EARTH & PLANETARY SCIENCES

AT HARVARD UNIVERSITY

2025 Senior Thesis Presentations

Sharmila Dey

Brahm Erdmann

Sophia Ludtke

Julia Mansfield

Sarah Packman

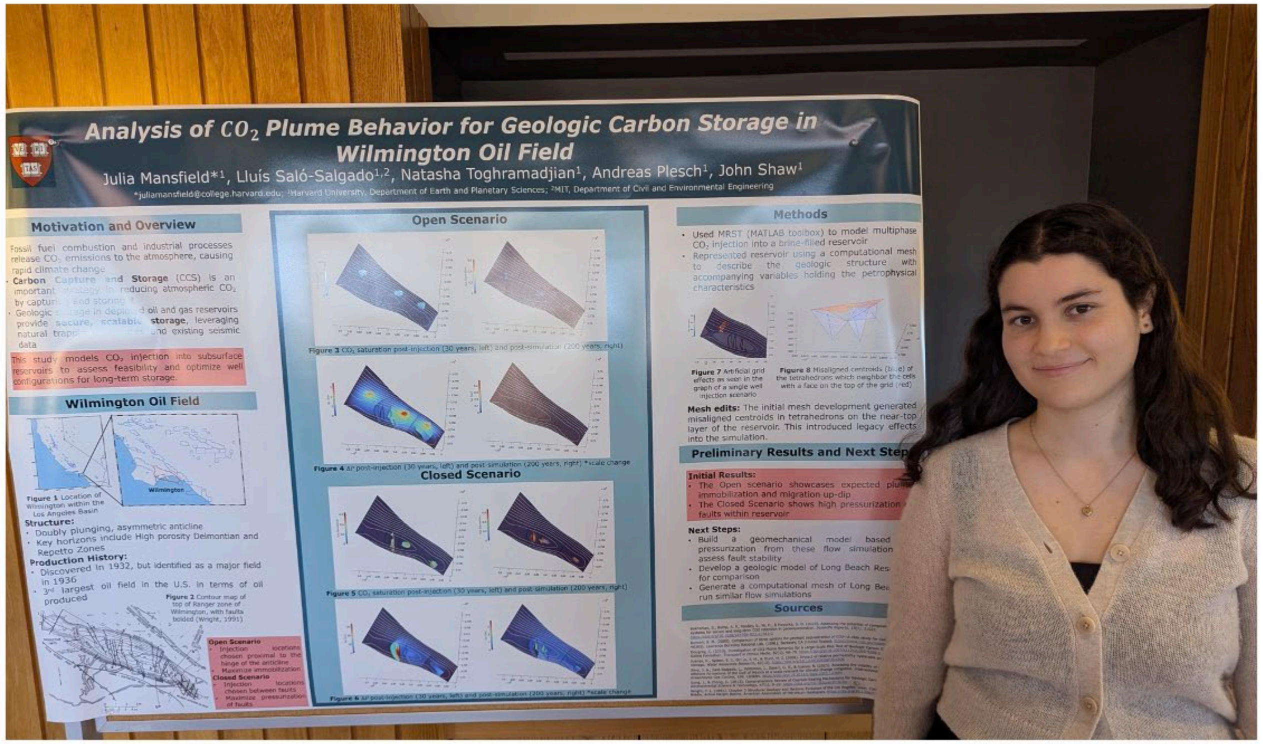
Ian Palk

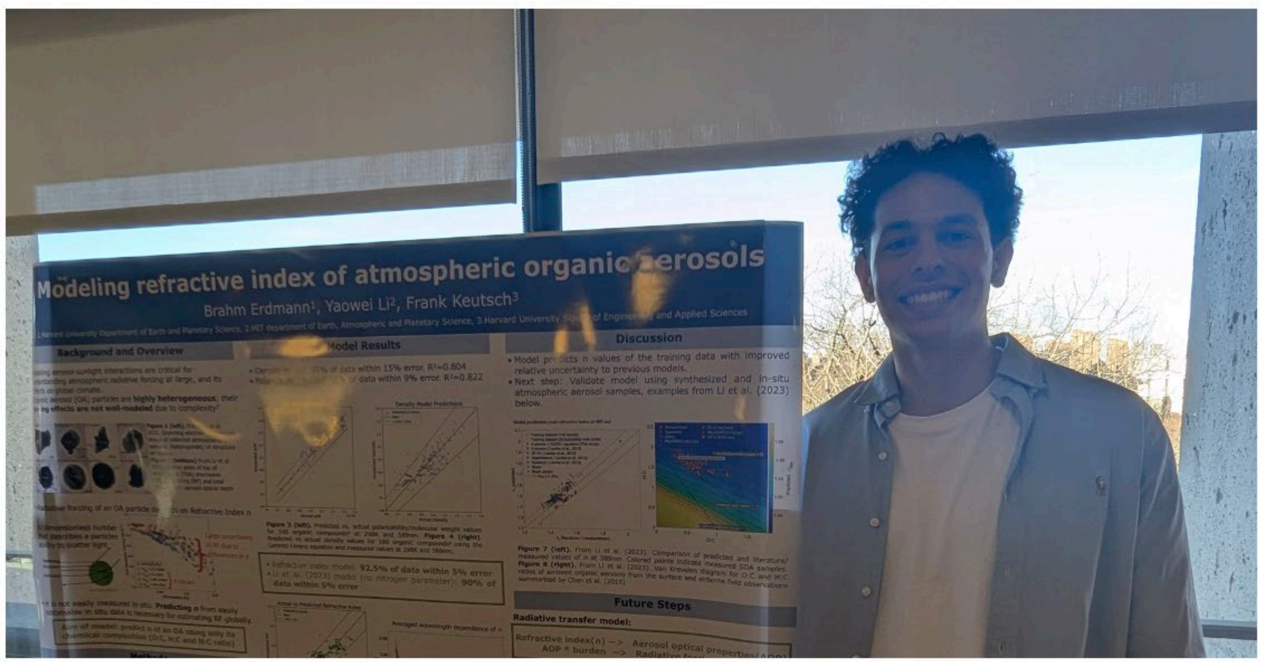
Thursday, April 25th, 2025 11:30 am-1:30 pm
Haller Hall, Geological Museum 102

Please join us for an Undergraduate End-of-Year Reception beginning at 2:00 pm in the Student Lounge (4th Floor, Hoffman Labs).

Please join us for a reception honoring
all of our EPS Undergraduates
1:45 pm
Student Lounge
4th Floor, Hoffman Labs

Thank you for your support!





WELCOME

Message from the co-Head Tutors and Preceptors:

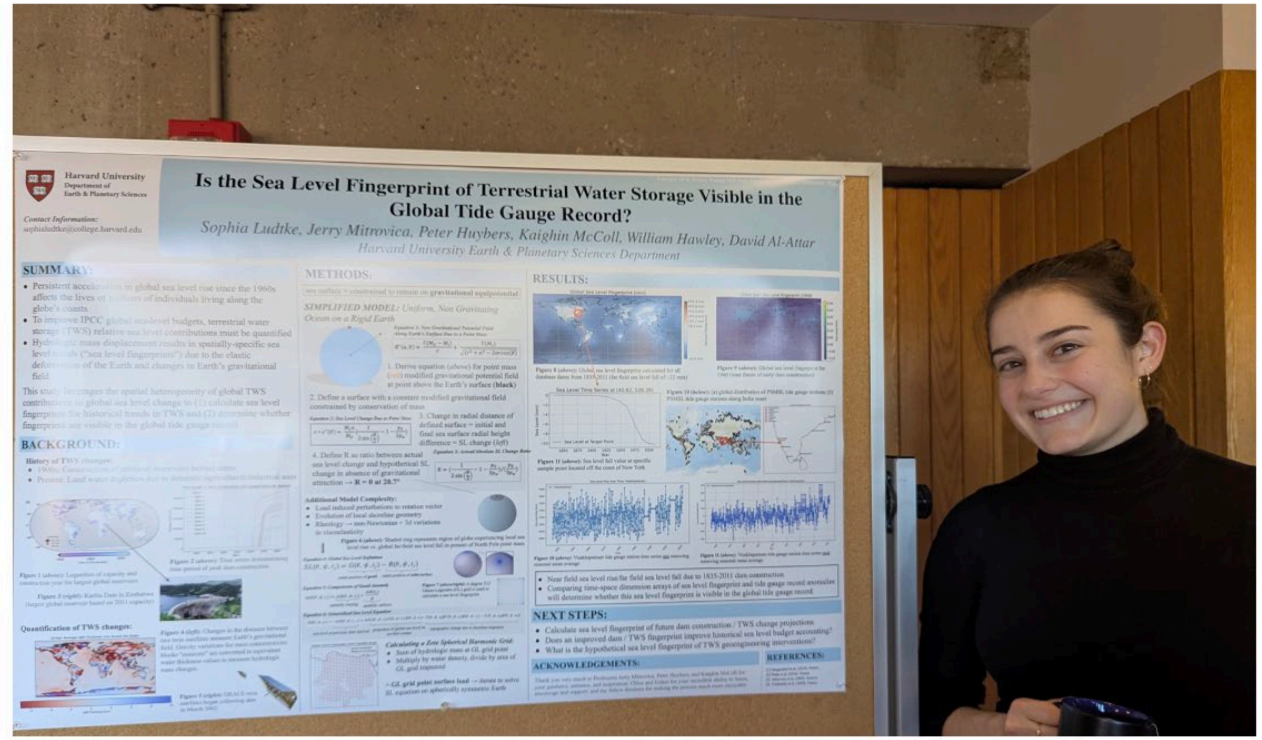
Thank you for joining us as we celebrate the accomplishments of our senior thesis writers who spent much of their senior year tackling an exciting range of scientific problems. The senior thesis provides an opportunity for students to gain firsthand experience in the full scope of research, from in-depth background study, to identification of core questions, design of a research plan, collection and analysis of data, and formation of rigorous conclusions. These theses and today's presentations reflect the academic excellence and dedication of these students. Their efforts would not be possible without the support of faculty advisors, graduate students, post docs, fellow undergraduate students, and family. We thank these mentors and friends and congratulate our seniors on their achievement.

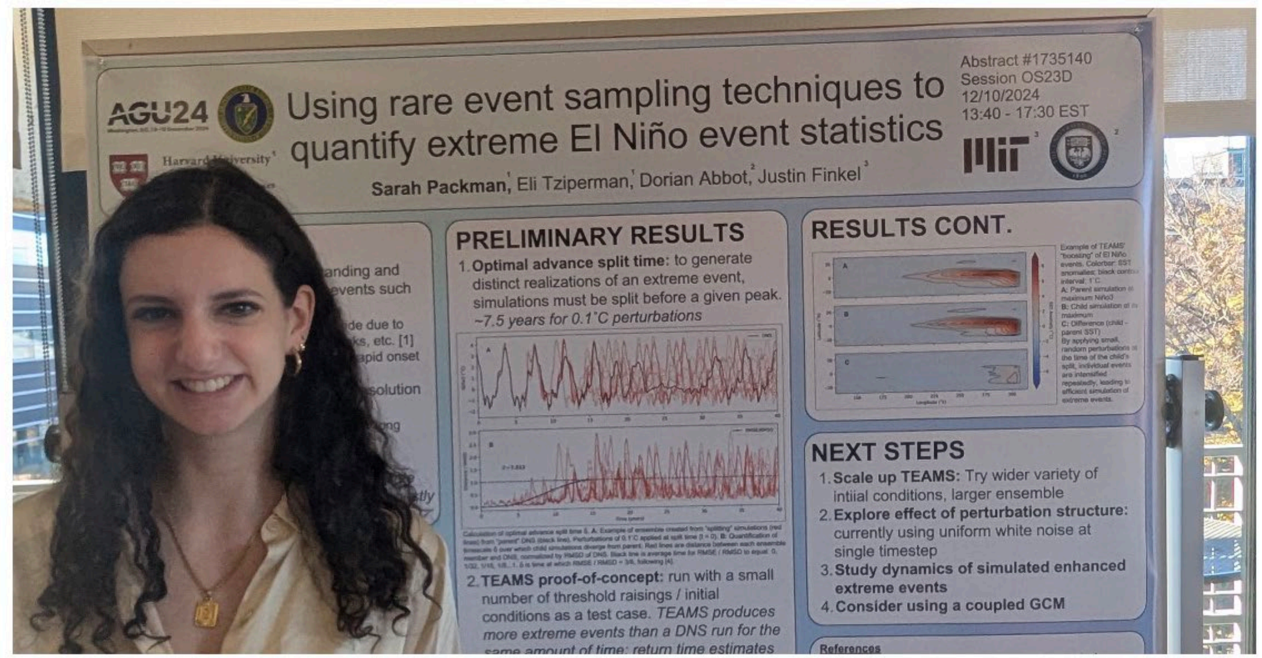
Roger Fu and Robin Wordsworth
Co-Head Tutors

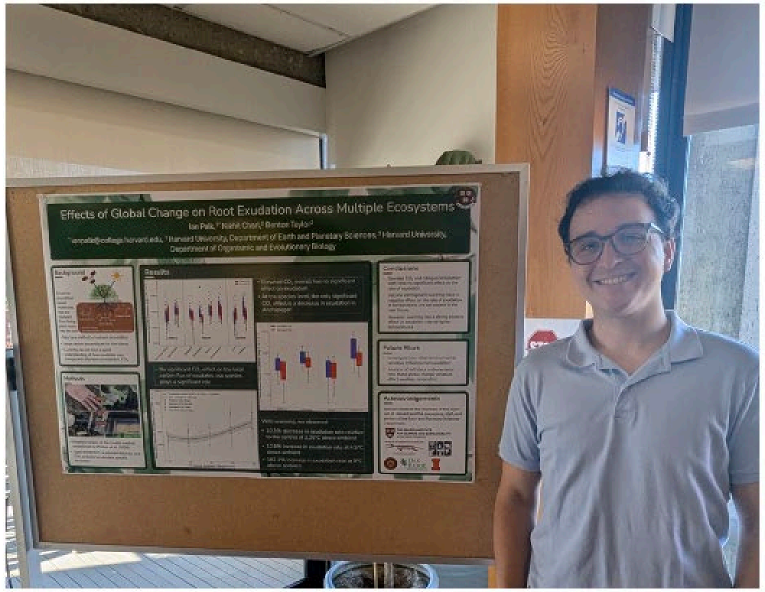
Chloe Anderson and Esther James
EPS Preceptors

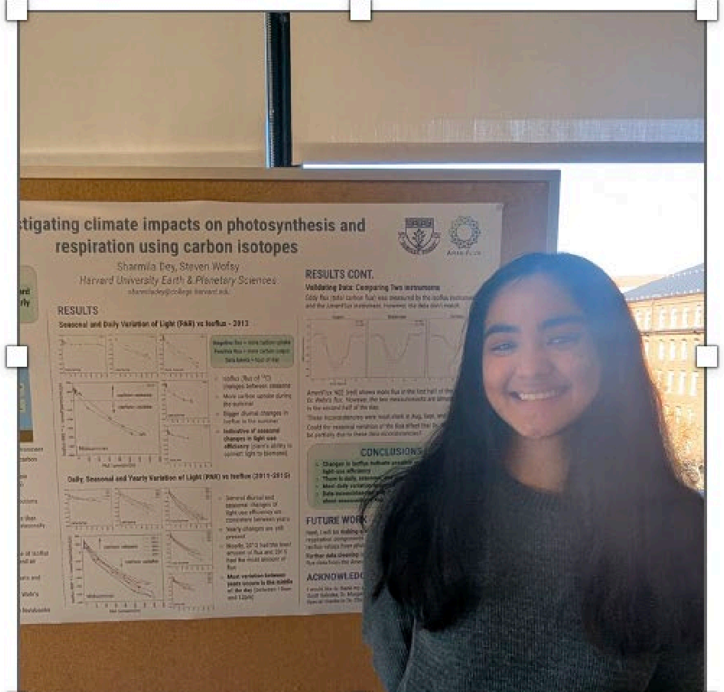
Roger Fu, Robin Wordsworth, Rebecca Fischer
Undergraduate Curriculum Committee

Campbell Halligan
Academic Programs Manager


Harvard University
Is the Sea Level Fingerprint of Terrestrial Water Storage Visible in the Global Tide Gauge Record?
Sophia Ludtke, Jerry Mitrovica, Peter Huybers, Kaighin McColl, William Hawley, David Al-Attar
Harvard University Earth & Planetary Sciences Department
SUMMARY:
BACKGROUND:
METHODS:
RESULTS:
NEXT STEPS:
ACKNOWLEDGEMENTS:
REFERENCES:


AGU24
Using rare event sampling techniques to quantify extreme El Niño event statistics
Abstract #1735140
Session OS23D
12/10/2024
13:40 - 17:30 EST
Sarah Packman, Eli Tziperman, Dorian Abbot, Justin Finkel
PRELIMINARY RESULTS
1. Optimal advance split time: to generate distinct realizations of an extreme event, simulations must be split before a given peak. ~7.5 years for 0.1°C perturbations
2. TEAMS proof-of-concept: run with a small number of threshold raisings / initial conditions as a test case. TEAMS produces more extreme events than a DNS run for the
RESULTS CONT.
NEXT STEPS
1. Scale up TEAMS: Try wider variety of initial conditions, larger ensemble
2. Explore effect of perturbation structure: currently using uniform white noise at single timestep
3. Study dynamics of simulated enhanced extreme events
4. Consider using a coupled GCM
References





Sharmila M. Najita Dey

Concentration: Earth and Planetary Sciences

How Forests Breathe: Evaluating New Isoflux Measurements at Harvard Forest and Their Long-Term Ecological Context

Advisor: **Steve Wofsy**, Abbott Lawrence Rotch Professor of Atmospheric and Environmental Science, Department of Earth and Planetary Sciences, Harvard University

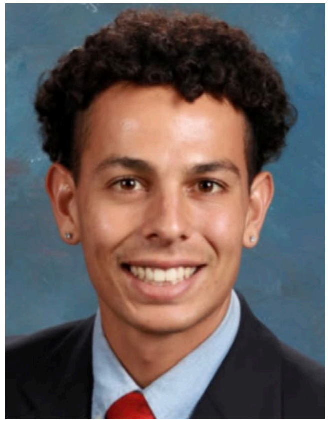
Accurately measuring forest carbon storage is necessary to understand the role terrestrial ecosystems play as carbon sinks. This requires a deep understanding of forest photosynthesis and respiration, the two processes that determine forest carbon storage. These processes are affected by environmental drivers like temperature and water availability as well as ecological drivers like canopy conductance, light-use efficiency, species composition, and succession. Total ecosystem fluxes of CO2 can be measured using eddy correlation methods, and the photosynthesis and respiration fluxes are calculated by partitioning the total carbon fluxes into these components. However, standard partitioning methods have recently been debated with the use of new flux measurements of isotopically heavy carbon at Harvard Forest. New partitioning methods suggest that previous partitioning methods overestimated daytime respiration and that daytime respiration is lower than nighttime respiration due to the Kok effect. However, uncertainties in the isoflux data and new partitioning method have yet to be addressed.

This study examines the long-term trends of environmental and ecological variables, as well as the long-term trends of the CO2 net ecosystem exchange between the forest and the atmosphere at Harvard Forest to better understand the role of Harvard Forest as a historical and current carbon sink. The updated ecological and carbon exchange history of Harvard Forest adds almost a decade to previous assessments. The recent isoflux data are contextualized in the extended record. Finally, this study examines the partitioning method and conclusions of the original publications for the Harvard Forest isoflux data.

I find that Harvard Forest remains a carbon sink and that many of the long-term trends at Harvard Forest agree with previous studies. However, some trends appear to have shifted, coincidentally at the time when the isoflux measurements were made, indicating changes in the ecosystem and potentially implying lower carbon uptake in the future. The Harvard Forest isoflux data was collected at an anomalous time period but is nonetheless a useful dataset that shows strong correlations with the environmental drivers that define new partitioning models.

Brahm K. Erdmann

Concentration: Earth and Planetary Sciences



Characterizing the Optical Properties of Organic Aerosols in the Atmosphere

Advisor: **Frank Keutsch,** Stonington Professor of Engineering and Atmospheric Science; Professor of Chemistry and Chemical Biology

Understanding the optical properties of organic aerosols (OA) is essential for improving estimates of their direct radiative forcing. This thesis builds on the semi-empirical model by Li et al. (2023) to predict the real refractive index (n) of OA using only elemental composition—specifically, oxygen-to-carbon (O:C), hydrogen-to-carbon (H:C), and nitrogen-to-carbon (N:C) ratios. Based on the Lorentz-Lorenz relationship, the model was trained on 160 nitrogen-containing organic compounds and validated against measured refractive indices of laboratory-generated secondary organic aerosols (SOA).

The nitrogen-inclusive model outperforms previous elemental composition-based approaches, predicting n589nm within 5% error for 95.1% of samples in the atmospherically relevant range (RMSE = 0.0376). Accuracy improves further when density is known (RMSE = 0.0326). A generalized wavelength dependence function—fit using Cauchy's equation and SOA data from this study and previous work—extends predictions of n(λ) across the UV–NIR spectrum using only elemental inputs.

These properties were used in Mie theory and a simplified top-of-atmosphere radiative forcing (RFTOA) framework. Assuming a homogeneous OA layer with average composition from Aiken et al. (2008), the model yields an RFTOA estimate of –1.38Wm−2, compared to –1.11Wm−2 (Li et al.) and –2.20Wm−2 (Cappa et al.). The findings highlight how improved refractive index modeling can significantly impact estimates of aerosol-driven climate forcing.

Congratulations to the Senior Thesis Class of 2025!

Ian Palk

Concentration: Earth and Planetary Sciences and Intergrative Biology (secondary)

When Roots Sweat: Changing Plant Root Exudation Patterns Under Global Change and Their Potential Impacts on Soil Carbon Dynamics

Advisors: **Benton Taylor**, Assistant Professor of Organismic and Evolutionary Biology; Faculty Fellow of the Arnold Arboretum

Dave Johnston, Professor of Earth and Planetary Sciences, Harvard University

Terrestrial carbon sequestration accounts for one-third of anthropogenic CO_2 emissions, and it is mediated by carbon translocation from the atmosphere, through plants, and into soils. Root exudates—organic carbon compounds released by living plant roots into soil—represent a significant yet understudied component of this process. In this study, we investigated how plant root exudation responds to elevated CO_2 (eCO_2), warming, and nitrogen fertilization in situ. We collected 441 samples from three global change experiments in different ecosystems spanning diverse plant functional types (a forested peatland, an oak savanna, and an agricultural field) during the summers of 2022 and 2024. We found that eCO_2 has minimal effect on root exudation, contrary to our hypothesis that excess carbon would increase exudation rates. On the other hand, warming exerted strong effects on exudation, with an initial decline in rates at lower temperatures (+2.25ºC) followed by dramatic increases at higher warming levels (+9ºC). Our molecular-level analysis further revealed that this is driven primarily by changes in sugar and Krebs cycle intermediate exudation patterns that differently affect soil carbon stabilization and decomposition. Exudation of different plant species varied in both rate and composition, with implications for carbon cycling as climate change induces shifts in community composition. Our results demonstrate that global warming and biodiversity shifts, rather than eCO_2, will predominantly influence soil carbon dynamics through altered exudation patterns. These findings represent the most comprehensive assessment to date of how root exudates will respond to global change and identify previously unrecognized plant-soil feedback mechanisms that could significantly alter terrestrial carbon storage under continued climate change.

Sophia Kozart Ludtke

Concentration: Earth and Planetary Sciences and Physics (joint)

Is the Sea Level Fingerprint of Terrestrial Water Storage via Dam Impoundment Visible in the Global Tide Gauge Record?

Advisors: **Jerry X. Mitrovica,** Frank B. Baird, Jr. Professor of Science, Earth and Planetary Sciences Department, Harvard University

Peter Huybers, Professor of Earth and Planetary Sciences and Environmental Science and Engineering, Harvard University, and **Department Chair, Earth and Planetary Sciences, Harvard University**

Both the magnitude and sign of terrestrial water storage (TWS), the sum of all continental hydrologic mass, has been subject to historical uncertainty and debate. Constraining the contribution of anthropogenic and natural climate terrestrial water storage variability to global sea level change is necessary in order to close the global sea level budget. This thesis examines one important source of anthropogenic water storage on land: artificial dams. Rapid construction of global dams in the second half of the 20th century produced a spatially specific sea level fingerprint: water mass redistribution, such as terrestrial water storage in an artificial reservoir, alters Earth's gravitational field, rotation, and viscoelastic deformation, resulting in a pattern of local sea level rise and global sea level fall relative to the hydrologic point mass. Using a database recording the geographic distribution and time series of global dam impoundment from 1835–2011 (totaling nearly 8000 cubic kilometers of cumulative water storage), this thesis calculates annual sea level fingerprints based on displacement of hydrologic mass due to dam construction by applying hydrologic mass load values to a 512-degree Gauss–Legendre grid and calculating the resultant spatially-specific sea level change.

The second portion of this thesis constructs a linear mixed effects model to determine whether the sea level fingerprint of global dam construction is visible in the global tide gauge record recorded by a subset of global Permanent Service for Mean Sea Level (PSMSL) tide gauges. This model estimates the relationship between modelled sea level fingerprints due to dam impoundment and measured tide gauge sea level values, while accounting for other fixed and random effects, including vertical land motion, thermal expansion, and both universal and station-specific baseline sea level values. Inclusion of a dam-specific sea level fingerprint matrix for each tide gauge location improved the fit of the sea level model compared to a counterfactual. A coefficient of 3.34 relating modelled fingerprint and measured sea level values suggests current sea level fingerprint calculations underestimate the total sea level change associated with dam impoundment, perhaps due to seepage, confounding sea level change contributors, or incomplete accounting of total water storage in artificial reservoirs across the globe.

Julia Mansfield

Concentration: Earth and Planetary Sciences

A Comparative Assessment of the Capacity for CO2 Storage in Depleted Hydrocarbon Reservoirs of the Los Angeles Basin, California, Using Multiphase Flow Simulations

Advisor: **John Shaw**, Harvey C. Dudley Professor of Structural and Economic Geology and Harvard College Professor; **Vice Provost for Research**

Carbon capture and storage (CCS) is a critical component of climate mitigation strategies aimed at limiting global warming caused by anthropogenic emissions. Among available storage options, CO_2 injection into depleted oil and gas reservoirs offers a scalable, readily available solution for the long-term geologic sequestration of CO_2. This thesis investigates the feasibility, trapping behavior, and pressure response associated with CO_2 storage in two structurally distinct fields in the Los Angeles Basin: Wilmington and Long Beach. 3D geologic models were constructed in GOCAD and converted into unstructured tetrahedral meshes for multiphase flow simulation using the MATLAB Reservoir Simulation Toolbox (MRST). Simulations implement a black-oil formulation adapted for analyzing CO_2 solubility and phase behavior in brine, incorporating temperature and salinity dependent PVT tables derived from empirical CO_2 property calculations. Models incorporated structurally accurate fault geometries, reservoir trap structures, and petrophysical properties informed by historical field data, allowing for the site-specific modeling of CO_2 storage behavior. Results from injection scenarios across both fields showed that residual and solubility trapping dominated in dipping, open formations and enabled updip and lateral migration of the CO_2 plume, while injection into fault-bounded compartments led to localized, high-pressures and reliance on structural trapping. In both Wilmington and Long Beach, storage capacity was governed by how pressure evolved during and after injection, with structural barriers shaping plume migration paths, limiting pressure dissipation, and ultimately determining the volume of CO_2 that could be securely stored. Under a 2 MPa pressure change cap implemented in our models, Wilmington and Long Beach stored 1440 Mt and 540 Mt of CO_2, respectively, exceeding the total injected volume across all currently operating CCS projects. These findings demonstrate that storage potential depends not only on pore volume, but on how reservoir structure controls the buildup, dissipation, and spatial distribution of pressure during and after injection. This thesis provides a foundation for future geomechanical modeling to evaluate fault stability and refine the pressure caps used in storage capacity estimation. Such studies would build upon my fluid injection simulations, helping to refine assessment of storage capacity in these fields while mitigating related environmental risks.

Sarah Lillian Packman

Concentration: Earth and Planetary Sciences and Physics (joint)

Using a rare event sampling technique to quantify extreme El Niño event statistics

Advisor: **Eli Tziperman,** Pamela and Vaco McCoy, Jr. Professor of Oceanography and Applied Physics; Professor of Environmental Science and Engineering at the School of Engineering and Applied Sciences

Extreme El Niño events, such as the event of 1997–1998, can induce severe weather events on a global scale, leading to significant socioeconomic damages and changes to ecosystem function. As a result, quantifying the statistics of extreme El Niño events is a key priority for long term risk planning. However, extreme El Niño events are rare and therefore difficult to model due to computational limitations. In a very long direct numerical simulation (DNS), too few extreme events occur to robustly characterize extreme event statistics. Furthermore, it is not feasible to run a sufficiently long DNS in a full-complexity global climate model (GCM) to allow the study of extreme El Niño events, as it is too expensive in terms of data storage and computation time.

This study seeks to generate more extreme El Niño event model data at a lower cost using a rare event sampling technique called trying-early adaptive multi-level splitting (TEAMS). This technique is ideal for modeling events that have a shorter duration than the ensemble dispersion timescale. TEAMS involves generating a large, branched ensemble of interrelated trajectories through successive iterations of "killing", "splitting", and "level raising," which preferentially devote computational resources toward trajectories that are likely to result in extreme events. We apply TEAMS to the Zebiak-Cane model, an inexpensive, intermediate complexity ENSO model for which it is feasible to run a long DNS (500,000 years). We compare extreme El Niño event return time estimates from TEAMS to those from the long DNS to assess TEAMS' accuracy and efficiency.

We find that TEAMS accurately reproduces the return time estimates of the DNS, and that TEAMS' accuracy is robust to changes in its hyperparameters. In our current implementation, which is still a work in progress, TEAMS requires a larger number of model years to produce return time estimates with the same variance (error estimate, measured by bootstrapped 95% confidence intervals) as the DNS. If TEAMS and the DNS use the same number of model years, TEAMS return times have larger uncertainties for return periods between 100–10,000 years; for longer return periods, TEAMS and the DNS have comparable error estimates. Therefore, for the most extreme events, TEAMS is as efficient (but not more so) than a DNS. Future work could likely improve TEAMS' efficiency by tuning the various hyperparameters and exploring the effect of different splitting schemes. Eventually, it should be possible to successfully apply TEAMS to a full-complexity GCM.