EPS 231: Climate Dynamics

Spring 2025

Canvas course web page for EPS 231

last updated: Saturday 21st December, 2024, 18:44

logistics	outline	prerequisites	syllabus	homework	requirements

1 Logistics

This is: Earth and Planetary Sciences 231: Climate Dynamics.

Instructor: Eli Tziperman (eli@eps.harvard.edu)

TF: Andrea Salazar (mailto:andreasalazar@g.harvard.edu); office hours: Canvas course website.

Day, time: Tuesday, Thursday, 10:30–11:45

Location: Geological Museum, 4th floor, room 418. 24 Oxford St, Cambridge.

Office hours: Eli: Monday/ Wednesday 1–2, please write or call me with any questions.

Electronic homework submission: via https://www.gradescope.com/courses/: upload your submission as a PDF file following this tutorial video.

Course forum: Please post questions regarding HW to the course forum on *Ed Discussions* (https://edstem.org/us/courses/), you are very welcome to respond to other student questions.

Course downloads: http://www.seas.harvard.edu/climate/eli/Courses/EPS231/Sources/

Detailed teaching notes: including links to source materials, Python & Matlab codes and more

Contents

2 Outline

The course covers climate change, climate dynamics and climate variability phenomena and mechanisms. It provides hands-on experience running and analyzing climate models and using dynamical system theory tools. The material includes principles of climate dynamics, from feedbacks that maintain different mean climates to phenomenology and mechanisms of climate variability on multiple time scales; Energy balance and climate equilibria, stability and bifurcations with Snowball Earth as an example. Climate variability: El Niño (roughly 4 yr period), the Atlantic meridional overturning circulation (AMOC) and its multiple equilibria and variability (decadal and longer); AMOC variability as a possible explanation for the medieval warm period and the Little Ice Age (hundreds of years); the Dansgaard-Oeschger warming events observed in the Greenland ice cores (every 1500 yr), Heinrich events involving massive collapses of ice during glacial times (every 7–10,000 yr), glacial-interglacial variability (100,000 yr) including ocean, atmospheric and ice dynamics, ocean carbonate chemistry and CO_2. Warm climates, from the Pliocene's (3–5 Myr) permanent El Niño to the Eocene (50 Myr) equable climate, and with lessons to possible surprises in a future warmer climate. We will discuss physical mechanisms and demonstrate them with a hierarchical modeling approach, from toy models to General Circulation Models. The needed background in nonlinear dynamics will be covered.

An important goal of the course is to have students learn and gain experience with running and analyzing a global climate model (GCM). The students will be involved a class-time hands-on introduction to running and analyzing GCMs. A variety of climate applications will be presented, including running simulations of the El Niño-Southern Oscillation (ENSO), Atlantic meridional overturning circulation (AMOC), abrupt CO2 changes, preindustrial climate, and high CO2 scenarios. We will use the Community Earth System Model (CESM2), which is used extensively to study future climate change and is a major participant in the coupled model inter-comparison project (CMIP6) which is the base of much of the IPCC assessment reports.

Course homepage: http://www.seas.harvard.edu/climate/eli/Courses/EPS231/2025spring/

3 Prerequisites

The course may be taken as a sequel to MIT's Climate Physics and Chemistry (12.842) or Harvard's Introduction to Climate Physics (EPS 208) but can also be taken independently of these courses. Familiarity with the fundamentals of Geophysical Fluid Dynamics (the equivalent of MIT 12.800 or Harvard EPS 232) is assumed.

4 Syllabus

A detailed outline of the lectures and a complete list of reference materials used in each lecture is available here. The course Supporting materials, including slides, notes, and code are available here.

1. Outline and motivation: supporting material,

2. Basic climate feedbacks: supporting material.

   - Energy balance, greenhouse, bifurcations, hysteresis and snowball
   - (Time permitting) Small ice cap instability
   - ***Climate modeling:*** Introduction.

     (a) Logging in to Derecho, the arrangement of directories (home, work, scratch), git-clone CESM2.

     (b) Submission of most basic global run (compset B1850, 10 days, follow online CESM2 tutorial)

3. El Niño—Southern Oscillation: supporting material.

   - Phenomenology: basics: Gill atmosphere; reduced gravity models, equatorial ocean waves
   - Coupled ocean-atmosphere dynamics
   - Delayed oscillator/recharge oscillator:
   - Irregularity: chaos, nonlinear phase locking to the seasonal cycle
   - Irregularity: stochastic forcing, non-normal dynamics, optimal initial conditions, and stochastic optimals.
   - Westerly wind bursts as state-dependent stochastic forcing.
   - Atmospheric teleconnections, Rossby ray tracing
   - ENSO diversity
   - ***Climate modeling:*** Netcdf processing, composites, PCA.

     (a) Composites and PCA

(b) Calculating and plotting index time series and composite spatial average from a netcdf file.
(c) Creating a matrix for PCA analysis from the two-dimensional SST data, each column being one monthly snapshot.

4. Meridional overturning circulation: supporting material.

- Phenomenology, mixed boundary conditions, Stommel model
- Stability, bifurcations, multiple equilibria, tipping points
- Advective and convective feedbacks; flip-flop and loop oscillations.
- Stochastic forcing; linear vs nonlinear; non-normal dynamics, noise-induced transitions between steady states
- ***Climate modeling:*** Running an abrupt $4\times CO_2$ scenario (50–100 years).
  (a) The GMST time series and its adjustment timescale(s).
  (b) AMOC stream function contour, and index time series of maximum stream function.
  (c) The "warming hole" in the North Atlantic.

5. D/O and Heinrich events: supporting material.

- DO events: AMOC flushes vs sea ice changes;
- Heinrich events: binge-purge oscillator, climatic effects, synchronous collapses

6. Glacial cycles: supporting material.

- Phenomenology
- Milankovitch forcing
- Ice sheets and glaciology basics: Glenn's law, mass balance, equilibrium parabolic profile
- Proposed mechanisms for glacial cycles
- Phase locking to Milankovitch forcing
- CO_2 and the ocean carbonate system
- ***Climate modeling:*** Analyzing [Paleo] Modeling Intercomparison Project/[P]MIP LGM model output.
  (a) The (Lat, Lon) June 21st insolation at the LGM vs. present day.
  (b) Surface temperature/ sea ice fraction at the LGM vs. present-day.
  (c) Using model intercomparison/ [P]MIP data, analyzing model in/consistency.

7. Pliocene, 2–5Myr: supporting material.

- Major two problems: "permanent El Niño", and the dramatic warming of mid-latitude upwelling sites.
- Proxies, proxies, proxies.
- Proposed ideas for explaining the "permanent El Niño":
  - Tectonic movement of Papua/ New Guinea
  - Opening of the Central American Seaway
  - Hurricanes and ocean mixing
  - Collapse of the equatorial thermocline due to enhanced N. Pacific precipitation
  - Atmospheric superrotation

8. Equable climate: supporting material.
   - The challenge: the existence of frost-intolerant flora and fauna (palm trees and alligators) in high-latitude mid-continental areas.
   - Proposed ideas:
     - Equator-to-pole Hadley cell
     - Polar stratospheric clouds
     - Hurricane mixing and ocean MOC
     - Breakup of subtropical marine stratocumulus clouds
     - Low clouds suppressing Arctic air formation
     - Convective Arctic cloud feedback
   - ***Climate modeling:*** Warm climate simulations: analyze a $8\times CO_2$ run.
     (a) Plotting the PDF of minimum daily temperatures
9. Data analysis tools for observations and model output (hands-on practice in sections): supporting material.
   - Composite analysis
   - PCA/EOFs
   - SVD analysis of two co-varying fields
   - Linear inverse models, POPs
   - Spectral analysis
10. Review. supporting material.

5 Homework assignments

Assignments from a recent time this course was taught, although not necessarily from this current year, are available here; please email if you are teaching a similar course and are interested in the solutions.

6 Requirements

Homework assignments, every 9–10 days, are 50% of the final grade, and a final course project constitutes the remaining 50%. There is an option to take this course as a pass/fail with an instructor's approval during the first week of classes. The subject of the final project will be discussed in a couple of individual meetings with students during the semester. It would ideally be related to either climate subjects, modeling approaches, nonlinear dynamics methods, or data analysis covered in class. It may be related to the student's research project. The length of the final report should be some 6–10 pages, including a few figures, 12pt, in PDF format, and the expected effort is some 6–8 days of work. Please include an abstract, an introduction with the background/ motivation, and a methods section, including the precise details of data sources or model versions/ configuration with relevant links, results, and discussion/ conclusions.

Collaboration policy. We **strongly** encourage you to discuss and work on homework problems with other students and with the teaching staff. Of course, 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. Please appropriately cite any books, articles, websites, lectures, etc., that have helped you with your work.