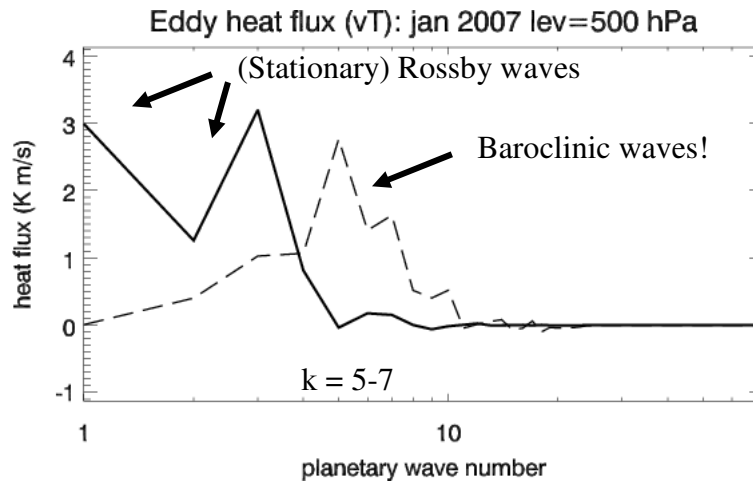


## Announcements

- Next week: Computer tutorial/exercise  
Hart Lab: Stadium, RM 136C (between gates 5 and 6)
- Make sure you can log onto atoc
- Project 2 assignment (hand out on Thursday!)
- (Part 1 is to comp up with a 1 sentence proposal)

## Baroclinic waves

## Heat flux by waves



Total stationary eddy heat transport = 8.5 K m/s

Total transient eddy heat transport = 9.5 K m/s

## Normal mode analysis

Understand method way in which instabilities occur and develop

1. Come up with a/some wave equation(s)
2. Linearize (very small initial disturbance)
3. Assume solution

$$\psi' = A \exp[ik(x - ct)]$$

(i.e., construct wave equation knowing we want to do this)

4. Develop dispersion relationship:  $c = c(k, u, \beta, f, \dots)$
5. Examine conditions for growth  
defining  $k$  real and positive

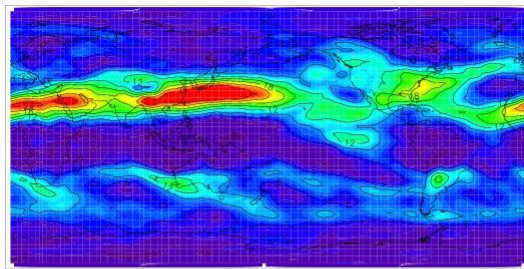
*What does dispersion relation look like?*

## Baroclinic cycle

- Warming in the tropics, cooling at poles:  $U_T$  increases
- For given stability (~moist adiabatic),  $U_T$  reaches critical value and most unstable wave grows
- Potential energy is converted to (eddy) kinetic energy
- Geopotential gradient is reduced, thus  $U_T$  is reduced below (to) critical threshold

Net effect is to transport heat poleward  
(This avoiding “geostrophic paradox” in zonal mean)

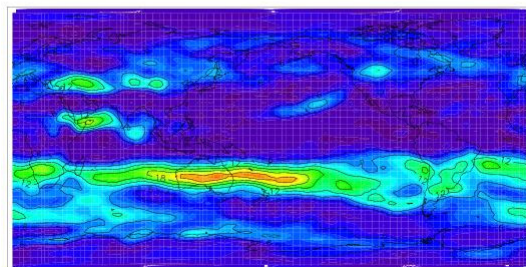
### Baroclinic growth rate (“alpha”)



January



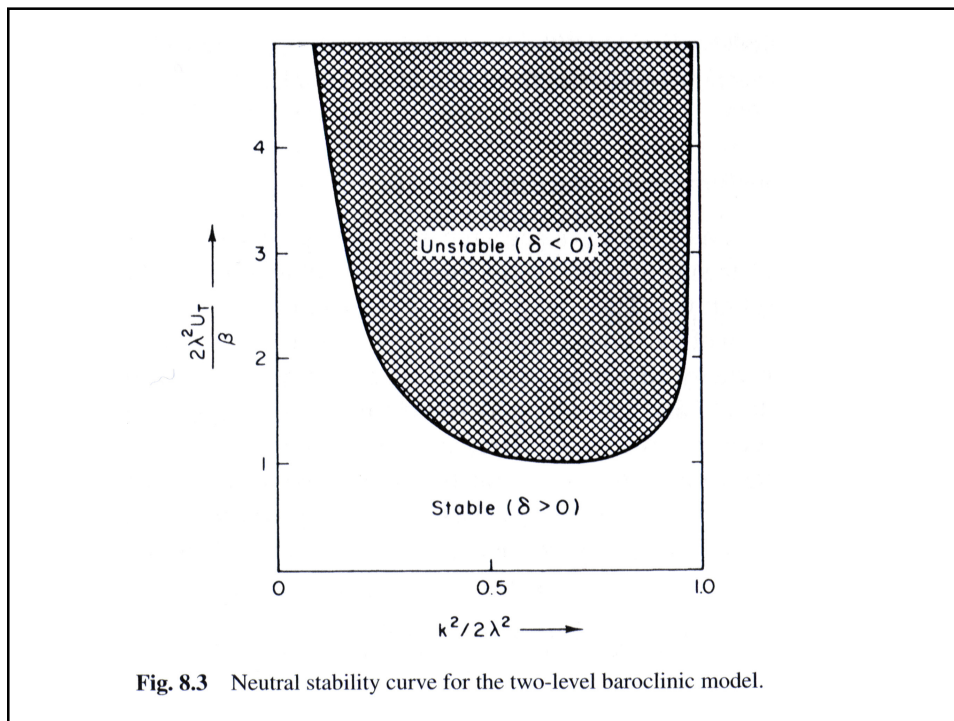
24xday<sup>-1</sup>



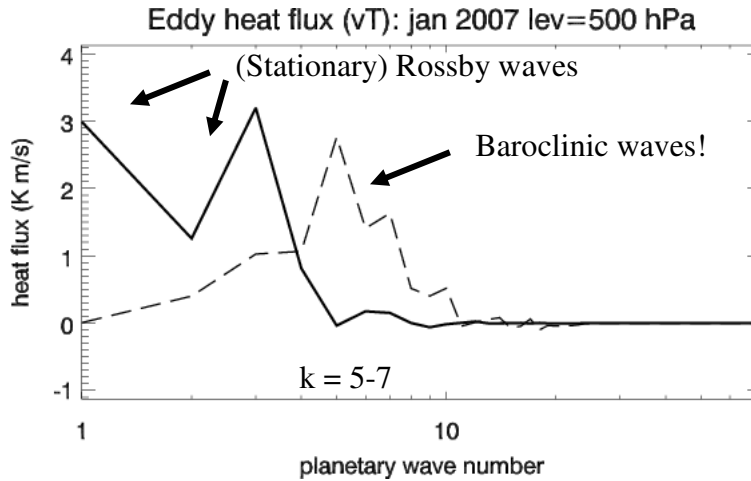
July

## Baroclinic growth (predictions 1)

- Thermal wind balance (geostrophic/hydrostatic) continually maintained
  - Vertical motion causes stretching, and vorticity generation at lower levels
1. Short waves always stable ( $k^2 > 2k_R^2$ )
  2. Beta effect stabilizes flow for long waves (leads to a minimum  $U_T$  (or  $\Delta T$ ) for instability)
  3. For given stability, increasing  $U_T$  will give a wave number that becomes unstable first (the most unstable wave)
4. Depends on
    - $\sigma$  stability)
    - $F$  rotation rate, and
    - $U_T$  temperature gradient/difference
- Baroclinic waves in midlatitude typically on scale of most unstable wave ( $k \sim k_R \Rightarrow L \sim 4000\text{km}$ , planetary wave 6-7)



# Heat flux by waves



Total stationary eddy heat transport = 8.5 K m/s

Total transient eddy heat transport = 9.5 K m/s

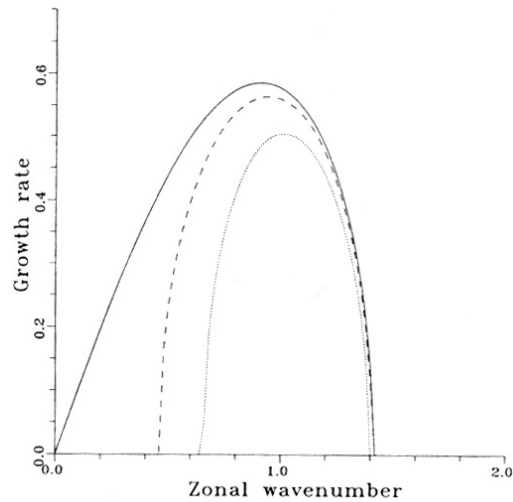
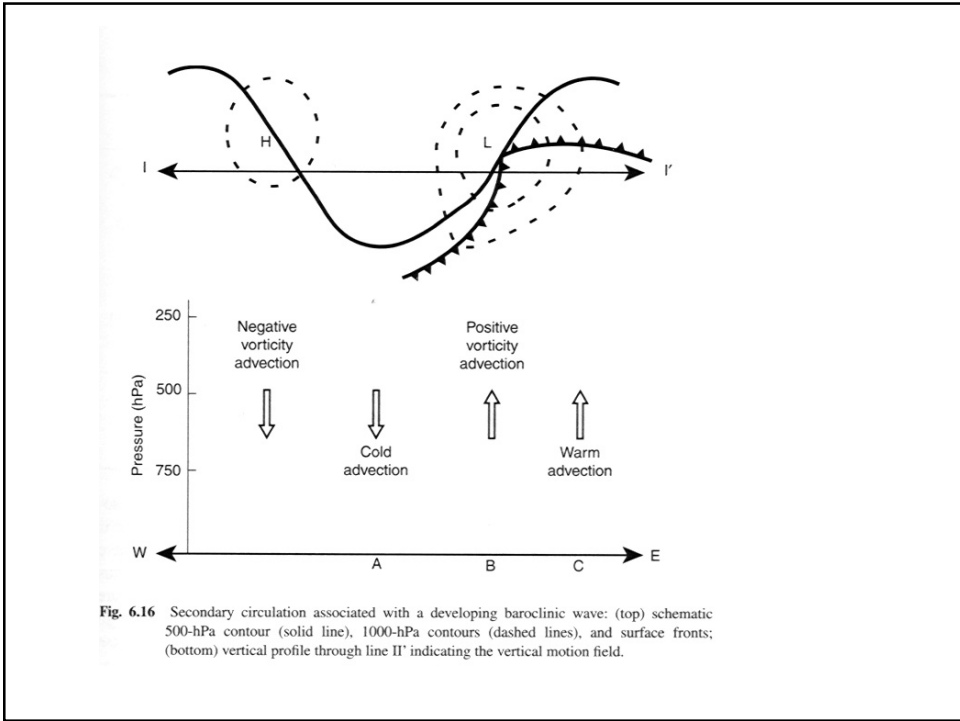
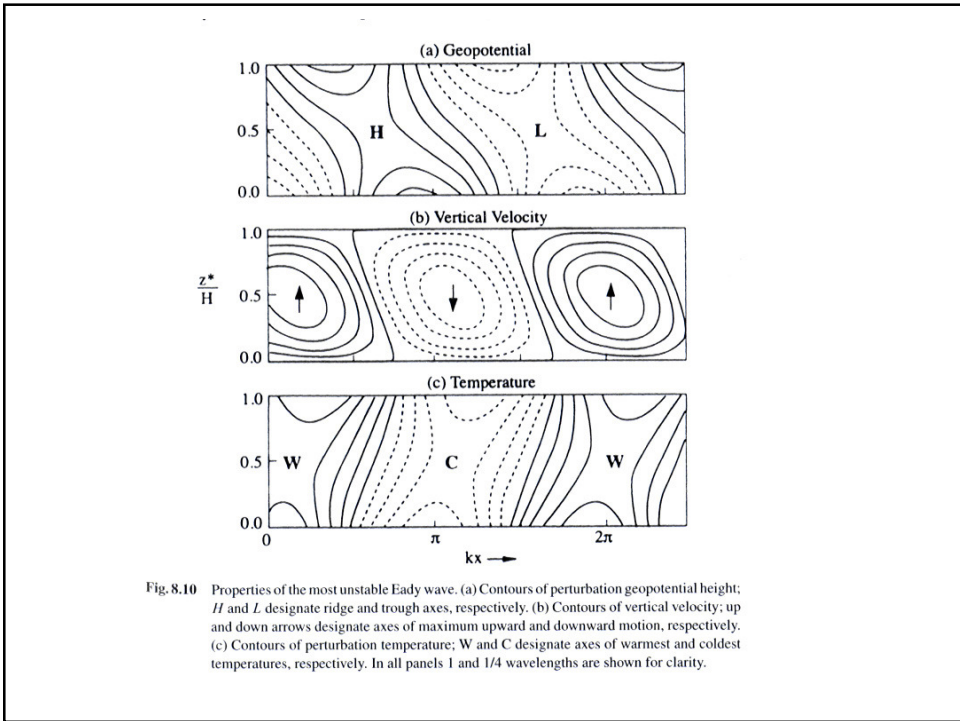
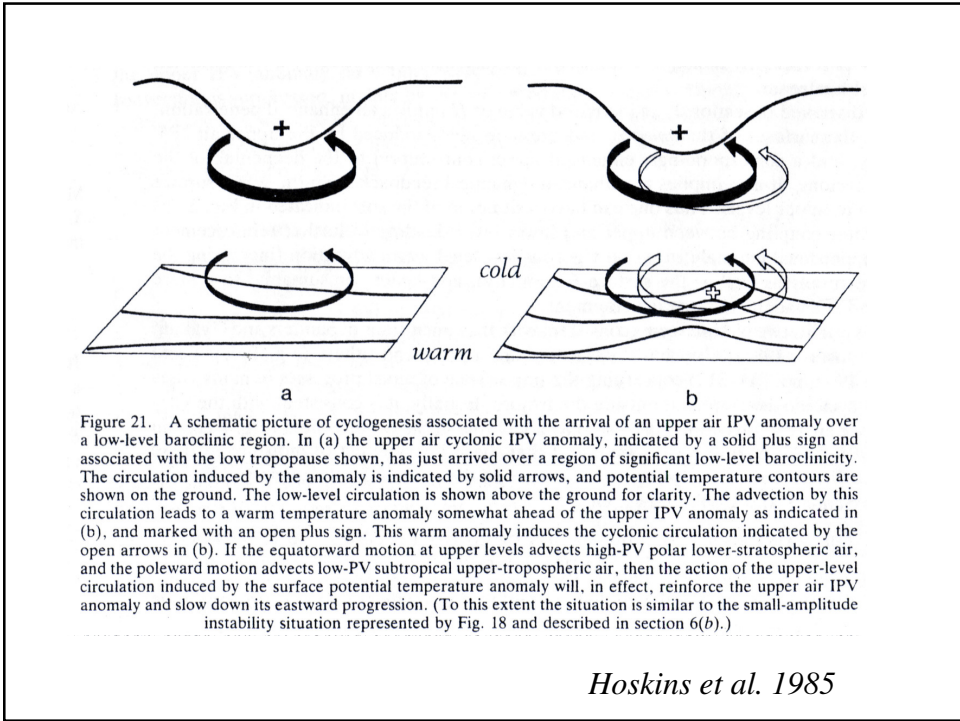


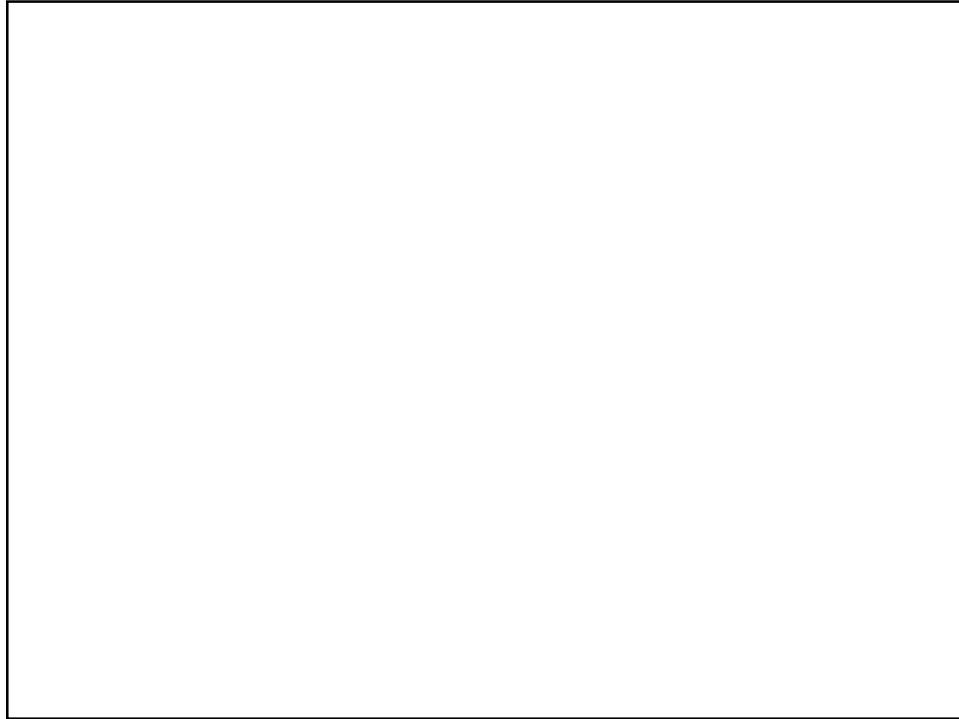
Fig. 5.23. Growth rate versus wavenumber for the two-level model for various values of  $\beta$ , calculated from Eq. (5.59). Growth rates are scaled by  $K_R \Delta U$  and wavenumbers by  $K_R$ . Basic parameters are for a  $\beta$ -plane centred at  $45^\circ$  with  $N^2 = 10^{-4} \text{ s}^{-2}$  and a vertical shear of  $40 \text{ m s}^{-1}$ , roughly corresponding to northern hemisphere winter. Solid curve:  $\beta = 0$ . Dashed curve:  $\beta = 8.1 \times 10^{-12} \text{ m}^{-1} \text{ s}^{-1}$ . Dotted curve:  $\beta = 1.6 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ .

James. 1994



**Fig. 6.16** Secondary circulation associated with a developing baroclinic wave: (top) schematic 500-hPa contour (solid line), 1000-hPa contours (dashed lines), and surface fronts; (bottom) vertical profile through line II' indicating the vertical motion field.





## Analogies with rotating annulus experiment?

What is  $\beta$

What is  $f$

What is “stability”  $\sigma$

What is Rossby radius  $L_R$  or  $\lambda$

1. What is the critical  $U_T$  for instability ( $\Delta T$ ,  $\Omega$ ,  $\sigma$ , ...)
2. What is the most unstable wave number/wave length?  
(for a given rotating rate and temperature difference)

First need to justify the analogy between the incompressible (Boussineq) case with the stratified atmosphere case from Chapter 8. Hints in chapter 10!

