Altimetry involving fine spatial scales: the GFD lab the subpolar ocean

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View from above: SSH field in 1m diameter rotating cylinder, configured as a polar-cap ocean and excited by a buoyant source of upper-ocean water at center.
This talk introduces a laboratory analog of satellite altimetry in work funded by the Vetlesen Foundation of New York and NSF-OCE. Using the parabolic surface of a rotating fluid as a Newtonian reflecting telescope we are able to image the entire surface elevation field of a fluid circulation experiment with accuracy better than 1 micron. This makes it possible to see and quantitatively analyze dynamical features of model ocean circulations that were invisible previously. We argue that future wide-swath satellite altimetry, SWOT, should reveal not only more detail in features we know to be there (boundary currents, fronts, convective structures, river plumes) but can also discover surface flow structures as yet unanticipated.
WHY lab experiments?

- painless inclusion of many dynamical regimes (linear waves, nonlinear eddies, fully turbulent, geostrophic, ageostrophic, adiabatic, thermally active): *textured* is not the same as spectral slope
- the opportunity to explore fluid physics absent or heavily parameterized in numerical models: phase change, wave breaking, ageostrophic deep convection, double diffusion, layering, boundary layers (top, bottom...[the ocean has no sidewalls])
- high resolution when in 3 dimensions ...though only moderate Reynolds number (~$10^4$) Ekman number $\sim 10^{-2}$
- once you’ve built it, you own it (easy to do long experimental runs...)
- more surprises, aesthetics, and the observed fact that labs are social places.
(1) Altimetry in the GFD lab

- Taylor-Proudman: rotational stiffness
- topographic influence on SSH: barotropization of eddy fields
- interaction of topography with circulation
  - form drag …. end of the baroclinic cascade: a major sink of mesoscale energy and momentum
- creation of jets and basin oscillations
- the surface image of deep circulation, including the global Meridional Overturning
- Rossby waves shaping gyre-scale circulations
  - further β-plane creation of jets and wakes with topographic ridges/rises
- internal waves interacting with quasi-geostrophic flows:
  - near-inertial wave trapping in shear zones
  - inertial/internal waves (non-hydrostatic) wrapped round eddies
- deep convection: texture
- combine altimetry with drifters, tracers, bio-color, SST, subsurface hydrography
- non-geostrophic interactions with mesoscale field
  - baroclinic β-plume; baroclinic instability,
  - radiation of near inertial waves from quasi-geostrophic flows
- vortex/gravity wave interaction in upper ocean
- dynamics of thin, buoyant upper layers and boundary currents
Forcing of a rotating bowl-shaped basin by a disk of surface cooling...the circulation is most intense far from the convective energy source. Boundary currents, gyres and deep convection develop from this compact source.

Condie & Rhines ‘Topographic Hadley Cells JFM 1994
at high rotation (or large horizontal length scale) multiple jets form, guided by the topography of the basin

Figure 7b. As in figure 7a, except at double the rotation rate. Now an intricate banded circulation occurs, in which the basic pair of gyres is riddled with jets directed primarily along depth contours, but connecting across them (Boubnov and Rhines, priv. comm.)
Evolution of balanced, geostrophic eddies from 3-dimensional turbulence

Initially 3-dimensional turbulence converts to tall, geostrophic, cyclonic eddies.

A 2mm glass cylinder is held vertically... at rest in the non-rotating frame... in a rotating fluid... its 3D turbulent wake evolves into barotropic cyclones

(Cormac Flynn, Univ. of Washington GFD lab)

(numerical sims: Smith & Waleffe PhysFl 99 Morize, Moisy & Ribaud, PhysFl 05)
Carl-Gustav Rossby in the mid 1920s, with a large rotating platform for gfd experimentation: such an apparatus can ‘calculate’ barotropic polar $\beta$-plane circulations and $f$-plane baroclinic circulations with high resolution.
the laboratory polar β-plane
(GFD lab, Univ. of Washington):

stiffness along the rotation axis:
2D ribbons of tracer
The entire free-surface elevation field of a rotating fluid in the laboratory can be imaged and analyzed, by using it as a parabolic telescope mirror (Newton & Huygens 1672).

This ‘optical altimetry’ readily achieves a precision of better than 1 micron of surface elevation. The surface topography corresponds to the pressure field just beneath the surface. It is the stream-function for the geostrophic, hydrostatic circulation, which can be resolved to better than 0.1 mm sec⁻¹.

Rhines, Lindahl & Mendez, J. Fluid Mech, 2007;
Afanasyev, Rhines & Lindahl, Physics of Fluids 2008 (accepted)
Experiments in fluids, 2008 (accepted)
J. Atmos Sciences 2007
Rhines, J. Atmos Sciences 2007
Gharib & Dabiri, Exp. Fluids, 2001, slope detector probe (FSGD)
robotically positioned light source and camera

test fluid
\[ k(r) = H_0 + \frac{\Omega^2}{2g} \left( r^2 - \frac{\Omega^2}{2} \right) \]

focus at \( z = \frac{g}{2\Omega^2} \approx 1 \text{ m} \) for \( \Omega = 2.2 \text{ s}^{-1} \)
For quantitative inversion of surface elevation, velocity, potential vorticity we use colorometric mapping with a light source in the form of a square multi-hued panel: the imaged color field encodes the surface slope.

CIE (Commission Internationale d’Eclairage) L*a*b color space.
Inversion from surface elevation to velocity

\[
\frac{\partial \vec{V}}{\partial t} = -\nabla \left( \frac{1}{2} \vec{V}^2 \right) - g \nabla \eta + \left( \vec{k} f_0 + \nabla \times \vec{V} \right) \times \vec{V}.
\]

\[
\vec{V}_g = (u, v) = \frac{g}{2\Omega} (\eta_y, -\eta_x).
\]

giostrophic

\[
\vec{V} = \vec{V}_g - \frac{\vec{V}_g \cdot \vec{V}_g}{f_0}.
\]

gradient

\[
\vec{V} = \frac{g}{f_0} \vec{k} \times \nabla \eta - \frac{g}{f_0^2} \nabla \eta_t - \frac{g^2}{f_0^3} J(\eta, \nabla \eta).
\]

semi-geostrophic

accuracy of the method: simply change the rotation rate over a known range...altimetry accurate to 0.05% (std)

\[
\zeta = \frac{\Omega^2 - \Omega_0^2}{\Omega}.
\]

Y. D. Afanas'ev, P. B. Rhines, and E. G. Lindahl

\[
h(r) = H_0 + \frac{\Omega^2}{2g} \left( r^2 - \frac{D^2}{8} \right),
\]

....PV inversions
a high-wavenumber ‘test mountain’, a panel of ~ 1 cm squares beneath 15 cm of mean water depth
the SSH image of the test mountain: an accurate Taylor-column transmitted replica of the topography (left: slower flow; right: faster flow but both with small Rossby number.)
Two ‘test mountains’ (red circles) with azimuthal flow forced over them yield a pattern of near-inertial waves and turbulent yet geostrophic eddies.
Seaglider velocities between Iceland and Faroes, showing strongly barotropic velocity field (resolving tides): here we illustrate the strong barotropic component of the oceanic velocity field at high latitude (the depth-average and surface velocities track closely).
Long hydrostatic Kelvin waves, short inertial waves, shed cyclonic eddies generated by oscillatory body force with isolated mountain (oscillating the rotation rate of the table)
Here we drive a uniform-angular-velocity zonal flow westward in the 1 m diameter polar $\beta$-plane. An isolated mountain generates lee-near-inertial waves which are ducted along the sharp shear line behind the mountain. A nearly stagnant Taylor column sits over the mountain. In this and other views the surface elevation (SSH) is seen as if illuminated from the side.
Particle trajectories (‘surface drifters’) superimposed upon the SSH field.
Lee Rossby-waves in the wake of a cylindrical mountain
(McCartney JFM 1976)

Rossby waves are ‘one-way’: their phase propagation has a westward component relative to the fluid: thus they exist as lee waves for an *eastward* flow but not a westward flow. Wave drag peaks at:

$$8.2 \frac{\delta}{\varepsilon} \times \text{naive estimate},$$

$$\rho f U L^2 \delta H$$

where $\delta=h/H$ is the fractional mountain height, $\varepsilon$ the Rossby number, $U$ the mean flow, $L$ the radius and $H$ the total fluid depth.

Note strong correlation of meridional velocity and topographic height.....wave drag
The same as the experiment above, yet with the mean flow reversed. A westerly (prograde, cyclonic) zonal flow encounters a small mountain (at 2 o’clock). Rossby wave dynamics produces standing waves downwind, a convoluted lee cyclone, intense jet structure wrapping round the mountain, and a ‘Lighthill block’ upstream. This stagnant blocking region is (in linear, yet finite topography theory, a Rossby wave with vanishing intrinsic frequency and upstream group velocity for merid. wavenumbers $< (\beta/U)^{1/2}$.

Note the ruddy pressure features which are fine-scale evaporative convection cells, pillar-like cyclones. The edge of the block is outlined by convective rolls.

Here the controlling parameter $\beta a^2/U > 1$ meaning that the wake is stable; smaller values of this parameter yield unstable wake and transient Rossby waves which ironically fill the hemisphere (they are not simple lee waves). See Polvani, Esler, Plumb JAS 1999 for a numerical study with some of these features.
Streak image of the same experiment (dots 2 sec apart) showing intensity of jets near mountain, lee Rossby waves and upstream block
A field of tornadic convection cells as seen in SSH. Here the amplitude of the elevation features is $\sim 10^{-6}\text{m}$ (1 micron).
Dye tracer view of the same convection cells
A key discovery using satellite altimetry is the Rossby wave/nonlinear eddy structure of the upper km of the ocean (Chelton and collaborators). Almost everywhere mesoscale eddies drift westward, as large-amplitude Rossby waves similar in structure to the baroclinic eddy described in the MODE 1973 experiment in the western N Atlantic. The Antarctic Circumpolar Current is the main exception where eddies are systematically advected eastward.

And, many of these eddies carry fluid with westward with them, in what amounts to a new form of general circulation. They have been tracked with RAFOS floats and, tentatively, with their own potential vorticity signature.

We have carried out a series of experiments to investigate the mixed wave/eddy properties using barotropic and baroclinic disturbances generated by a towed circular cylinder

(Afanasyev, Rhines & Lindahl 2008).
Dudley Chelton
Here the colormetric altimetry scheme shows SSH gradient as a perturbed color field. The quantitative inversion gives SSH (right panels), velocity (arrows on left panels) and potential vorticity. (Every 1/100\textsuperscript{th} velocity vector is plotted).

The flow is generated by towing a circular cylinder rapidly eastward (upper panel), rapidly westward (middle panel) or slowly westard (lower panel) about this polar $\beta$ plane, generating both a vortex wake and Rossby waves.
on a $\beta$ plane cyclonic eddies drift poleward (as in Dudley Chelton’s analysis of altimetric SSH), while anti-cyclones drift equatorward.

This is seen here, with the vortices in the cylinder wake for eastward (left) and westward (right) moving cylinders.

The lower Hovmøller plot shows the wake propagation speed for the respective cases.
calibrating the altimetric elevation and slope against known solid body rotation: snapshot; std of slope = 2.0 \times 10^{-4} \text{ corresponding to velocity of } 0.5 \times 10^{-3} \text{ m sec}^{-1} \text{ temporal smoothing readily increases the accuracy by at least a factor of 10. (The azimuthal velocity at mid radius is } 8 \times 10^{-3} \text{ m s}^{-1}. )
Independent surface velocity data come from PIV (particle imaging velocimetry)

PIV: 10 pixel  AIV: 100 x
Buoyant source of fluid produces a ‘β-plume’ in a thin surface upper-ocean surface layer, radiating west of the source and producing an unstable boundary current. *This is a video…sorry.*
The boundary current’s baroclinic instability radiates near-inertial waves \cite{afanasyev2007}

\begin{itemize}
\item zoom of the boundary current reconstructed from altimetry. The wave radiation site is shown.
\end{itemize}
We combine alimetry with an optical thickness measurement of the upper layer of a stratified fluid, giving both barotropic and baroclinic velocity fields, which is complete in the case of 2 layers. A wedge-shaped cuvette with uniformly dyed fluid calibrates the optical layer thickness.
Figure 9. Eastward jet at \( t = 75 \) s after the cylinder was stopped. Cylinder performed one full circle in eastward direction, \( d = 4.8 \) cm, \( U = 4.8 \) cm/s. (a) gradient wind velocity; (b) surface elevation \( \eta = -0.025:0.004:0.045 \) cm; (c) particle tracks for the period of 30 s; (d) PV varies from 0 to 0.5 (cms)\(^{-1}\)
While this is a talk about a GFD lab analogue of satellite altimetry, we want to emphasize the pattern structure of the real ocean surface which, like the lab experiments, shows rich textures at fine scales when the appropriate imaging is available…for example in SST imagery, and here in SeaWiFS ocean color.

Our NASA-funded research in the subpolar Atlantic has demonstrated the way in which thin, fine-scale layers of low-salinity water exert strong control over deep convection in the Labrador Sea. We first analyzed these through their altimetric SSH field, with deep-sea ground truth from our robotic Seagliders. Then it became apparent that these buoyant surface layers determine the shape and intensity of the dominant spring phytoplankton bloom in the western subpolar Atlantic. (see Hatun et al., *J. Phys. Oceanogr.* 2007, Williams, Rhines & Eriksen, *J.G.R. submitted* 2008).
a plume of buoyant, low salinity water flows southwestward from the coast of Greenland, as part of the cyclonic subpolar gyre.
Labrador Sea: altimetry, SST, ocean color, Seaglider subsurface hydrography and bio-optics

Eleanor Williams, UW
missing here: video of satellite altimetry showing coherent eddies crossing the Labrador Sea, which reinforce their importance in controlling deep convection and biological productivity.

AVHRR satellite SST image with Seaglider track superimposed. This mission provided the subsurface structure of the eddies and mean offshore circulation as well as the vertical structure of the phytoplankton bloom

(Hatun, Eriksen & Rhines JPO 2007, Williams, Rhines & Eriksen 2008)
Altimetry showing strong anticyclonic eddy spinning off the Greenland coastal current, with Seaglider deep thermal structure, along its path round the eddy.
Seaglider based cross sections of the anticyclonic eddy (for radius 0 to 40 km) shown in the previous slide. The cold, low salinity water in the top 100m provides a buoyancy barrier for deep convection and a stable environment for phytoplankton growth.
Azimuthal velocity cross section of the eddy, showing deep penetration of strong currents (> 1 knot) to 1000m. The surface velocity matches the altimetric velocity well. This is encouraging, since the velocity core extends only 25 km from the center at the surface.
cold Arctic water flowing south through Davis Strait
warmer Irminger Sea water circulating in subpolar gyre

subsurface, small-scale detail (here, of temperature) is traced out by high resolution (~ 3 km) Seaglider sections to 1000m depth

mixed layer deepening southward and as winter arrives
The important global mapping of Rossby waves and their nonlinear Rossby-eddy cousins by Chelton and collaborators motivates us to follow in more detail Rossby wave dynamics in the GFD lab.

Rossby wave mode (5,1) on barotropic, polar $\beta$-plane (North Pole at center), excited at frequency $0.11f$ by plunger at lower left. $\Omega=3.5$ s$^{-1}$
Rossby wave Green’s function for an oscillatory point source
\[ \psi = \exp(-i\beta x/2\omega - i\omega t) \left( H_0^{(2)}(\beta r/2\omega) \right) \]
viewed from southwest of the ‘tweak’.
Parabolic wave crests sweep westward
Polar $\beta$-plane, oscillating Rossby wave source, no initial mean zonal flow (*video*)

The PV elasticity...the restoring effect for Rossby waves...is very scale-dependent
Altimetric SSH field, oscillatory Rossby wave source, polar $\beta$-plane

long Rossby waves propagate westward and poleward from their source

short Rossby waves appear east of the forcing region
sorry...more videos
In the lab we stress the immense influence of seafloor topography on the circulation. In the subpolar Atlantic altimetry has been combined with *in situ* drifting RAFOS floats to pinpoint the dynamics of the North Atlantic Current as it is guided through topographic fracture zones. (*Bower & Van Appen, JPO 2008*)
North Atlantic Current: a shallow upper ocean current yet its path is controlled by deep fracture zones: altimetry verified by floats

Bower & van Appen JPO 2008
Topographic control over circulation, waves and mesoscale eddies: a bowl-shaped basin divided by radial ridges into 4 basins
yet another video that you can’t see!
Subpolar ocean climate is 3-dimensional, with intense topographic control.
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  radiation of near inertial waves from quasi-geostrophic flows

  vortex/gravity wave interaction in upper ocean

- dynamics of thin, buoyant upper layers and boundary currents
The GFD lab analog suggests the value to be found with a future wide-swath altimeter: high resolution reveals features invisible with present technology. Boundary currents, deep convection sites, intricate topographically controlled circulation, mid-ocean jets, ecologically important fronts should all be visible with this new capability.

Hakkinen and Rhines are using satellite altimetry, sea-surface drifters, deep Seagliders and models to reconstruct the meridional circulation of the northern Atlantic. Many of the elements described in the previous slide from our GFD lab analogue are present in nature.

For papers and more lab images (including videos) visit www.ocean.washington.edu/research/gfd
Thanks to NASA Ocean Surface Topography Science Team funding we have been able to pursue the *real thing:* altimetrically observed ocean circulation and climate change.