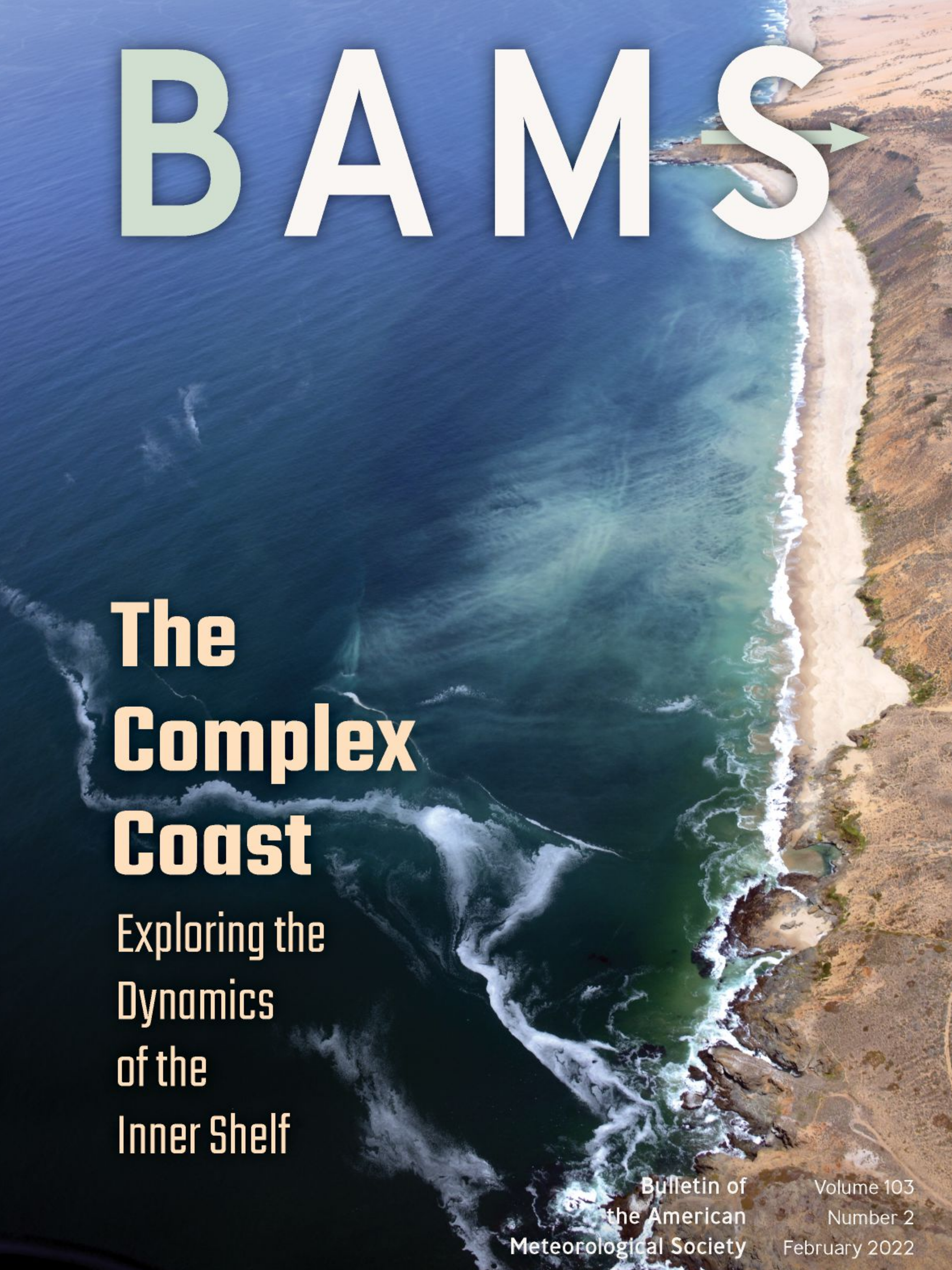


BAMS

The Complex Coast

Exploring the Dynamics of the Inner Shelf

Bulletin of the American Meteorological Society

Volume 103
Number 2
February 2022

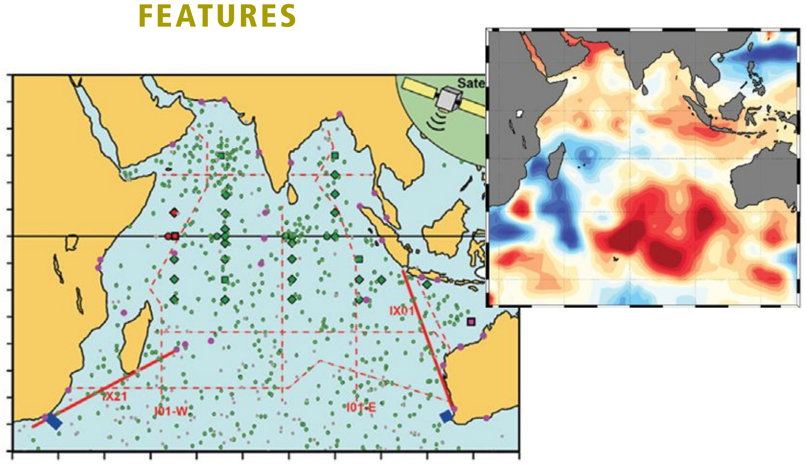

AMS Journals
The world's home for
weather, water, and climate research
High impact. Global reach.
Artificial Intelligence for the Earth Systems
Earth Interactions
Journal of Atmospheric and Oceanic Technology
Journal of Applied Meteorology and Climatology
Journal of Climate
Journal of the Atmospheric Sciences
Journal of Physical Oceanography
Journal of Hydrometeorology
Weather and Forecasting
Monthly Weather Review
Meteorological Monographs
Weather, Climate, and Society
AMS
American Meteorological Society

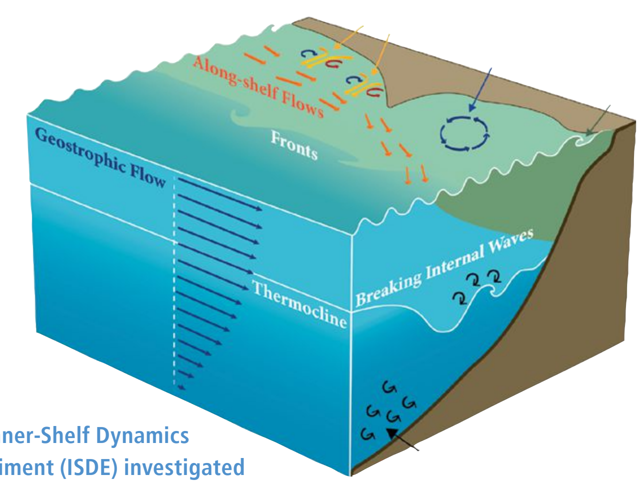
BAMS

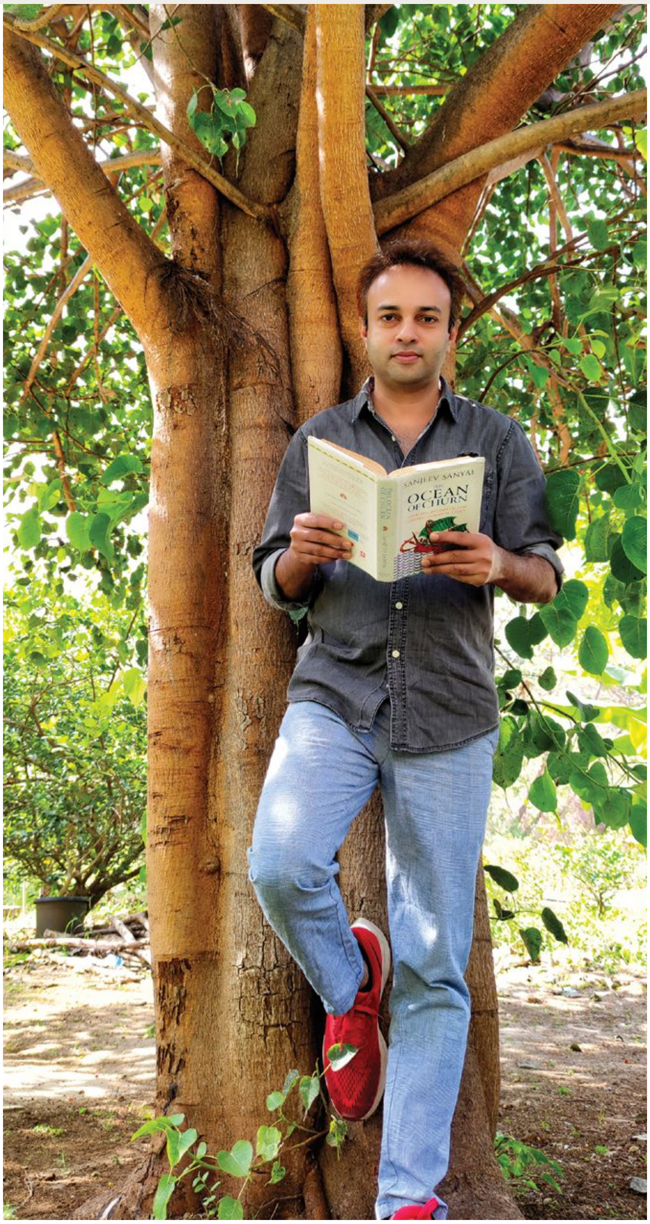
Bulletin of the American Meteorological Society

Volume 103, Number 2, February 2022

FEATURES







Roxy Koll next to a species of fig native to the Indian subcontinent (*ficus religiosa*), with a book that details the history of the Indian Ocean from a local perspective.

“ My passion for the Indian Ocean began as a graduate student when I joined my first scientific cruises out of Africa and the Middle East. Both the landscapes and the seascapes of the western Indian Ocean are dynamic and wild, and that draws me back again and again to this region. ”

— Lisa Beal, University of Miami

PAGE 108

Lisa Beal swimming in the Atlantic off Miami Beach, Florida, in summer 2021.

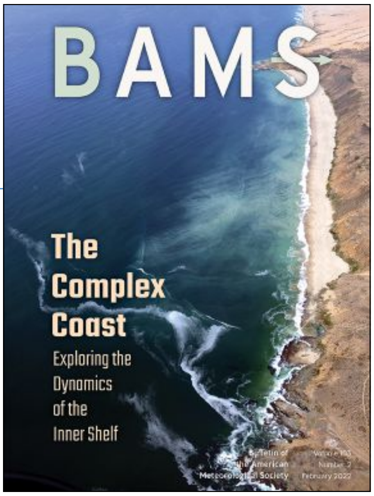
“ I live away from the sea, but the monsoon winds that travel over the Indian Ocean bring me half-a-million gallons of rain every year [per capita estimates of all India rainfall]. I remember how the first day at school after summer always meant coming back home drenched in the first rains of the monsoon season. This was every school year in Kerala during my childhood, three decades ago. ”

— Roxy Koll, Indian Institute of Tropical Meteorology

PAGE 108

ON THE COVER: The study site of the Inner-Shelf Dynamics Experiment near Point Sal, California, reveals various processes that were studied, including flows around headlands, internal waves, and the offshore ejection of surfzone waters from rip currents. (Photo courtesy Nick Statom, Scripps Institution of Oceanography)

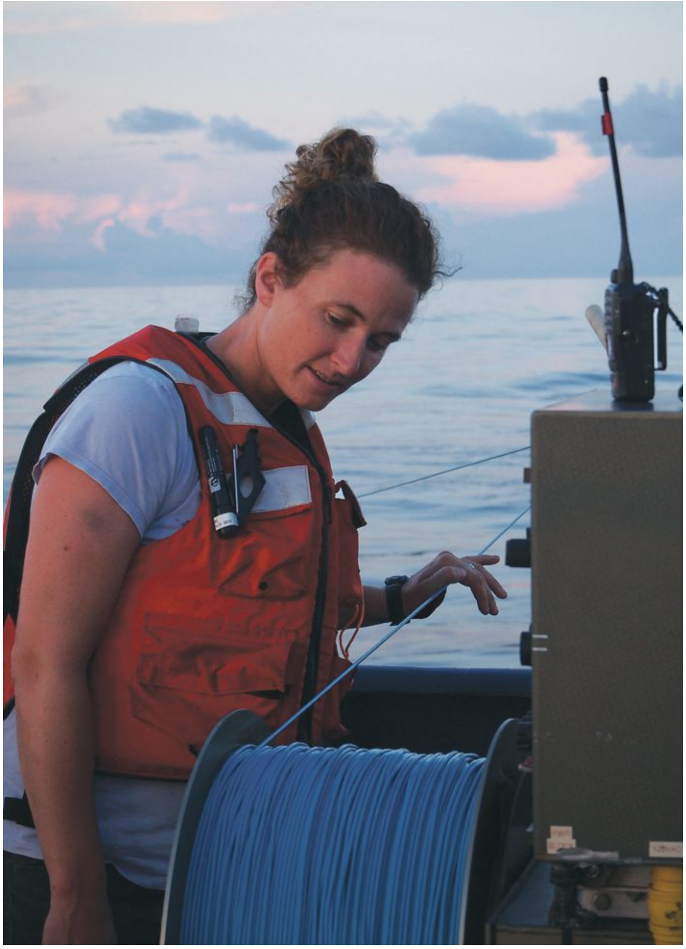
See page 117.



The *Bulletin of the American Meteorological Society* is the official organ of the Society, devoted to editorials, articles of interest to a large segment of the membership, professional and membership news, announcements, and Society activities. Editing and publishing are under the direction of Stella Kafka, executive director. Contributors are encouraged to send proposals to be considered for publication. For guidance on preparation and style, see the Instructions to Authors at www.ametsoc.org/authors.

The Bulletin of the American Meteorological Society (ISSN 0003-0007) is published monthly by the American Meteorological Society, 45 Beacon St., Boston, MA 02108- 3693. Periodical postage paid at Boston, MA, and at additional mailing offices. Subscription price to members is included in annual dues. Subscription price to nonmembers is available on request; single issues are $12.50 each for members, $20 for nonmembers (prices incl. shipping and handling). Address all business communications to the Executive Director, AMS, 45 Beacon St., Boston, MA 02108-3693 (617-227-2425).

POSTMASTER: Send address changes to Bulletin of the American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693.



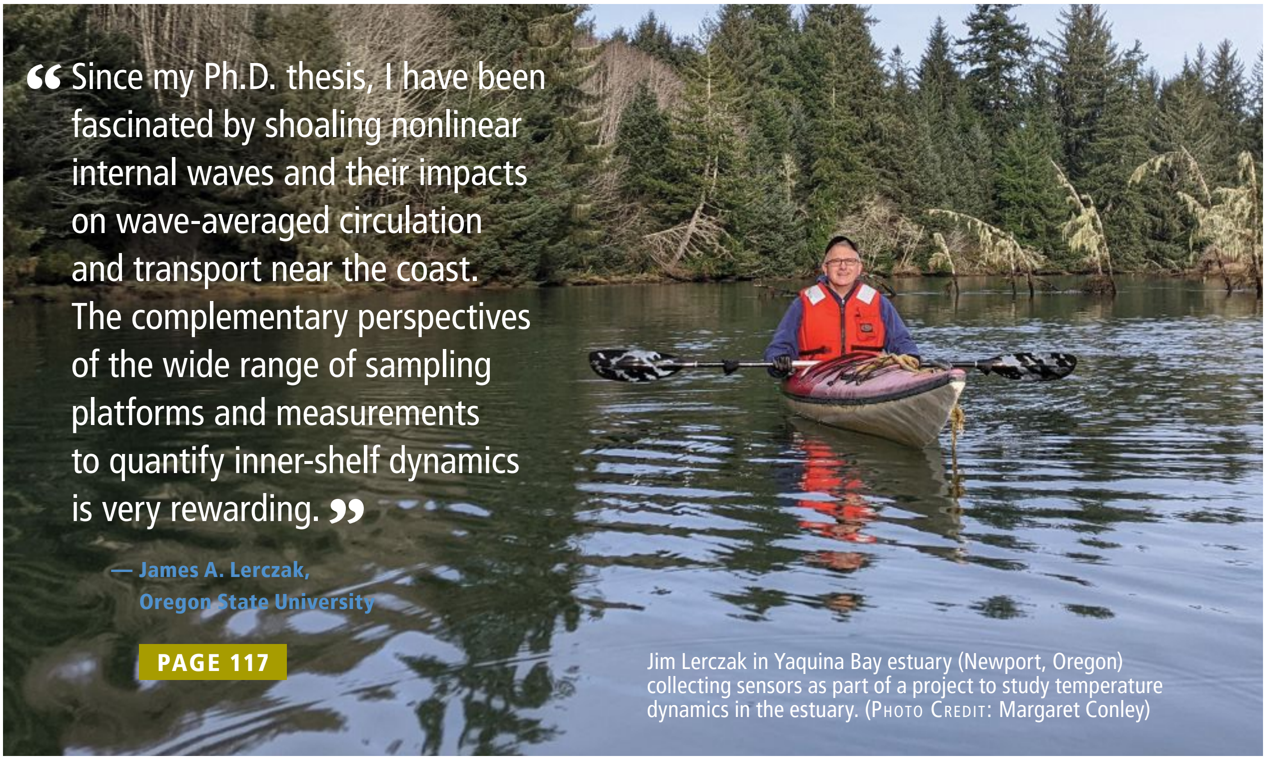
Amy Waterhouse operating a microstructure winch aboard the R/V *Revelle*. (Photo Credit: Sam Fletcher)

“Understanding how heat and momentum are transported across the continental shelf has always been a puzzling and important process that I've been interested in. The inner shelf contains a veritable zoo of physical processes that control what gets across the entire shelf.”

— Amy F. Waterhouse, Scripps Institution of Oceanography

PAGE 117

Harry van Loon



“Since my Ph.D. thesis, I have been fascinated by shoaling nonlinear internal waves and their impacts on wave-averaged circulation and transport near the coast. The complementary perspectives of the wide range of sampling platforms and measurements to quantify inner-shelf dynamics is very rewarding.”

— **James A. Lerczak, Oregon State University**

PAGE 117

Jim Lerczak in Yaquina Bay estuary (Newport, Oregon) collecting sensors as part of a project to study temperature dynamics in the estuary. (Photo Credit: Margaret Conley)

Recently published in BAMS online:

IN BOX

ARTICLES

The Boundary Layer Air Quality-Analysis Using Network of Instruments (BAQUNIN) Supersite for Atmospheric Research and Satellite Validation over Rome Area—*Anna Maria Iannarelli et al., February 2022, E599–E618*

Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA)—*Jian Wang et al., February 2022, E619–E641*

MEETING SUMMARIES

Climate Adaptation for Tropical Island Land Stewardship: Adapting a Workshop Planning Process to Hawai'i—*Ryan J. Longman et al., February 2022, E402–E409*

Enhancing the Student Experience with Numerical Weather Prediction: Advantages of Integrating Container and Cloud Technologies into Course Curricula—*Jamie K. Wolff et al., February 2022, E531–E535*

Developing a Framework for an Interdisciplinary and International Climate Intervention Strategies Research Program—*Simone Tilmes et al., February 2022, E591–E598*

All BAMS content published online is open access.

AMS Corporate Funding

The goal of the American Meteorological Society (AMS) Policy Program is "to help the nation, and the world, avoid risks and realize opportunities associated with the Earth system." Yet the AMS has Lockheed Martin Corporation as a corporate sponsor and their logo appears at the bottom of many AMS web pages, including the home page. The greatest risk the Earth system faces is nuclear war, and Lockheed Martin is one of the major U.S. defense contractors working on nuclear weapons. In 2020, Lockheed Martin received $2,050,000,000 in contracts to work on the Trident III ICBM land-based nuclear missiles and the Trident nuclear submarines (ICAN 2021). The approximately $100,000 per year AMS receives from Lockheed Martin is less than 0.005% of the money they receive to enhance and support weapons, that, if ever used, would produce catastrophic global climate change and impacts on the world food supply (e.g., Robock and Toon 2010; Coupe et al. 2019; and see all our publications and work on this topic at http://climate.envsci.rutgers.edu/nuclear/). And in 2019, Lockheed Martin gave between $100,000 and $249,999 to the Atlantic Council, an American think tank that advocates for more nuclear weapons (ICAN 2021).

In 2015 I received the AMS Jule G. Charney Medal, "For fundamental contributions toward understanding the climatic effects of stratospheric aerosols from volcanoes and other potential sources, and the role of soil moisture in climate." Those other "potential sources" included smoke from fires that would be ignited by nuclear weapons, and I spend much of my research and public advocacy to continue to warn the world about nuclear winter, the same work that AMS endorsed with the Charney Medal. Having the AMS being complicit in this Lockheed Martin greenwashing, which makes them look good by banking on our good name, is, in my opinion, a disgrace. I hereby recommend that AMS cease to accept funds from Lockheed, so as to not unwittingly be part of the military-industrial complex that President Eisenhower warned us about in his farewell address. This would emulate the American Geophysical Union, which ceased to accept funds from Exxon several years ago because of their disinformation campaign about global warming. Yes, Lockheed Martin builds satellites that provide Earth observations, and yes, the money Lockheed Martin gives to AMS supports valuable AMS programs, but what is the message we send by accepting money from them? AMS should be better than that, and live up to our pledge "to help the nation, and the world, avoid risks."

For further reading

Coupe, J., C. G. Bardeen, A. Robock, and O. B. Toon, 2019: Nuclear winter responses to global nuclear war in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE. *J. Geophys. Res. Atmos.*, **124**, 8522–8543, doi:10.1029/2019JD030509.

ICAN (International Campaign to Abolish Nuclear Weapons), 2020: *Complicit: 2020 Global Nuclear Weapons Spending*, June, 2021, (ICAN, Geneva, Switzerland), available at https://d3n8a8pro7vhmx.cloudfront.net/ican/pages/2161/attachments/original/1622825593/Spending_Report_Web.pdf

Robock, A., and O. B. Toon, 2010: Local nuclear war, global suffering. *Sci. Amer.*, **302**, 74–81.

Alan Robock
Department of Environmental Sciences
Rutgers University
New Brunswick, New Jersey
robock@envsci.rutgers.edu

In consideration of Dr. Alan Robock's inquiry into the subject of corporate sponsorship, the AMS Council has reviewed our current practice with respect to corporate funding and provides the following rationale for maintaining this practice as it stands.

The mission of the AMS is enabling the advancement of the atmospheric and related sciences, technologies, applications, and services for the benefit of humanity. We translate this mission into action through AMS programs, which benefit greatly from both internally generated funds such as publications and meetings support and external funds.

The AMS only accepts external funding, whether it be corporate support, federal grants, foundation support, or any other source, that is aligned with our mission and with the Society's integrity and reputation. AMS corporate partners recognize that Society programs enrich and strengthen the entire weather, water, and climate enterprise of which they are a part, so that the success of AMS activities and initiatives is synergistically linked to their own success.

A major area of corporate support is in the AMS scholarship and fellowship program, and over the years, more than 1300 students have benefitted from scholarships or fellowships provided by corporate funding, including travel grants that bring students to the annual meetings. Corporate sponsorships allow the AMS to provide invaluable career and networking opportunities for students and generally help expand activities in ways that ensure a more successful and engaging meeting for all those participating. Both the AMS Policy Program and Education Program have also benefitted from corporate support over the years. The Policy Program depends on corporate support to help underwrite policy study activities and having this support augment federal agency funding for these studies is a great example of a public–private partnership made possible through Society programs. The corporate patrons providing support do not have control over how those funds are used, so there is no conflict or bias introduced through their sponsorship. In the AMS Education Program, corporate support *has been instrumental in several aspects of the training and professional development activities the Society provides for K–12 teachers nationwide, including the creation of curriculum materials and travel support for K–12 teachers.*

The AMS values all the sectors of the U.S. weather, water, climate enterprise, including those associated with national defense. These corporate patrons provide critical support to the atmospheric and related sciences, primarily through space-based, ground-based, and airborne observation platforms, and it is those divisions of these corporations that provide the funding for important Society programs. Employees of these corporate sponsors are themselves valued members of the AMS, who like members across all sectors, volunteer their time and expertise to advance the mission of the Society. These members take back to their respective organizations the values and imperatives of the Society. AMS is proud of the support provided by its long-standing Corporate Patrons, and respectfully disagree with the premise that there is anything wrong with associating with Lockheed Martin or any other similar company.

AMS Executive Committee

AMS Weather Band

YOUR FORECAST

JOIN	LEARN	SHARE	ACCESS	ENJOY	SAVE	SUPPORT
A passionate online community of weather enthusiasts from all over the world.	Cutting-edge insights about the weather that interests you most.	Your love of science, from wild weather stories to jaw-dropping photos and videos.	Weather experts, plus lots of fun content and interactive features.	Your unique certificate, exclusive Weather Band pin, and guitar pick keychain.	10% off your first store order and 40% off a Weatherwise magazine subscription.	Weather, water, and climate science. Help change the world!

The AMS Weather Band reaches beyond our core membership of professionals to engage with anyone eager to learn more about how the atmosphere works. Weather enthusiasts from all over the world and all walks of life are joining now to share, connect, and learn.

Join the Band or contribute content at

amsweatherband.org

Making Connections for Better Predictions

PROBLEM: Numerical models used for weather and climate forecasting have limitations in simulating underlying atmospheric and oceanic processes, which can delay the prediction of extreme events like floods and droughts. That time lost can be costly in terms of both lives and property

SOLUTION: A new mathematical forecasting approach that analyzes the connectivity and patterns between geographical locations shows promise in significantly improving prediction times for extreme events.

THE NEW APPROACH, which was recently discussed in the *Proceedings of the National Academy of Sciences,* utilizes network-based forecasting, which looks at the connectivity between different geographical locations. "This connectivity is detected by measuring the similarity in the evolution of physical quantities like air temperatures at these locations," explains lead author Josef Ludescher of the Potsdam Institute for Climate Impact Research (PIK). "For instance, in the case of El Niño, a strong connectivity in the tropical Pacific tends to build up in the calendar year before the onset of the event." This method is different from numerical models, which examine large amounts of local interactions to represent physical processes such as heat or humidity exchange. Ludescher and colleagues found that their approach improved prediction time—in some cases by months or up to a year—for a number of extreme events. For example, their method predicted an El Niño event up to one year ahead of time, compared with about a six-month prediction time using standard methods. Other events, such as heavy rain in the Andes, currently have no reliable prediction at all, but the new method was able to predict such events two days in advance. "These patterns—that is, the connectivity between the locations and their evolution in time—can provide critical new information for forecasting—and, so we hope, make the respective regions safer," says coauthor Maria Martin, also of PIK. [SOURCE: Potsdam Institute for Climate Impact Research]

Less Wood Means Less Ice

…Get the *Drift?*

Driftwood on the shoreline of the island of Martensøya, Norway. [PHOTO CREDIT: Georgia Hole]

WHO: A research team led by Georgia Hole of the University of Oxford

WHEN: The summers of 2016 and 2018

WHERE: The northern beaches of the Norwegian archipelago of Svalbard, located in the Arctic Ocean about halfway between the northern coast of Norway and the North Pole

WHY: The scientists were looking for driftwood—some of it hundreds of years old— that had frozen in sea ice and drifted to Svalbard's shores. Dying trees in North America and Eurasia can naturally fall into high-latitude rivers that drain into the Arctic Ocean. The wood can then become locked into sea ice as the ocean freezes and then can float across the ocean, making it a valuable proxy for sea ice extent. Hole noted that "this is the first time driftwood has been used to look at large-scale changes in Arctic sea ice dynamics and circulation patterns."

WHAT: After collecting the driftwood on the beaches, Hole and colleagues brought it back to a lab, where their analysis of tree rings allowed them to trace the wood samples to their sources and approximate their paths across the Arctic Ocean. They combined this data with sea ice observations from the years 1600–1850 taken from fishers, hunters, and ships, as well as more recent records from airplane and satellite images. By comparing the driftwood tracks with sea ice conditions and currents, they found that the lowest-latitude sea ice followed a slow and consistent northward migratory path. According to Hole, their findings also showed "an increase in variability in the driftwood record from 1700 to 1850, which we interpret as increased variability in sea ice." Additionally, the team discovered a significant decline in new driftwood arrivals over the last 30 years. The findings, which were published in the *Journal of Geophysical Research: Oceans*, are evidence of warming in the Arctic that is driving an extreme loss of sea ice coverage in the region. When temperatures were colder and sea ice was more prevalent, there was a greater range of sources for the driftwood, but as that ice cover diminishes, fewer fallen trees make the long ocean voyage. "It's such a fragile system," Hole says. [SOURCE: American Geophysical Union]


300 miles
>> How a silver lining forms
>> It starts at sea.
>> Tropical waters heat up.
>> Warm air soars skyward.
>> Cold air rushes to the void.
>> Cold air warms up.
>> Cycle repeats.
>> Faster and faster–a 50,000 foot engine of air.
>> At seventy four miles per hour it earns a name.
>> Harvey, Irma, Katrina.
>> Then landfall.
>> Roads rendered useless.
>> Buildings destroyed.
>> Families stranded.
>> But for a brief moment,
>> A silver lining appears.
>> People see neighbors instead of strangers.
>> And labels that divide are forgotten.
>> But when rains ease,
>> when clouds part,
>> silver linings need not fade.
>> Let's embrace our shared humanity.
>> Let's connect with one another.
>> Let's find our love for each other.
>> Every single day.
>> Come together at lovehasnolabels.com
love has no labels
ad COUNCIL
29.7604° N, 95.3698°, W SFC 134

HIGHS AND LOWS

Urban Pollution Injustice

28%— The proportion of nitrogen dioxide (NO_2) concentrations greater in lower-income neighborhoods of color compared to upper-income white neighborhoods, according to recent research highlighting pollution disparities in urban neighborhoods. A combustion pollutant that combines in the atmosphere to form particulate matter and ozone, NO_2 can be harmful to human health. Its concentration can be highly variable between neighborhoods, but that inequality has been challenging to accurately quantify. The new study, which was published in *Geophysical Research Letters,* utilized the satellite-borne Tropospheric Monitoring Instrument (TROPOMI) to measure NO_2 levels in 52 U.S. cities. TROPOMI can acquire data at a greater spatial resolution than formerly possible and provides near-daily measurements, allowing for comparisons of different neighborhoods within urban areas. "Previously, we had been limited in our ability to address air pollution inequality, but with improvements in satellite resolution we are now able to get spatially and temporally continuous data at finer resolutions within cities," notes lead author Angelique Demetillo of the University of Virginia. Combined with demographic information, the satellite data helped Demetillo and colleagues quantify inequality down to the neighborhood level. Their findings showed that NO_2 amounts are 12%–19% higher in communities of color compared to white communities and 17% higher for people living below the poverty line. The researchers also discovered that in the cities they studied, diesel trucks are the primary cause of the NO_2 disparity, responsible for up to half of urban NO_2 emissions even though such vehicles account for at most 5% of total traffic. Phoenix, Los Angeles, and Newark, NJ, showed the greatest NO_2 pollution inequality (>40%) between lower-income neighborhoods of color and upper-income white areas, and only one city—San Antonio—showed negative inequality (i.e., higher pollution levels in upper-class white neighborhoods). [Source: American Geophysical Union]

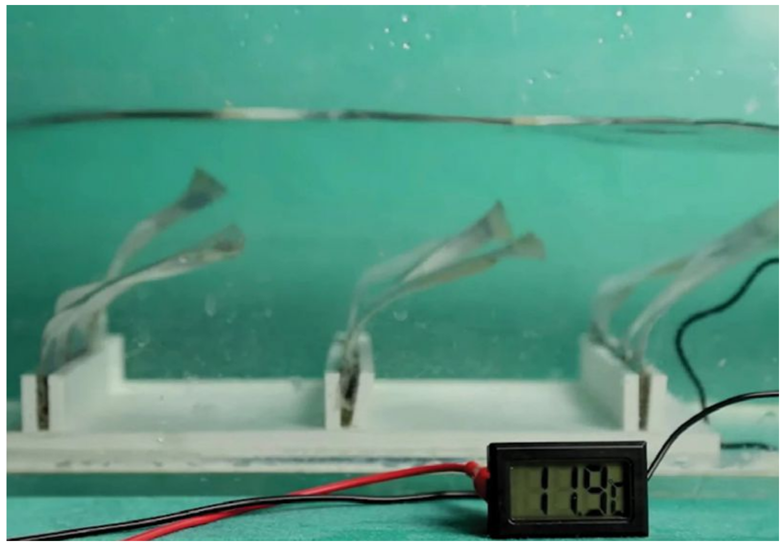
Seeing Energy in the Weeds

PROBLEM:

The network of underwater ocean sensors known as the "Marine Internet of Things" provides valuable data on ocean processes. But the sensors are mostly battery-powered, and their maintenance can be expensive and time-consuming.

SOLUTION:

A research team has developed generators that undulate like seaweed to convert underwater wave energy into electricity that can be used to power the sensors.



A video screen-capture showing the TENG's swaying seaweed powering a digital thermometer. [IMAGE CREDIT: American Chemical Society]

The idea of flexible generators originated from a conversation between Minyi Xu of Dalian Maritime University and Zhong Lin Wang of Georgia Tech. "Professor Wang mentioned that seaweed vibrates softly in ocean flow and can live well even in huge waves," Xu explains.

To test their theory, Xu, Wang, and colleagues created triboelectric nanogenerators, or TENGs, which generate static electricity when two objects rub against each other. They coated strips of two different polymers in a conductive ink and attached a small sponge between the strips to create a thin air gap. They then sealed the entire unit to form the TENG. They found that moving it vertically in the water caused the internal layers of the TENG to continuously scrape against each other and generate electricity, even at pressures comparable to those in coastal zones where there is very little underwater wave activity. Testing of multiple TENGs in a wave tank highlighted their potential use for a small underwater station that could power a thermometer, a miniature LED lighthouse beacon, or 30 LEDs. The researchers believe their TENGs could be an affordable alternative to batteries in supplying energy to marine sensors in coastal zones. They also point out that TENGs don't create noise or heat, making them more environmentally friendly than batteries. "A seaweed bush made of millions of flexible TENGs may be suitable for fish living," Xu notes. He also estimates that, if agitated two or three times per second, a network of these devices over an area equal to the size of Georgia could meet the entire world's energy needs. Their research was published in *ACS Nano*. [SOURCE: fastcompany.com]

Written in the Skies

QUESTION: What can ancient literature tell us about auroras?

ANSWER: Historical Norwegian and Japanese writings corroborated the findings of a recent modeling study that mapped changes in Earth's auroral zone over time. ▶

RYUHO KATAOKA of the National Institute of Polar Research and Shin'ya Nakano of the Institute of Statistical Mathematics and the Joint Support Center for Data Science Research used models of paleomagnetism—which can determine Earth's magnetic field in history by examining magnetic evidence in rocks—to study how the auroral zone has shifted over the last 3,000 years. An auroral zone normally forms as an oval-shaped band about 20–30 degrees from Earth's magnetic poles, but during extreme magnetic storms the zone can occasionally expand toward midlatitude regions. Kataoka and Nakano used their models to create maps of the auroral zone dating back to 1000 BC, and then compared their findings to historical auroral witness records. They discovered the writings confirmed their modeling in some occurrences of auroral zone shifts. For example, an Old Norse text titled *The King's Mirror* includes depictions of auroras around 1200 AD over what is now Greenland, whereas a collection of poems (*The Poetic Edda*) from southern Norway written about 100 years earlier has no descriptions of auroras. This corresponds with the study's maps, which show the zone dipping over Greenland around 1200, but not over southern Norway in the twelfth century. Similarly, the maps agreed with a Japanese text (*Nippon Kisho-Shiryo*) penned around the same time as *The King's Mirror,* which describe auroras as curtain-like white and red lights. The new maps also showed that the auroral zone dipped over Europe in the eighteenth century, which corresponds with writings from that time describing auroras over the United Kingdom. "The auroral zone changes over time, and the deformation and sporadic expansion of the auroral oval are recorded in historical documents over a thousand years from across the world," notes Kataoka. The study, which was published in the *Journal of Space Weather and Space Climate,* also stated that "the 12th and 18th centuries were excellent periods for Japan and the United Kingdom, respectively, to observe auroras over the last 3,000 years." The researchers hope to use their findings to predict future movement of the auroral zone and help mitigate the harmful effects of the magnetic storms causing auroras. [SOURCE: Research Organization of Information and Systems]

Fingerprinting

Suspected Attribution

PROBLEM:

Despite recent progress, the attribution of specific extreme weather events to climate change remains challenging for a number of reasons, including the limitations of climate models and the effects of natural variability.

SOLUTION:

Valerio Lucarini of the University of Reading and Vera Gálfi of Uppsala University developed a methodology that merges climate models with statistics to determine whether events were caused by global warming or natural factors. The researchers first simulated Earth's climate with no climate change effects for a 1,000-year period and identified extreme events in the data. They characterized the properties defining these events using large deviation theory, a statistical approach used to define what constitutes a rare event. They then compared the patterns of the simulated events to real events, with similarities indicating the event is part of natural climate variability and differences indicating the potential influence of climate change. Lucarini and Gálfi's analysis revealed that all of the extreme events they simulated are in the same "universality class," meaning they have similar properties. Because of this universality, the new method not only shows promise for improving attribution studies, but also "tells us we can have a predictive climate science," according to Lucarini. Other attribution methods are largely empirical and, while they do well indicating the odds that climate change caused a past extreme event, they cannot predict the probability of the occurrence of future extreme climate events. The new methodology can. The researchers tested their method on two 2010 incidents—a Russian heat wave that had temperatures 11°C above average, and a Mongolian cold snap when temperatures plummeted to –50°C—and discovered that both were "associated with atmospheric patterns that are exceptional compared to the typical ones but typical compared to the climatology of extremes," according to the paper, which was published in *Physical Review Letters.* They also found that climate change is likely to make heat waves more extreme in both regions. [Source: *Physics*]

Monthly Weather Review

Monthly Weather Review (*MWR*) publishes research relevant to the analysis and prediction of observed atmospheric circulations and physics, including technique development, data assimilation, model validation, and relevant case studies. This research includes numerical and data assimilation techniques that apply to the atmosphere and/or ocean environments. *MWR* also addresses phenomena having seasonal and subseasonal time scales.

Open Access option for authors. All papers publicly accessible 12 months after publication.

2019 Impact Factor: 3.435 (2019 Journal Impact Factors by Clarivate Analytics: Meteorology and Atmospheric Science category)

Editorial Board

AMS
American Meteorological Society

Monthly Weather Review (*MWR*)
ISSN: 0027-0644; eISSN: 1520-0493

Save the date!

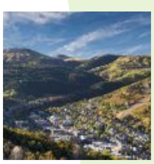
Join us at one of our upcoming meetings!

2022 AMS Washington Forum
25–28 April 2022, Washington, DC

35th Conference on Hurricanes and Tropical Meteorology
9–13 May 2022, New Orleans, LA

23rd Conference on Atmospheric and Oceanic Fluid Dynamics
13–17 June 2022, Breckenridge, CO

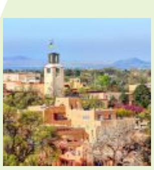
49th Conference on Broadcast Meteorology/Sixth Conference on Weather Warnings and Communication
14–17 June 2022, Milwaukee, WI



20th Conference on Mountain Meteorology
27 June–1 July 2022, Park City, Utah

24th Symposium on Boundary Layers and Turbulence
11–15 July 2022, Šibenik, Croatia

Collective Madison Meeting
8–12 August 2022, Madison, WI



30th Conference on Severe Local Storms
24–28 October 2022, Santa Fe, NM

Learn more at ametsoc.org/meetings

AMS
American Meteorological Society

COLLABORATIONS

A Succession of Cloud, Precipitation, Aerosol, and Air Quality Field Experiments in the Coastal Urban Environment

Michael P. Jensen, James H. Flynn, Laura M. Judd, Pavlos Kollias, Chongai Kuang, Greg Mcfarquhar, Raj Nadkarni, Heath Powers, and John Sullivan

The interactions and feedbacks among clouds, aerosols, pollutants, and the thermodynamic and kinematic environment remains an area of active research with important implications for our understanding of climate, weather, and air quality. These linkages are further complicated in coastal and urban environments where local circulations and anthropogenic influences impact each of these components and their interactions. Within this context, fundamental questions regarding the life cycle of convective clouds, aerosols, and pollutants have brought together a diverse, integrated, and interagency collaboration of scientists to collect and analyze measurements, in the Houston, Texas, area, from the summer of 2021 through the summer of 2022, with subsequent modeling studies to address these important research objectives. The U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Facility and Atmospheric System Research (ASR) Program, the National Science Foundation's (NSF's) Physical and Dynamic Meteorology Program, the National Aeronautics and Space Administration's (NASA's) Tropospheric Composition Research and Health and Air Quality Applied Sciences Programs and the Texas Commission on Environmental Quality (TCEQ) are collaborating on a joint set of field campaigns to study the interactions of cloud, aerosol, and pollutants within the coastal, urban environment. In the Houston area, onshore flow from the Gulf of Mexico and the associated sea-breeze circulation generates numerous isolated convective cells, particularly in the summer months, that interact with a variety of urban and industrial emissions.

Fundamental questions regarding the life cycle of convective clouds, aerosols, and pollutants have brought together a diverse, integrated, and interagency collaboration of scientists to collect and analyze measurements.

TAQ

The Tracking Aerosol Convection interactions Experiment (TRACER) Air Quality (TAQ) campaign, led by NASA with contributions from TCEQ, probed Houston air quality through the integration of observations from multiple perspectives with platform deployments staggered throughout July–August 2021 and an intensive operational period during September 2021. These perspectives included ground-based measurements of in situ and remotely sensed air quality measurements (Fig. 1c) from a suite of supersites, mobile laboratories, and shipborne platforms linked with overflights from the NASA Johnson Space Center Gulfstream V (Fig. 1h) mapping out the spatial distribution of aerosols, ozone, and ozone precursors over the greater Houston region multiple times per day. The measurements collected during TAQ will be used to

AFFILIATIONS: Jensen and Kuang—Environmental and Climate Sciences Department, Brookhaven National Laboratory, Upton, New York; Flynn—Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas; Judd—Earth Sciences Division, NASA Langley Research Center, Hampton, Virginia; Kollias—Environmental and Climate Sciences Department, Brookhaven National Laboratory, Upton, and School of Marine and Atmospheric Sciences, Stony Brook University, State University of New York, Stony Brook, New York; McFarquhar—Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, Oklahoma; Nadkarni—Air Quality Division, Texas Commission on Environmental Quality, Austin, Texas; Powers—Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico; Sullivan—Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland

CORRESPONDING AUTHOR:
Michael P. Jensen, mjensen@bnl.gov

DOI:10.1175/BAMS-D-21-0104.1

In final form 28 December 2021

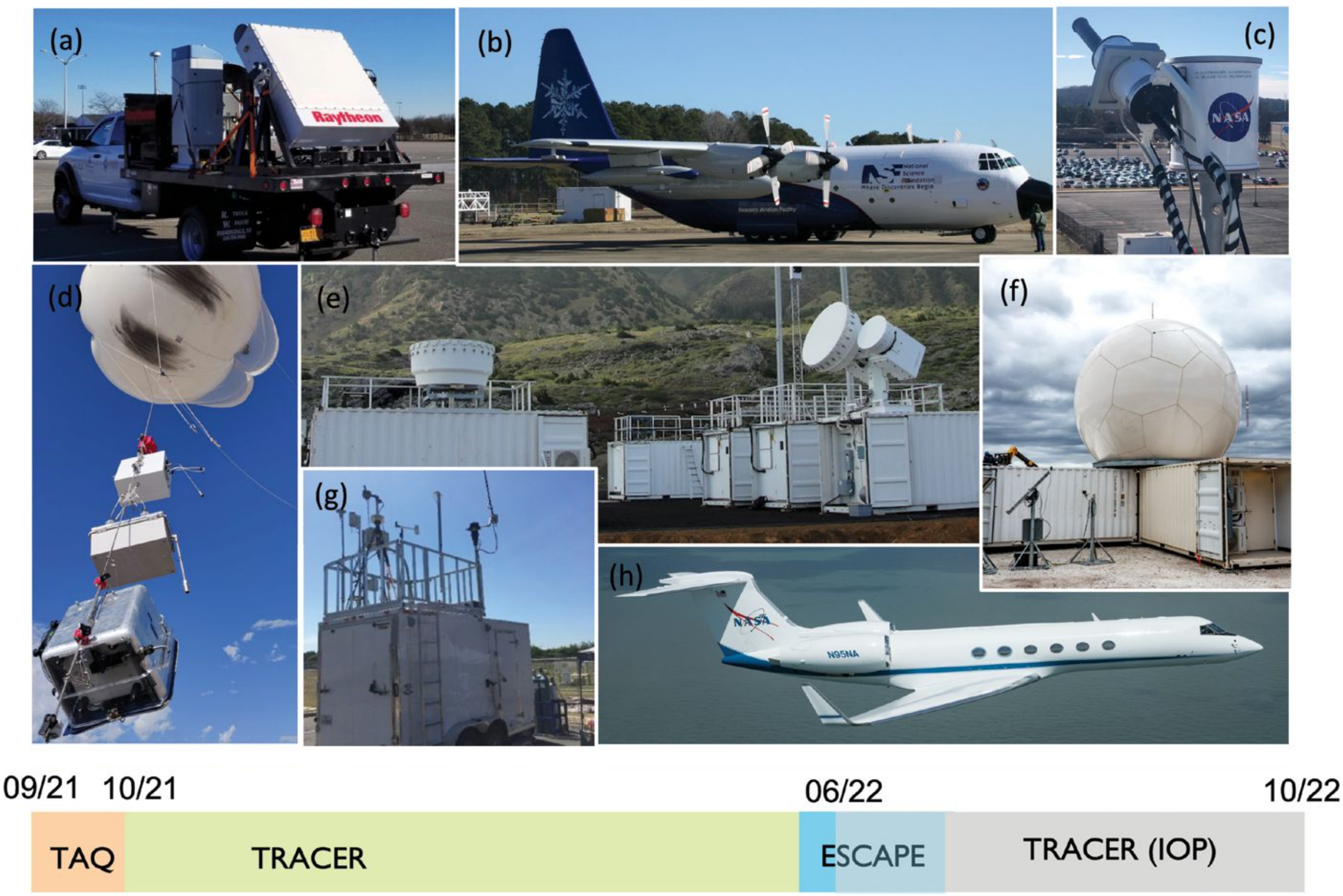


FIG. 1. Measurement platforms to be deployed: (a) Stony Brook University Weather Truck including dual-polarization X-band phased array radar (ESCAPE), (b) NCAR C-130 aircraft (ESCAPE) (photo credit: C. Wolff), (c) Pandora Spectrometer (TAQ) (photo credit: B. Swap), (d) ARM Tethered Balloon System (TRACER), (e) ARM Mobile Facility (TRACER), (f) C-Band ARM Scanning ARM Precipitation Radar (TRACER), (g) Baylor University–University of Houston–Rice University Mobile Air Quality Laboratory (TAQ, TRACER), (h) Johnson Space Flight Center Gulfstream V aircraft (TAQ). Field campaign timeline is indicated in the bar along the bottom.

evaluate the current conceptual model for air quality in the region by linking measurements to air quality models and satellite observations, including the creation of proxy data for the NASA Tropospheric Emissions: Monitoring Pollution (TEMPO) mission, as well as to assess the intersection of air quality and socioeconomic factors.

TRACER

The DOE TRACER campaign brings the ARM Mobile Facility (Fig. 1e), a comprehensive suite of remote sensing and in situ instrumentation, along with a C-Band Scanning ARM Precipitation Radar (CSAPR; Fig. 1f) for a period of 1 year that began in October 2021. During the summer months, June–September 2022, an intensive operational period will bring additional measurement platforms to further characterize the local aerosol, cloud, and environmental properties along with their regional variability. A number of these additional measurements are contributed through ASR-funded projects and include characterization of the regional and time-varying aerosol and cloud condensation nuclei (Fig. 1g) and measurements of the local thermodynamic structure from balloons, remote sensors, and remote-piloted aircraft. A unique component of the TRACER campaign will be the use of automated software to track convective cells with the CSAPR sampling the polarimetric signatures of cloud and precipitation microphysics at high-resolution through the convective life cycle. The scientific focus of the TRACER campaign is the study of atmospheric processes that drive cloud and aerosol processes with a particular focus on the role that aerosols play in impacting convective properties including updraft strength, microphysical properties, total precipitation, and anvil cloud coverage. These aerosol impacts on convective cloud systems remain a topic of significant debate in the scientific literature.

ESCAPE

The NSF Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment (ESCAPE) campaign will take place from 25 May through 1 July 2022, and includes two aircraft, and surface-based fixed and mobile measurements. The scientific focus of ESCAPE involves characterization of the life cycle of convective cloud systems, particularly the dynamics of updrafts and downdrafts, and how it is impacted by the coastal and urban environment and aerosol composition and concentration. The planned aircraft platforms include the NCAR C-130 (Fig. 1b) and the Stratton Park Engineering Company (SPEC) Learjet, both of which will deploy payloads that include in situ sampling of cloud and aerosol microphysics, and remote sensing of cloud properties. On the ground, multiple fixed and mobile radar systems (Fig. 1a) will be used to track convective cells and perform multi-Doppler analysis for the derivation of velocities within the convective systems over the course of their life cycle. Two additional mobile sensing trucks with additional remote sensing and in situ instrumentation, will focus on characterizing the two-way interactions between convection and the environment, particularly the characteristics of downdraft driven cold pools and subsequent convective redevelopment. Links between cloud microphysics, vertical motion, and lightning will also be examined.

Synergies and opportunities

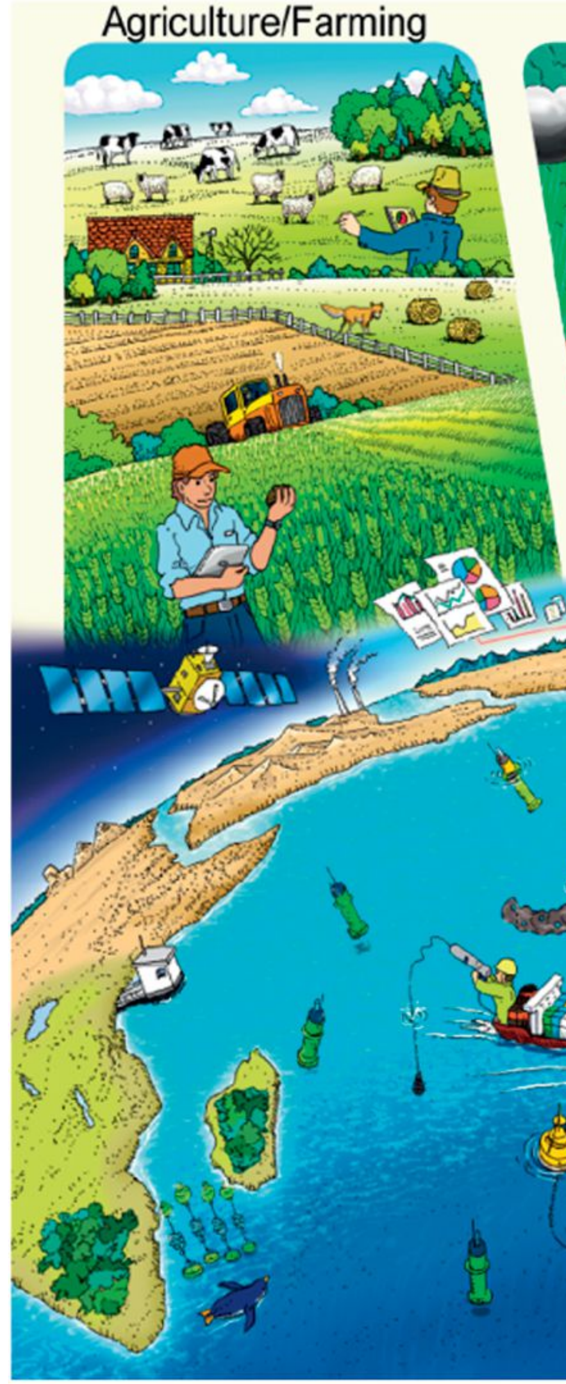
A particular advantage of the Houston region for the deployment of a major atmospheric field campaign is the existence of several operational networks that provide important contextual measurements across the region. The TCEQ air monitoring network includes 75 sites within the Houston area that collect air quality, meteorological, and solar radiation measurements. The HoustonNet Global Positioning System Network provides precipitable water vapor retrievals at more than 130 sites around the Houston area and the Houston Lightning Mapping Array (with additional support from NSF ESCAPE) measures four-dimensional lightning discharge including charge distribution, flash location, and flash rate.

A multiagency set of field campaigns as large as the TRACER/ESCAPE/TAQ effort requires a great deal of planning, coordination, and cooperation. These components have been impacted and complicated by the ongoing COVID-19 global pandemic. During the planning stages, the health and safety of participating scientists, technicians, and other campaign participants has always been placed at the forefront of program management concerns and decisions, while at the same time assuring that the planned measurements and science could be accomplished. Necessarily, this caused changes in the timelines for site selection and preparation, instrument shipping and testing, and in eventuality the operational dates of the campaign. New health and safety protocols have been developed, accounting for the varying working conditions and operational needs, compared to previous campaigns. While some compromises have been necessary, the expectations are for continued support among the interagency partners toward accomplishment of all scientific goals in a manner that is safe for all participants.

Each agency has its own data sharing and availability guidelines. Data collected during TRACER by the ARM instrument platforms will be available to researchers and the public through the ARM Data Center via Data Discovery in near–real time, while data collected by the ASR contributors and ARM guest instrumentation will be available at the same location within 6 months of the end of the campaign. Data collected during TRACER-AQ will be available upon finalization after the field campaign at the campaign web page as well as ingested into a NASA-supported Distributed Active Archive Center in the future. Data collected during ESCAPE will be publicly available after an initial period of quality control through the ESCAPE field catalog, which will be maintained at the NCAR Earth Observing Laboratory. The data collected during these field campaigns will be used by the science teams though we invite the larger atmospheric science community to tackle critical knowledge gaps in our understanding of the interactions among convective clouds, aerosols, and air quality and how they are influenced by the environment.


AMS Journals
The world's home for
weather, water, and climate research

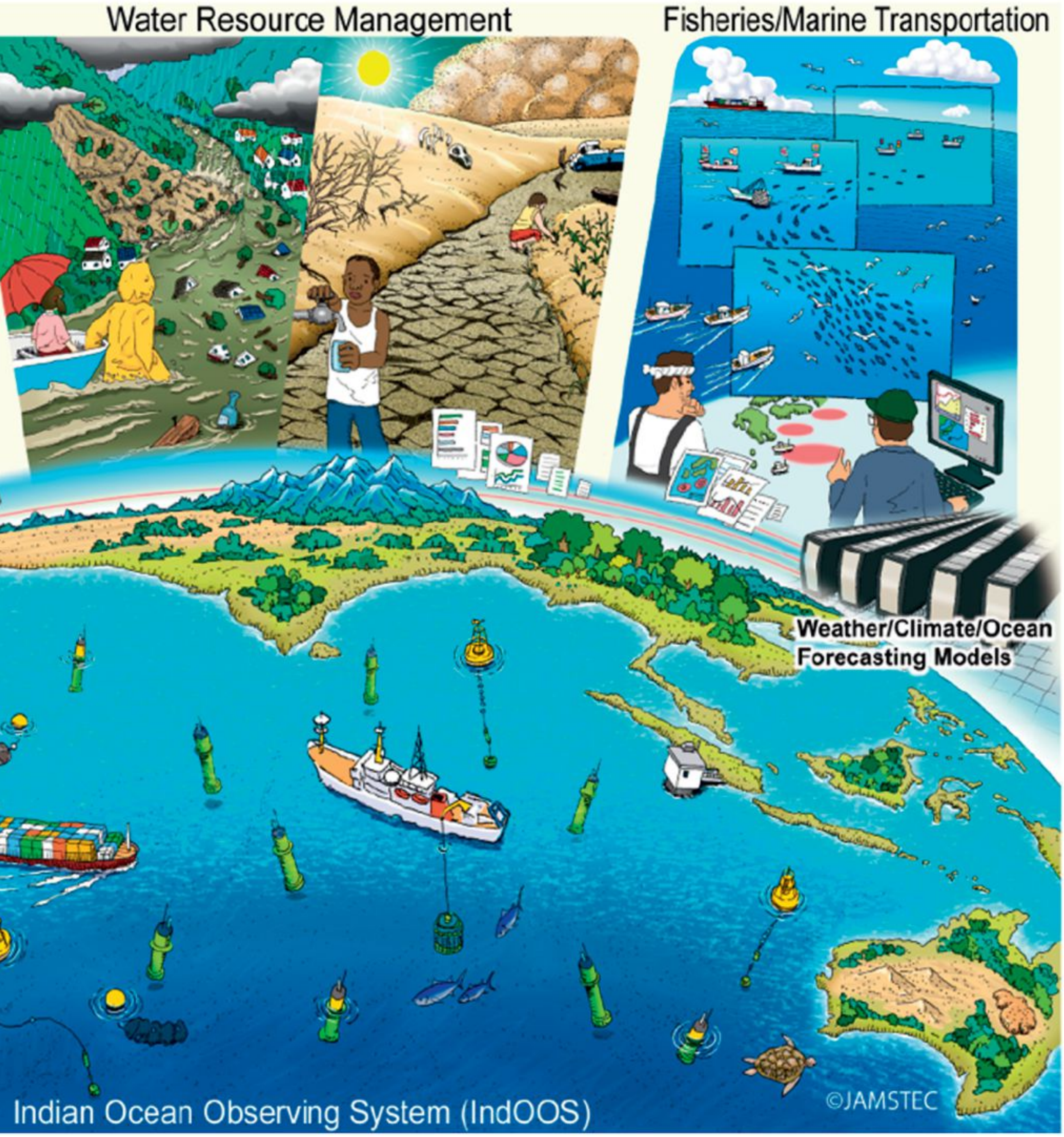
Better Observations of the Rapidly Warming Indian Ocean



Adapted from "A Road Map to IndOOS-2: Better Observations of the Rapidly Warming Indian Ocean," by **L. M. Beal**, **J. Vialard** (Pierre and Marie Curie University), **M. K. Roxy, J. Li, M. Andres, H. Annamalai, M. Feng, W. Han, R. Hood, T. Lee, M. Lengaigne, R. Lumpkin, Y. Masumoto, M. J. McPhaden, M. Ravichandran, T. Shinoda, B. M. Sloyan, P. G. Strutton, A. C. Subramanian, T. Tozuka, C. C. Ummenhofer, A. S. Unnikrishnan, J. Wiggert, L. Yu, L. Cheng, D. G. Desbruyères**, and **V. Parvathi**. Published online in *BAMS*, November 2020. For the full, citable article, see **DOI:10.1175/BAMS-D-19-0209.1**. For supplemental material, see **DOI:10.1175/BAMS-D-19-0209.2**.

We present an internationally coordinated plan to consolidate and enhance the Indian Ocean Observing System (IndOOS) to meet future societal needs for climate information and prediction.

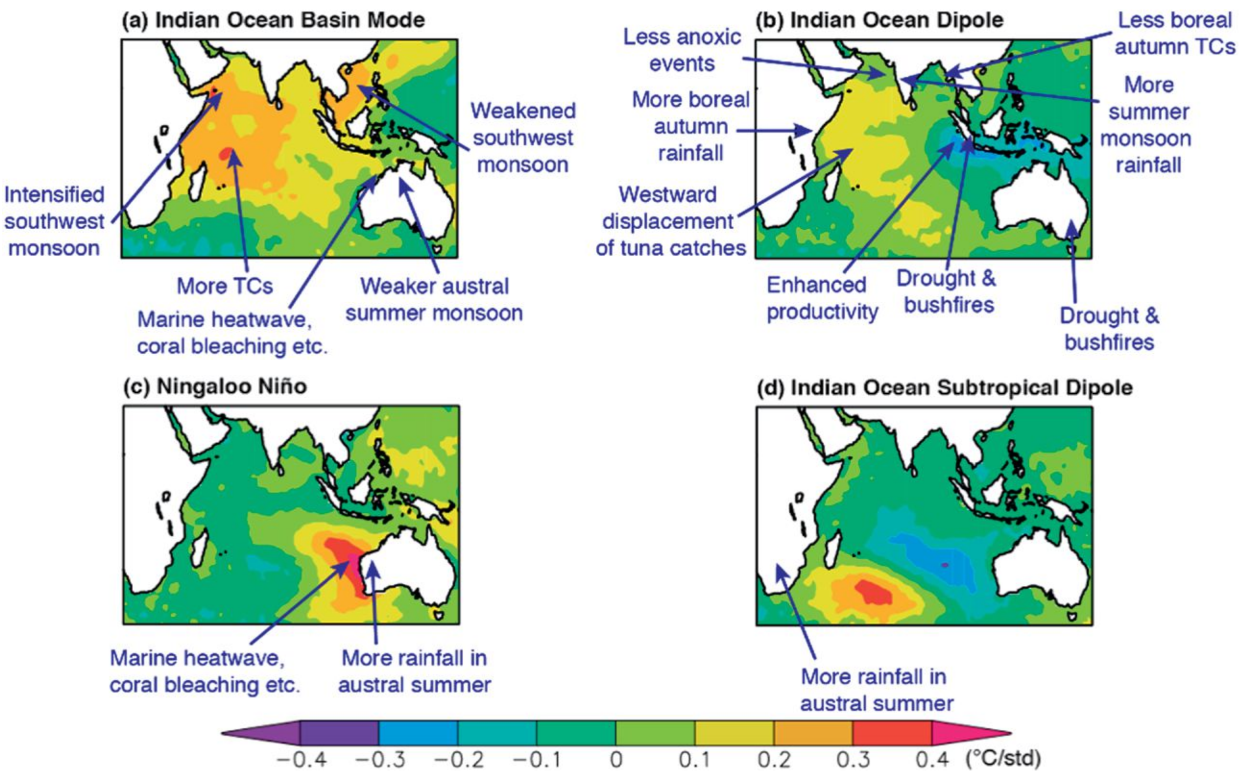
The Indian Ocean Observing System (IndOOS), established in 2006, is a multinational network of sustained oceanic measurements that underpin understanding and forecasting of weather and climate for the region and beyond. While the Indian Ocean is the smallest of the four major oceanic basins, close to one-third of humanity lives in the 22 countries around its rim. Many of the people of these rim countries are particularly vulnerable to the impacts of accelerating climate change, which include a greater frequency of floods and droughts over India, Africa, and Australia, and more wildfires in



Indonesia and Australia. Drought in East Africa alone is predicted to increase the number of undernourished people there by 50% by 2030. All these impacts are related to a rapid warming of the Indian Ocean, which has been the fastest warming of the oceans over the past two decades.

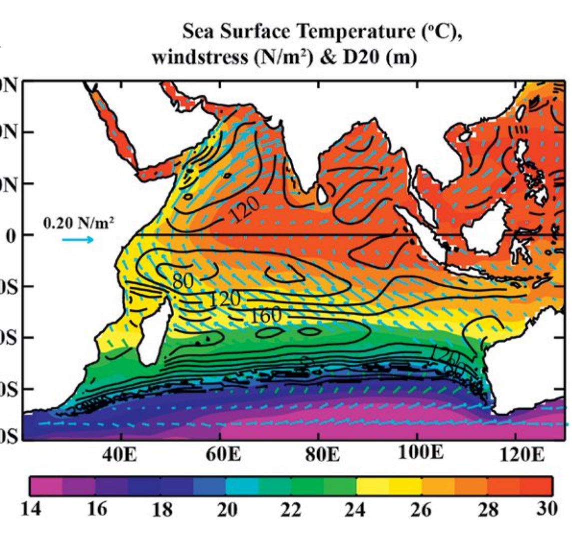
Beyond direct impacts on rim countries, it influences climate globally. The Indian Ocean affects the evolution of El Niño–Southern Oscillation (ENSO) in the neighboring Pacific, and it is the breeding ground for the 30–90-day Madden–Julian oscillation (MJO), which modulates rainfall

The Indian Ocean Observing System and its societal applications. The IndOOS data support research to advance scientific knowledge about the Indian Ocean circulation, climate variability and change, and biogeochemistry, as well as societal applications by virtue of its contribution to operational analyses and forecasts. Credit: JAMSTEC.

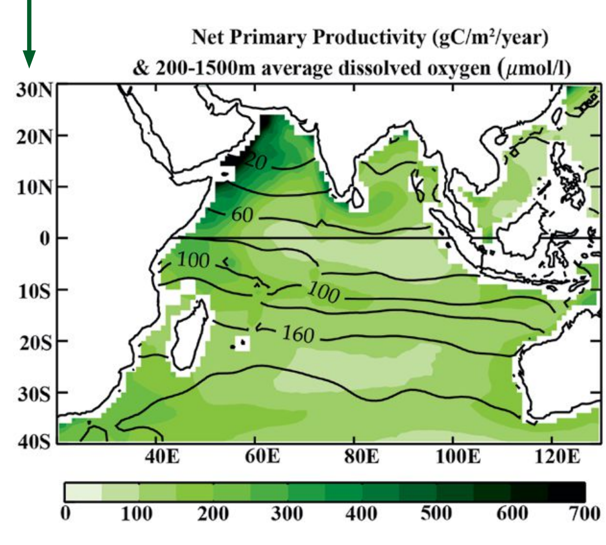


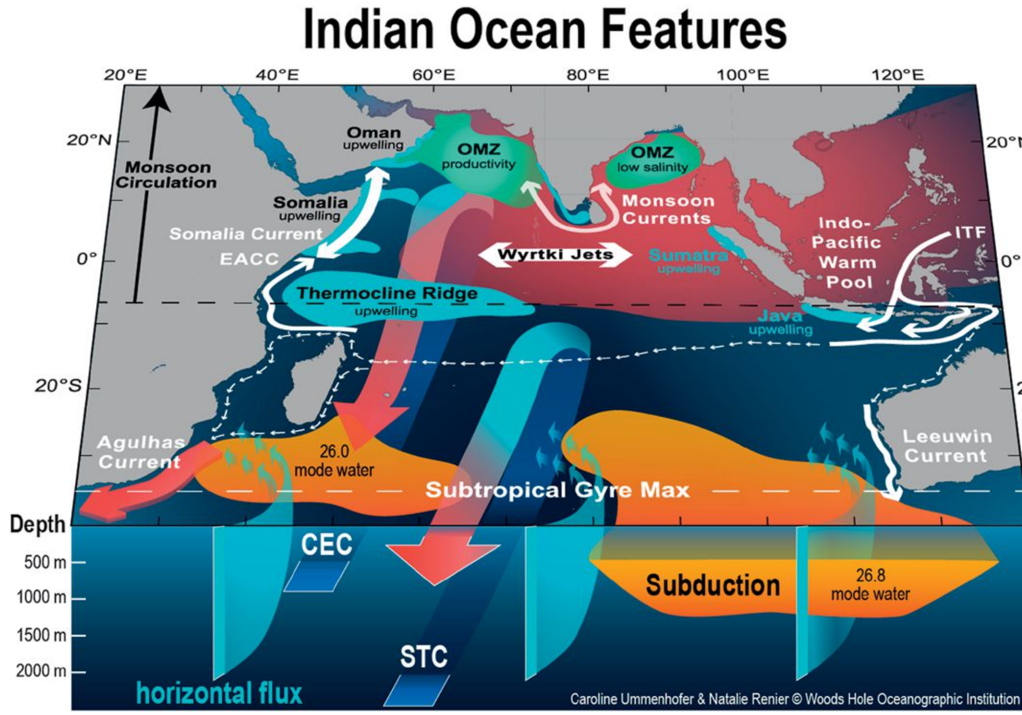
Until 20 years ago, the Indian Ocean was seen as passively responding to its giant Pacific neighbor. We now know that there is intrinsic climate variability (arising from regional air–sea interactions) in the Indian Ocean, with important climatic consequences regionally and beyond. SST signals associated with the four main Indian Ocean climate modes: (a) Indian Ocean Basin Mode (IOBM), (b) Indian Ocean dipole (IOD), (c) Ningaloo Niño (NN), and (d) Indian Ocean subtropical dipole (IOSD). The four climate modes induce year-to-year SST and rainfall fluctuations over the Indian Ocean region. They peak in FMA, SON, DJF, and JFM, respectively. El Niño events induce subsidence over the Indian Ocean, which warms almost uniformly as a result. In addition to their impacts on regional rainfall, these climate modes have biogeochemical and ecosystem signatures. The IOD and IOBM are thought to feed back into the ENSO cycle in the Pacific. The IOD, IOSD, and Ningaloo Niños are sometimes forced by ENSO, which is thus a source of predictability. The subsurface structure of the Indian Ocean also yields predictability for the IOD.

Boreal summer (JJAS) observed climatologies of sea surface temperature (colors) and wind stress (vectors). The heating of the Asian landmass by the sun's movements yields strong winds and rainfall in the boreal summer. Strong alongshore winds in the western Arabian Sea during the southwest monsoon induce coastal upwelling of cold subsurface waters, which modulates evaporation and moisture transport toward India and provides a globally significant source of atmospheric CO_2.

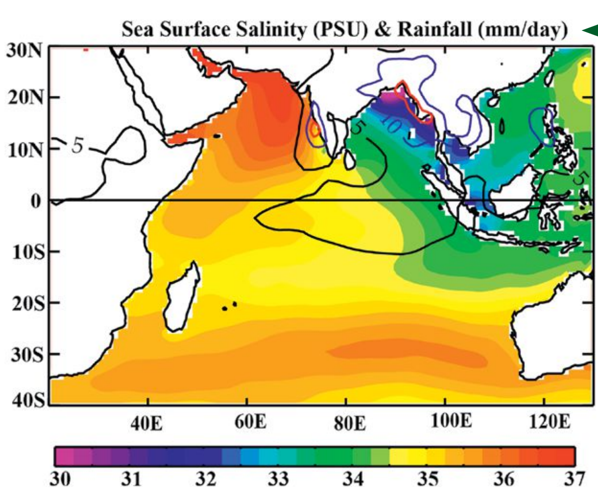


Boreal summer (JJAS) observed climatologies of primary productivity estimate (colors) and 200–1,500-m average oxygen (contours). The upwelled waters also bring nutrients to the surface, fostering intense oceanic productivity, which induces large oxygen consumption within the poorly ventilated lower layers. The result is a thick oxygen minimum zone (OMZ) between about 200- and 1,500-m depth.





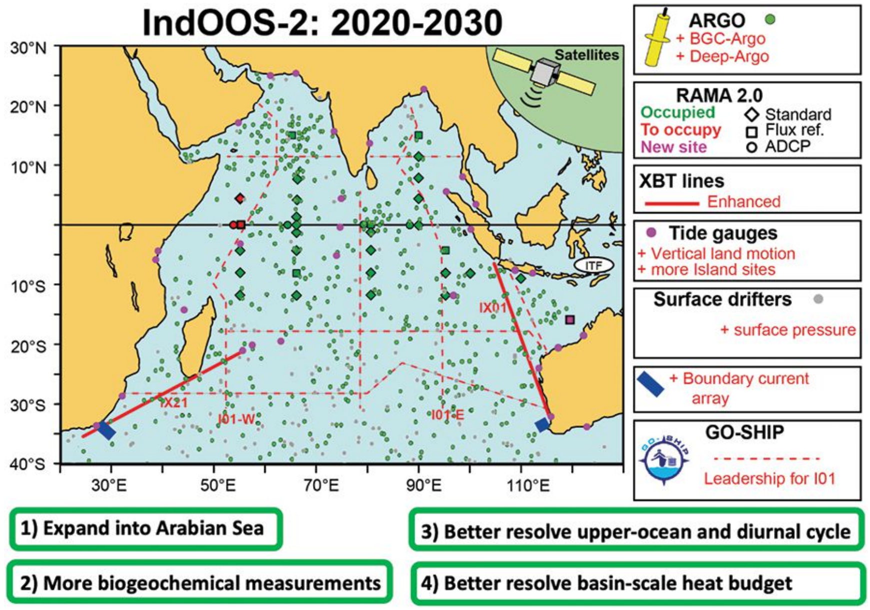
The Indian Ocean is the only tropical ocean that is bounded by a landmass to the north, resulting in the strongest and most extensive monsoon on Earth and many unique oceanographic features. Under the influence of monsoons, the surface circulation seasonally reverses north of 10°S. The summer monsoon also promotes the intense Somali current as well as upwelling and high productivity in the western Arabian Sea. High surface-layer productivity, sinking of biomass, and its remineralization at depth also lead to the formation of subsurface oxygen minimum zones (OMZs) in the Arabian Sea and Bay of Bengal. The Indo-Pacific warm pool is a region of intense air–sea interactions, where the Madden–Julian oscillation, monsoon intraseasonal oscillation, and Indian Ocean dipole develop. The Indian Ocean is a gateway of the global oceanic circulation, with inputs of heat and freshwater through the Indonesian Throughflow. The exit from the basin is through boundary currents, mainly the Agulhas Current along Africa, but also the Leeuwin Current along Australia. While variations in the ITF and Leeuwin Current have been linked to Indian Ocean heat content and sea level changes, lack of measurements in the Agulhas Current and the large uncertainties in surface heat fluxes currently make it difficult to constrain the basin-scale heat budget at interannual and longer time scales. There are two vertical overturning cells connecting subducted waters south of 30°S to the tropical Indian Ocean: the shallow subtropical overturning cell where water upwells in the "thermocline ridge" open-ocean upwelling region, and the cross-equatorial cell where water upwells farther north in the Arabian Sea off the coast of Somalia and Oman. These cells are the main source of subsurface ventilation due to the continents to the north. The annual-mean westerly winds along the equator in the Indian Ocean damp the equatorial upwelling that is found to the east of other tropical oceans. Instead, wind-driven open-ocean upwelling is found in the southwestern tropical Indian Ocean, forming the Seychelles–Chagos thermocline ridge (SCTR). Concentrated tuna fishing activities are documented in the SCTR upwelling. The SCTR hosts warm SSTs and a shallow thermocline, such that small perturbations in the atmosphere can easily induce an SST response, and vice versa. This results in strong air–sea coupling at various time scales linked to tropical cyclones, the Madden-Julian oscillation (MJO), and the Indian Ocean dipole (IOD). Accounting for SST responses and their feedbacks that are larger in the Indian Ocean than in the Pacific Ocean—particularly in the northwestern Australian Basin, SCTR, and Bay of Bengal—can improve the forecast range of the MJO by about 10 days, yielding enhanced rainfall predictability throughout the tropics.



Boreal summer (JJAS) observed climatologies of sea surface salinity (color) and rainfall (contours). In the Bay of Bengal, excess freshwater input from monsoon rains and river runoff creates a shallow, low-salinity surface layer. By inhibiting vertical mixing of heat, nutrients, and oxygen, this salinity stratification is thought to favor warmer SSTs, which promote monsoon rainfall and more intense cyclones, reducing oceanic productivity.

and cyclogenesis throughout the global tropics. The Indian Ocean also influences the Atlantic Meridional Overturning Circulation (AMOC) across multiple time scales through atmospheric and oceanic teleconnections, advection, and mixing. The basin accounts for about one-fifth of the global oceanic uptake of anthropogenic CO_2, helping to buffer the effects of global warming.

While the IndOOS has profoundly changed our understanding of the Indian Ocean and its links to weather and climate over the past fifteen years, there remain some critical gaps, not least a lack of monsoon predictability. A recent 3-year, international review by more than 60 scientific experts lays out a roadmap for an observing network that can more effectively meet societal needs and provide data that result in more reliable forecasts in the future. There are four key recommendations: 1) geochemical and biological measurements alongside physical parameters to track and forecast marine ecosystem changes; 2) expansion into the western tropics to improve understanding of the monsoon circulation; 3) better-resolved upper-ocean measurements to improve understanding of air–sea coupling and yield subseasonal-to-seasonal predictability; and 4) expansion into key coastal regions and the deep ocean to better constrain the basin-wide energy budget. These goals will require new agreements and partnerships with and among Indian Ocean rim countries, creating opportunities to enhance monitoring and forecasting capacity as part of IndOOS-2.



Main IndOOS-2 recommendations. These recommendations can be summarized in four core findings of the review, listed in green in the frames below the map.

Components of IndOOS

IndOOS is currently composed of five in situ observing networks: profiling floats (Argo), a moored tropical array [Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA)], repeat lines of temperature profiles [expendable bathythermograph (XBT) network], surface drifters, and tide gauges. Augmenting these networks are critical observations of the ocean surface from satellites, as well as a wide range of full-depth ocean sections via the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP).

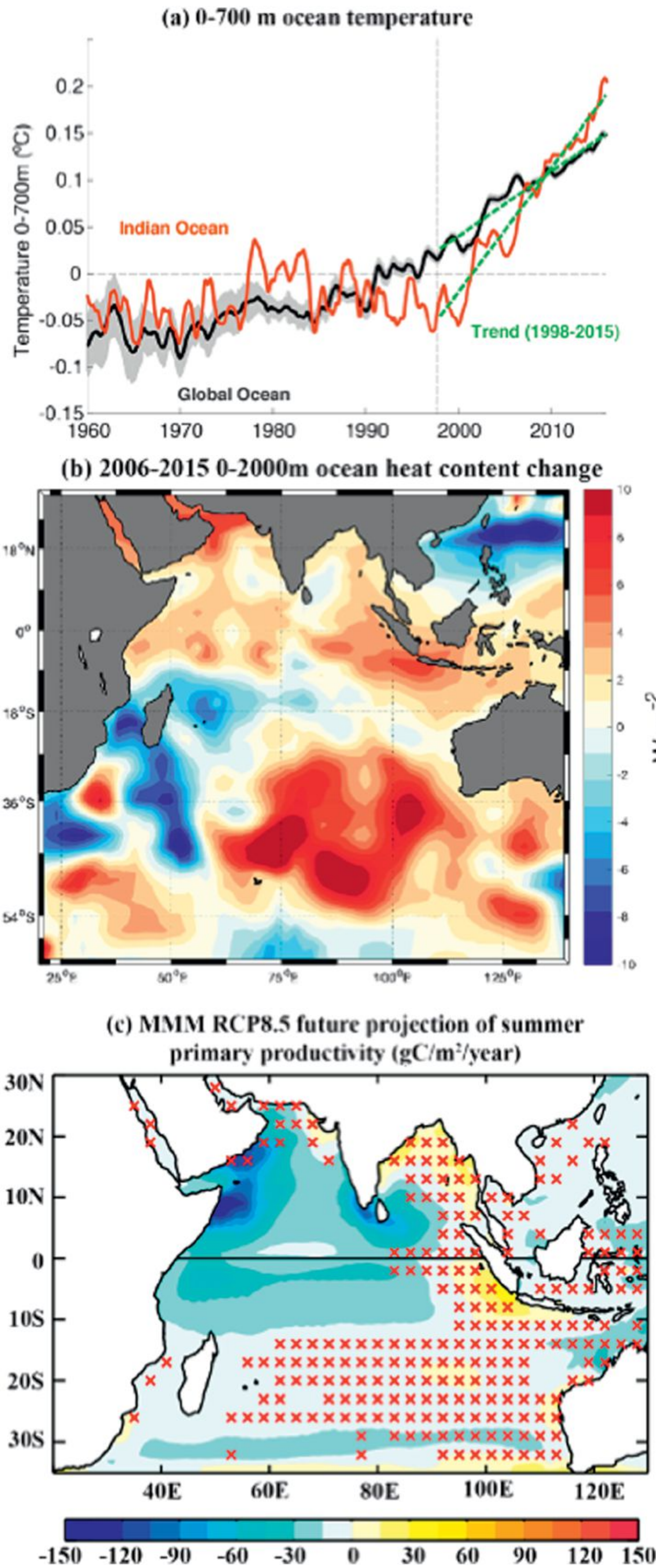
Argo. This global array has a target of one autonomous profiler per 3° × 3° region, each profiling the ocean every ten days to measure temperature, salinity, and pressure down to 2,000 m. A growing number of profilers, mostly in the Arabian Sea and Bay of Bengal, are equipped with biogeochemical sensors to measure key processes related to, for example, plankton blooms, oxygen minimum zones (OMZs), and fisheries.

RAMA. As a component of the Global Tropical Moored Buoy Array, RAMA provides subdaily time series of key oceanographic and surface meteorological variables in real time in a region where the oceanic response to atmospheric forcing is rapid and coupled feedbacks are critical.

XBT. The voluntary observing ship network collects temperature observations over the upper ~1 km of the ocean along regular commercial shipping routes.

Global drifter program. Surface drifters are drogued to follow ocean currents at 15 m. The design density is one drifter per 5° × 5° region with 90% coverage in the Indian Ocean. All drifters also measure temperature and about half now measure sea level pressure. These parameters are important for forecasting.

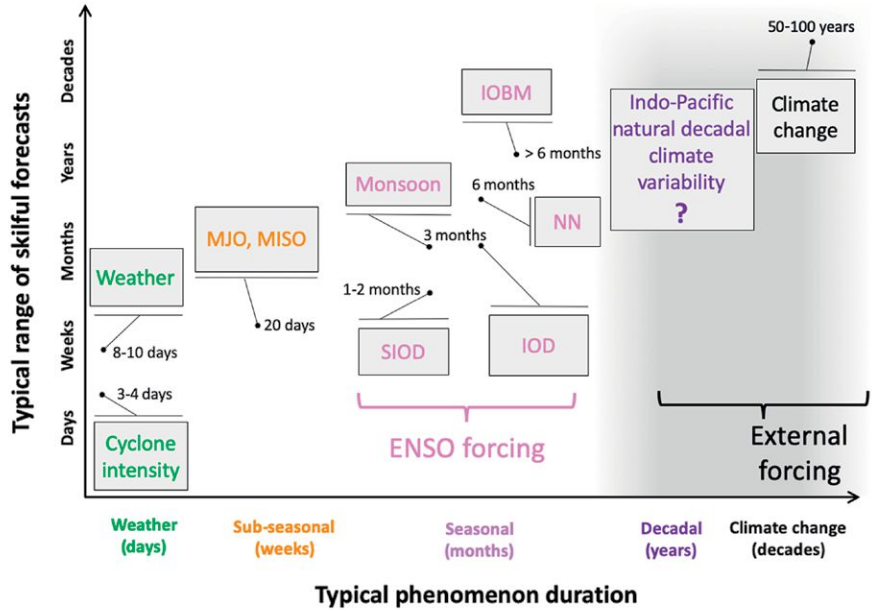
Tide gauges. The tide-gauge network provides measurements of sea level at coasts



◀* **The Indian Ocean is responding to anthropogenic climate change, with evidence of increasing surface temperatures and heat content, rising regional sea level, increased carbon uptake, and an intensified water cycle. Due to its large heat capacity, the ocean absorbs more than 90% of the anthropogenically induced excess heat into the Earth system The Indian Ocean has been warming faster than the global ocean over the last 20 years, accounting for about 25% of the global ocean heat content increase (despite representing only 13% of the global ocean surface), with the strongest 0–2,000-m warming in the southeastern subtropics. Since decadal variations of heat storage seemed to play an important role in the recent hiatus of global surface warming, there is a strong need to improve our understanding of the Indian Ocean heat storage via better measurements of the surface (air–sea fluxes), entrance (ITF), and exit (Agulhas and Leeuwin Current) fluxes. The consequences of heat content changes for biogeochemical cycles and extreme weather events are serious with, for example, more intense cyclones in the Arabian Sea and Bay of Bengal, and long marine heat waves like that north of Australia in 2016. (a) The 1998–2015 linear trends for both series are displayed as green dashed lines. (b) The 2006–15, 0–2,000-m heat content change ($W m^{-2}$), computed from the optimal interpolation of Argo profiles. Deep, 700–2,000-m heat content changes represent about 20% of the trend over the entire Indian Ocean. (c) CMIP5 historical and RCP8.5 multimodel-mean (23 models) projected changes (2080–2100 minus 1980–2000) in boreal summer (JJAS) primary productivity. Red × symbols indicate regions where less than 80% of the models agree on the sign of the projected change. Rapid warming and expansion of the Indo-Pacific warm pool has altered the life cycle of the MJO, resulting in changing rainfall patterns across the tropics and the United States. Basin-scale warming, acidification, and an expansion of OMZs are putting stress on marine ecosystems. A dramatic shift in the ecosystem of the Arabian Sea is already evident as a result of hypoxia. Observations indicate a decrease in Indian Ocean primary productivity over 1998–2015, consistent with climate models that project a ~20% decrease by the end of the twenty-first century. In contrast, present and future evolution of subsurface oxygen concentration are both inconsistent across models and with observational estimates. Understanding regional patterns of change, attributing them to natural variability or anthropogenic forcing, and being able to project them into future decades is an ongoing challenge. Only a well-planned and sustained IndOOS can provide the necessary information.**

or on islands. A subset of these stations monitors land motion, necessary to quantify long-term trends in absolute sea level. The network also provides tsunami warnings.

Satellites. As the only source of basin-scale measurements at subseasonal frequencies, satellite measurements of sea surface temperature and salinity, sea surface height, ocean color (a proxy for primary productivity), significant wave height, and ocean mass provide key measurements of the state of the Indian Ocean and atmospheric variables, including surface wind and wind stress, to allow for the estimation of ocean surface currents.



Range of skillful state-of-the-science forecasts for Indian Ocean weather and climate phenomena, as a function of their time scale. Some studies suggest that decadal climate forecasts could be most skillful for the Indian Ocean, because the externally forced climate change signal overwhelms the inherently less predictable decadal variability in this basin.

GO-SHIP. An internationally coordinated program of decadally repeated multidisciplinary scientific cruises that collect a wide variety of high-quality measurements including physical and geochemical properties of seawater to full ocean depth.

Evaluating IndOOS

Extreme events. Sea level pressure and upper-ocean (<200 m) temperature and salinity observations from RAMA, Argo, and drifters are essential for cyclone forecasts and for weather forecasting more generally, but they do not capture every storm. Cyclones making landfall around the rim of the Indian Ocean are the deadliest on the planet owing to the vulnerability of infrastructure and populations there. New satellite technologies are needed to observe SST through cloud and rainfall during these extreme events.

Subseasonal variability. The IndOOS has characterized the leading modes of subseasonal variability in the Indian Ocean—the MJO and monsoon intraseasonal oscillations (MISO). Yet, predictions of these coupled oscillations, which modulate tropical rainfall, remain disappointing, with little skill beyond 20–30 days. There is potential for improvement in prediction skill through better representation of air–sea coupling at diurnal scale, including the SST response to the MJO.

Monsoons. The southwest and northeast monsoons dominate Indian Ocean circulation and climate everywhere north of 10°S, and the IndOOS has greatly refined our understanding of these phenomena and how they redistribute heat around the northern basin and across the equator. In particular, RAMA velocity data have improved our understanding of the intense intermonsoon Wyrtki jets, and a decade of surface drifter data describe the complex surface monsoon circulation relatively well. However, strong biases in monsoon rainfall persist in climate models, and this motivates new measurements that can initialize and validate these models. There remains a gap in observations in the western equatorial Indian Ocean, where piracy has precluded measurements for decades, including in the Somali Current and its associated upwelling cells.

Interannual variability. Basin-scale surface signatures of the IOD [SST, sea surface height (SSH), wind, and sea surface salinity (SSS)] are well described by the IndOOS, as are the associated equatorial dynamics and some subsurface signals and predictors. Nevertheless, the skill of IOD forecasting quickly drops beyond 3 months. Lack of measurements in the IOD eastern pole, including in the Java–Sumatra coastal upwelling, are thought to be a major contributor to this lack of forecast skill. Ocean dynamics and sea level in the SCTR also influence the IOD.

Gliders, additional moorings, and island tide gauges could capture these signals.

The interannual variability of mass and heat fluxes into the Indian Ocean from the Pacific is well constrained by 30+ years of XBT measurements across the mouth of the Indonesian Throughflow (ITF). However, we now know that freshwater variability has first-order effects on the ITF, and this means that observations of salinity are needed alongside temperature. The subtropical gyre hosts the subtropical dipole and Ningaloo Niño modes but lacks the sustained observations of the Agulhas and Leeuwin Current/Undercurrent systems that are needed to constrain and understand the variability of the gyre.

Decadal variability and change. The relative paucity and irregularity of past observations compared to the Pacific and Atlantic means that natural decadal climate variability has yet to be discerned from anthropogenic change in the Indian Ocean.

Biogeochemical cycles and change. There are no repeat measurements of air–sea flux of CO_2 as part of the IndOOS; very limited observations of nutrients, bio-optics, and oxygen; and no baseline for biodiversity or biomass in the Indian Ocean. Pilot programs for biogeochemical measurements have been conducted on some IndOOS platforms, including RAMA moorings and the highly successful Indian–Australian Bio-Argo program.

IndOOS 2020–30: The way forward

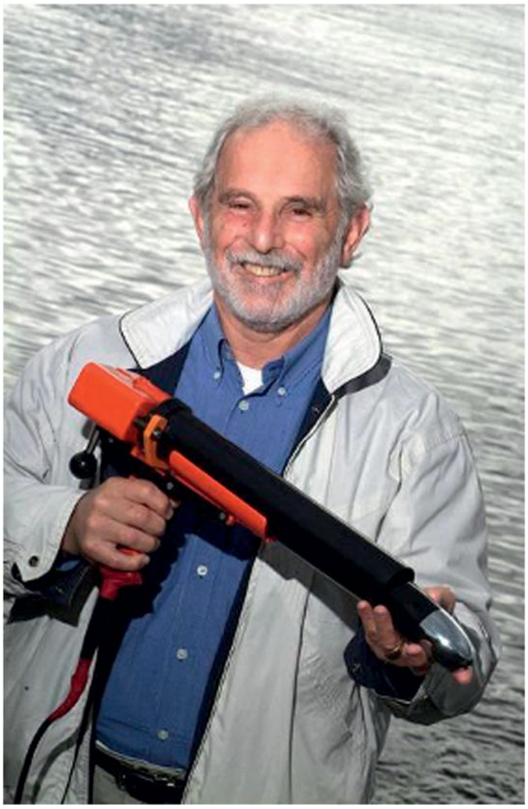
Our evaluation of the IndOOS emphasizes significant limitations to our knowledge and predictive capabilities of Indian Ocean climate, but stresses that these limitations can be overcome with future enhancements.

A clear priority is to sustain the essential observing networks of IndOOS—Argo, RAMA, tide gauges, surface drifters, XBT, GO-SHIP lines, and satellite missions—to support understanding and prediction, and for detection and attribution of anthropogenic changes. Innovative, low-cost instrumentation and platform technologies must transform the IndOOS in the near future. Some of these technologies—such as gliders and Saildrones—have immediate potential for reaching unmeasured regions like upwelling zones and boundary currents.

As far as enhancements of IndOOS, the top priority is to establish sustained measurements of the carbon cycle and of ecosystem variability and change. Recent U.S. funding for a biogeochemical (BGC)-Argo program paves the way for these revolutionary observations over the next decade. Key regions that need such measurements include the OMZs in the northern Indian Ocean and the highly productive upwelling systems of Somalia–Oman and Java–Sumatra.

Dedication to Gary Meyers

This article is dedicated to Gary Meyers (1941–2016), a visionary and leader of ocean observing systems. He was the founding chair of the CLIVAR/ IOC-GOOS Indian Ocean Region Panel, leading the initial design and development of a sustainable observing system for the Indian Ocean and effectuating the birth of IndOOS. Gary was an eminent oceanographer who received many awards, including the 2006 Australian Meteorological and Oceanographic Society Medal for Leadership in Meteorology and Oceanography. The Indian Ocean scientific community will miss his warm personality, deep scientific knowledge, and inspiring leadership.



The late Gary Meyers, former cochair of the Indian Ocean Region Panel, and one of the promoters of the IndOOS observing system.

To meet the regional need for seasonal-to-subseasonal forecasting, including monsoon predictability, key processes of the near-surface ocean, especially diurnal mixed-layer and barrier-layer variability, need to be better measured and understood. These processes are notoriously small-scale, requiring continuous measurements of the upper water column at unprecedented time and space scales. Such measurements could be made at existing RAMA sites.

It is vital that IndOOS covers key shelf/slope regions in the future, particularly in the subtropics, where swift boundary currents dominate the basin-wide heat, freshwater, carbon, and nutrient budgets and where coastal upwelling systems drive primary productivity, air–sea fluxes, and climate variability. Integrating observations of boundary systems into IndOOS may be the biggest challenge yet for the community, requiring new cooperative agreements and a suite of relatively novel technologies that can capture a cascade of dynamical scales.

Finally, seasonal-to-decadal climate forecasts need to be constrained by more measurements in the deep ocean. We recommend that IndOOS be expanded below 2,000 m using a suite of Deep-Argo floats, with priority in the southern subtropical Indian Ocean where deep heat content change is largest.

Alongside these in situ observing system needs, three overarching ingredients are necessary for the future success of IndOOS. First, continuous and overlapping satellite missions provide the only spatially coherent view of the ocean and remain essential—in particular SST, SSH, surface wind, ocean color, SSS, and rainfall. Second, improved data assemblage and data assimilation are urgently needed for long, homogeneous, climate-quality records, particularly to constrain models and predictions. Finally, and perhaps most importantly, increased engagement and partnerships with and among Indian Ocean rim countries are needed to expand their ocean-observing capabilities in collaboration with the IndOOS community. This expansion requires open access to exclusive economic zones, resource sharing, and capacity building between nations.

The United Nations has proclaimed 2021–30 as the Decade of Ocean Science for Sustainable Development. IndOOS-2 recommendations align with the UN Decade program, and implementing them is crucial for accomplishing its key societal goals.

METADATA

BAMS: What would you like readers to learn from this article?

Lisa Beal (University of Miami): *That the Indian Ocean matters!*

BAMS: What surprised you the most about the work you document in this article?

LB: *I was surprised and delighted by how many people volunteered their time to realize this work. We all learned a great deal about the ocean and about ourselves. One of the revelations that sticks with me is that satellite ocean color data—used to estimate chlorophyll and biomass in the ocean—has never been ground-truthed in the Indian Ocean. There has never been a baseline for biomass and biodiversity of the Indian Ocean. So we will never know the half of what was out there when the system was pristine.*

Roxy Koll (Indian Institute of Tropical Meteorology): *I was surprised to find that, despite high-density observational arrays like ARGO since the early 2000s, we still have glaring gaps in ocean data. These gaps prevent us from understanding how much heat is being transported in and out of the ocean basins or how many fish are out there and if the expansion of hypoxic zones is making it unlivable for them.*

BAMS: What was the biggest challenge you encountered while doing this work?

LB: *By far the biggest challenge was trying to be sure everyone was heard and then synthesizing and focusing all the input. We could not have done it without Jing Li and the International CLIVAR Project Office.*

RK: *The biggest challenge is that our recommendations for building a comprehensive observing system in the Indian Ocean will remain on paper without strong regional and international partnerships. This is where scientists must go beyond science and work on strategies to build these networks.*

The operational costs of ocean observations have gone up, while funding at national levels has flattened or declined. Hydrographic data along crucial coastal zones of the Indian Ocean are inaccessible to the global scientific community for geopolitical reasons. Since coastal dynamics are a crucial factor regulating weather and extreme events, lack of data compromises the accuracy of monitoring and forecasts. We urgently need to scale up our investments in ocean observations, and we need to share the data in a fair, accessible way.

Examining the Inner Shelf

A Coastal Dynamics Experiment

Adapted from "The Inner-Shelf Dynamics Experiment," by **Nirnimesh Kumar** (Deceased; University of Washington), **James A. Lerczak, Tongtong Xu, Amy F. Waterhouse, Jim Thomson, Eric J. Terrill, Christy Swann, Sutara H. Suanda, Matthew S. Spydell, Pieter B. Smit, Alexandra Simpson, Roland Romeiser, Stephen D. Pierce, Tony de Paolo, André Palóczy, Annika O'Dea, Lisa Nyman, James N. Moum, Melissa Moulton, Andrew M. Moore, Arthur J. Miller, Ryan S. Mieras, Sophia T. Merrifield, Kendall Melville, Jacqueline M. McSweeney, Jamie MacMahan, Jennifer A. MacKinnon, Björn Lund, Emanuele Di Lorenzo, Luc Lenain, Michael Kovatch, Tim T. Janssen, Sean R. Haney, Merrick C. Haller, Kevin Haas, Derek J. Grimes, Hans C. Graber, Matt K. Gough, David A. Fertitta, Falk Feddersen, Christopher A. Edwards, William Crawford, John Colosi, C. Chris Chickadel, Sean Celona, Joseph Calantoni, Edward F. Braithwaite III, Johannes Becherer, John A. Barth**, and **Seongho Ahn**. Published online in *BAMS*, May 2021. For the full, citable article, see **DOI:10.1175/BAMS-D-19-0281.1**.

The Inner-Shelf Dynamics Experiment involved observing and numerical modeling of complex and influential geophysical interactions along the Pacific margin of California.

The coastal ocean spans the shoreline to the midcontinental shelf. These waters range from 0 to about 100 m deep, and the inner shelf, in particular, is dynamically complex. In this transition region between the surfzone and the midshelf, the evolution of circulation and stratification is driven by multiple physical processes.

We conducted an intensive, multi-institution field experiment to investigate the dynamics of circulation and transport in the inner shelf and the role of coastline variability in regional circulation dynamics. The experiment ranged from the midshelf through the inner shelf and into the surfzone off a 50-km section of central California, in the vicinity of Point Sal, during September–October 2017. We call this effort the Inner-Shelf Dynamics Experiment (ISDE). Coordinated by the Office of Naval Research, ISDE involved satellite, airborne, shore- and ship-based remote sensing, in-water moorings, and ship-based sampling, as well as numerical ocean circulation models forced by observations of winds, waves, and tides.

Coastal ocean circulation regulates the transport of tracers like nutrients, pathogens, and pollutants critical to maintaining healthy ecosystems. The circulation also controls lateral movement of heat and entrained gasses, resuspension of sediment, and advection and mixing of organic and inorganic particles contributing to variable optical clarity of coastal waters.

The surfzone extends from the shoreline to the offshore extent of depth-limited wave breaking, The midshelf, by contrast, is categorized by nonoverlapping surface and bottom boundary layers separated by a distinct interior. As the transition between these zones, the inner shelf is where the boundary layers can overlap.

For decades, the offshore extent and the dynamical definition of the inner shelf has remained somewhat ambiguous—it is dependent on the dominant processes driving the circulation in a particular coastal region. The inner shelf has been defined in the context of coastal wind-driven dynamics. In this context, the outer boundary of the inner shelf begins at the boundary layer overlap, which causes a divergence and eventual shutdown in Ekman transport.

The complicated dynamics within and immediately outside the inner shelf include surface waves, internal waves, wind, barotropic tidal processes, buoyancy, submesoscale eddies, and boundary layer–driven processes, all contributing to changing the circulation pattern and local stratification on frictional, rotational, and longer time scales.

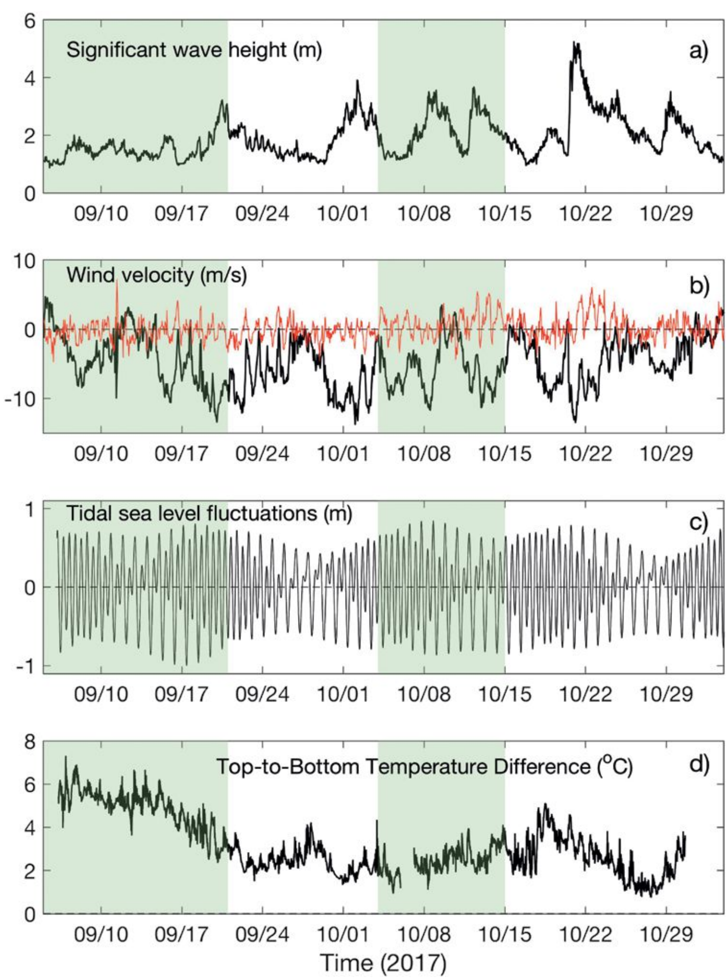
Previous studies targeting the inner shelf have documented the wind-driven and surface gravity wave–driven dynamics on simple coastlines and bathymetry, yet the role of complex coastlines in modifying inner-shelf dynamics on subtidal and shorter time scales have not been well understood. Furthermore, nonlinear interactions between wind, surface gravity waves, internal waves, surface heat fluxes, turbulence, and rip currents have yet to be quantified: prior studies generally treated processes like subtidal wind-driven circulation in isolation from other inner-shelf physical processes.

A defining feature of this field program is the capability to observe the complex superposition (and interaction) of multiple physical features. The project focused on quantifying circulation dynamics and stratification evolution and on understanding and predicting tracer exchange. The resulting high spatial and temporal resolution oceanographic measurements and numerical simulations provide a central framework for studies exploring this complex and fascinating oceanic region. ISDE allows for unprecedented investigations into spatial heterogeneity, and nonlinear interactions between various inner-shelf physical processes.

In the experiment, onshore-propagating nonlinear tidal bores and solitons often propagated through wakes. The dataset is rich with signatures of processes driving exchange between the surfzone and inner shelf. Fronts or internal waves were often observed in radar or airborne data to reach the surfzone edge (several hundred meters from the shoreline), sometimes appearing to "wrap around" rip-current plumes that extended up to several surfzone widths offshore (up to 1 km from the shoreline).

Among other insights, the dataset demonstrates that high-frequency elevation waves

The article online has a supplemental animation of the phenomena observed and modeled in ISDE that can be found at 10.1175/BAMS-D-19-0281.2.



(top) A 1-h temperature time series 5–30 m above the bed (mab) from a lander at 35-m depth shows a packet of high-frequency waves of elevation. (middle) East–west velocity profiles over the 3 mab (black box in the top panel) from a pair of up- and down-looking, pulse-coherent, high-resolution ADCPs showing strong near-bed velocities during the same time. (bottom) East–west velocity component from an ADV located roughly 1 mab (blue line in the middle panel) shows the amplitude of currents associated with the time scale (~12 min) of internal waves to be typically 4 to 5 times greater than the amplitude of currents associated with the time scale (~8 s) of surface gravity waves. The ADV and ADCPs logged for 20 min every half hour. The observed near-bed flows exceeded the critical threshold for sediment motion. Suspended particulates may not settle between internal waves within a packet.

generate bed shear stresses that exceed the critical threshold for sediment motion, and suspended particulates may not settle between internal waves within a packet (based on grab sample measurements of sediment size).

To complement observations, regional numerical simulations were used to identify the potential generation region of tidally forced internal waves.

Analyses and insights

Analysis of filtered temperature measurements from ISDE in water depths of 9–16 m reveals alongshore dependence in temperature variability in subtidal, diurnal, and semidiurnal frequency bands, with Point Sal being a location of strong changes in variability. Subtidal temperature variability was relatively uniform alongshore with a small gradient just south of

Primary Physical Processes of Inner-Shelf Transport: A Brief Overview

Seminal studies demonstrate at subtidal time scales the sensitivity of cross-shore transport to cross-shore, upwelling-favorable, and downwelling-favorable winds, strength of stratification and structure of mixing, alongshore pressure gradients, and the presence of cross-shore buoyancy gradients. In addition, Stokes drift by surface gravity waves outside the surfzone may be a dominant mechanism for cross-shore transport, and radiation stress gradients may be a potential leading-order term in the inner-shelf cross-shore momentum budget. Meanwhile, highly nonlinear internal tides and high-frequency internal waves in the inner shelf are responsible for large changes in stratification and strong cross-shore currents over short time scales and also transport heat from the inner shelf to the surfzone.

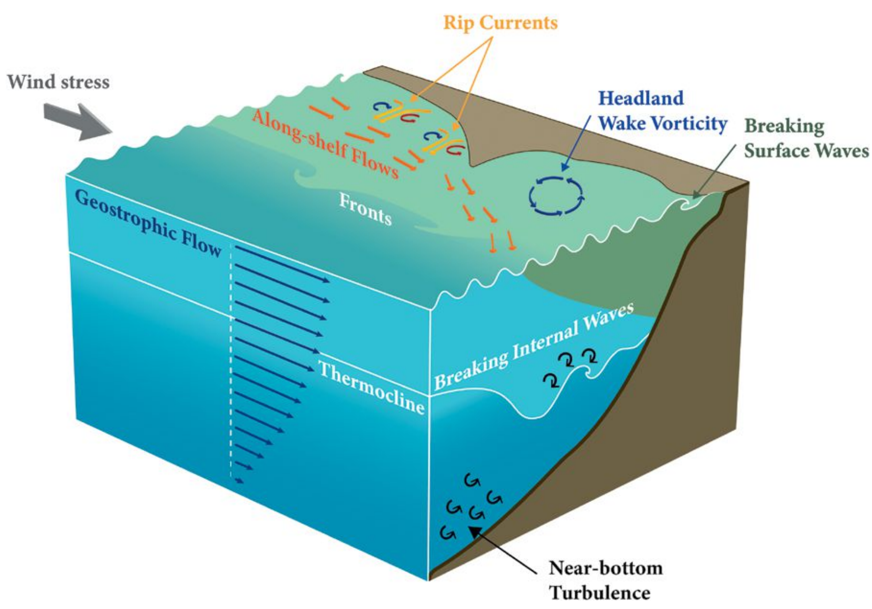
Internal waves also transport plankton and nutrients and can resuspend and transport sediment. Turbulence and mixing generated by internal wave dissipation lead to vertical fluxes of tracers and enhance stresses that may augment the surface and bottom boundary layer. Diurnal processes including heating and winds can also change currents and stratification.

Analogous to saturated waves in the surfzone, internal tides propagating into the inner shelf can reach a saturated state. The internal tide saturation region starts where the incident internal tide amplitude becomes comparable to the water depth. This typically occurred at water depths between 40 and 80 m during ISDE.

Mesoscale and submesoscale variability due to eddies, filaments, and fronts are dominant mechanisms for exchange between the continental shelf and open ocean, delivering nutrients to coastal ecosystems. Rip currents and surfzone eddies are the primary known mechanisms for cross-shore transport. Flow separation past abrupt bathymetry such as headlands leads to vorticity generation.

In addition, buoyancy-driven flows (e.g., river discharge) can dominate the inner-shelf circulation, and there are other inner-shelf processes not mentioned in this brief summary.

Inner-shelf processes in ISDE. ✱▶ **Surface waves become nonlinear and break, generating surfzone circulation like rip currents, which eject onto the shelf. Wind and tidally driven along-shelf flows separate from the coastline and generate eddies. Onshore-propagating internal waves also become nonlinear and lead to overturning and mixing. Additional mixing occurs at the bottom-boundary layer. The onshore-propagating warm bore was at least 10 m thick with 0.2–3-m s^{-1} onshore velocities.**

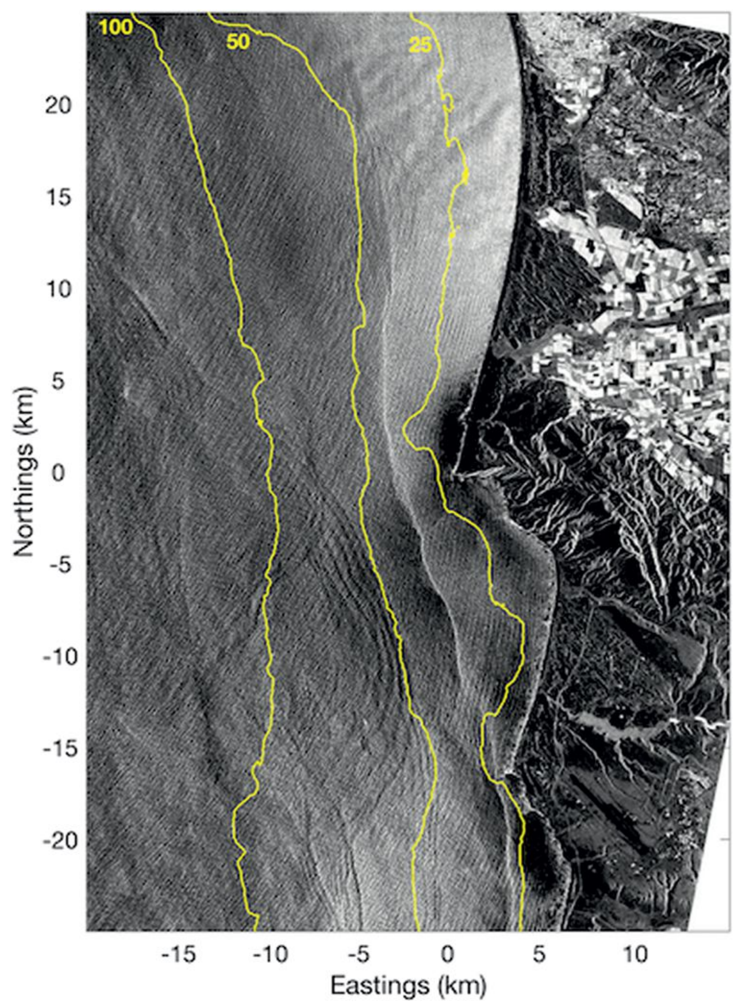


Point Sal. Diurnal variability was high north of Point Sal and was reduced south of Point Sal and Point Purisima. The same analysis reveals southward propagation of the diurnal baroclinic signal. Ongoing analysis including moorings from 9- to 50-m water depth also shows a consistent diurnal band variability on the length scales of tens of kilometers. Semidiurnal band temperature variability is found to be substantial, especially around the headlands. Variable stratification and Doppler shift associated with eddy activities might lead to this along-shelf inhomogeneity.

Spatial heterogeneity of the semidiurnal internal tide signals from the outer to the inner shelf have been investigated using both observations and numerical model simulations. Mean (September 2017) semidiurnal internal tidal energy fluxes at the 50- and 30-m isobaths are strongest adjacent to Point Sal, decreasing in magnitude both toward the north and south. The flux magnitude also decreases as internal tides propagate onshore and dissipate, a pattern that is also seen in the mean horizontal kinetic energy. Furthermore, internal tide properties, such as energy, amplitude, and frontal structure, are influenced by the spatial heterogeneity of stratification. For example, nonlinear internal bore fronts are found to be alongshore continuous $O(10)$ km at the 50-m isobath and only $O(1)$ km at the 25-m isobath.

The role of turbulence-enhanced mixing of mass and momentum as well as turbulence energy dissipation in controlling the inner-shelf subtidal cross-shelf circulation has been a poorly understood topic. ISDE allowed for the first comprehensive mapping of the turbulent dissipation rates over the inner shelf.

The distribution of depth-averaged dissipation rate over a portion of the inner shelf with smooth topography is enhanced in shallower regions decreasing smoothly from onshore to offshore. The enhanced dissipation rates in the shallower reaches of the smoother inner shelf may be associated with a variety of processes including surface-layer turbulence by wind and nonlinear internal-wave dynamics. Enhanced dissipation occurs at the headlands and complicated bathymetry of Points Sal, Purisima, and Arguello, with a more randomly distributed pattern with offshore distance.



Observed nonlinear internal waves (NLIWs) included steep bores, undular bores, and high-frequency waves of elevation and depression. Internal bores propagated into the region every 6 h and were detectable in both in situ and remote observations. Data from satellite SAR and land- and ship-based radar stations demonstrate that internal bores were alongshore-coherent of order tens of kilometers, with additional short-scale horizontal variability. This alongshore coherence decreased toward shore. As internal waves propagated into shallower water, their evolution depended on the shelf stratification and background shear. COSMO-SkyMed X-band synthetic aperture radar (SAR) satellite image at 0158:49 UTC 9 Sep 2017 shows surface signatures of multiple internal waves. Yellow contours indicate the 25-, 50-, and 100-m isobaths. COSMO-SkyMed Product Agenzia Spaziale Italiana (ASI) 2017 processed under license from ASI. All rights reserved. Distributed by e-GEOS.

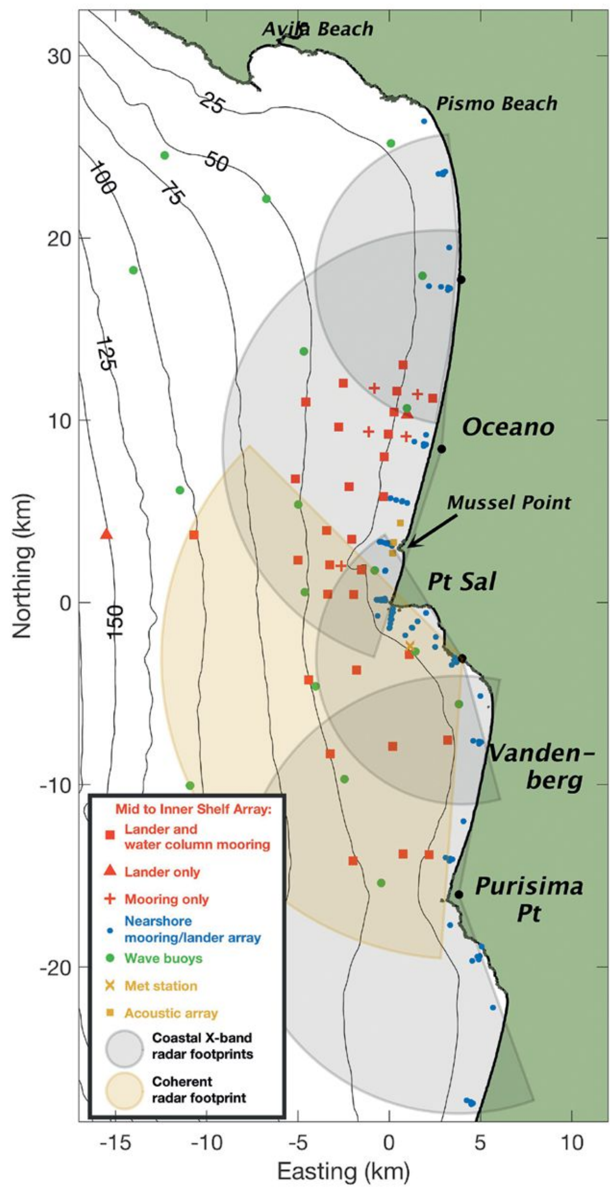
Sensors and Platforms

A total of 173 moorings and bottom landers were deployed during the experiment to measure temperature, salinity, current velocity, turbulence, surface gravity waves, and suspended sediment. Water-column temperature and salinity were measured along vertical mooring lines at 95 locations. Temperature sensors spanned the water column with vertical spacing of 1–5 m between sensors at the deeper locations and 1 m or less in shallow water. Sensor sample intervals varied from 0.5 to 30 s. Each lander had an upward-looking acoustic Doppler current profiler (ADCP) to measure current velocities. The vertical resolution ranged between 0.25 and 3 m. Most landers were also equipped with temperature sensors, programmed to sample at the same rate as the mooring sensors. In addition, high-precision pressure sensors (Ppods) were deployed on landers at five locations. Two of the landers were instrumented to observe near bed currents, turbulence, and seabed roughness using a suite of acoustic Doppler velocimeters (ADVs), high-resolution ADCPs (2 MHz), and high-frequency seabed imaging sonars. As noted above, some ADCPs resolved turbulent stresses. Temperature microstructure was measured along mooring lines and landers using χ pods. A newly developed instrument for this experiment, the GusT, was equipped to measure temperature and velocity microstructure as well as pressure and instrument orientation, pitch, roll, and acceleration. Approximately 80 GusT instruments were deployed on moored and shipboard platforms, providing greatly enhanced coverage of turbulence over the inner shelf.

Surface gravity wave directional spectra were measured using Sofar Spotter buoys at 18 locations and one miniature wave buoy near Point Sal. In addition, meteorological measurements were made from a mooring near Point Sal as well as from two locations on land.

In addition, there were drifters, land-based X-band radar, sUAS-based imaging, and along-coast surveys coordinated from as many as three ships (R/Vs *Oceanus*, *Sally Ride*, and *Robert Gordon Sproul*) and three small boats (R/Vs *Kalipi*, *Sally Ann*, and *Sounder*) with downward-looking ADCPs and profiling conductivity–temperature–depth (CTD) instruments.

Some ships also had echosounders, turbulence profilers (VMP-250, χ pods, and GusTs), fluorometers, and meteorological sensors. Bow-chains were deployed from the R/V *Sally Ride* and the R/V *R. G. Sproul* and measured temperature, salinity, and turbulence in the upper 20 m of the water column. The R/V *Sally Ride* conducted more than 5,100 vertical profiles using the VMP-250, while the R/V *Oceanus*—equipped with a towed CTD installed with a GusT probe, attached at the leading edge of the CTD—conducted more than 4,200 profiles. The R/V *R. G. Sproul* conducted more than 3,900 profiles with a towed CTD. Also, on 14 separate days, approximately 30 surface drifters were deployed from small boats on daily (or longer) missions designed to target specific processes—for example, along- and across-shore transport and dispersion flow around the headland (Point Sal). Most drifters measured surface temperature. Some were designed to directly measure surface vorticity. Others were equipped with sensors to measure surface shear and turbulence, wave statistics, and meteorological fields.



Contour lines show water depths in meters. A dense array of directional wave buoys (along the 100-m, 50-m, and 20-m isobaths) allowed for reconstruction of the regional mean wave field in real time.

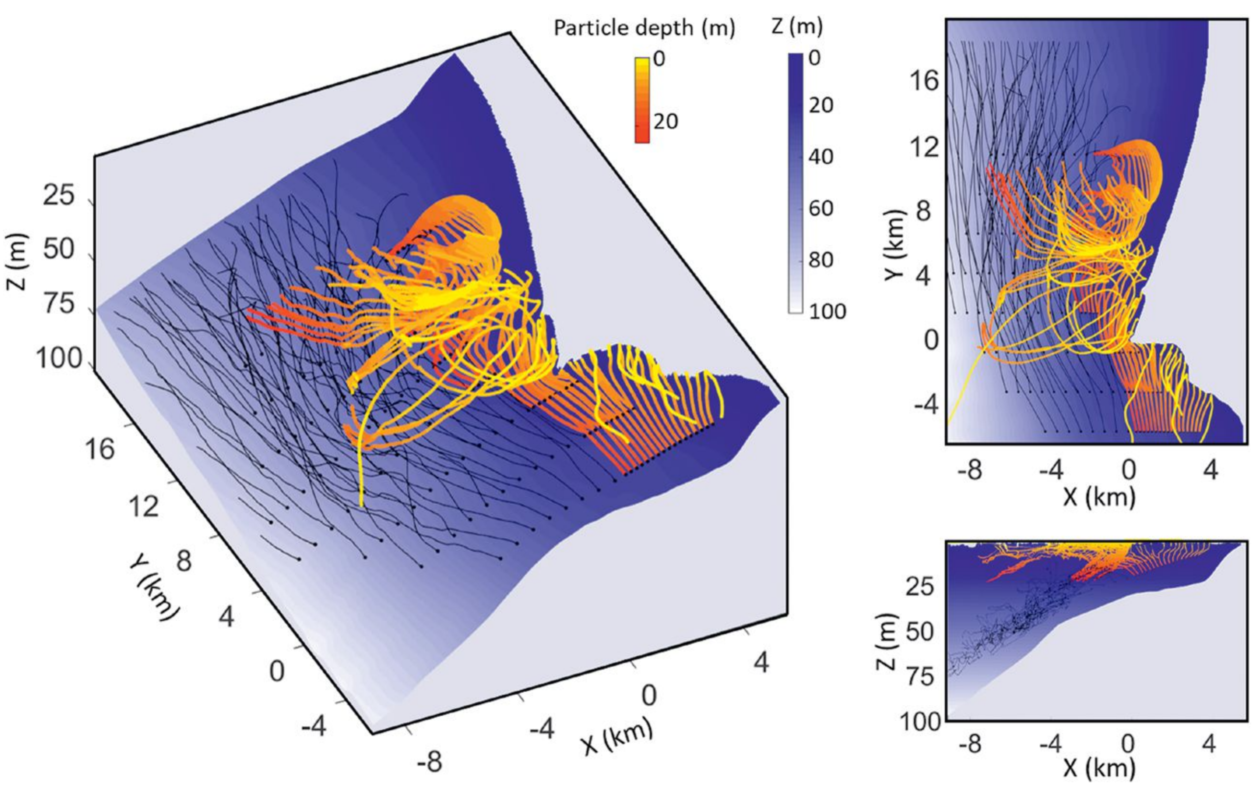
Elevated near-bottom dissipation from internal bores was also observed.

On the regional modeling scale, ISDE hindcast simulations suggest that the addition of remote baroclinic tides reduces the subtidal continental shelf stratification by up to 50% relative to simulations without tidal processes. A further analysis using passive particle dispersion in these simulations showed horizontal relative and vertical dispersion of three-dimensional drifters to be a factor of 2 to 3 times larger when including baroclinic tides.

Inner-shelf Interactions. Concurrent measurements of temperature, velocity, and turbulence at fixed-mooring locations supplemented by shipboard observations and numerical model results will allow for investigation of the interactions between inner-shelf physical processes. For example, mid- to inner-shelf stratification variability driven by synoptic variations in winds is expected to modify the propagation of semidiurnal internal tides.

One objective of the ISDE was to quantify the role of the surfzone as an onshore "boundary condition" to the shelf. In particular, it is not known how cross-shore exchange, or the magnitude of onshore or offshore material transport, varies along a complex coastline. The extent to which shelf and surfzone processes, including rip currents and internal waves, influence each other is poorly understood. X-band radar imagery in ISDE has suggested periods when nonlinear internal tidal bores interact with offshore-directed rip currents. These interactions have unknown consequences for exchange between the surfzone and the inner shelf and will be pursued in detailed analysis of observations supplemented by idealized modeling studies.

Form drag associated with coastline variability influences flow separation, wakes and eddies, and enhanced mixing. This is clearly



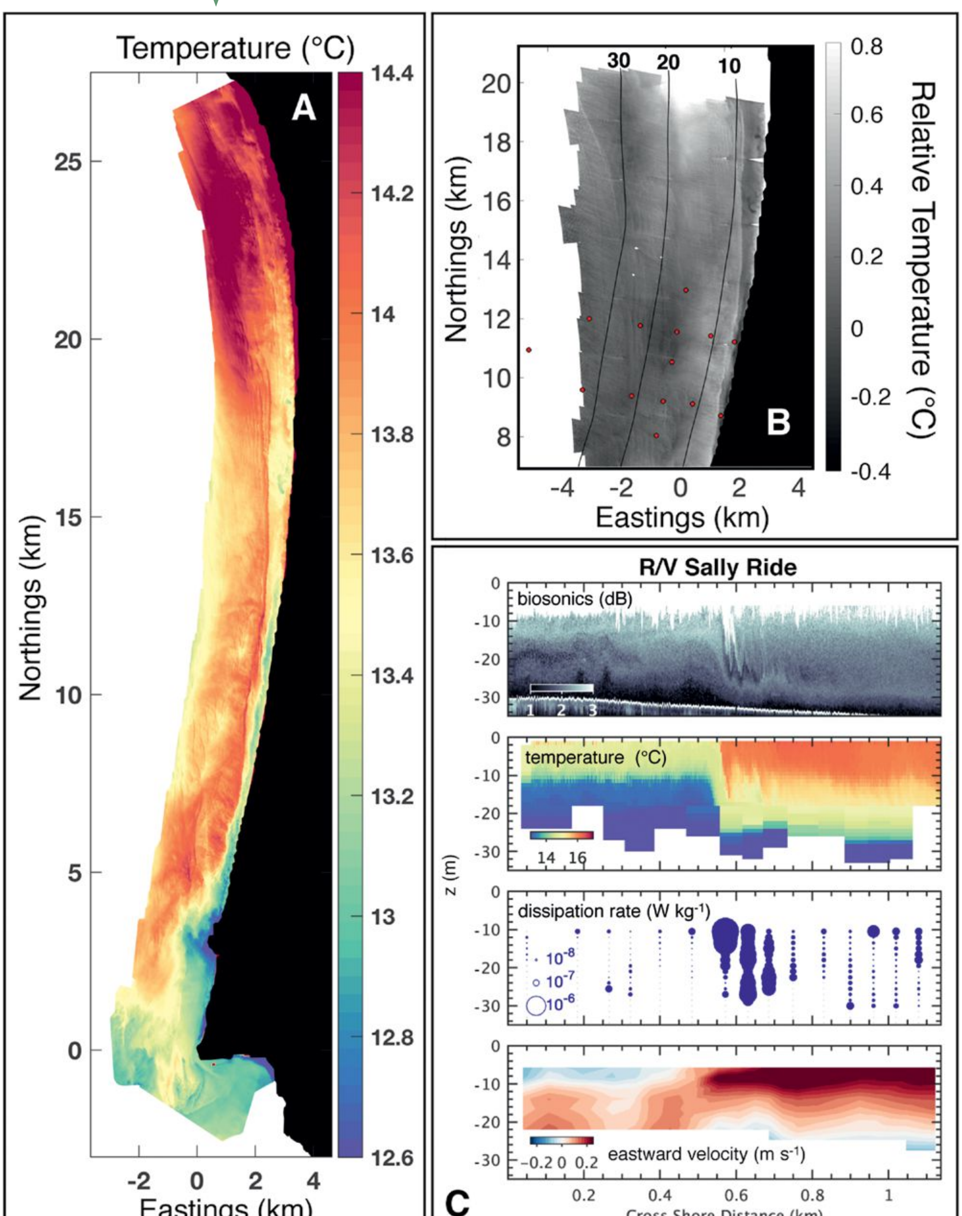
A modeling study with Lagrangian trajectories for particles launched offshore of Point Sal near the seafloor, at 80% of the water-column depth, along 15 cross sections during an upwelling event in 2015. Particles launched inshore of the 25-m isobath are colored yellow to red depending on their depth, and those released deeper are black. Racks are shown for 1.5 days. This model behavior agrees with the moored-array and shipboard observations: through interaction of the wind- and pressure-driven along-shelf flows, near-surface (20–25-m depth) water from the inner shelf is fluxed offshore at this promontory. This flow–topography mechanism is important for expelling upwelled water from the shelf.

exhibited by a rapid change in diurnal and semidiurnal variability in temperature around headlands. It is expected that the momentum transfer from mean flows into eddies and turbulence will be important to the along-shelf momentum balance. Detailed pressure measurements around Point Sal supplemented by mooring measurements and shipboard observations will facilitate further investigation of this problem. In addition, the eddies shed in the lee of the headland may interact with buoyancy fronts in the inner shelf, changing the circulation in thermal wind balance and inducing ageostrophic secondary circulations.

It has been known for a while that changes in vertical mixing as represented by an eddy

Aerial image of sea surface temperature from airplane-mounted longwave infrared (LIWR) camera reveals an internal wave front that extends ~20 km alongshore.

Nonlinear internal waves (NLIW) can drive strong thermal fronts in the inner shelf. Elevated turbulence behind the internal bore front suggests that NLIWs generate strong midwater-column mixing due to shear and/or convective instabilities.



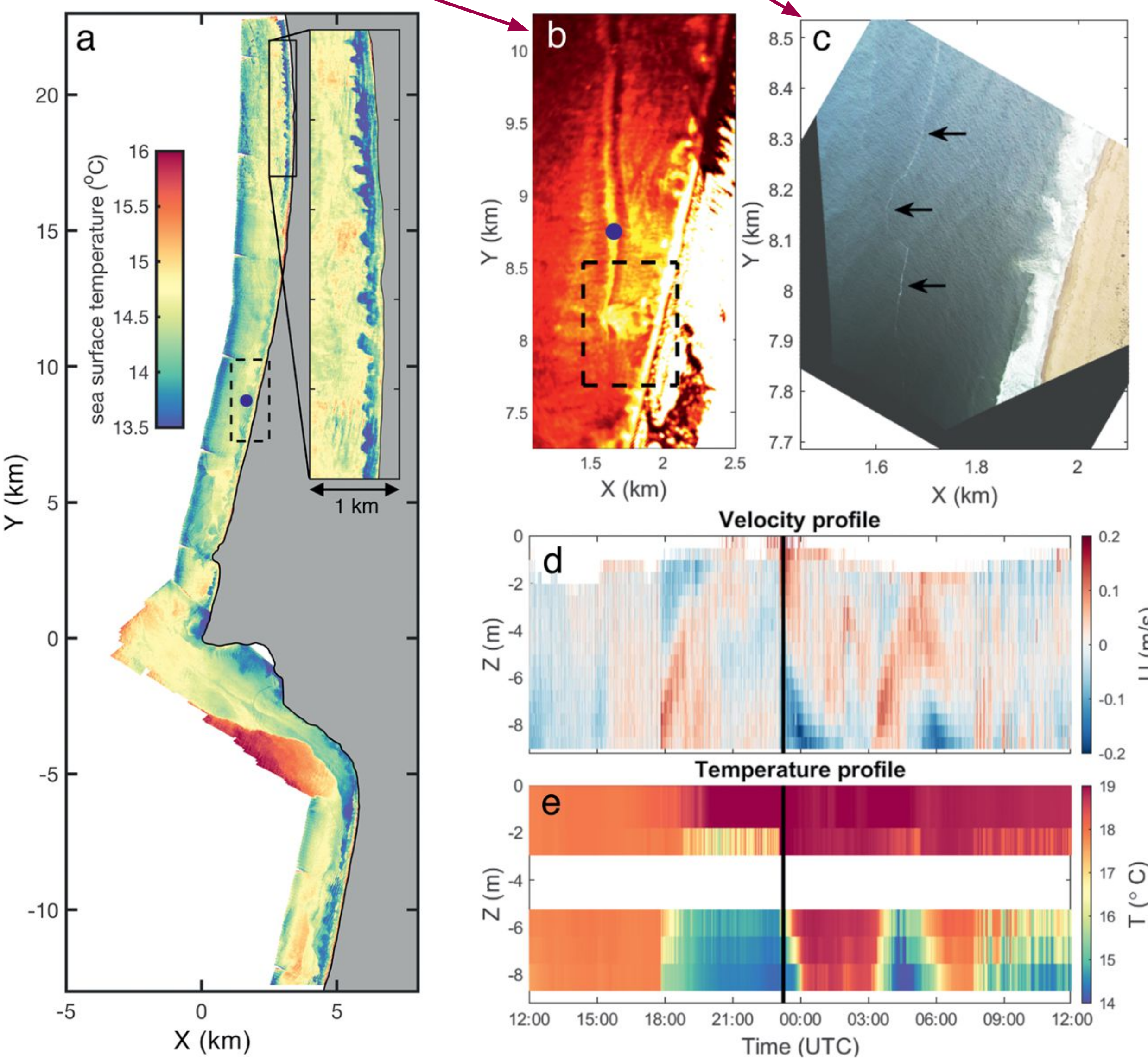
Relative temperature from the plane-mounted LIWR. The front is relatively warm (1°C) offshore of the front compared to the water inshore.

The NLIW temperature gradient is also evident from cross-front ship transects, which additionally show the internal bore vertical structure and elevated turbulence behind the front. (top to bottom) biosonics from the ship's echosounder; temperature data from a bow-chain temperature profiler (top layer) and a towed CTD (bottom layer); dissipation rates from a VMP-250; and eastward velocity from a pole-mounted, downward-looking ADCP.

A large rip current (high intensity feature at $y = 8.1$ km) appearing to interact with an onshore-propagating internal bore (alongshore bands of high and low backscatter in this X-band radar image).

A white foam line (indicated by arrows) carried by the internal bore as it bends around the rip current plume. The bright linear radar feature (transecting the blue dot) is collocated with the back face of a cold pulse at depth.

The cold pulse is 5°C cooler than the surface water and lasts around 6 h at the sensor location. These and other mooring data indicate that internal waves alter the stratification outside of the surfzone on relatively short time scales. This rapid stratification of an unstratified region is expected to influence offshore material transport by rip currents.



Particularly striking are events in which surfzone rip currents appear to collide with shoreward-propagating internal waves and fronts. (a) Airborne thermal infrared image (°C, calibrated with radiometer), taken on 15 Oct 2017 starting at 1639 UTC, composed of a mosaicked set of images from a continuous nearly 50-km along-coast transect centered at Point Sal (near *y* = 0 m). Cool "plumes" driven by rip currents (e.g., cool features emerging from the surfzone) with several-hundred-meter cross-shore scales at 0 < *y* < 22 km and −12 < *y* < −7 km are observed, along with signatures of fronts and internal waves (e.g., strong frontal signature at −4 < *y* < −6 km). In the southernmost half of the image, a strong front was observed to intersect with plumes in the surfzone. Inset shows zoom to 1 km × 5 km region with cool plumes. Dashed box in (a) shows the location of the radar image in (b) and the blue dot shows mooring location in both panels. (b) X-band radar. Dashed box in (b) shows the location of the sUAS image in (c). (c) Rectified visible image from sUAS. (d) Mooring time series of the east–west velocity profile. (e) Temperature vs depth time series for an event in which an internal wave [bright band in (b), white foam line in (c)] intersected with a rip current [plumelike feature in (b) and (c) near *y* = 8 km] on 12–13 Sep 2017. The time of the radar image is shown with a vertical line in the velocity and temperature profiles. The gap in the temperature profiles in (e) from approximately *z* = −3 to −5 m is due to the loss of two temperature sensors during the deployment period.

diffusivity can modify the wind-driven circulations. Recent work has analogously quantified the contribution that turbulent momentum fluxes make to the cross-shore and alongshore momentum budgets: episodic turbulence from passing bores and solitons dominates the long-term average of turbulent stresses over diurnal to seasonal time scales. The recent finding that the turbulent stresses play an order-one role in the cross-shore momentum budget at all depths pointed to the need to revise our conceptual model of dynamical balances offshore of the surfzone. Similarly, turbulence at the leading edge of an internal tidal bore may control the propagation (phase speed) and nonlinear evolution of subsequent bores. This question is being explored using mooring and shipboard measurements.

In Memoriam

Nirnimesh Kumar, 1984–2020

Nirnimesh (Nirni) was a coastal physical oceanographer at the University of Washington. He completed his Bachelor of Science in 2007 at the Indian Institute of Technology in West Bengal, India, where he studied ocean engineering and naval architecture. Following that, Nirni completed his M.Sc. and Ph.D. at the University of South Carolina under the supervision of George Voulgaris in 2010 and 2013. Before moving to Seattle, he was a postdoctoral scholar at the Scripps Institution of Oceanography, where he worked on a range of coastal-zone projects including becoming a leader on the ONR-funded Inner- Shelf DRI that this paper describes.

Technically deft and creative, Nirni was blossoming as a leader across a range of research topics. He valued scientific collaboration, and the exchange of ideas, and delighted in sharing achievements with others. He had an uncanny ability to develop and maintain collaborations across a wide range of coastal oceanographic regions, from the nearshore of Southern California to the high Arctic polar regions. Nirni was an enthusiastic scientist and an incredibly thoughtful mentor. His gregarious spirit brought an energy to our community that is irreplaceable. He will be remembered for his mischievous smile, his eagerness to help others, his deep scientific insights, and his rigorous work ethic.

This paper is dedicated to our friend, shipmate, and colleague Nirnimesh Kumar. We will miss you more than you can imagine.

Nirnimesh Kumar aboard the R / V *Sally Ride* during the Inner-Shelf Dynamics Experiment, 2017.

Sean Haney, 1987–2021

"The coexistence and intermingling of these two distinct features (gravity currents and internal bores) remind us that as students of turbulent flows we cannot restrict ourselves to the study of a single scale or type of ocean dynamics. This may be only one of many cases of intersections and interactions between nominally distinct phenomena that are yet to be appreciated."

—Sean Haney (Scripps Institution of Oceanography, University of California, colleague, coauthor), from his *Journal of Physical Oceanography* paper on ISDE research (DOI:10.1175/JPO-D-21-0062.1).

Sean Haney on the 2017 Inner Shelf DRI Cruise.

BAMS: What would you like readers to learn from this article?

James A. Lerczak (Oregon State University): *While many of the physical mechanisms that drive circulation, transport, and dispersion in the inner shelf have been identified, it is an exciting challenge to execute a large-scale and collaborative field and modeling experiment to understand when, where, and how these mechanisms interact. Such interaction results in drastically different circulation, transport, and dispersion patterns from what would be predicted by a particular mechanism in isolation, or the sum of the mechanisms considered without their interactions.*

Jaqueline M. McSweeney (Oregon State University): *The physical processes that determine the oceanic circulation and fate of material on the inner shelf are complex and intertwined. Trying to isolate the relative contribution of a specific process is challenging because it necessitates us to observe a very wide range of spatial and time scales. Even with the rich dataset collected through the inner-shelf dynamics experiment (ISDE)—one of the most resolved datasets in existence—there are processes that are difficult to adequately resolve or separate.*

BAMS: What got you initially interested in coastal physical oceanography?

JL: *I enjoy studying the complex, clearly observable, and immediate impacts of coastal ocean physical processes on ecosystems and humans. I am particularly fascinated by processes occurring on short time scales (tidal and shorter). You can go out on a small boat or a kayak for a day and make some interesting measurements while watching the sea change around you.*

BAMS: How did you become interested in the topic of this article?

JM: *I'm intrigued by the challenge of identifying the relative importance of multiple processes with overlapping spatiotemporal scales, and the inner shelf is a fascinating place to study for this exact reason! When I learned the scope of the ISDE project, I was ecstatic to take on such a complex topic and collaborate with this amazing team.*

BAMS: What surprised you the most about the work you document in this article?

JM: *I was especially surprised to find that internal waves are present approximately every 6 hours in this region. Based on previous work, we were expecting to observe internal waves approximately every 12 hours! I was also excited to discover that the complex spatial heterogeneity of each internal wave is different, dependent both on the low-frequency shelf conditions and the influence of the previous wave.*

Amy F. Waterhouse (Scripps Institution of Technology): *Every time we make measurements on the ocean, we always learn new and very unexpected things. As we develop new and better instruments, we will keep discovering new exciting physical processes. ISDE was special in that we were able to make oceanographic measurements on the inner shelf from almost all the oceanographic platforms available at an incredibly high resolution, on a part of the coast that is complicated and full of exciting physical dynamics.*

BAMS: What was the biggest challenge you encountered while doing this work?

JL: *This experiment involved many instruments and sampling methods. Working with colleagues to coordinate ISDE was an exciting challenge, from experiment design, construction of platforms, and executing a coordinated field plan to effectively centralizing the vast and diverse datasets to make them easily accessible and usable for the group, and now the entire science community. Fortunately, this group of creative and energetic scientists worked very well together.*

JM: *Trying to characterize and explain the variability in the internal wave field has been extremely challenging! There are many factors that influence the evolution and fate of an internal wave, and I found it insightful to evaluate those factors at an event scale (one wave at a time). However, scaling that analysis up to look at a 2-month dataset (with 4 internal bores per day) is really nuanced and time-consuming.*

AW: *There is so much interacting physics that we were able to observe on the inner shelf during ISDE. Trying to detangle all the various processes to understand what is really driving the cross-shelf exchange has been a fun, yet difficult, task.*

Reflections on the Environmental Security Theme of the 102nd Annual Meeting

Now that the successful 102nd Annual Meeting has concluded, it is a good time to reflect on the theme of the meeting and the future implications for the AMS and the weather, water, and climate enterprise at large. The theme, "Environmental Security: Weather, Water and Climate for a More Secure World," was organized around the linkage between weather and climate changes and their influence on the security of nations and their people. With a rapidly increasing global population (including a growing percentage that is migrating to coastal areas and/or away from areas of crises), coupled with the evolving human and national security impacts from disruption of weather and climate norms, we are seeing a growing influence of weather, water, and climate on national security and the security of their peoples. As such, the theme of the meeting was intended to inform the broad AMS membership on the connections of our weather, water, and climate disciplines to larger societal impacts, and to demonstrate how important our contributions are to the basic security needs of the citizens of the United States and the world. Another motivation was to bring world-class experts on the impacts of extreme weather and climate on water quality/scarcity, energy, food, and health to the Annual Meeting and share their experiences and insights with AMS members who may not often see those downstream linkages to their specific discipline.

The environmental security content of the Annual Meeting began with a world-class panel discussion at the Presidential Forum followed by 15 scheduled Presidential Sessions on environmental security that occurred during the remainder of the meeting. These sessions featured experts in the areas of health, energy, water, food, science and diplomacy, and environmental justice, as well as local expertise and perspectives from security impacts in our host city of Houston and across Texas. These sessions offered two-way exchanges, where AMS members were able to help these policy experts learn more about how our research and operations can inform their efforts, and with the experts helping our AMS members learn more about the broader societal impacts of our weather, water, and climate disciplines. If you were not able to see these sessions live, please take advantage of the recordings and watch them at your convenience.

With the 102nd Annual Meeting successfully behind us, what opportunities lie ahead of us to continue these conversations and expand our thinking on the national and human security impacts from weather, water, and climate changes? First, we should build on the success of this Annual Meeting with the continued engagement of environmental security policymakers and leaders in the diverse areas of energy, health, food security, water quality/security, diplomacy, development/aid, national security, and environmental justice and others. We should encourage these experts to embrace AMS as a partner and even become members themselves. Second, AMS members can broaden our horizons to consider the broader societal implications of our Earth system sciences to include making those linkages in scientific works suitable for the AMS *Weather, Climate, and Society* journal as well as *BAMS*. Third, for those who wish to get personally involved in building the momentum for greater synergies between our environmental sciences and security-related impacts on society, please consider joining the AMS Committee on Environmental Security. More information on the committee can be found at https://www.ametsoc.org/index.cfm/cwwce/committees/committee-on-environmental-security/.

Mike Farrar
2021 AMS President

MEMBER SPOTLIGHT

KATHERINE CALVIN has been appointed as NASA's chief scientist and senior climate advisor to Administrator Bill Nelson. As chief scientist and senior climate advisor, Calvin will serve as principal advisor to the administrator and other agency leaders on NASA science programs, strategic planning, and policy. She will also represent the agency's strategic science objectives and contributions to the national and international science communities.

Previously, Calvin was an Earth scientist at the Pacific Northwest National Laboratory's Joint Global Change Research Institute in College Park, Maryland. She worked on the institute's Global Change Analysis Model, a system for exploring and analyzing the relationships between human and Earth systems, and the Department of Energy's Energy Exascale Earth System Model, a system for analyzing the Earth system.

Calvin holds master's and doctoral degrees in management, science, and engineering from Stanford University and a bachelor's degree in computer science and mathematics from the University of Maryland.

MICHAEL MORGAN has been announced by President Joe Biden as a nominee for assistant secretary for environmental observation and prediction, Department of Commerce. Morgan is a professor in the Department of Atmospheric and Oceanic Sciences at the University of Wisconsin—Madison, where he serves as the associate chair of the department's undergraduate program.

Morgan has served on the AMS Board on Women and Minorities and the AMS Scientific and Technological Activities Commission for Atmospheric and Oceanic Fluid Dynamics, and as an AMS Councilor. He was elected an AMS Fellow in 2018 and has served on the World Meteorological Organization World Weather Research Program's Science Steering Committee since 2014. Morgan is completing a second term on the University Corporation for Atmospheric Research (UCAR) Board of Trustees and currently serves as a member of the Board of Directors of the American Institute of Physics.

Morgan was an AMS/UCAR Congressional Science Fellow working in the office of U.S. Senator Benjamin Cardin as a senior legislative fellow on energy and environment issues in support of the Senator's service on the Environment and Public Works Committee. From June 2010 until June 2014, Morgan served as division director for the Division of Atmospheric and Geospace Sciences at the National Science Foundation. His research interests include the analysis, diagnosis, prediction, and predictability of midlatitude and tropical weather systems. Morgan earned his S.B. in mathematics and Ph.D. in meteorology from the Massachusetts Institute of Technology.

CLEAR SKIES AHEAD

"You're also helping to review other individuals' publications and papers and their grant proposals. You're participating also on committees and things of that nature. So it really allows you the opportunity to engage with other people throughout the field and also to meet other people who are doing incredible science as well. You can operate in this pool where you leverage expertise one to another. That's one of the most engaging things about it and encouraging things about it...it's different from the Ph.D. process, where it's really all on you. When you finally are in a position as a researcher, tenure-track professor, or a tenured professor, you get to reach out to other people in collaborative ways and ask really complex questions."

—Brad Johnson, assistant professor of geography at Florida State University in Tallahassee, talks about pursuing tenure in academia. For more, listen to the Clear Skies Ahead podcast, with new episodes released every other Tuesday.

DO POINTS

The AMS Food Security Committee has released a new podcast where they talk to meteorologists, sociologists, and policy experts about all aspects of how to improve food security in a rapidly warming climate, from what makes an impactful early warning system to how technological advancements in agrometeorology can help in the battle for food security. Listen at https://anchor.fm/foodsecurity2022.

PROFILES

Jeff Yuhas

Teacher, Oak Knoll School, Summit, New Jersey

BAMS: How did you first become involved with AMS?

YUHAS: It's a threefold story. As a meteorology grad student at Penn State, we basically all had to join AMS. Then, in my first career as an air quality meteorologist, I presented at the Annual Meeting talking about dispersion modeling of point sources. I stepped away for a bit when I started my teaching career. Ten years into my teaching career I was looking for a spark and renewed my AMS membership around 2010. I then presented, with a high school meteorology student of mine, at the Annual Meeting in Atlanta about using green screen technology in a meteorology class, and things took off from there.

BAMS: What would you like to tell others about AMS Education programs?

YUHAS: Take the courses! At a minimum you'll get credits that will move you along the pay scale and help with recertification. But don't let that be it. For me it's been about the relationships I've developed with instructors, fellow students, and my students when I was an instructor. I may have recruited a couple into the ranks of AMS.

BAMS: What benefit has your engagement with AMS (or AMS Ed) had on your career?

YUHAS: Anytime I participate in an AMS activity—attend the Annual Meeting, take an AMS Education Program class, go to AMS Policy events in Washington, D.C.—I find myself reenergized. I have met many people there, which has led to acquiring content for classes, bringing in speakers, and planning trips.

As much as anything, I have developed a network of colleagues at AMS that I continue to collaborate with to plan curriculum and prepare AMS presentations. This is being amplified by the new Teachers Community in the AMS Community.

BAMS: What excites you most about being a member of the AMS community?

YUHAS: I love the opportunities to contribute to AMS. In 2011, I was recruited to be a member of the Board of Outreach and Pre-College Education. From there

I chaired the Battan Book Award Committee and cochaired the Conference on Education. It was very exciting to be part of the team that planned and organized the Annual Meeting in Boston, celebrating the 100th anniversary of AMS. I also was a teacher for Project Atmosphere. Each of these experiences has allowed me to meet more and more people in more and more professions and industries.

BAMS: What else do you do for fun besides engaging in weather, water, and climate education?

YUHAS: With my youngest son having headed off to college, I have begun a coaching career at my school. I took my years of youth soccer coaching experience and started coaching the fifth and sixth grade boys at Oak Knoll. I enjoy spending part of my summer back in New England in Ogunquit, Maine.

I have developed a network of colleagues at AMS that I continue to collaborate with to plan curriculum and prepare AMS presentations.

CHAPTER SPOTLIGHT

Regularly scheduled production is back in full swing for the Iowa State AMS chapter. Every Tuesday and Thursday, the members are in the broadcast meteorology studio producing their weather broadcast show, *Cy's Eyes on the Skies*.


She can
STEM
SO CAN
YOU.
SARAI LLAMAS + AMPLIFIER.ORG
S T E M
@SheCanSTEM
ad COUNCIL

HARRY VAN LOON 1925–2021

Harry van Loon was a wonderful person and a great scientific colleague. He passed away on December 13, 2021 at the age of 96. His enthusiasm was boundless and influenced all those around him. He was always full of ideas and very generous and friendly.

Harry was born in Denmark in 1925 and finished high school in 1943. During WWII, he was a member of the Danish underground and actively resisted the Nazi occupation of Denmark. In addition to smuggling weapons and damaging German vehicles, he was part of a network that assembled banned war news from the BBC. At great personal risk, Harry helped secretly publish and distribute uncensored information. Immediately after the war, he joined the Weather Bureau in Denmark in the summer of 1945 and was drafted into the Danish military in 1946. He was interested in archeology but developed and then pursued his life-long passion for meteorology and climate. This led to a research fellowship with Hurd Willett at the Massachusetts Institute of Technology (MIT) from 1951 until 1954. At MIT he enjoyed the frequent synoptic labs and interacted with Victor Starr, Fred Sanders, and Dick Reed. Phil Thompson, Ed Lorenz, and Larry Gates came along while he was there.

Harry in his greenhouse garden (ca. 2001).

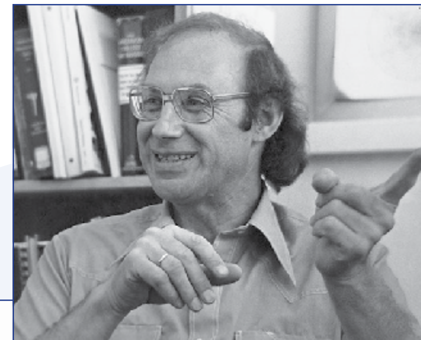
Willett started a Southern Hemisphere Project that led to interactions with the South African Weather Bureau, who were establishing a similar project. Data over the Southern Hemisphere were extremely sparse and were not transmitted at all from regions south of 40°S. The World Meteorological Organization and South Africa helped by sending data from whaling ships. He wrote two papers while at MIT. His first was published in 1954 and the second was never published. When interviewed by Hans von Storch, George Kiladis, and Rol Madden in 2004, Harry was asked he if did his own quality control of the data. He answered, "When you have so few data, you are very careful about it. You study every aspect of the observation, pressure, pressure tendency, clouds, cloud heights, cloud types, temperature, dewpoint, wind, weather, every aspect is closely scrutinized. So you get the most out of every observation."

After MIT, he briefly returned to the Weather Bureau in Denmark, but soon thereafter moved to South Africa, where he completed a geography degree and became involved in their Southern Hemisphere project that included producing unprecedentedly detailed synoptic weather maps over the Southern Ocean based on weather data reported by whaling ships. Hence, he developed an expert knowledge of Southern Hemisphere weather and climate and wrote definitive papers on topics such as blocking in the Southern Hemisphere

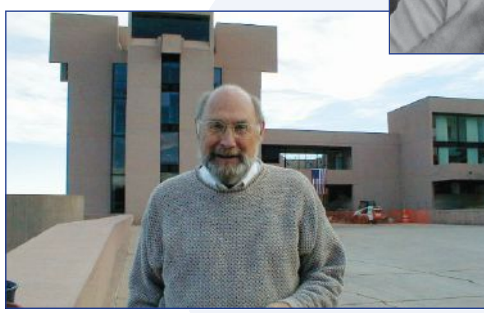
Harry met up with Harry Wexler, which ultimately led him to travel to Antarctica in October 1957 until March 1958 as new facilities were being established for the International Geophysical Year (July 1957–December 1958). The many flights to and from Antarctica required forecasts, and Harry obliged. Once back in South Africa, his contract was extended for another three years.

In 1963, Harry was invited by Phil Thompson to come to the National Centers for Atmospheric Research (NCAR).

A month later, Chester Newton arrived and formed the Synoptic Group. Paul Julian moved over from the High Altitude Observatory, and they were joined by Henry van de Boogaard and Jim Fankhauser, and somewhat later by Ed Zipser. Warren Washington and Akira Kasahara joined NCAR about the same time. Roy Jenne came to NCAR about 1966 and Rol Madden joined the group in 1967. Roy brought in computer processing capabilities and accelerated data processing enormously; for instance, working with J. J. Taljaard without computers, Harry reported it took three days to complete a single analysis of the Southern Hemisphere surface, thickness, and 500-hPa maps after all the observations were carefully plotted by hand. However, as Harry never mastered computers, he worked with others to get data processed and mapped. The Data Support Section (Jenne, Dennis Joseph, and Will Spangler in particular) often helped Harry, and there are many Van Loon and Jenne papers. Ultimately, these efforts led to the *Meteorology of the Southern Hemisphere*, which was published in 1972. This AMS Meteorological Monograph, edited by Newton, with its associated knowledge about the Southern Hemisphere synoptic weather, circulation, and climate, was truly groundbreaking.



Harry in July 1976.



Harry at NCAR in 2001.

Members of NCAR's Empirical Study Group, (left to right) Paul Julian, Roland Madden, Dennis Shea, and Chester Newton, listening attentively to Harry (ca. 1980).

Harry published more than 100 papers and inspired many more. His ideas have influenced collaborators from all over the world.

Dennis Shea arrived in April 1972, but the Synoptic Group was dissolved in 1973. With widespread reorganization taking place, most members eventually transitioned to the Empirical Studies Group in 1977 (Image 1), led by Newton and briefly by Madden until 1987, when it evolved to become the Climate Analysis Section (CAS) led by Kevin Trenberth, who had arrived in 1984. Dennis was a key programmer for Harry. Jim Hurrell arrived in 1990 and joined CAS in 1991, Clara Deser joined in 1997, and Jerry Meehl was also a member of CAS during that time.

In 1965, Karen Labitzke visited NCAR and formed a lifelong collaboration with Harry that resulted in more than 30 papers. In terms of other work, Harry's 1967 paper on the semiannual oscillation in the Southern Hemisphere mid- and high latitudes won the first NCAR Publication award prize. According to Harry, those were the golden years (up until about 1973). Over this period, Harry wrote a series of papers on annual and semiannual variations in the atmosphere of both hemispheres, and in ocean currents and stratospheric winds, which have provided considerable insight into the workings of seasonal forcings.

He later wrote a series of innovative papers on waves in the Southern Hemisphere, then switched to waves in the north and the tropics: the North Atlantic Oscillation, then the Southern Oscillation. The latter involved nine papers published from 1981 to 1989, each titled and numbered "The Southern Oscillation: Part I-IX." In addition to Labitzke, key collaborators on his papers in the 1980s and 1990s included Jeff Rogers, Jill Williams (now Jaeger), Jerry Meehl, Dennis Shea, George Kiladis, and Jim Hurrell. Harry demonstrated the importance of changing advection patterns to show changes in temperature and documented the relation between eddy heat transports and temperature gradients. He then went on to explore the quasi-biennial oscillation and solar–climate relationships.

Harry published more than 100 papers and inspired many more. His ideas have influenced collaborators from all over the world. Several of them came together at NCAR in 1984 to join in a symposium dedicated to honor his continuing contributions to our science. In October 1997, a second Harry van Loon Symposium took place at NCAR and was published as proceedings as NCAR Tech. Note 433.

In 1991, at age 65, he stepped down as a senior scientist at NCAR but continued actively doing science well into the twenty-first century with Ralph Milliff, Meehl, and others. His final paper with Meehl and Julie Arblaster on the Southern Hemisphere semiannual oscillation and El Niño events, published in 2017 when Harry was 91, capped a remarkably long career of insightful and productive scientific research. His insights, enthusiasm, and encouragement lie behind many papers that don't bear his name.

Harry was honored by a named glacier in Antarctica: (71°1'S 163°24'E), 13 kilometers long, draining the eastern slopes of the Bowers Mountains. The Advisory Committee on Antarctic Names selected the name "Van Loon" because Harry was a member of the Antarctic Weather Central team at Little America on the Ross Ice Shelf in 1957–58 and had written numerous scientific papers on Antarctic and Southern Hemisphere atmospheric research.

In his personal life, Harry's enthusiasm for science was matched by his fervor and love for his family: wife, Kirsten; sons, Mikael and Paul; daughter, Helen; and their families. Harry was also well known for his love of gardening and the amazing plants that filled his NCAR office and that he cultivated in his greenhouse at home. Also memorable were his wonderful puns and his viselike handshake. He will be greatly missed, but his spirit lives on in the many he inspired.

—Kevin Trenberth, Jim Hurrell, Rol Madden, Dennis Shea, and Jerry Meehl

LIVING ON THE REAL WORLD

with William H. Hooke

Remedial Reading.

April Lawson's Essay on Building Trust across the Political Divide

You'll want to read her absolutely brilliant and uplifting 2021 article (https://comment.org/building-trust-across-the-political-divide/). But first please indulge a bit of *LOTRW* backstory.

Each year, come January 1, most of the world's eight billion people share a common aspiration—to make their next 365 days "better" than the last. Definitions of "better" may vary. Some seek happiness. Some desire accomplishment. Some seek peace—whether world peace or simply peace of mind. Given the 2021 we've just experienced, a better 2022 seems like a low bar, whatever your aspiration.

Close to home, that's certainly been true here at *Livingonthe-RealWorld*. Take, for example, the last few posts of 2021, which have made reference to stream of consciousness.

> *(In literary criticism, stream of consciousness is* ***a narrative mode or method that attempts "to depict the multitudinous thoughts and feelings which pass through the mind"*** *of a narrator.)*

But those previous posts at *LOTRW* date no more recently than early November! After ten years and one thousand posts (about one post every four days over the period), the *LOTRW* stream of consciousness slowed to an intermittent trickle in 2021; now the stream bed seems nothing more than a dry wadi. *(What was/is the cause of this? You might argue that I've run out of ideas. Think what you want. But like everyone and everything else these days, I prefer to blame the psychological drought on climate change. Everything is drying up.)*

But somewhere in the uplands of the watershed, the consciousness precip must have made its return, because the stream is running again. Here's what it has looked like for me over the past couple of days:

One of the realities of our world of eight billion people and 200 million square miles of surface area, is that a lot happens while our backs are turned. So what do six billion smartphone users do? Sometimes idly, sometimes driven by FOMO, we surf the web. My search has yielded oodles of turn-of-the-calendar content. One *NYT* post that caught my attention mentioned a David Brooks column devoted to his annual "Sidney awards." I checked it out.

In Mr. Brooks' own words:

> At the end of every year, I pause from the rush of events to offer the Sidney Awards, which I created in honor of the late, great philosopher Sidney Hook. The Sidneys go to some of the year's best long-form journalism—the essays that touch the deeper human realities. During this shapeless year, waiting endlessly for this pandemic to be over, I've found myself drawn to stories of fascinating individuals.

Unsurprisingly, Brooks' offerings this year featured a number of somber pieces, plumbing great depths of sorrow and brokenness. At the end Brooks acknowledges this:

> OK. Enough grimness. Let's find some hope. We've all read a zillion pieces on political polarization, but April Lawson's essay "Building Trust Across the Political Divide," in Comment, is like none other. The secret is that Lawson has actually been working in the field of political bridge-building, and she deftly dissects why so many of those well-intentioned efforts go wrong.

Wow.

April Lawson's piece, dating back all the way to the prior January, is an absolute gem. Rather than attempt a summary, I'll let you discover it for yourselves (or, perhaps you'd already read it, as early as a year ago?). Her analysis of our polarized predicament is insightful by itself, but learning (however belatedly—remember, we're talking *remedial* reading here) about her work at Braver Angels Debate to pave a new way forward is truly energizing. Exhilarating to see that such work is ongoing, and to contemplate the possibilities. I hope you're able to give it a careful read.

A closing note. That wasn't the last bend in the stream-of-consciousness. The whole issue of remedial reading—the search for useful information in today's "noisy" information world (flow) of consciousness and the attraction of chasing around the web hoping to stumble across such gems—reminded me of something I hadn't thought about for years. In the late 1950s and early 1960s my statistician dad, Robert Hooke, and a colleague, Terry Jeeves, were both working at the Westinghouse Research Laboratories in Pittsburgh. They developed a strategy for direct search for optima in the performance of any physical or chemical system (or in seeking information on the internet?) when analytical methods were of no avail. They published a paper on the technique (Hooke R & Jeeves T A. "Direct search" solution of numerical and statistical problems. *J. Ass. Comput. Mach.*, 8:212-29, 1961). While admitting that *"direct search is a crude, brute force method having no mathematical elegance,"* Hooke later suggested that the resulting large number of citations to this paper (over 270 by 1980; ballooning to over 5,000 to date) hint *"there are more* [such intractable] *problems around than one might think. Among real nonlinear multivariate problems, those that are solvable analytically or by socially acceptable numerical methods seem to constitute a set of measure zero."* Dad used to share his work along these lines with his teenage sons at the dinner table during those years. Nowadays you can find YouTube lectures on the Hooke and Jeeves direct search systems. If he were alive today, this continuing interest in his work would (a) come as a surprise, and (b) trigger one of his signature wry smiles…

➜ William H. Hooke is AMS associate executive director and former director of the AMS Policy Program. This essay was posted January 1, 2022 on his blog, https://www.livingontherealworld.org. In 2010, AMS published his book, Living on the Real World: How Thinking and Acting Like Meteorologists Will Help Save the Planet.

AMS STATEMENTS

Extreme Cold Temperature Outbreaks: A Call to Action for Better Preparation

A Best Practice Statement of the American Meteorological Society

(Adopted by the AMS Council on 20 December 2021)

A Call to Action

The cascading impacts brought by the February 2021 Arctic cold outbreak across Texas and much of the central United States demonstrate how compound disasters can quickly occur in the absence of adequate preparation by businesses (specifically essential services), communities, and individuals. The extreme cold event highlights the need for stronger community resilience should essential services (e.g., water, electricity) fail for extended periods of time. Prolonged Arctic outbreaks will occur again and will find vulnerabilities in critical infrastructure if mitigation and preparedness efforts are not taken. This statement focuses on how local governments, businesses, community organizations, and individuals can contribute to improved preparedness and resilience to Arctic outbreaks to minimize loss of life and damage to property. This statement, however, does not address specific actions for utilities, which goes beyond the scope.

If no meaningful action is taken to strengthen the infrastructure, power outages will continue as the threat of severe local storms, tropical cyclones, flooding, wildfires, winter storms, and extreme temperatures continues.

Motivation

As witnessed during February 2021, the unusually prolonged and anomalous subfreezing temperatures in Texas led to an unusually widespread power outage. This power outage resulted in the loss of potable water supplies as well as increased scarcity of food and fuel. Entire communities became uninhabitable when homes were damaged from burst plumbing and shortages of necessities became widespread. The estimated damage to homes and lost economic productivity is likely to exceed $200 billion, according to a report from the University of Houston's Hobby School of Public Affairs (hereafter referred to as the Hobby Report; see https://uh.edu/hobby/winter2021/). This easily matches the losses from Hurricane Harvey (which occurred in 2017). Over 150 Texans lost their lives in this Arctic outbreak with most of them succumbing to carbon monoxide poisoning or hypothermia (Trevizo et al. 2021). According to the Hobby Report (based on ~1,500 survey participants representing 213 counties), over 70% of surveyed Texas residents lost power, 50% suffered a loss of water, and 31% experienced water damage to their homes. Black, Hispanic, and Asian residents tended to be more vulnerable to carbon monoxide poisonings (Trevizo et al. 2021). Blacks, Hispanics, and Asians also suffered from the cold as they were less likely to go to a warm shelter or find alternative means of heating their homes (Ura and Garnham 2021).

If no meaningful action is taken to strengthen the infrastructure, power outages will continue as the threat of severe local storms, tropical cyclones, flooding, wildfires, winter storms, and extreme temperatures continues. If the past trend in the number of major power outages continues, the United States will experience even greater hardships both as our dependence on electricity increases and as a changing climate exposes us to more power-disrupting storms (Zamuda et al. 2018). As a result, it is more important than ever to prioritize actions on the part of businesses, community organizations, local governments, and individuals in improving preparedness and resilience. Community preparedness and resilience cannot be attained without all parties involved. Vulnerable populations, including those with lower income, the elderly, children, those with preexisting health conditions, and those with disabilities, must be protected if a community is to become resilient.

The Arctic outbreak of 2021 motivates AMS to promote best practices that individuals, businesses, and community/government leaders can take to identify vulnerabilities, strengthen preparedness, and minimize loss of life and property should essential services fail in future Arctic outbreaks.

Access to and Response to Forecasts

Residents were accessing information from a variety of sources before and during the Arctic outbreak. The most widely used source, nearly 50% of residents, was local TV, according to the Hobby Report. However, they also received information from local radio and online news sites. One quarter of residents also received alerts from local government websites and city-based text alerts. Neighbors and friends were reaching about 27% of residents. Social media and newspapers appeared to be somewhat less influential but still an important contributor to the information portfolio of residents.

What the residents did to prepare and respond to the Arctic outbreak was a mix of appropriate and worrisome actions. Most residents appropriately purchased extra food and either purchased extra water bottles or stored tap water. Almost half of all residents insulated pipes, and just over a quarter purchased extra batteries. However, a significant number of residents took actions that increased their risk of property damage and injury. Of those who lost power and stayed home, a concerning number used heaters not intended for indoor use: 8% brought in a grill or smoker, 5% used outdoor propane heaters, and 26% used their ovens or cooktops.

Local governments were aware of the vulnerabilities of their residents, and the accurate forecasts by the Weather Enterprise (see https://www.weather.gov/about/weather-enterprise) days in advance prompted many communities to mitigate the risks, especially for those with increased vulnerabilities. They included opening more warming centers than typical to account for social distancing requirements and to increase the number of available beds (e.g., in Fort Worth). Local governments used citizen academy ambassadors such as in Bellaire, Texas, to help check up on vulnerable residents. City and county emergency managers were also actively engaged with National Weather Service briefings.

As the extremely cold air arrived, local governments used social media, automated notification systems, and other channels to notify residents of emergency situations. As an example, Fort Worth used their emergency notification system to disseminate a boil water advisory. Vulnerable residents were also proactively checked upon by local governments if they used the State of Texas Emergency Assistant Registry (STEAR), both before and during the Arctic outbreak. When the water supply was threatened, local governments distributed water bottles, such as in Houston, and notified residents to stop the protective action of dripping their faucets as Norman, Oklahoma, officials did when the municipal water pressure dropped to concerning levels.

After-action reviews by local governments and media reports revealed a combination of successful actions and challenges to overcome. The Bellaire after-action review found that deficiencies in integrated databases slowed down incident responses (City of Bellaire 2021). The city of Fort Worth realized that cold reservoirs facilitated water main ruptures; up to 650 ruptures occurred in the city. In San Antonio, Bellaire, and possibly others, insufficient training hindered city council members and staff. None of the initial reviews revealed plans to anticipate and respond to potential utility failures based on the forecast.

What the residents did to prepare and respond to the Arctic outbreak was a mix of appropriate and worrisome actions.

Audience

The first set of best practices below are recommended by AMS for use by local governments, community organizations, and businesses. The second set of best practices are recommended for individuals.

Best practice actions by local governments, community organizations, and businesses

The February 2021 disaster brought on by the Arctic outbreak speaks clearly to the need to anticipate and mitigate the impacts brought on by the weather hazards as well as the loss of essential services in seasonal preparation. The temperature forecasts were accurate, but there was an information gap in converting weather predictions to societal impacts. The best practices identified here represent actions that were successful and are recommended for future winter seasons. To better prepare, local governments, community organizations, and businesses should do the following:

- **Engage with experts.** Engage with the Weather Enterprise in routine exercises and education to train their staff (including elected officials for local governments) and volunteers. Develop and implement plans from several days in advance of, to the arrival of the cold air, regularly adapting their plans to the latest forecast information from the Weather Enterprise. Work with the meteorological, climatological, hydrological, social science, and emergency management personnel, including both practitioners and researchers, to improve identification of hazard vulnerabilities and create plans for mitigation and response.
- **Anticipate potential impacts to critical infrastructure.** Adjust operations based on weather forecasts from the Weather Enterprise. They should utilize the products from a growing impacts-based forecasting sector to anticipate impacts and distribute a more efficient response. Already, forecasts are available from services provided by the Weather Enterprise that take the predicted weather and hydrologic parameters and convert them to potential impacts to utilities.
- **Work to improve outreach.** Proactively reach out to residents/customers on ways to mitigate damage to their homes, such as frozen plumbing, and reduce the risk of fires from heaters.
- **Encourage/incentivize preparedness activities.** Efforts should recognize and respond to needs of individuals with higher vulnerability (e.g., people with lower income, people of color, and those with poor English comprehension).
- **Emphasize dangerous actions.** Find ways to inform individuals on how to reduce the use of dangerous methods to heat homes through education and incentive programs for those with limited finances.
- **Strive to provide NOAA weather radios and/or other alerting capabilities.** Encourage use and/or incentivize the purchase of NOAA Weather Radios, other alerting options such as apps and phone alerts, and carbon monoxide/smoke detectors to residents that may not have the means to acquire and/or install them.
- **Promote civic participation in disaster planning.** Emphasize participation by disadvantaged neighborhoods in programs that are similar to STEAR and develop neighborhood watch groups to check on vulnerable groups (e.g., isolated, access and functional needs).
- **Establish methods for communicating weather risks internally and externally.** Encourage use of multiple sources such as traditional and social media, websites, utility bills, etc.
- **Consider best practices from peers on improving resilience.** An example organization is the Resilient Cities Network (https://resilientcitiesnetwork.org/).
- **Include an after-action review and planning for the next season.** Participants in the reviews would include feedback from nongovernmental organizations (NGOs), neighborhood leaders, and business partners.

Best practice actions by individuals
Whereas local governments must focus on community mindedness, residents play their part in making sure they are as resilient as possible with mindfulness toward supporting the community. The steps toward greater resilience in extreme cold include the following:

Whereas local governments must focus on community mindedness, residents play their part in making sure they are as resilient as possible with mindfulness toward supporting the community.

- **Build an emergency kit.** The kit should be made portable enough to take in case of evacuation. Kits should include items needed for basic survival, communication, cash, pet care, and entertainment. The sites Ready.gov (https://www.ready.gov/kit), CDC.gov (https://www.cdc.gov/disasters/winter/guide.html), and the American Red Cross (https://www.redcross.org/get-help/how-to-prepare-for-emergencies/survival-kit-supplies.html) provide an excellent list of items to include in a kit. Make sure to include cold weather protection in the kit such as emergency blankets, and keep perishable items fresh, like batteries.
- **Rely on multiple sources of weather and emergency communication.** Extreme heat and Arctic outbreaks are some of the most predictable hazards where the National Weather Service and commercial weather providers can give multiple days of lead time. Hazard information can greatly mitigate damage to property and life when used properly. The NWS explains their products and suggested actions to take in their Cold Weather Safety site (https://www.weather.gov/safety/cold). Residents should plan to receive more than one form of communication to ensure they can take timely action when the potential for communications breakdowns are at their greatest. Examples include NOAA Weather Radio, wireless emergency alerts, and commercial alerts via phone calls, text messages, or apps. Some communities provide automatic notification services to send urgent information that individuals can sign up for by checking with local emergency management or government pages. Last, many communities have check-in programs, like STEAR, to check on the more vulnerable residents.
- **Install and regularly check smoke and carbon monoxide detectors.** There are several websites with information on how to detect and avoid carbon monoxide buildup. The National Fire Protection Association (https://www.nfpa.org/Public-Education/Fire-causes-and-risks/Top-fire-causes/Heating) has an excellent site for tips on avoiding fires. FEMA provides tips (https://www.usfa.fema.gov/prevention/outreach/carbon_monoxide.html) on detecting and avoiding carbon monoxide. Ready.gov provides more information on safely weathering power outages (https://www.ready.gov/power-outages).
- **Mitigate plumbing damage.** When the power goes out, water lines in homes may freeze, resulting in inadequate shelter. There are tips available on how to mitigate damage due to frozen plumbing from several sources, including the American Red Cross (https://www.redcross.org/get-help/how-to-prepare-for-emergencies/types-of-emergencies/winter-storm/frozen-pipes.html) and *Consumer Reports* (https://www.consumerreports.org/home-maintenance-repairs/how-to-keep-pipes-from-freezing-a2277945570/).
- **Be community minded.** Simply checking up on neighbors creates a more resilient neighborhood. When residents plan for winter weather, they increase the likelihood of building extra capacity to be able to help their neighbors with supplies and information. The most vulnerable neighbors include those who live alone, have health issues, have limited income, lack nearby relatives or friends, and are people of color. Also, communities may ask residents to take action to save energy and water. The degree that residents work together to conserve limited resources may determine whether a community can prevent a wider disaster.

When residents plan for winter weather, they increase the likelihood of building extra capacity to be able to help their neighbors with supplies and information.

References

City of Bellaire, 2021: 2021 February winter storms. After-Action Report/Improvement Plan, 46 pp., https://www.bellairetx.gov/DocumentCenter/View/26751/2021-February-Winter-Storm-AAR_IP-FinalReport1.

Trevizo, P., and Coauthors, 2021: Texas enabled the worst carbon monoxide poisoning catastrophe in recent U.S. history. *Texas Tribune*, **29** April 2021, https://www.texastribune.org/2021/04/29/texas-carbon-monoxide-poisoning/.

Ura, A., and J. P. Garnham, 2021: Already hit hard by pandemic, Black and Hispanic communities suffer the blows of an unforgiving winter storm. *Texas Tribune*, **19** February 2021, https://www.texastribune.org/2021/02/19/Texas-winter-storm-suffering-inequities/.

Zamuda, C., D. E. Bilello, G. Conzelmann, E. Mecray, A. Satsangi, V. Tidwell, and B. J. Walker, 2018: Energy supply, delivery, and demand. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*, D. R. Reidmiller et al., Eds., Vol. II, U.S. Global Change Research Program, 174–201, https://doi.org/10.7930/NCA4.2018.CH4.

[This statement is considered in force until July 2026 unless superseded by a new statement issued by the AMS Council before this date.]

Weather and Forecasting (*WAF*)
ISSN: 0882-8156; eISSN: 1520-0434

AMS STATEMENTS

Weather Analysis and Forecasting

An Information Statement of the American Meteorological Society

(Adopted by the AMS Council on 20 December 2021)

Forecasters are also increasingly responsible for effectively communicating forecasts and anticipated impacts to end users and stakeholders in collaboration with affected sectors.

Introduction

Across the United States, government agencies (including the military), private industry, and private citizens consult weather analyses and forecasts to support decisions ranging from the routine (e.g., whether to hold an event) to important and urgent actions to help protect life and property when threatened by hazardous weather. Weather's impacts are substantial and wide-reaching and occur on multiple temporal and spatial scales. Examples include the following:

- 291 billion-dollar weather and climate disasters (e.g., tornadoes, hurricanes, extreme temperatures, and floods) have occurred in the United States since 1980, including 22 billion-dollar disasters in 2020 alone. Of these billion-dollar weather and climate disasters since 1980, tropical storms and hurricanes have been the costliest, with losses totaling nearly $1 trillion.
- Excessive heat is the leading cause of weather-related fatalities, with recent peer-reviewed estimates of excess mortality ranging from 5,600 to 12,000 per year.
- As of March 2021, approximately 70% of air traffic delays are caused by adverse weather conditions. The FAA also reports an annual average of nearly 167,000 total delay hours, at a cost to airlines between $1,400 and $4,500 for each delay hour.
- High-impact weather events, including billion-dollar disasters such as the 2019 California wildfires, August 2020 Midwest derecho, and 2021 central United States cold-air outbreak, account for 90% of all large (>50,000 affected customers) U.S. power outages.

Motivated by weather's significant impacts, this statement discusses who uses weather and forecast information to make important decisions, describes how weather forecasts are made and communicated to others, illustrates the types and overall quality of forecasts that are used to inform people and become the basis of decision-making in a range of settings, and provides insight into how forecast skill and communication can be further improved to benefit society.

How are weather information and forecasts used?

Steady improvements in forecast technology and quality have enabled meteorologists to provide end users with increasingly precise and skillful forecasts (each relative to established baselines for forecasts at a given lead time) tailored to their needs on which those end users can base subsequent actions that increase economic efficiency and productivity and mitigate impacts from weather hazards. Forecast improvements include better accuracy at finer spatial scales and longer lead times (i.e., for deterministic weather forecasts out to 10 days and for probabilistic predictions at monthly to seasonal time scales), as well as probabilistic representations of uncertainty. Specific examples include, but are not limited to the following:

- Government officials use hurricane forecasts to inform evacuation decisions, declare states of emergencies, and spur the public to action in advance of the expected hazards.
- Power companies use forecasts of high-impact weather events such as severe thunderstorms, hurricanes, extreme heat and wildfires, and freezing rain and blizzards to deploy equipment and personnel to help restore power after the associated threats have subsided.
- Departments of Public Works or Transportation use forecasts to order supplies such as salt and de-icer, prepare equipment, and coordinate staffing to prepare for and respond to winter storms.
- Water management and treatment agencies use short- to medium-range forecasts to determine if water should be released from a reservoir or treated and released from a water-treatment facility in advance of anticipated rainfall.

How are forecasts made and communicated?

Forecasters are tasked with synthesizing observations, output from numerical weather prediction (NWP) models, scientific theory, and experience-based intuition to arrive at a forecast. Whether in the public or private sector, these forecasts are often made collaboratively among teams of meteorologists that routinely integrate new information as it becomes available. Forecasters are also increasingly responsible for effectively communicating forecasts and anticipated impacts to end users and stakeholders in collaboration with affected sectors.

Analyses of weather data

Weather forecasting begins with an analysis of the current state of the atmosphere, ocean, and land surface. Reliable observations drawn from many platforms, including satellites, radar, weather balloons, surface stations, and aircraft (both crewed and uncrewed) are crucial for generating accurate analyses. Because forecast quality is partially reliant on the quality of the underlying analysis, scientists continue to develop techniques to integrate observations into four-dimensional model representations of the Earth system. In addition to their vital role in weather forecasting, these analyses support scientific investigations designed to help develop improved weather prediction tools and techniques.

Forecast techniques

Meteorologists have traditionally used their intuition and available observations to create forecasts up to a few hours ahead of time. Thorough human diagnosis of some complex scenarios, such as severe-thunderstorm environments, remains necessary to optimize situational understanding and to make and communicate high-quality forecasts. In addition, rapidly updating numerical models, as well as statistical tools and artificial intelligence–based models that blend observations with NWP outputs, are increasingly used to make short-term forecasts, whether those issued by official forecast agencies or those available through popular smartphone applications.

Beyond a few hours ahead of time, NWP has long been the dominant forecasting tool. Modern NWP models start from an initial analysis of meteorological conditions produced through data assimilation and then apply the physical and dynamical equations that govern atmospheric evolution to predict the weather. Such models are continuously developed and collaboratively maintained by multiple entities. Despite their increasing skill and ability to depict progressively smaller-scale phenomena, NWP models are imperfect. Model shortcomings exist due to limited observations, imperfect data assimilation methods, and the approximations required to represent small-scale physical processes such as energy exchanges between the surface and atmosphere as well as phase changes of water. Approaches such as statistical bias correction, model blending, ensemble forecasts, and artificial intelligence/machine learning are increasingly used to mitigate NWP models' shortcomings while improving forecast skill.

Because forecast quality is partially reliant on the quality of the underlying analysis, scientists continue to develop techniques to integrate observations into four-dimensional model representations of the Earth system.

Role of humans

Forecasters apply their expertise to create forecasts by interpreting and adding meaning to the abundant and complex data and information drawn from observations and NWP. Humans add value to the forecast process by utilizing this expertise and maintaining situational awareness, which can build trust and deepen valuable relationships with end users while creating a solid foundation for the enhanced communication of predicted weather impacts.

The effective translation of a forecast relies on three key dimensions: 1) scientific understanding and information interpretation; 2) data access and the skilled use of forecast tools; and 3) an understanding of the needs of the diverse community of end users reliant upon weather information, developed through ongoing collaboration between forecasters and end users. Forecasters must frequently interact with and gain understanding of stakeholders, end users, and partners. This enables weather information to be tailored to user needs and enables users to be more engaged in the dissemination process. In addition, forecasters must devote time to completing training, reviewing best practices, and engaging local communities to learn how to best communicate actionable forecast information underpinning life- and property-saving decisions.

Recent advances in forecast skill and technology allow for increasingly reliable, although still imperfect, uncertainty information to be provided to end users.

Humans are not necessarily involved with all forecasts that are disseminated to end users. For example, many popular smartphone applications provide users with accessible, often graphically appealing forecasts drawn from computer-based weather prediction systems. Furthermore, private- and public-sector forecast entities increasingly rely on computer-based weather prediction systems to develop a baseline forecast that humans are primarily responsible for disseminating and communicating rather than making themselves. Humans' roles in the forecast process are likely to continue to evolve toward communication as predictive abilities continue to improve.

Forecast dissemination and communication

As technology improves, methods for disseminating weather information and forecasts continue to evolve. For example, location-specific information including hourly forecasts, storm-based severe weather warnings, and radar data now can be directly delivered to smartphones and other smart devices. Forecasters must also consistently collaborate with end users and stakeholders to better optimize forecast dissemination methods and tools.

Forecast products have historically provided users with the best estimate of what may potentially happen, such as high temperature and snowfall amounts. However, because users often consider the *range of possible scenarios* beyond just the most likely outcome when evaluating risk, they also require forecast confidence and uncertainty information to make optimal decisions to protect life and property. Since each user's requirements are unique to their specific operations, optimal decision-making requires effective and continual communication between forecasters and users. Recent advances in forecast skill and technology allow for increasingly reliable, although still imperfect, uncertainty information to be provided to end users. Further, collaborative research between physical and social scientists has recently led to improvements in communicating forecast uncertainty, although further research is warranted to identify how to optimally design and communicate weather information.

How reliable are today's forecasts?

Background

Meteorologists use specific metrics to quantify forecast quality and reliability. Forecast skill is a measure of accuracy compared to a baseline prediction (e.g., persistence, climatology, or other human standard). The *predictability* of potential meteorological events is dictated by an event's size and timing, with predictability being higher for larger-scale features (those spanning hundreds of miles/kilometers or more) at shorter lead times (less than a few days) and so is based on the weather phenomenon itself. A skillful forecast acquires *value* when it can inform specific user actions because people can understand it and use it to make decisions.

Very-short-range forecasts

Very-short-range forecasts, colloquially referred to as "nowcasts," are produced for smaller-scale phenomena such as thunderstorms at lead times of minutes to hours. Examples include tornado, severe-thunderstorm, and flash-flood warnings containing actionable information to help protect life and property (e.g., telling people to shelter in place, or used by air traffic controllers to reroute aircraft). Very-short-range forecasts have become increasingly skillful, reliable, and actionable in recent years as novel tools such as artificial intelligence-based models (particularly in the private sector), NOAA's ProbSevere statistical models, and NOAA's operational High-Resolution Rapid Refresh (HRRR) NWP model have been developed.

Short-range forecasts

Short-range forecasts, such as those of benign weather conditions for specific locations and those issued over broader regions for high-impact weather events (including snow and ice, severe thunderstorms, excessive heat, and hurricanes), encompass lead times of a few hours up to two days. Short-range forecasts have increased in both skill and value in recent years: specifically, these forecasts are increasingly used to inform future actions by users ranging from citizens (e.g., whether to hold a scheduled event) to government officials (e.g., whether to issue an evacuation notice for flooding or a hurricane).

Medium-range forecasts

Medium-range forecasts, typically defined as those at lead times of 2–10 days, continue to improve with discernible subcontinental-scale skill extending to lead times of 8 days. The chaotic nature of the atmosphere results in predictability progressively decreasing with lead time, but improvements in ensemble NWP, machine learning techniques, data assimilation, and our understanding of the relationships between weather conditions and more slowly evolving climate conditions have led to increased forecast skill for large-scale weather features. This skill is often leveraged to facilitate useful probabilistic forecasts of potential high-impact weather, such as the NOAA Weather Prediction Center's Days 3–7 Hazards Outlook.

Subseasonal forecasts

Subseasonal forecasts are typically issued for meteorological phenomena that cover areas up to the size of a continent and involve lead times from 1 to 2 weeks to less than a season. Subseasonal forecasts are generally prepared using numerical weather prediction outputs, knowledge of shorter-term climate variability such as the Madden–Julian oscillation and Arctic Oscillation, and, at longer lead times, long-term trends and knowledge of longer-term climate variability such as that associated with El Niño–Southern Oscillation. Presently, deterministic forecasts of specific weather conditions typically have low accuracy at these lead times. However, probabilistic forecasts issued to highlight significant trends (e.g., warmer than normal, wetter than normal, higher likelihood of extreme events) can be skillful when compared to a baseline forecast. Subseasonal forecasts have generally become more skillful in recent years, leading to the development of new forecast products such as the ECMWF's Extreme Forecast Index and NOAA Climate Prediction Center's Week 2 Probabilistic Hazards and Weeks 3–4 Probabilistic Temperature and Precipitation Outlooks.

Seasonal forecasts

Seasonal forecasts are typically issued for meteorological phenomena that cover areas ranging from the size of a continent to the entire planet for multiple months. Seasonal forecasts are generally prepared using knowledge of longer-term climate variability such as that associated with El Niño–Southern Oscillation, numerical climate-model outputs, and long-term trends. Skill in monthly and seasonal forecasts is variable but generally increasing. Increases in forecast skill at these lead times can largely be attributed to an improved understanding of and ability to forecast major modes of large-scale climate variability such as El Niño–Southern Oscillation, the Arctic Oscillation, and the Madden–Julian oscillation.

Realizing opportunities to improve forecast skill begins with continued fundamental and applied research to better understand the physics and dynamics of high-impact weather systems.

The value of weather forecasts will increase with continued collaborations between forecasters and users that help effectively incorporate information into decision-making processes.

Opportunities for future improvement

Realizing opportunities to improve forecast skill begins with continued fundamental and applied research to better understand the physics and dynamics of high-impact weather systems. This research is likely to result in NWP improvements, including collecting and assimilating more-numerous, higher-quality observations of the atmosphere, ocean, and land surface, improved physical parameterizations and numerical methods, increased spatial and temporal resolution facilitated by advances in computing power, and the increased reliability of ensemble prediction systems. This research is also likely to result in advances beyond NWP, including the continued development and application of machine learning, artificial intelligence, data mining, and data visualization techniques to aid forecasters in preparing accurate forecasts. These activities will require constructive collaborations between researchers and forecasters.

The value of weather forecasts will increase with continued collaborations between forecasters and users that help effectively incorporate information into decision-making processes. Using social science to fully connect forecasts with end users' needs is necessary to achieve this goal. Opportunities to do so include the following:

- Developing infrastructure to deliver weather warnings across multiple media to reach vulnerable populations.
- Taking insights from studies of how different public groups perceive risk and uncertainty and incorporating those insights into forecast operations and dissemination.
- Continuing to investigate how various user groups decide whether to take protective actions when confronted with a potential weather-related hazard.

Conclusion

Weather forecasts are increasingly skillful and useful, and their benefits extend widely across the economy. The forecasting community works closely with users to ensure that forecast information meets their specific needs. This includes collaborations between physical and social scientists to ensure that accurate and reliable forecast information is communicated in ways that enable users to incorporate it in their decision-making processes. Simultaneously, the forecasting community is improving existing forecast tools, developing new forecast techniques, and leveraging new and expanding observation networks to help improve forecast skill. These efforts have increased, and continue to increase, the value of forecast information to everyone.

[This statement is considered in force until December 2026 unless superseded by a new statement issued by the AMS Council before this date.]

Virtual Short Courses

2022

March

AI in Weather Radars
28 March, 10:00–2:00 ET
Registration deadline: 21 March 2022

2022

February

13th International Conference on Southern Hemisphere Meteorology and Oceanography
8–12 February, Christchurch, New Zealand
Abstract deadline: 31 August 2021
Preregistration deadline: 30 November 2021
Preliminary Announcement: May 2021
Call for papers published: July 2021

May

35th Conference on Hurricanes and Tropical Meteorology
9–13 May, New Orleans, Louisana
Session topic proposal deadline: 26 May 2021
Abstract deadline: 10 January 2022
Preregistration deadline: 10 April 2022
Supplementary info deadline: 13 June 2022
Call for papers published: August 2021

June

23rd Conference on Atmospheric and Oceanic Fluid Dynamics
13–17 June, Breckenridge, Colorado
Abstract deadline: 7 March 2022
Preregistration deadline: 9 May 2022
Supplementary info deadline: 13 July 2022
Call for Papers published: Nov 2021

49th Conference on Broadcast Meteorology
14–17 June, Milwaukee, Wisconsin
Abstract deadline: 15 February 2022
Preregistration deadline: 10 May 2022
Supplementary info deadline: 14 July 2022
Call for papers published: TBD

Sixth Conference on Weather Warnings and Communication
14–17 June, Milwaukee, Wisconsin
Abstract deadline: 15 February 2022
Preregistration deadline: 10 May 2022
Supplementary info deadline: 14 July 2022
Call for papers published: TBD

20th Conference on Mountain Meteorology
27 June–1 July, Park City, Utah
Abstract deadline: 14 February 2022
Preregistration deadline: 30 May 2022
Supplementary info deadline: 14 Aug. 2022
Call for papers published: October 2021

July

24th Symposium on Boundary Layers and Turbulence
11–15 July, Sibenik, Croatia
Session topic proposal deadline: 6 Dec. 2022
Abstract deadline: 1 February 2023
Preregistration deadline: 1 May 2022
Supplementary info deadline: 13 Aug. 2022
Call for papers published: TBD

Complete information about these events can be found on the meetings & events page of the AMS website: https://www.ametsoc.org.

To list an event in the calendar, please submit the event name, dates, location, and deadlines for abstracts, manuscripts, and preregistration to amsmtgs@ametsoc.org at least two months prior to the month of first publication.

August

22nd Conference on Satellite Meteorology

8–12 August, Madison, Wisconsin

Session topic proposal deadline: 15 Oct. 2021
New Abstract deadline: 14 April 2022
Preregistration deadline: 1 July 2022
Supplementary info deadline: 12 Sept. 2022
Call for papers published: TBD

17th Conference on Polar Meteorology and Oceanography

8–12 August, Madison, Wisconsin

Session topic proposal deadline: 15 Oct. 2021
New Abstract deadline: 14 April 2022
Preregistration deadline: 1 July 2022
Supplementary info deadline: 12 Sept. 2022
Call for papers published: TBD

16th Conference on Cloud Physics

8–12 August, Madison, Wisconsin

Session topic proposal deadline: 15 Oct. 2021
New Abstract deadline: 14 April 2022
Preregistration deadline: 1 July 2022
Supplementary info deadline: 12 Sept. 2022
Call for papers published: TBD

16th Conference on Atmospheric Radiation

8–12 August, Madison, Wisconsin

Session topic proposal deadline: 15 Oct. 2021
New Abstract deadline: 14 April 2022
Preregistration deadline: 1 July 2022
Supplementary info deadline: 12 Sept. 2022
Call for papers published: TBD

October

30th Conference on Severe Local Storms

24–28 October, Santa Fe, New Mexico

New abstract deadline: 15 June 2022
New preregistration deadline: 15 Sept. 2022
Call for papers published: October 2021
Supplementary info deadline: 24 Nov. 2022

2023

January

103rd AMS Annual Meeting

8–12 January, Denver, Colorado

Session topic proposal deadline: TBD
Abstract deadline: TBD
Preregistration deadline: TBD
Supplementary info deadline: TBD
Call for papers published: TBD

August

40th Conference on Radar Meteorology

27 August–1 September, Minneapolis, Minnesota

Session topic proposal deadline: TBD
Abstract deadline: TBD
Preregistration deadline: TBD
Supplementary info deadline: TBD
Call for papers published: TBD

Meetings of Interest

2022

February

2022 BPS Annual Meeting

19–23 February, San Francisco, California

June

Frontiers in Hydrology Meeting

19–14 June, San Juan, Puerto Rico

July

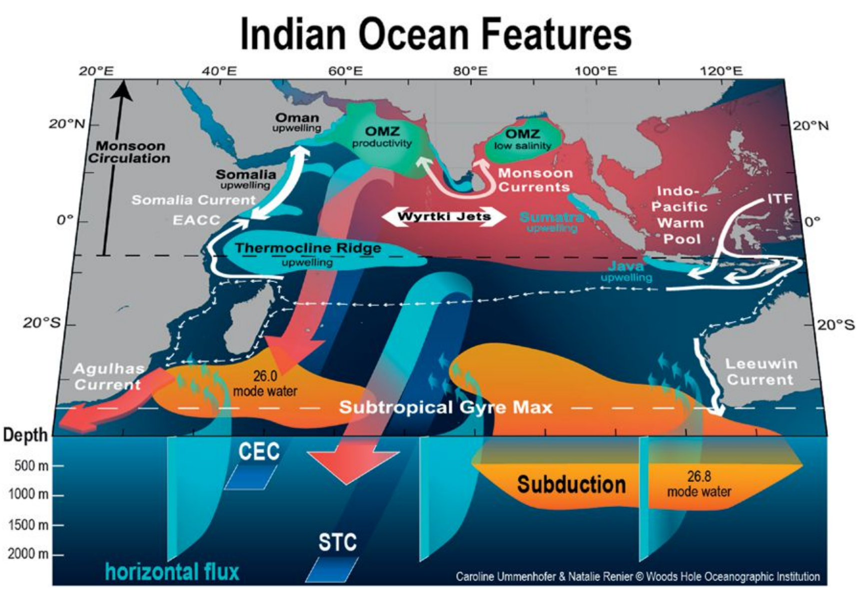
44th COSPAR Scientific Assembly and Associated Events

16–24 July, Athens, Greece

"My next steps are to refine our criteria for identifying internal waves from in situ measurements and explore the longer-term variability of internal wave properties. Currently, I'm digging into other existing datasets that may aid in this pursuit and planning fieldwork to collect complimentary data."

— **Jaqueline M. McSweeney, Oregon State University**

PAGE **117**



"Next up for me is to support the future of Indian Ocean observing, research, and services in any way I can by listening, consulting, and collaborating better with colleagues from Indian Ocean rim nations."

— **Lisa Beal, University of Miami**

PAGE **108**

Jack McSweeney and Jim Lerczak aboard the R/V *Sally Ride* on Halloween 2017 during the inner-shelf dynamics experiment (ISDE), dressed as acoustic Doppler current profilers (ADCPs).


Let's get them back together again, safely.
Get the latest facts on protecting them from
COVID-19 and dangerous new variants.
GetVaccineAnswers.org
IT'S UP TO YOU
COVID-19 VACCINATION
American Academy of Pediatrics
DEDICATED TO THE HEALTH OF ALL CHILDREN®
ad COUNCIL