BAROCLINIC INSTABILITY ON EXTRASOLAR PLANETS

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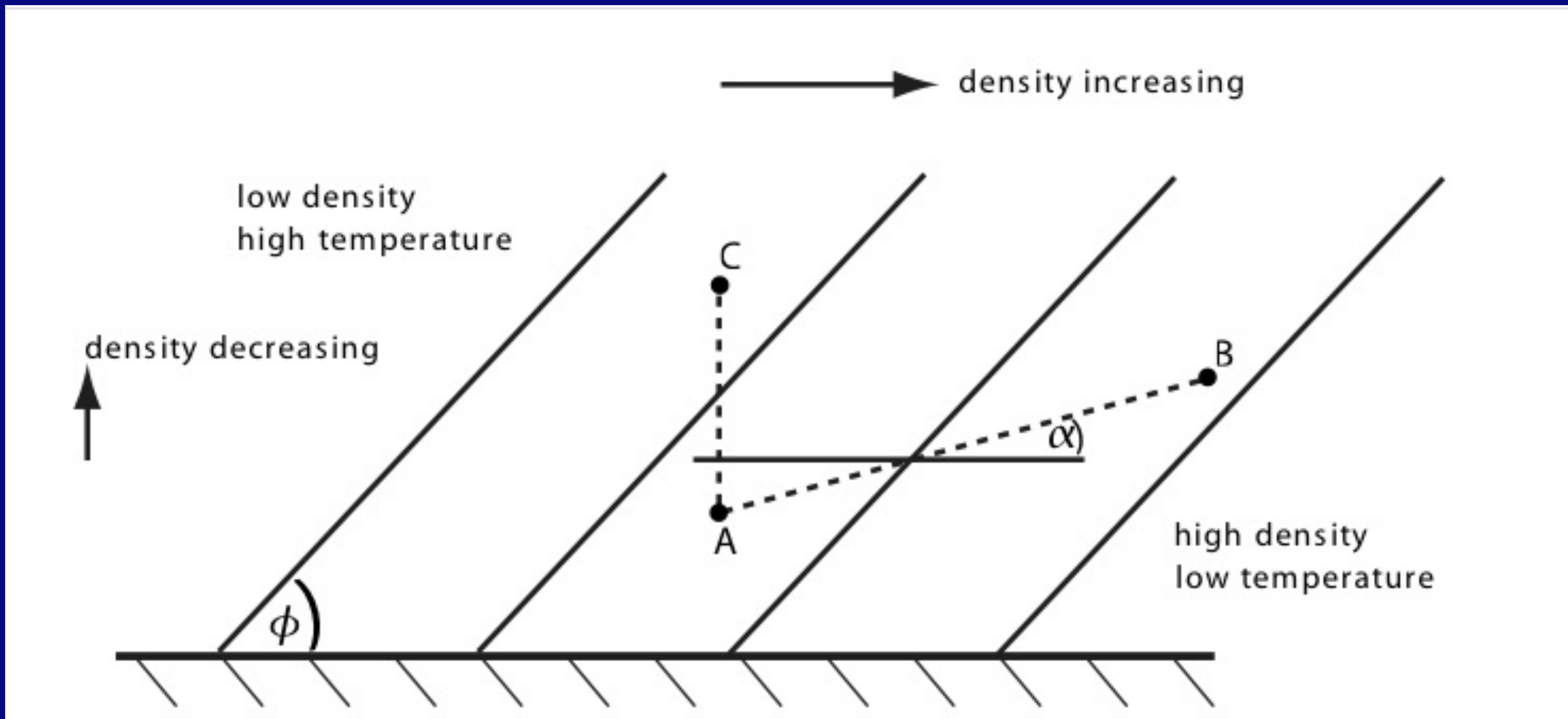
BAROCLINIC INSTABILITY



• Baroclinic instability is an generic process occurring in *rotating*-stratified fluids with horizontal temperature gradients.

• Exchange of fluid elements A and B lead to release of potential energy, which can be tapped to power large- and *meso*-scale eddies.

Baroclinic instability is an important, and *well-understood*, dynamical process that occurs in planetary atmospheres.

It helps to even out the equator-pole temperature gradient and drives the mid-latitude weather systems, *inter alia*.

BACKGROUND

- Question: Is baroclinic instability a viable mechanism for heat transport and turbulence generation on extrasolar planets?
- This question is important because temperature structure (transport) and variability (turbulence) on extrasolar planets is currently not really understood.
- Until better understanding of processes like this, characterization is.. *uncertain at best*.

THE MODEL

- We use a 3D, global general circulation model (GCM), using a parallel pseudospectral algorithm.
- It is capable of very high resolution (e.g., T341L20).
- It solves the full primitive equations for a "thin atmospheric layer".
- In this talk, focus is on adiabatic instability process.

$$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} = -\nabla_p \Phi + F - D$$

$$\frac{\partial \Phi}{\partial p} = -\frac{1}{\rho}$$

$$\frac{\partial w}{\partial p} = -\nabla_p \cdot \mathbf{v}$$

$$\frac{D\theta}{Dt} = F - D$$

$$p = \rho R T$$

Φ = geopotential
$\mathbf{v}$ = 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

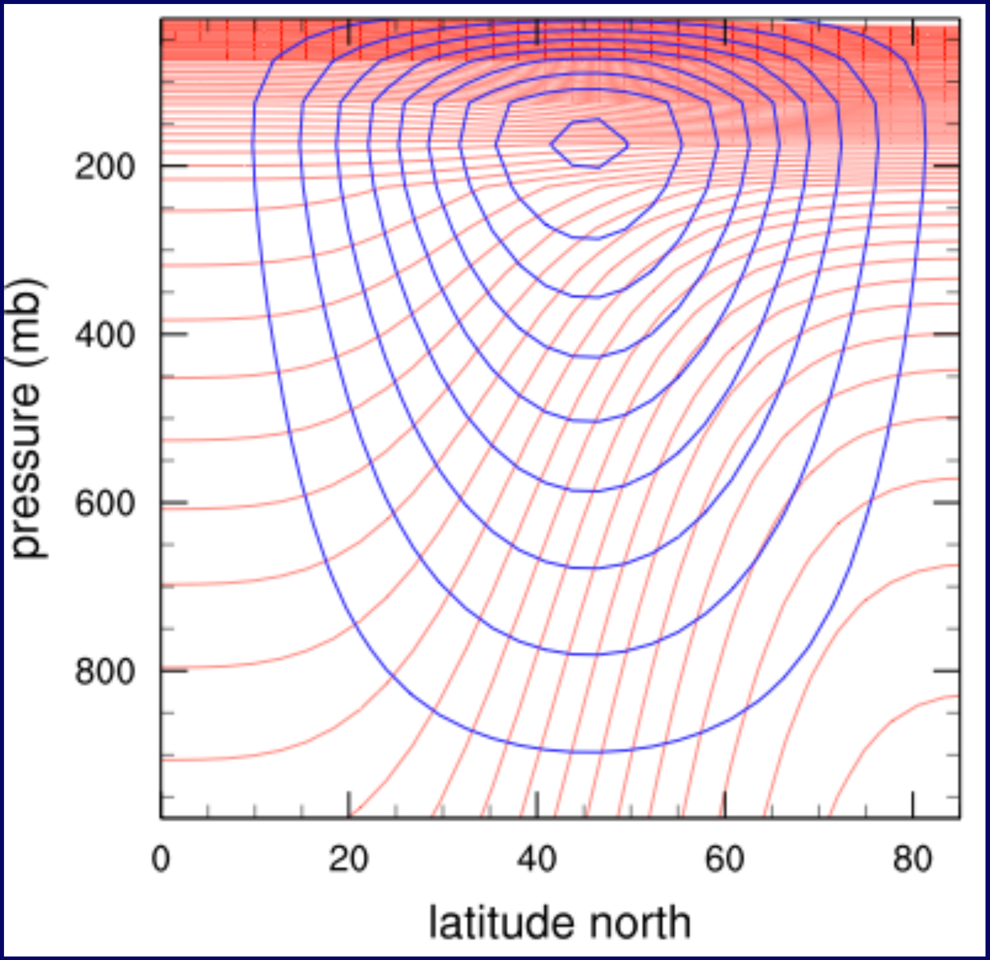
CONDITION(S) FOR INSTABILITY

- *Necessary* conditions for the instability is given by one of the following, Charney-Stern-Pedlosky (CSP), criteria:
  - Meridional potential vorticity gradient ($\partial Q/\partial y$) changes sign in the fluid interior
  - ($\partial Q/\partial y$) is the same sign as vertical zonal wind gradient ($\partial U/\partial z$) at the lower boundary
  - ($\partial Q/\partial y$) is the opposite sign to ($\partial U/\partial z$) at the upper boundary
  - ($\partial U/\partial z$) is the same sign at the upper *and* lower boundary
- CSP criteria also leads to estimates of the growth rates and gravest modes of the instability

THE SETUP

- A series of runs (~100) performed. Resolution is typically T42L40 (128x64x40), with vertical domain extending from ~ 1--1000 mb. We have checked that the solutions are converged.

- Simulations initialized with typically 500 ms^{-1} eastward or westward zonally-symmetric jet, centered at from 55N to 0N, in gradient wind balance (see right). Jet is perturbed by a single, small heat bump at all pressure levels.

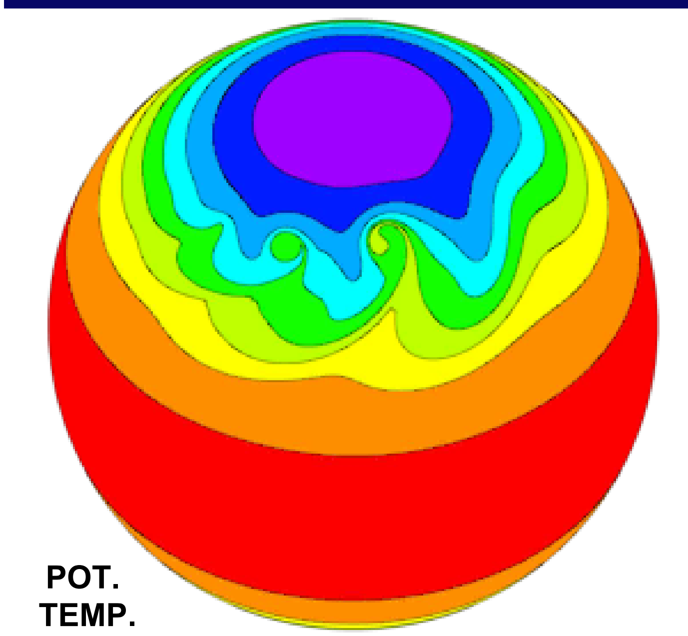


SUMMARY OF RESULTS

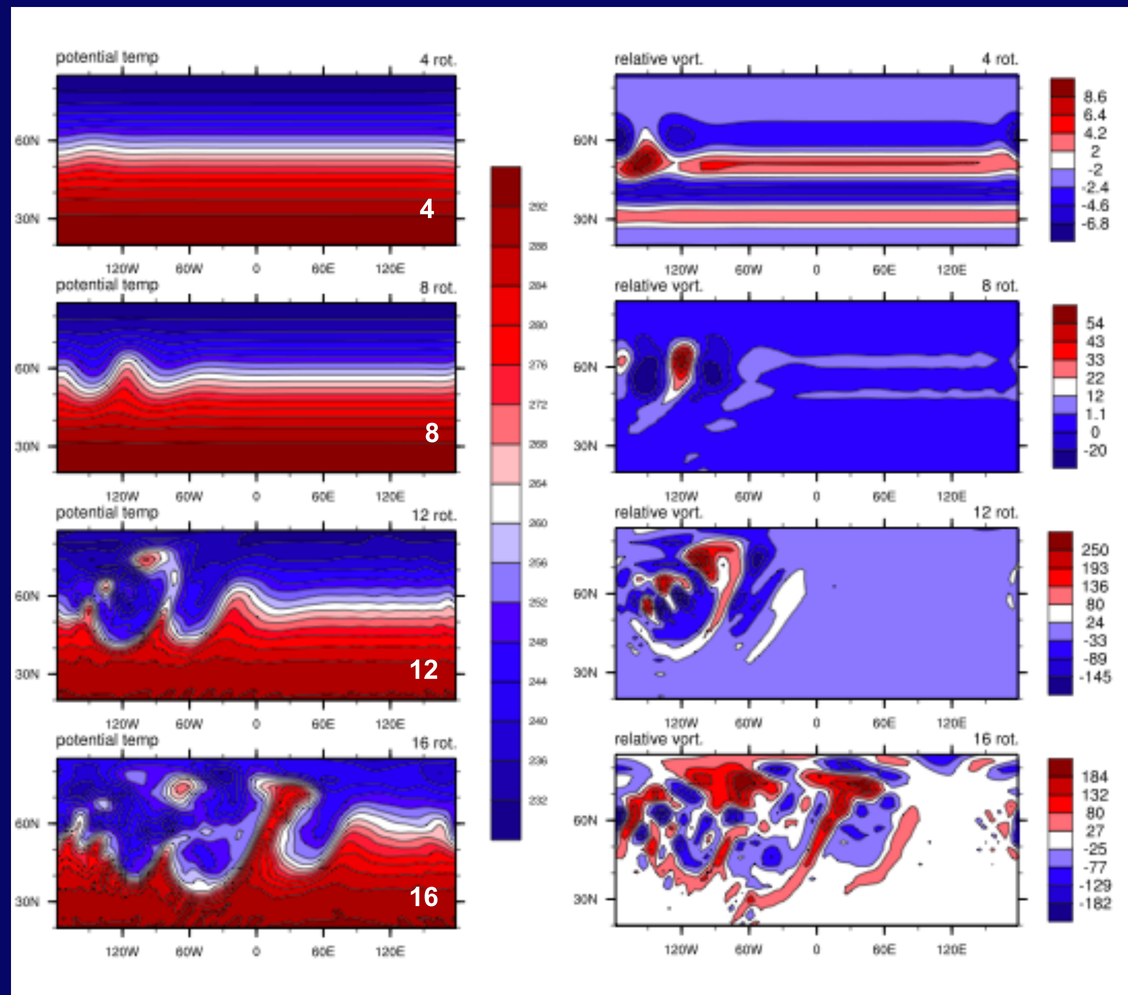
- Baroclinic instability is present at latitudes down to 5^{o}N for an eastward jet
- Westward jet is baroclinically *stable* for all latitudes with flow speed < 500 ms^{-1} (but can still be *barotropically* unstable at high latitudes)
- The gravest mode is ~2 -- 3 (compared with ~4 -- 6 for the Earth) at mid-latitude
- Growth rate is smaller than the Earth at mid-latitude and decreases towards lower latitudes

EARTH: VALIDATION

- Growth rate of ~4 days
- Gravest mode: ~4
- “Turbulence” at ~16 days



Potential temperature (K) Relative vorticity ($*10^{-6}\ m^2s^{-2}$)



Surface layer (975 hPa) evolution of potential temperature and relative vorticity for eastward jet centered at 55N, 4--16 days

HD209458b

- Growth rate:

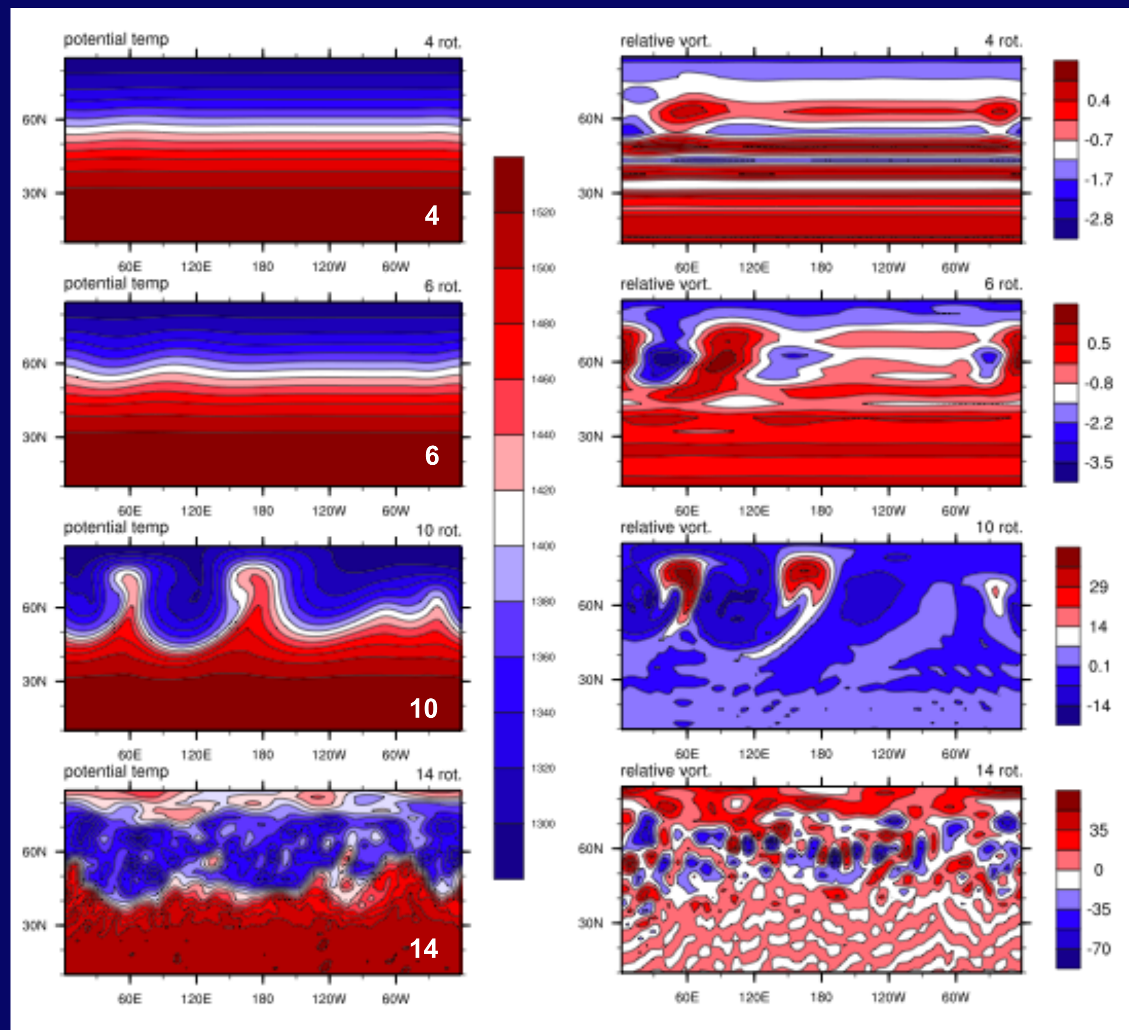
  ~5 planet rotations

- Gravest mode: ~2

- Turbulence after ~14

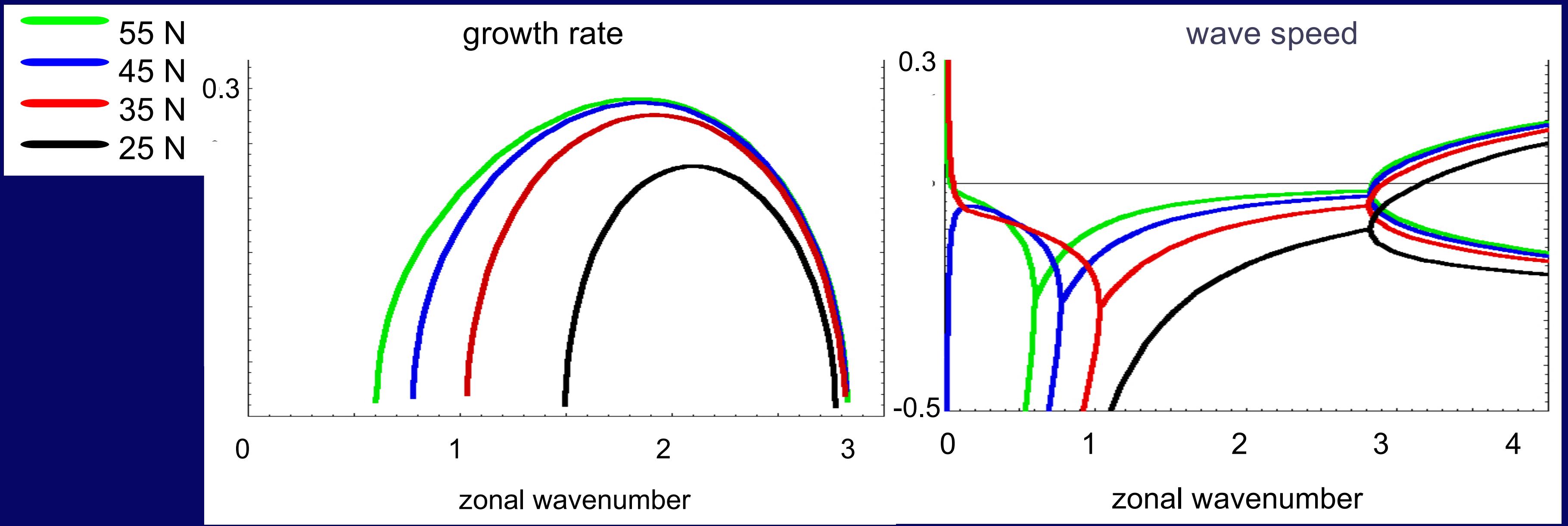
  HD209458b rotations

Potential temperature (K) Relative vorticity ($*10^{-6}$ m^2s^{-2})



Reference pressure layer (975 hPa) evolution of potential temperature and relative vorticity for eastward jet centered at 55N

WAVE ANALYSIS



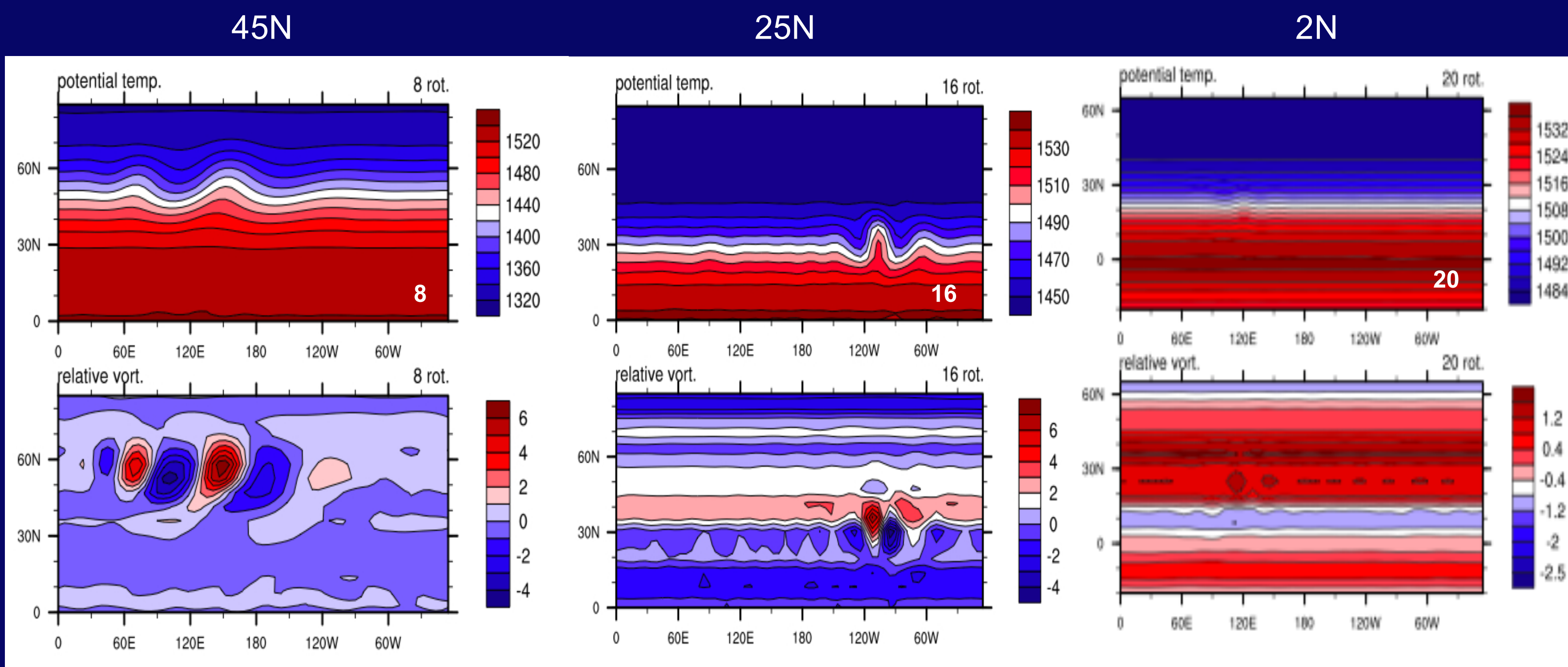
Scaled using deformation radius, L_d = NH/f, and flow speed, U = 500 ms^{-1}

for HD209458b. *

Results are in good agreement with linear theory. BUT, *linear* theory predicts stability for latitudes < 20 N, whereas instability present even at ~5 N (see next slide).

* Obtained from Phillips dispersion relation

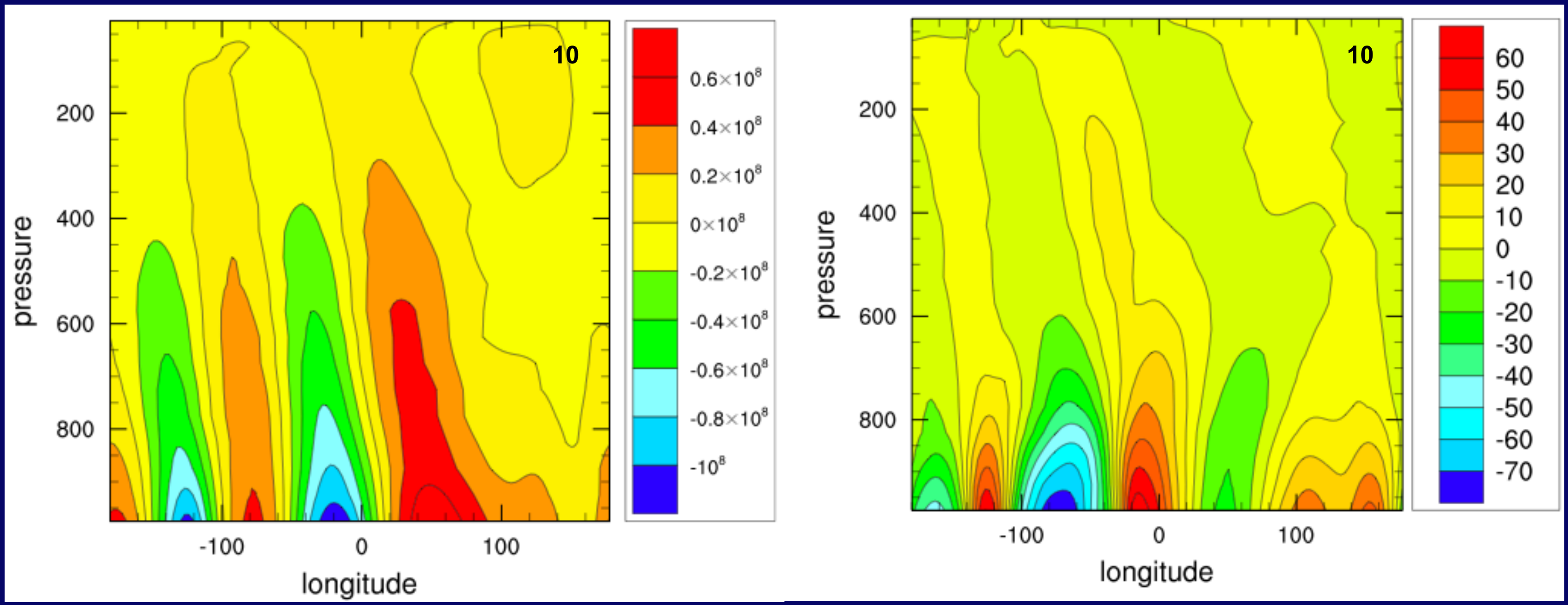
LATITUDE VARIATION



Temperature and relative vorticity at 975 hPa for eastward jet

- Eastward jet baroclinically unstable even at low latitudes
- Slower development of instability at low latitudes

HEAT TRANSPORT



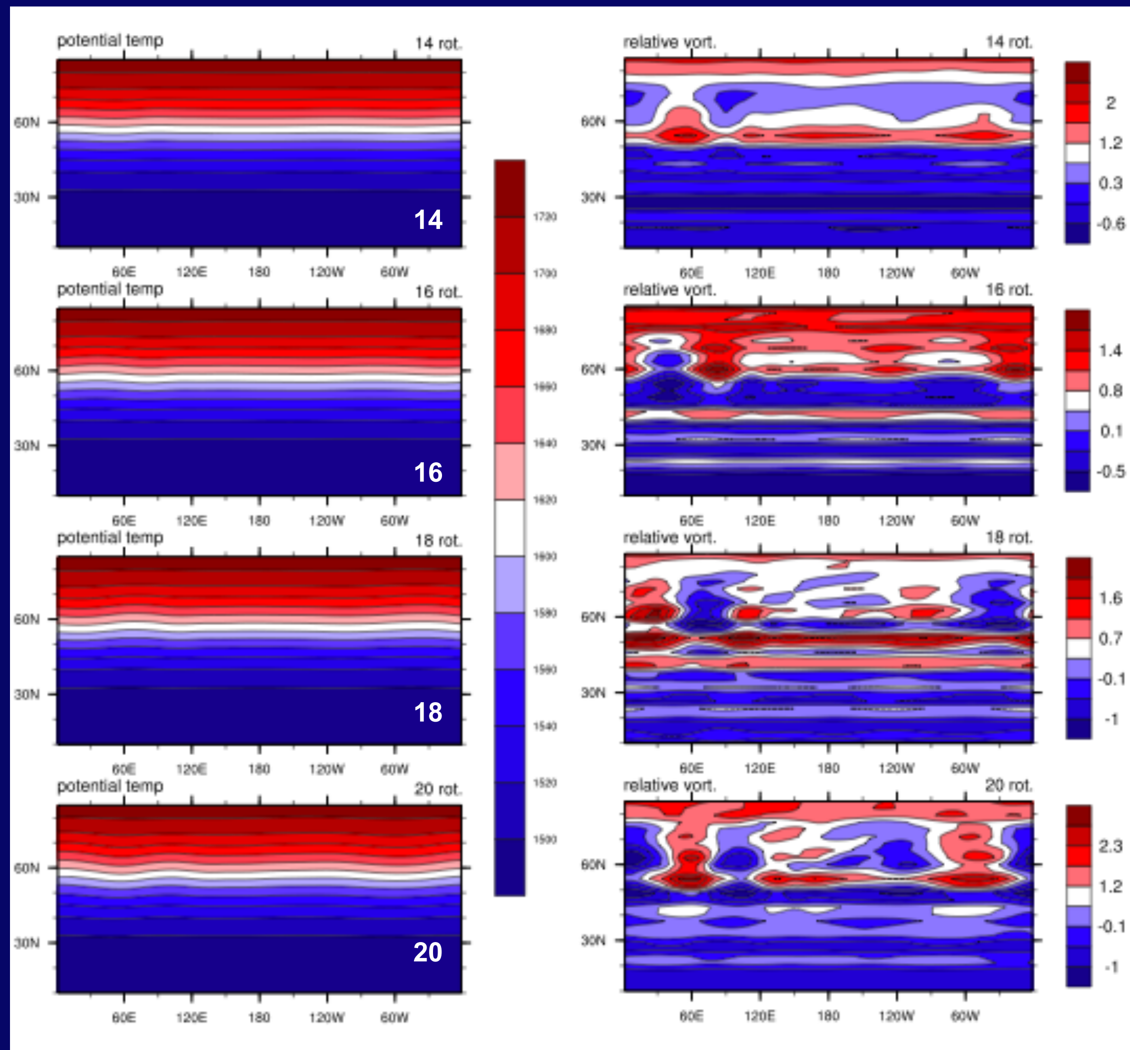
Perturbation streamfunction (kg s^{-1}) (Left) and temperature (K) (Right) longitude-height cross-section for eastward jet centered at 55^{o}N. Plot at latitude 55^{0}N at 10 rotations

Westward tilting of streamfunction and eastward tilting of temperature with height indicate poleward heat transport by eddies from baroclinic instability.

WESTWARD JET

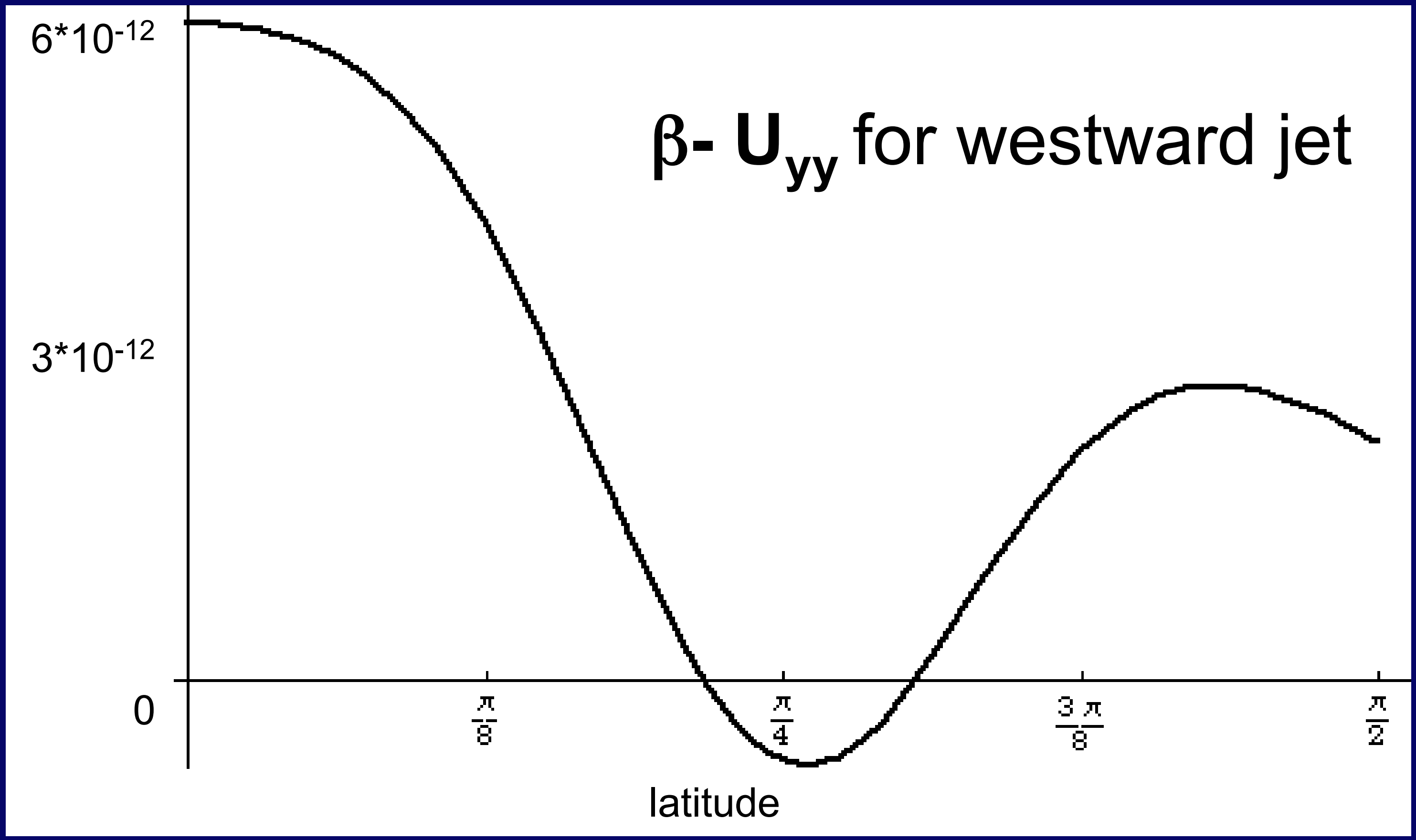
- Baroclinically stable or only weakly unstable for jet speed < 500 ms^{-1}
- But, westward jet is barotropically unstable at latitudes 55 -- 40 N (see next slide)

Potential temperature (K) Relative vorticity ($*10^{-6}\ m^2s^{-2}$)



Reference pressure layer (975 hPa) evolution of potential temperature and relative vorticity for westward jet centered at 55N

BAROTROPIC INSTABILITY

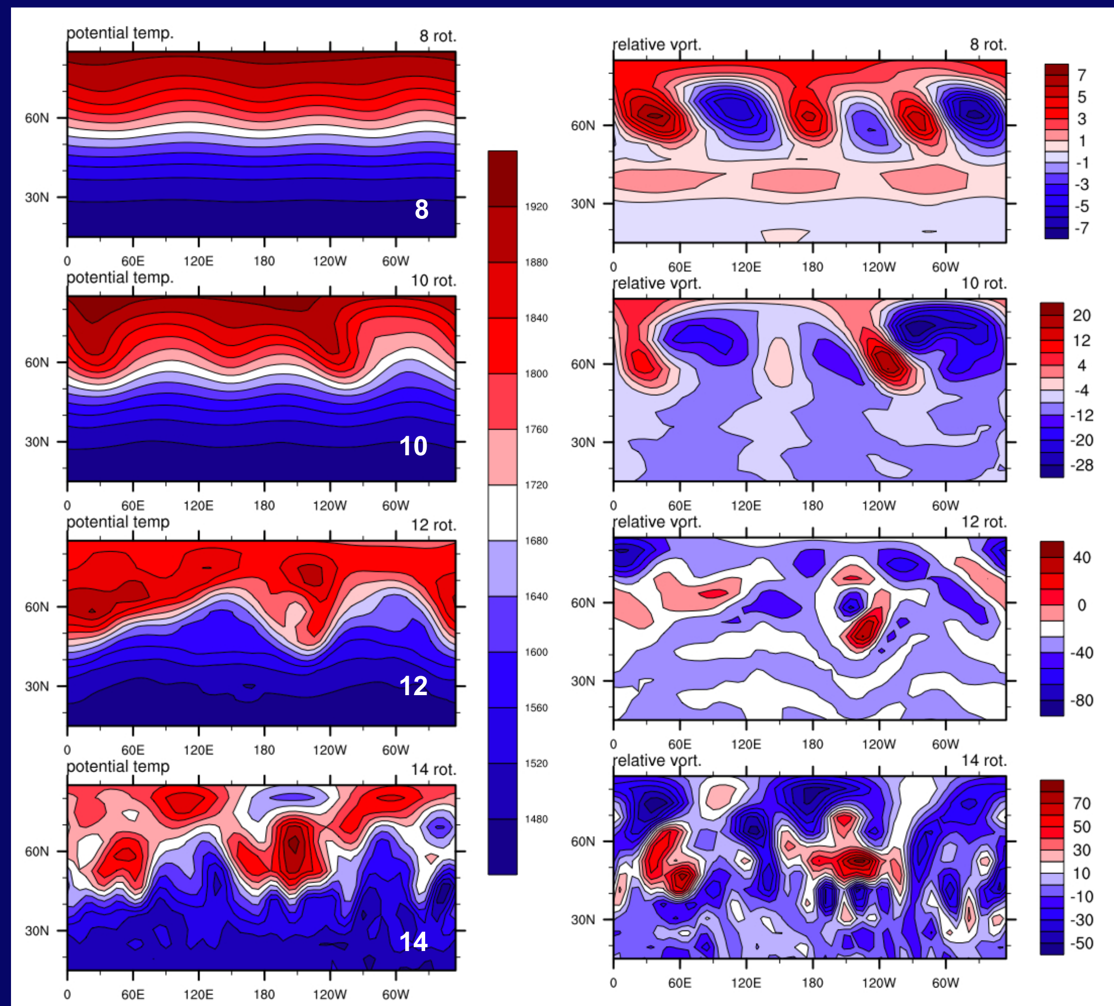


Necessary condition (β - U_{yy} < 0) for barotropic instability is satisfied for westward jet

HIGH SPEED WESTWARD JET

Instability present for westward jet with $U > 1000\ ms^{-1}$

Potential temperature (K) Relative vorticity $(10^{*}\ m^2 s^{-1})$



Evolution of reference layer (975 hPa) potential temperature and relative vorticity for westward jet at 55N and $U_{max} = 1000\ ms^{-1}$

DISCUSSION

- Some Thinking Points:
  - Baroclinic instability is *much more possible* than suggested by “textbook” analysis
  - Given that the instability is a viable -- and apparently robust -- process, *how valid is it to start circulation model sims at rest?*

- Evolution in more complex, “realistic” jet profiles needs to investigated, as do incorporation of diabatic conditions (e.g., thermal and Rayleigh drag). These are currently being addressed.

- Fundamental studies like this are essential to help guide and interpret observations, as well as to extend theory to more general or ”exotic” conditions.