Temporal oceanic variability and Rossby waves

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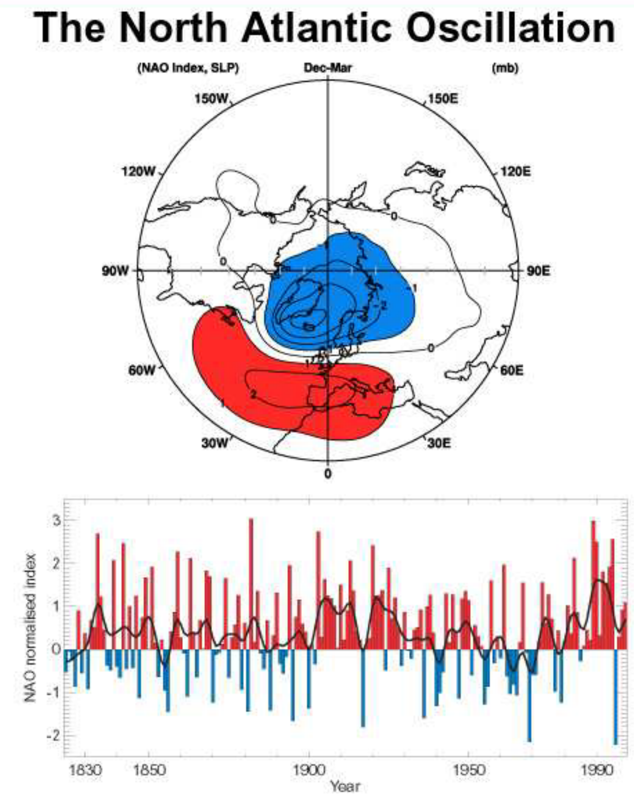
North Atlantic Oscillation

Surface pressure records in the North Atlantic exhibit decadal variability

Similar variability seen in:

- Changes in surface winds
- Changes in sea surface temperature
- Cod fish stocks
- Precipitation in western Europe

North Atlantic Oscillation



Upper panel: Observed Dec-March change in SLP associated with a 1 standard deviation change in the NAO index (after Hurrell, 1995, Science, 269, 676-679).

Lower Panel: Winter (December to March) index or the NAO based on the difference of normalized pressure between Lisbon, Portugal and Stykkisholmur, Iceland from 1864 to 1995. The SLP anomalies at each station were normalized by division of each seasonal pressure by the long-term mean (1864-1995) standard deviation. The heavy solid line represents the meridional pressure gradient smoothed with a low pass filter with seven weights (1,3,5,6,5,3, and 1) to remove fluctuations with periods less than 4 years (after Hurrell, 1995, Science, 269, 676-679, this version: courtesy of T. Osborn, CRU, UEA.

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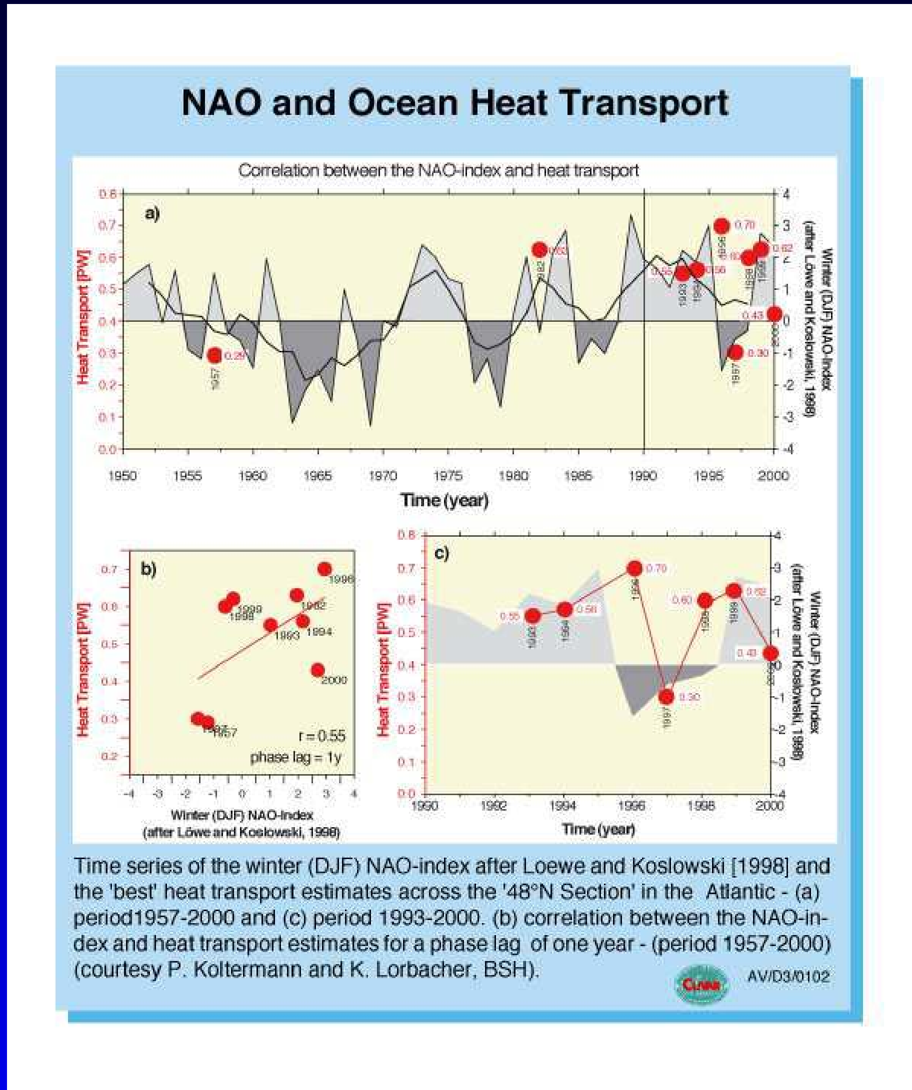
North Atlantic Oscillation



Wind-driven variability

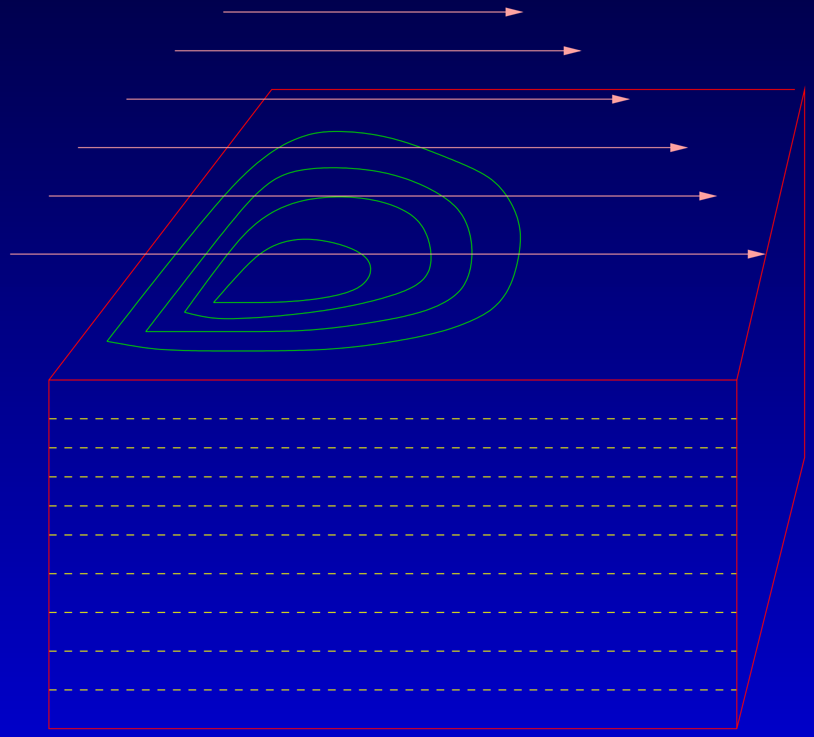
To understand phenomena like NAO, (probably) must understand how the ocean changes in response to the winds

Major currents (e.g. Gulf Stream) are wind-driven, so wind variability reflected in ocean

But how? What time scales? What magnitude?

Wind driven variability

Anderson and Gill, 1975



Anderson and Gill

Change the wind stress impulsively

Mean circulation changes

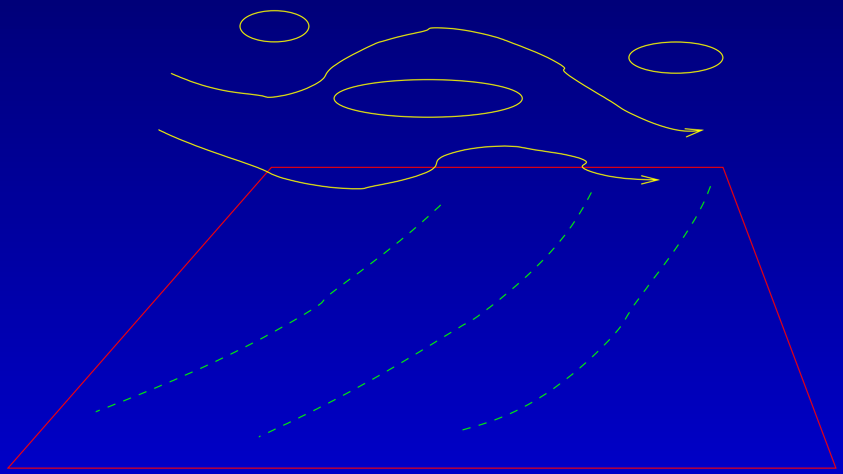
Changes are mediated by <u>Rossby waves</u>

Waves propagate westward, from the eastern boundary, changing circulation

At mid-latitudes, waves can take 10 years to cross basin $\rightarrow$ decadal variability

Subsequent theory

Stochastic climate models
(e.g. Hasselman, 1976; Frankignoul et al., 1997; Cessi and Louzel, 2001)



Idealized model

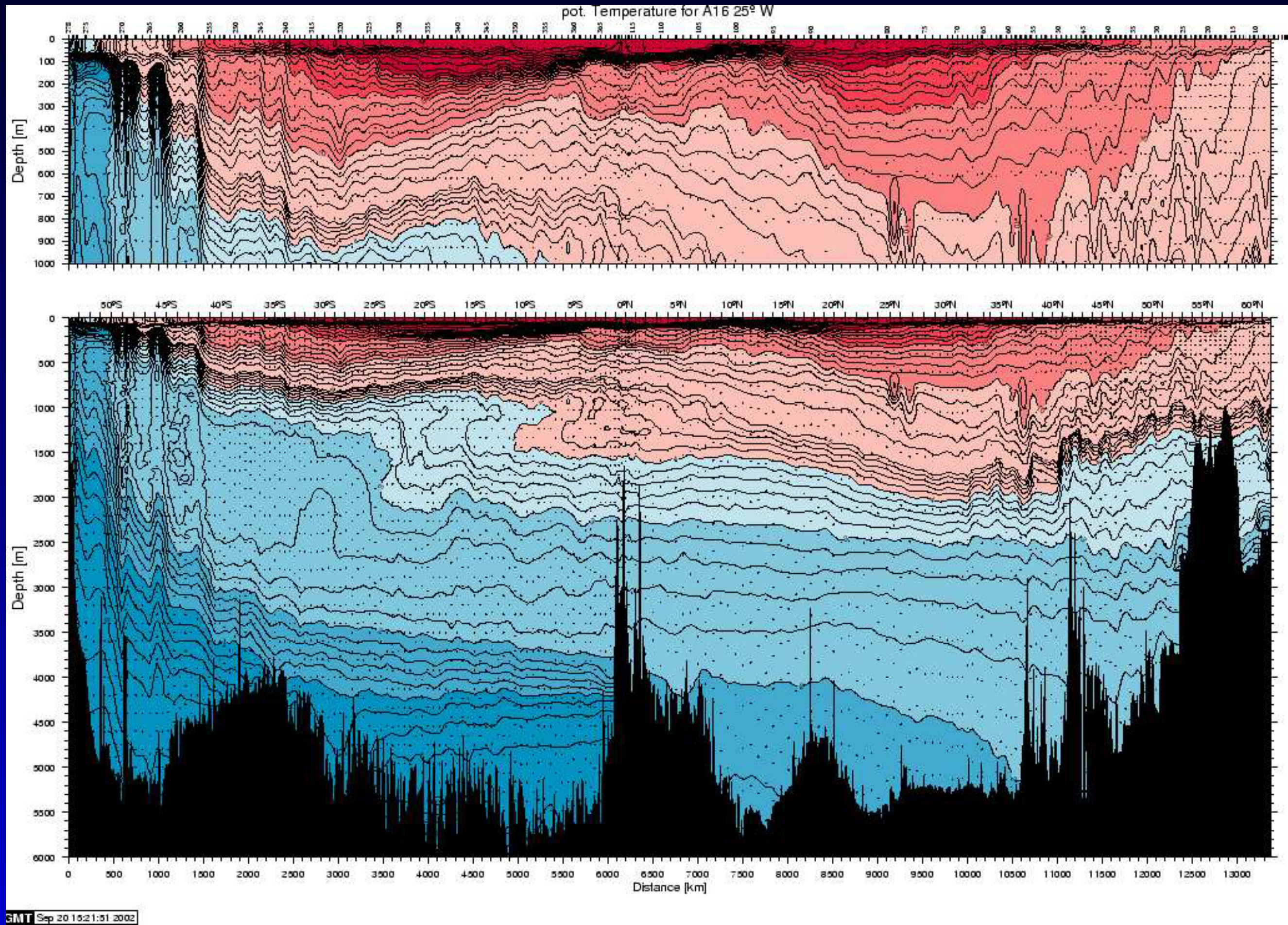
Geostrophy:

$$f u_0 = -\frac{1}{\rho}\frac{\partial}{\partial y}P, \quad f v_0 = \frac{1}{\rho}\frac{\partial}{\partial x}P$$

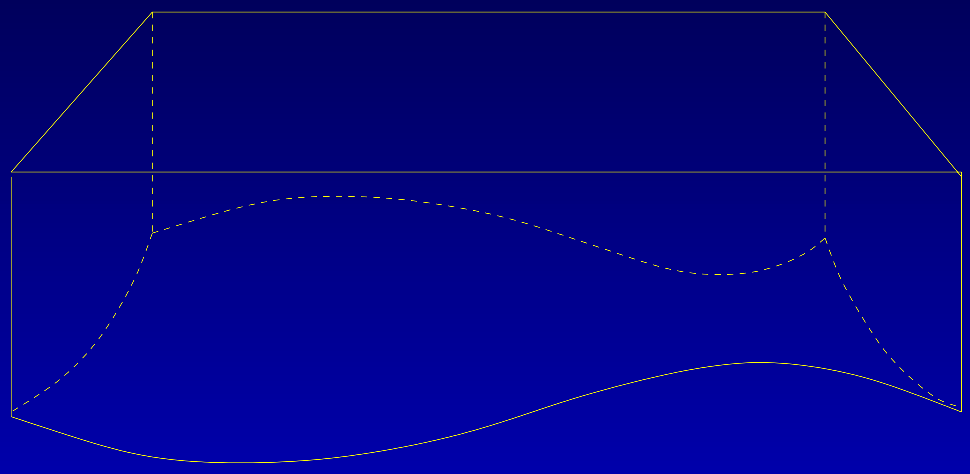
(so we can define a streamfunction):

$$(u_0, v_0) = \hat{k} \times \nabla\psi$$

Stratification



The 1.5 layer model



Baroclinic equation

$$\frac{\partial}{\partial t} q_T \;+\; \beta \frac{\partial}{\partial x} \psi_T \;+\; J(\psi_T, \nabla^2 \psi) \;=\; \mathcal{T} - \mathcal{D}$$

where the "potential vorticity" is:

$$q_T \equiv \nabla^2 \psi - F\psi$$

and

$$\beta \equiv \frac{\partial}{\partial y} f, \qquad F = \frac{\rho_0 f^2 L^2}{g \bigtriangleup \rho D} \equiv \frac{L^2}{L_D^2}$$

where $L_D(y)$ is the "deformation radius"

Long wave equation

- Linear dynamics
- No forcing
- Large scales ($L \gg L_D$)

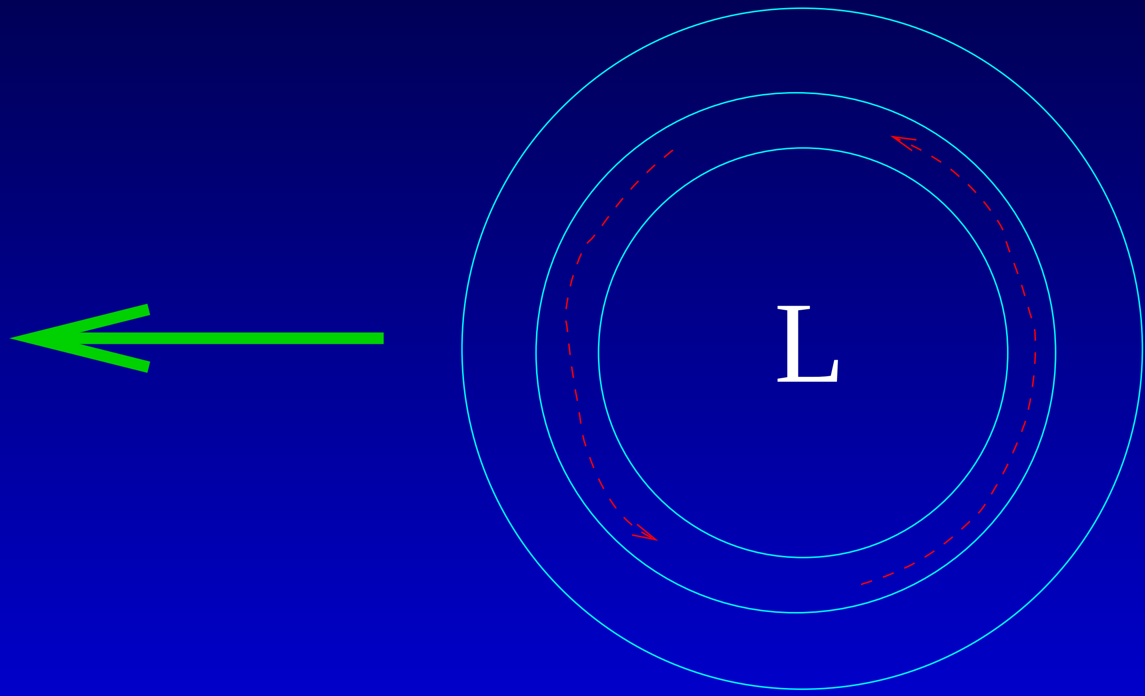
$$\frac{\partial}{\partial t}\psi_T - \frac{\beta}{F}\frac{\partial}{\partial x}\psi_T = \frac{\partial}{\partial t}\psi_T - \frac{\beta}{F}v_T \ \approx \ 0$$

Then a wave solution, $\psi = A\,cos(kx + ly - \omega t)$, has

$$\omega \approx \frac{-\beta k}{F} \quad \rightarrow \quad c = \frac{\omega}{k} \propto -\beta L_D(y)^2$$

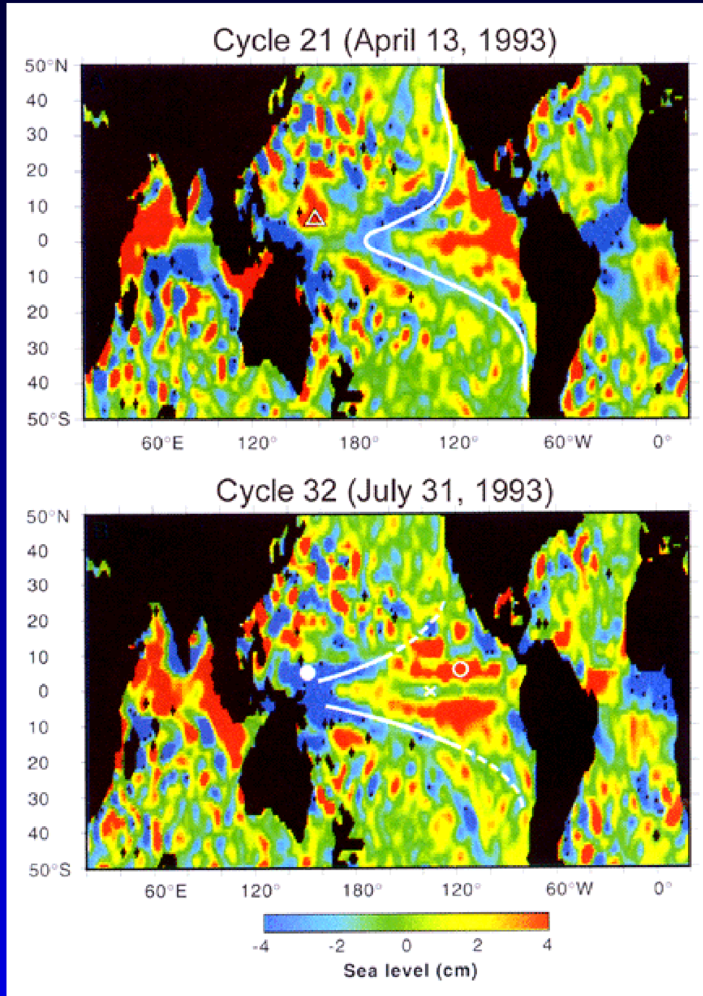
Rossby waves

Exist because the Coriolis force changes with latitude



Satellite observations

Chelton and Schlax, 1996



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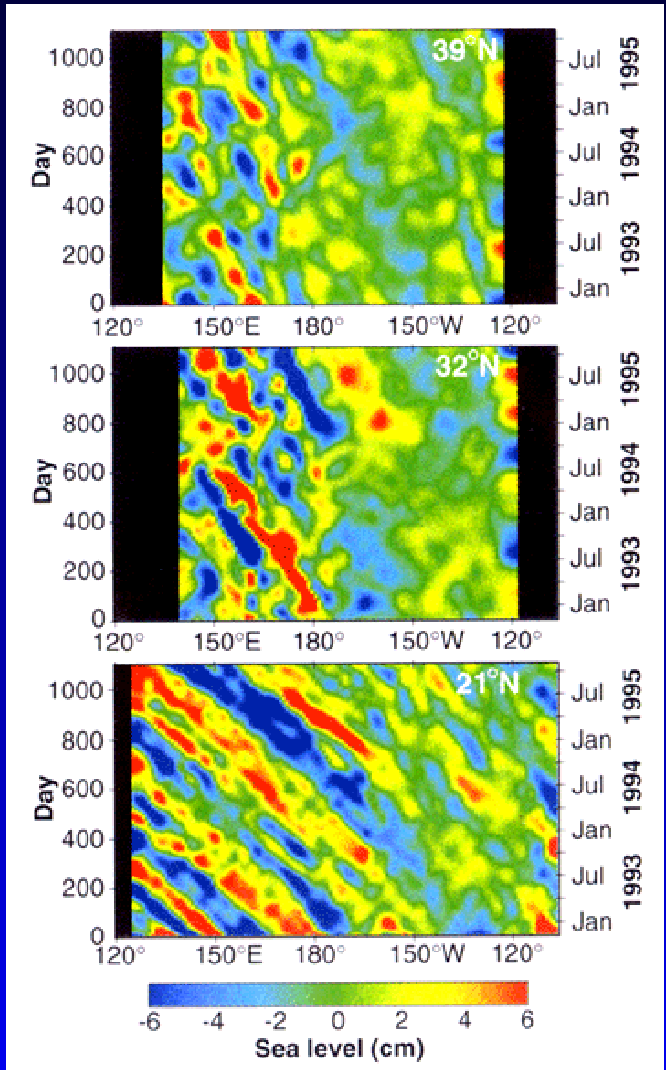

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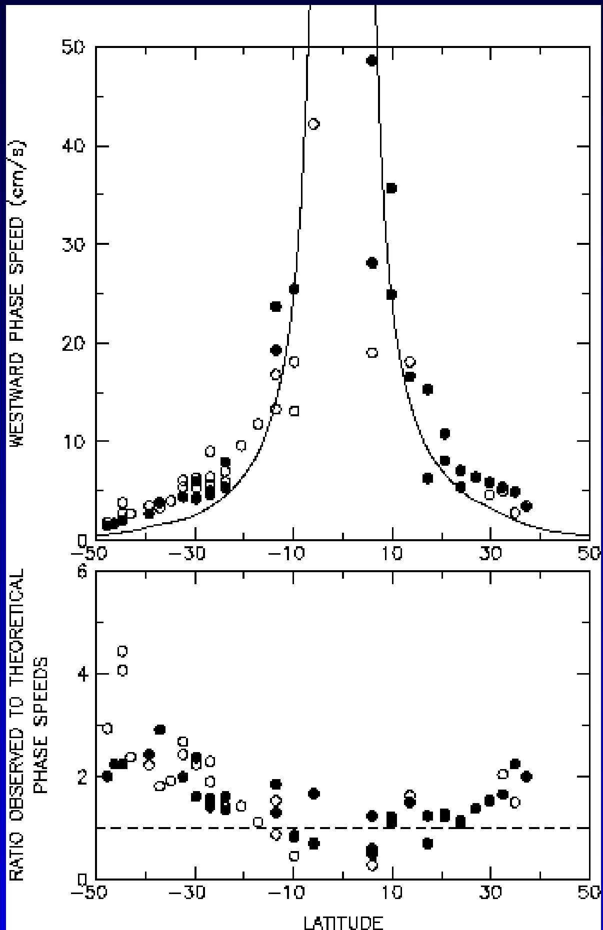


Too-fast waves

Frequency also higher—changes oceanic response

Prompted many theoretical studies

- Mean flow (Killworth et al.)
- “Homogenized PV” (Dewar, DeSzoeke)
- Eastern boundary effect (Qiu, White)
- Basin modes (Cessi, LaCasce)

Basin modes

Lateral boundaries should affect Rossby waves

Can the boundaries alter phase speeds?

$\rightarrow$ Can a closed ocean basin be excited *resonantly*?

Basin modes: theory

Flierl, 1977; LaCasce, 2000; Cessi and Primeau, 2001

$$\frac{\partial}{\partial t} q_T \; + \; \beta \frac{\partial}{\partial x} \psi_T \; = \; 0$$

with boundary condition:

$$\psi = \Gamma(x.y.t)$$

Assume L_D constant (QG approximation)

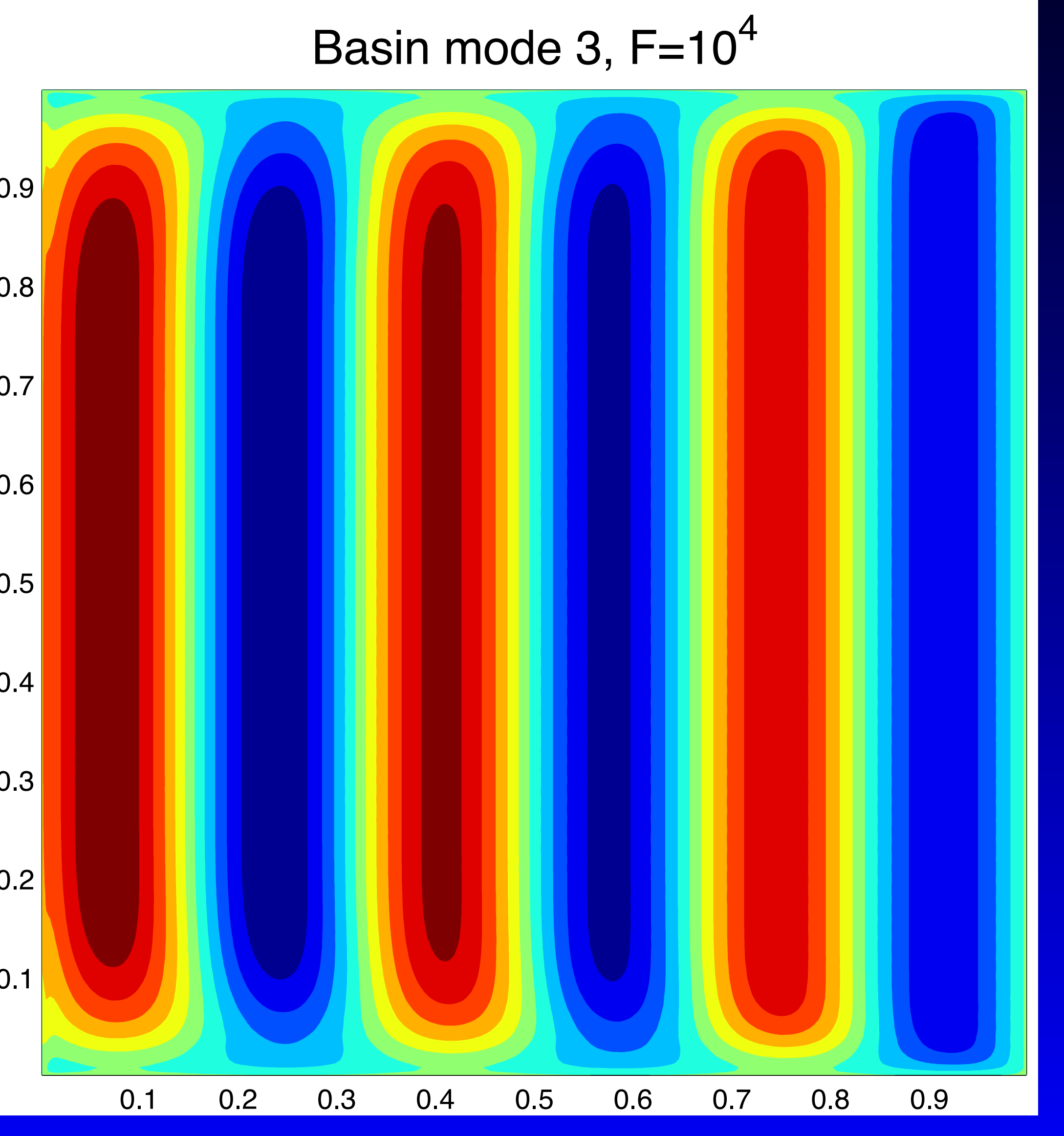
- phase speed constant with latitude
- $\Gamma(x.y.t) = \Gamma(t)$

Solution

Resonances found

- If weak dissipation
- If basin much larger than L_D

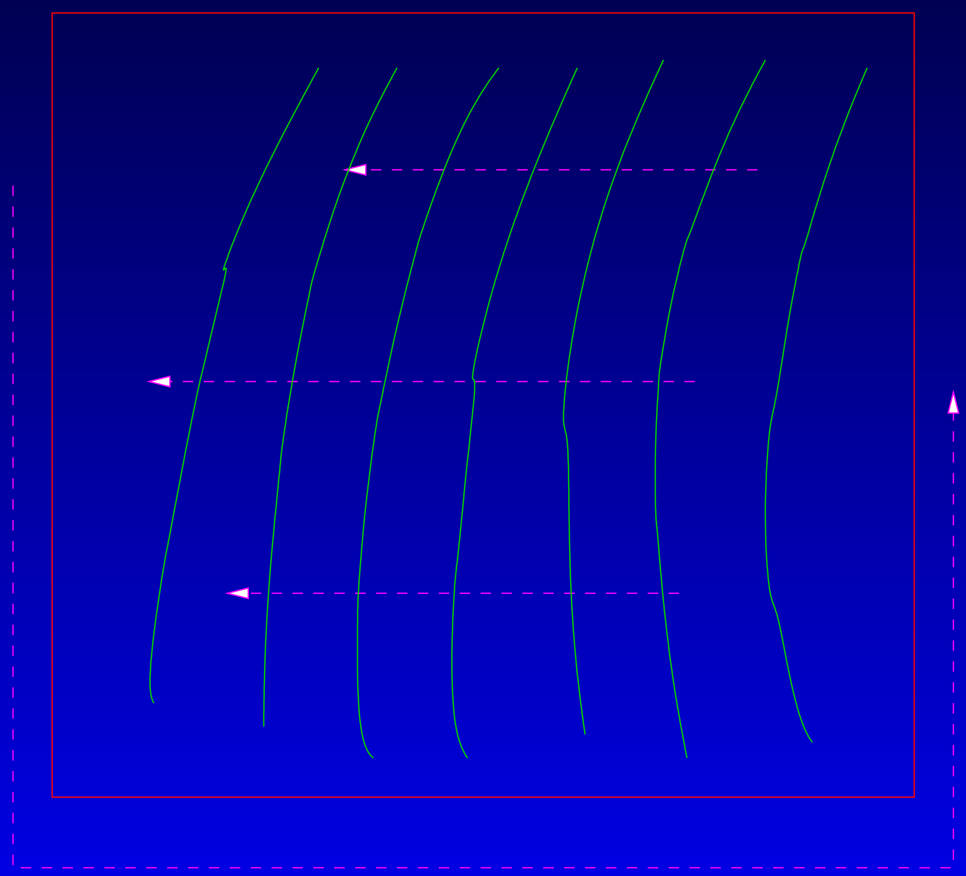
Mode 3



Basin mode 3, F=10^4
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Basin modes

Conceptually:



Properties

- Long wave phase speed in interior
- Gravest modes have *decadal* periods
- Exist in irregular basins (LaCasce and Pedlosky, 2002)
- Excited by stochastic forcing (Cessi and Louazel, 2001)

$\rightarrow$ Important for climate variability?

Baroclinicity

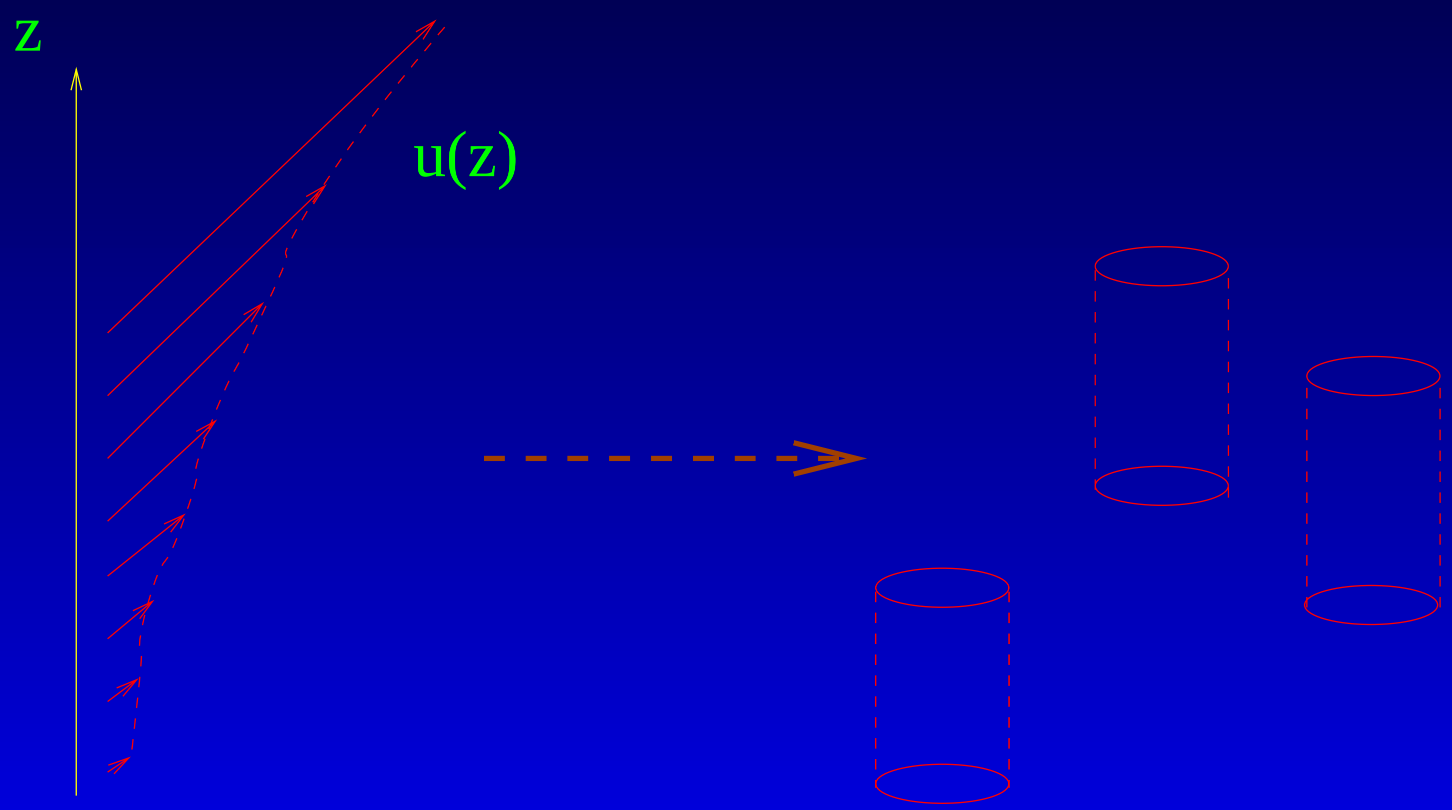
Previous studies focused on the 1.5 layer model

No “baroclinic instability”

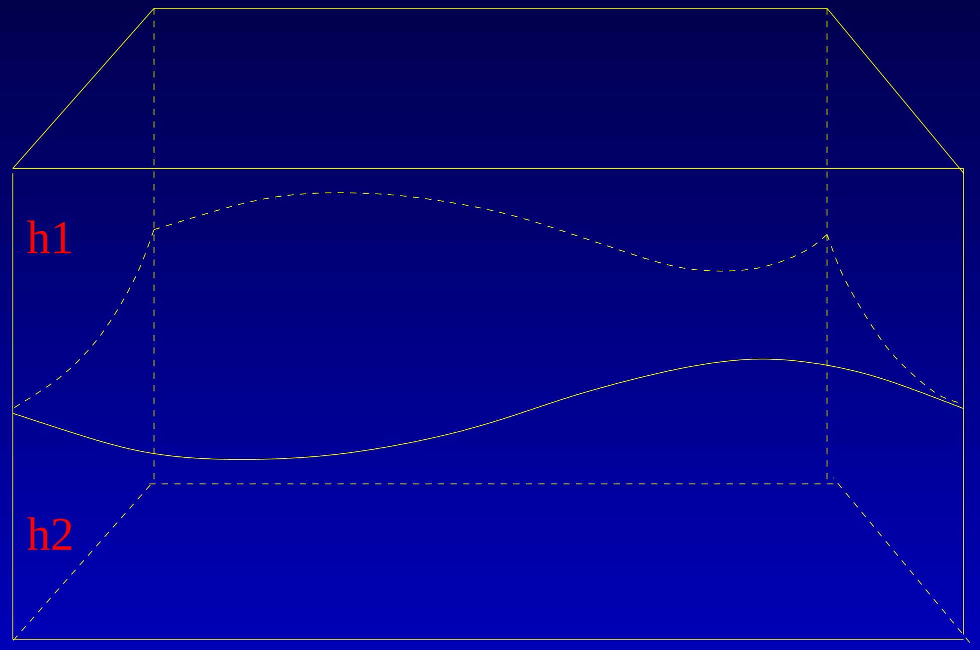
Do the modes persist if the deep ocean allowed to move?

Baroclinic instability

Vertical sheared flows break up into eddies with less shear



The 2 layer model



Barotropic/baroclinic modes

With two layers, are now two modes:

1) Baroclinic:

$$\psi_T = \psi_1 - \psi_2, \qquad q_T \equiv (\nabla^2 - F)\psi_T$$

2) Barotropic:

$$\psi_B = h_1\psi_1 + h_2\psi_2, \qquad q_B \equiv \nabla^2\psi_B$$

Barotropic/baroclinic equations

$$\frac{\partial}{\partial t} q_T \; + \; \beta \frac{\partial}{\partial x} \psi_T \; + \; (h_2 - h_1) J(\psi_T, q_T) + $$
$$J(\psi_B, q_T) \; + \; J(\psi_T, q_B) \; = \; 0$$

$$\frac{\partial}{\partial t} q_B \; + \; \beta \frac{\partial}{\partial x} \psi_B \; + \; J(\psi_B, q_B) + $$
$$h_1 h_2 \, J(\psi_T, q_T) \; = \; 0$$

Barotropic wave

- Baroclinic waves have surface and bottom velocities out of phase
- Barotropic wave has *depth-independent* velocities

$$\omega_B = \frac{-\beta k}{k^2 + l^2}$$

Barotropic waves propagate faster and have shorter periods (weeks to months)

Wave instability

Will a baroclinic Rossby wave in two layers break up into barotropic eddies?

If so, under what conditions (i.e. different latitudes)?

And what are the properties of resulting barotropic eddies?

Two time scales

1) $T_R = L/(\beta L_D^2)$

Time for baroclinic wave to cross basin

2) $T_g = L_D/U$

Time for unstable growth

Ratio is $Z \equiv T_R/T_g$

Small Z

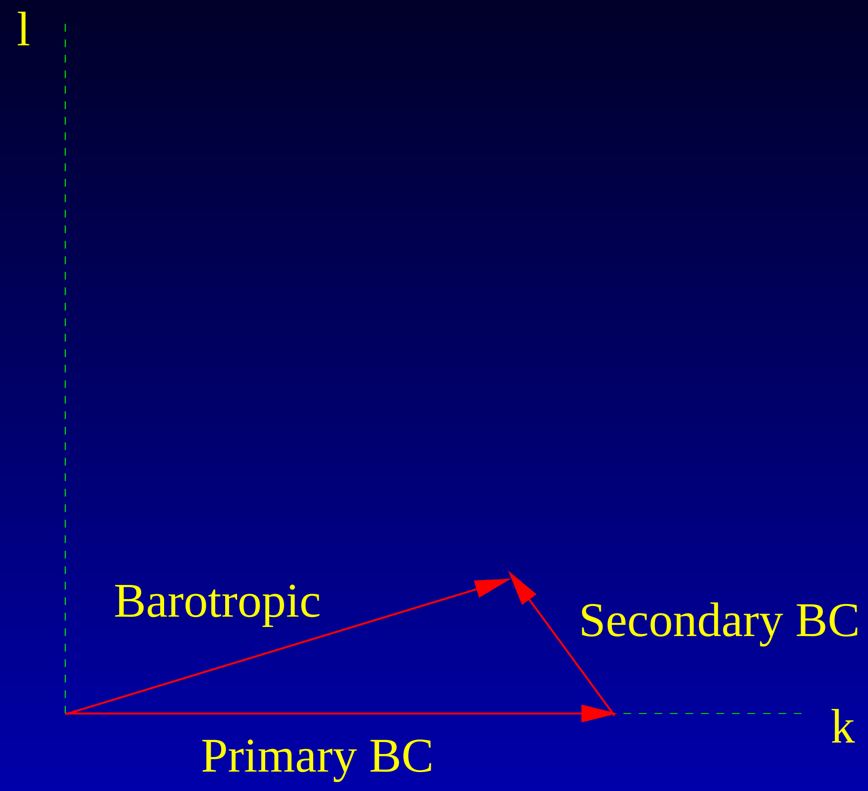
Expand the equations in the two time scales

Energy transfer occurs between groups of three Rossby waves ("triads")

By assuming the primary wave is initially much stronger than the other two, can linearize the problem and obtain growth rates

Triads

Wavevectors



Linear stability

Baroclinic Rossby waves *always* unstable

Exponential growth with rate:

$$\lambda \propto \left(\frac{L_D^2 - L^2}{L^2 + L_D^2}\right)^{1/2} V$$

$\rightarrow$ Barotropic eddies approximately deformation scale

Large Z

Can also be treated analytically

Wave effectively motionless during growth

Result: growth rate is only about 65 % larger than with small Z

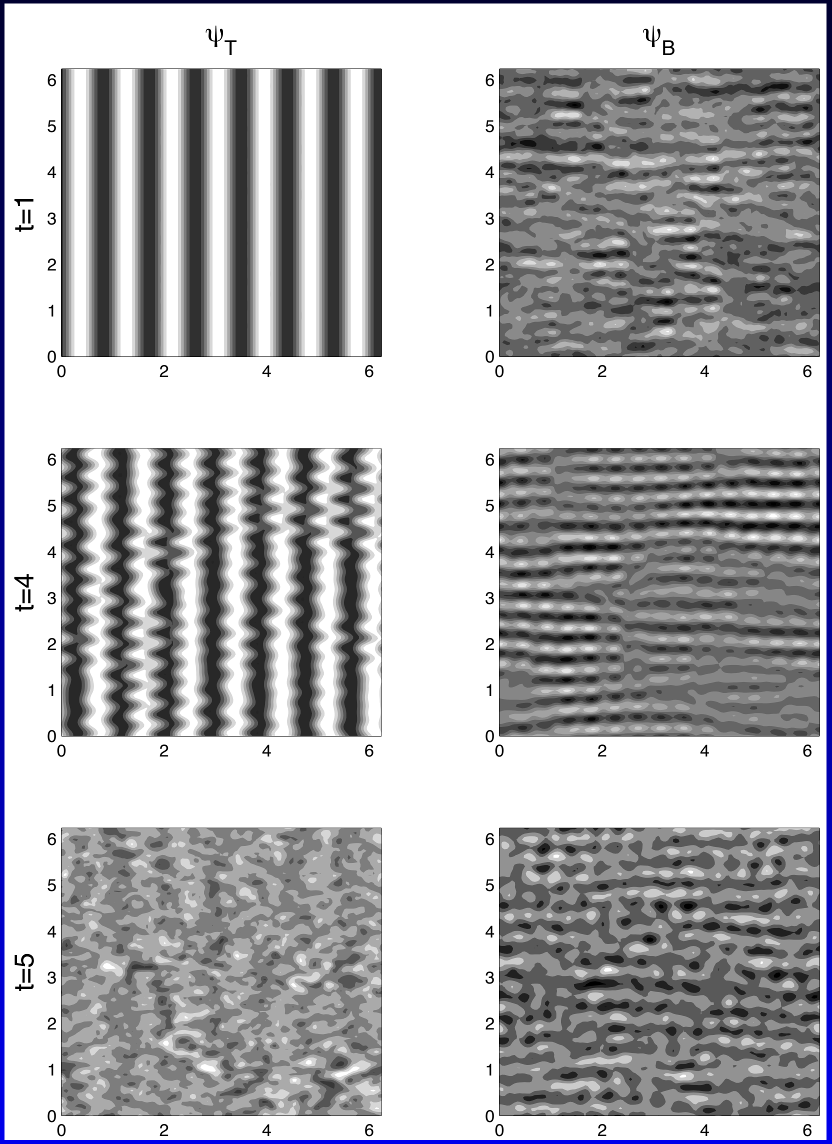
Numerical models

Simulate the nonlinear barotropic/baroclinic equations using two models:

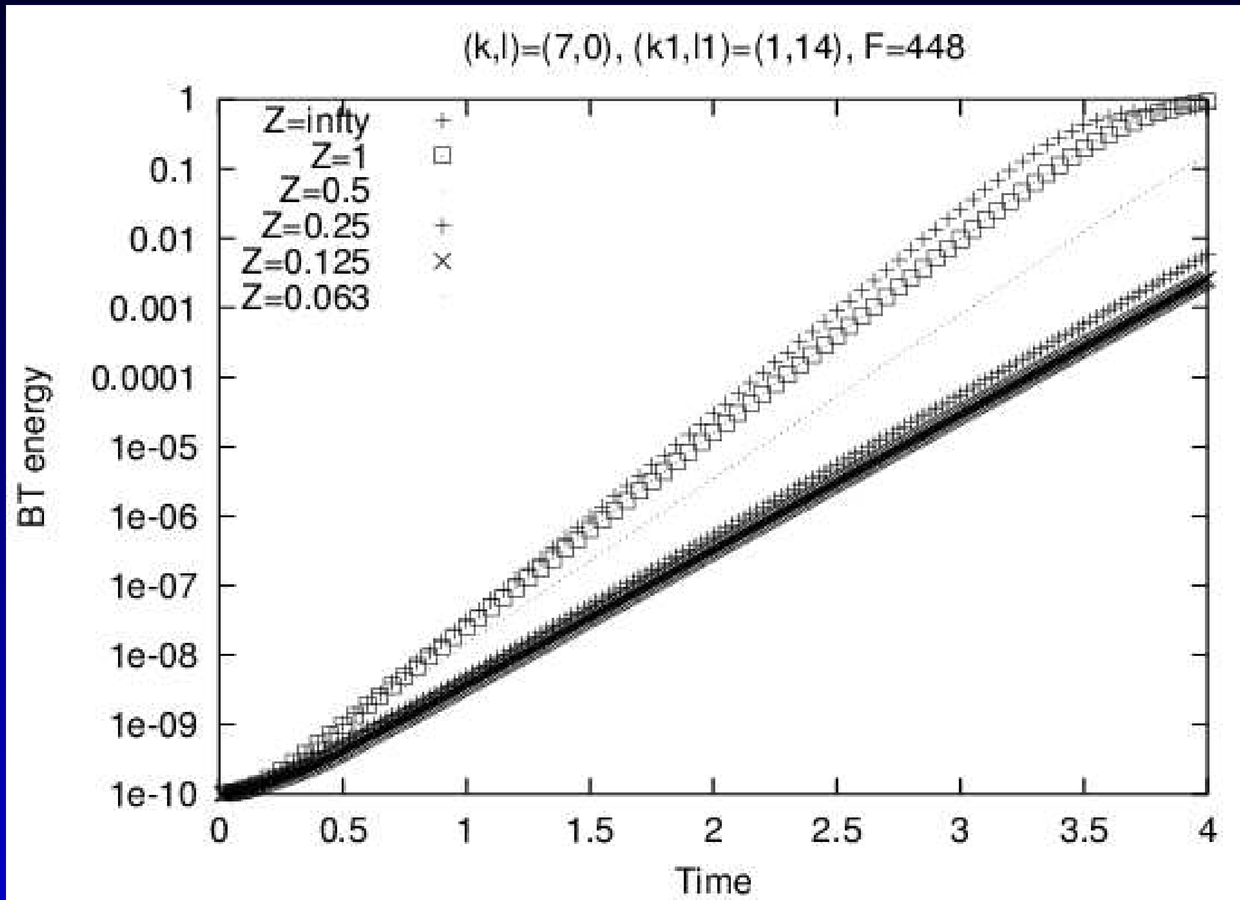
- Spectral QG model in periodic domain
- Semi-spectral QG model in a basin

Initialize with either baroclinic wave or basin mode, perturb with barotropic “noise”—wait and see

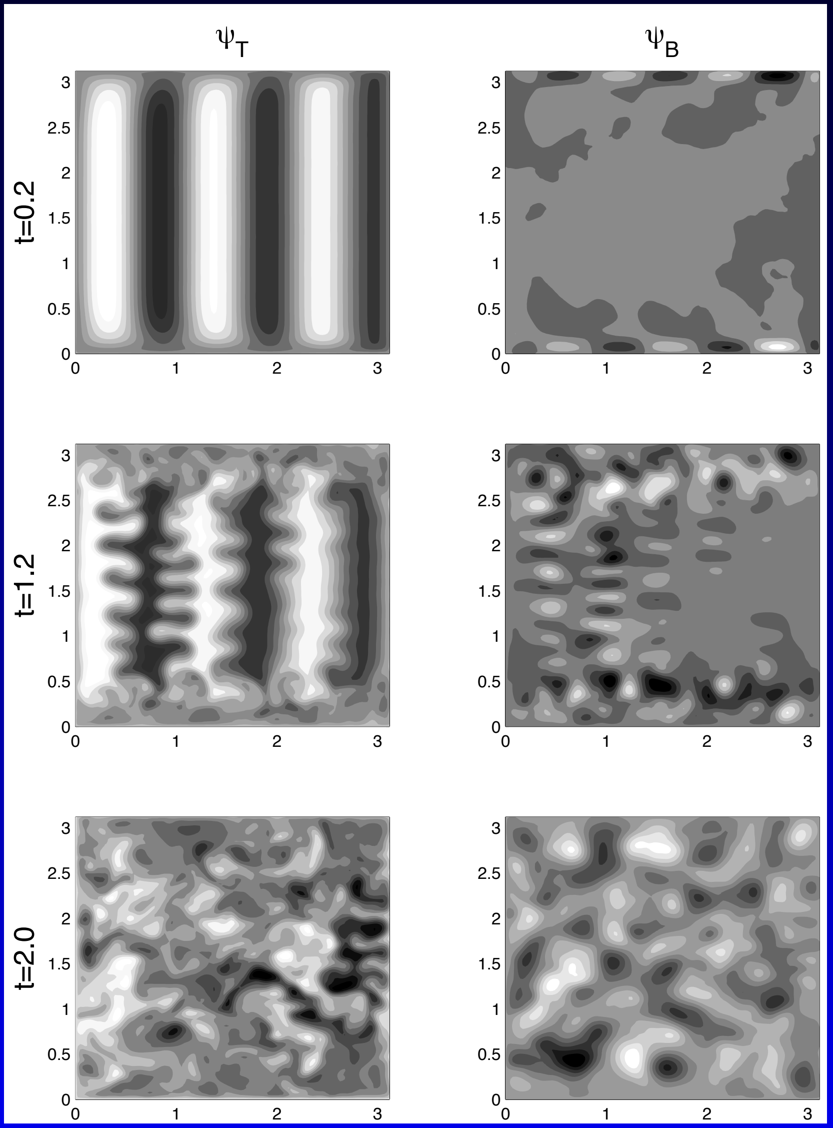
Spectral model (Z=1)



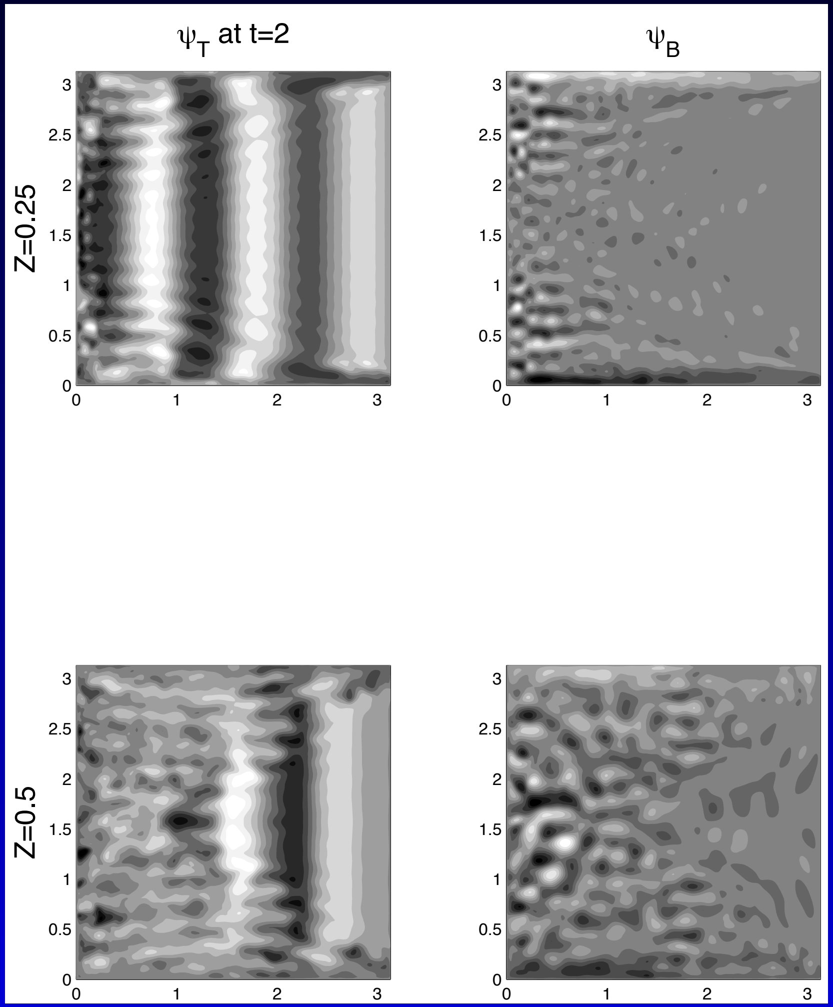
Plane wave growth



Basin mode (Z=5)



Basin mode instability



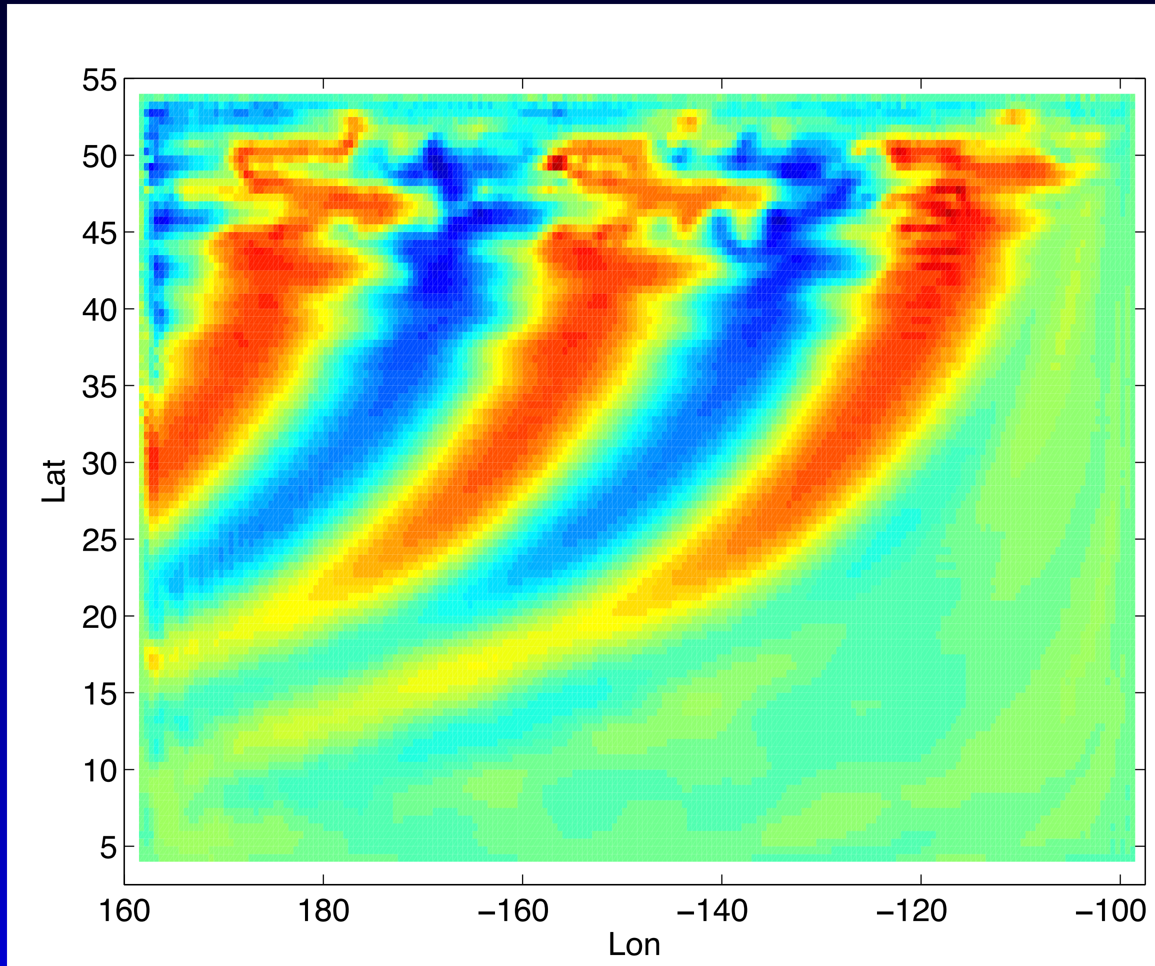
Beyond QG

Work thus far assumed constant L_D

Questionable assumption for large basins

Do Rossby waves in GCMs break up too?

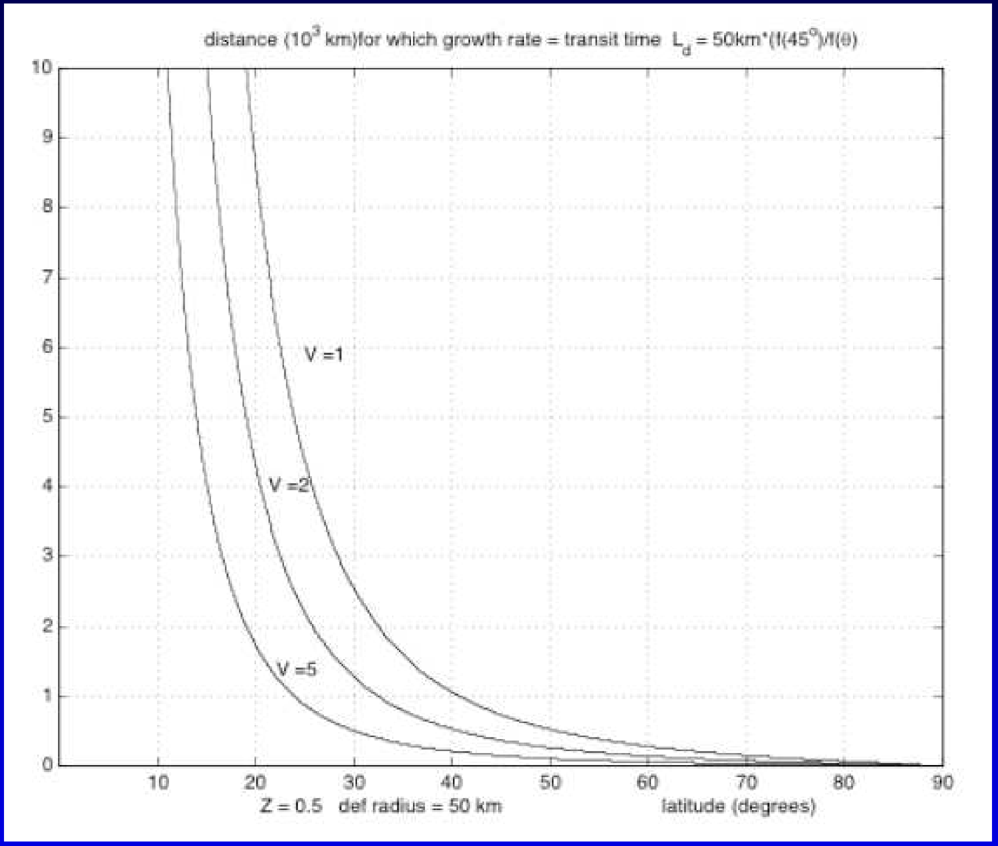
Realistic models



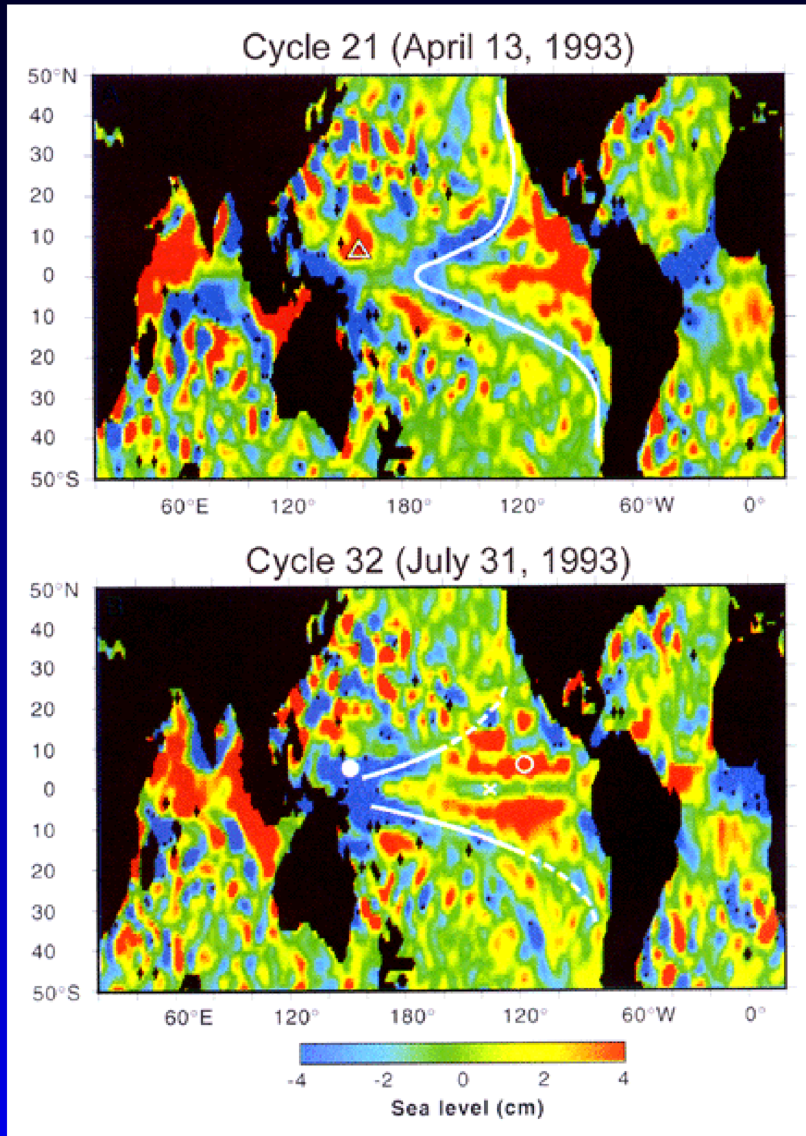
courtesy P. E. Isachsen

Consequence 1

Coherent Rossby waves only at *low* latitudes



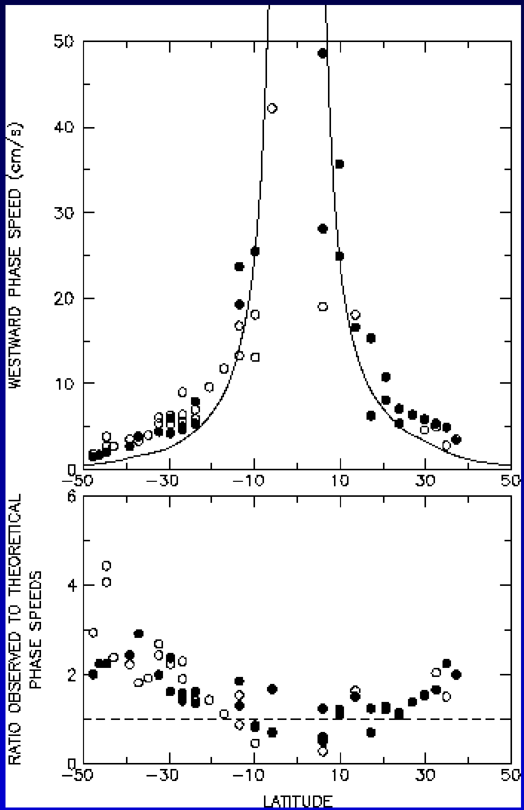
Satellite



Cycle 21 (April 13, 1993)
50°N
40
30
20
10
0
10
20
30
40
50°S
60°E
120°
180°
120°
60°W
0°
Cycle 32 (July 31, 1993)
50°N
40
30
20
10
0
10
20
30
40
50°S
60°E
120°
180°
120°
60°W
0°
-4
-2
0
2
4
Sea level (cm)

Consequence 2

At higher latitudes, have *faster* barotropic waves



Consequence 3

Basin modes probably not relevant for mid-latitude climate (!)

Westward phase propagation, but smaller eddies

Anderson and Gill (1975) adjustment?

Exception possibly near equator

Consequence 4

Rossby waves possible source of mid-latitude "turbulence"

Historically associated eddies with mean flow (Gulf Stream) instability

$\rightarrow$ More widespread activity

Consistent with satellite (Stammer, 1997)

Summary

- Baroclinic Rossby waves are unstable
- Probably no “resonant” oceanic response to wind forcing at decadal scales
- Simple instability calculation predicts observed features of oceanic wave field
- New perspective on time-dependent ocean
- How does this turbulent ocean interact with the atmosphere?