

Ocean Circulation

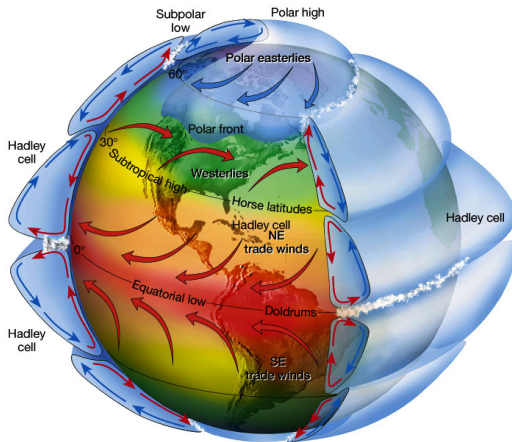
Joe LaCasce
Section for Meteorology and Oceanography

October 21, 2015

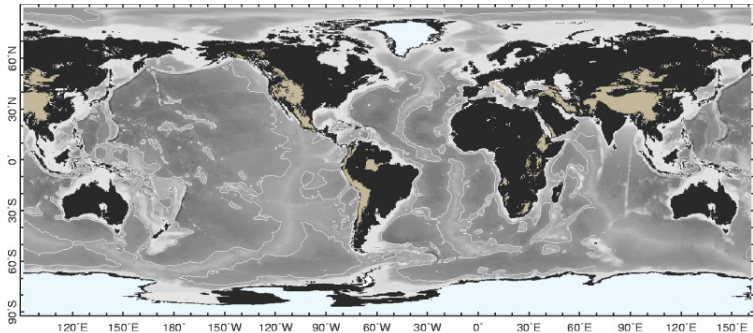
Outline

- Physical characteristics
- Observed circulation
- Geostrophic and hydrostatic balance
- Wind-driven circulation
- Buoyancy-driven circulation

Atmospheric geometry



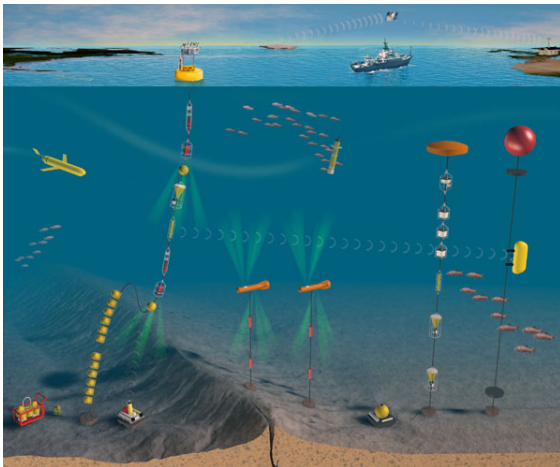
Oceanic geometry



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- Covers 71 % of the earth's surface
- Average depth is 3.7 km
- Volume is $3.2 \times 10^{17} \text{ m}^3 = 1.3 \times 10^{21} \text{ kg}$
- Heat capacity is 1000 time greater than atmosphere's
- Substantial fraction in ice sheets (Greenland, Antarctica)

Ocean observations



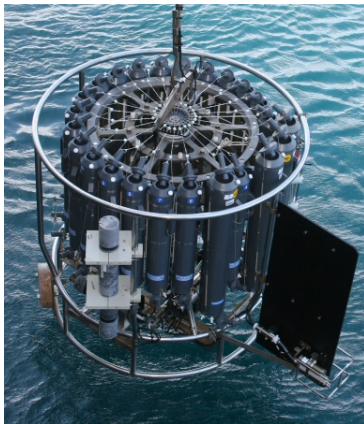
Woods Hole Oceanographic Inst.

Ships



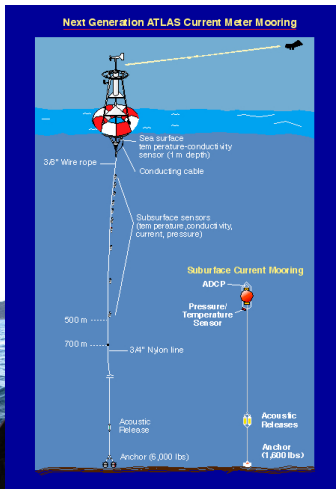
University of Washington, Scripps Inst. of Oceanography

Conductivity, temperature and depth sensor



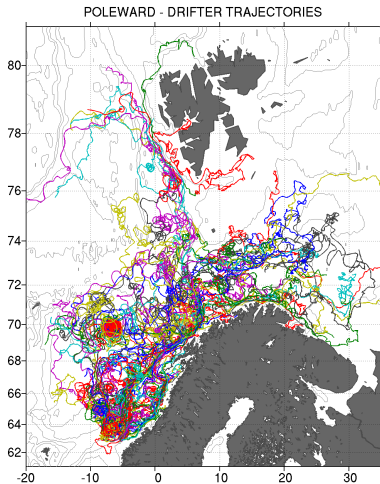
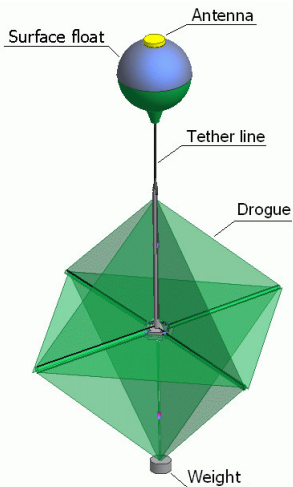
National Oceanographic Center, Southampton

Current meters

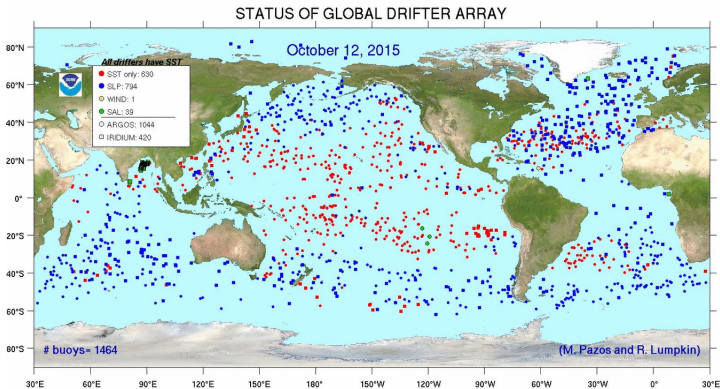


UiO and Falmouth Scientific

The surface drifter

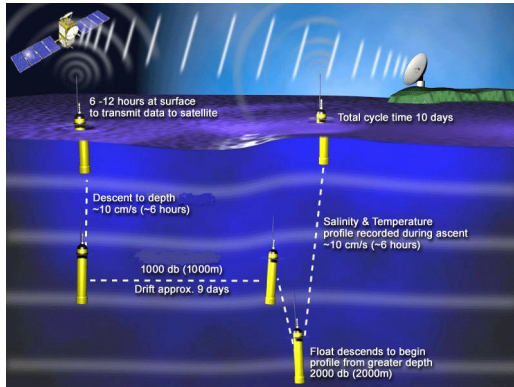


Surface drifter locations: Oct. 12, 2015



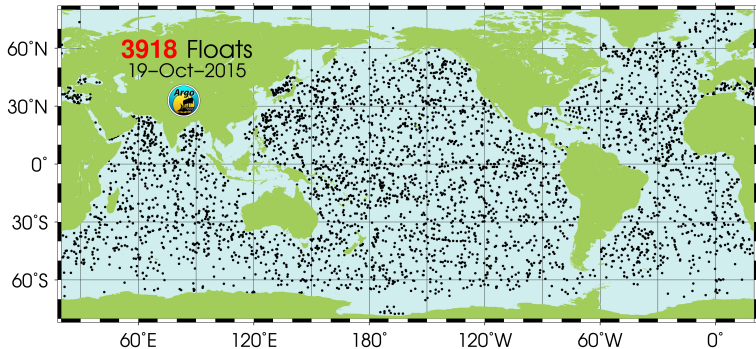
NOAA/AOML

ARGO Floats



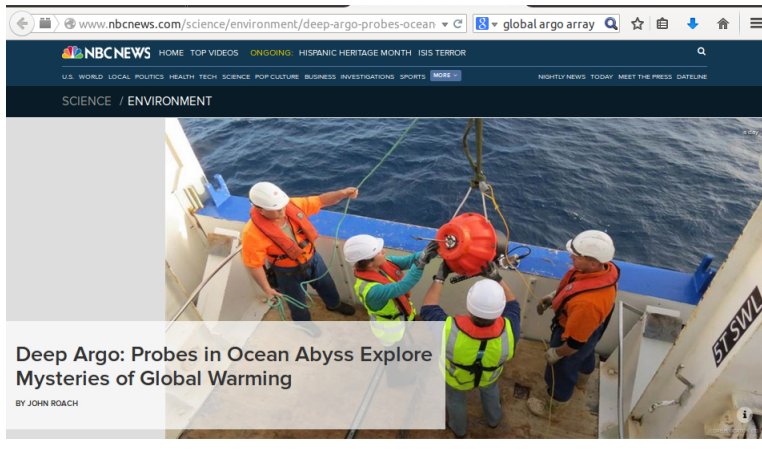
Scripps Inst. Oceanography

ARGO positions, 19 Oct. 2015



Scripps Inst. Oceanography

Deep ARGO floats



The image is a screenshot of a web browser displaying an NBC News article. The browser's address bar shows the URL www.nbcnews.com/science/environment/deep-argo-probes-ocean. The page header includes the NBC News logo and navigation links for HOME, TOP VIDEOS, ONGOING, HISpanic HERITAGE MONTH, and ISIS TERROR. Below the header, there are categories for U.S., WORLD, LOCAL, POLITICS, HEALTH, TECH, SCIENCE, POP CULTURE, BUSINESS, INVESTIGATIONS, SPORTS, and MORE. The main content area features a large photograph of four crew members on the deck of a ship, wearing orange and yellow safety gear and white hard hats, working with a large red spherical buoy. The text overlay on the image reads "Deep Argo: Probes in Ocean Abyss Explore Mysteries of Global Warming" by John Roach. The ship's hull number "57 SWL" is visible on the right side of the image.

www.nbcnews.com/science/environment/deep-argo-probes-ocean

global argo array

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SCIENCE / ENVIRONMENT

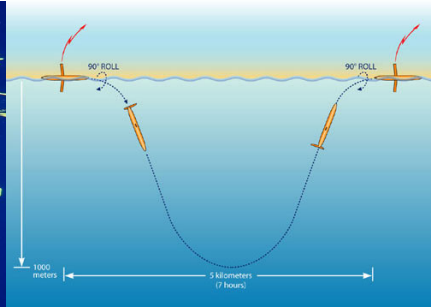
Deep Argo: Probes in Ocean Abyss Explore Mysteries of Global Warming

BY JOHN ROACH

57 SWL

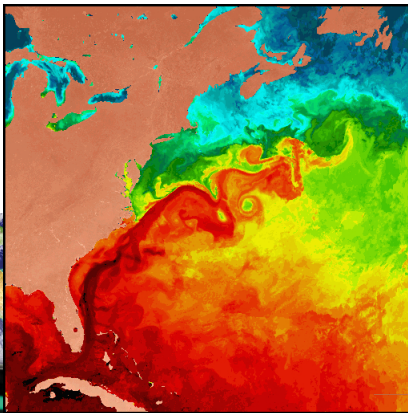
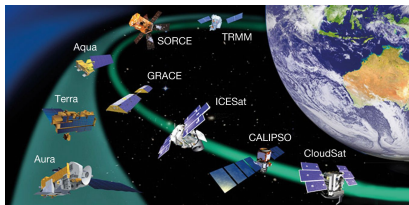
NBC News

Gliders



Webb Research Inc., Woods Hole Oceanographic Inst.

Satellites



NASA

Observations: measurements

- **Surface temperature** and **salinity** (satellite)
- **Surface height** (satellite)
- **Subsurface temperature** and **salinity** (ships, floats, gliders)
- **Subsurface velocities** (current meters, floats)

Interpreting the observations

- Temperature, salinity and pressure → density
- Sea surface height → surface velocities
- Density profiles → velocity profiles

Calculating density

Density is determined from temperature, salinity and pressure:

$$\rho = \rho(T, S, p) = \rho_c [1 - \alpha_T(T - T_{ref}) + \alpha_S(S - S_{ref}) + \dots]$$

where: $\rho_c = 1000 \text{ kg m}^{-3}$

- Warm water is lighter than cold water
- Salty water is heavier than fresh water

Seawater characteristics

Typical temperatures: 0 – 30C

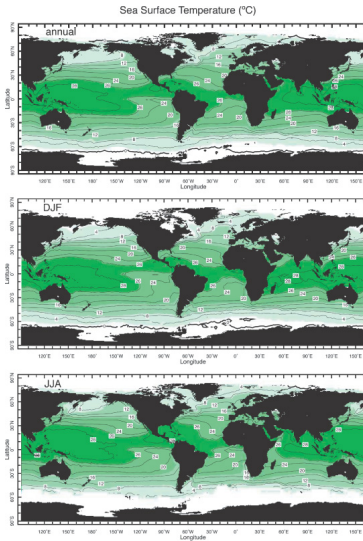
Typical salinities: 33 – 36 psu (practical salinity units)

Compare:

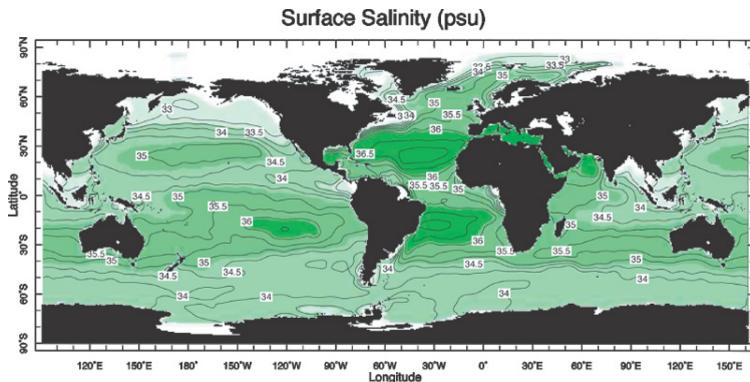
- Fresh water: 0 psu
- Dead Sea: 337 psu

→ Usually temperature dominates changes in density

Sea surface temperature (SST)

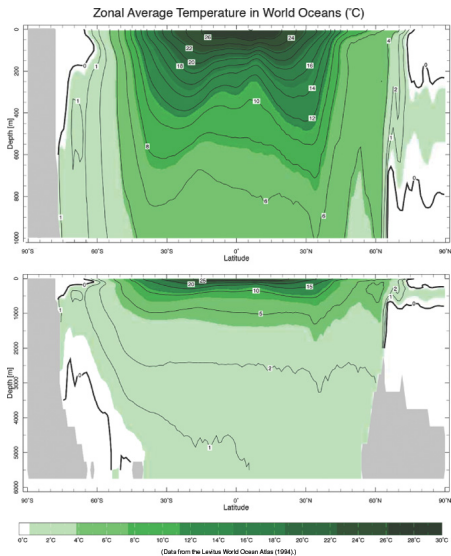


Sea surface salinity

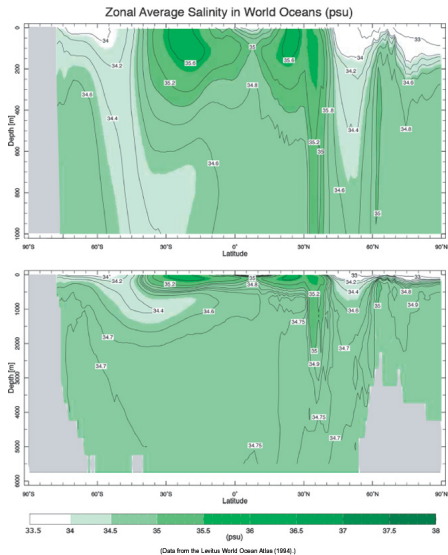


(Data from Levitus World Ocean Atlas (1994).)

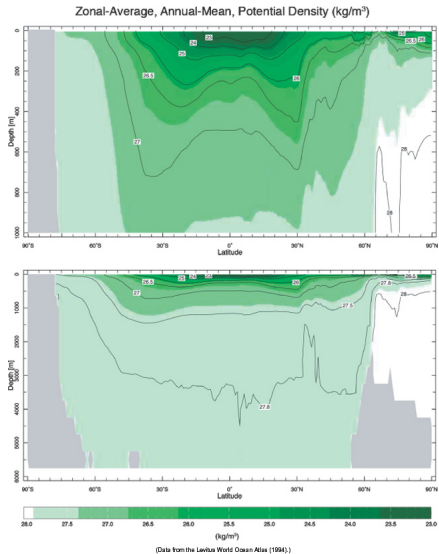
Zonally-averaged temperature vs. depth



Zonally-averaged salinity vs. depth



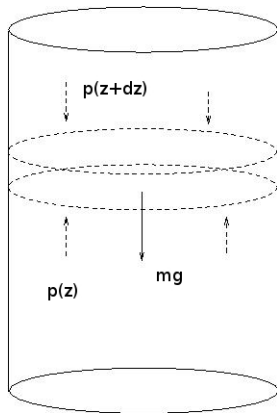
Zonally-averaged density vs. depth



Interpreting the observations

- ~~Temperature, salinity and pressure~~ → density
- Sea surface height → surface velocities
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Basic balances: hydrostatic



Basic balances: hydrostatic

Downward force: $-mg = -\rho Vg = \rho(A dz)g$

Upward force: $(p(z + dz) - p(z))A$

The fluid is static if these are equal:

$$[p(z + dz) - p(z)]A = -\rho g A dz$$

or:

$$\frac{dp}{dz} = -\rho g$$

Basic balances: geostrophy

The momentum equations can be scaled:

$$\frac{d}{dt} \vec{u} + f \hat{k} \times \vec{u} = -\frac{1}{\rho_c} \nabla p$$
$$\frac{U}{T} \quad fU \quad \frac{\Delta p}{\rho_c L}$$

Divide by fU :

$$\frac{1}{fT} \quad 1 \quad \frac{\Delta p}{\rho_c fUL}$$

The temporal Rossby number is given by:

$$\epsilon \equiv \frac{1}{fT}$$

Basic balances: geostrophy

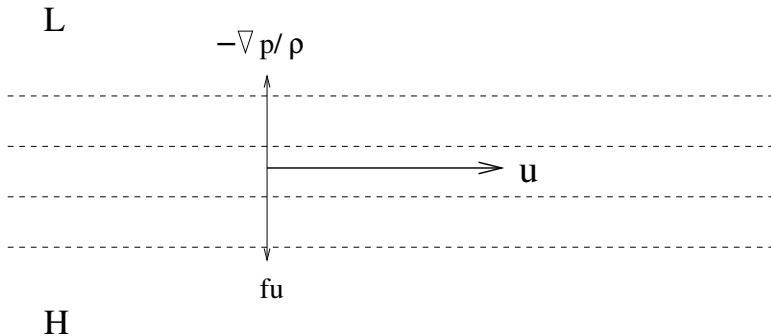
Large scale currents and eddies have a typical time scale of a week:

$$\epsilon = \frac{1}{10^{-4}(10^6)} = 0.01 \ll 1$$

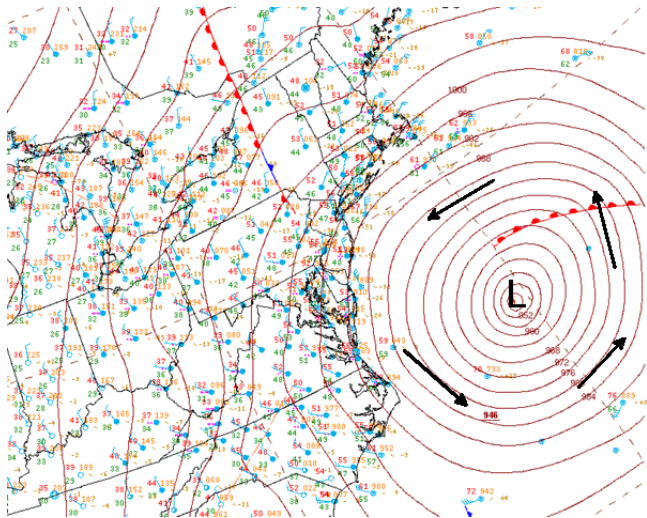
The horizontal velocities are approximately in geostrophic balance:

$$fu = -\frac{1}{\rho_c} \frac{\partial}{\partial y} p, \quad fv = \frac{1}{\rho_c} \frac{\partial}{\partial x} p$$

Basic balances: geostrophy



Hurricane Sandy



Combine geostrophic and hydrostatic balances

Integrate hydrostatic relation from z to the surface ($z = \eta$):

$$\int_{-z}^{\eta} \frac{\partial p}{\partial z} dz = p(\eta) - p(-z) = -g \int_{-z}^{\eta} \rho dz$$

The density is roughly constant and $p(\eta) = p_{atmos}$, so:

$$p(-z) = p_{atmos} + \rho_c g(\eta + z)$$

The atmospheric pressure has little effect:

$$\nabla p(-z) = \nabla p_{atmos} + \rho_c g \nabla \eta \approx \rho_c g \nabla \eta$$

Surface velocities

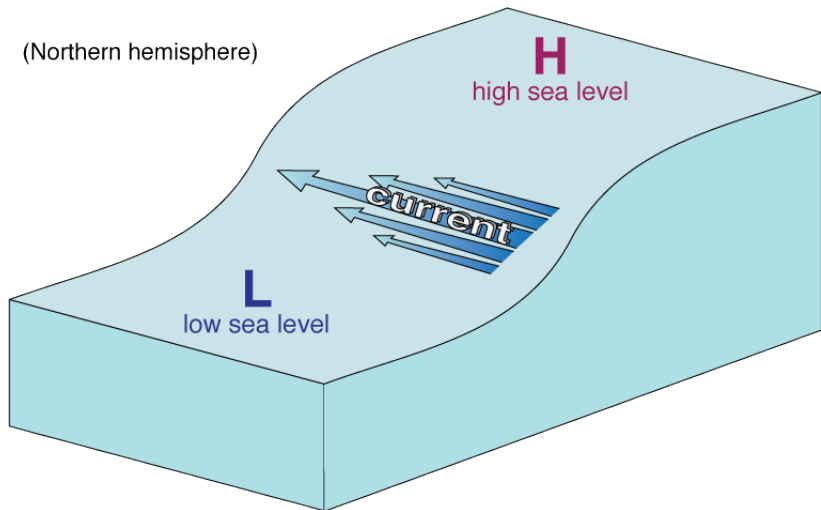
Thus the geostrophic surface velocities are:

$$u_g = -\frac{g}{f} \frac{\partial}{\partial y} \eta, \quad v_g = \frac{g}{f} \frac{\partial}{\partial x} \eta$$

This is how satellite measurements of sea surface height can be used to estimate surface velocities

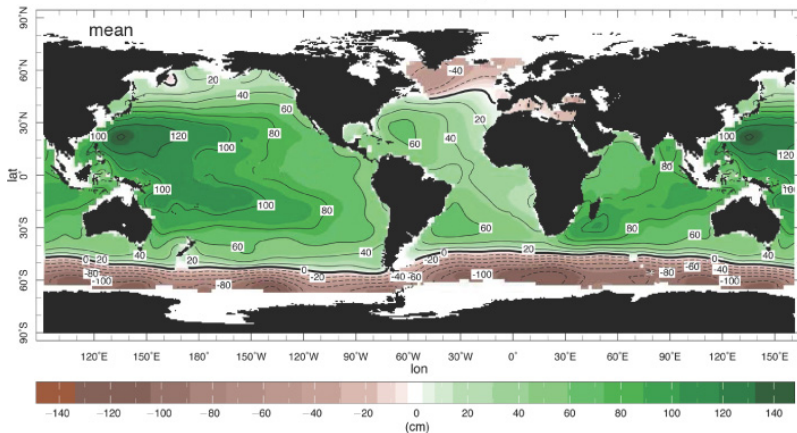
Can obtain global pictures of the surface velocity, with the same resolution as the satellite data (roughly 100 km)

Surface geostrophic flow

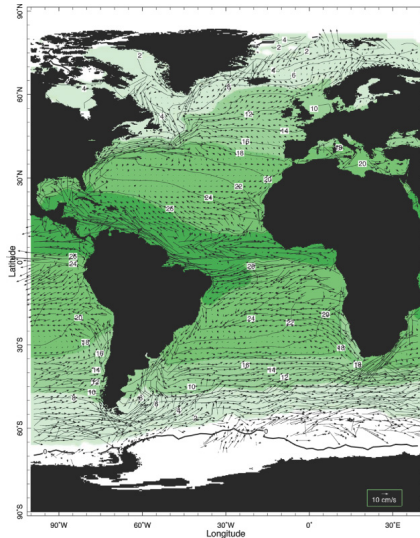


Mean sea surface height, global

Sea Surface Height

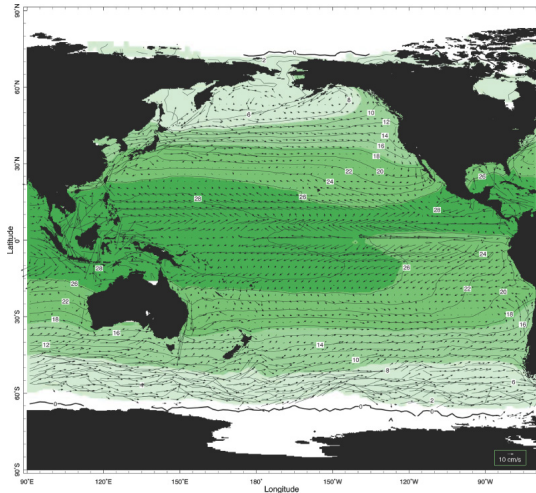


Surface velocities, Atlantic

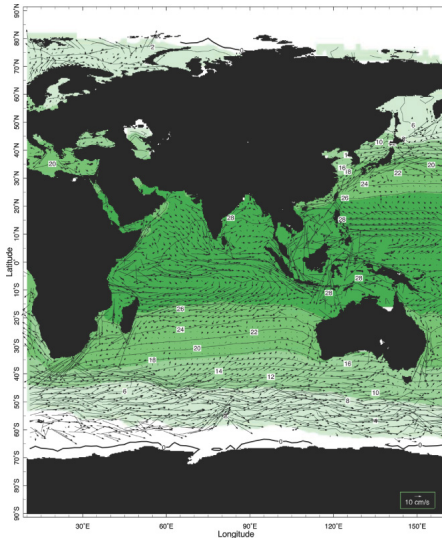


(Data courtesy of Maximeiko and Miller (personal communication, 2003).)

Surface velocities, Pacific



Surface velocities, Indian



[Data courtesy of Masmerico and Nair (personal communication, 2003).]

Interpreting the observations

- ~~Temperature, salinity and pressure~~ → density
- ~~Sea surface height~~ → surface velocities
- Density profiles → velocity profiles

Basic balances: thermal wind

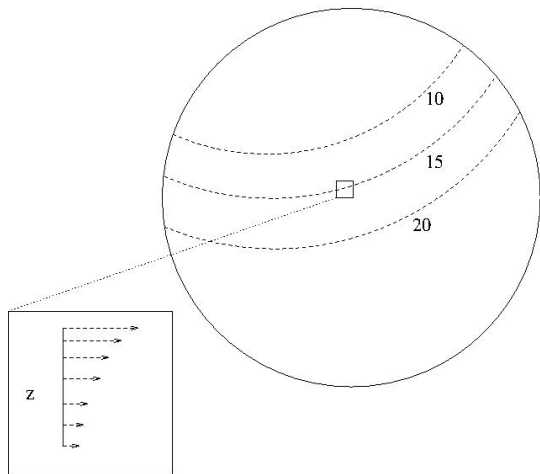
Combine the geostrophic and hydrostatic balances:

$$\begin{aligned}\frac{\partial}{\partial z} u_g &= \frac{\partial}{\partial z} \left(-\frac{1}{\rho_c f} \frac{\partial p}{\partial y} \right) \\ &= -\frac{1}{\rho_c f} \frac{\partial}{\partial y} \left(\frac{\partial p}{\partial z} \right) \\ &= -\frac{1}{\rho_c f} \frac{\partial}{\partial y} (-\rho g) \\ &= \frac{g}{\rho_c f} \frac{\partial}{\partial y} \rho\end{aligned}$$

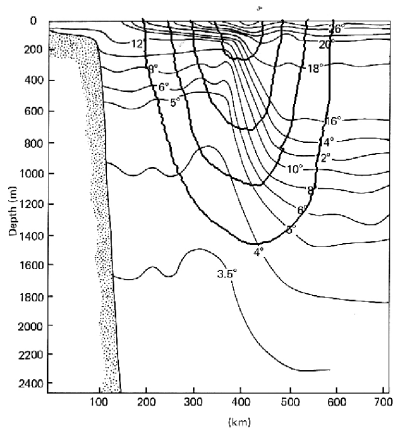
Likewise:

$$\frac{\partial}{\partial z} v_g = -\frac{g}{\rho_c f} \frac{\partial}{\partial x} \rho$$

Basic balances: thermal wind



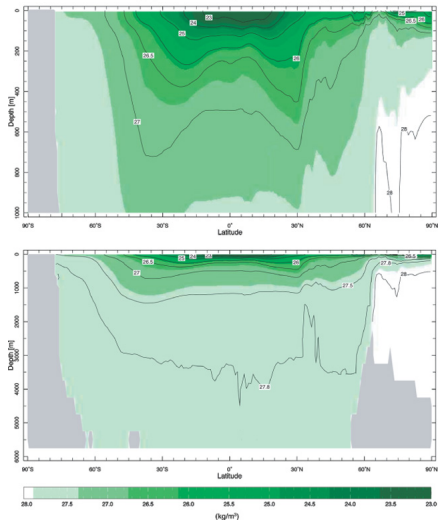
Basic balances: thermal wind



Gulf Stream velocity (dark) and temperature (thin) contours

Deducing the velocity

Zonal-Average, Annual-Mean, Potential Density (kg/m^3)



(Data from the Levitus World Ocean Atlas (1994))

Deducing the velocity

Integrate the thermal wind relation vertically:

$$\int_{-z_{ref}}^{-z} \frac{\partial}{\partial z} u_g dz = \int_{-z_{ref}}^{-z} \frac{g}{\rho_c f} \frac{\partial}{\partial y} \rho dz$$

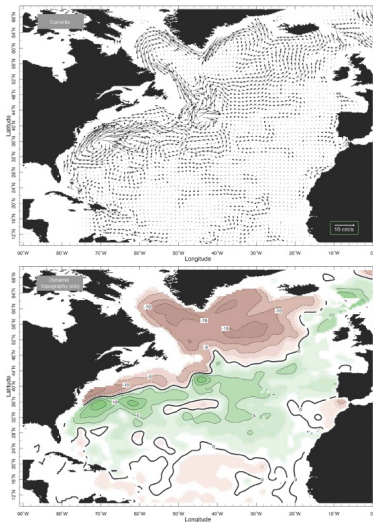
Or:

$$u_g(-z) = u_g(-z_{ref}) + \frac{g}{\rho_c f} \frac{\partial}{\partial y} \int_{-z_{ref}}^{-z} \rho dz$$

- Must specify the reference level velocity, $u_g(-z_{ref})$

Subsurface velocity

Currents And Pressure at 700m in The Atlantic



[Data courtesy of Steve Jayne, WHOI]

Basic balances: incompressibility

The full continuity equation is:

$$\frac{\partial}{\partial t}\rho + \vec{u} \cdot \nabla\rho + \rho(\nabla \cdot \vec{u}) = 0$$

In the ocean, $\rho \approx \rho_c = \text{const.}$ So:

$$\nabla \cdot \vec{u} = \frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v + \frac{\partial}{\partial z}w = 0$$

Ocean velocities are approximately incompressible

Basic balances: incompressibility

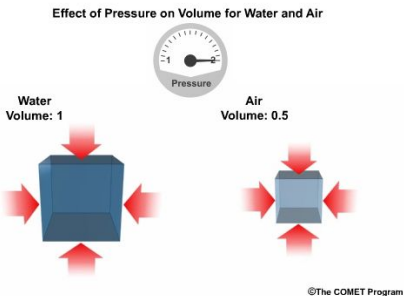
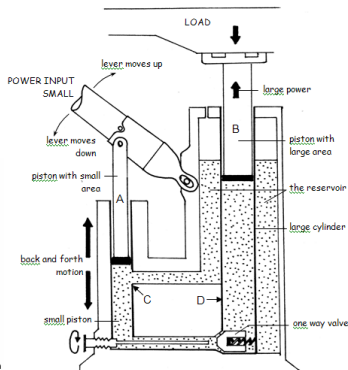


Figure 2: This is a cross-section of a simple hydraulic jack.



Basic balances: summary

- Hydrostatic balance

$$\frac{\partial p}{\partial z} = -\rho g$$

- Geostrophic balance

$$fu = -\frac{1}{\rho} \frac{\partial p}{\partial y}, \quad fv = \frac{1}{\rho} \frac{\partial p}{\partial x}$$

- Incompressibility

$$\nabla \cdot \vec{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$