Global Climate meets dynamics in the fluids laboratory

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www.ocean.washington.edu/research/gfd/gfd.html

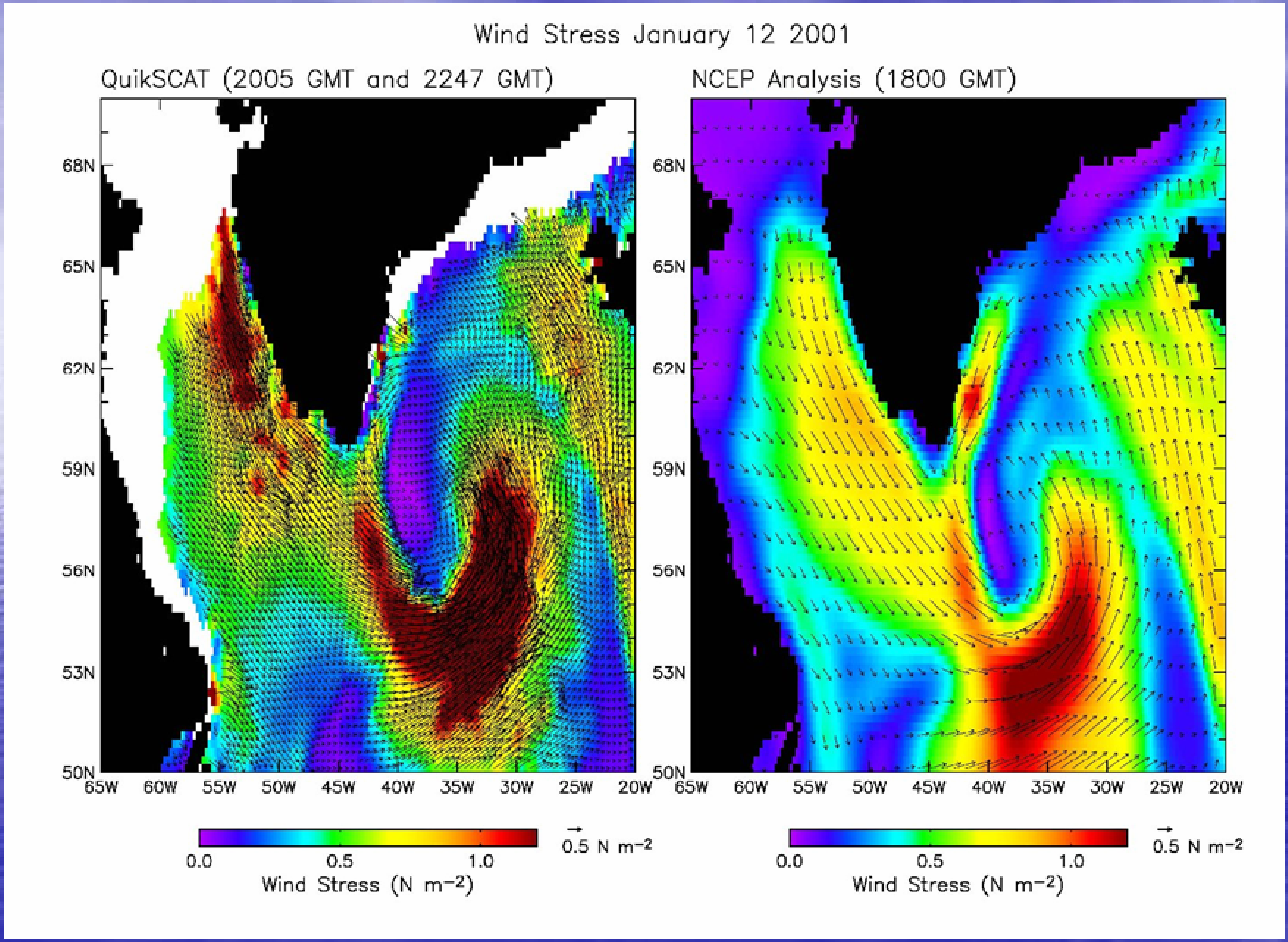
with Eric Lindahl,
Alex Mendez

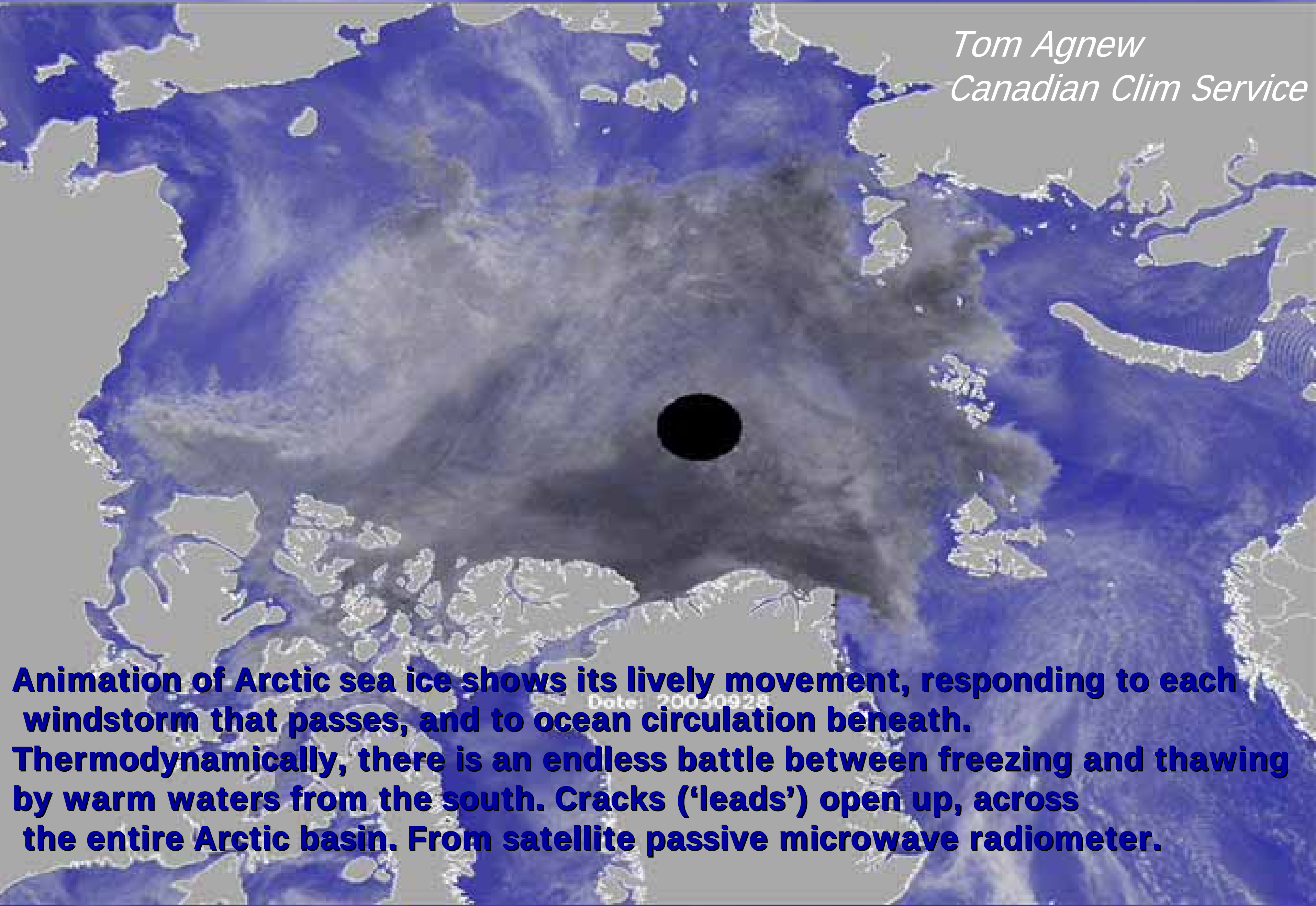
The state of and change of the environment motivates our science: partly as prediction but also as 'assessment' of the current state of oceans, atmosphere, and land surface. But…how does one proceed in the face of 10 decades of length scales in the macroscopic, plus many more in the microphysics?

Numerical climate modeling is challenged by unresolved dynamics, leading to the necessity of better observations and more underlying dynamical principles. It is a matter of *texture.*

Here we will go to high latitudes for examples, where climate change is observed to be particularly rapid and intense……….***1. Some observations***

scatterometer winds **pressure sounding derived winds**





Tom Agnew
Canadian Clim Service

Animation of Arctic sea ice shows its lively movement, responding to each windstorm that passes, and to ocean circulation beneath. Thermodynamically, there is an endless battle between freezing and thawing by warm waters from the south. Cracks ('leads') open up, across the entire Arctic basin. From satellite passive microwave radiometer.

Beneath the ocean surface the dynamics is dominated by

layering in stable stratification

stiffening of the fluid by Earth's rotation

intense atmosphere-ocean interaction:

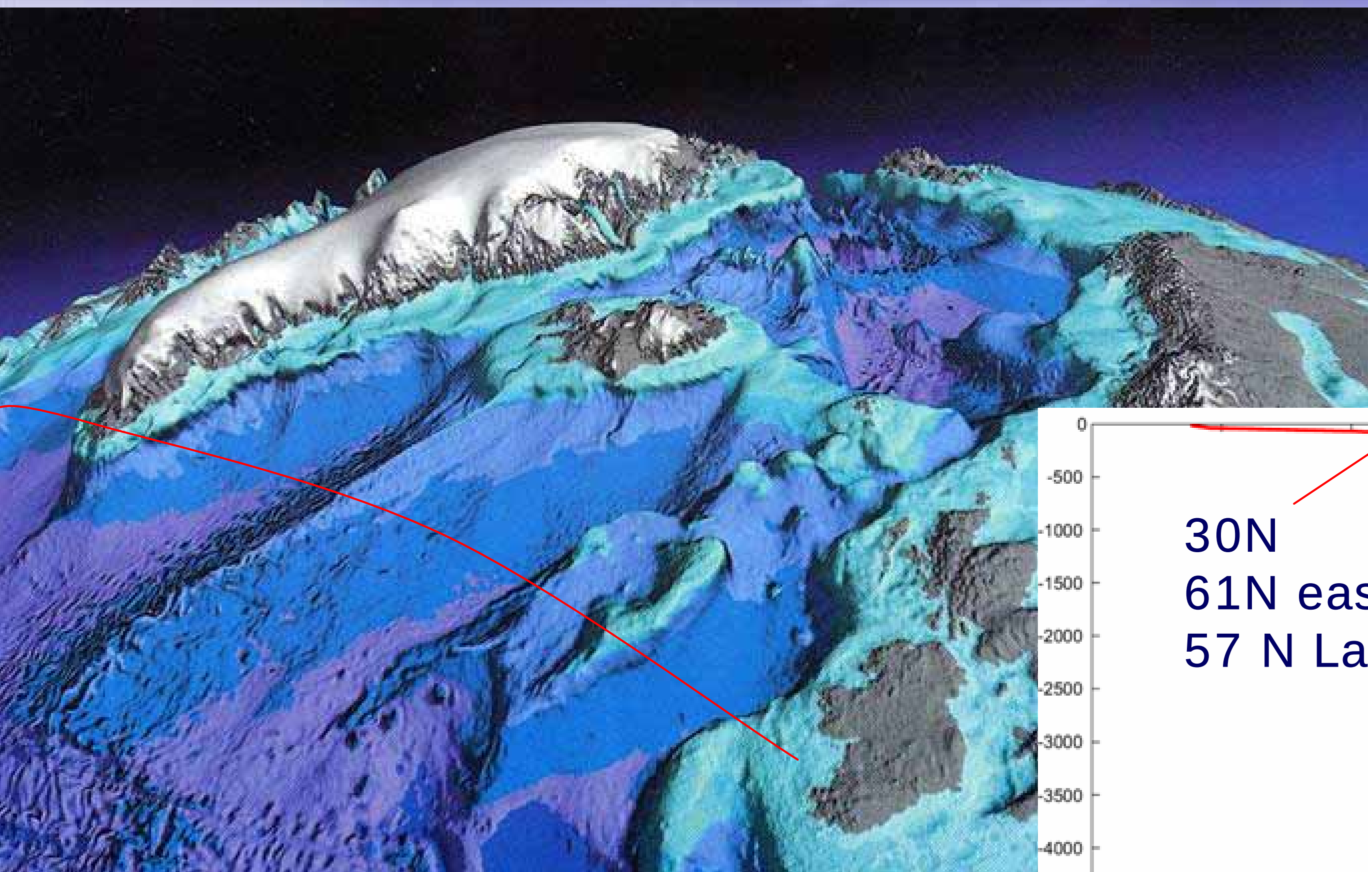
winds, moisture flux, heat flux

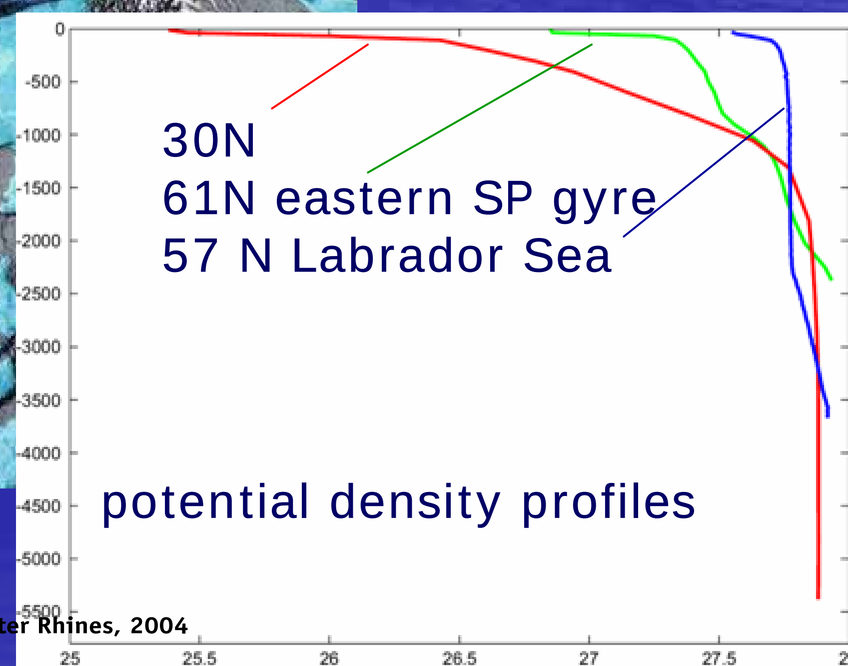
meridional energy transport

topography

ice

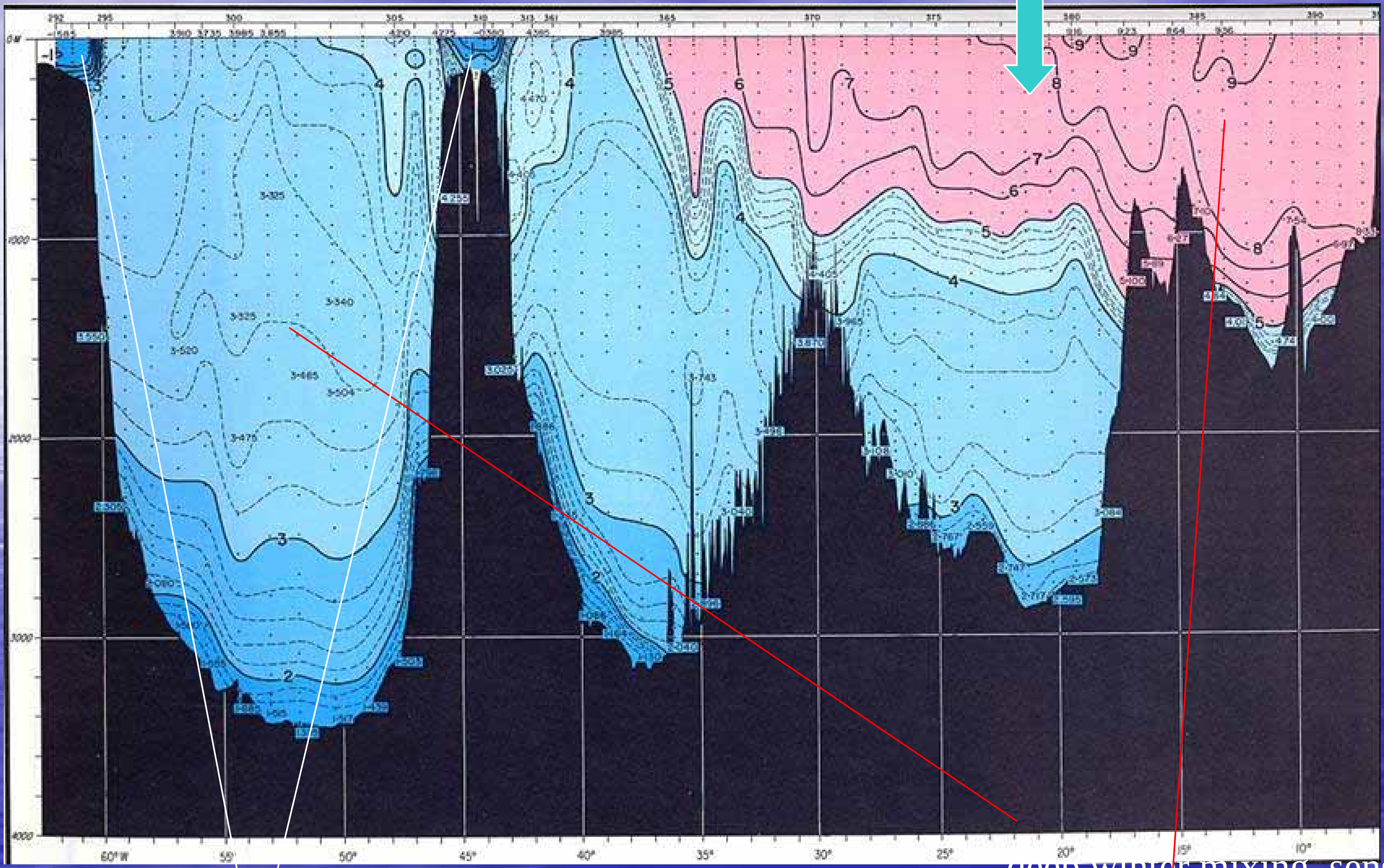
Heat moving north, fresh water moving south in ocean....
Subpolar Atlantic and exchange with the Arctic: well-defined passages, ridges, gaps. With weak subpolar density stratification, Taylor-Proudman rotational 'stiffness' leads to strong topographic control over circulation





Erika Dan temperature section, 60^{0}N
Labrador-Greenland-Rockall-Ireland
Worthington+Wright, 1970

warm, saline water moving north from the subtropics



Shallow continental shelf circulation (unresolved in CCMs)

deep winter mixing, sensitive to upper ocean low-salinity waters

Notice that the data comes from profiles spaced on average 70 km apart, whereas the energy containing scale of the general circulation is of order 10 to 50 km (dominant eddies, boundary currents).

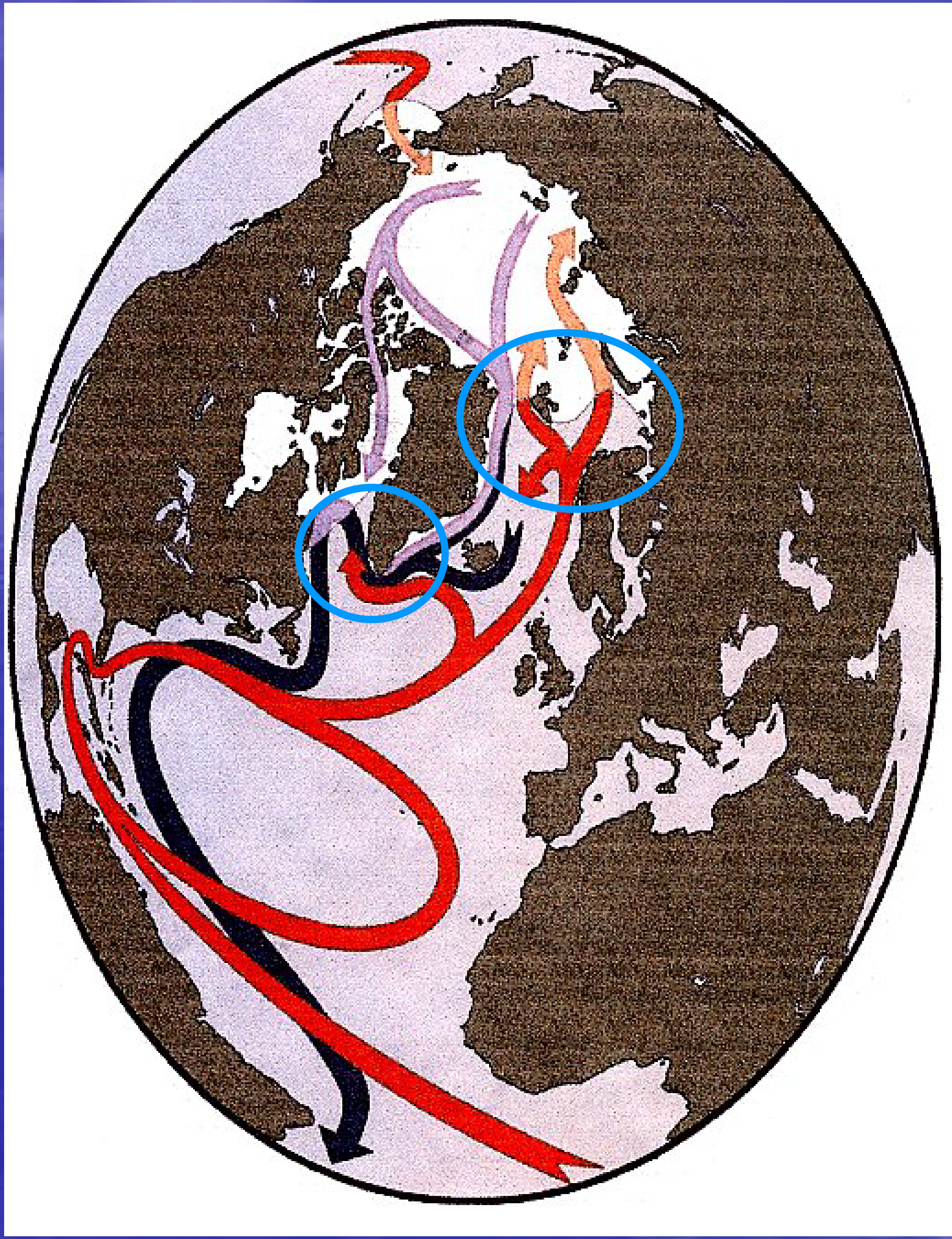
Oceanic global overturning circulation

where does it sink,
where does it rise?

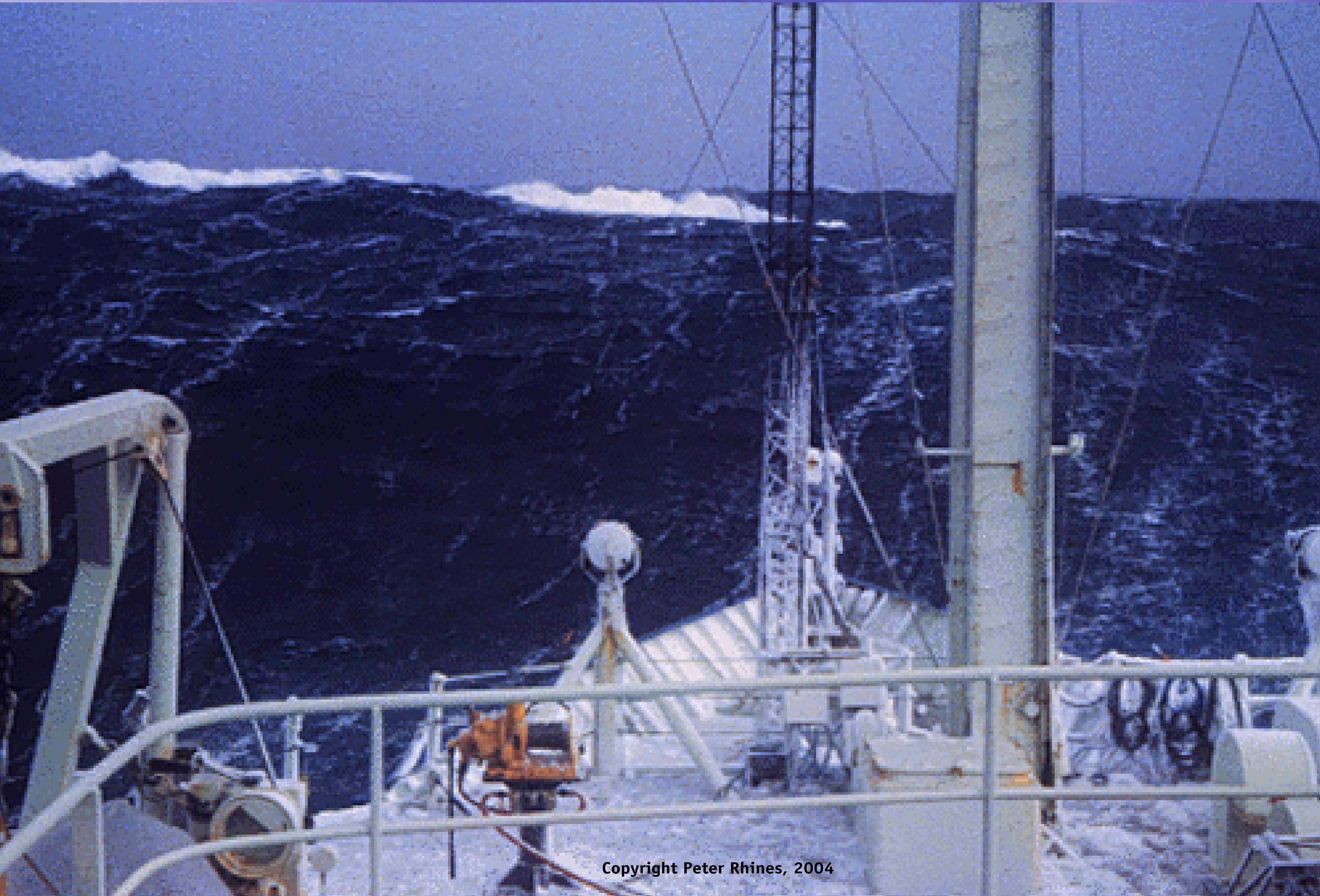
red: warm, poleward surface currents;

black: cold, deep Equatorward currents

purple: low salinity, buoyant surface currents



The subpolar gyre in winter R. Pickart R/V Knorr

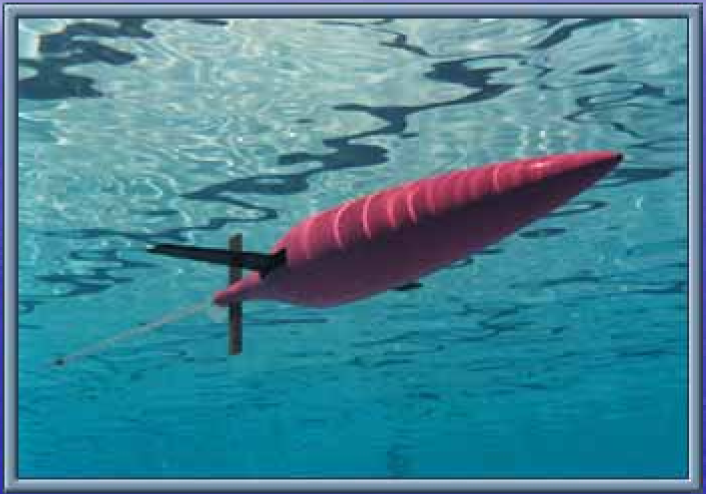


Are we having fun yet?

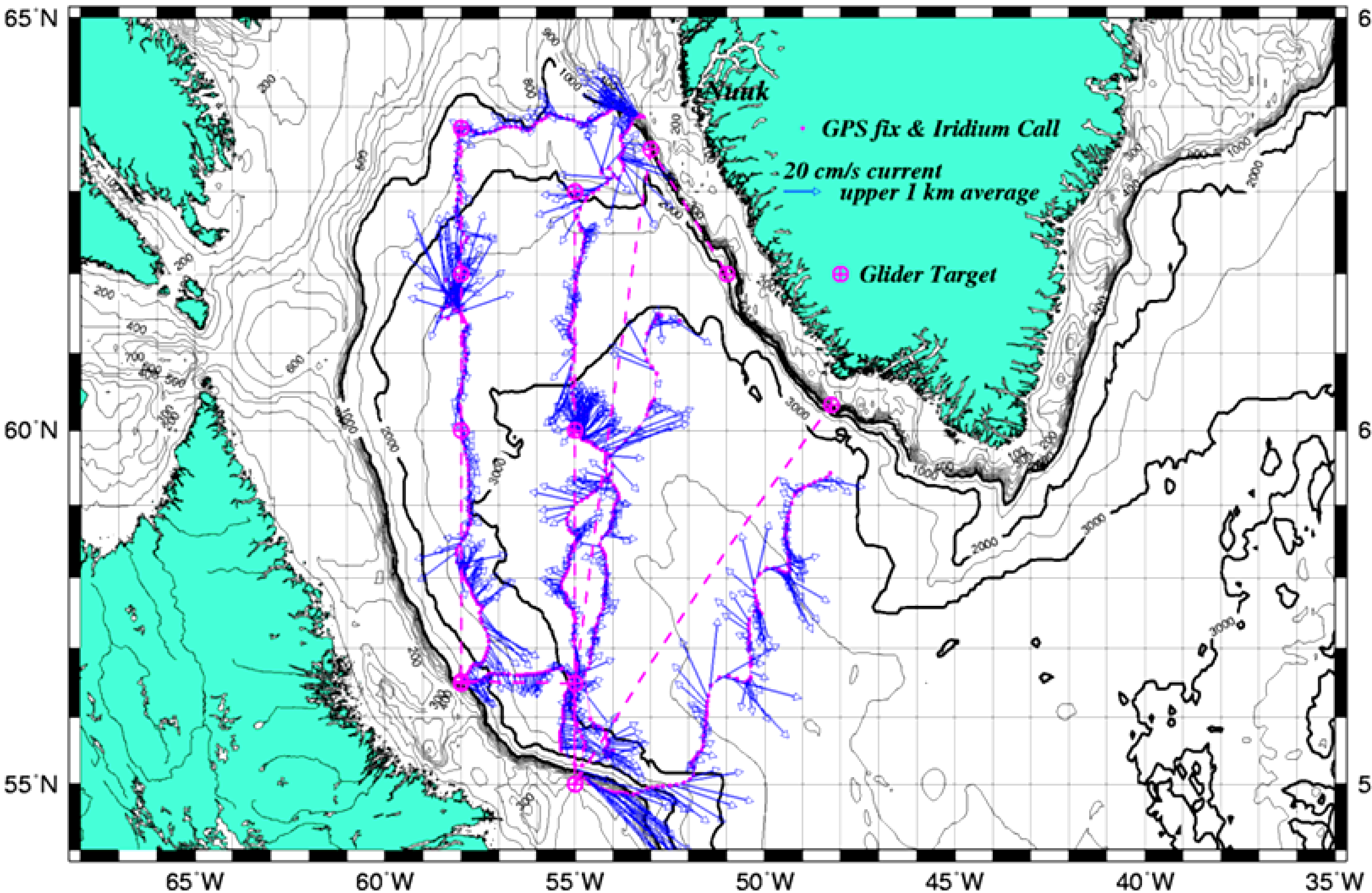
Enlightenment comes in so many ways …..

Help is on the way, thanks to Charlie Eriksen of U Washington (and many other creators of new platforms and sensors):

- Use long-range AUVs (e.g. Seagliders) to measure temperature, salinity, oxygen, chlorophyll....
- Skip the ship
- See the data in real time, all the time...phone home 3 times per day
- Control vehicle from any telephone or internet connection
- Spend a few thousandths as much money
- Spend more time with family & friends

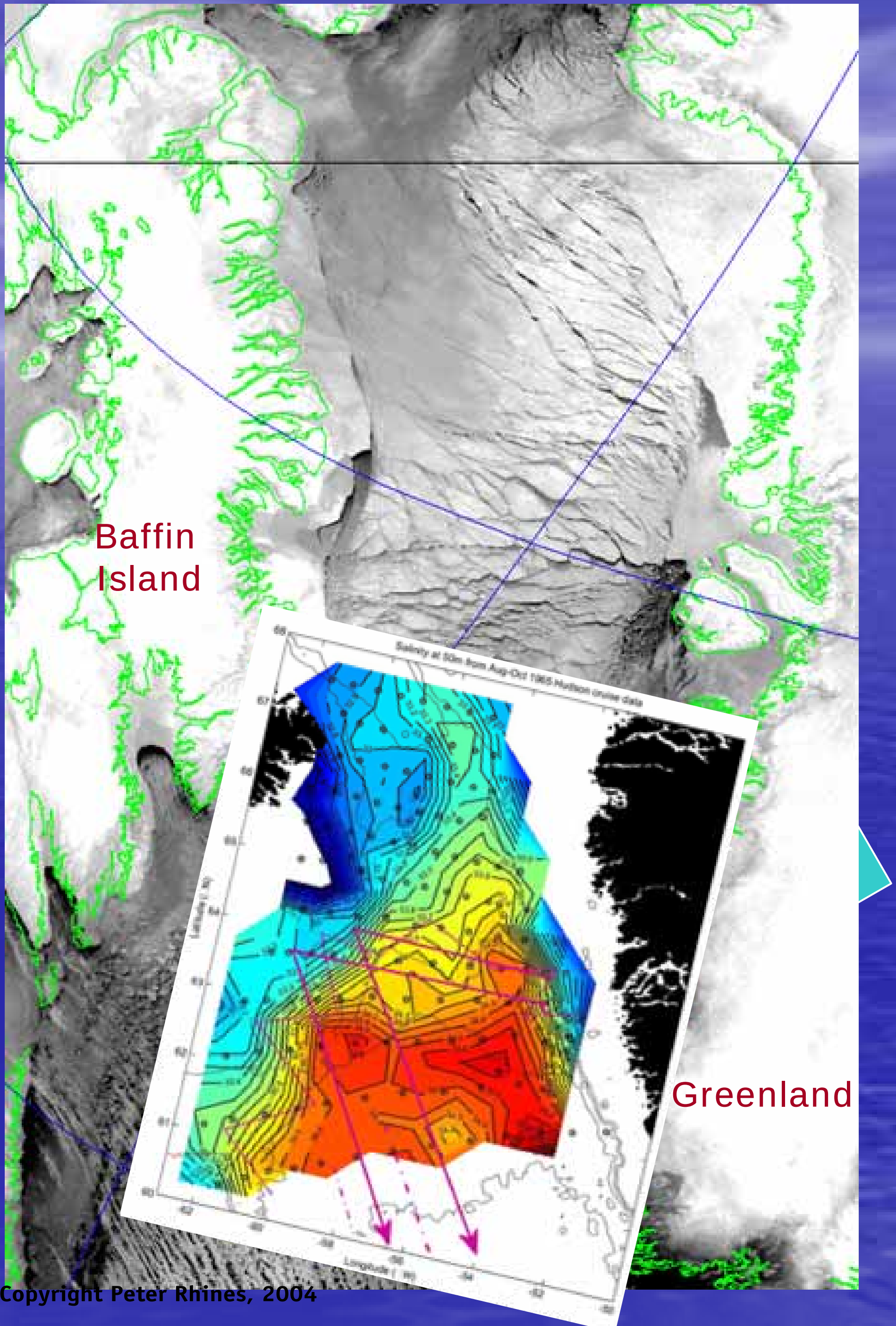


The first major deployment of autonomous undersea vehicles in the Atlantic Ocean: winter 2003-4



Beneath the surface.....

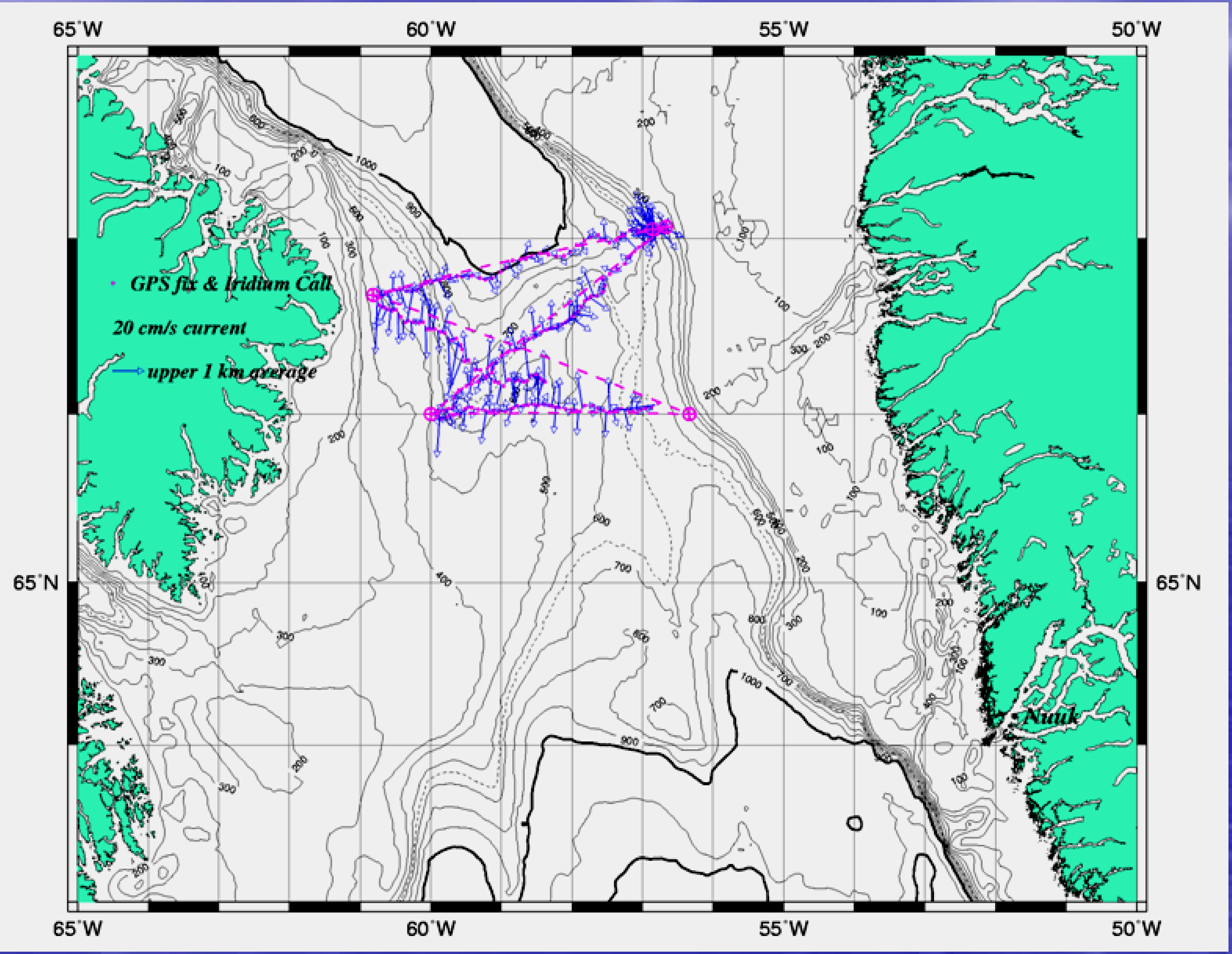
Davis Strait west of Greenland. Here, and along the Greenland-Scotland ridge east of Greenland collect much of the transport out of the Arctic This figure shows the salinity at 50m depth during the one (only) 3-dimensional survey ever carried out (in 1965-66) overlaid on a wintertime ice cover image.



data from John Lazier, Bedford Inst. of Oceanography

plot by Jerome Cuny, Univ. of Washington

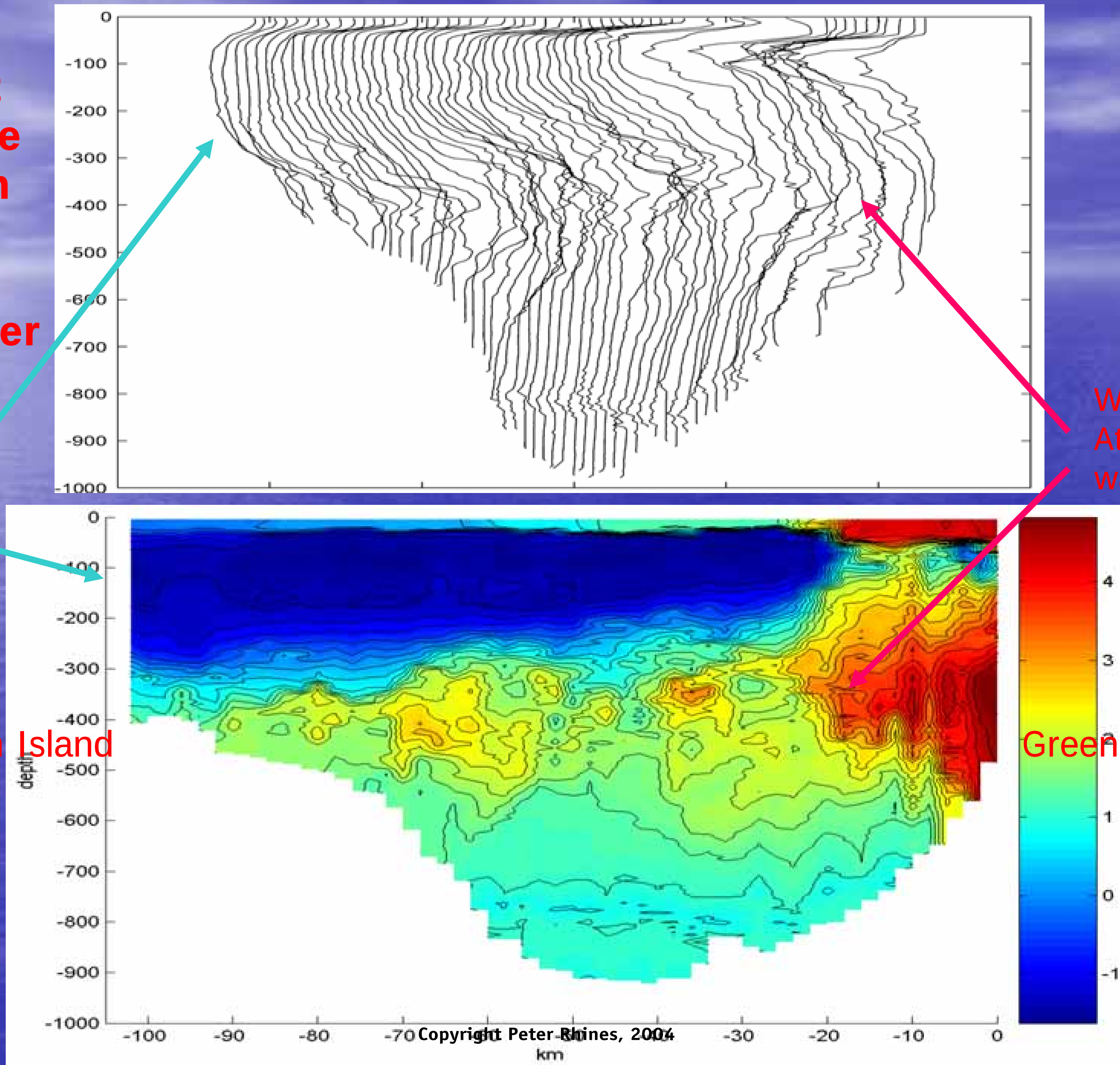
satellite image from Yanling Yu, U of W.



65˚W
60˚W
55˚W
50˚W
65˚N
GPS fix & Iridium Call
20 cm/s current
upper 1 km average
Nuuk

Davis Strait temperature at 1 to 3 km resolution

UW Seaglider section, Oct 2004



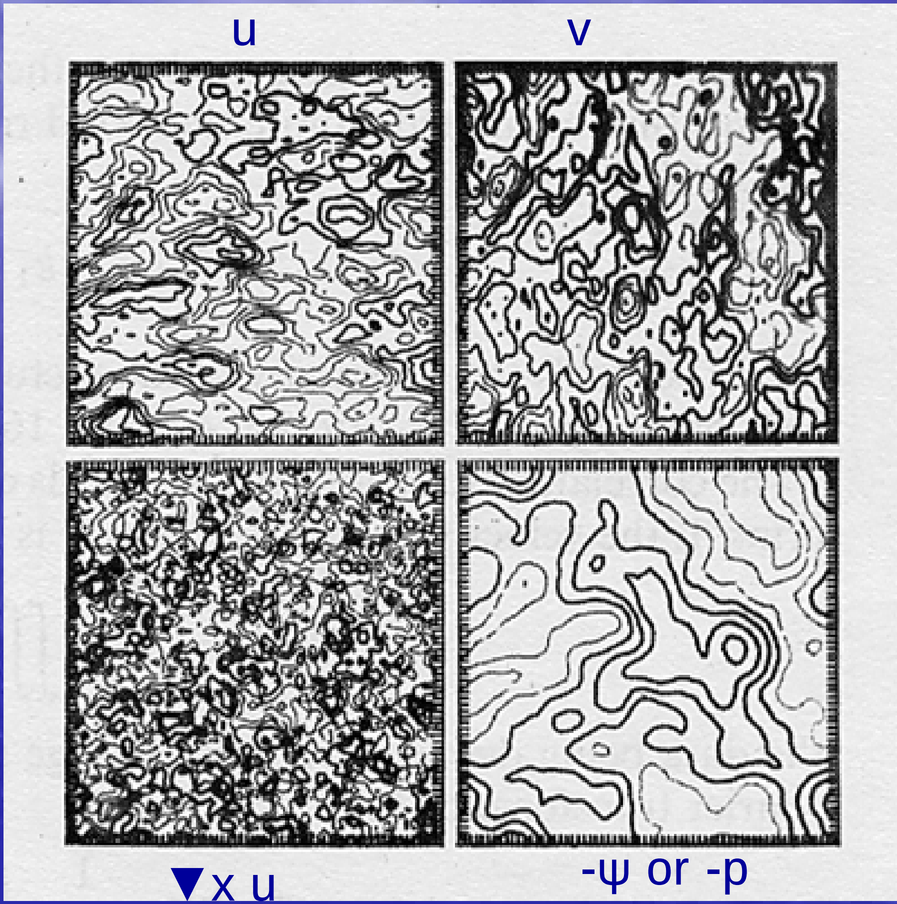
These devices have told us that the subpolar and polar oceans are undergoing massive, often abrupt changes in physical circulation, stratification, thermodynamics, ice cover, and ecosystems:

-not simple warming but warming superimposed on strong dynamical modes like the North Atlantic Oscillation, involving jet stream, Atlantic storms, stratospheric polar vortex as well as the ocean circulation and ice fields.

2. Dynamics

Fluid flows are textured. By *texture* we mean something like wavenumber content.

The appearance of pressure, streamfunction, velocity, vorticity, divergence, density, potential temperature, salinity and advected tracer fields all differ;



but also the spatial form of an advected tracer, teased out by fluid straining.

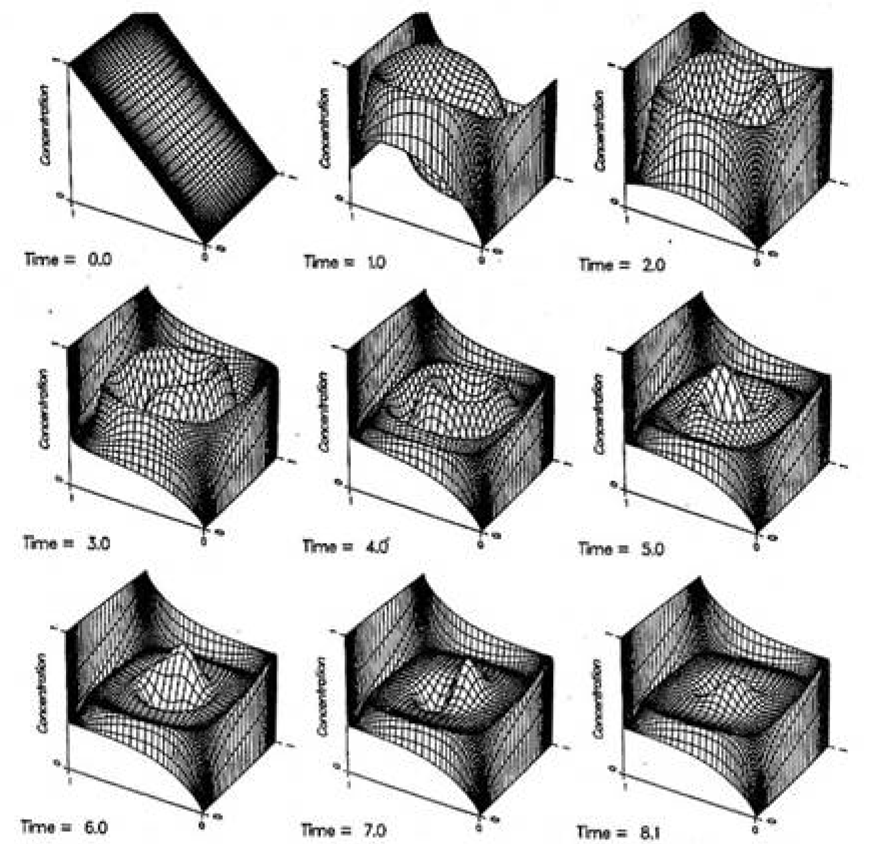
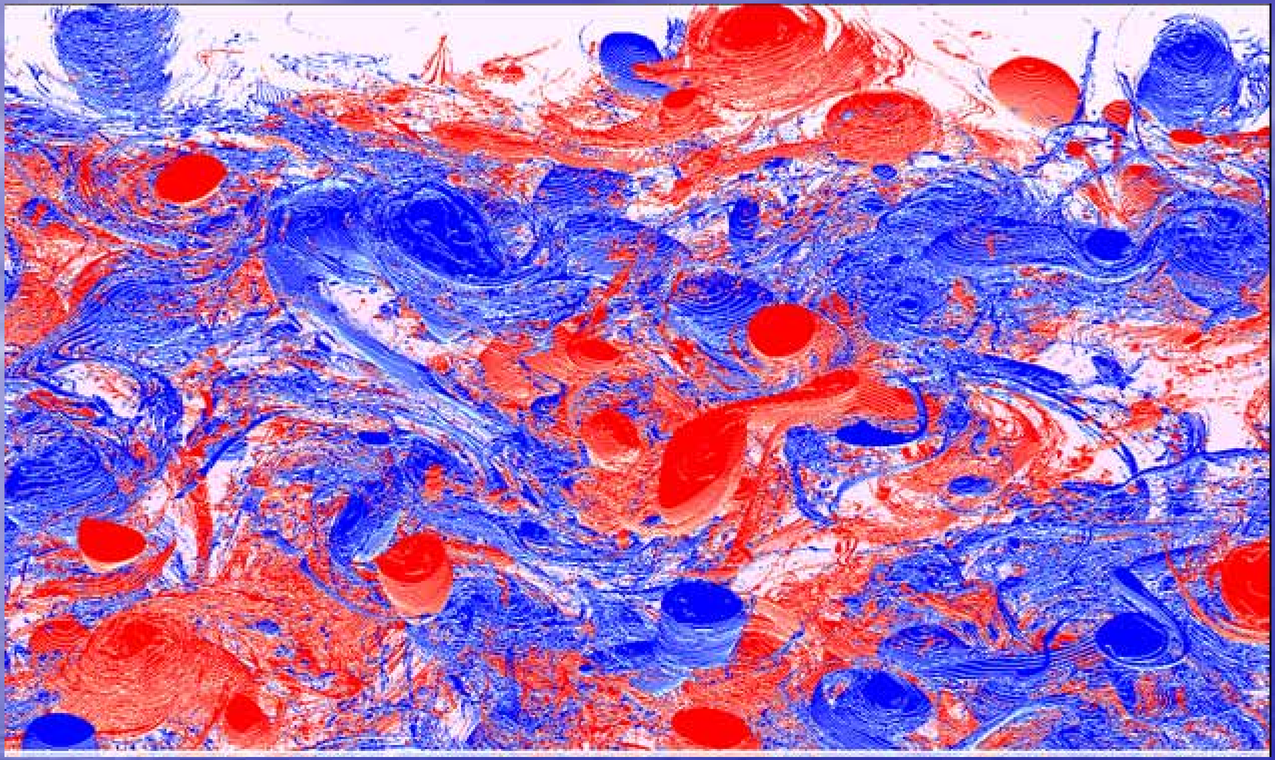


Figure 10 The spin-up of a passive tracer in a gyre circulation with Péclet number of 2.5×10^3, based on the basin scale and interior velocity (Musgrave 1985). The ridge of high values does not follow the streamlines but represents the winding up of the initial conditions. A weak diffusive spiral crossing ψ-lines remains in the steady state upon the homogenized plateau. The injected boundary values can be followed through the western-boundary current, but they are quickly assimilated by horizontal mixing. The large tracer flux through the system depends on thin boundary layers, which are treated with a stretched grid.

Musgrave, JMR 1985



Some conservative tracers are dynamically active: potential density, potential temperature, salinity, potential vorticity field in stratified geostrophic turbulence (David Dritschel)

Potential vorticity, q

F = external forcing (stress, buoyancy)

D = dissipation, mixing

σ = potential density

f = Coriolis frequency

N = buoyancy frequency

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

$$q = \rho^{-1}\nabla \bullet \sigma\vec{\omega}_a \quad baroclinic$$

$$= \nabla^2\psi + \frac{\partial}{\partial z}\left(\frac{f^2}{N^2}\frac{\partial\psi}{\partial z}\right) + f(y) \quad quasi-geostrophic$$

$$= \frac{f + \nabla\times\vec{u}}{h} \quad barotropic$$

h: layer thickness

$$\vec{\omega}_a = \nabla\times\vec{u} + 2\vec{\Omega}$$

$\vec{\omega}_a$: absolute vorticity

Kelvin's circulation theorem in disquise

q = f/h or fN^2 for large scale, weak currents (L >> Rossby radius)

- The two kinds of potential vorticity, PV,

barotropic (f/total depth)

baroclinic (absolute vorticity x N^2)

can be reunited in a generalized PV in which the intesections of potential density surfaces with boundaries provides δ – function sheets of PV

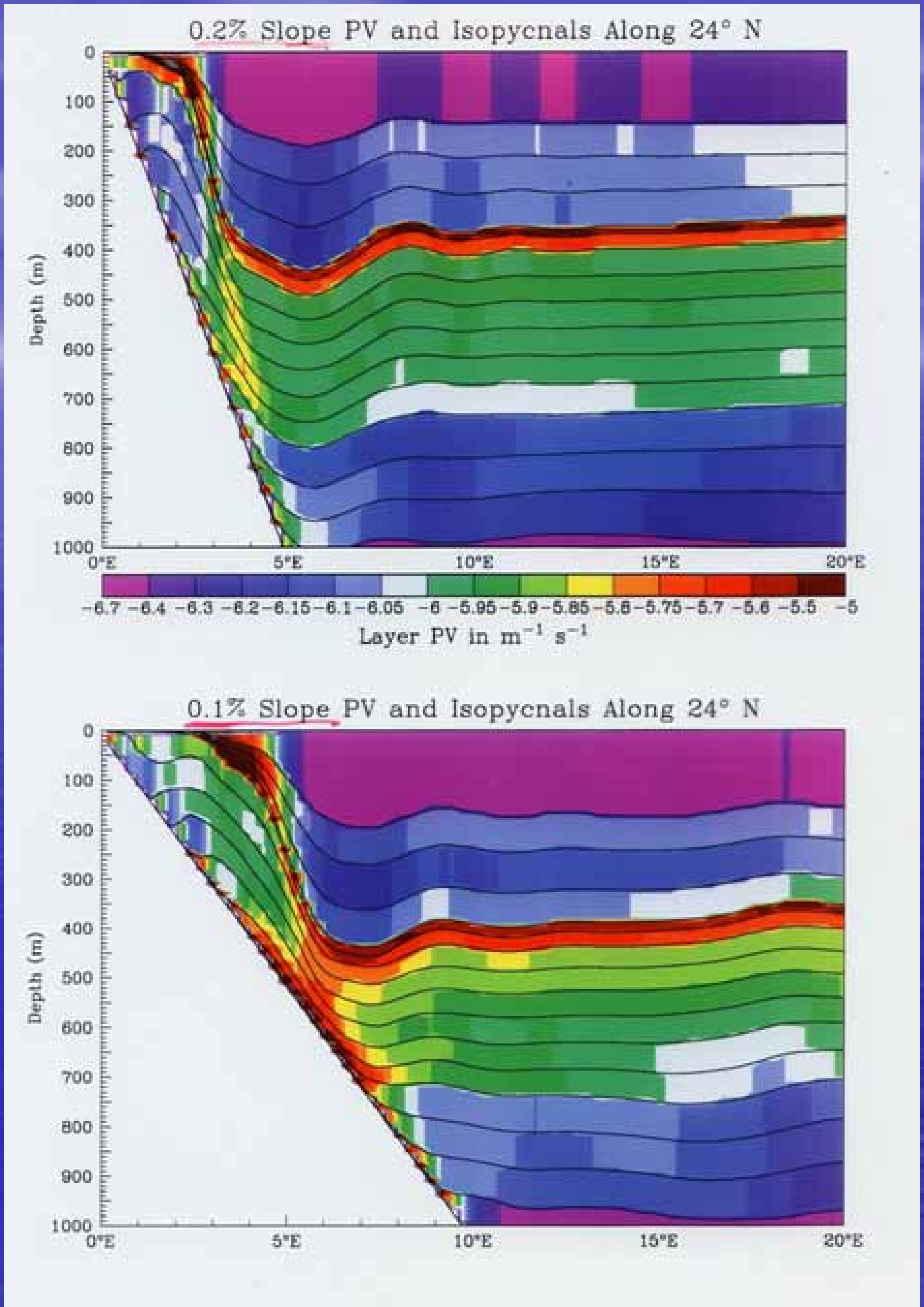
(Bretherton, QJ Royal Met Soc 1966,

Rhines, Ann Revs Fluid Mech 1979,

Schneider,Held+Garner JAS 2003)

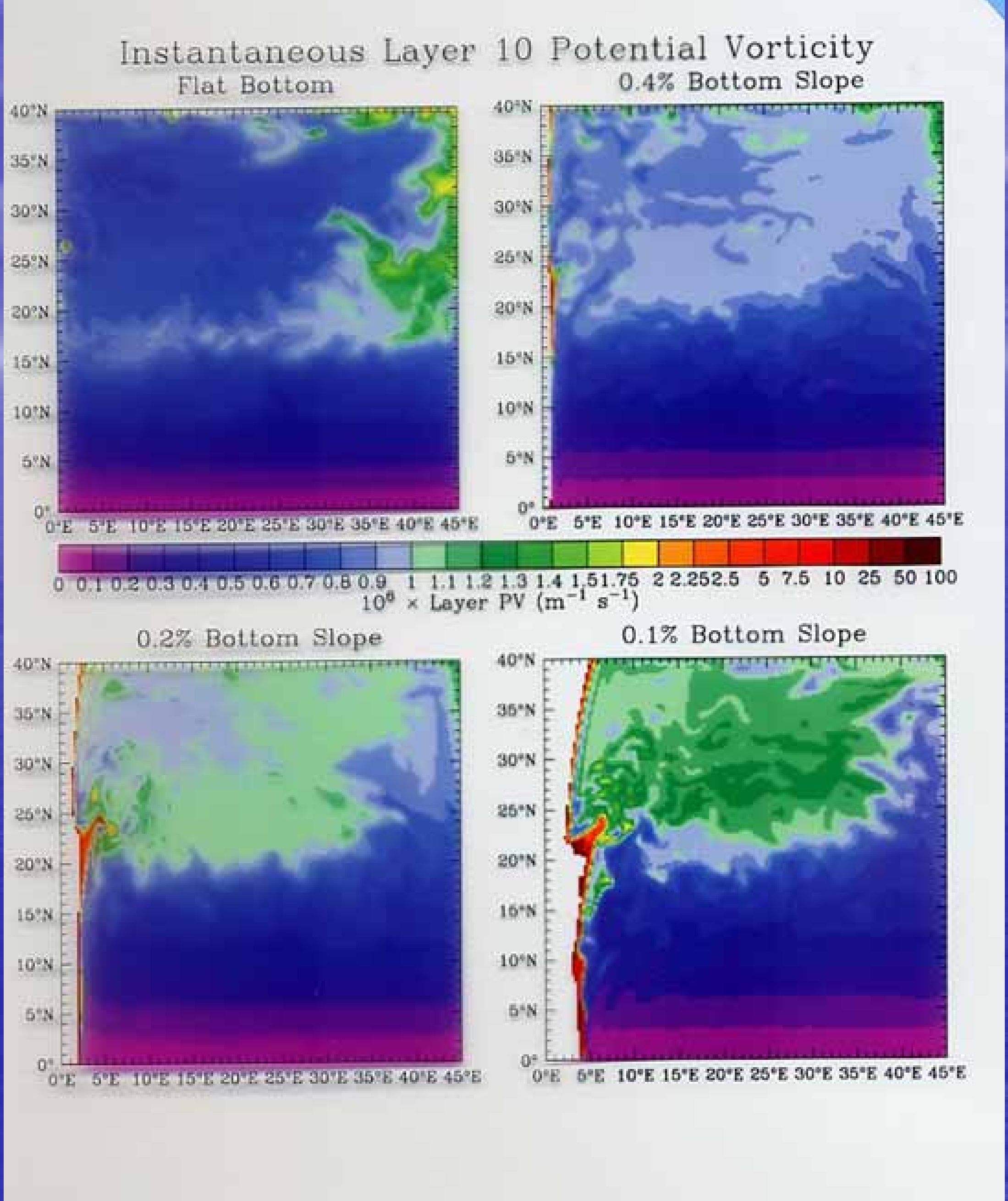
cross-section of Gulf Stream/ deep boundary current in isopycnal HIM model simulation of wind-driven circulation: note high PV region adjacent to slope

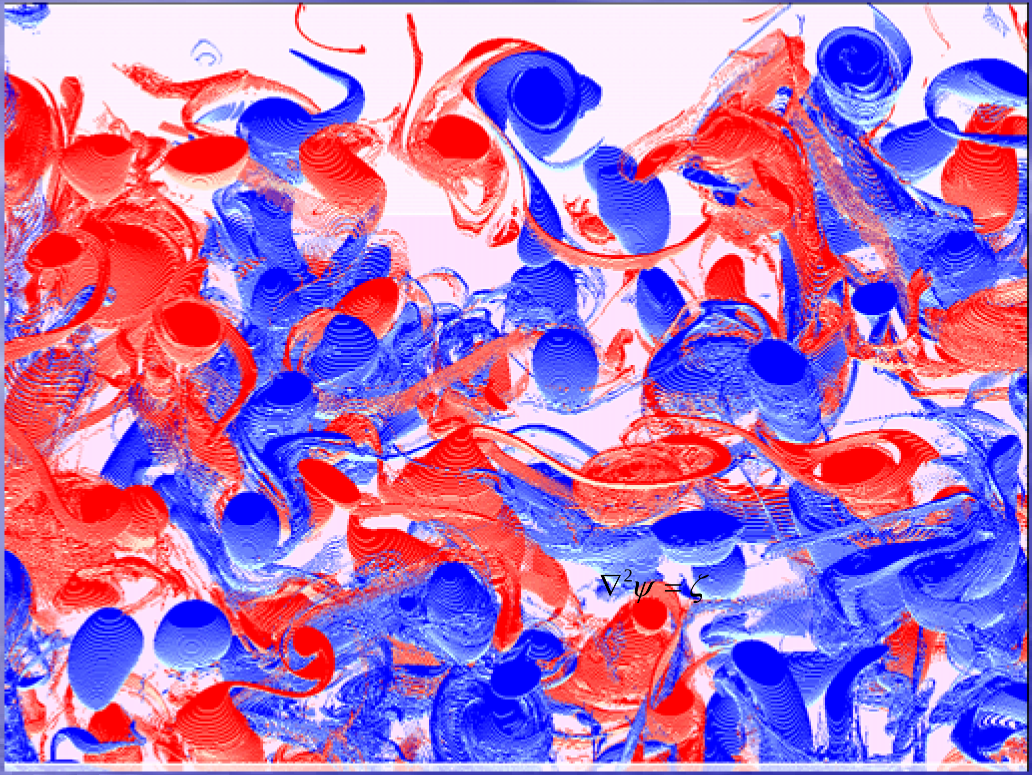
(*Hallberg+Rhines, Dev. Geophys. Turb, Kimuraand Kerr Eds., Kluwer, 2000).*



A western boundary with a continental slope can flood the subtropical gyre with high PV (or, mixing and deep convection can drive it the other way, toward low PV...low stratification)

Hallberg+Rhines, St. Geophys. Turb, 2001, R.Kerr Ed.





Stretching of contours of constant PV is equivalent to a cascade of PV to large wavenumber, and with it a cascade of velocity and pressure spectra to small wavenumber. This is the Poisson-equation,

$$\nabla^2\psi = \zeta$$

at work: the pressure image of an elongated vorticity streak is much larger than the width of the streak (imagine depressing a membrane with a streak-shaped force).

enstrophy cascade:

horizontal and vertical scales of pressure and velocity increase through pairing and barotropization (which is the true 'life-cycle of baroclinic instability);

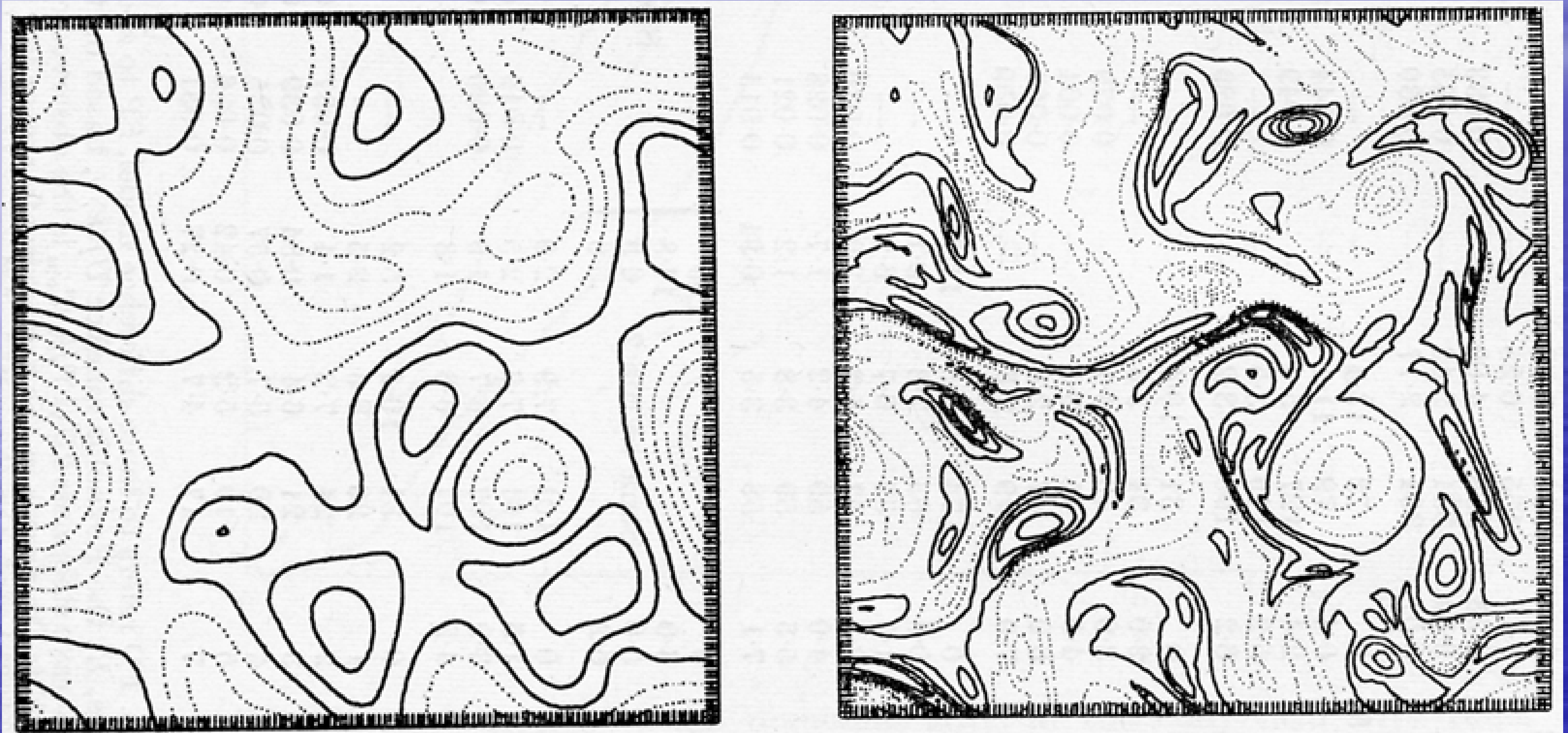
except, 'hard-core' vortices which can emerge, with long life-times. PV inversion is analogous to finding electrostatic fields from charge distributions, or membrane deflections from distributions of weight upon them

$$\nabla^2\psi + (\frac{f^2}{N^2}\psi_z)_z + f$$

is a stretched Laplacian

streamfunction,
or geostrophic pressure

vertical vorticity



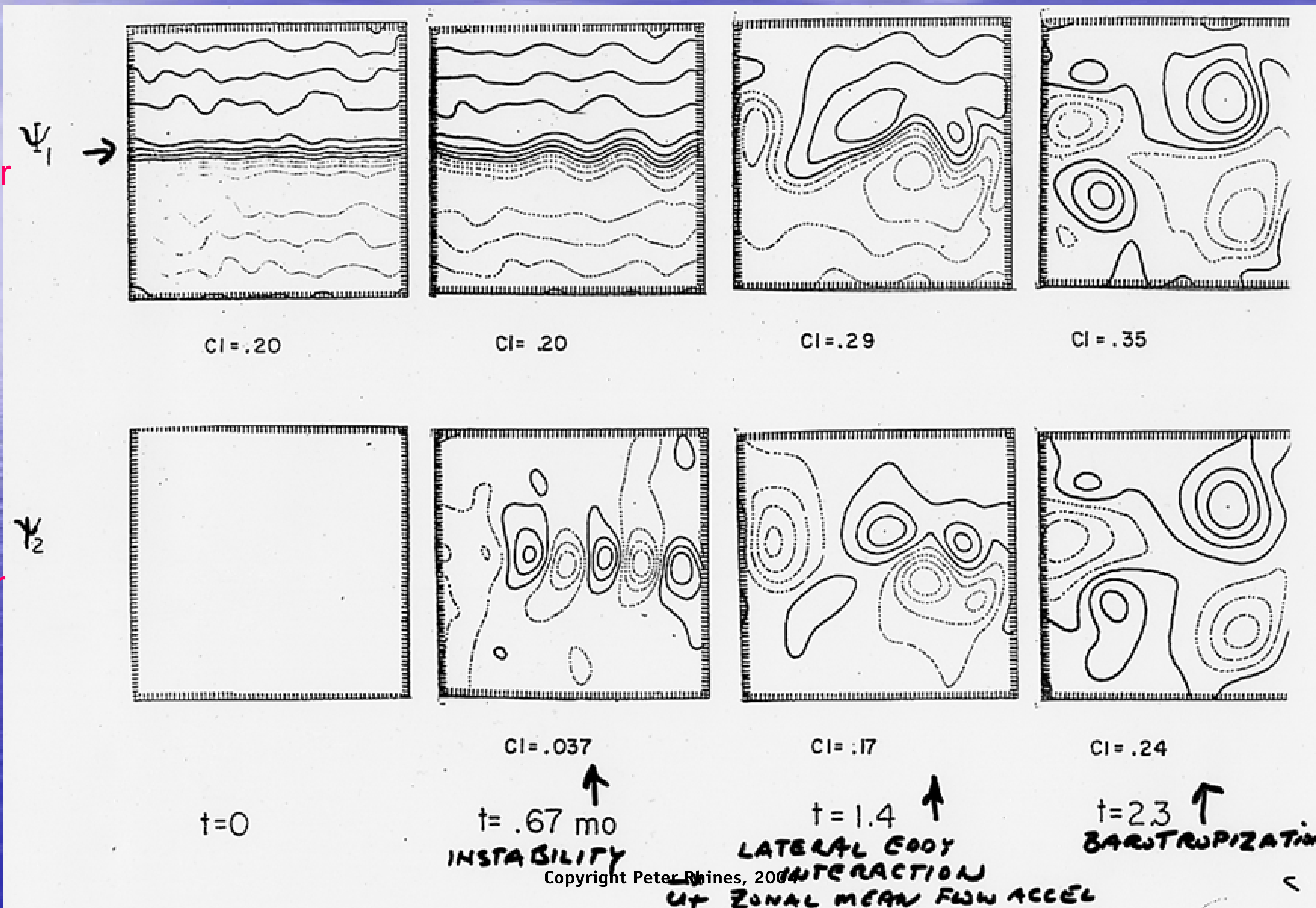
(c)

(d)

Barotropization of a two-layer zonal jet (*Rhines The Sea 1977)*

upper layer

lower layer



large-scale PV field due to

mean circulation (velocity and density fields)

topography at the base of the fluid and spherical shape of the Earth

PV 'elasticity'

linear (generalized) Rossby waves

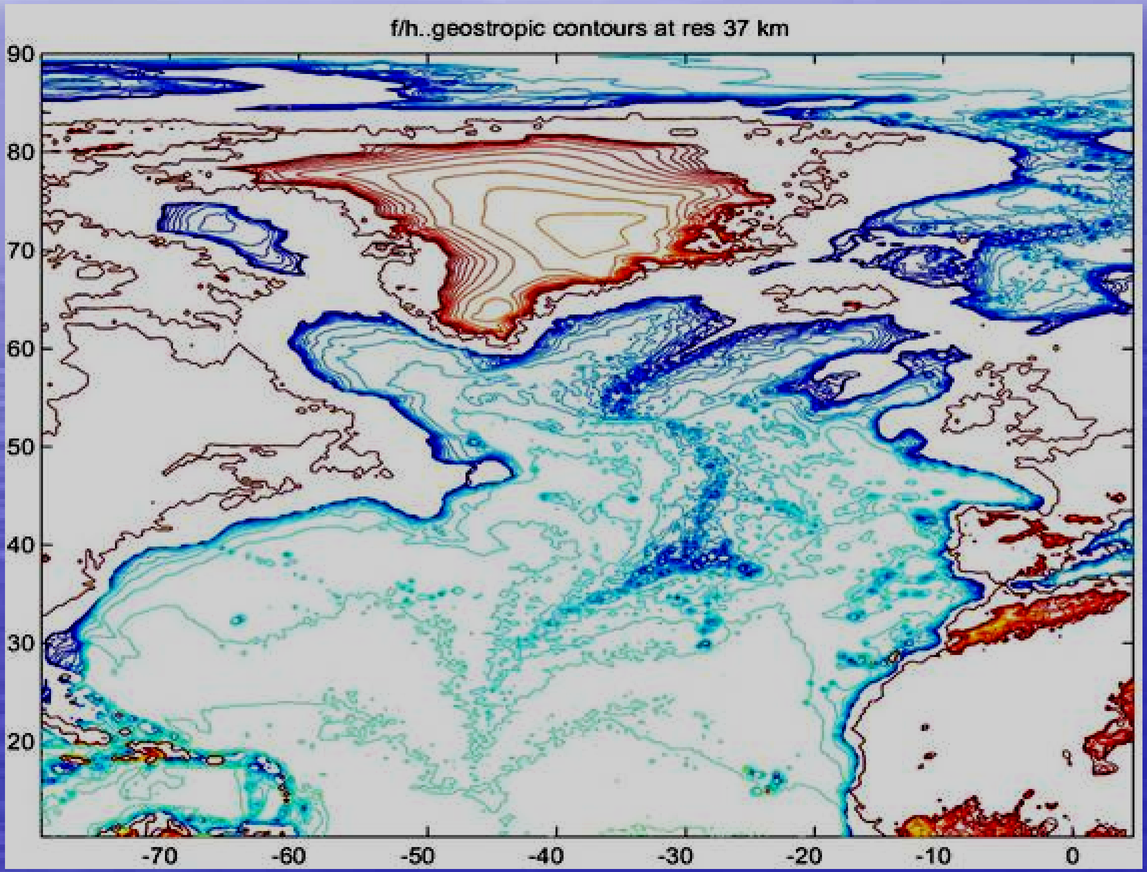
scale-dependent elasticity: weak at small scale

inhibited meridional mixing

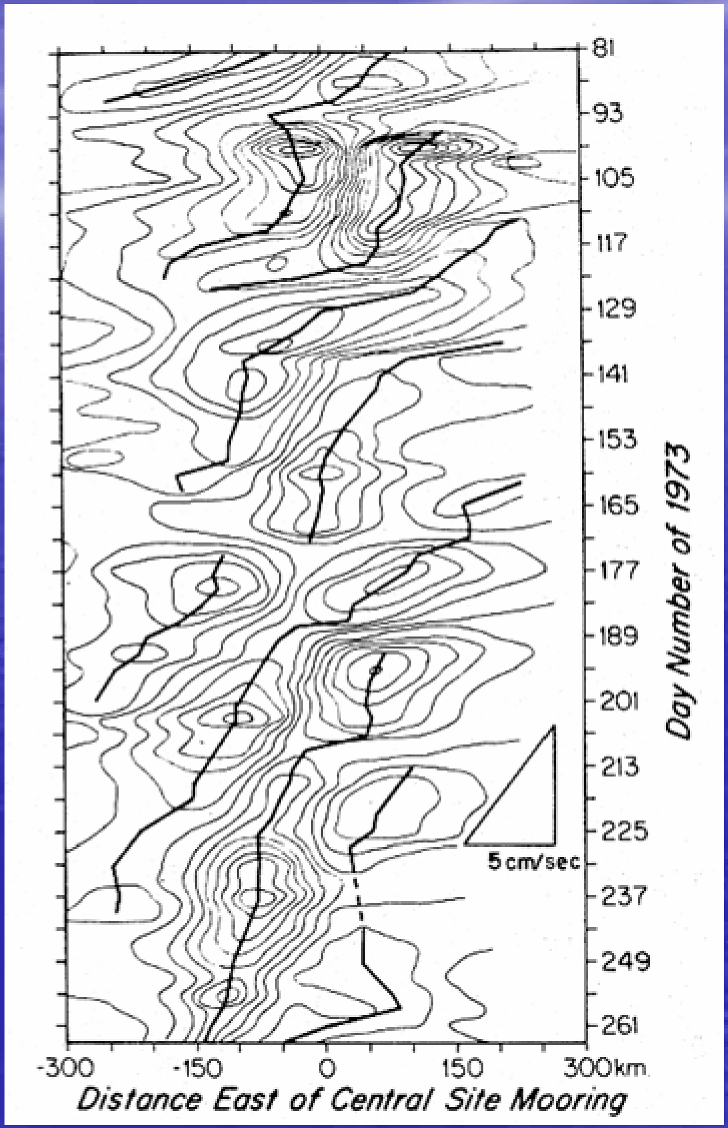
enabling unstable eddy/mean flow development and access of mean-flow energy

f/h (barotropic PV) contours for N Atlantic and troposphere

(37 km resolution ETOPO data)



barotropic Rossby waves in the western North Atlantic (based on 1500m depth Sofar float velocities). This space-time plot shows westward propagation of 100 km scale eddies. The propagation speed, 5 cm/sec, is comparable with the mean horizontal fluid velocity, so this is a mixture of geostrophic turbulence and Rossby waves



Freeland, Rhines, Rossby
J Marine Res 75

1st baroclinic mode Rossby waves, central Pacific from satellite laser altimeter: TOPEX/Poseidon sea-surface heights
Chelton and Schlax, Science 1995

Rossby waves are the principal mode involved in establishing the shape and form of the ocean circulation, as it responds to winds and buoyancy forcing by the atmosphere.

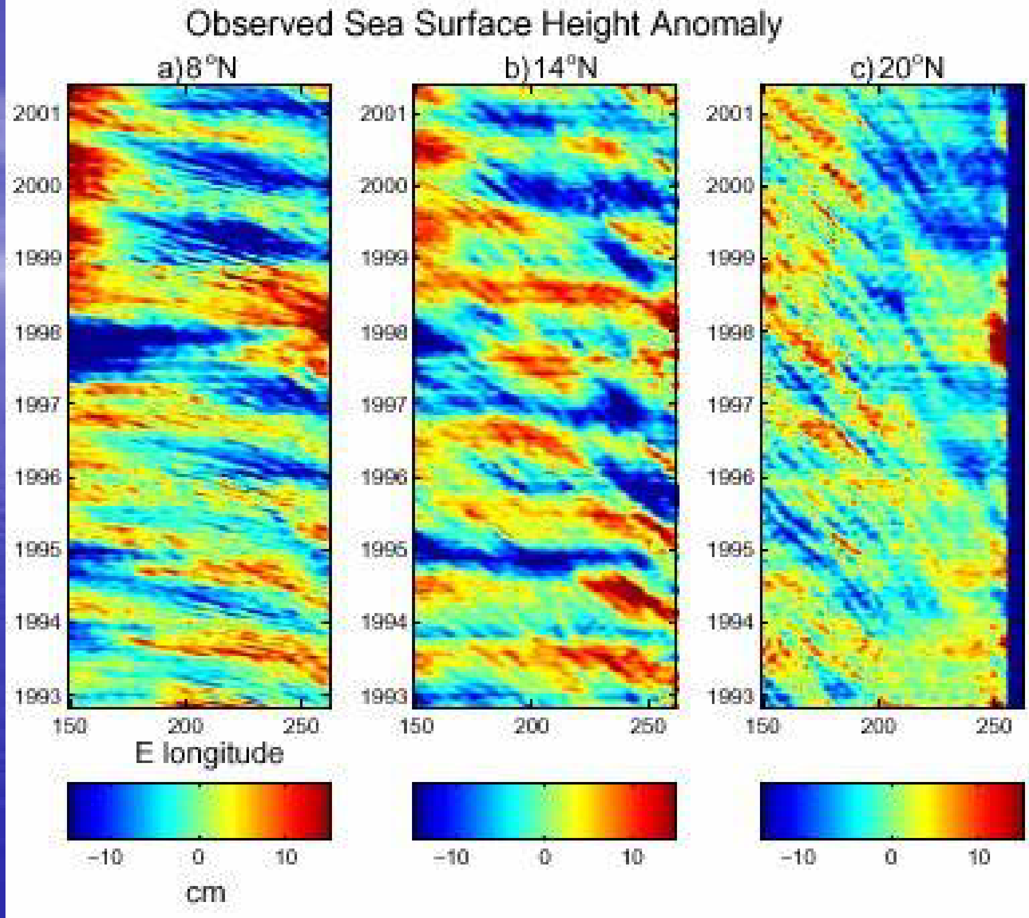


Figure 1. Time-longitude plots of SSH anomalies at (a) 8, (b) 14, and (c) 20°N from the TOPEX/POSEIDON altimeter. Units are meters.

In the fluids lab, simulating Rossby waves is challenging because the Earth has radial gravity field. We have simulated this with ferromagnetic fluid clinging to a rotating sphere in which magnets are embedded, simulating Earth's gravity. Equatorial Kelvin & Rossby waves are seen in this view from above the south pole *Ohlsen+Rhines JFM 1997*

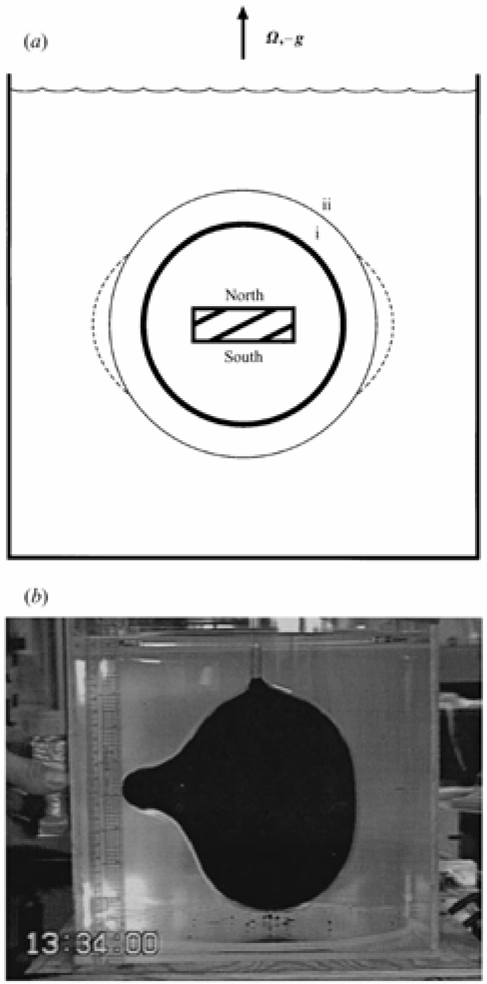
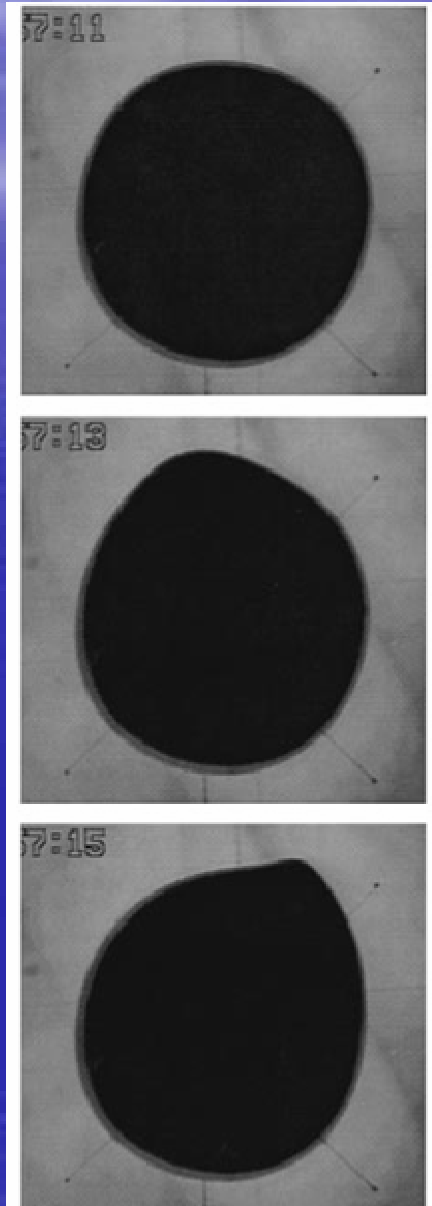


FIGURE 2. (a) Schematic cross-section of the axisymmetric experiment. A cylindrical tank holds a silicone oil – dibromotetrafluoroethane mixture (ii) surrounding a ferrofluid layer (i) on a plaster ball (whose surface is the thick circle) which surrounds a strong permanent magnet. The magnet poles are indicated by North and South for reference but the field line orientation is not important, only the field strength, $|\mathbf{H}|$, and its gradient, ∇H. The entire apparatus rotates at angular veocity, $\mathbf{\Omega}$. (b) Side view photograph of the laboratory experiment with an external magnet forcing a large-amplitude wave.

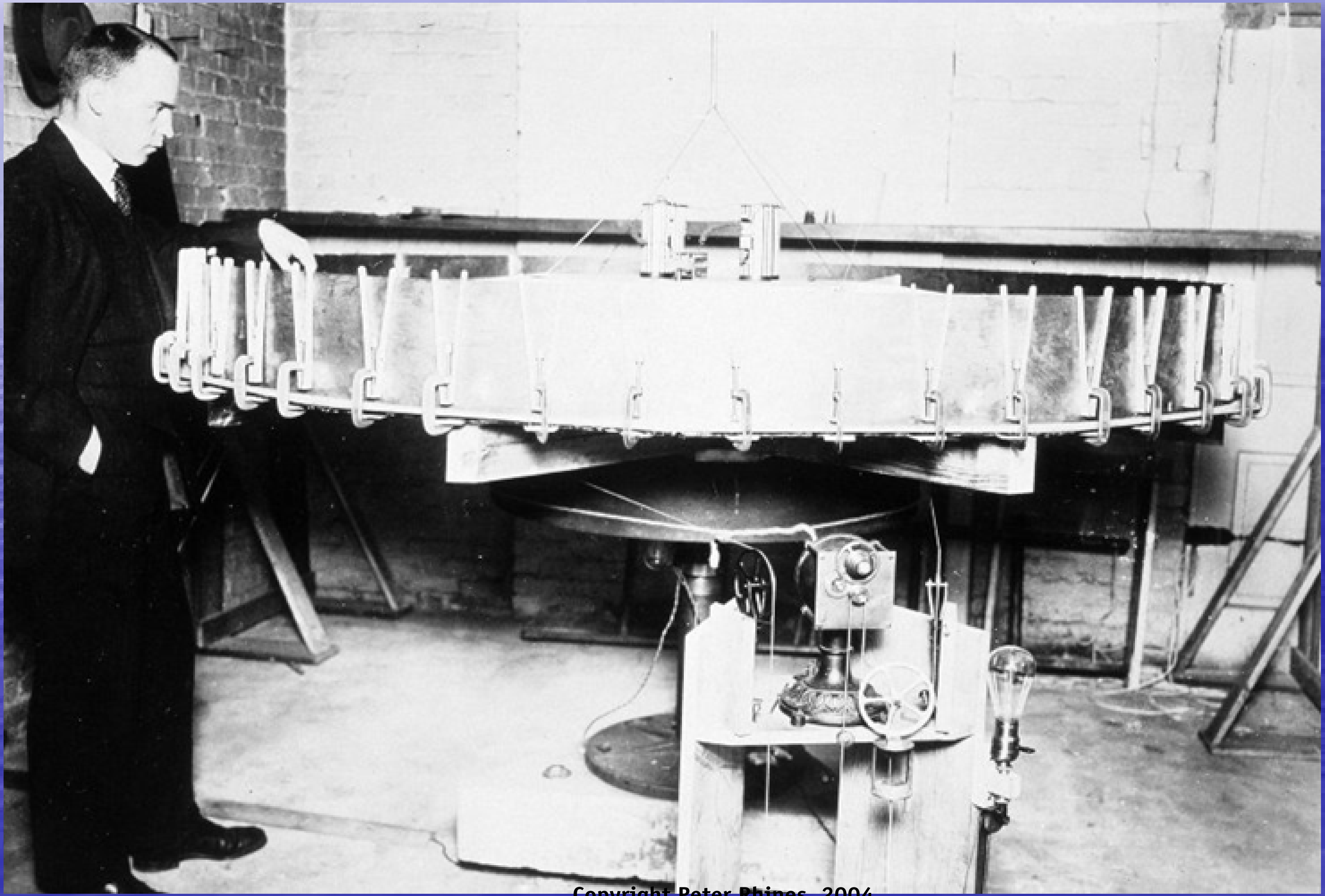
Seen from above the South Pole, an equatorial Kelvin wave progates eastward

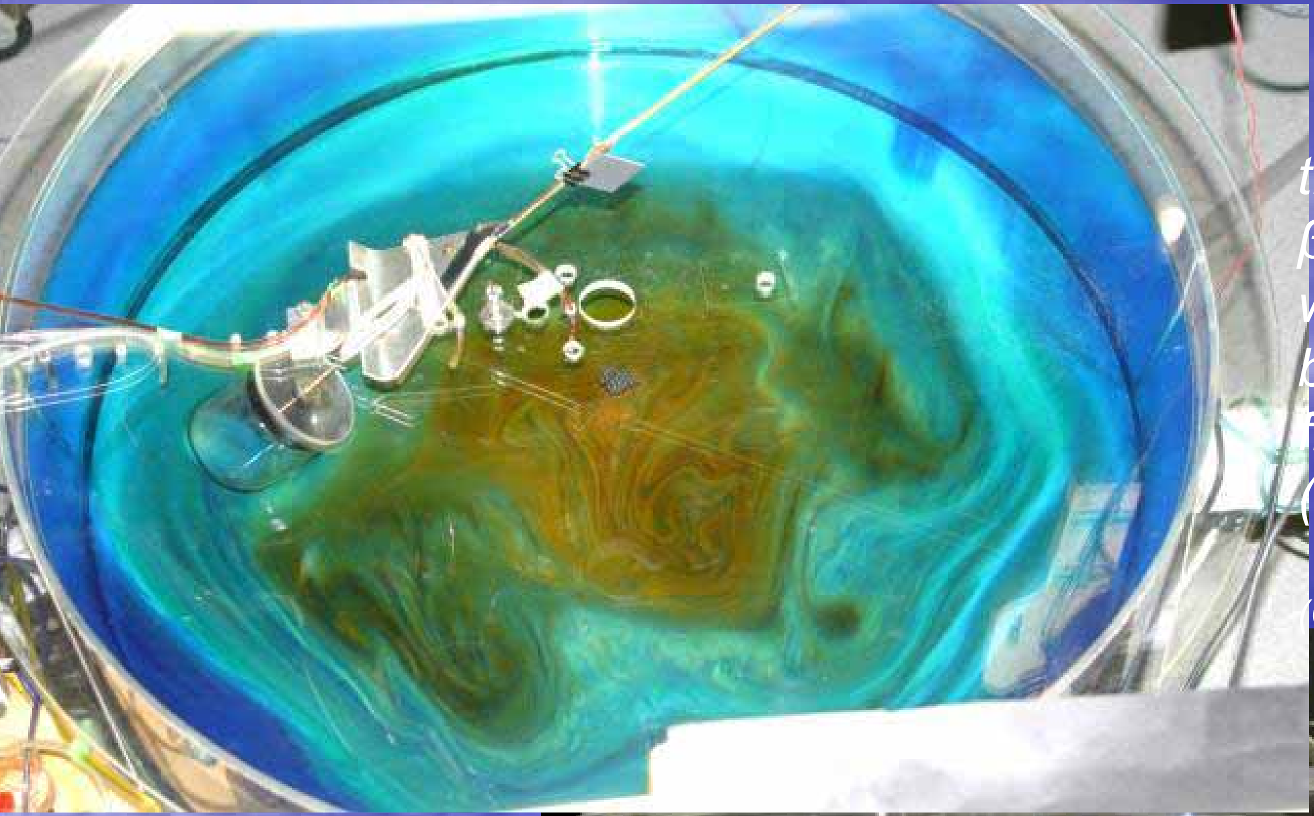


Hough, Haurwitz, C.G. Rossby

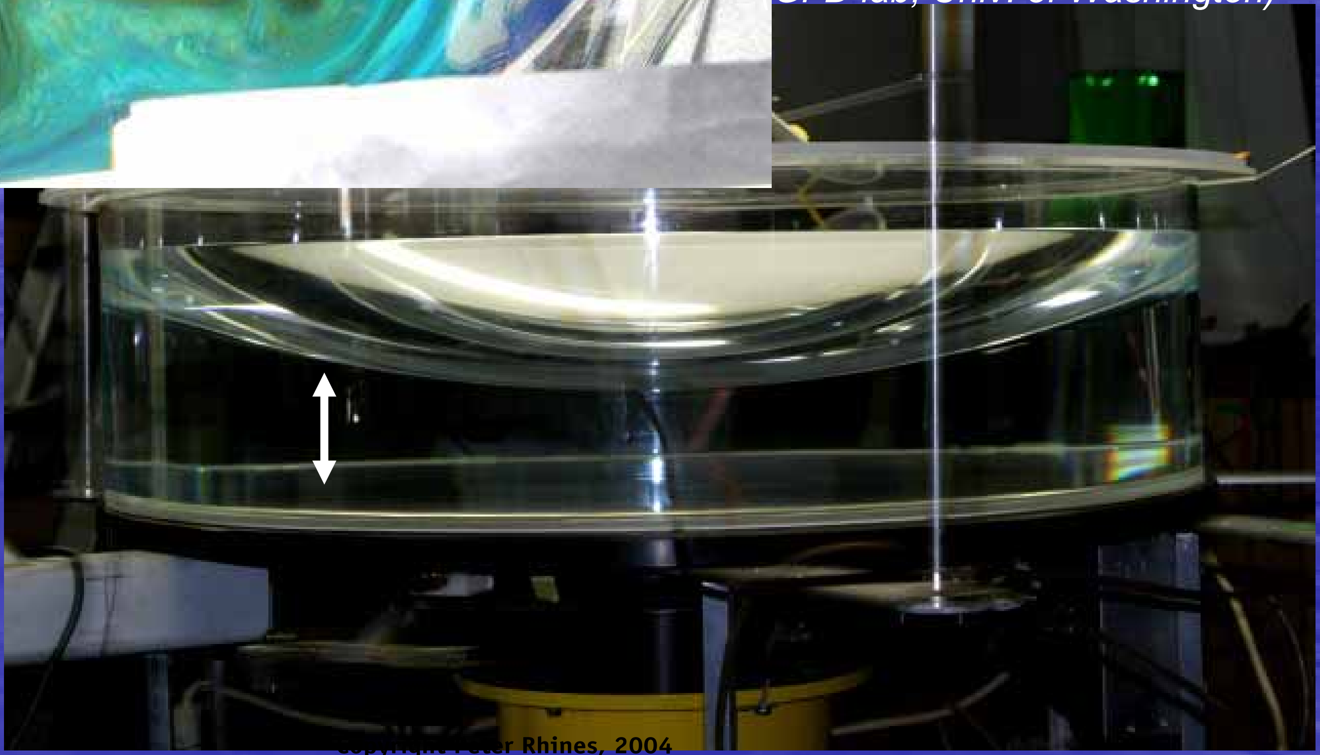
Carl-Gustav Rossby in the mid 1920s, in the basement of the Weather Bureau in Washington. This rotating table could have shown him Rossby waves, but it collapsed and apparently was not repaired.

NOAA photo archive



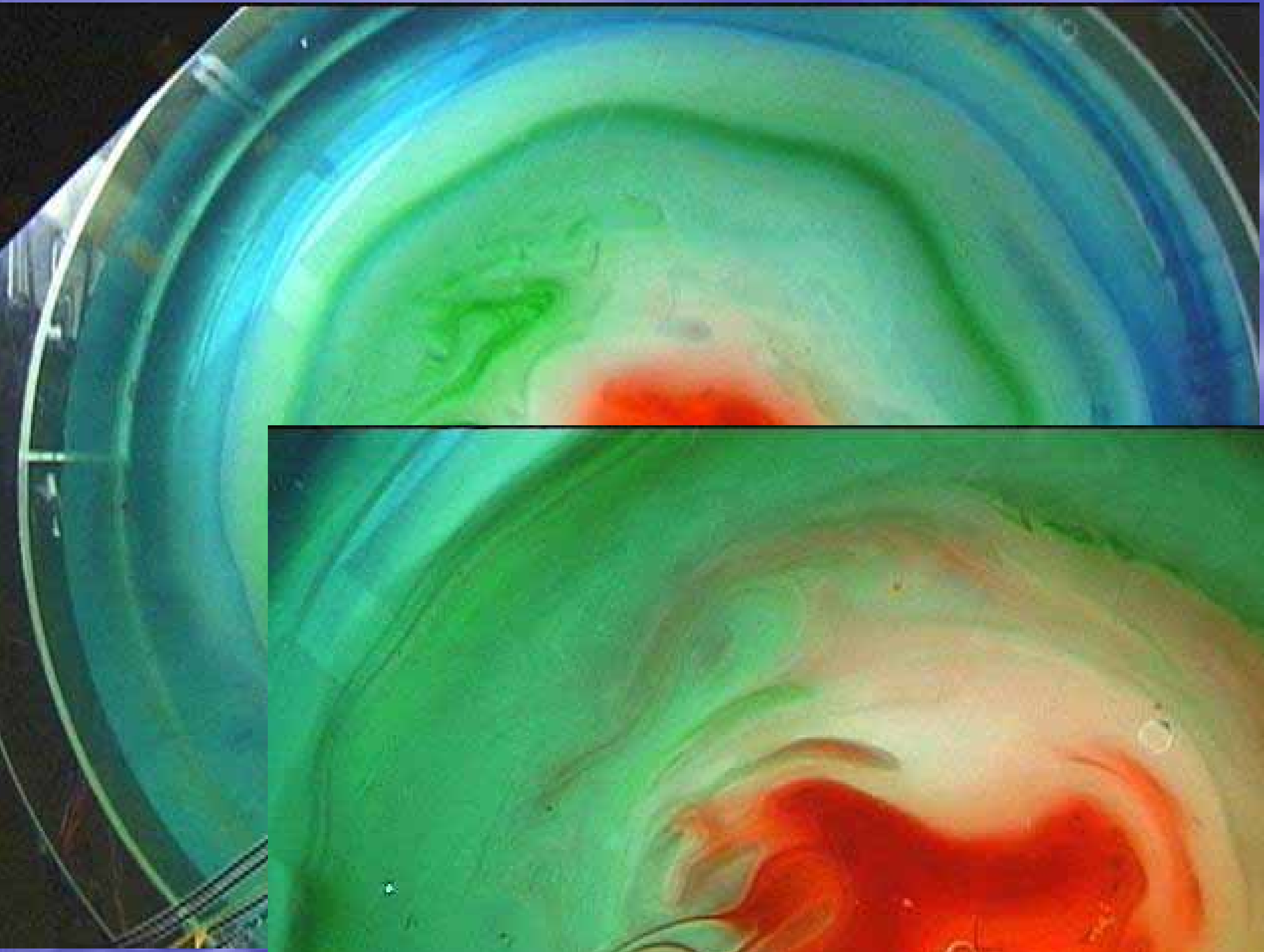


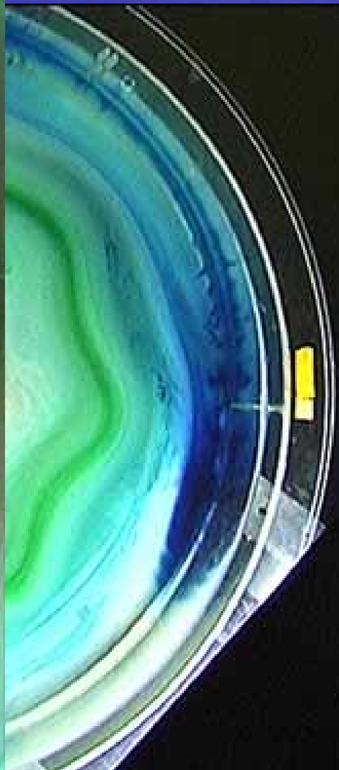
the laboratory polar β-plane: the paraboidal water surface provides a basic potential vorticity field that makes barotropic (one-layer fluid) Rossby waves possible
(GFD lab, Univ. of Washington)



polar β-plane with small cylinder oscillating normal to free surface (1 m diameter experiment)

RW a1,a3



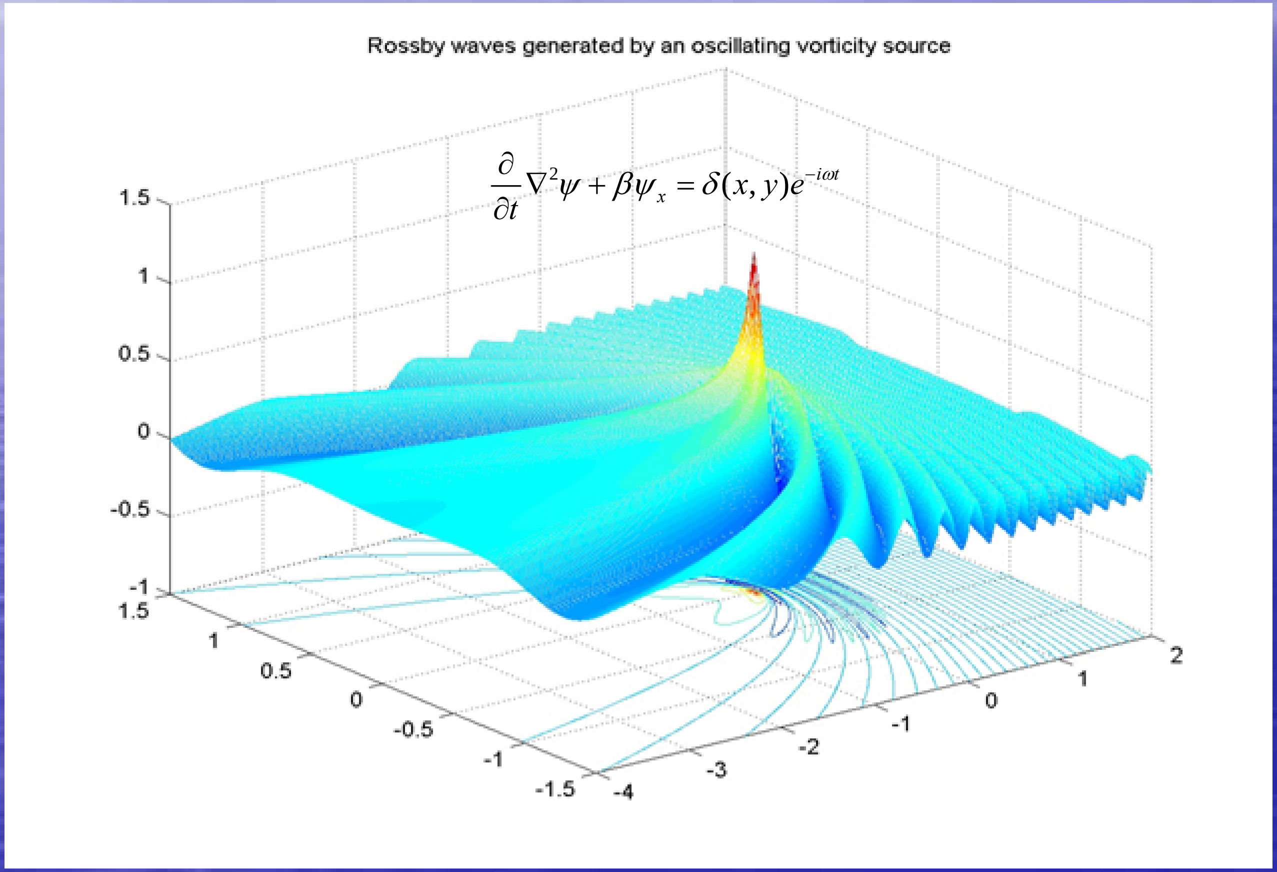


Rossby wave Green's function for an oscillatory point source

$\psi=\exp(-i\beta x/2\omega-i\omega t)\ H_0^{(2)}(\beta r/2\omega)$

pressure or streamfunction viewed from southwest of the oscillating stress-curl

$$\frac{\partial}{\partial t}\nabla^2\psi+\beta\psi_x=\delta(x,y)e^{-i\omega t}$$

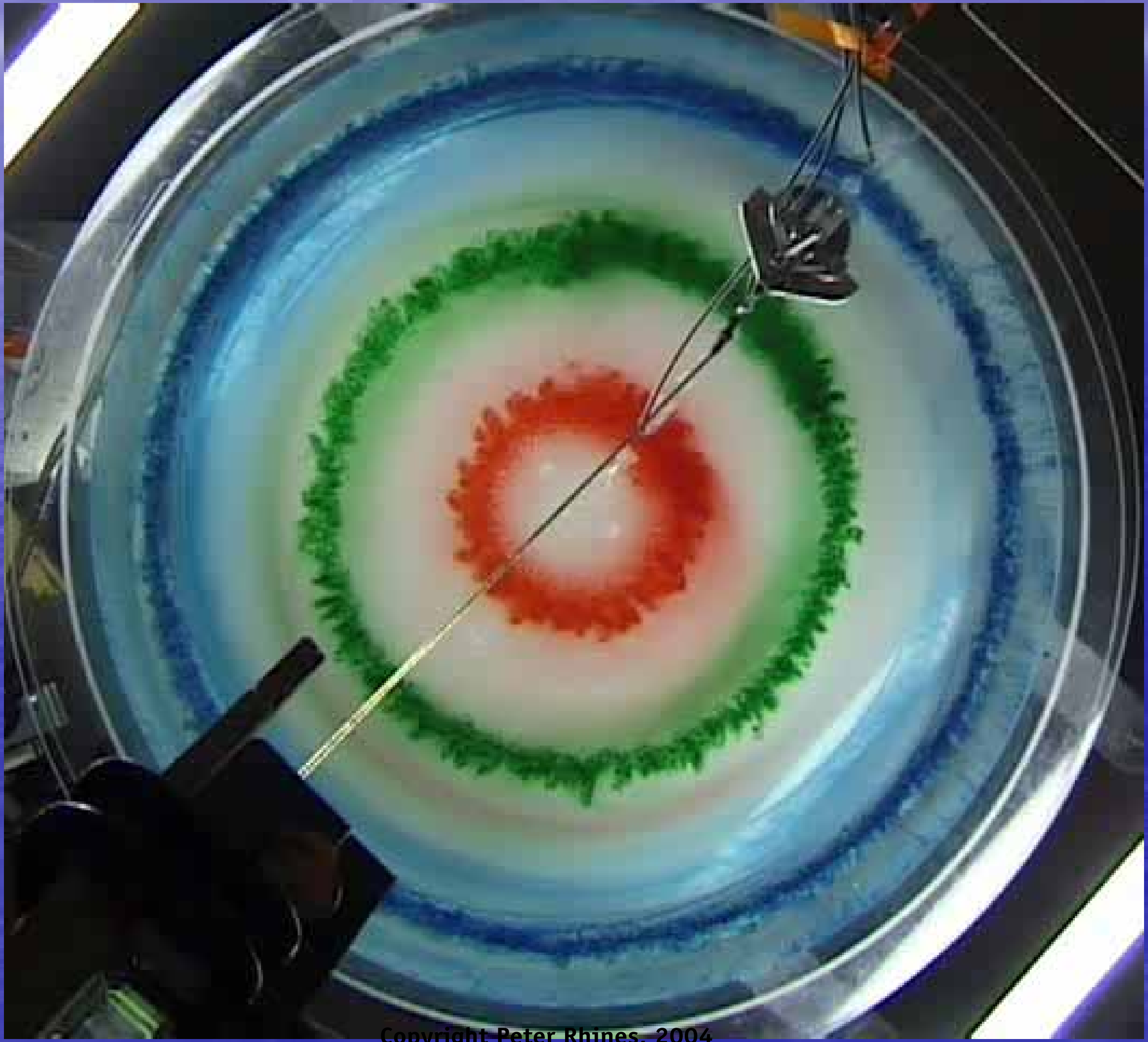


Rossby waves on a polar β-plane, homogenous water; oscillatory forcing in upper right quadrant

polar-cylindrical Green function: short waves to east of wavemaker

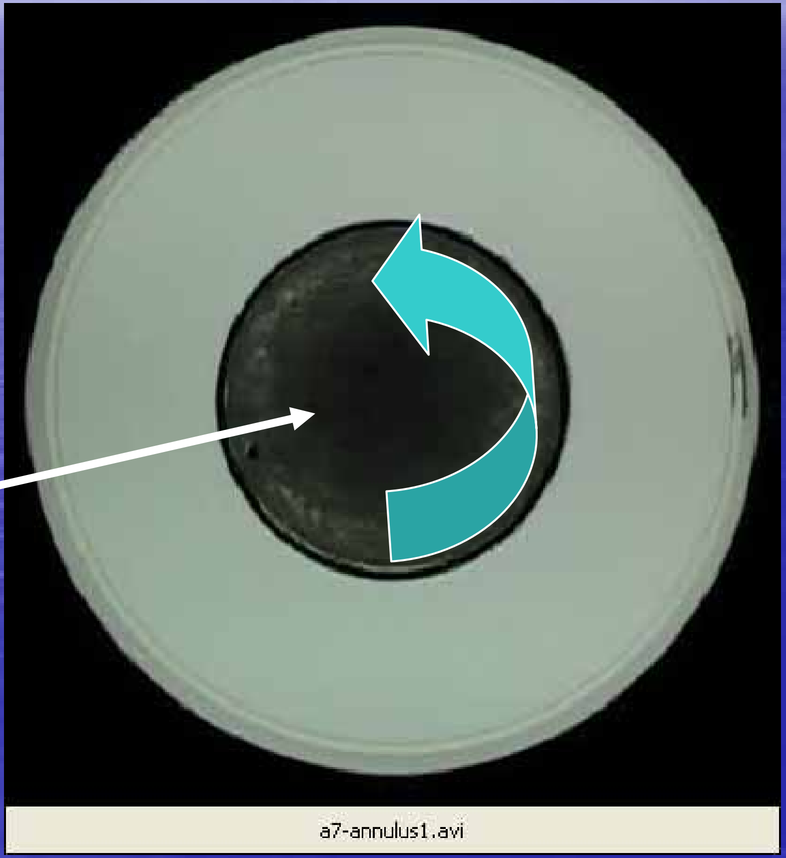
Scale dependent PV elasticity: mixing and debris

Zonal flow induced by PV stirring: mixes away the PV max at polar cap

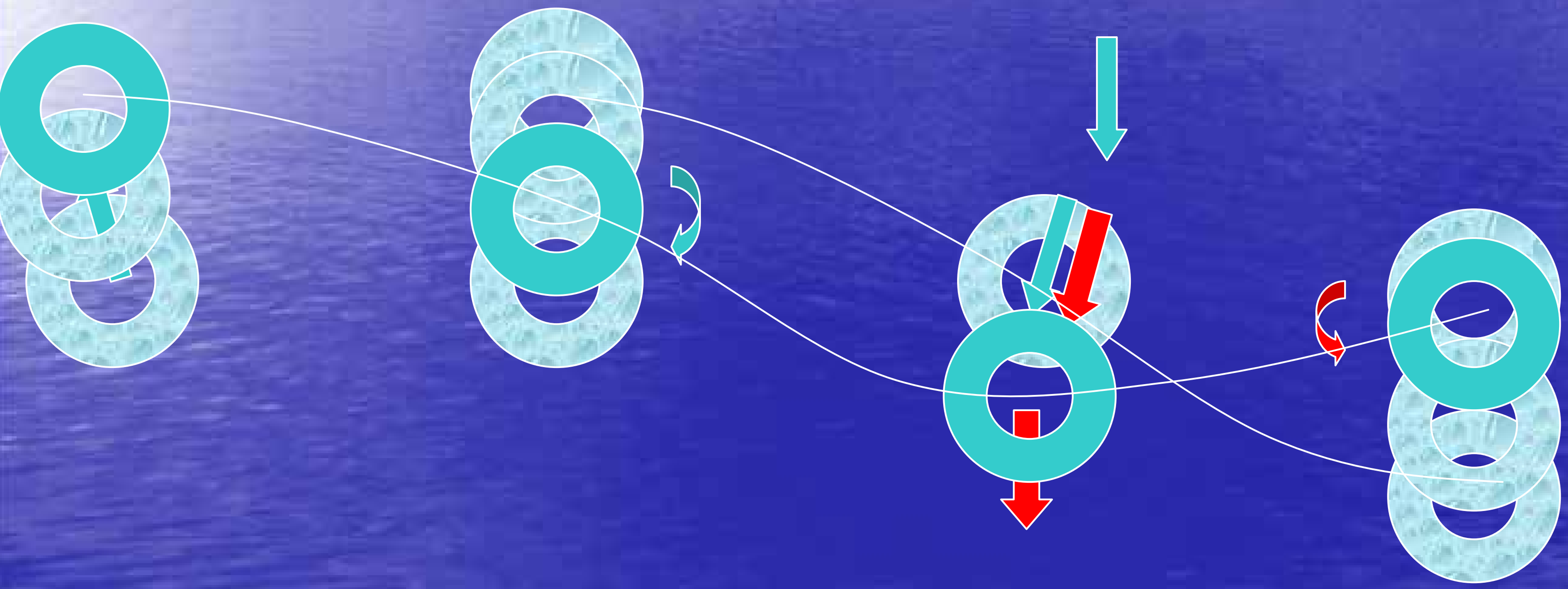


In the classic rotating annulus experiment, baroclinic waves, isolated eddies and jet streams have many associations with Rossby waves.

Ice...cold polar wall



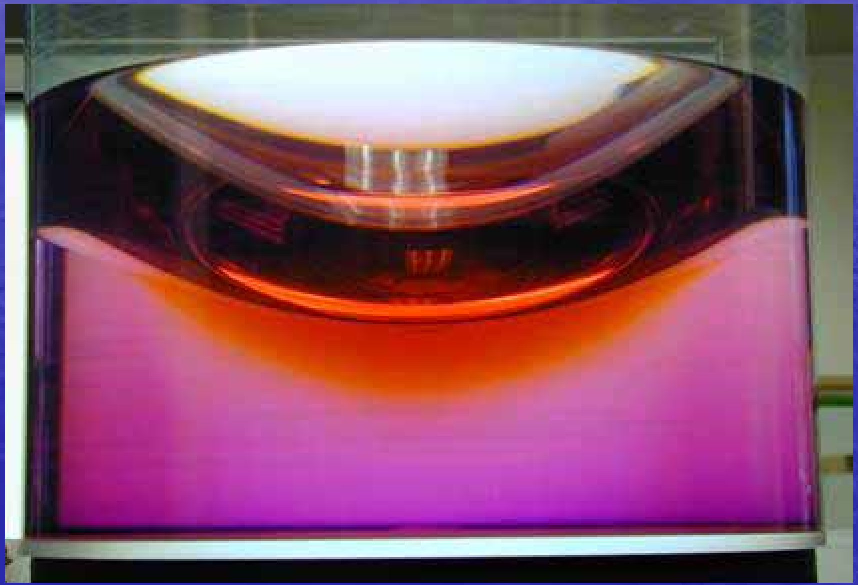
Vortex induction in a Rossby wave is a model for stable and unstable waves in many kinds of flows with a potential-vorticity gradient.



Optical altimetry for a rotating fluid (Rhines, Lindahl and Mendez, 2004)

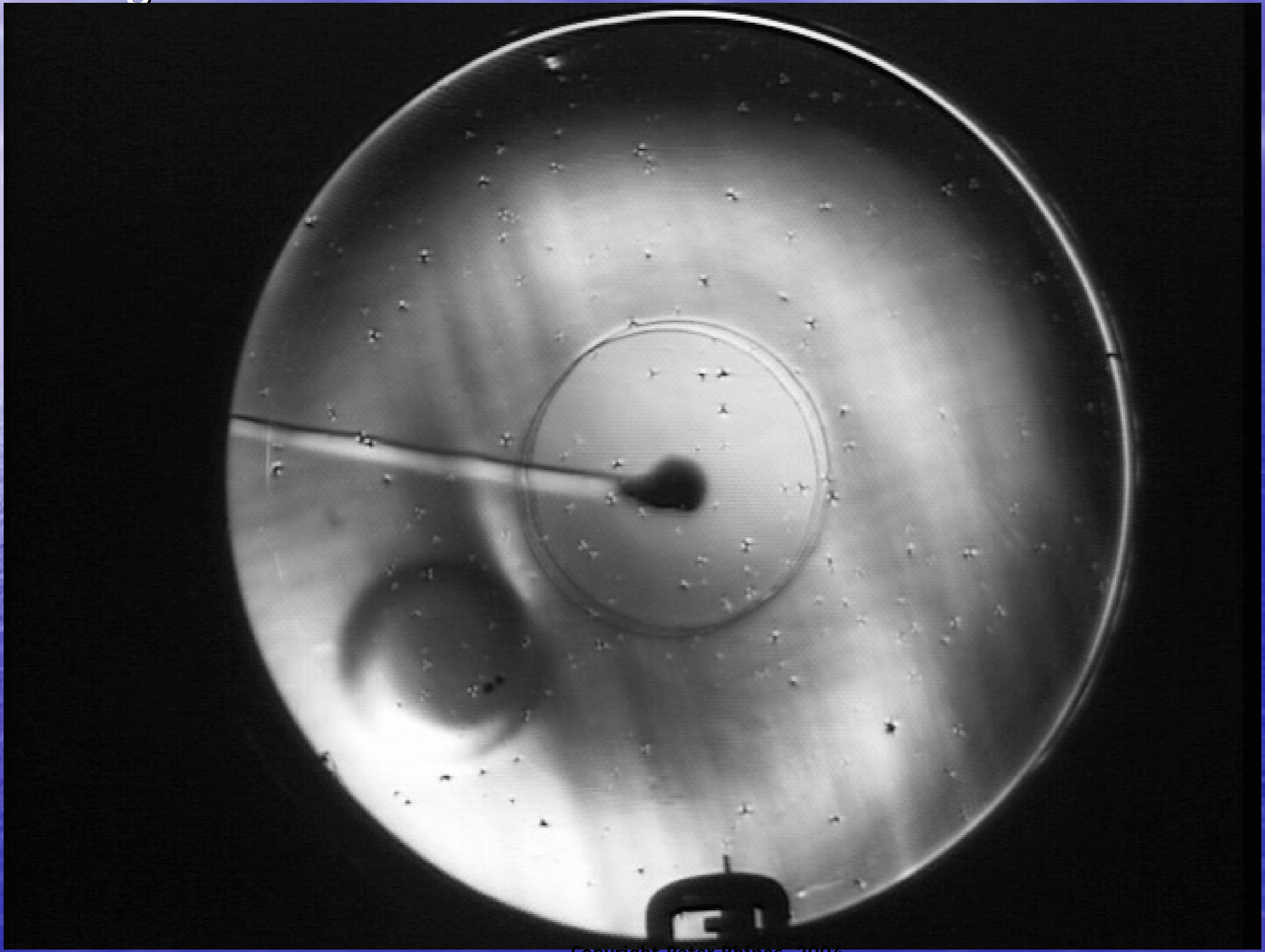
The free surface of a rotating fluid is a paraboloid, the shape of a telescope mirror (and indeed this is how such mirrors are made). It is an equipotential surface for the combined centrifugal potential (½ $\Omega^2 r^2$ and local gravity potential, (gz) (which of course is a combination of 'true'gravity and Earth's centrifugal potential).

It is a parabolic lens with which one can bathe the entire surface of the fluid with light, all converging on the camera lens. With a point source of light the resolution is to within a small fraction of the wavelength of light (for a telescope: Raunchy Rulings).For a fluid experiment we have to 'dumb down' the technique by using a fat light source, giving altimetry observations of order 10^{-6} m.



The focus is at height $g/2\Omega^2$ above center surface

(animation) Here, the rotation rate is periodically altered, and a shallow mountain acts as a Rossby wave source in the sloshing flow



Winding of the pressure and PV fields by topographic Rossby waves over a mountain

Spiral is a group-velocity induced shear dispersion.

Strong umbilical jet in the lee

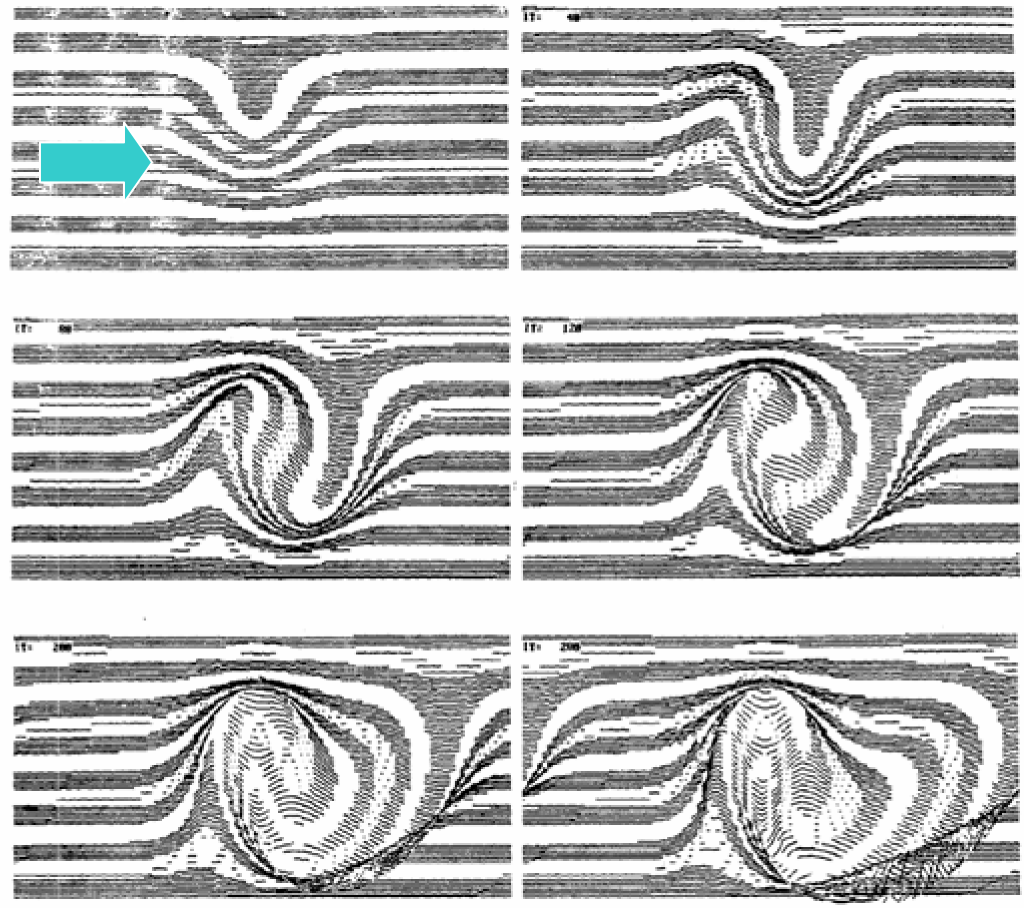
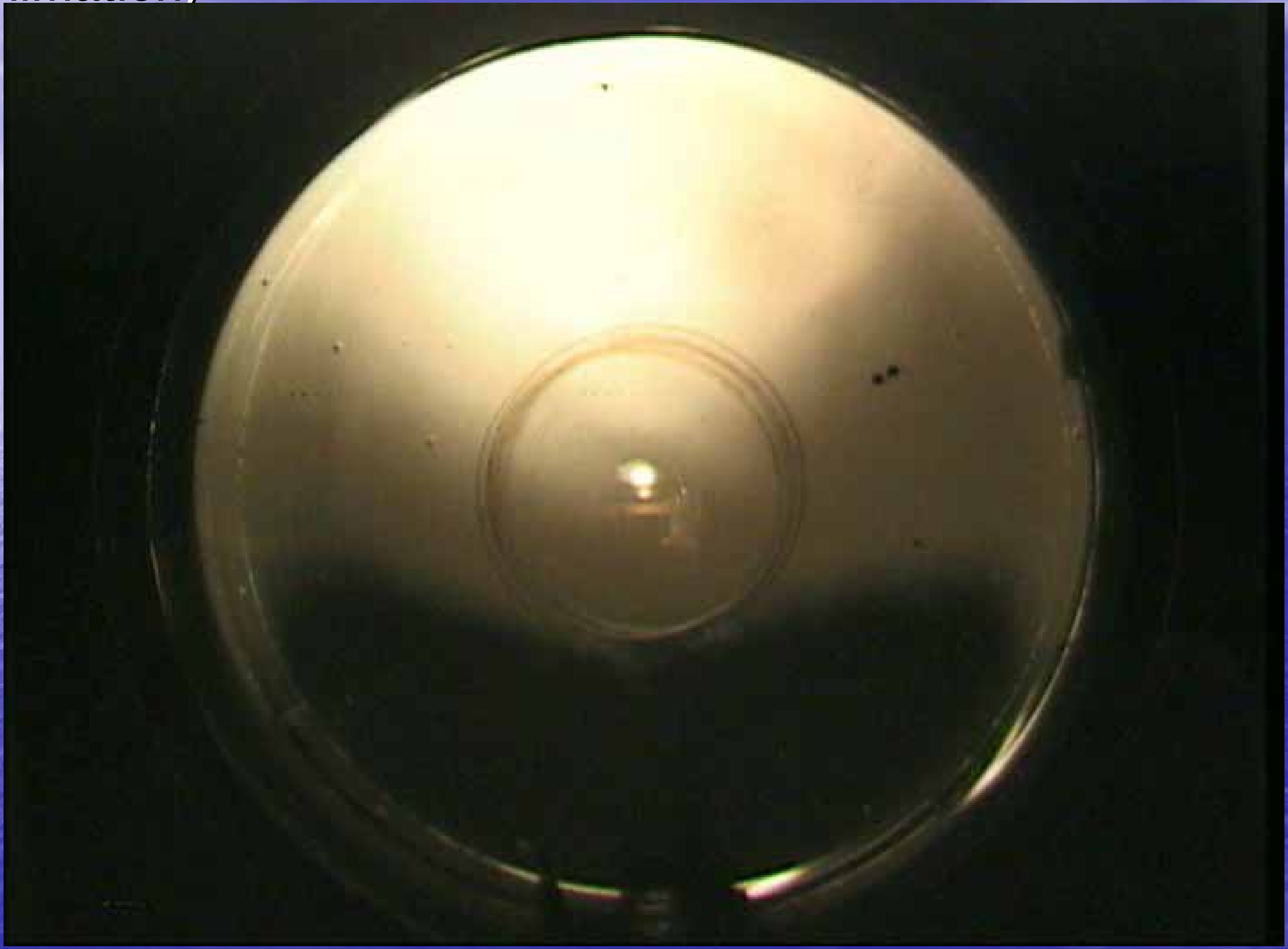


FIG. 9. *Nonlinear supercritical.* Read across, then down. Evolution of an initially uniform eastward barotropic flow over 280 days. Strong eastward flow, as in Fig. 8, except with a broader ridge (600 km half-width in the *y*-direction) and slightly faster flow (0.08 m s^{-1}). Potential vorticity contours, shown as bands superimposed on the interface surface plot, are wound into the region above the ridge. The slope of η increases, and correspondingly, the velocity. The free vortex moving eastward is connected to the bound vortex above the ridge by a long trough, which draws in high potential vorticity fluid from a great distance poleward.

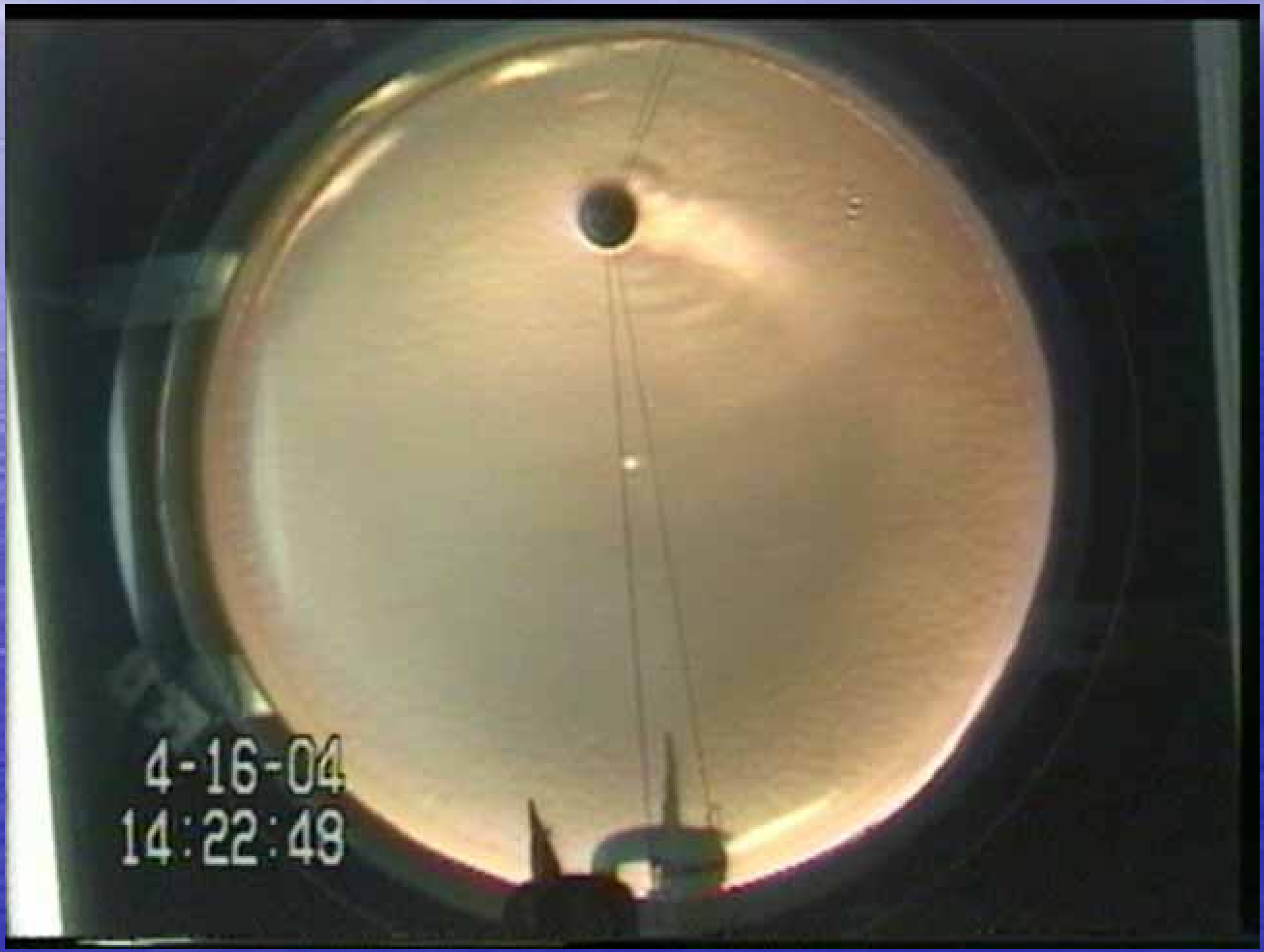
Rhines, JPO 89

(animation)

(animation)

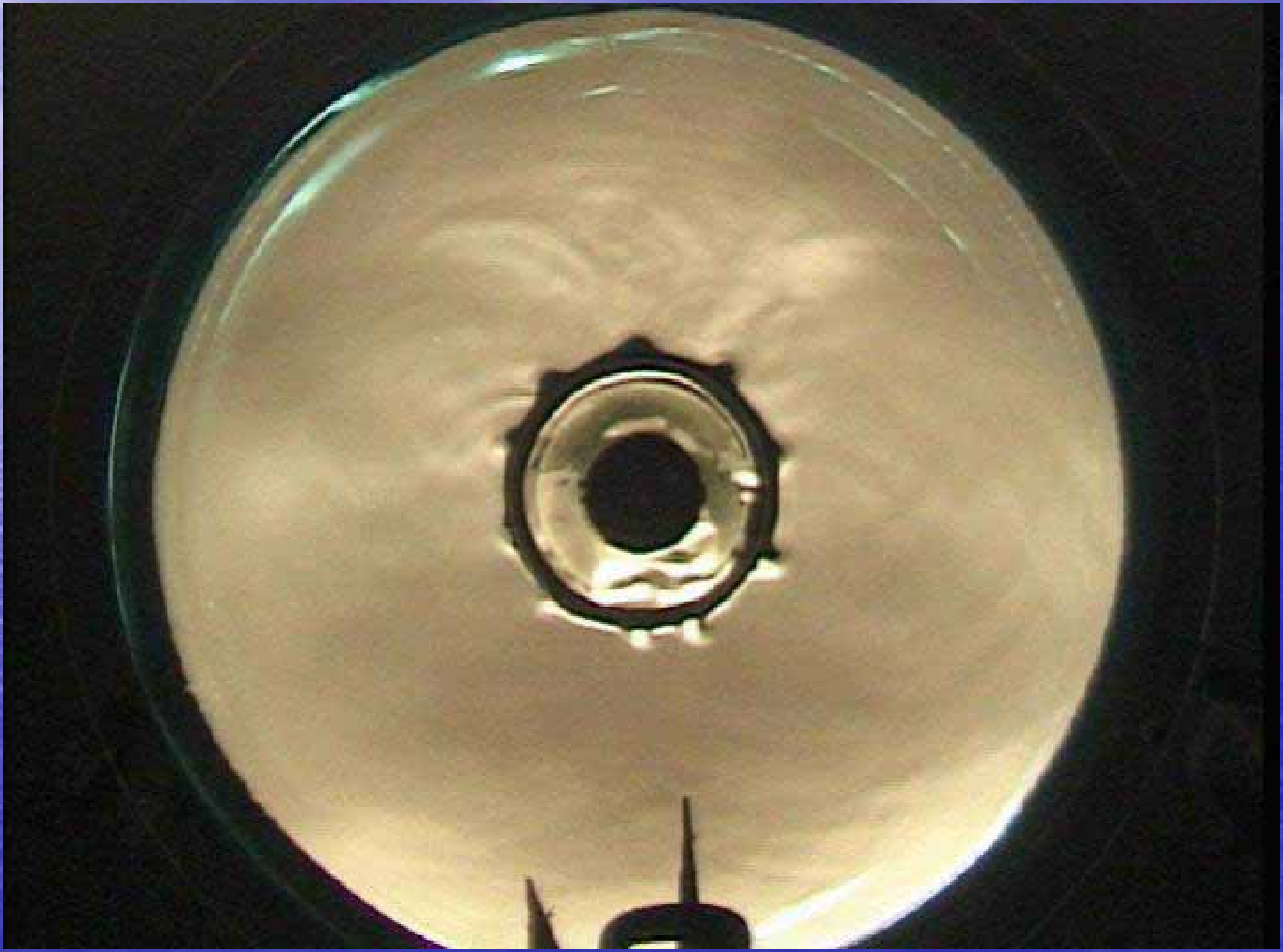


Inertial waves and modes forced by a bobbing sphere (animation)



(animation) Image of a ‘waffle-grid’ mountain on the water surface: Taylor-Proudman *par excellance*. (1 cm tall mountain in 10 cm of water). Very low Rossby number indictated by drifting flotsam

(animation) Rotating convective eddies generated by hot inner cylinder



☼ interaction of Rossby waves and mean circulation:

waves set up the mean circulation ('pathfinders')

wave-action conservation $E/(\omega - Uk)$

wave-momentum flux $E c_g/(\omega - Uk)$

(E = wave energy density, U = mean flow, c_g *=group velocity, ω=frequency, k= east-west wavnumber)*

Lateral momentum transport

accompanying stirring of large-scale PV field: $u - u_0 = -\frac{1}{2}\beta\eta^2$

- easterly acceleration related to north south particle displacement, η
- westerly near energy source (classic jet sharpening)
- surface polar anticyclonic vortex (in tandem with diabatic forcing, wintertime cooling)
- mountain topography: easterly momentum source
- transmission by Rossby waves (non-local PV flux; CLs)
- induction by synoptic scale QG turbulence
- zonal β-plane jets, zonal spiralling bands
- long, upwind propagating Rossby waves ('Lighthill' modes)
- restructuring of the flow induced PV, limiting on homogenized PV …ocean, stratosphere, troposphere

The paradigm for atmospheric circulation is Rossby waves superimposed on a mean westerly (eastward) wind.

Linear stationary waves: circular lee Rossby waves plus upwind and downwind wake blocks. This elementary solution contains both the semicircular lee waves and upwind/downwind blocks (missing from McCartney solution..though strictly linear topography does not generate them) **Upstream penetration of long Rossby waves occurs if $\beta a^2/U>1$ (1/a=north-south wavenumber)**

Lighthill JFM 1968

$$U\frac{\partial}{\partial x}(\nabla^2\psi + \beta\psi) = 0$$

*Charney-Drazin theory for a stratified atmosphere: wavenumbers lie on an **ellipsoid** whose base plane is this circle,*

,3

$$U\frac{\partial}{\partial x}(\nabla^2\psi + \beta\psi) = 0$$

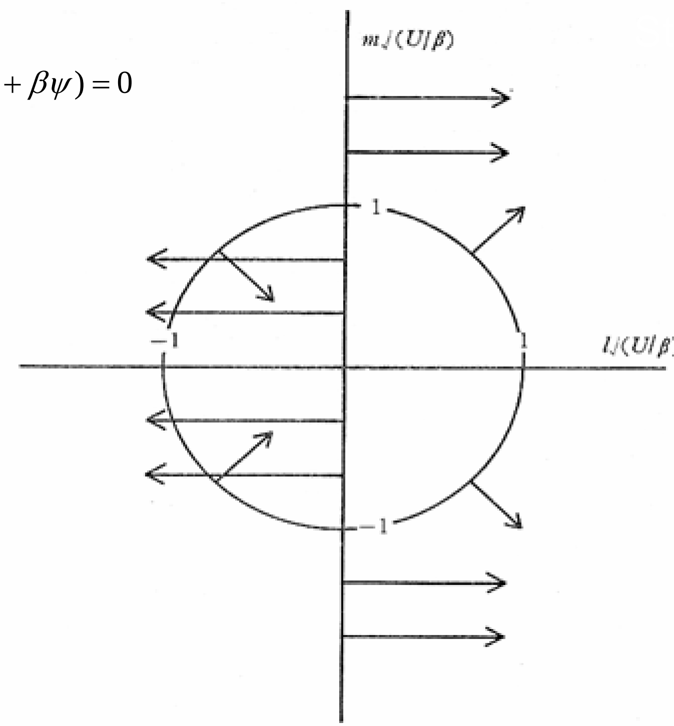
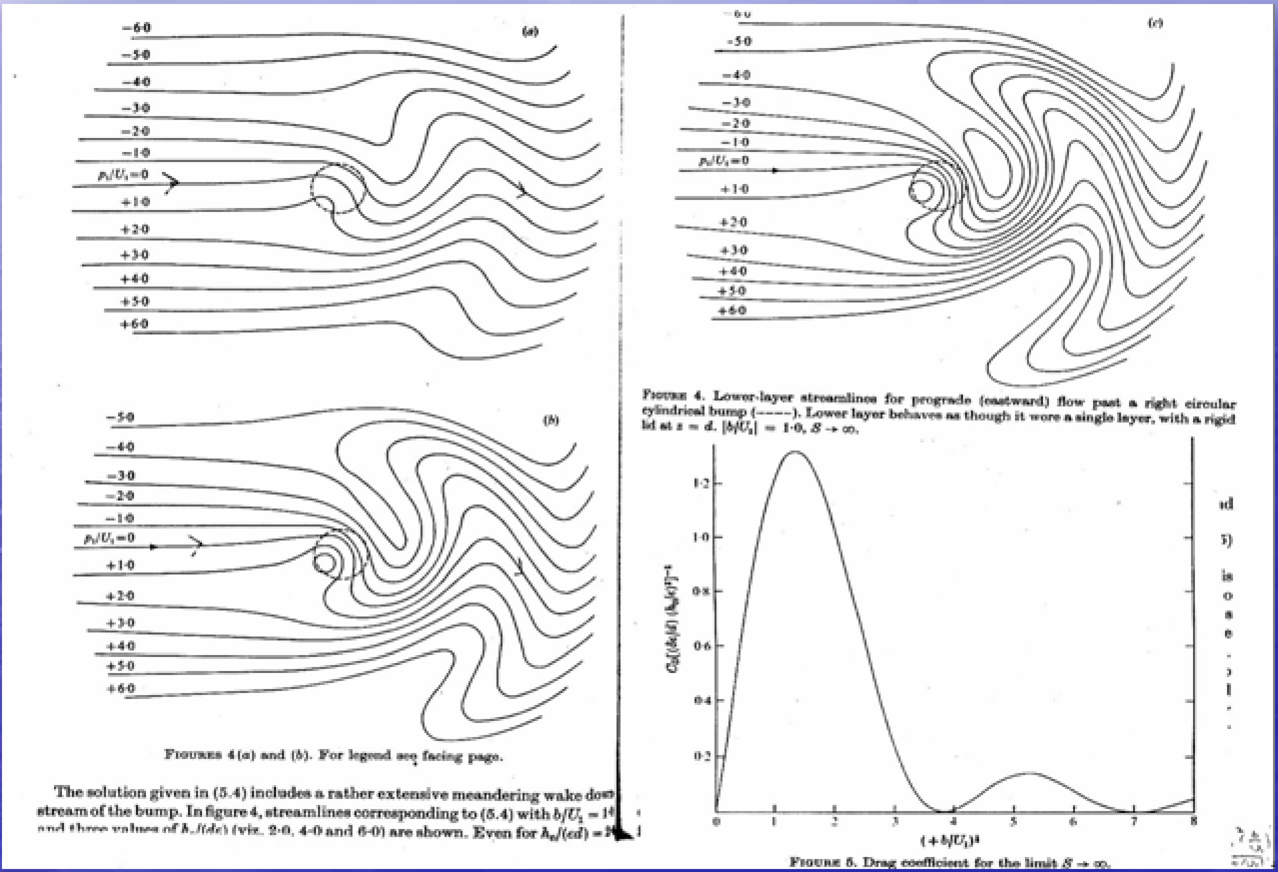


FIGURE 1. Wave-number curve for Rossby waves generated on a beta-plane ocean by a steady forcing effect travelling westward, with velocity $(-U, 0)$.

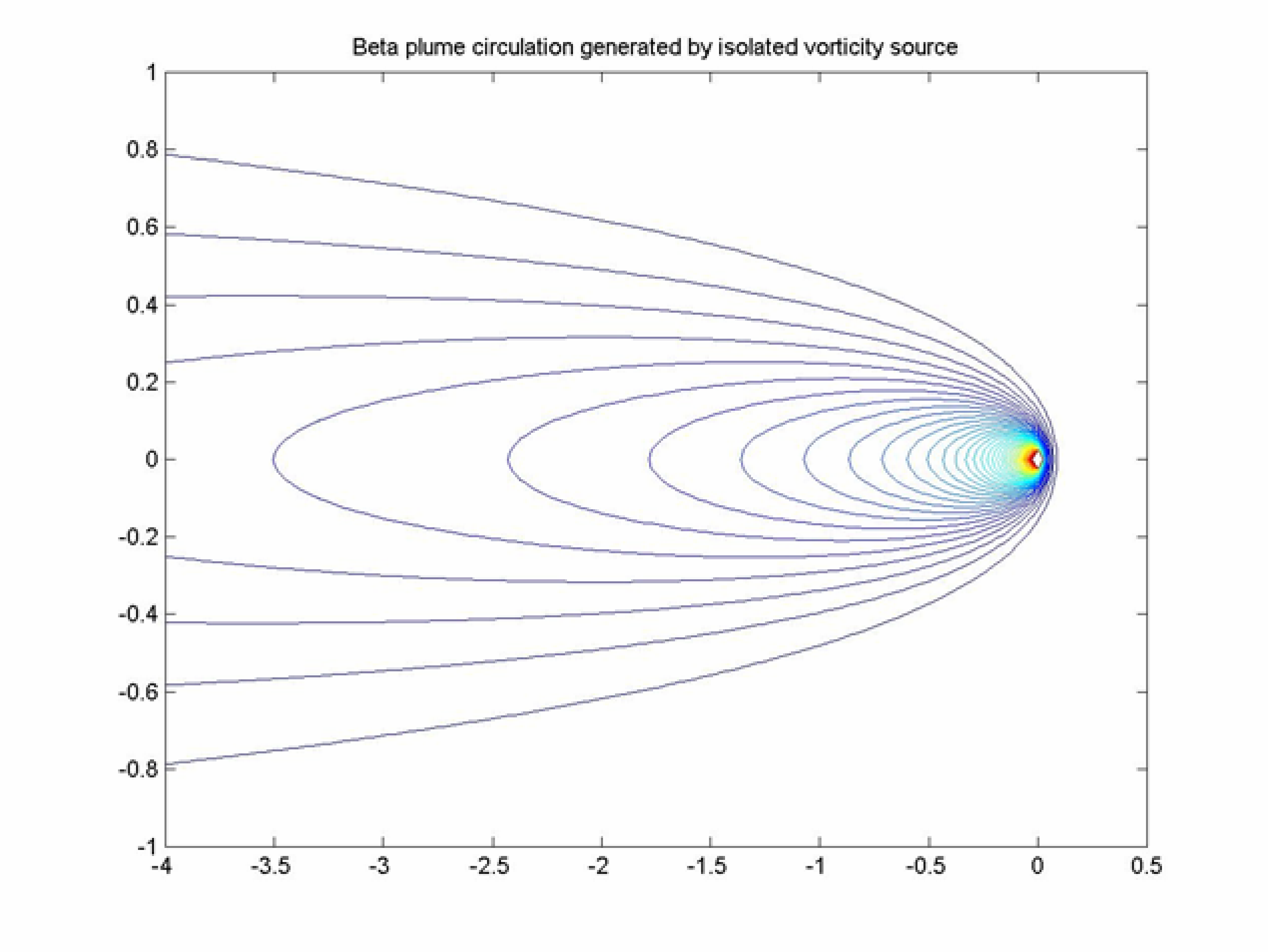
Linear theory for stationary Rossby waves, verifying the semi-circular wave-crests predicted by ray theory. Cylindrical mountain. The form drag (which is $-p h_x$ for finite slopes) is plotted as a drag coefficient in lower right panel, as a function of the stationary wavenumber $(\beta/U)^{1/2}$. *McCartney, JFM 1976*



the β-plume: Rossby wave Green's function for an steady point source with no zonal flow

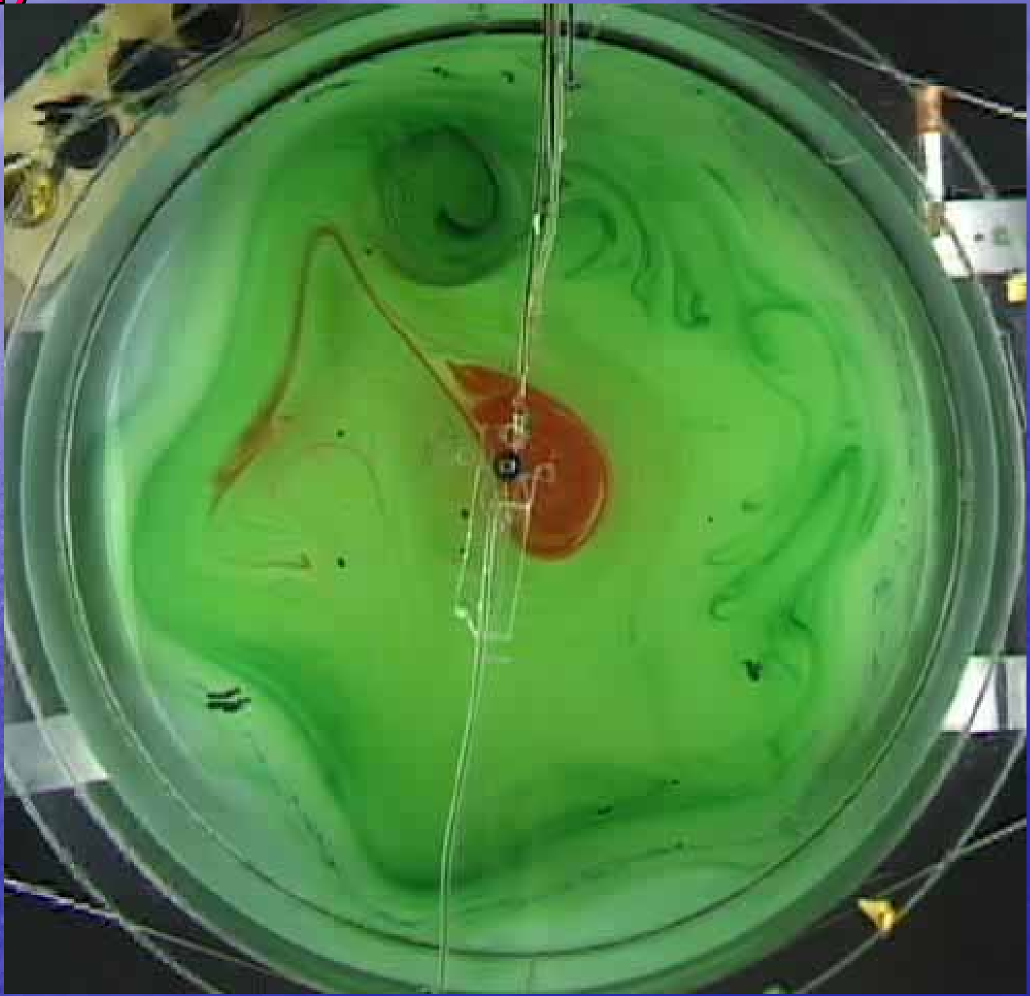
$$\psi = \exp(-\beta x/2R)\ K_0(\beta r/2R)$$

(R = linear Ekman friction coefficient)

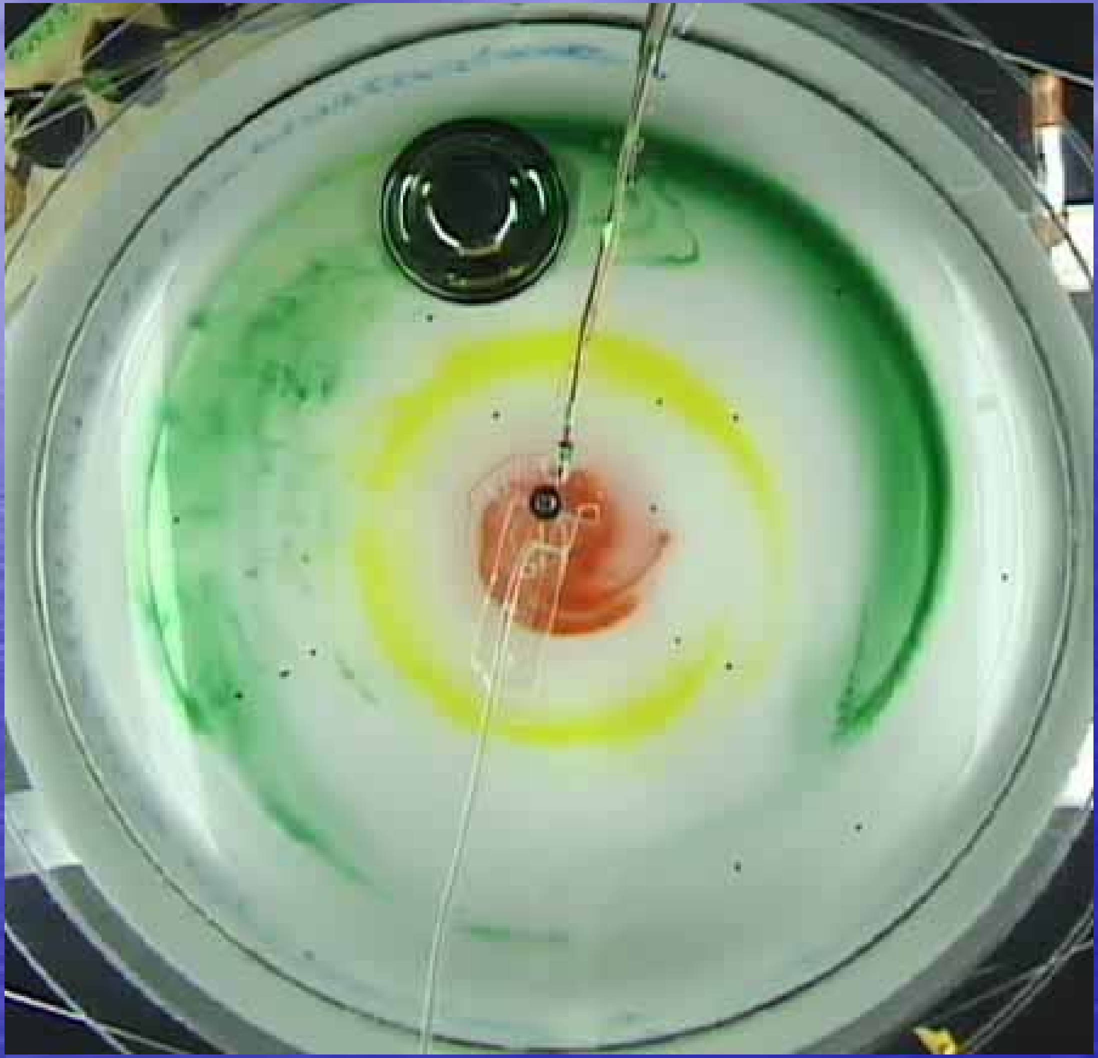


$\beta a^2/U<1$: no blocking, steady lee Rossby waves (animation)

$\beta a^2/U \sim 1$: beginning to block and wake waves unstable (animation)



$\beta a^2/U>1$: strong upstream blocking and very unstable wake generates transient Rossby waves (animation)

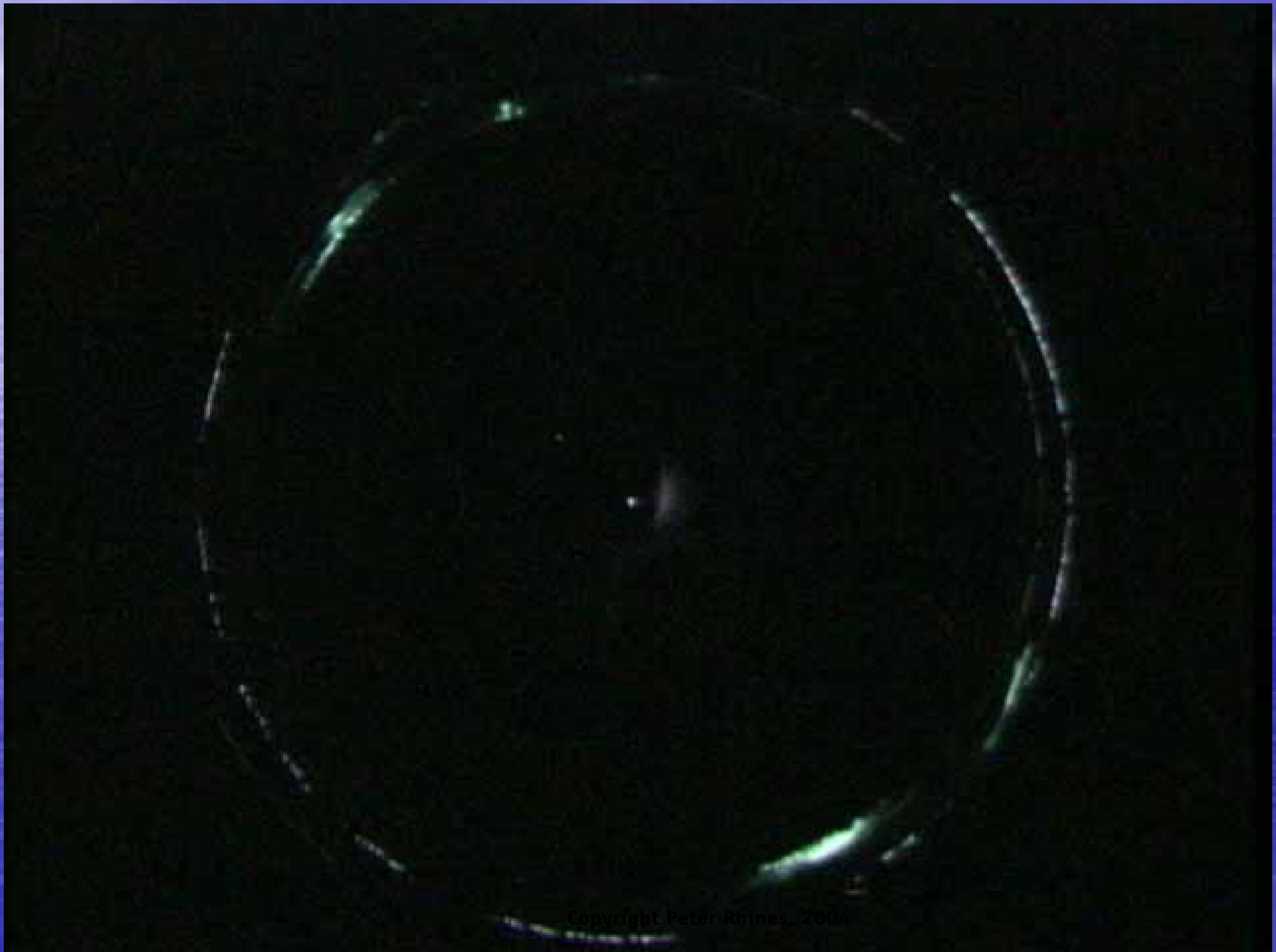


Note upwind blocking east of mountain,

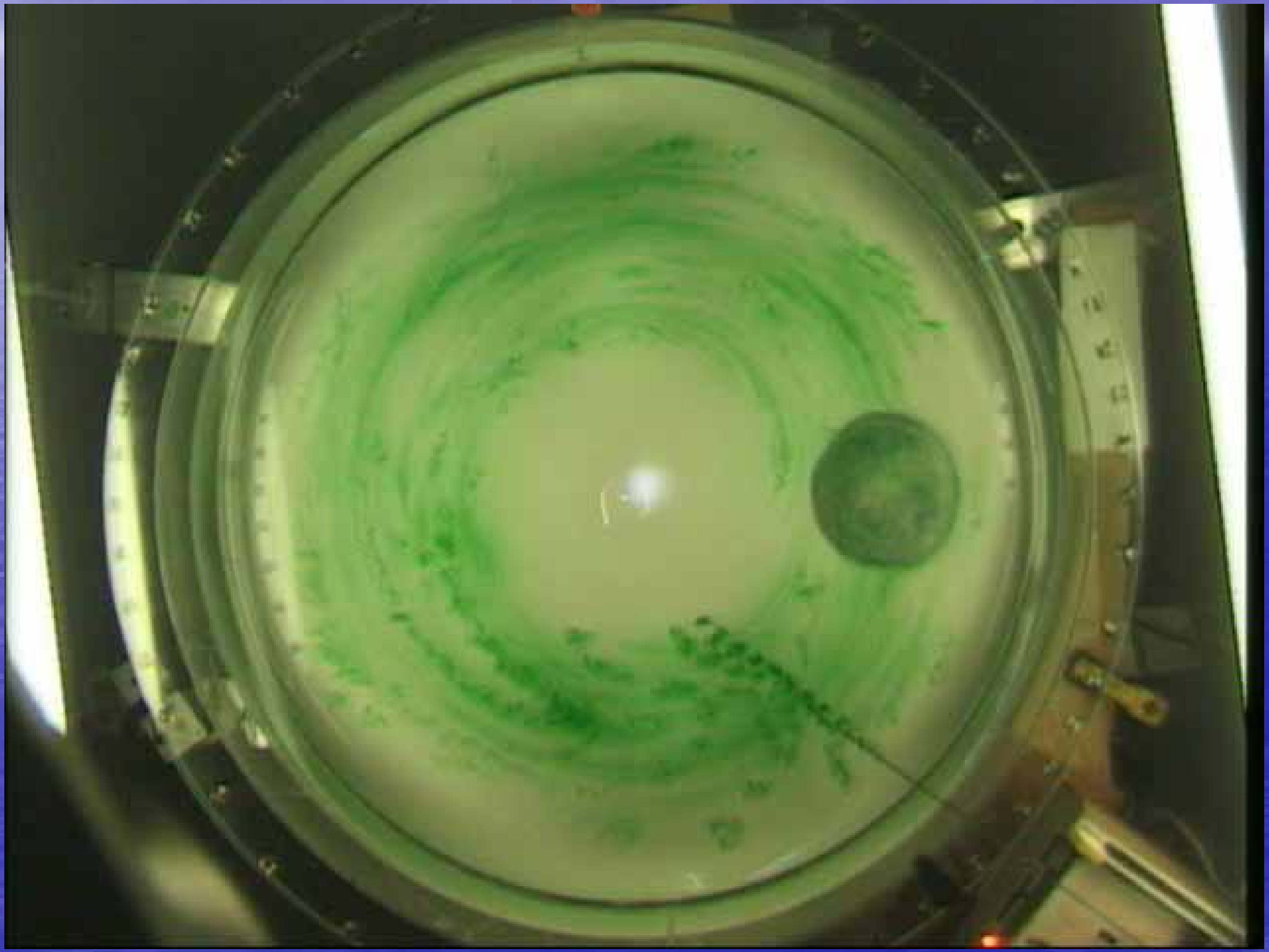
unstable Rossby wake, induced anticyclonic polar vortex

$\beta a^2/U > 1$

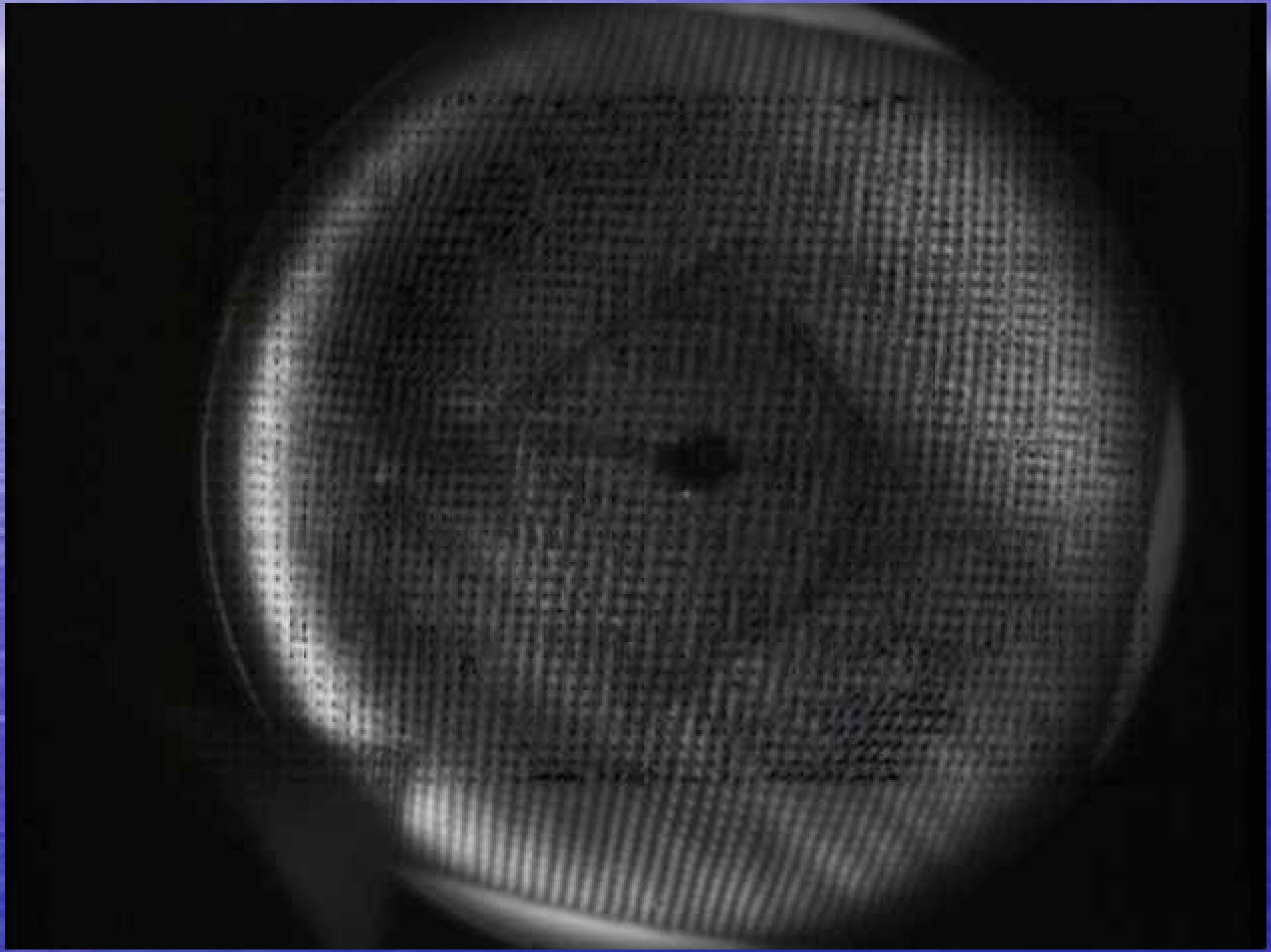
altimetric view of surface pressure (geostrophic stream function) (animation)

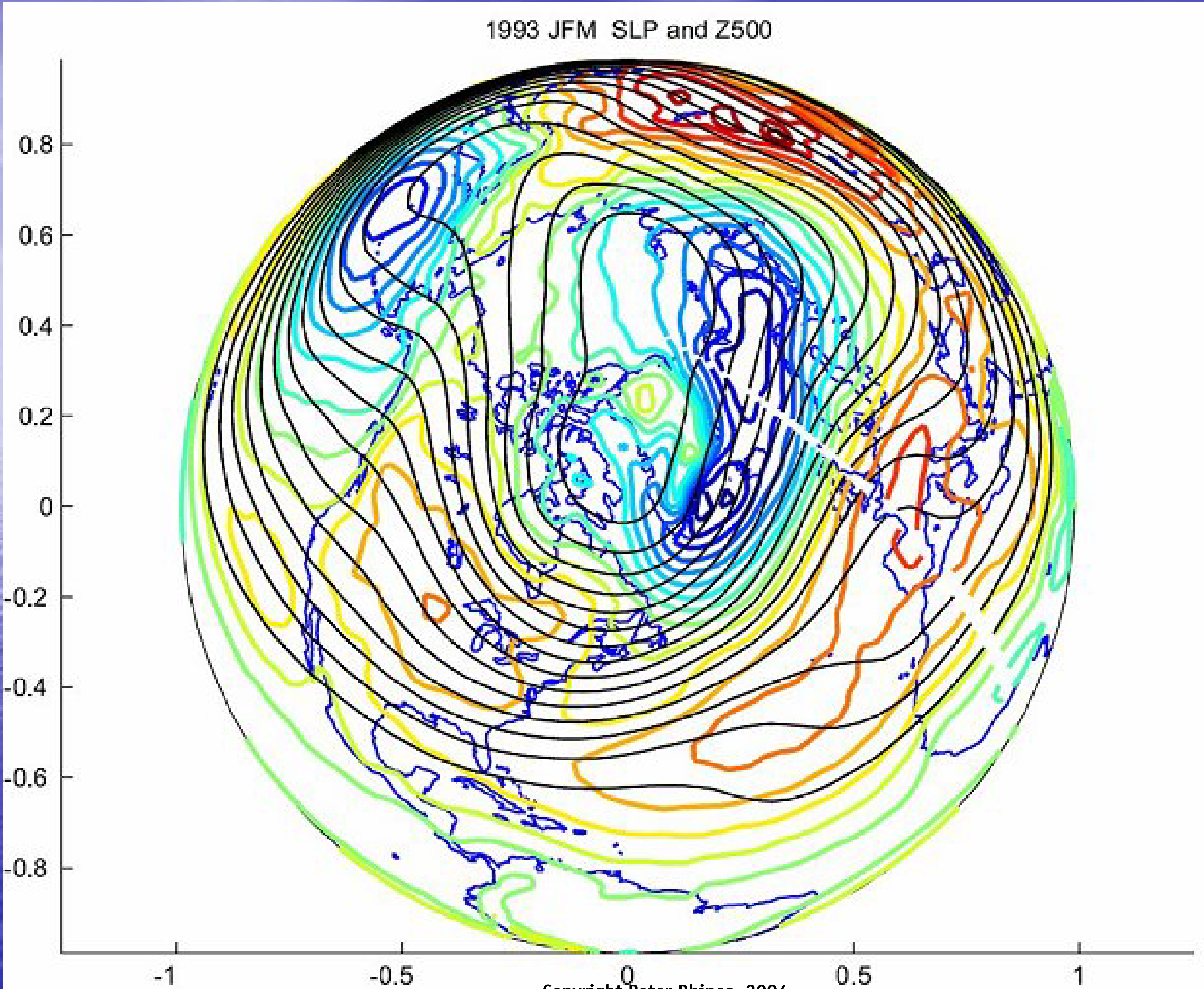


$\beta a^2/U \sim 1$ (animation)

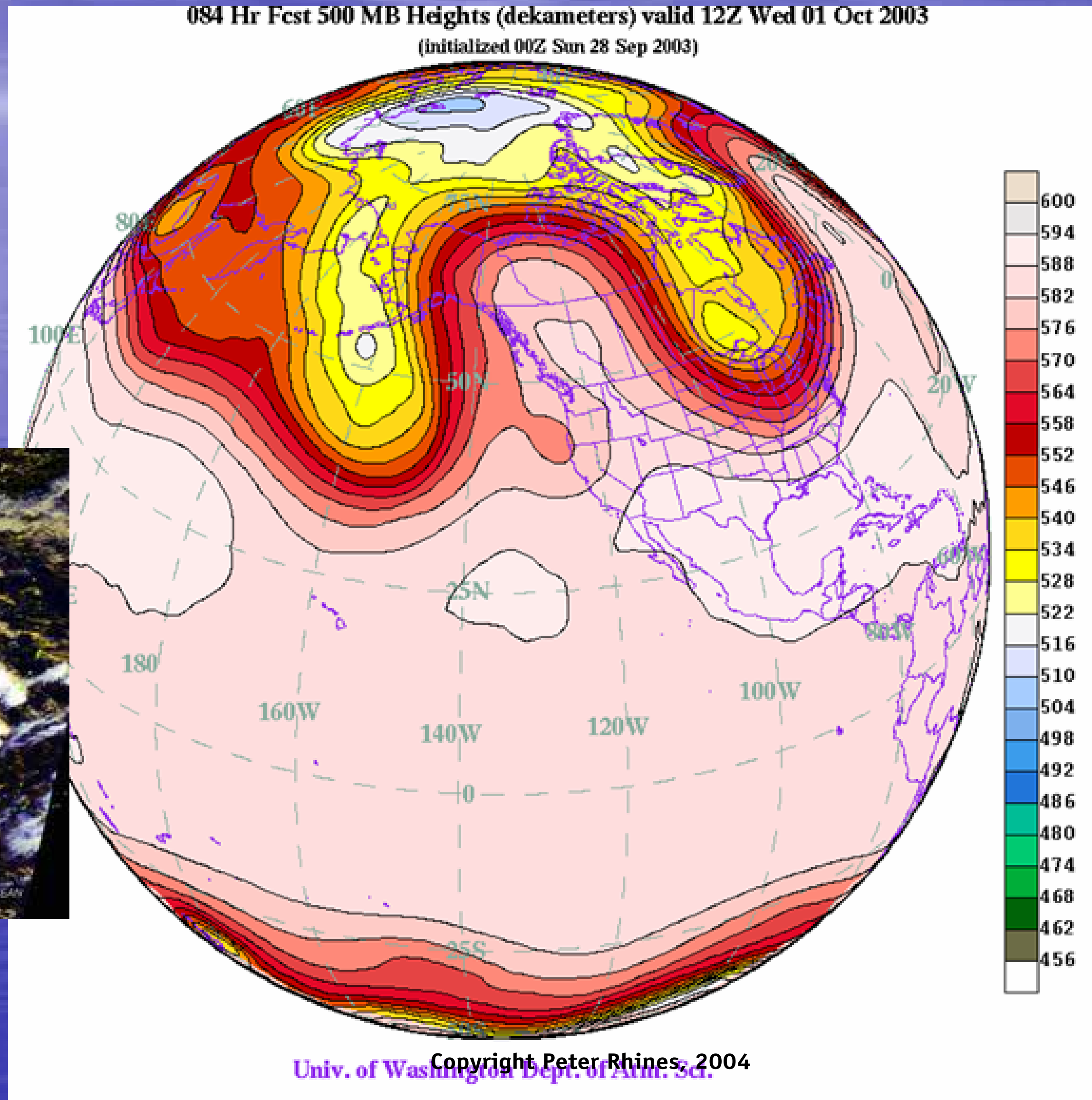


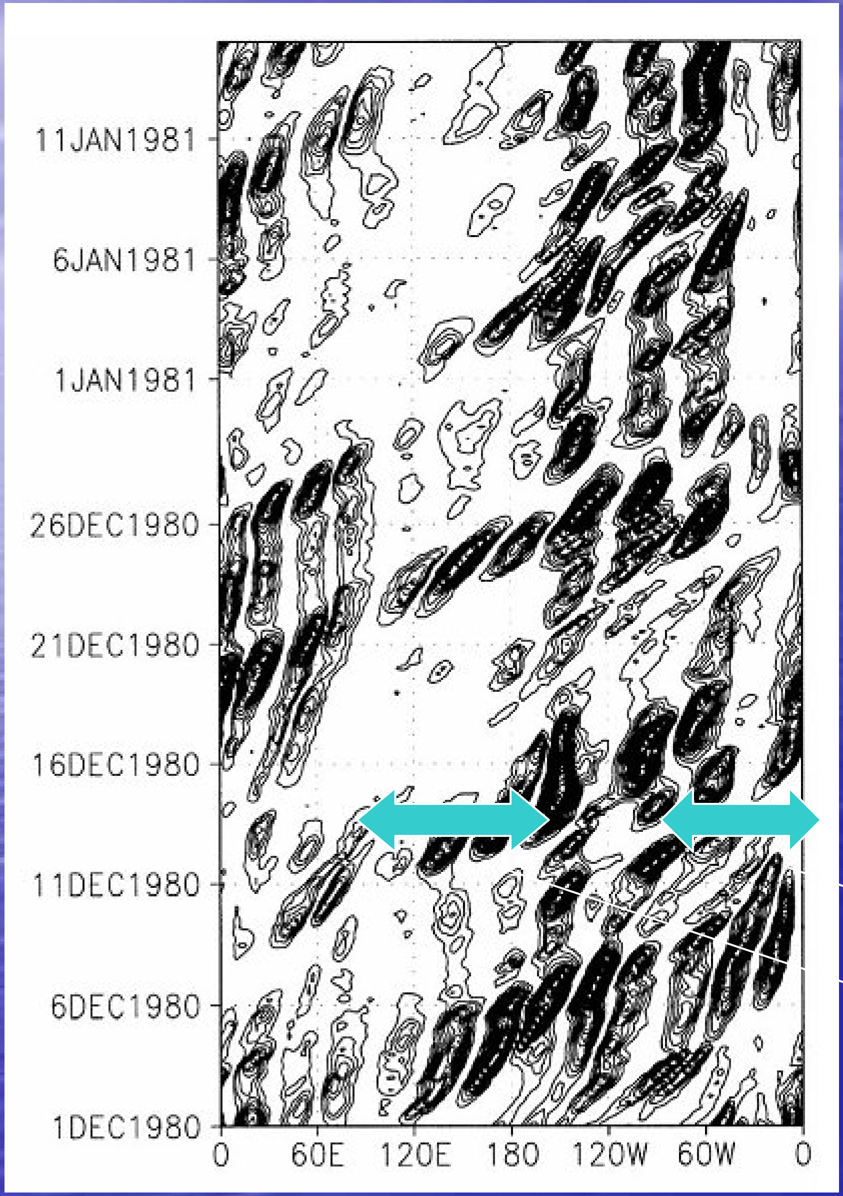
Slope vectors from piv-equivalent analysis of altimetry image (animation)




1993 JFM SLP and Z500
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.5
0
0.5
1

October 2003: In Greenland, strong winds were supplied by fast-moving lows arriving from the Great Lakes, where a deep trough in the jetstream was stationary for some days. Three hurricanes reached Greenland in the autumn. re-energizing when they passed beneath the jetstream. 'Super' typhoon Lupi impacted the jetstream in the western Pacific in late November, exciting the 'waveguide' as far as Europe.

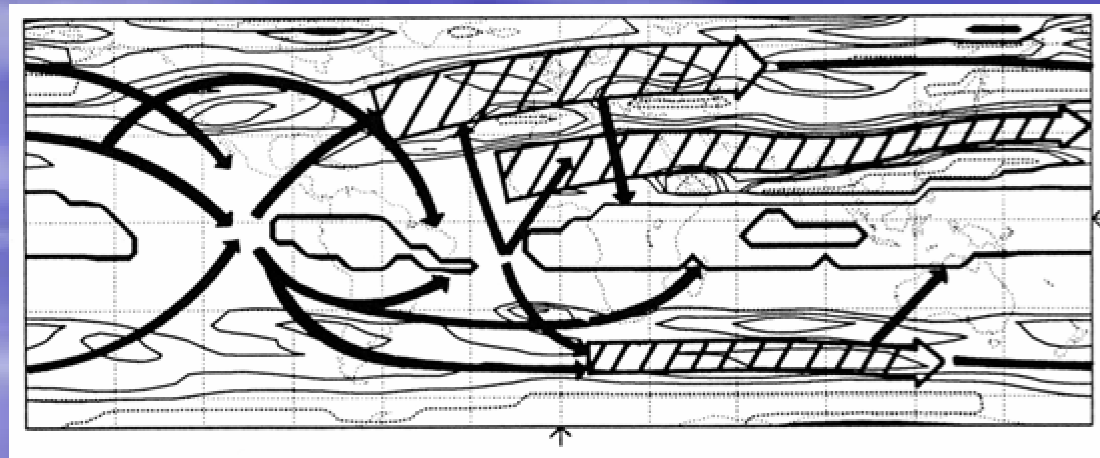




5-week Høvmüller (time-longitude) plot following the principal storm tracks (*Chang, Lee and Swanson J Clim 2002).*

This is variance of meridional velocity at 300 mb. Individual synoptic eddies move slowly eastward while they spawn new systems with a more rapid eastward group velocity

The jet stream is a Rossby waveguide



Hoskins+Ambrizzi JAS 93

0^0

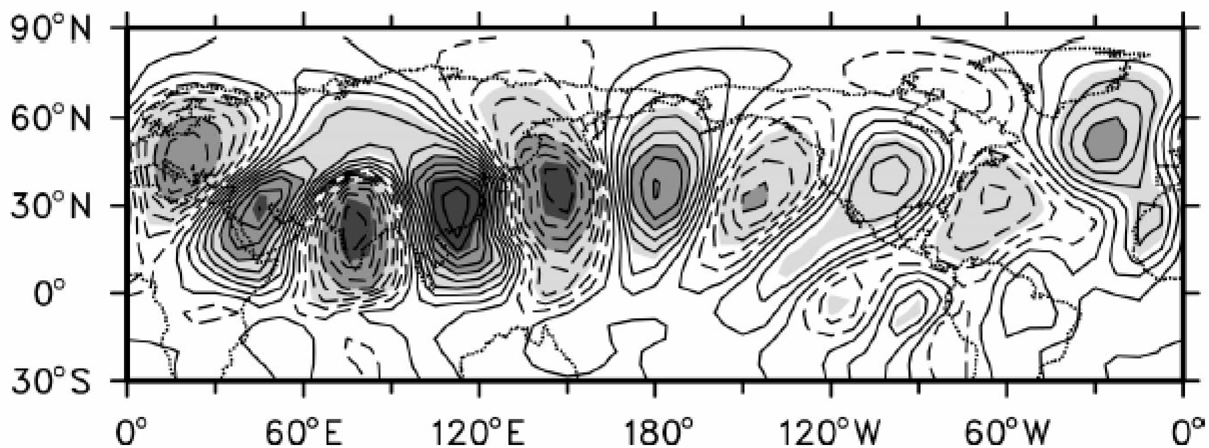


FIG. 4. One-point correlation plot for CCM3 mean Dec–Feb (DJF) 300-mb nondivergent v wind component internal variability for a base point at (28.9°N, 112.5°E). Contour interval is 0.1.

Branstator JClimate 02

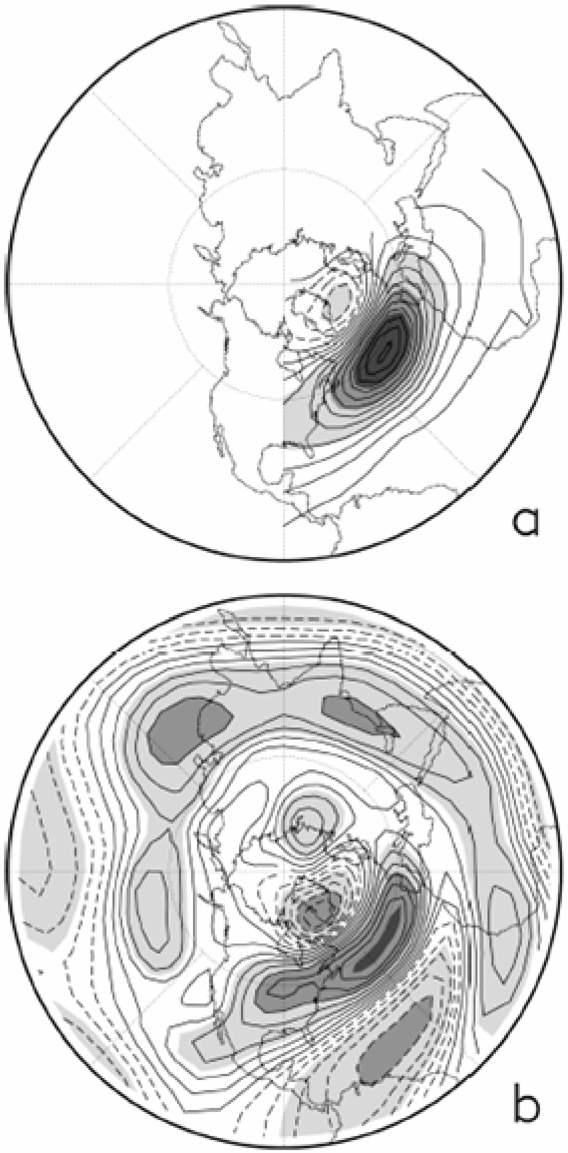


Fig. 16. Same as Fig. 10 except for observed monthly mean DJF departures from centered 3-month means.

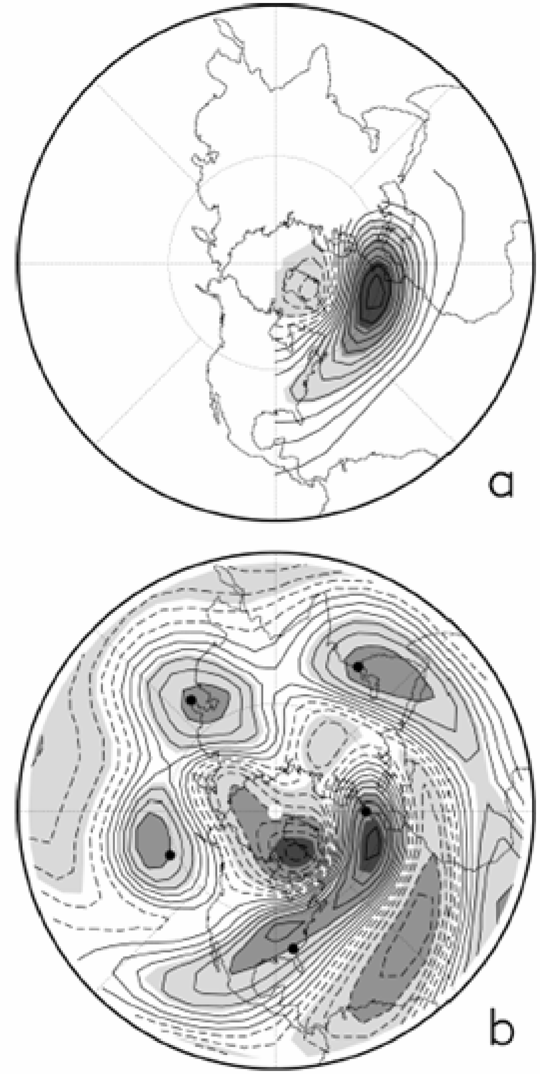
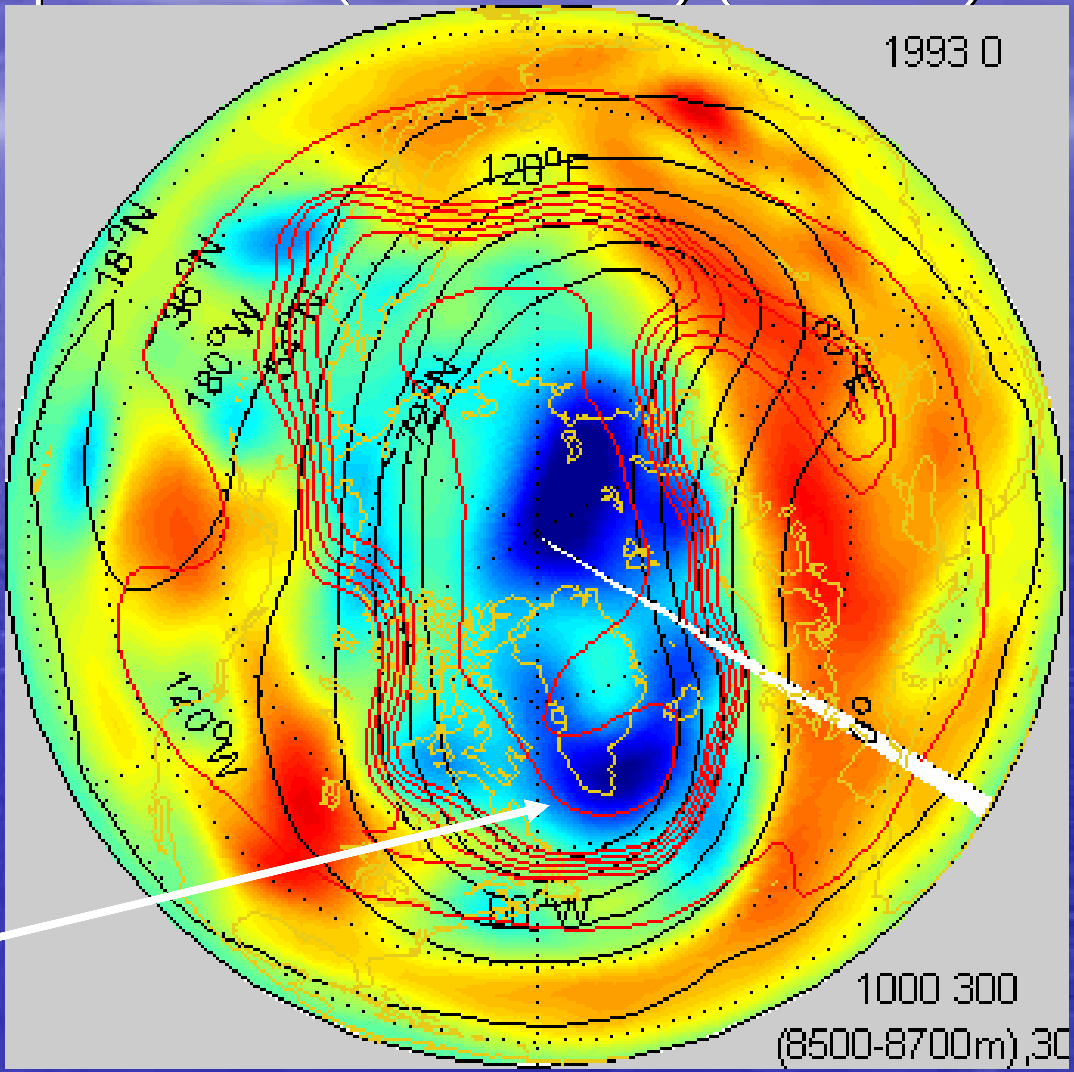


Fig. 10. (a) Leading EOF of CCM3 mean DJF 850-mb streamfunction internal variability for the Northern Hemisphere sector between 90°W and 30°E. (b) Correlation of CCM3 mean DJF 300-mb streamfunction internal variability with the principal component associated with the EOF of (a). The five heavy dots mark the centers of the five lobes in the streamfunction plot of Fig. 8a. Contour interval is 0.1.

Branstator J Clim 2002

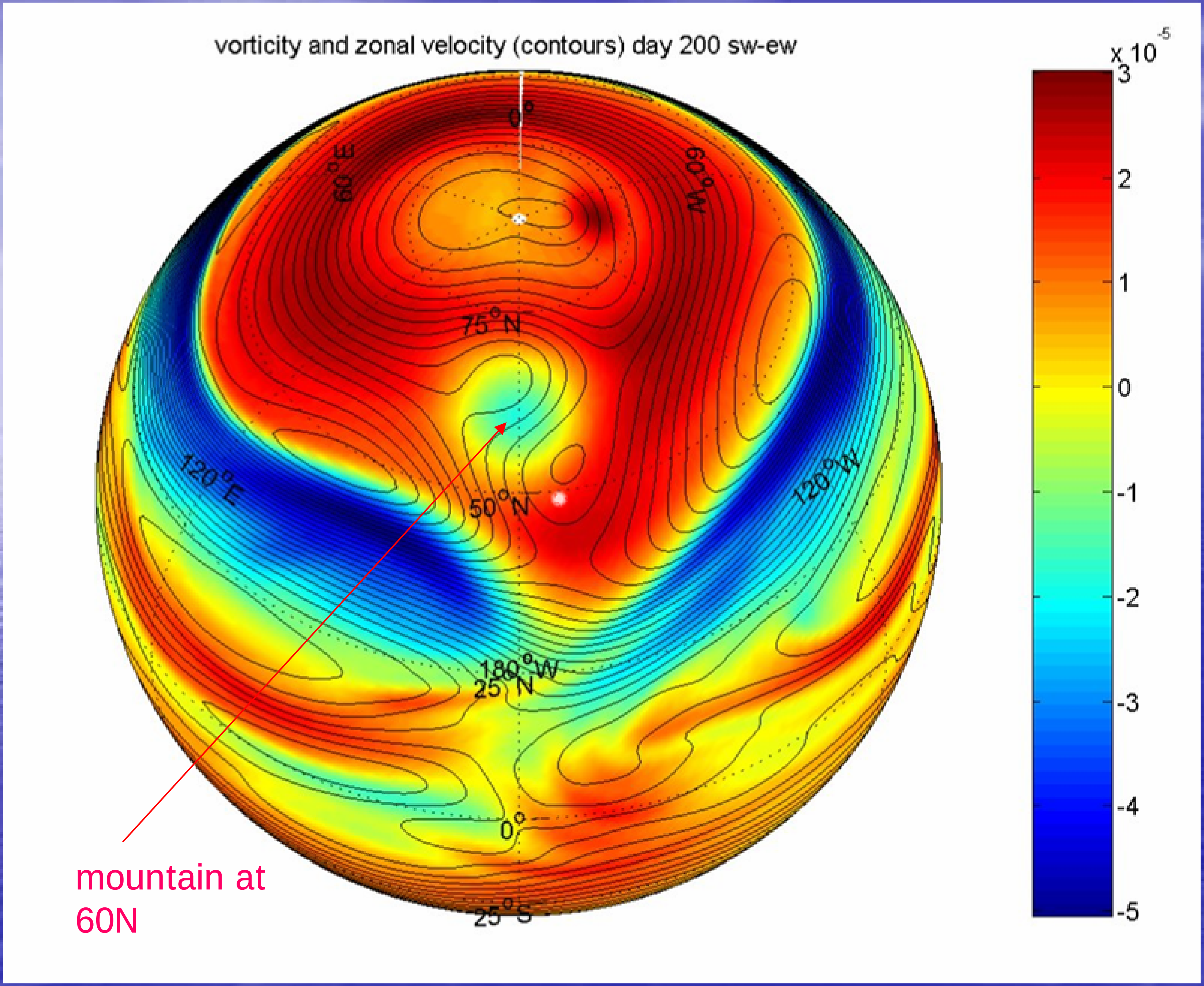
Pressure field (winter 1993) at 3 levels in the northern hemisphere: 1000mb, 300mb and 30 mb: surface storms (blue, low pressure); jet stream (red contours) and stratospheric polar vortex (dark contours) (animation)



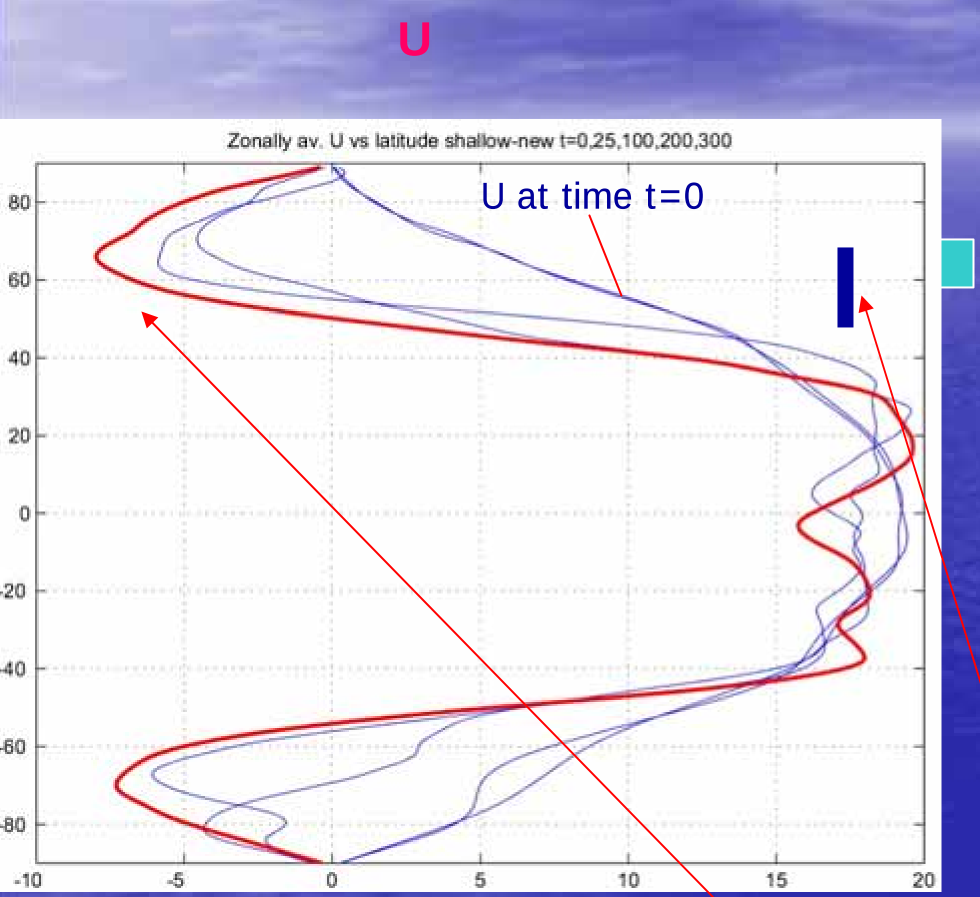
North Atlantic, Greenland

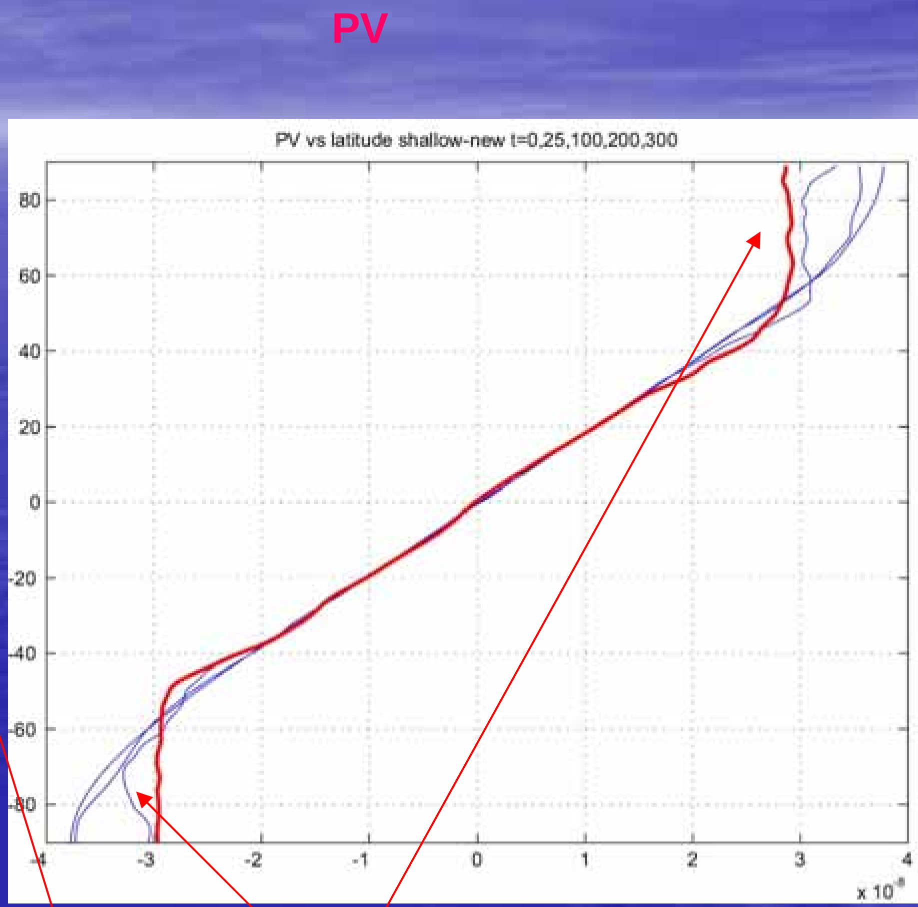
Super-rotation driven Rossby waves, isolated mountain

- standing Rossby waves/wakes
- 'Lighthill' blocking (low-frequency Rossby waves $\sim e^{ily}$ with zonal wavecrests, intrinsic group velocity β/l^2 : upstream (west) if $\beta a^2/U>1$)
- weakening of stationary lee waves by altered oncoming winds
- lee cyclonic wake, PV bridge to polar vortex
- instability of lee bt shear produces transient eddies/Rossby waves with a broader spectrum of group velocity for large $\beta a^2/U$
- critical line where U=0 absorbs zonal westward momentum, reducing scope of wave propagation, totally changing upwind block


vorticity and zonal velocity (contours) day 200 sw-ew
x 10^-5
3
2
1
0
-1
-2
-3
-4
-5
0°
60°E
60°W
75°N
120°E
120°W
50°N
180°W
25°N
0°
25°S
mountain at
60N

Shallow water on a sphere: T127 model: zonally averaged zonal flow and PV: (initially *uniform* super-rotation)





both hemispheres filled with wave activity

mountain here

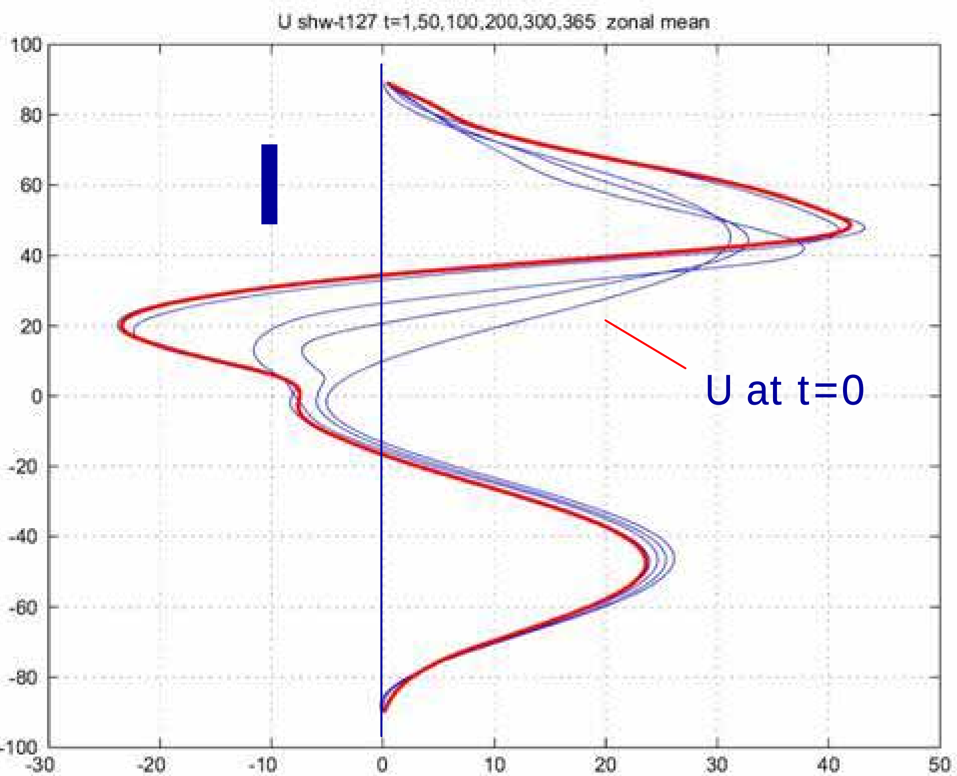
upstream blocking

PV homogenization, polar anticyclones

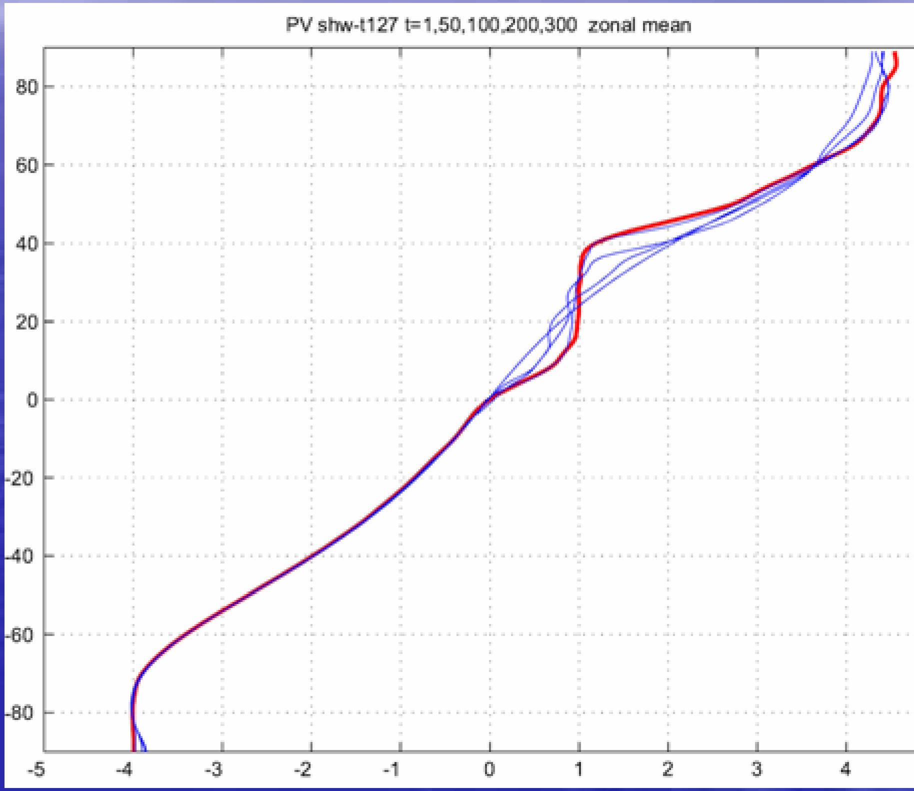
however if initial zonal wind reverses at low latitude, produces a migrating critical layer, instead of polar vortices/blocking

(mountain at 60N, easterly/westerly initial zonal flow with tropical easterlies and critical layer for stationary waves)

zonal veloc (zonal average)



PV

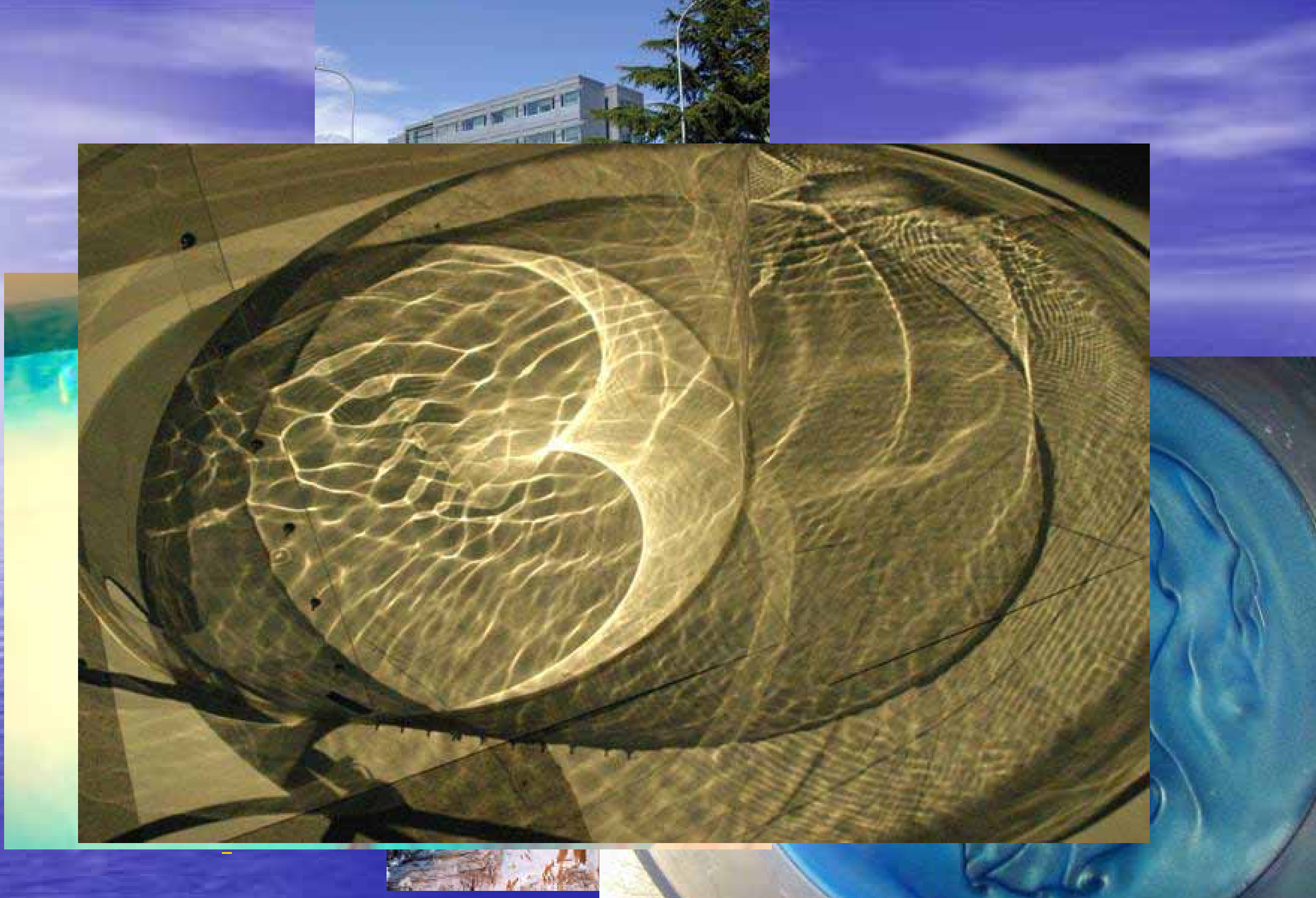


Conclusions

- Simple barotropic models are rich with Rossby wave propagation, flow instability and mean-flow induction by transients. Optical altimetry in the *gfd* lab combined with particle imaging, dye and laser velocimetry, spans many scales. Inertial waves and microscale convection interact with larger scale geostrophic circulations. Models of both oceanic and atmospheric Rossby waves are relevant to the structure of the general circulation, as stirring and mixing of potential voriticity (PV) redistributes the angular momentum, and Rossby wave propagation shapes the spin-up of the circulation.

- Baroclinic dynamics involves subtle buoyancy effects and thermodynamics. Yet potential vorticity and its quasi-horizontal transport continue to exert control over the dynamics. Many features of the barotropic system continue to be relevant: lateral PV transport, which also produces vertical momentum transport. Barotropization (the development of tall, z-independent flows) is widely active, and can be idealized as vertical propagation of Rossby waves, combined with eddy pairing.

- The *texture* of geophysical fluids expresses these interactions.



Ripples, waves and hydraulics interact in flows round bumps...at all scales (click image for more).

www.ocean.washington.edu/research/gfd/gfd.html

..\..\images\gfd\animations-gfd\Standing6.avi