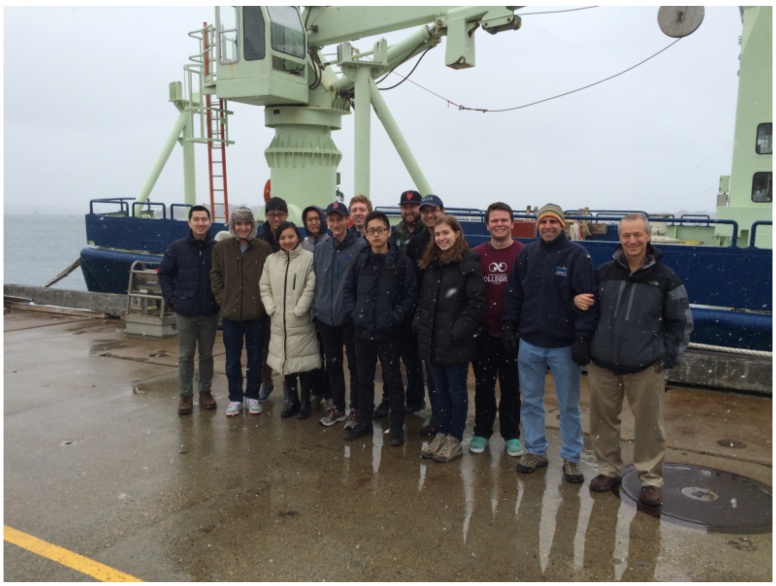
Introduction to Physical Oceanography and Climate

Spring 2016

FAS course web page for EPS 131



Field trip to Woods Hole oceanographic institution, spring 2016.

Instructor: Eli Tziperman, office hours: please see FAS course web page.

TF: Chris Horvat, horvat@fas.harvard.edu. Tel, office, office Hours: please see FAS course web page.

Day, time: Tuesday, Thursday, 1:00-2:30.

Location: University Museum, 24 Oxford St, first floor, room 105 Daly Seminar Room

Field Trip! To Woods Hole Oceanographic Institution, March 4, 2016. Departing early morning, returning around 6pm.

Matlab Intro Session: Matlab will be used occasionally for HW assignments and class demonstrations. If you have not been exposed to Matlab or would like a refresher, we recommend that you consider attending the *Matlab boot camp* which involves 3-4 lectures and takes place during the beginning of the term. If interested, you need to register in advance at https://canvas.harvard.edu/courses/1858 and the number of students may be limited.

Section: time and location: see FAS course web page.

Source materials: are available here. In order to access notes and other course materials from outside the Harvard campus or from the Harvard wireless network, you'll need to use the VPN software which can be downloaded from the FAS software download site.

Important past events. . . :

- Field trips to the Woods Hole Oceanographic Institution: 2005, 2008, 2010, 2012, 2014, 2016.
- EPS 131 Oscar events: 2005: surface waves; 2008: internal waves; 2010: great Pacific garbage patch; 2012: thermohaline circulation; 2014: surface waves; 2016: brine rejection;
- zeta vs xi (ζ vs ξ) competition: 2008, 2010, 2012, 2014, 2016.

Contents

Announcements
Last updated: January 28, 2017
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.

(Obligatory & fun) field trip to the Woods Hole Oceanographic Institution (WHOI): date TBA, 2016. We'll be leaving Cambridge very early in the morning, back in the late afternoon. Our Host will be Dr. Bob Pickart; in previous trips we visited the R/V Atlantis, R/V Knorr, the submersible Alvin, and toured the labs of WHOI; photos;

1 Textbooks

Main ones, although it wont be followed very closely:

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

Also useful: see additional readings below.

2 Outline

Observations and understanding of ocean physics, from local beach waves to the effects of the oceans on global climate. Topics covered include wave motions such as ocean surface waves, internal waves, tsunamis and tides; currents, including the wind driven circulation, and the Gulf stream; coastal upwelling and fisheries; temperature, salinity, the overturning thermohaline circulation and its effect on global climate stability and variability; the basic fluid dynamics equations will be gradually introduced; El Nio evens in the equatorial Pacific Ocean; the oceans and global warming; Ocean observations by ships, satellites, moorings, floats and more.

A field trip to the Woods Hole Oceanographic Institution on Cape Cod will be held during the course, which will be an opportunity to learn about sea-going oceanography.

Prerequisite: Applied Mathematics 21a,b; Physical Sciences 12a,b, Physics 15a,b,c or Applied Physics 50a,b; or equivalents/ permission of instructor.

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

3 Syllabus

Detailed lecture notes, directory with all source materials for the lectures.

1. **Outline and motivation**
   MICOM ocean model animations and lecture 1

2. **Temperature and salinity**
   downloads;

   Background reading: **Kn** Chapters 1, 3, and pp 163-179 from chapter 8.

   (a) *Globally-averaged temperature:* how come ocean is not frozen? Calculating the expected averaged temperature given the solar radiation, the greenhouse effect keeping us warm. notes.

   (b) *Global warming:* will sea level rise? Why? (thermal expansion vs land-ice melting, what about sea ice melting; arctic animations) 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 thermal expansion coefficient. notes.

   (c) *North-south and vertical temperature profiles:* GEOSECS/WOCE latitude-depth temperature sections and a typical vertical exponential temperature profile. *Motivation:* Why is the deep ocean so cold? What's setting the vertical temperature profile? *Explanation:* meridional insolation gradient, tropical ocean is warmer, equator-to-pole meridional surface temperature gradient, implied convection and overturning ocean circulation. Back to deep ocean vertical temperature profile, upwelling and vertical mixing, "abyssal recipes", notes.

   (d) *Salinity:* consider meridional temperature section from GEOSECS again, why is the coldest water not always at the bottom?! *Observation:* ocean is composed of different "water masses" characterized by temperature *and* salinity, formed at small areas and can be tracked throughout the ocean. (Temperature and salinity from GEOSECS sections and water masses). *Explanation:* evaporation/ precipitation and salinity, equation of state including both T,S.

   (e) *Analysis of water masses:* 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?

   (f) Stability and σ_θ vs σ_4: show both as contour plots as function of T and S, demonstrate how stratification seems unstable on σ_θ but is clearly stable when plotted using σ_4. This is due to the pressure nonlinearity of equation of state.

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: *horizontal momentum budget: 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) Geostrophy, weather map atmospheric example: notes on course web page.

(e) Hydrostatic equation: Vertical momentum balance

(f) Boussinesq approximation: dynamics density and pressure.

(g) Sea level variations and ocean currents: altimeter satellite observations; Temperature/ density section across the Gulf Stream and apparent contradiction between gulf stream direction and observed stratification;

(h) Competing effects of sea level and density gradients: pressure gradient across the Gulf Stream. Qualitative discussion and then specific example of geostrophy in stratified fluid, barotropic vs baroclinic, level of no motion.

(i) Thermal wind balance: how to calculate ocean currents from observations, how to monitor the ocean circulation to observe early signs of thermohaline collapse?:

(j) Stream function: geostrophic pressure as a stream function.

(k) (Time permitting) 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, rapid homepage.

(l) Geostrophy, stratified ocean example: see notes.

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) Wave basics and shallow water waves (beach waves/ Tsunamis): *Observations:* why do wave crests always arrive parallel to the beach? Why do Tsunamis propagate so fast across the ocean? 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) Deep water surface gravity waves/ scaling: 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; phase velocity in 2d, phase velocity is not a vector.

(d) Buoyancy oscillations: (using notes from course web page)

(e) Internal waves: *Observation:* temperature signal of internal waves, surface signal, "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. notes.

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, Ekman** 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) Damped inertial oscillations: Non scale-selective friction and Coriolis, Bottom friction parameterization (**Kn** p 96-97); damped inertial oscillations (**Kn** p 120);

(c) Ekman transport and coastal upwelling: Coriolis and vertical friction, 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); Vertical frictional stress in the ocean and Ekman transport as function of wind stress, first in terms of the frictional stress tau without relating the stress to the velocities (see notes, also **Kn** p 122-123). Coastal upwelling. Shallow Ekman cells from a 3d numerical model solution.

(d) Scale-selective friction: how the wind drives the ocean circulation: deriving the expression for vertical viscosity and horizontal viscosity. Why is it called scale-selective friction vs non scale-selective friction? On the selective destruction of small scales by viscosity.

(e) Ekman spiral: 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, *Observation/ motivation:* icebergs do not move with the wind direction (Ekman 1905). Nor does the ocean water itself: Ekman spiral (notes, or **Kn** p 124);

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 depends on upwelling occurring throughout the ocean. That, in turn depends on mixing (abyssal recipes). Mixing seems to actually be lower than one expects, see estimates from tracer release experiments. Sources of mixing are also interesting, see in particular tidal-induced mixing.

8. **Horizontal circulation II: Gulf Stream and other western boundary currents, vorticity, Rossby waves**
   downloads;
   Background reading: **OU** sections 4.1-4.3, pages 79-133; **Kn** p 128-131; **Kn** p 131-133;

(a) Preparation, vorticity: definition, examples: (i) solid body rotation: $v(\text{rotation}) = \omega r$ and f as a "planetary vorticity"; (ii) irrotational vortex: $v(rotation) = \omega/r$ (**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) 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, follow equations in Box 6.2); show curl tau from observations; mention relation to North Atlantic subtropical and sub polar gyres.

(d) Momentum and vorticity equations for a simple linear, shallow water/ barotropic, time dependent, bottom friction, rotating case (**Kn** p 128-131)

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

(e) Simplest balance: time rate of change and friction: decay of vortices.

(f) Approximate of vorticity equation in ocean interior: Sverdrup balance: $\beta V = curl\tau$.

(g) Sub tropical and sub polar gyres. Given a wind stress

$$\tau = (\tau^{(x)}, \tau^{(y)}) = (\tau_0 \cos(4\theta), 0)$$

the curl is $-\partial_y \tau^{(x)} = -4\tau_0 \sin(4\theta)$, giving in the range of $20N < \theta < 70N$ a subpolar gyre and a subtropical gyre.

(h) A boundary current is required to close the mass balance.

(i) Vorticity balance in boundary current: $\beta v = -rv_x$. Heuristic explanation of why this requires that the boundary current is in the west. (**Kn** p 131-133; **OU**, p 85-98).

(j) Rossby waves in a shallow water ocean from vorticity equation plus geostrophy. First two heuristic explanations for Rossby waves. Then using $\zeta_t + \beta v = 0$ and $-f_0 v = -g\eta_x$, $f_0 u = -g\eta_y$ to find $\partial_t(\eta_{xx} + \eta_{yy}) + \beta\eta_x = 0$, looking for a wave solution $\eta = \eta_0 \cos(kx + ly - \omega t)$ to find $\omega = -\beta k/(k^2 + l^2)$.

(k) As a summary, show the vorticity balance slide.

9. **El Nino**
downloads; Background reading: **OU** section 5.4, pages 170-176.

(a) Introductory presentation
(b) Reminder: coastal Kelvin waves
(c) Equatorial Kelvin waves
(d) Reminder: Rossby waves
(e) Slide with delayed oscillator mechanism

10. **Abrupt climate change**
downloads; Background reading: Alley et al (2003);
Can climate change rapidly when CO_2 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;

    (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 $E = \nu/(fL^2)$; both are small for large-scale ocean flows, and derivation of geostrophy (**Kn** p 110).

12. **Waves and oscillations II: deep ocean surface 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); 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 readings

Beginning texts:

- John A. Knauss, Introduction to Physical Oceanography, 320 pages; 2nd edition, 2005.
- J. Marshall and R. A. Plumb, Atmosphere, ocean, and climate dynamics, Elsevier Academic Press, Burlington, MA, USA, 2008, 319pp.
- Lynne D. Talley, George L. Pickard, William J. Emery and James H. Swift, Descriptive Physical Oceanography - An Introduction, 2011 (sixth edition) available on-line at http://www.sciencedirect.com/science/book/9780750645522
- Stephen Pond and George L. Pickard, Introductory dynamical Oceanography, 3rd edition, Butterworth-Heinemann, 1993.
- Open university: Ocean Circulation (Second Edition); Evelyn Brown, Angela Colling, Dave Park, John Phillips, Dave Rothery and John Wright
- Open university: Waves, Tides and Shallow-Water Processes, Second Edition;
- (**St**) Robert H. Stewart, on-line physical oceanography book

- On-line version of 'Regional oceanography'

Intermediate texts:

- Philander, S. G. H., El Nino, La Nina, and the Southern Oscillation., Academic Press, 1990,
- (**Ku**) Kundo P.K. and Cohen I.M., Fluid mechanics. 2nd edition 2002.
- Benoit Cushman-Roisin, Introduction to geophysical fluid dynamics, Prentice-Hall, 1995,

Advanced texts:

- Vallis, G., 2005, Atmospheric and oceanic fluid dynamics, fundamentals and large-scale circulation, Cambridge University Press.
- 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 assigned every 9-10 days throughout the course. The best 90% of the homework assignments 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 and possibly do a class presentation of a fluid experiment (30%), see details here for a list of possible subjects. The final exam will be a take home (30%).

Collaboration policy: Discussion and the exchange of ideas are essential to doing academic work, and we strongly encourage you to discuss and work on homework problems with other students (and with the teaching staff, of course). However, after discussions with peers, make sure that you can work through the problem yourself and ensure that any answers you submit for evaluation are the result of your own efforts, reflect your own understanding and are written in your own words. In addition, you must cite any books, articles, websites, lectures, etc that have helped you with your work using appropriate citation practices.

Please note: Course materials are the property of the instructional staff, Harvard University, or other copyright holders, and are provided for your personal use. You may not distribute them or post them on websites without permission of the course instructor.

6 Links

- Coriolis force movies and resources: here, here, and here.
- Greenpeace "bottom trawling" and Greenpeace "save our seas", see here.
- Shifting baselines: "pristine";
- NOVA program about the Sumatra Tsunami of 2004 here;
- Ocean acidification NRDC video
- PBS "ocean adventures" videos, in particular: Orca (killer whales) hunting (5 min); the great Pacific garbage patch (4 minutes);
- Ocean data sources: Marine Explorer, Ocean Data Viewer, and the IRI/LDEO Climate Data Library.