Introduction to Physical Oceanography and Climate

Spring 2020

FAS course web page for EPS 131

Field trip to the Woods Hole Oceanographic Institution, spring 2018.

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

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Day, time: Tuesday, Thursday, 1:30-2:45.

Location: Geological Museum, 24 Oxford St, third floor, room 375

Field Trip! To the Woods Hole Oceanographic Institution/ WHOI, *obligatory & fun*; hosted by Dr. Bob Pickart; **Friday, March 27, 2020**. Departing 7am, returning around 6pm.

Matlab will be used for HW and class demonstrations. If you would like a refresher, consider the *Matlab boot camp*, 3-4 lectures during the beginning of the term. Register here.

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

Source materials: Here. To access from outside campus or from the Harvard wireless network, use the VPN software available from the FAS software download site.

Important past events. . . :

- WHOI field trip. In previous trips we visited the R/V Atlantis, R/V Knorr, R/V Armstrong, the submersible Alvin, and we toured WHOI labs. Photos: 2005, 2008, 2010, 2012, 2014, 2016, 2018.
- EPS 131 Oscars (video project) events: 2005: surface waves; 2008: internal waves; 2010: great Pacific garbage patch; 2012: thermohaline circulation; 2014: surface waves; 2016: brine rejection; 2018: phase speed in 2d; 2020: sweet viscosity;
- zeta vs xi (ζ vs ξ) competition: 2008, 2010, 2012, 2014, 2016, 2018, 2020.

Requirements: Homework will be assigned every 9-10 days (40% of course grade, lowest grade dropped). Each student will give a short (10 min) presentation (details), which, together with a small-group video project (examples above) and/ or a wikipedia entry-writing project, will constitute another 30%. The final exam will be an open-book take-home (30%).

Collaboration policy: we strongly encourage you to discuss and work on homework problems with other students and with the teaching staff. However, after discussions with peers, you need to work through the problems 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. You must appropriately cite any books, articles, websites, lectures, etc that have helped you with your work.

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Announcements

Last updated: May 12, 2020

Feel free to write or call with any questions:

Eli Tziperman; eli@eps.harvard.edu

Office hours: see course web page.

Contents

1 Outline

Observations and fundamentals of ocean dynamics, from the role of the oceans in global climate and climate change to beach waves. Topics include the greenhouse effect, oceans and global warming; El Niño evens in the equatorial Pacific Ocean; currents: the wind driven ocean circulation and the Gulf stream; coastal upwelling and fisheries; temperature, salinity, the overturning circulation and its effect on global climate stability and variability; wave motions: surface ocean waves, internal waves, tsunamis and tides; 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: Mathematics 21a, 21b; Physical Sciences 12a, Physics 15a or Applied Physics 50a; or equivalents/ permission of instructor.

Software for scientific computation and graphics will be introduced (students may choose either Matlab or python), which will be used for some homework assignments.

2 Syllabus

Detailed syllabus, directory with all source materials and lecture notes.

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) *Greenhouse effect and globally-averaged temperature:* Calculating the expected averaged temperature given the solar radiation and the atmospheric greenhouse effect.

(b) *Global warming:* will sea level rise? Why? (thermal expansion vs land-ice melting) By how much? *Analysis:* heat penetration into the ocean, sea level rise due to thermal expansion of sea water. Equation of state, thermal expansion of sea water.

(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. Explaining the exponential deep ocean vertical temperature profile, as a balance of upwelling and vertical mixing, "abyssal recipes",

(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. *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? Are they already changing?

(f) Stability and σ_θ vs σ_4, why stratification seems unstable on σ_θ but is clearly stable when plotted using σ_4. Explanation via 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. Western boundary current measurements.

(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 (section 1 in notes).

(b) Wave basics: wave length, period, wave number frequency, dispersion relation, phase and group velocities; phase velocity in 2d, phase velocity is not a vector (section 2 in notes).

(c) Surface shallow-water gravity waves (beach waves, tides and 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; mechanism of breaking waves; tidal resonance and large tides in Bay of Fundy (section 3.1-3.7 in notes).

(d) 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; the sea surface at any given time is affected of many wavelength propagating at different speeds, (Knaus picture of sea level with a random wave field), refraction; particle trajectories of deep waves, near the surface and deeper; (Time permitting:) Stokes drift; (section 3.8-3.9 in notes).

(e) Buoyancy oscillations: (section 4 in notes)

(f) 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 (section 5 in notes)

(g) Waves in the presence of rotation: Coastal Kelvin waves and Poincare waves (sections 6.1 and 6.2 in 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**
downloads;
Background reading: **OU** pages 39-44; **Ku** pages 122-128;

(a) *Observation/ motivation:* icebergs do not move with the wind direction (Ekman 1905), nor do ocean surface currents. Background: 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, nutrients, fisheries and El Nino (**OU** p 133-137, 153-155); 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).

(d) Scale-selective friction: deriving the expression for vertical viscosity and horizontal viscosity. 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, 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?
- The RAPID observing system in the North Atlantic ocean, RAPID homepage.
- *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 (notes on course web page).
- *Perspective:* Stommel box model vs full complexity Global Climate Models(GCMs);
- THC depends on upwelling occurring throughout the ocean. That, in turn depends on mixing (abyssal recipes).

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; vorticity, Rossby waves, Sverdrup balance, western boundary currents.

Notes: here.

Summary: Vorticity balance slide.

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

(a) Introduction
(b) Reminder: coastal Kelvin waves
(c) Equatorial Kelvin waves
(d) Reminder: Rossby waves
(e) Reminder: Ekman pumping

(f) Delayed oscillator mechanism

10. Time permitting:

    (a) **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?

        i. 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;

        ii. Dynamical explanations for the dramatic past climate phenomenology: advective instability feedback; THC flushes;

3 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

4 Links

- Coriolis force movies and resources: here, here, and here.
- A nice El Niño animation
- 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.
- A day in the life of a fluid dynamicist