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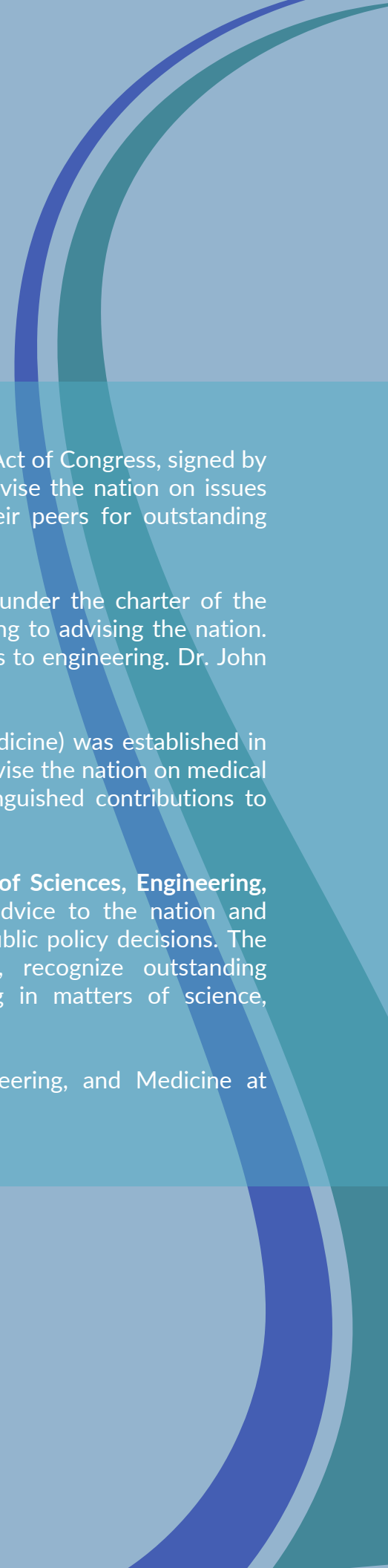
25TH ANNUAL ROGER REVELLE
COMMEMORATIVE LECTURE

EQUITABLE SCIENCE AND SOLUTIONS FOR A WARMING WORLD

Featuring Kim Cobb, Ph.D.



Thursday, June 13, 2024 | 5:30 pm PDT
Scripps Seaside Forum



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DEAR LECTURE PARTICIPANT

On behalf of the Ocean Studies Board of the National Academies of Sciences, Engineering, and Medicine, we would like to welcome you to the 25th Annual Roger Revelle Commemorative Lecture. This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between the ocean sciences and public policy.

TONIGHT'S LECTURE

This evening, for the 25th annual lecture, the Scripps Institution of Oceanography is hosting the event on the campus where Roger Revelle began his career in oceanography and later served as director. The lecture will be given by Kim Cobb, an oceanographer who also started her career at Scripps. The title of her talk is "Equitable science and solutions for a warming world." Margaret Leinen, the current director of Scripps, will provide the introduction.

SPONSORSHIP

The Ocean Studies Board thanks the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Geological Survey. This lecture series would not be possible without their generous support.

We hope you enjoy tonight's event.

Claudia Benitez-Nelson, *Chair, Ocean Studies Board*

Susan Roberts, *Director, Ocean Studies Board*

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Kim Cobb

Kim Cobb is the Director of the Institute for Environment and Society at Brown University, and Professor in Environment and Society as well as Earth, Environmental, and Planetary Sciences. As a climate scientist, she uses observations of past and present climate to advance our understanding of future climate change impacts, with a focus on climate extremes and coastal flooding. She received her B.A. from Yale University in 1996, and her Ph.D. in Oceanography from the Scripps Institute of Oceanography in 2002. Prior to joining Brown in 2022, she served as Director of the Global Change Program at Georgia Tech, Professor in the School of Earth and Atmospheric Sciences, and ADVANCE Professor for Diversity, Equity, and Inclusion. In her research, Kim has sailed on oceanographic cruises to the remote central Pacific and led caving expeditions in the Borneo rainforests. She received a NSF CAREER Award, a Presidential Early Career Award for Scientists and Engineers, and the Hans Oeschger Medal from the European Geosciences Union in 2019. She was elected Fellow of the American Association for the Advancement of Science in 2021, and Fellow of the American Geophysical Union in 2023. She served as Lead Author for the IPCC Sixth Assessment Report, released in 2021. In 2023, President Biden appointed her to the President's Intelligence Advisory Board. As a mother to four, Kim is a strong advocate for women in science, and champions diversity and inclusion in all that she does. She is also devoted to the communication of climate change to the public through media appearances, public speaking, and social media channels, and enjoys frequent exchanges with policymakers about climate impacts and solutions.

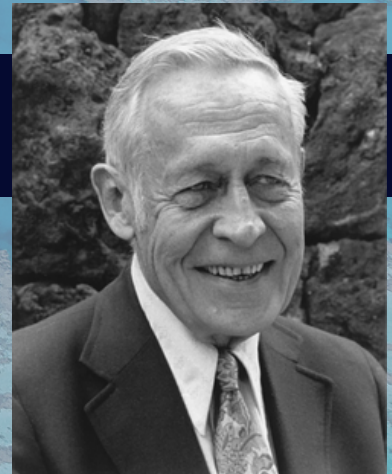


Margaret Leinen

Margaret Leinen is the director of the Scripps Institution of Oceanography and the vice chancellor for Marine Science at the University of California, San Diego. She is an ocean biogeochemist and paleoceanographer whose research includes the study of ocean carbon cycling and the role of the oceans in climate. During 2017 and 2018 Dr. Leinen was a U.S. Department of State Science Envoy for the oceans to Latin America and the Pacific. She served as the assistant director for geoscience at the National Science Foundation from 2000 to 2007. She has also served as the president of the American Geophysical Union, president of The Oceanography Society, and chair of the American Association for the Advancement of Science Section on Atmospheric and Hydrospheric Science. She is a Fellow of all three societies and an elected member of the American Academy of Arts & Sciences.

Roger Revelle

Revelle was a pioneer in oceanography who over his 50-year career pursued innovative research and created a vision that still influences the field of oceanography to this day. A strong proponent of science communication and public policy, Revelle was a leader in encouraging the scientific community to devote time to address the “long-range problems of society” (Day, 2000, quoting Revelle, 1957). For his contributions to geophysics, Revelle was elected to membership in the National Academy of Sciences (NAS). Revelle’s commitment to science policy is evident in his extensive contributions to the work of the NAS. Revelle served as a member of the Ocean Studies Board and its predecessor (Ocean Sciences Board) from 1983 to 1987. He also served on the Board on Atmospheric Sciences and Climate (1982–1986) and as a committee member for several influential National Academies’ studies.

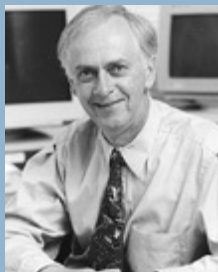


Munk, 1997. Copyright 1997, National Academy of Sciences, U.S.A.

REFERENCE

Day, D. 2000. Quotations from Roger Revelle. Scripps Institution of Oceanography Archives. https://library.ucsd.edu/scilib/biogr/day_quotations-from-roger-revelle.pdf (accessed April 6, 2023).

Roger Revelle Commemorative Lecturers 1999-2023



1999
Peter Brewer



2006
Roger Pielke, Jr.



2000
Shirley Pomponi



2007
Ken Caldeira



2001
Marcia McNutt



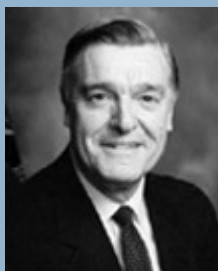
2008
Michael Freilich



2002
Michael Orbach



2009
Paul Falkowski



2003
James Watkins



2010
Jane Lubchenco



2004
Richard Alley



2011
Nancy Rabalais



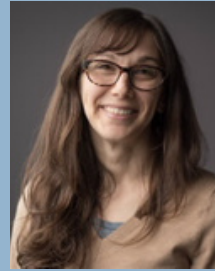
2012
Eddie Bernard



2019
Lisa Levin



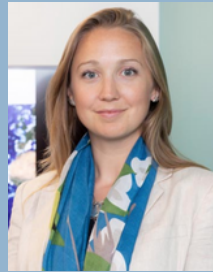
2013
John Walsh



2020
Chelsea Rochman



2014
David Karl



2021
Harriet Harden-Davies



2015
Susan Lozier



2021
Alfredo Giron-Nava



2016
Philip Clapham



2022
John Dabiri



2017
Dawn Wright



2023
Kathy Sullivan



2018
Jeffrey Bolster



2023
Margaret Leinen

Equitable Science and Solutions for a Warming World

The Ocean Studies Board is proud to present the 25th Annual Roger Revelle Commemorative Lecture featuring Dr. Kim Cobb. This lecture provides an opportunity to share work occurring at the intersection of public policy and science, continuing Revelle's legacy of scientific research that advances knowledge and provides critical information on issues of importance to society.

HOW IT STARTED

From the moment I learned about human-caused climate change, my mind has been ablaze with questions that haven't stopped to this day. How bad would it get? If more people understood the problem, would society intervene in the path towards a rapidly warming world? What role could science play in painting a picture of our possible climate futures? It was 1993. While my college textbooks contained no mention of human-caused climate change – Jim Hanson's Congressional testimony had occurred only 5 years prior – my geology professors included it in their lectures. Now a college professor myself, I delight in teaching students about the latest climate science findings, and in supporting them on their explorations of climate solution-focused career paths.

An early internship at the Scripps Institute of Oceanography would cement my goals to pursue a graduate degree in Oceanography, with a focus on reconstructing past climate extremes for comparison to present-day and potential future climate extremes. My internship saw me conducting independent research in the lab of Dr. Tim Herbert, hunting the sedimentary signatures of late 20th century El Niño events in Santa Barbara marine sediment cores.

El Niño events have their origins deep in the tropical Pacific Ocean, where winds and currents work across a vast expanse of ocean to swing the Pacific between warm and cool extremes every few years. The El Niño warm phase takes hold for roughly six months over the end of the calendar year, altering atmospheric circulation patterns across the globe that drive a large number of weather extremes. El Niño events drive flooding in California and along the west coasts of Central and South America, while Brazil, Indonesia, and portions of East Africa are plagued by drought. These events also drive an increase in typhoon activity across the eastern Pacific, and a reduction in North Atlantic hurricane activity. The La Niña cool phase has largely opposite effects. Together these climate variations define the El Niño-Southern Oscillation - the largest source of year-to-year global climate variability outside the seasonal cycle.

At the time of my internship in 1994, the 1982-83 El Niño event was the strongest event on record. It left an indelible mark in the form of a thick, dark layer of flood-driven debris in the sediments I was studying. News accounts of damaging coastal flooding in California were but one small part of a surge of weather extremes associated with the 1982-83 El Niño. While a large El Niño event had occurred in 1972-73, the full force of earlier events was obscured by scant instrumental coverage of the remote tropical Pacific Ocean prior to the advent of temperature-recording satellites in the late 1970's.

As a graduate student at Scripps, I would spend years honing my skills as an El Niño hunter through extensive fieldwork on remote Pacific Ocean islands. My first oceanographic cruise took place during an exceptionally strong El Niño in fall of 1997, when we arrived at the equator under a deluge of rainfall and storms fueled by the bath-like ocean surface. Underwater, the corals at our research destination, Kiritimati Island (part of the Republic of Kiribati) were experiencing severe bleaching, an adaptation designed to help corals survive short-lived temperature extremes lasting less than a few months. I had my first taste of El Niño's havoc, and I was hooked. Was the 1997-98 El Niño a sign of El Niño's to come under continued global warming? Or was this event part of the spectrum of natural variability that hadn't changed over the last centuries?

Just six months later, I would return to the same islands as the tropical Pacific Ocean plunged into one of the longest and strongest La Niña cooling events on record. It was during this trip that I collected some misshapen, weathered coral heads strewn across beaches on a small island called Palmyra, located at the center of the Pacific Ocean. A postdoctoral fellow in my lab, Dr. Michael Moore, drilled a 3 meter-long core from a large coral head growing on the reef, providing critical insights into how 20th century El Niño-Southern Oscillation (ENSO) extremes were recorded in the coral skeletal chemistry of the resulting 110-year-long, monthly resolved reconstruction. Back home, initial radiocarbon dates would reveal that the corals grew at various intervals during the last millennium,

ranging in age from 900 CE to 1900 CE. This initial collection was greatly augmented by an additional trip to Palmyra in 2000, providing a trove of 30+ individual coral cores for the reconstruction of central tropical Pacific climate over the last millennium. ENSO's recent history would slowly be revealed over decades of ensuing research.



*The author posing with a large *Porites* coral colony emblematic of the type of coral used for tropical climate reconstruction. Kiritimati Island circa 2013. Credit: Pamela Grothe/Cobb Lab.*

CORAL RECORDS OF EL NIÑO

By the 1990's, decades of research had established corals as the archive of choice for ENSO reconstruction. Studies dating back to the early 1970's documented a strong relationship between ambient ocean temperature and the oxygen isotopic composition ($\delta^{18}\text{O}$) of coral skeletons (Weber and Woodhead, 1972). Subsequent work revealed that coral oxygen isotopes also captured changes in the oxygen isotopic composition of seawater (Dunbar and Wellington, 1990), that mirror changes in seawater salinity (Mook, 1970). Early investigations of ENSO signatures in corals from the Galapagos (Druffel, 1985), the Great Barrier Reef (Lough and Barnes, 1989), and the central Pacific (Cole et al., 1990) foreshadowed an explosion of new records from across the tropical oceans. A largely parallel line of research witnessed the development of coral skeletal strontium to calcium ratios (Sr/Ca) as an additional source of temperature information in corals (Weber, 1973; Smith et al., 1979) paving the way for the paired application of coral Sr/Ca and $\delta^{18}\text{O}$ to quantify changes in surface temperature and salinity, respectively.

Monthly-resolved coral $\delta^{18}\text{O}$ and Sr/Ca records from the central tropical Pacific Ocean mirrored changes in ENSO with exceptional fidelity (Evans et al., 1999), as ENSO-related changes in temperature and salinity dominate climate in this region. The secret to the success of coral ENSO reconstructions in the central tropical Pacific Ocean is that during El Niño events, warm and rainy conditions work together to drive coral

$\delta^{18}\text{O}$ signatures lower, and vice versa during cool, dry La Niña events. It is fortuitous that a string of relict volcanic islands - the Northern and Southern Line Islands - extends on either side of the equator in the core of the central Pacific Ocean, where coral $\delta^{18}\text{O}$ -based reconstructions of ENSO benefit from relatively high signal to noise ratios. These islands also fall under the influence of lower-frequency Pacific Ocean climate variability such as the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; Newman et al., 2016) and the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2016) that operate on decadal timescales. As such, coral records from these locations provide invaluable archives of decadal to interdecadal climate variability, allowing for the separation of natural from anthropogenic low-frequency climate drivers over the data-scarce 20th century.

2,000 YEARS OF LINE ISLAND CORAL CLIMATE RECONSTRUCTIONS

Over two decades of research, including nine field expeditions, my students and postdoctoral fellows worked with collaborators from other lab groups to generate a large dataset of monthly-resolved coral records from Palmyra (6°N, 162°W), Fanning (4°N, 160°W), and Kiritimati (2°N, 157°W) Islands - part of the Northern Line Island chain. These records yielded a trove of insights about tropical Pacific Ocean climate change spanning the last 6,000 years, based on analyses of both living coral colonies (hereafter "modern corals") and long-dead coral heads collected from rubble deposits on ocean-facing beaches (hereafter "fossil corals"). Nurhati et al., 2009, 2011 applied paired Sr/Ca and $\delta^{18}\text{O}$ analyses to a suite of modern corals from 2, 4, and 6 degrees latitude to uncover a prominent late 20th century freshening trend whose magnitude scaled with latitude. Against a millennium-long pre-industrial baseline of tropical Pacific climate provided by fossil corals (Cobb et al., 2003), this late 20th century freshening trend is unprecedented, implying an anthropogenic origin.

The hardest target of our research, by far, has centered on the question of if and how ENSO characteristics changed in response to anthropogenic greenhouse gas emissions. In order to address such a question, hundreds of years of ENSO data are required owing to the high degree of decade-to-decade variations in the frequency and amplitude of ENSO extremes (see Stevenson et al., 2012). And while monthly-resolved coral records from the Line Islands proved to be exceptionally high-fidelity archives of ENSO activity (Cobb et al., 2001, 2013; Grothe et al., 2019), it would take years to amass enough data to enable a robust, quantitative comparison. The analysis of 30 coral $\delta^{18}\text{O}$ measurements, representing 2 years of coral growth, requires 24 hours of mass spectrometry time. Such instruments are notoriously fickle, for which

extended downtimes of 6 months are not unusual. Thus the production of many centuries' worth of coral $\delta^{18}\text{O}$ would take decades of lab work.

The culmination of our efforts to reconstruct ENSO extremes resulted in over 2,000 years of monthly-resolved Line Island coral $\delta^{18}\text{O}$ data, revealing that recent ENSO extremes were significantly stronger than those of the pre-industrial era (Grothe et al., 2019). Specifically, we found a 25% increase in interannual coral $\delta^{18}\text{O}$ variance in the last 50 years as compared to the preceding multi-millennium baseline. In the preceding years, a number of studies had provided evidence for an anthropogenic increase in ENSO variability (Li et al., 2013; Liu et al., 2017; McGregor, et al., 2013). In the same year, additional lines of evidence from studies using both instrumental climate data (Wang et al., 2019) and data derived from a large network of coral records (Freund et al., 2019) would strengthen the finding that ENSO characteristics had already shifted in response to greenhouse gasses. The strongest lines of evidence pointed to a shift in the atmospheric response to underlying ENSO-related ocean warming, as summarized by Cai et al. (2021). Under this interpretation, our coral $\delta^{18}\text{O}$ data reflect an increase in the hydrological component of ENSO's impact at our site (i.e., rainier conditions during El Nino events drive increased seawater $\delta^{18}\text{O}$ variability, resulting in increased interannual coral $\delta^{18}\text{O}$ variability). At the same time, a shift in ENSO maximum temperatures from the eastern to central Pacific Ocean is strongly supported by the paleoclimate data (Freund et al., 2019), and cannot be ruled out (see review in Capotondi et al., 2020). In this scenario, the increase in ENSO variability indicated in our coral $\delta^{18}\text{O}$ data reflect this shift towards maximum sea surface temperatures in the central Pacific Ocean. In reality, the increase of interannual coral $\delta^{18}\text{O}$ variations at our central Pacific site could reflect one or all of the following drivers: an increase in the hydrological impact of ENSO extremes, a shift in the locus of maximum warming from the eastern to central Pacific, and/or a wholesale intensification of the ENSO phenomenon itself.

A key limitation of our Line Islands' coral-based ENSO reconstructions is that they reflect ENSO variability as recorded at a single (albeit well-positioned) location. A full characterization of ENSO properties requires similarly long, detailed views of western, central, and eastern equatorial Pacific Ocean interannual climate variability. Such records are not yet available, and may never be. Nonetheless, our lab's research has managed to provide some further constraints on the temperature versus hydrological contributions to our coral $\delta^{18}\text{O}$ signals, thanks to close observation of the off-scale 2015-16 El Niño event. In O'Connor et al. (2021), we estimate that temperature contributed roughly 70% of the coral

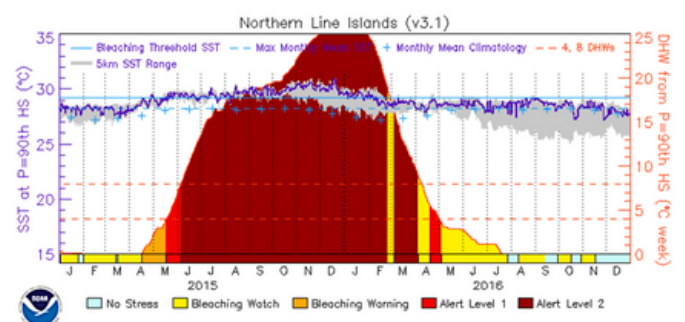


Installing a temperature logger on the reef at Kiritimati Island, with field guide Tiito Teabi. Source: Cobb Lab.

$\delta^{18}\text{O}$ signal across the 2015-16 El Niño, with ~30% ascribed to changes in seawater $\delta^{18}\text{O}$.

THE 2015-2016 EL NIÑO EVENT

During a series of closely spaced expeditions to Kiritimati Island beginning in summer, 2015, our lab group joined collaborators from the University of Victoria to document the ecological, geochemical, oceanographic, and atmospheric impacts of the 2015-16 El Niño. Dr. Julia Baum had been monitoring Kiritimati reefs for seven years at that point, painstakingly photographing transects, tagging corals, and collecting tissue samples to monitor coral algal symbiont populations. Forecasts of the El Niño event six months in advance gave us much-needed lead time to seek National Science Foundation funding to support the expeditions, arrange for research permits, book travel, and file dive safety plans. Our lab measured rainwater and seawater $\delta^{18}\text{O}$, photographed our coral sampling sites, and installed both temperature and salinity loggers on various reefs across the island. By the time we had finished setting up our monitoring and sampling programs in August 2015, ocean temperatures were exceeding 30°C in foreboding bursts. The coral reefs were pushed deep into the "red alert" status for NOAA's Coral Reef Watch, a program that flags reefs in danger of temperature-related bleaching and mortality in real-time. Indeed, during our July 2015 expedition, our teams would document widespread bleaching that had turned all the large "table" corals, *Acropora palmata* - a sickly white.



Thermal heat stress across the Northern Line Islands during the 2015-16 El Niño event. Corals were exposed to ocean temperatures above the bleaching threshold for 9 months. Source: NOAA Coral Reef Watch.

At the peak of the El Niño in November 2015, water temperatures exceeded 31°C for several weeks, resulting in wholesale bleaching that impacted 90% of the reef as documented by our team over dozens of dives. Looking back, those were the most eerie dives, painstakingly photographing and videotaping a whole ecosystem on the brink of death. All but the *Acropora palmata* heads, which had long succumbed to warmer temperatures, were still hanging on by a thread, waiting in vain for cooler temperatures that would not come for another seven months. Our lab members toiled under grueling conditions, under a steady stream of rainfall by day and besieged by mosquitoes at night. The unusually wet conditions had caused a population explosion of disease-carrying mosquitoes that caught the normally dry island, and our team, unprepared. One of my students and I contracted mosquito-borne illnesses (dengue and chikungunya, respectively) that ravaged the island's population that year.

By April 2016, our expedition members had the grim task of documenting a mass mortality event that took place underwater at Kiritimati Island. It seems impossible to comprehend that it was a surprise to many of us, given the many months of scorching water temperatures that we knew had gripped the Island. But when I first jumped into the water and looked down at the reef below, nothing could have prepared me for the shock of seeing a carpet of red-brown algae covering the now-dead reef as far as the eye could see. On that trip, Dr. Baum's team estimated that 90% of the corals on the island had perished, with 5% bleached, and 5% healthy.



Photo of pre-El Niño and post-El Niño corals at Kiritimati Island, Republic of Kiribati. Source: Cobb Lab.

Our team's observations of coral mass mortality I would and us on the front page of the New York Times (www.nytimes.com/2016/04/10/world/asia/limate-related-death-of-coral-around-world-alarms-scientists.html), one of the first of many ensuing articles documenting the global-scale bleaching and mortality event of 2016. To this day, 2016 holds a grim record in terms of scale and severity of losses (Hughes et al., 2017; Eakin et al., 2022). The corals at Kiritimati are

recovering, but it will take decades to recoup the loss of coral colony diversity and size class, given that the largest colonies on the island (roughly 50 years old) had all perished. This year, the 2023-2024 El Niño brought the reef into NOAA's Coral Reef Watch's Alert Level 2 - the highest alert level, indicating "severe bleaching and mortality likely" - for many months, likely extracting a toll on a reef system still very much in recovery.

A RECKONING FOR A CLIMATE SCIENTIST

For me, the 2016 El Niño was a bellwether event. It demanded an accounting on several fronts. First, I had to face the fact that despite my intellectual fluency about the pace of anthropogenic climate change and its many global impacts, I had managed to mostly escape emotional engagement with those scientific facts. Second, I had to face the idea that my entire career spent characterizing the present-day impacts and mechanisms of human-caused climate change would not in and of itself accelerate solutions to the crisis. The former is a challenge for nearly everyone who has not lost something precious to the climate crisis. Although many thousands have lost their lives as a consequence of climate change, most of us have been spared the emotional sense of loss. This has no doubt impeded progress at all scales. For climate scientists like me, the lack of response despite the accumulating scientific evidence is an invitation to think about short-circuiting the usual science-to-policy process by allowing our voices to extend far beyond the realm of the traditional mode of scientific expression - the peer-reviewed literature.

On a personal level, my commitment to explore a lower-carbon lifestyle of increasing ambition beginning in 2017 meant that climate change would be a daily presence in my life. I began biking to work, installed solar panels on my house, upgraded our HVAC system to air source heat pumps, insulated our basement and attic, began composting, reduced my flying year-on-year, and shifted our family's diet to mostly vegetarian foods. I also joined our neighborhood board as transportation chair and became deeply involved in local advocacy efforts to improve bike and pedestrian infrastructure.

As a climate scientist, I began to add my voice to a small but growing group of climate scientists willing to speak out in defense of climate science findings. While climate science, and scientists, had always been subject to politicized attack, those attacks dramatically increased beginning in 2017, as federal policy shifted away from evidence-based climate and energy policy towards continued dependence on fossil fuels. A steady drumbeat of climate-fueled disasters, including a record-breaking 2017 hurricane season and devastating wildfires across the western U.S., to name a few, provided ample

opportunity to highlight the ways in which climate change was threatening our health, our economy, and our national security. I found myself engaged in a steady stream of media appearances (www.youtube.com/watch?v=VM0jC_3TEUs; www.youtube.com/watch?v=PGI2YSYdfak) that continue to this day. I also used my growing social media presence (<https://twitter.com/coralsncaves>) to showcase the relevance of climate science to policy-making around emissions mitigation and climate adaptation. Through public lectures and exchanges, I shared climate science findings with schools, churches, community clubs, corporate headquarters, chambers of commerce, parks, and elected officials at the local, state, and federal levels (www.youtube.com/watch?v=6W2ypw4bUxc). Such activities demanded many hours per week of my time - time away from my other professional obligations and my family - but seemed like a readily available lever for large-scale action, when replicated across dozens of my colleagues doing similar work. The fact that such efforts are not only not rewarded but are all too often frowned upon in certain segments of academia, was not lost on me. In part, this would motivate me to explore ways in which work on climate solutions, whether through public engagement, research, and/or education could be woven into the fabric of an institution of higher education. Ultimately, it would also drive me to a career in university administration, where I might shift cultural norms and practices to embrace as many levers of climate solutions as possible. In 2018, I was appointed as the inaugural Director of the Global Change Program (globalchange.gatech.edu/) at Georgia Tech, with a charge to advance climate solutions research and education across the campus.



Speaking at a 'Stand Up for Science' rally at the Fall AGU Meeting, December, 2016. Credit: Randy Showstack (<https://eos.org/articles/scientists-explore-how-best-to-communicate-about-climate-change>).

TRANSDISCIPLINARY CLIMATE SOLUTIONS RESEARCH

As a climate-vulnerable state with a low-lying coastline and triple-digit summer temperatures, Georgia presented many opportunities to apply climate science skills and knowledge to advance climate solutions. However, as I learned more about the nature of Georgia's climate

vulnerabilities, and efforts to address them, I quickly realized that such systems-level challenges required a systems-level solution that would require expertise across multiple academic disciplines. Not only that, it would require direct and sustained engagement with community members and organizations, policymakers, and planners who had expert knowledge of local culture, economy, politics, and geography. In other words, it would require the deployment of a "transdisciplinary" research framework (see Berstein, 2015 for a review). In this research mode, experts from different disciplines of academia partner with non-academic experts to co-develop research questions, methods, and products as a coordinated research team.

In 2018, the "Smart Sea Level Sensor" (www.sealevelsensors.org/) project took shape, bringing a socio-technical approach to flood mitigation along the Georgia coastline that continues to grow its impact to this day. Comprised of officials from Savannah and surrounding Chatham County, the project from Day 1 leveraged unique skill sets from Georgia Tech computer scientist Dr. Russ Clark, ocean modeler Dr. Emanuele Di Lorenzo, and an observational climate scientist (me). Early meetings would identify the opportunity to design and deploy comms-enabled, ultrasonic water level sensors in flood-prone locations around the city and county. The sensors would relay real-time information about water levels to emergency planners and responders, enabling advanced warning of imminent flooding as well as post-event flags for bridges and other critical infrastructure that would require safety inspections prior to opening. The sensor data streams also provided a much-needed training dataset for an sophisticated model that would be developed to forecast coastal flooding along the entire Georgia coast (Park et al., 2022). Biweekly project team calls and quarterly public workshops in Savannah supported the project's rapid growth in terms of accomplishments and partnerships up and down the coast. Within months, social and education scientists would join the team, bringing expertise in digital media, K-12 pedagogy, sociology, and urban planning. It took well over a year to welcome our first community organizational partner - the environmental justice NGO Harambee House - to our growing research team. This costly delay resulted in some overdue reworking of our community engagement strategy to center Savannah's frontline and fence communities most impacted by climate change. To date, over sixty sensors have been deployed, several data portals launched, including a public-facing portal, and over \$6.5M in funding has been secured. In recent years, the addition of the Pin Point Gullah-Geechee community as a core partner has allowed for a focus on Indigenous definitions and practices of community resilience, including workforce development, land deeds, and

preservation of cultural heritage. The project now exists as the Coastal Equity and Resilience Hub (www.cearhub.org/), and includes a local HBCU, Savannah State, as well as the University of Georgia as core partners.



Photo of Jenkins High School student assembling a Smart Sea Level Sensor as part of her Engineering curriculum. Credit: Russ Clark, Georgia Tech.

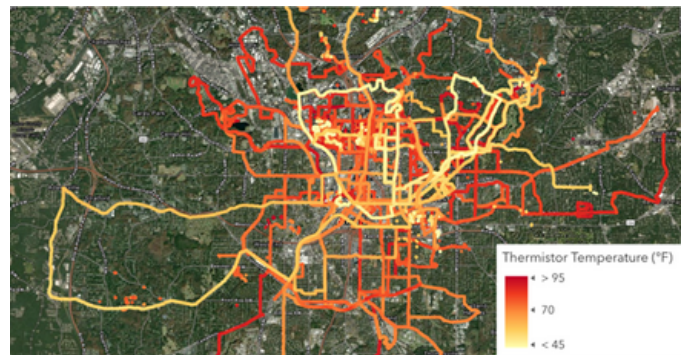
In 2020, at the height of the COVID19 pandemic, I joined forces with Dr. NaTaki Osborne-Jelks, an environmental health expert from nearby Spelman College, to launch UrbanHeatATL (<https://urbanheatatl.org/>). The goal of the project was to create meter-scale maps of urban temperature extremes with data captured by community scientists. Our work was inspired by Dr. Jeremy Hoffman's efforts to map urban temperatures across Richmond, VA, wherein he documented that historically 'redlined' neighborhoods were significantly hotter than surrounding areas (Hoffman et al., 2020). Redlining refers to a federal policy that rated neighborhoods across America on a scale of favorable to less favorable investment opportunities, whereby lower-income communities of color received lower ratings. As such, these neighborhoods were subject to decades of disinvestment, such that their modern-day landscapes and geographies contain more impervious surfaces and less greenspace. Today, even decades after redlining was discontinued, the hottest areas in major cities are often associated with historically redlined neighborhoods. The goals of UrbanHeatATL were to i) work with community scientists to co-develop a new hyperlocal dataset of "hotspots" across Atlanta, and ii) leverage this data in identifying potential heat resilience strategies, with a focus on Atlanta's most vulnerable residents.

At the height of the project, in 2021, over 100 community scientists supplied temperature data to the UrbanHeatATL dataset, supplemented by data collected from 22 fixed meteorological stations installed in heat vulnerable regions across the metro area. The West Atlanta Watershed Alliance, an Atlanta-based NGO focused on advancing environmental justice, served as a keystone partner, together with Spelman College and Georgia Tech. Collaborations with the Mayor's Office of

Sustainability and Resilience, the Atlanta chapter of the National Weather Service, and the Fulton County Emergency Management Agency, informed the collection and analysis of data. Community workshops surfaced research questions to guide the continued development of the project, and summer interns from both Georgia Tech and Spelman brought many aspects of the project's transdisciplinary goals to life. In 2022, we launched a K-12 pilot program (<https://blog.thepocketlab.com/thomasville-students-participate-in-nationwide-research-project>) at Thomson High School in southern Georgia, where students used the sensors to learn about climate change and urban heat islands in their neighborhoods. As of 2023, the project's data and collaborative network transitioned to a home at Georgia Tech's Urban Climate Lab (<https://urbanclimate.gatech.edu/>), under the direction of Dr. Brian Stone.



Community scientists from UrbanHeatATL displaying the PocketLab portable temperature sensor, which recorded ambient temperatures every 1 second via an app on their phones.



Map of UrbanHeatATL temperature data collected during 2021.

PATHWAYS FOR CLIMATE SOLUTIONS LEADERSHIP IN SCIENCE

In previous sections, I've illustrated how basic climate research, policy-relevant climate research, and transdisciplinary climate solutions research provide key avenues for supporting the development of evidence-based climate solutions. However, in order to unlock the full potential of the scientific research enterprise towards that end, I argue that the research ecosystem must accelerate its evolution along several discrete axes:

1. deepening the role of public engagement in research, as a vehicle for guiding the genesis of research questions and for shaping research outcomes for maximum impact,
2. working to advance justice, equity, diversity, and inclusion in research, so that the research enterprise benefits from diverse perspectives and lived experiences. This includes working to redefine the definition of “experts” to include a wide variety of knowledge holders whose contributions are valued and equitably structured in the context of compensation, data stewardship, project governance, and more.
3. contributing to institutional and cultural change, whereby social norms and practices, as well as institutional norms and practices, are brought into closer alignment with science-based emissions targets, resilience, and adaptation efforts.

These are broad categories inclusive of dozens of potential avenues for engagement that allow the tailoring of one’s effort to discreet topics and scales of interest. Ideally, the effort will give new meaning to the science enterprise by providing an opportunity for community-building and the cultivation of new skills and networks. These efforts may require challenging the status quo and given the lack of institutional support for such activities. Also, it requires a tolerance for trial and error. In far too many cases, negative experiences with early forays into these areas of work or fears of negative professional consequences prevent many scientists from pursuing these dimensions of the scientific research ecosystem. Senior scientists and administrators play an especially important role; they can serve as role models, engaging in these three axes of work and advancing institutional policies and practices that encourage others to engage.

The landscape for advancing transdisciplinary scholarship in science is somewhat compromised by the fact that it is undervalued relative to basic scientific research in part because its products may or may not include scientific journal publications and federal grants. Despite a dearth of resources, training opportunities, and avenues for professional advancement, more early career researchers are interested in pursuing transdisciplinary applications of their work than their senior faculty counterparts. It is therefore incumbent on senior scientists and administrators to put time and effort towards achieving the following outcomes: 1) changing hiring, tenure, and promotion criteria to include aspects of these four areas of professional scientific work, 2) nominate scholars – both senior and junior – whose work extends deeply into one or more of these four areas for prestigious honors and awards, and 3) advocate for, pilot, contribute to, and continually cultivate training ecosystems and

communities of practice that scholars of all career stages can benefit from, whether as a first-timer or a seasoned practitioner.

Not everyone will feel compelled to extend their efforts beyond the traditional domains of basic research and education. For many scientists, the challenge and thrill of discovery-driven research is sufficient. However, the status quo favors basic research with insufficient recognition of other components of the scientific enterprise. We owe it to the next generation of scientists, to the relevance and durability of the scientific enterprise, to a public more eager than ever for evidence-based policymaking, and to our collective vision for a just, sustainable future.



A schematic illustrating possible components of a professional portfolio geared towards advancing culture, policies, and practices in science that contribute to the development and deployment of climate solutions. These levers for action are applicable across a wide range of scales of impact, including the hyperlocal, local, city, state, national, and/or international levels. Source: Kim Cobb, 2023 Emiliani Lecture, American Geophysical Union Fall Meeting

REFERENCES

- Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.-S., Lengaigne, M., McPhaden, M. J., Stuecker, M. F., Taschetto, A. S., Timmermann, A., Wu, L., Yeh, S.-W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X.-T., Bayr, T., Brown, J., Capotondi, A., Cobb, K. M., Gan, B., Geng, T., Ham, Y.-G., Jin, F.-F., Jo, H.-S., Li, X., Lin, X., McGregor, S., Park, J.-H., Stein, K., Yang, K., Zhang, Li., & Zhong, W. (2021). Changing El Niño-southern oscillation in a warming climate. *Nature Reviews Earth & Environment*, 2(9), 628–644. doi:10.1038/s43017-021-00199-z
- Capotondi, A., Wittenberg, A. T., Kug, J., Takahashi, K., & McPhaden, M. J. (2020). ENSO diversity. *Geophysical Monograph Series*, 65–86. doi:10.1002/9781119548164.ch4
- Cobb, K. M., Charles, C. D., & Hunter, D. E. (2001). A Central Tropical Pacific Coral demonstrates Pacific, Indian, and Atlantic decadal climate connections. *Geophysical Research Letters*, 28(11), 2209–2212. doi:10.1029/2001gl012919
- Cobb, K. M., Charles, C. D., Cheng, H., & Edwards, R. L. (2003). El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, 424(6946), 271–276. doi:10.1038/nature01779
- Cobb, K. M., Westphal, N., Sayani, H. R., Watson, J. T., Di Lorenzo, E., Cheng, H., Edwards, R. L., & Charles, C. D. (2013). Highly variable El Niño-southern oscillation throughout the Holocene. *Science*, 339(6115), 67–70. doi:10.1126/science.1228246
- Cole, J. E., & Fairbanks, R. G. (1990). The Southern Oscillation recorded in the δ18O of corals from Tarawa Atoll. *Paleoceanography*, 5(5), 669–683. doi:10.1029/pa005i005p00669

- Di Lorenzo, E., Schneider, N., Cobb, K. M., Franks, P. J., Chhak, K., Miller, A. J., McWilliams, J. C., Bograd, S. J., Arango, H., Churchitser, E., Powell, & T. M., Rivière, P. (2008). North Pacific Gyre oscillation links ocean climate and Ecosystem Change. *Geophysical Research Letters*, 35(8). doi:10.1029/2007gl032838
- Druffel, E. R. (2013). Detection of El Niño and decade time scale variations of sea surface temperature from banded coral records: Implications for the carbon dioxide cycle. *The Carbon Cycle and Atmospheric CO₂ : Natural Variations Archean to Present*, 111–122. doi:10.1029/gm032p0111
- Dunbar, R. B., & Wellington, G. M. (1981). Stable isotopes in a branching coral monitor seasonal temperature variation. *Nature*, 293(5832), 453–455. doi:10.1038/293453a0
- Eakin, C. M., et al. (167 co-authors) (2022). The 2014-17 Global Coral Bleaching Event: The Most Severe and Widespread Coral Reef Destruction (preprint, in review). doi:10.21203/rs.3.rs-1555992/v1
- Evans, M. N., Fairbanks, R. G., & Rubenstone, J. L. (1999). The thermal oceanographic signal of El Niño reconstructed from a Kiritimati Island coral. *Journal of Geophysical Research: Oceans*, 104(C6), 13409–13421. doi:10.1029/1999jc900001
- Freund, M. B., Henley, B. J., Karoly, D. J., McGregor, H. V., Abram, N. J., & Dommenges, D. (2019). Higher frequency of Central Pacific El Niño events in recent decades relative to past centuries. *Nature Geoscience*, 12(6), 450–455. doi:10.1038/s41561-019-0353-3
- Grothe, P. R., Cobb, K. M., Liguori, G., Di Lorenzo, E., Capotondi, A., Lu, Y., Cheng, H., Edwards, R. L., Southon, J. R., Santos, G. M., Deocampo, D. M., Lynch-Stieglitz, J., Chen, T., Sayani, H. R., Thompson, D. M., Conroy, J. L., Moore, A. L., Townsend, K., Hagos, M., O'Connor, G., & Toth, L. T. (2019). Enhanced El Niño–Southern Oscillation variability in recent decades. *Geophysical Research Letters*, 47(7). doi:10.1029/2019gl083906
- Hoffman, J. S., Shandas, V., & Pendleton, N. (2020). The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. *Climate*, 8(1), 12.
- Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkemans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., Eakin, C. M., Figueira, W. F., Gilmour, J. P., Harrison, H. B., Heron, S. F., Hoey, A. S., Hobbs, J.-P. A., Hoogenboom, M. O., Kennedy, E. V., Kuo, C.-Y., Lough, J. M., Lowe, R. J., Liu, G., McColloch, M. T., Malcolm, H. A., McWilliam, M. J., Pandolfi, J. M., Pears, R. J., Pratchett, M. S., Schoepf, V., Simpson, T., Skirving, W. J., Sommer, B., Torda, G., Wachenfeld, D. R., Willis, B. L., & Wilson, S. K. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, 543(7645), 373–377. doi:10.1038/nature21707
- Lough, J. M., & Barnes, D. J. (1989). Possible relationships between environmental variables and skeletal density in a coral colony from the Central Great Barrier Reef. *Journal of Experimental Marine Biology and Ecology*, 134(3), 221–241. doi:10.1016/0022-0981(89)90071-3
- Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society*, 78(6), 1069–1080. doi:10.1175/1520-0477(1997)078%3C1069:APICOW%3E2.0.CO;2
- Mook, W. G. (1970). Stable Carbon and Oxygen Isotopes of Natural Waters in the Netherlands. In *Isotope Hydrology 1970: Proceedings of a Symposium on Use of Isotopes in Hydrology Held by the International Atomic Energy Agency in Co-Operations with The United Nations Educational, Scientific, and Cultural Organization*, pp. 177–190
- Newman, M., Alexander, M. A., Ault, T. R., Cobb, K. M., Deser, C., Di Lorenzo, E., Mantua, N. J., Miller, A. J., Minobe, S., Nakamura, H., Schneider, N., Vimont, D. J., Phillips, A. S., Scott, J. D., & Smith, C. A. (2016). The Pacific Decadal Oscillation, revisited. *Journal of Climate*, 29(12), 4399–4427. doi:10.1175/jcli-d-15-0508.1
- Nurhati, I. S., Cobb, K. M., & Di Lorenzo, E. (2011). Decadal-scale SST and salinity variations in the Central Tropical Pacific: Signatures of natural and anthropogenic climate change. *Journal of Climate*, 24(13), 3294–3308. doi:10.1175/2011jcli3852.1
- Nurhati, I. S., Cobb, K. M., Charles, C. D., & Dunbar, R. B. (2009). Late 20th century warming and freshening in the Central Tropical Pacific. *Geophysical Research Letters*, 36(21). doi:10.1029/2009gl040270
- Park, K., Federico, I., Di Lorenzo, E., Ezer, T., Cobb, K. M., Pinardi, N., & Coppini, G. (2022). The contribution of Hurricane Remote Ocean forcing to storm surge along the Southeastern U.S. Coast. *Coastal Engineering*, 173. doi:10.1016/j.coastaleng.2022.104098
- Smith, S. V., Buddemeier, R. W., Redalje, R. C., & Houck, J. E. (1979). Strontium-calcium thermometry in coral skeletons. *Science*, 204(4391), 404–407. doi:10.1126/science.204.4391.404
- Stevenson, S., Fox-Kemper, B., Jochum, M., Neale, R., Deser, C., & Meehl, G. (2012). Will there be a significant change to El Niño in the twenty-first century? *Journal of Climate*, 25(6), 2129–2145. doi:10.1175/jcli-d-11-00252.1
- Wang, B., Luo, X., Yang, Y.-M., Sun, W., Cane, M. A., Cai, W., Yeh, S.-W., & Liu, J. (2019). Historical change of El Niño properties sheds light on future changes of extreme El Niño. *Proceedings of the National Academy of Sciences*, 116(45), 22512–22517. doi:10.1073/pnas.1911130116
- Weber, J. N. (1973). Incorporation of strontium into reef coral skeletal carbonate. *Geochimica et Cosmochimica Acta*, 37(9), 2173–2190. doi:10.1016/0016-7037(73)90015-x
- Weber, J. N., & Woodhead, P. M. (1972). Temperature dependence of oxygen-18 concentration in reef coral carbonates. *Journal of Geophysical Research*, 77(3), 463–473. doi:10.1029/jc077i003p00463

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