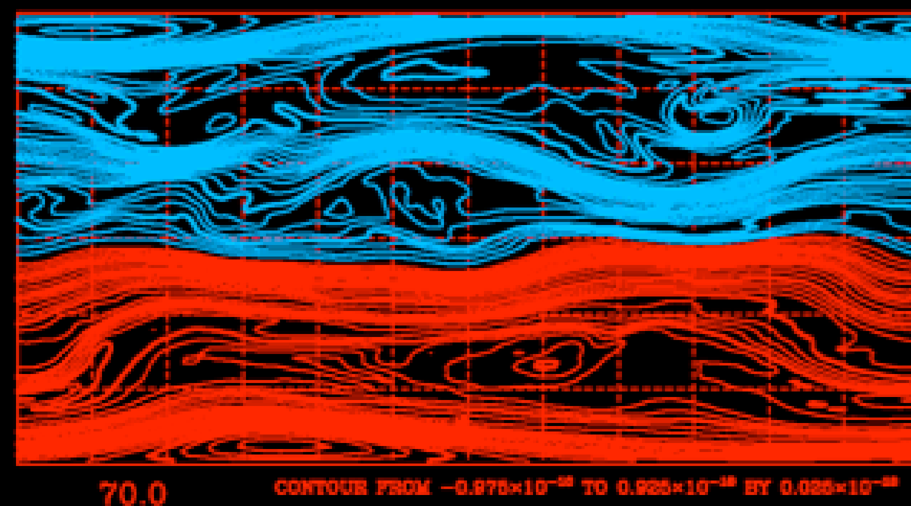


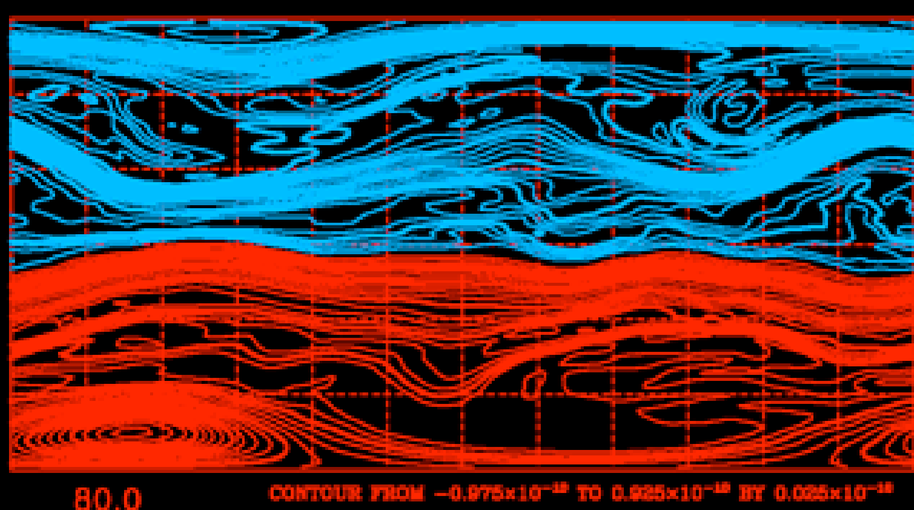
Waves propagate and bounce from top, corrupt calculation after t ~30 *for this I.C.*
THE PROBLEM IS THE CODE HAPPILY MARCHES ON.

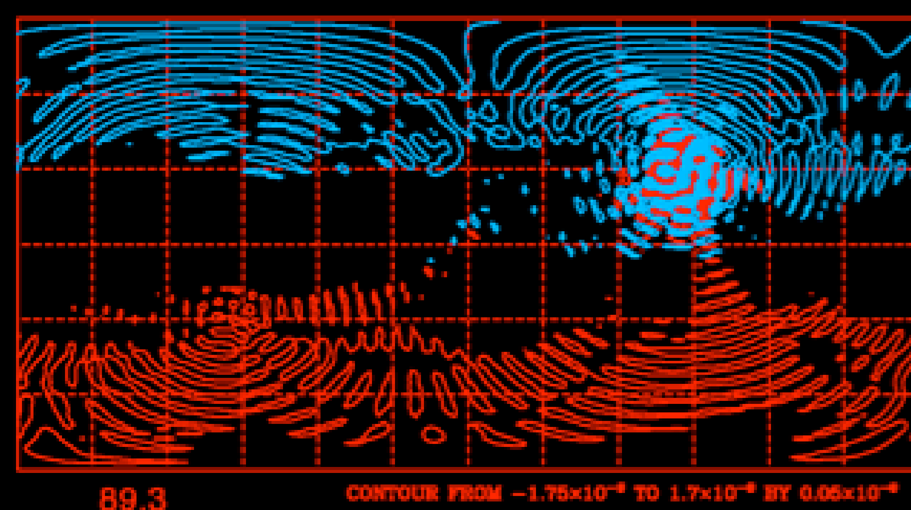
EXAMPLE OF WHAT A PROPERLY WORKING CODE SHOULD DO

“2-h waves” (these are NOT real waves)









"The main point with numerical models is to find out what's wrong with them."

ANONYMOUS

Perhaps this is just a little too cynical a view.

But, it is worth reminding ourselves the importance of checking and really understanding what comes out of numerical models/simulations.

SENSITIVITY

- Did I mention the equations are differential equations? Did I also mention they are NONLINEAR?
- Many gross features (e.g., wind direction and speed, “hot spots”, inversions, etc.) sensitively depend on I.C. and B.C.
- That’s IF models (numerical and analytical) are being used correctly in the first place <= NOT NECESSARILY TRIVIAL.
- Sensitivity has not been characterized in circulation models so far; hence, some “predictions” are only good for the stock market (and some fortune tellers).

One crucial piece of physics NOT included in circulation models so far..

gravity waves

GRAVITY WAVE PRIMER

Gravity (buoyancy) waves exist in stratified fluids. Small amplitude waves are governed by:

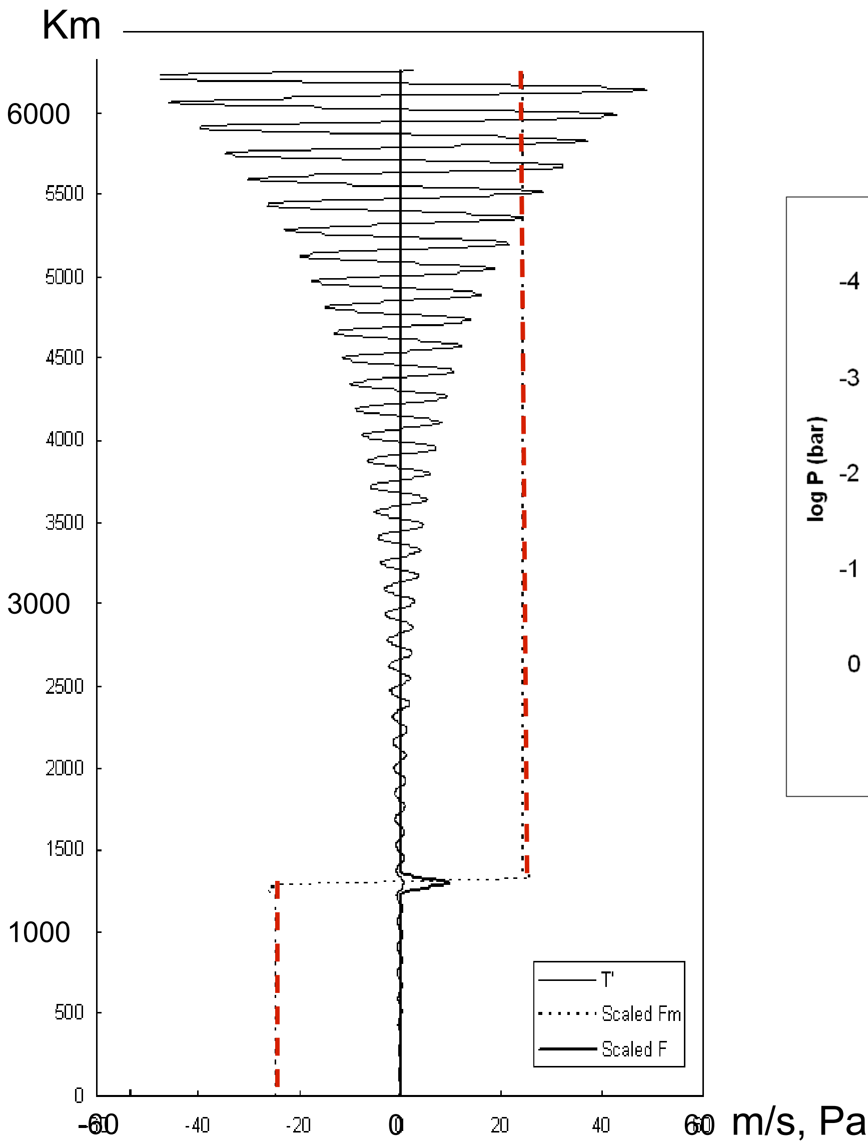
- **Taylor-Goldstein equation (TGE):**

$$\frac{d^2\hat{w}}{dz^2} + \left[\frac{N^2}{(U-c)^2} - \frac{U''}{(U-c)} - k^2 + \cdots\right]\hat{w} = 0,$$

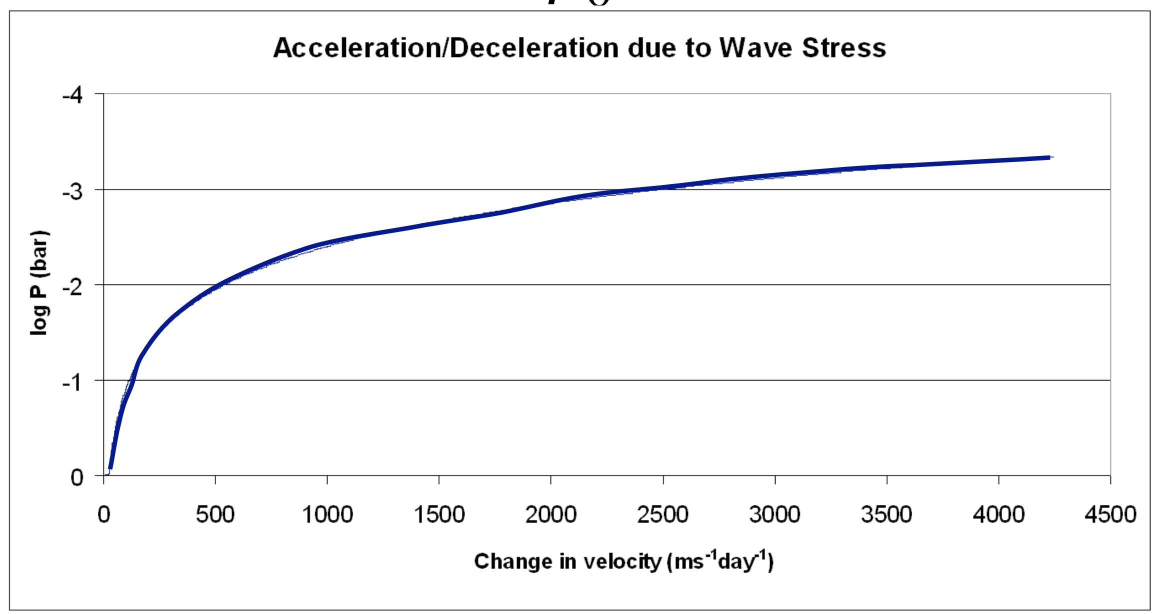
$\hat{w}_k(z)$ = vert. vel. perturb. amplitude $[\sim w(\mathbf{x},t)\, e^{-ik(x-ct)}]$
$N(z)$ = Brunt-Väisälä (buoyancy) frequency
$U(z)$ = background flow speed, with $U'' = d^2U/dz^2$
z = height
c = wave phase speed
k = horizontal wavenumber.

Gravity waves 1) transport momentum and heat, 2) induce turbulence and mixing, and 3) modify circulation and temperature and mixing ratio structure.

ONE EFFECT OF GRAVITY WAVES



$$\frac{\partial U}{\partial t} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0 \overline{u'w'}\right)$$



DECELERATION DEPENDS ON HEIGHT:

~10^{-3} m s^{-2} per wave at 100 mbar,

~10^{2} m s^{-2} per wave at 10 mbar

(i.e., ~10^{3} m s^{-1} day^{-1} per wave).

ROBUST FEATURES IN NUMERICAL SIMS

- Few number (mostly 3, but occasionally 4 or 5) of jets. The jets are strongly barotropic with 1 and 2 baroclinic modes dominant in the beginning.

- Coherent vortices (both cyclones and anticyclones). As in GFD studies, 1-layer approaches continue to be useful, WHEN USED APPROPRIATELY.

- Temperature distribution surprisingly UNIFORM. Initial ~1500K day-night difference ==> only a few hundred K difference max, localized. Else, a uniform T distribution is a good zeroth-order description.

- 3-D simulations by several groups appear consistent, THOUGH PROPER I.C., B.C. and physical regimes still under debate.

SUMMARY

- Atmospheric dynamics modeling REQUIRED for characterization (e.g., T-P profiles needed over the globe).

  Good atmospheric dynamics modeling and understanding is needed for SCIENCE advancement.

- The models are poorly constrained (as expected), but their limitations (both physical and numerical) are poorly understood as well. More studies are warranted before models can make “predictions”.

- Hierarchy of models (analytical and numerical) still absolutely necessary for good understanding: there is no such thing as a perfect model.

  A BIGGER MODEL IS NOT A BETTER MODEL: IT’S USUALLY JUST AN OPPORTUNITY FOR BIGGER CONFUSION.

- *There is hope: understanding is definitely increasing (as well as confusion).*