EPS/ESE 131: Introduction to Physical Oceanography and Climate

Spring 2022

Canvas course web page for EPS/ESE 131

Last updated: Monday 26th September, 2022, 20:37.

Field trip to the Woods Hole Oceanographic Institution, spring 2022.

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1 Logistics

This is: Earth and Planetary Sciences/ Environmental Science and Engineering 131: Introduction to Physical Oceanography and Climate.

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

TF: Camille Hankel, Camille_Hankel@g.harvard.edu. Office Hours: Canvas course webpage.

Day, time & location: Tuesday, Thursday, 10:30–11:45, 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; **Thursday, April 7, 2022**. Departing at 7:00 am, returning around 6 pm.

Section/HW help session: time and location: see Canvas course web page.

Sources directory: with all class notes, demos, code, data! here, or DropBox link from Canvas page.

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, 2020 no trip, Covid 🙁, 2022.
- 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; 2022: sea level;
- zeta vs xi (ζ vs ξ) competition: 2008, 2010, 2012, 2014, 2016, 2018, 2020, 2022.
- The real stuff: Three 2022 EPS131 veterans on a cruise with Bob Pickart on the R/V Norseman II to the northern Bering/Chukchi/western Beaufort Seas!

Requirements: Homework will be assigned every 9–10 days (40% of course grade, lowest HW grade dropped). Each student will give one to two short (10 min) presentation(s) (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%).

Course forum: Please post questions regarding HW or other issues to the course forum (piazza.com/harvard/spring2022/epsci131). You are very welcome to respond to other students' questions.

Electronic homework submission: Your submission, via www.gradescope.com/courses/279832, may be typeset or scanned, but must be clear, easily legible, and correctly rotated. A scan using a phone app (e.g., this) may be acceptable if done carefully. Upload different files for the different questions, or upload a single pdf and mark which pages contain answers to which question; see tutorial video. Unacceptable scans could lead to a rejection of the submission or to a grade reduction of 15%.

Recommended Prep: Mathematics 21a, 21b; Physical Sciences 12a, Physics 15a or Applied Physics 50a; or equivalents/ permission of instructor. Basic programming for scientific computation and graphics will be introduced (students may choose either Matlab or python) and will be used for some homework assignments, no prior programming experience is assumed.

Academic Integrity and Collaboration policy. We strongly encourage you to discuss and work on homework problems with other students and 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. In the case of assignments requiring programming, you need to write and use your own code; code sharing is not allowed. You must appropriately cite any books, articles, websites, lectures, etc. that have helped you with your work.

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Contents

2 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 events 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. Basic programming will be introduced in sections (students may choose either Matlab or python) and for some homework assignments.

3 Detailed syllabus

Here is a link to the pdf of the detailed syllabus, and to the directory with all source materials and lecture notes.

1. **Outline and motivation,** downloads.

2. **Temperature and salinity,** downloads.

   (a) *Greenhouse effect:* Calculating the expected globally averaged temperature given the solar radiation and the atmospheric greenhouse effect. Atmospheric lapse rate and the mechanism of anthropogenic global warming.

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

   (c) *North-south and vertical temperature profiles:* Why is the deep ocean so cold? What's setting the near-exponential vertical ocean temperature profile? *Explanation:* meridional insolation gradient and the equator-to-pole meridional surface temperature gradient, implied polar area convection and overturning circulation. Explaining the exponential deep ocean vertical temperature profile, as a balance of upwelling and vertical mixing, Munk's "abyssal recipes".

   (d) *Salinity:* why is the coldest water not always at the bottom? The ocean is composed of different "water masses" characterized by temperature *and* salinity, which form in polar areas and can be tracked throughout the ocean. Evaporation/precipitation and salinity, equation of state including both T, S.

   (e) *Analysis of water masses:* T–S diagrams, mixing of two and three water masses;

(f) *Potential density:* 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.

   (a) MOTIVATION: What drives the great ocean gyres and the Gulf Stream? *Phenomenology:* the Hadley and Ferrell cells, surface winds, wind-driven ocean circulation, western boundary currents, abyssal ocean circulation.

   (b) INTRODUCTION TO THE MOMENTUM BALANCE, $F = ma$, FOR FLUIDS: density×acceleration = pressure gradient force + Coriolis force + friction + gravity + wind forcing;

   (c) GEOSTROPHY: *horizontal momentum budget: Geostrophy in the ocean and atmosphere:* wind around highs and lows on a weather map, currents around the subtropical gyre in the North Atlantic. *Explanation:* pressure force, Coriolis force (qualitatively, movies), steady state, geostrophy. *Example:* Calculating winds from sea level pressure in a weather map.

   (d) HYDROSTATIC EQUATION: the vertical momentum balance.

   (e) BOUSSINESQ APPROXIMATION: dynamics density and pressure.

   (f) SEA LEVEL VARIATIONS AND OCEAN CURRENTS: altimeter satellite observations; Temperature/ density section across the Gulf Stream and the apparent contradiction between Gulf Stream direction and observed stratification;

   (g) COMPETING EFFECTS OF SEA LEVEL AND DENSITY GRADIENTS: what drives the vertical structure of the Gulf Stream.

   (h) THERMAL WIND BALANCE: calculating ocean currents from temperature and salinity observations, monitoring the ocean circulation to observe early signs of AMOC collapse.

4. **Waves,** downloads.

   (a) INERTIAL MOTIONS: *Observation:* circular water motion at the inertial period after a passing storm. *Explanation:* Coriolis force, inertial oscillations, equations and circular trajectories of fluid parcels (section 1 in notes).

   (b) Wave basics: wavelength, period, wave number frequency, dispersion relation, phase and group velocities; phase velocity in 2d, the 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 the 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: The dispersion relation; shallow, deep, and finite depth dispersion relations; the sea surface at any given time is affected by many wavelengths propagating at different speeds; 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, 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.

   (a) *Observation/ motivation:* icebergs do not move with the wind direction (Ekman 1905), nor do ocean surface currents. Coastal upwelling regions that are responsible for a significant part of fisheries exist due to friction effects and are driven by coastal winds.

   (b) DAMPED INERTIAL OSCILLATIONS: Non-scale-selective friction and Coriolis, Bottom friction parameterization, damped inertial oscillations.

   (c) EKMAN TRANSPORT AND COASTAL UPWELLING: Coriolis and vertical friction, coastal upwelling, nutrients, fisheries and El Nino; Ekman transport as a function of wind stress, first in terms of the frictional stress tau without relating the stress to the velocities.

   (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, wind speed and wind stress, the balance of friction and rotation in the mixed layer, Ekman spiral.

7. **The meridional overturning circulation,** downloads.

- *Motivation:* The day after tomorrow... Can the ocean meridional overturning circulation collapse due to global warming?
- The RAPID observing system in the North Atlantic ocean.
- *Background:* meridional overturning (thermohaline) circulation: mean state, present-day variability; different atmospheric response and surface boundary conditions for temperature and salinity; driving by temperature, breaking by Salinity; meridional ocean heat flux.
- *Analysis:* the Stommel box model, multiple equilibria, tippling points and catastrophes.
- *Perspective:* Stommel box model vs full complexity Global Climate Models (GCMs);

8. **Horizontal circulation II: vorticity, Gulf Stream and other western boundary currents, Rossby waves, abyssal circulation,** downloads.
   (a) The critical effect of latitudinal changes in the Coriolis force, beta plane
   (b) Vorticity
   (c) Ekman pumping
   (d) Vorticity equation
   (e) Rossby waves
   (f) Wind driving of currents away from western boundary current: the Sverdrup balance
   (g) Western boundary currents (Gulf Stream, Kuroshio, and more)
   (h) Abyssal circulation and deep western boundary currents
9. **El Nino,** downloads.
   (a) El Niño and La Niña: observations and global weather effects
   (b) Equatorial Kelvin and Rossby waves
   (c) Delayed oscillator mechanism
10. (Time permitting) **Abrupt climate change,** downloads.
    (a) Introduction to paleo climate variability; proxies, ice cores and sediment cores; ice ages, abrupt events (Heinrich and D/O events).
    (b) Ocean-related abrupt climate change mechanisms:
        i. MOC variability (Welander flip-flop) & sea ice amplification,
        ii. Ice shelf collapse via hydrofracturing,
        iii. Ice sheet collapse via the Marine Ice Sheet Instability or via basal melting (binge-purge).

4 Homework assignments

Assignments are available here; please email if you are teaching a similar course and are interested in the solutions.

5 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*, 319pp, 2008.
- Lynne D. Talley, George L. Pickard, William J. Emery, and James H. Swift, *Descriptive Physical Oceanography — An Introduction* (6th edition), online, 2011.
- Stephen Pond and George L. Pickard, *Introductory dynamical Oceanography* (3rd edition), 1993.
- Evelyn Brown, Angela Colling, Dave Park, John Phillips, Dave Rothery, and John Wright, *Open university: Ocean Circulation* (2nd Edition), 2001.
- Wright, John, Angela Colling, and Dave Park, *Open university: Waves, Tides, and Shallow-Water Processes* (2nd Edition), 1999.
- Robert H. Stewart, *Physical Oceanography*, online, 2008.
- Matthias Tomczak and J. Stuart Godfrey, *Regional oceanography*, online, 1994.
- Eli Tziperman, *Global Warming Science: A Quantitative Introduction to Climate Change and Its Consequences*, details, 2022.

Intermediate texts:

- Philander, S. G. H., *El Niño, La Niña, and the Southern Oscillation*, 1990.
- Kundo P.K. and Cohen I.M., *Fluid mechanics* (2nd edition) 2002.

Advanced texts:

- Vallis, G., *Atmospheric and oceanic fluid dynamics, fundamentals and large-scale circulation* (2nd edition), 2017.
- Pedlosky, J., *Geophysical Fluid Dynamics* (2nd edition), 1987.
- Pedlosky, J., *Ocean circulation theory*, 1996.
- Pedlosky, J., *Waves in the ocean and atmosphere*, 2003.
- Gill, A. E, *Atmosphere-ocean dynamics*, 1982.

6 Misc links

- Greenpeace bottom trawling and protect the oceans.
- Shifting baselines: "pristine".
- NOVA documentary about the Sumatra Tsunami of 2004, with more here.
- Ocean acidification NRDC video
- Orca hunting video
- The great Pacific garbage patch.
- Ocean data sources: Marine Explorer, Ocean Data Viewer, and the IRI/LDEO Climate Data Library.
- A day in the life of a fluid dynamicist