

# Introduction to physical oceanography and climate

EPS 131 (Spring 2008)



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**Matlab Intro Session:** Thursday Feb 7th 9-10am, location: Geo Mus 103C

**Section:** Mondays 4-5pm (starting Feb 11), location: Geo. Museum room 418.

**Day, time:** Monday, Thursday, 2:30-4.

**Location:** University Museum (24 Oxford St), first floor, room 105 (Daly Seminar Rm)

## Announcements

Last updated: May 7, 2008

The final course time will be determined during the first two weeks of classes, to minimize conflicts with other courses for interested students

Feel free to write or call me with any questions:  
Eli Tziperman; eli AT eps.harvard.edu  
Office hours: call/ write.

Field trip to the Woods Hole Oceanographic Institution (WHOI): March 13 2008; We'll be leaving Cambridge very early in the morning, back in the late afternoon. Our Host will be Dr. Bob Pickart; last time we visited to the [R/V Atlantis](#) and the submersible [Alvin](#), plus toured the labs of WHOI; [photos](#);

**Homework:**

**Homework solutions:**

**What's the point of optional/ extra credit challenge problems: apart from the fun of doing them, they will count against homework problems in the same HW in which you may have missed an answer. . .**

## 1 Textbooks

Main ones:

- **(Kn)** J. A. Knauss, introduction to physical oceanography, 2nd edition, 1996, Prentice Hall, Upper Saddle River, New Jersey.

Also interesting:

- **(St)** Robert H. Stewart, on-line physical oceanography [book](#)
- On-line version of '[Regional oceanography](#)'
- **(OU)** The open university team, ocean circulation, 2nd ed, 2002.
- **(OU-W)** The open university team, waves, tides and shallow water processes, 2nd ed, 2002.
- **(Ku)** Kundo P.K. and Cohen I.M., Fluid mechanics. 2nd edition 2002.

## 2 Outline

This course will cover observations and the understanding of ocean phenomena from local surface beach waves to the effects of the oceans on global climate. We will discuss ocean waves, the Coriolis force and ocean currents, the large scale temperature and salinity distributions and more. As part of the ocean's role in climate we will cover the wind-driven circulation and the Gulf stream, the thermohaline circulation and the potential instability of Europe's climate due to global warming, El Nino events in the equatorial Pacific ocean, and more. The basic fluid dynamics equations will be gradually introduced. A field trip to the Woods Hole Oceanographic Institution on Cape Code will be held during the course, which will be an opportunity to learn about practical aspects of sea-going oceanography as well.

The students will be introduced to the Matlab software for scientific computation and graphics, which will be used for some of the homework assignments.

Prerequisite: Mathematics/ Applied Mathematics 21, Physics 11/ 15, or equivalents, or permission of instructor.

### 3 Detailed syllabus (under construction)

#### 1. Outline and motivation

[lecture 1](#)

#### 2. Temperature and salinity

[downloads](#); Background reading: **Kn** Chapters 1, 3, and pp 163-179 from chapter 8.

- (a) Overview of temperature and salinity fields
- (b) *Background*: heat budget of the ocean, (**St** chapter 5.2), geographical distribution of the fluxes (5.6) and meridional fluxes (5.7); similarly for evaporation and precipitation (5.8);
- (c) *Motivation*: will sea level rise due to global warming? Why (thermal expansion vs melting)? By how much? *Analysis*: heat penetration into the ocean, sea level rise due to thermal expansion of sea water. Equation of state, linear equation of state with alpha and beta expansion coefficients. [notes](#).
- (d) *Observation*: ocean is composed of different “water masses” that are formed at small areas and can be tracked throughout the ocean. (Temperature and salinity from GEOSECS sections and water masses). *Analysis*: T-S diagrams and mixing of two and three water masses (**OU** p 225-229); T, S geographic distributions (**Kn** p 163-183); How have these water masses and deep water formation changed in past periods (last glacial maximum)? How might they change in the future? Or are they already changing?
- (e) *Motivation*: Why is the deep ocean so cold? what’s setting the vertical temperature profile? *Observation*: GEOSECS/WOCE sections and a typical exponential temperature profile. *Explanation*: the overturning ocean circulation, upwelling and vertical mixing, “abyssal recipes”, [notes](#).

#### 3. Horizontal circulation I: currents, Coriolis force

[downloads](#); Background reading: **OU** section 3.3, pages 46-63;

- (a) *Motivation*: can the wind-driven Gulf Stream switch off because of global warming? During an ice age? Was Benjamin Franklin just lucky when he discovered the Gulf Stream right after the little ice age? *Phenomenology*: the Hadley and Ferrell cells, surface winds, wind driven ocean circulation, western boundary currents, abyssal ocean circulation.
- (b) Introduction to the momentum equations,  $F=ma$  for fluids: density\*acceleration = pressure gradient force + Coriolis force + friction + gravity + wind forcing;
- (c) *Geostrophy and related observations*: wind around highs and lows on the weather map, currents around the subtropical high in the North Atlantic. *Explanation*: pressure force, Coriolis force (qualitatively, movies), steady state, geostrophy.
- (d) *Motivation*: how do we monitor the ocean circulation to observe early signs of thermohaline collapse? *Analysis*: Sea level variations due to ocean currents, and altimeter satellite observations; Temperature/ density section across the Gulf Stream; how to calculate ocean currents from observations: thermal wind balance, level of no motion, competing effects of sea level and density gradients on pressure gradient across the Gulf Stream. Geostrophic calculation of “dynamic height” or “dynamic topography” of sea level. Geoid and mean sea level (wrong schematic plots by geophysicists who ignore oceanographic sea level signal). Alternative to level of no motion: closing the mass/ heat/ salt balance to find the circulation, inverse methods. Western

boundary current measurements. The RAPID observing system in the North Atlantic ocean, <http://www.soc.soton.ac.uk/rapid/rapid.php>.

#### 4. Waves and oscillations I: basics

[downloads](#); Background reading: Inertial motions: **Kn** p 108-109; **OU-W**: section 3.2, pages 44-46; surface water waves, shallow and deep: **Kn** chapter 9, pages 192-217, skip box 9.1. **OU-W**: pages 11-49; buoyancy oscillations: **Kn** p 29-34, 38;

- (a) Inertial motions: *Observation*: circular water motion at the inertial period after a passing storm. *Explanation*: Coriolis force, inertial oscillations (**Kn** p 108-109), equations and circular trajectories of fluid parcels. [notes](#).
- (b) Beach waves/ Tsunamis: *Observations*: why do wave crests always arrive parallel to the beach? Why do Tsunamis propagate so fast across the ocean? *Explanation*: Wave basics: wave amplitude/ length/ number (scalar and vector)/ period/ frequency. Shallow water waves in 1 dimension (scaling arguments for period, 1d shallow water mass conservation, momentum balance, wave equation, solution). [notes](#). Scaling argument for dispersion relation of 1d deep water waves. [notes](#). More wave basics: phase speed/ group speed.
- (c) Why is the dispersion relation called that; shallow, deep and finite depth dispersion relations; deriving the shallow and deep limits from the finite depth formula; show all three together; an actual sea surface is made of many wavelength propagating at different speeds, show Knaus picture of sea level with a random wave field; why do waves arrive parallel to the beach, refraction; particle trajectories of deep waves, near the surface and deeper; stokes drift;  $C_{ph}$  in 2d, phase velocity is not a vector.
- (d) Internal waves: *Observation*: “dead water” phenomenon of ships trapped in closed lagoons; *Explanation*: The vertical ocean stratification, Brunt Vaisala frequency (**Kn** p 29-34, 38) buoyancy oscillations, internal waves in one horizontal dimension.

#### 5. Sea-going physical oceanography

Finally, the real stuff. Two lectures by [Dr. Bob Pickart](#) from the [Woods Hole Oceanographic Institution](#), and a field trip to Woods Hole.

#### 6. Friction moving icebergs and feeding the fish

[downloads](#);

Background reading: **OU** pages 39-44; **Ku** pages 122-128;

- (a) *Background*: things never go smoothly in the ocean... friction between a channel flow and a suspended ball; molecular Brownian motion in a laminar flow vs eddy mixing and viscosity; Reynolds number and turbulence,  $Re_{\#}$  for the ocean, turbulence, bottom and internal friction, dissipation of energy; ([stirring animation](#) from [here](#)). Horizontal vs vertical eddy motions and eddy viscosity in the ocean (**Kn** p 97-99, Fig 5.9);
- (b) *friction and Coriolis*: *Observation/ motivation*: icebergs do not move with the wind direction (Ekman 1905). Nor does the ocean water itself: coastal upwelling, nutrient supply to fish, collapse of Ecuador’s fisheries during El Nino events. Coastal upwelling; upwelling, nutrients, fisheries and El Nino (**OU** p 133-137, 153-155);
- (c) Non scale-selective friction and Coriolis, damped inertial oscillations: Bottom friction parameterization (**Kn** p 96-97); damped inertial oscillations (**Kn** p 120);

- (d) Scale-selective friction, how the wind drives the ocean circulation: deriving the expression for vertical viscosity and horizontal viscosity. *Solution of Ekman's puzzle*: combined effects of vertical friction, wind and rotation: shear stress (**Kn** p 100), wind speed and wind stress, balance of friction and rotation in mixed layer, Ekman transport (**Kn** p 122-123); shallow Ekman cells.
- (e) Ekman pumping: 3d continuity equation; integrating it over the mixed layer and using the expression for the Ekman transport to derive Ekman pumping as the curl of tau (**Kn** p 125-128); curl tau from observations; North Atlantic subtropical and sub polar gyres.
- (f) Ekman spiral (**Kn** p 124);
- (g) Why is it called scale-selective friction vs non scale-selective friction? On the selective destruction of small scales by viscosity.

## 7. The thermohaline circulation

[downloads](#); Background reading: **OU** section 6.6, pages 240-249.

- *Motivation*: The day after tomorrow... Can the ocean thermohaline circulation collapse due to global warming?
- *Background*: thermohaline circulation, thermohaline circulation phenomenology, mean state, present-day variability; different atmospheric response and surface boundary conditions for Temperature and salinity; driving by T, breaking by S; Solar radiation and long wave radiation, earth energy balance, ocean vs land heat capacity, air-sea heat flux components and geographic distribution, meridional ocean heat flux (**Kn** p 39-61; on-line figures from **St** sections 5.1,5.2,5.4,5.6,5.7 and two heat-flux images from supporting material directory).
- *Analysis*: the Stommel box model, multiple equilibria and catastrophes, saddle node bifurcation and hysteresis.
- *Perspective*: Stommel box model vs GCM inter-comparison; THC and tidal mixing, mixing estimates from tracer release experiments.

## 8. Horizontal circulation II: Gulf Stream and other western boundary currents

[downloads](#);

Background reading: **OU** sections 4.1-4.3, pages 79-133; **Kn** p 128-131; **Kn** p 131-133;

- (a) Preparation, vorticity: definition, two examples: (i) solid body rotation:  $v(\text{rotation})=ar$  and  $f$  as a “planetary vorticity”; (ii) irrotational vortex:  $v(\text{rotation})=a/r$  (**Ku** p 125, use the table of curl operator in cylindrical coordinates from the downloads directory); Coriolis parameter as the planetary vorticity.
- (b) Effects of changes in Coriolis force and the general ocean circulation: beta plane,  $f=f(y)$ ,  $\beta=df/dy$ ;
- (c) Momentum and vorticity equations for a simple linear, shallow water/ barotropic, time dependent, bottom friction, rotating case (**Kn** p 128-131):

$$\begin{aligned}\frac{\partial u}{\partial t} - fv &= \frac{-1}{\rho} \frac{\partial p}{\partial x} - ru + \tau^{(x)} \\ \frac{\partial v}{\partial t} + fu &= \frac{-1}{\rho} \frac{\partial p}{\partial y} - rv + \tau^{(y)} \\ \frac{\partial \zeta}{\partial t} + \beta v &= -r\zeta + \text{curl}\tau\end{aligned}$$

- (d) Approximate of vorticity equation in ocean interior: Sverdrup balance:  $\beta V = \text{curl } \tau$ . Why a boundary current is required to close the mass balance.
- (e) Vorticity balance in boundary current:  $\beta v = -r \, dv/dx$ . Heuristic explanation of why this requires that the boundary current is in the west. (**Kn** p 131-133; **OU**, p 85-98).

## 9. El Nino

[downloads](#) Background reading: **OU** section 5.4, pages 170-176;  
[powerpoint lecture](#)

## 10. Abrupt climate change

[downloads](#); Background reading: **XX**

Can climate change rapidly when CO<sub>2</sub> increases slowly? What can we learn from past climates?

- (a) paleo climate perspective: introduction to paleo climate variability, proxies, ice cores and sediment cores; THC during LGM, possible variability during Heinrich and D/O events;
- (b) dynamical explanations for the dramatic past climate phenomenology: advective instability feedback; THC flushes;

## 11. Some fluid dynamics fundamentals

[downloads](#); Background reading: **XX**

- (a) *Basics, Kinematics*: Continuum hypothesis, pressure, hydrostatics (**Ku** 1.4-1.5, p 4; 1.7 p 9-11). Kinematics: Eulerian vs Lagrangian, material derivative (**Ku** 3.1-3.3 p 50-53). Continuity equation (mass conservation, **Kn**, Box 4.1 p 69), incompressible fluids. Stream line **Ku** 3.4, p 53-56), stream function (**Ku** 3.13, p 69-70). Temperature and salinity equations (conservation of heat and salt, **Kn**, end of Box 4.1 p 70-71 and Box 4.2 p 74-75),
- (b) *Momentum equations*: acceleration, pressure force, gravity, friction, Coriolis force, Navier Stokes equations. wind stress (**Kn**, chapter 5, p 80-107; for Coriolis, a better source is **Ku** section 4.12 p 99-101); equation of state.  
*Ocean/ Atmosphere*: The Boussinesq approximation (**Ku** 4.18, p 117-119); scaling of continuity equation, smallness of vertical velocity, and the hydrostatic balance as an approximation to the z-momentum equation. Primitive equations. Scaling of momentum equations, Rossby number  $R=U/(fL)$ , and Ekman number  $E=v/(f^*L^2)$ ; both are small for large-scale ocean flows, and derivation of geostrophy (**Kn** p 110).

## 12. Waves and oscillations II: deep ocean waves and waves affected by the Coriolis force

[downloads](#); Background reading: **Kn** box 9.1 and chapter 9 (again).

- (a) Surface ocean waves: (1) Qualitative phenomenology: typical periods/ wave lengths of ocean surface waves; particle trajectories (in deep, finite and shallow water); scaling arguments for dispersion relation in deep/ shallow water; refraction when approaching a curved beach; dispersive (deep) and non-dispersive (shallow) waver waves; mechanism of breaking waves; (2) Math (**Kn** 192-198): vector vorticity, irrotational flow (vorticity=0, velocity=gradient of potential); Bernoulli function and boundary conditions on velocity potential; wave solution in 2d (x,z) (**Kn** p201, Table 9.1) and dispersion relation; particle trajectories; phase and group velocities (**Kn** 201-204); qualitatively again: phase and group velocity in 2d, phase velocity is not a vector and its components in (x,y) directions. Math again: phase shallow water waves: shallow water momentum and continuity equations, wave solution, dispersion relation; Tsunamis as shallow water waves, waves refraction when approaching a curved beach.

- (b) Other waves: Poincare (inertial-gravity) waves, coastal and equatorial Kelvin waves, Rossby waves and a heuristic explanation of westward propagation. Stratification, reduced gravity and internal waves.
13. **Misc Advanced topics** (time permitting); Background reading: XX; Water masses and vertical stability: nonlinearity of eqn of state: sigma theta inversion for AABW (**Kn** p 38 fig 2.9), cabbeling. Density, sigma-t, potential temperature, potential density, sigma-theta, sigma-4 (**OU** p 230-232); static stability;

## 4 Additional reading

Beginning texts:

- G. L. Pickard and W. J. Emery, Descriptive Physical Oceanography - An Introduction, Butterworth Heinemann, 1990,
- Stephen Pond and George L. Pickard, Introductory dynamical Oceanography, 3rd edition, Butterworth-Heinemann, 1993,

Intermediate texts:

- Philander, S. G. H., El Niño, La Niña, and the Southern Oscillation., Academic Press, 1990,
- Benoit Cushman-Roisin, Introduction to geophysical fluid dynamics, Prentice-Hall, 1995,

Advanced texts:

- Pedlosky, J., 1987, Geophysical Fluid Dynamics., 2nd edition, Springer-Verlag
- Pedlosky, J., 1996, ocean circulation theory, Springer-Verlag, Berlin-Heidelberg-New York.
- Pedlosky, J., 2003, waves in the ocean and atmosphere., Springer-Verlag, Berlin-Heidelberg-New York.
- Gill, A. E, 1982, Atmosphere–ocean dynamics, Academic Press, London

## 5 Requirements

Homework will be given throughout the course. The best 80% of the homework will constitute 40% of the final grade. Each student will be invited to present a brief informal description of some aspects of the ocean circulation and its role in climate (20%), see details [here](#) for a list of possible subjects. The final exam will be a take home (40%).

## 6 Links

- This course was previously taught by [Prof Allan Robinson](#)
- Coriolis force movies: [here](#) and [here](#);

- [Greenpeace bottom trawling](#); [Greenpeace “save our seas”](#); and [videos](#).
- Shifting baselines: [“pristine”](#);
- Three dimensional bottom topographies for any lon/lat coordinates: [here](#).
- Recipe for internal ocean waves in a bottle: [here](#) (basically blue food coloring in water filling 3/4 of a bottle, and the rest filled with oil).