2023 NOAA SCIENCE REPORT

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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2023 NOAA Science Report

Megan Deehan, Isha Renta, Sharon Yaary, Joseph Fillingham, Saiontoni Sarkar, Gary Matlock, Laura Newcomb, Eric Bayler, Judy Ghirardelli, Monica Grasso, Michelle Harmon, Michael Liddel, Felipe Arzayus, Jeffrey Wielgus, Kristen Schepel, John Schattel, Melissa Yencho, Paul DiGiacomo, Shelby Butz, Cammye Sims, Sarah Davis

NOAA
Silver Spring, Maryland

March 2024

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NOTICE

ACKNOWLEDGEMENTS

LAYOUT

Megan Deehan

CONTENT, COPY EDIT, AND PLAIN LANGUAGE REVIEWS

Megan Deehan, Isha Renta, Sharon Yaary, Joseph Fillingham, Saiontoni Sarkar, Monica Allen, Michael Murphy, Tom DiLiberto, Gina Eosco, Castle Williamsberg, Kristina Kiest, Jennifer Day, Erica Grow, Maria Torres, Thomas Helser, Marjorie Mooney-Seus, James Thorson, Kresimir Williams, Nicole Kruz, Gregory Dusek, Ruth Kelty, Nicole Rice, Tiffany Atkinson, Pam Heinselman, Karin Vergoth, Neil Christerson, Gregory Frost, Victoria Breeze, Theo Stein, Maureen Brooks, Heather Coleman, Kelly Goodwin, Nicole Miller, Emily Osborne, Thia Griffin-Elliot, Laura Chiabongsai, Ghassan Alaka, Ian Enochs, Shirley Murillo Susan, Cobb, Emily Crum, Kristen Crossett, Joseph Conran, Jeffrey Wielgus, Monica Grasso, Shanelle Naone, Sarah Mesnick, Chelsea Thompson, Jessica Mkitarian, Hunter Jones, Laurel Rachmeler, Shobha Kondragunta, Adam Smith, Satya Kalluri, Michael Brennan, Wes Moody, Henry Milliken, John Thibodeau, Felipe Arzayus, Liz Perotti, Sarah Davis, Victoria Moreno, Office of Inclusion and Civil Rights staff

COVER PHOTOS

(Left column descending) Altius model at NOAA's Aircraft Operations Center. Credit: NOAA/Aircraft Operations Center; NOAA scientist surveys bleached Cheeca Rocks corals. Credit: NOAA; NOAA-21 satellite in Earth's orbit illustration. Credit: NOAA; NOAA staff after research mission into Hurricane Fiona, 2022. Credit: NOAA Atlantic Oceanographic and Meteorological Laboratory;

(middle-left column) Deploying the stereo camera over the side of the Canadian Coast Guard vessel *John P. Tully.* Credit: NOAA Fisheries/ Paul Hillman; Rum Creek, OR fire, 2022.Credit: Robert Hyatt, NOAA's National Weather Service; Urban heat data-collecting sensors distributed to Chicago volunteers. Credit: 2023 Chicago Urban Heat Island Mapping Campaign; Sanibel, FL Causeway damaged after Hurricane Ian, 2022. Credit: Getty images; NOAA staff at 2023 American Possibilities: A White House Demo Day. Credit: Rafael DeAmeller;

(middle-right column) Deep-sea coral in the Aleutian Islands. Credit: NOAA Fisheries; Middle school students participating in NOAA Planet Stewards project, "Propagating Understory Restoration Plants for Longleaf Ecosystems." Credit: Rob Diaz De Villegas; Brain coral growing near the Port of Miami. Photo credit: Colin Foord/Coral Morphologic; NOAA staff and high school students taking part in the eeBLUE Young Changemakers Summit. Credit: NOAA;

(right column) HORUS glider and balloon prepared for a test flight in Colorado's Pawnee National Grasslands in 2023. Credit: NOAA; 2023 GeoColor imagery of wildfire smoke from Canada pulled across the Atlantic Ocean. Credit: NOAA National Environmental Satellite, Data, and Information Service; Mobile radar used in NOAA's 2023 Propagation, Evolution, and Rotation in Linear Storms project. Credit: NOAA National Severe Storms Laboratory; NOAA ship *Ronald H. Brown* at sea. Credit: NOAA

FOREWORD

It is my honor and privilege to introduce NOAA's eighth annual Science Report. NOAA is the Nation's premier ocean, weather, atmospheric and climate agency. We are deeply committed to science, service and stewardship for the betterment of our people and planet. The annual NOAA Science Report shares NOAA's exciting research accomplishments of the past year. This report not only documents the breadth and high caliber of our research, but also emphasizes the wide range of impacts that our scientific advancements have on the lives of the American people and the World.

We are continuing to experience climate change and expect to in the future. 2023 was the warmest year in NOAA's 174-year climate record. A warming planet means we need to be prepared for the impacts of climate change, happening here and now, like extreme weather events, becoming both more frequent and severe. We need both science and technology innovation at NOAA to deal with these changes, but also communication to make our advancements actionable. NOAA is progressing fundamental science, providing support for decision making, developing solutions for vulnerable communities and ecosystems, and ensuring our work represents the needs of the Nation. The report's scientific highlights demonstrate NOAA's progress and commitment to building a Climate Ready Nation that is resilient and well equipped to deal with present and future climate change, integrating equity into NOAA's services and operations, and supporting the sustainable growth of the Blue Economy.

Our partners are instrumental in helping us produce valuable work for the American people. Engagement with our stakeholders is key to addressing the needs of the user community and the Nation. Through these coalitions, shared capabilities and perspectives are leveraged to maximize the value of our work and inspire the development of innovative and impactful science.

As we look to the future, NOAA will need to continue to be at the cutting edge of understanding the dynamic Earth system and predicting and projecting future changes and impacts. NOAA science will need to reduce uncertainty and improve the communication around what is to come to not only inform the management of risks across timescales, but support new innovative solutions-oriented commerce.

Thank you to all who have contributed to NOAA scientific advancements, often only completed after years of dedication. Our workforce creativity, unique expertise, and dedication to the mission and the Nation is what makes these and future achievements possible.

Thank you.

Sarah Kapnick, Ph.D.
NOAA Chief Scientist

REPORT SUMMARY

The following sections of the 2023 NOAA Science Report describe NOAA's progress and accomplishments in research and development (R&D) and innovative scientific solutions for a wide range of present and future challenges affecting Earth systems and our society. Each section of this report is aligned with NOAA's R&D Vision Areas that guide NOAA's R&D Enterprise.

REDUCING SOCIETAL IMPACTS FROM HAZARDOUS WEATHER AND OTHER ENVIRONMENTAL PHENOMENA

Rapidly intensifying hurricanes, strong storm surge and flooding, and other extreme hazardous weather events impacted the Nation, making big headlines in 2023. Learn more about how NOAA has addressed challenges related to hazardous weather and improved forecasts, models, and other tools to reduce societal impacts from hurricanes, floodwaters, and other environmental phenomena in this section.

SUSTAINABLE USE AND STEWARDSHIP OF OCEAN AND COASTAL RESOURCES

Observations provide the foundation for scientific investigation and can help us better understand how to manage and take care of the ocean and coastal resources. NOAA's R&D advancements in observing techniques and technology, such as with environmental DNA sampling, are one of the many ways NOAA is gaining critical observations to fill information gaps. This knowledge is crucial to improve forecasts, models, and other products that address climate-related and other human-caused changes in our fisheries and other valuable resources of our oceans, Great Lakes, and coastal areas. Learn more about how NOAA's R&D is contributing to the resilience of our ocean and coastal resources in this section.

BUILDING A CLIMATE READY NATION

2023 was a year for record-breaking heat. Climate-related warming and changes have impacted the Nation and planet through extreme heat, marine heatwaves, drought and flooding events, wildfires, and air quality issues among others. In this section, learn more about how NOAA's R&D accomplishments impact the land, ocean, atmosphere, and beyond, supporting a Climate Ready Nation and overall planet that will be better prepared and more resilient in the face of climate change.

A ROBUST AND EFFECTIVE R&D ENTERPRISE

NOAA has leveraged artificial intelligence, uncrewed systems, satellites, instruments, and other technology to make significant advancements in R&D. These R&D accomplishments impact society in many ways ranging from uncrewed systems used in tornado research to help save lives, to validating critical data from satellites to better understand and help protect the Earth's geomagnetic field and our technological infrastructure from space weather impacts. In this section, learn about NOAA R&D's widespread accomplishments that span from the surface of the sun, to the atmosphere, to the land, and to the ocean and Great Lakes.

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INTRODUCTION

ENRICHING LIFE THROUGH SCIENCE

Extending from the surface of the Sun to the depths of the oceans, NOAA's mission of science, service, and stewardship depends on a strong foundation of R&D for observing and understanding the complex environmental systems of our planet and beyond. This understanding provides the information and knowledge needed to inform decision-making, protect lives and property, support livelihoods, and sustain critical ecosystems.

NOAA IS A SCIENCE AGENCY

To fulfill its mission of science, service, and stewardship, NOAA's science activities are driven by Guiding Principles and shaped through the development of Strategic Priorities. NOAA's objective is to transition R&D into operations, applications, commercialization, and other uses. NOAA produces and publishes credible science that is cited in peer-reviewed publications and highly recognized both internally and externally, through awards and program and laboratory reviews.

President Joe Biden and Allison Fundis, Chief Operating Officer of Ocean Exploration Trust, discuss how new technologies are improving our understanding of the creatures and features in Pacific waters while exploring a NOAA Office of Marine Sanctuaries exhibit at American Possibilities: A White House Demo Day, in November 2023. Credit: The White House

In November 2023, Chief Scientist, Sarah Kapnick, Ph.D., and NOAA staff attended American Possibilities: A White House Demo Day to showcase the virtual reality experience of the Urban Heat Island of Washington, D.C. Credit: Rafael DeAmeller

WHAT PRINCIPLES GUIDE NOAA RESEARCH AND HOW DO WE INVEST IN IT?

NOAA strives to follow eight principles when formulating, directing, and evaluating all agency research:

- Mission alignment
- Transition readiness
- Research balance
- Optimized partnerships
- Sustained facilities and infrastructure
- Workforce excellence
- Scientific integrity
- Accountability

These guiding principles, grounded in communication within the agency and between our partners, help establish and maintain the high quality of NOAA's R&D Enterprise. NOAA's investment in R&D helps to expand capabilities that advance observations, models, forecasts, and other services aiding the Nation and improving the lives of the American people.

NOAA maintains both internal and external research investments. Dynamic engagement between NOAA and its stakeholders drives the development of products, services, and new research initiatives that incorporate the needs of the people. NOAA also develops research initiatives to address legislative mandates and other requirements. For example, through multiple funding opportunities from the Bipartisan Infrastructure Law, NOAA is taking action in a variety of areas to do important research that will help address climate risks and impacts. NOAA balances a broad research portfolio that addresses the needs of the user community, serves the Nation, and advances fundamental scientific understanding.

NOAA partnerships, vital to the agency's R&D success, enable NOAA to leverage the expertise, results, equipment, and facilities of leading universities, federal agencies, private companies, non-governmental organizations, national and international partners, and other science innovators. Key mechanisms for partnerships include cooperative institute and cooperative science center agreements with universities, the network of university-based Sea Grant programs, external grant programs,

contracts, and Cooperative R&D Agreements with the private sector. These partnerships create valuable opportunities to advance NOAA's R&D and further NOAA's mission.

SCIENTIFIC INTEGRITY

NOAA's Scientific Integrity Policy exists to "promote a continuing culture of scientific excellence and integrity, and to establish a policy that ensures the integrity of the agency's scientific activities used to inform management and policy decisions."

The intent of the policy is to strengthen universal confidence — from scientists to decision-makers to the general public — in the quality, validity, and reliability of NOAA science. It also denotes the agency's commitment to a culture of support for NOAA's principal science asset, our employees.

Through NOAA's comprehensive scientific integrity policy, and resulting culture of excellence, NOAA scientists continue to conduct exemplary R&D. Learn more about scientific integrity at NOAA on the Scientific Integrity Commons website.

At the 2023 United Nations Climate Change Conference (COP28), in Dubai, UAE, youth leaders spoke directly with U.S. government officials about the impacts of the climate crisis and how to better engage youth in climate solutions. At COP28, NOAA Administrator Rick Spinrad, Ph.D., highlighted the agency's actionable climate data, information and services that are empowering people to address climate change. Credit: NOAA

NOAA'S PRIORITY OBJECTIVES

R&D are cornerstones of NOAA's wide-ranging scientific assessments, forecasting capabilities, advancement of environmental sensors and technologies, conservation and management, and engagement with stakeholders and international organizations.

The NOAA FY22-26 Strategic Plan identifies NOAA's three overarching priorities, objectives, strategies, and outcomes through 2026 within three goal areas:

1. Building a Climate Ready Nation by establishing NOAA as the primary federal authoritative provider of climate information and services in the whole-of-government response to tackling the climate crisis;
2. Integrating equity into our core operations; and
3. Promoting economic development while maintaining environmental stewardship with a focus on advancing the New Blue Economy.

The NOAA Research and Development Vision Areas: 2020-2026, aligned with the NOAA Strategic Plan, guide NOAA's R&D priorities by providing direction on NOAA's R&D. These R&D vision areas include:

1. Reducing societal impacts from hazardous weather and other environmental phenomena
2. Sustainable use and stewardship of ocean and coastal resources
3. A robust and effective research, development, and transition enterprise

Additionally, the agency endeavors to maximize the value of its products and services in the areas of 'omics, uncrewed systems, value of NOAA's data, citizen science, artificial intelligence (AI) for next-generation Earth science, and information technology cloud services. NOAA proactively works to align its resources, budget, and functional activities with these priorities.

The 2023 NOAA Science Report highlights the progress and impacts of NOAA's R&D in each of the three R&D Vision Areas, supporting NOAA's overall mission to advance science, service, and stewardship.

DIVERSITY, EQUITY, INCLUSION, AND ACCESSIBILITY

VISION AND COMMITMENT

NOAA's overall vision for diversity, equity, inclusion, and accessibility (DEIA) is an environment in which NOAA leverages DEIA to achieve mission goals and business objectives while also maximizing the potential of individuals within the organization. By prioritizing representation, equity, and inclusiveness, NOAA is fulfilling its core mission of science, service and stewardship to the nation as it emphasizes lasting, future change. NOAA also understands the importance of DEIA monitoring efforts as a way to be held accountable as a science-based, mission-oriented agency.

NOAA's 2020-2024 DEIA Strategic Plan describes how NOAA envisions, defines, assesses, values, and commits to DEIA. Implementation of this comprehensive plan assists NOAA in reaching its goals and moving forward as an agency that is fair to not only its employees and community, but also to the Nation.

NOAA recognizes that diversity is about more than race and gender, and strives to foster an inclusive culture that values the unique differences, perspectives, and shared values of each member of the NOAA team.

It is imperative that NOAA's R&D portfolio prioritizes DEIA initiatives to successfully address the needs of the public. Through building a diverse workforce and network of partners, incorporating traditional ecological knowledge, and increasing the accessibility of NOAA research to all, NOAA is not only strengthened as an agency, but is better positioned to meet its R&D mission.

NOAA's Diversity and Professional Advancement Working Group (DPAWG) focuses on attracting, retaining, supporting, and advancing a diverse NOAA workforce. Eight members are pictured clockwise from the top left: Vankita Brown, John Moore, Terence Lynch, Maddie Kennedy, DaNa Carlis, Lonnie Gonsalves, Ashley Turnbull, and Janae Elkins. Credit: NOAA

ADVANCING DEIA

NOAA is advancing DEIA initiatives, programs, and a growing number of Employee Resource and Affinity Groups to connect employees for support, collaboration, and action. These groups promote DEIA, resulting in a more productive, professional environment that champions mission achievement.

STRENGTHENING THE FOUNDATION

NOAA is working on several initiatives to continue strengthening the foundation of DEIA in the agency. In 2023, the NOAA established a new Barrier Analysis Working Group to identify and develop solutions for barriers to equal employment opportunities. Additionally, offices across the agency participated in the training, Creating A Culture of Inclusion: Unconscious Bias in the Workplace, that was offered on more than 10 occasions from September-November, 2023. These examples represent and align with the promising developments and recommendations for the future, featured in the DEIA report, developed by the NOAA Science Advisory Board (SAB), an external federal advisory board to NOAA, to help guide NOAA in addressing DEIA needs and areas for improvement.

NOAA has also made advancements in having a workforce that represents individuals with targeted disabilities. NOAA recognizes that there is still ample work to be done to address deficiencies in DEIA within the agency, and going forward will continue to make efforts and support initiatives to progress and improve diversity and inclusion in the work environment.

In July 2023, the inaugural cohort of the eeBLUE Young Changemakers Fellowship gathered for a three-day summit in Washington, DC. There, these nine high school students participated in hands-on workshops on environmental action and engaged in conversations with NOAA leaders, including NOAA Administrator Rick Spinrad, Ph.D. (right) and Special Advisor on Youth Engagement Lauren Gibson, Ph.D. (third from right). Through the Young Changemakers Fellowship, these students will have the opportunity to continue to influence decision-making at NOAA throughout the year. Credit: NOAA

SUPPORTING YOUTH AND YOUNG PROFESSIONALS THROUGH DEIA AT NOAA

Learning to recognize and respect people's differences from a young age can support a future workforce that values diversity. Providing opportunities for youth engagement with a diverse workforce, in a variety of disciplines, may inspire new career pathways for young professionals. In 2023, NOAA brought on its first ever Youth Engagement Special Advisor to the NOAA Administrator, who leads the agency's efforts to bring youth perspectives into agency

decision-making and strengthen NOAA career pathways for young professionals. NOAA also released its new NOAA student opportunities database which lists more than 60 NOAA-related internships, fellowships, and programs for students and emerging professionals.

NOAA provides many opportunities for students to gain experience and impact the work of our agency. Examples of these opportunities in 2023 include paid William M. Lapenta NOAA Student Program internships offering mentoring and project experience as well as an Educational Partnership Program with Minority-Serving Institutions that supports the education, training, professional development, and graduation of post-secondary students at NOAA-supported minority-serving institutions.

UNDERSTANDING THE VALUE OF NOAA R&D

NOAA aims to produce R&D that improves our fundamental understanding of the world and yields useful applications to society. Social science research at NOAA plays a critical role in understanding societal needs, improving NOAA's information and services, and evaluating the agency's contributions to society. In particular, NOAA's R&D activities help the organization achieve the following:

- Determine which research priorities, scientific capabilities including products and services, and improvements therein, will produce the greatest societal benefits;
- Assess how people interpret and perceive threats as well as manage and respond to risks relevant to changes in climate, weather, oceans, and coasts;
- Design products and services that maximize the utility of NOAA data while integrating an understanding of end-user decision needs;
- Consider human behavior and integrate social science data across the full spectrum of research design through the application of results;
- Evaluate societal outcomes and quantify the economic value of NOAA's products and services.

NOAA has produced several reports that detail the enormous benefit the agency contributes to the economy and in keeping Americans out of harm's way. NOAA's R&D impacts society by influencing human behavior, such as communicating risks of natural hazards to help save lives and property, and aiding the management of valuable natural resources that support the Nation's economy.

A strong economy depends on clean air and water, healthy coral reefs, soil, forests, a stable climate, and other elements of nature. The Nation's economy and environment are deeply interconnected, yet a knowledge gap exists to fully understand, track, and quantify the economic value that natural resources provide to society. NOAA has helped to address this challenge by contributing to the first national system of Natural Capital Accounts (NCA), which will put nature, and the oceans' natural resources, on the Nation's balance sheet. Released in January 2023, the National Strategy to Develop Statistics for Environmental-Economic Decisions guides a multi-year effort to integrate NCA within a system of national economic accounts for the first time. In accordance with this strategy, NOAA is developing the first Marine Natural Capital Account as part of the overall effort to use actionable data for the sustainable growth of our marine economy. In the long run, this account will be linked to the current U.S. statistics for the marine economy in the Marine Economy Satellite Account.

Members of the Collaborative Network for Valuing Earth Information, a new research consortium NOAA is helping develop, gathered for a group picture at their first workshop in May 2023. Credit: Judi Gould

NOAA is also collaborating with partners to develop a new research consortium to determine new ways to evaluate the socioeconomic impacts of Earth observations and better understand and communicate their potential value to society. This includes analyzing how the use of Earth observations can change perceptions, behaviors, decisions, and influence social and ecological outcomes. Earth observations provide information about the physical, chemical, and biological systems of the planet. Knowing how these systems function is essential for decision making that helps save lives and protects the planet, ranging from sending emergency response resources after a natural disaster to a farmer deciding when to water crops. New insights from the assessment of socioeconomic benefits of incorporating Earth observations in decision making will help inform policy development, management, and shape future endeavors aligned with NOAA's mission.

BIBLIOMETRICS

IMPORTANCE OF BIBLIOMETRICS

Illustrating the value and breadth of an organization's research is a daunting task. Bibliometrics can be used to gain a better understanding of the scope and impact of NOAA's world class research. Using peer-reviewed publications as a proxy for research effort and impact — one type of bibliometrics measurement — allows for the inclusion of a quantitative element in a qualitative analysis of NOAA's work and role in the community.

In Fiscal Year 2023 (FY23), 3,096 NOAA articles were published in 126 subject categories, representing the full spectrum of NOAA's research. Environmental sciences such as Meteorology and Atmospheric Sciences, Oceanography and Remote Sensing as well as social sciences such as Economics, Urban Planning and Public Health were all included in the categories. Like NOAA's research, these publications cover an extensive range of subjects relevant to a broad audience.

Select articles by NOAA researchers showcasing the high quality of NOAA's work have been featured throughout the report. Articles published by 1,121 NOAA authors in FY23 illustrate not only the important role publications play in NOAA's R&D but also NOAA's interagency collaboration across line offices and labs, supporting advancement of NOAA's science.

ACCESSIBILITY AND OPEN SCIENCE

NOAA recognizes the importance of making its research accessible and reproducible. Through the NOAA Institutional Repository (IR), the agency has made more than 52,000 research publications available, including more than 17,000 full-text peer-reviewed articles from NOAA-employed or NOAA-funded authors. Through the NOAA IR, these publications are available to the public in Section 508 compliant format and discoverable via popular search

engines.

NOAA is also increasingly making peer-reviewed publications accessible through Open Access (freely available online), demonstrating NOAA's commitment to supporting Open Science and increasing public accessibility of its research.

NOAA is progressing ongoing, open science initiatives like those being led by the Earth Prediction Innovation Center, enabling collaborations and contributions within the Unified Forecast System (UFS) and the broad weather community to advance operational forecast skill. NOAA is also continuing to advance public access to research results aligned with the White House Office of Science and Technology Policy.

COLLABORATION - WORKING TOGETHER FOR BETTER SCIENCE

NOAA's national and international research collaborations provide opportunities to leverage shared knowledge and resources, which can lead to the development of innovative solutions benefiting the scientific community and society overall. In FY23, NOAA-employed and NOAA-funded authors collaborated with researchers at 1,579 institutions in 113 countries and territories across all 50 U.S. states. These organizations span not only other federal research agencies, but local and state governments, academic institutions, corporate entities, and research foundations.

NOAA'S PUBLISHING IN FY23

3,096
Peer-reviewed articles

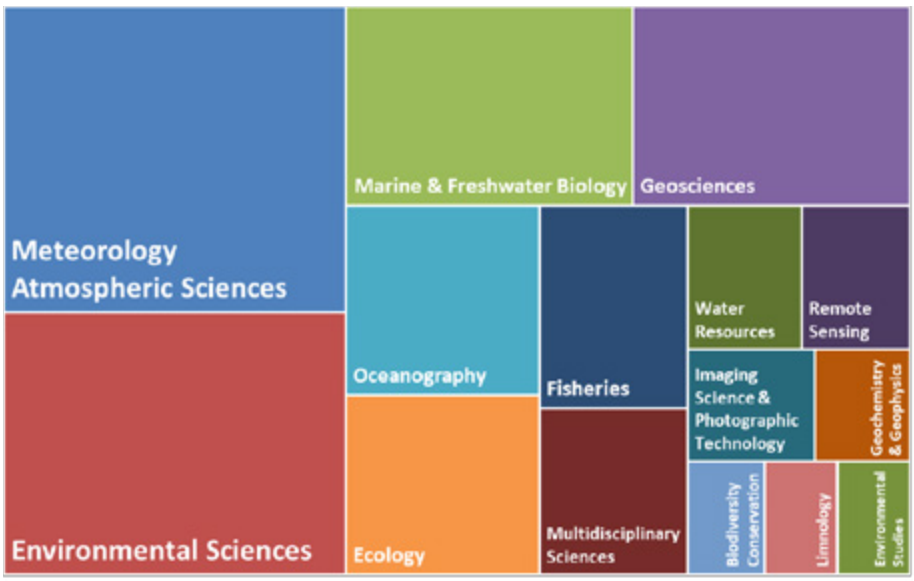
1,121
NOAA authors

1,800
Open Access Articles

1,656
Co-authoring institutions

These graphics analyze NOAA peer-reviewed articles published in Fiscal Year 2023, indexed in the Web of Science (WoS) Core Collection and identified by the NOAA Central Library Bibliometrics team as having one or more authors listing NOAA as their institutional affiliation or source of funding. This data is accurate as of January 31, 2024.

TOP NOAA SUBJECT AREAS



90% of NOAA articles published in FY2023 fell within these fifteen subject areas. Subject areas are defined, and assigned to articles, by WoS based on the journal in which a given article was published. A single article may be assigned to multiple subject categories.

SCIENCE HIGHLIGHTS

The stories behind NOAA's research

NOAA National Severe Storms Laboratory uses mobile radars (pictured here) to study different kinds of storms, mountain rainfall, and even swarms of bats. The information collected can enhance precipitation forecasts and improve predictions of thunderstorms. This is one of several instruments used in NOAA's Propagation, Evolution, and Rotation in Linear Storms project. Credit: NOAA National Severe Storms Laboratory

Damage caused by storm surge along the Sanibel Causeway in Florida during Hurricane Ian in September of 2022. Credit: Getty images

1. REDUCING SOCIETAL IMPACTS FROM HAZARDOUS WEATHER AND OTHER ENVIRONMENTAL PHENOMENA

Better extreme weather forecasts, communication of public risk, and warnings with greater accuracy and lead times are required to save lives, mitigate damage, and protect the livelihoods of vulnerable populations. NOAA is addressing the Nation's needs through a series of strategies, aligned with government policy, to improve forecasts, warnings, and risk communication to reduce the loss of life, property, and damages to the economy. Through the dedicated work of NOAA's staff and programs, goals were set and exceeded through research, development, and transition of the Hurricane Analysis and Forecasting System (HAFS), an upgraded Version 3.0 Probabilistic Storm Surge model, and improved risk communication products and services for hazardous weather. The measurable improvements to these products have widespread societal impact to help prepare and safeguard the American people from the effects of extreme weather.

In the past year, the U.S. has seen many examples of extreme weather ranging from severe precipitation and flooding to wildfires, extreme temperatures, and damaging storms. Although hazardous weather is not a new phenomenon, it still takes Americans by surprise in many instances, due to its seemingly unexpected increases in intensity and powerful impacts.

The pace of change is challenging to keep up with, making it more difficult to predict weather and environmental phenomena. According to NOAA's research, hurricanes are growing more severe and the sea level baseline for destructive storm surge is rising at an accelerating rate.

Anticipating that this trend of changing weather will only continue, NOAA is improving forecasts and warnings for hazardous weather and environmental phenomena.

Scientists at NOAA are now able to better predict where tropical cyclones are going and what kinds of impacts they will have with NOAA's next generation hurricane modeling system — the HAFS. Operationalized in 2023, the HAFS, part of the UFS, provides improved forecasting of storm track, intensity (hurricane winds), and structure by allowing scientists to "zoom in" and follow a close-up view of the storm. With this upgraded storm view, scientists can look for clues that may indicate conditions ripe for rapid intensification — tropical cyclone winds increasing by at least 35 mph in a 24 hour period — and other unique features of the storm.

1.1 HITTING TOO CLOSE TO HOME: NOAA SCIENTISTS ADVANCE HURRICANE RESEARCH

NOAA scientists achieved this up-close-and-personal view of hurricanes through efforts that began more than three decades ago. Extreme weather events like Hurricane Andrew in 1992, one of the most destructive hurricanes on record to hit the U.S., marked a pivotal time in the pursuit to better understand and prepare for hurricanes. In less than 36 hours, Hurricane Andrew rapidly intensified to a Category 5 storm, reaching the doorsteps of South Florida homes on August 24, 1992 with wind speeds of at least 165 mph, before destroying wind-speed observational instruments and everything else in its path. The hurricane resulted in $59.1 billion (Consumer Price Index-adjusted to 2023 dollars) in damage and, devastatingly, was the direct cause of 23 deaths in the U.S. The storm's impacts to Florida, Louisiana, and the Bahamas highlighted the need for better ocean, atmosphere and hurricane observations, forecast models, and analyses.

NOAA's Atlantic Oceanographic & Meteorological Laboratory (AOML) Meteorologist Stan Goldenberg in front of his home after Hurricane Andrew tore through southern Miami-Dade County in 1992. Personally affected by hurricanes, NOAA's staff are passionately driven to advance extreme weather forecasts and warnings that help save lives and protect communities. Credit: Stan Goldenberg/NOAA AOML

1.2 CREATING AN INFRASTRUCTURE AND RESOURCES TO IMPROVE HURRICANE FORECASTS

In 2007, the Hurricane Forecast Improvement Program (HFIP) was established in response to a series of damaging and deadly hurricanes which occurred in 2004-2005 (e.g., Charley, Frances, 2004; Katrina, Wilma, 2005). The new program provided the infrastructure and resources needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts, and accelerated the transition of this research into operations.

Since HFIP's inception, data assimilation and a better understanding of hurricane physics have helped improve forecasting errors. Track forecasting errors were reduced up to 50%, and intensity forecasting errors reduced by 56%, and 47% during rapidly intensifying storms.

Despite notable improvements in hurricane forecasting, 2017 brought Hurricane Harvey, Irma, and Maria along with $265 billion in damage, highlighting the need to further hone in research on several storm-related factors and hazards such as the abnormal rise in

sea level generated by a storm, above what would normally occur–called "storm surge." In response to the *Weather Research Forecasting Innovation Act of 2017*, NOAA refocused HFIP strategies to reduce forecast guidance errors (including rapid intensification), improve storm surge forecast guidance, and incorporate social and behavioral science research for risk communication and the development of more effective watch and warning products.

The NOAA SAB, helped to review the HFIP strategies, identify areas of need, and advise on accelerating the transition of promising hurricane research to weather forecasting operations. Establishing timelines and resources needed to achieve goals, leveraging scientific and technological industry and agency advances and collaborations, and entraining a broader network of experts were some of the NOAA SAB recommendations to speed up progress on these urgent actions. The HAFS is a prime example, achieved through teamwork and community-based collaboration, of improving hurricane modeling forecasts and streamlining the R&D transition process in approximately five years.

Lieutenant Commander (LCDR) Megan Gaston (left) and Flight Engineer Paul Darby (right) flying the WP-3D Orion Hurricane Hunter "Kermit" into Hurricane Elsa in 2021. Credit: NOAA Aircraft Operations Center

1.3 NOAA'S HURRICANE HEROES: NOAA'S SCIENTISTS LEAD INNOVATIVE R&D

Much like a photographer persistently trying to get the perfect shot, scientists at NOAA have tirelessly studied hurricanes from many different "angles" to get the best picture of how these powerful storms form, build, and intensify. Researchers, pilots, and crew making up NOAA's "Hurricane Hunters" bravely fly into inhospitable conditions within tropical cyclones to collect information that improves forecasts and helps prepare and protect communities at risk of the devastating effects of these storms. Some low or medium-altitude areas of the storm are too dangerous for humans to fly so that is where innovative technology–uncrewed systems and other instruments–are essential to aid and supplement storm observations above, below, and throughout the storm, providing valuable data used in models and forecasts.

2023 Hurricane Field Program Deputy Director Heather Holbach (left), Hurricane Research Division Acting Director Shirley Murillo (center), and Samantha Camposano (right), a National Hurricane Center Meteorologist, after their research mission into Hurricane Fiona in September 2022. Credit: NOAA Atlantic Oceanographic and Meteorological Laboratory

NOAA LEVERAGES KEY COLLABORATIONS TO ADVANCE R&D TECHNOLOGY

In 2023, at the Aircraft Operations Center, NOAA showcased exciting new technology stemming from NOAA's R&D and partners. Some of the instruments featured were small aircraft drones (uncrewed systems) like the *Altius 600*–flown into the eye of Hurricane Ian in 2022, and the *Blackswift S0*, being tested to fly at low altitudes to collect information where it would otherwise be unsafe for manned aircraft to fly. The capabilities of this new technology are crucial for collecting valuable data that are assimilated and coupled together in models with other existing observations, creating a more holistic view of hurricanes and better forecasts.

Altius demonstration model with Hurricane Hunter, NOAA WP-3D Orion "Miss Piggy," at NOAA's Aircraft Operations Center in Lakeland, FL on May 25, 2022. Credit: NOAA/ Aircraft Operations Center

1.4 IMPROVING MODELING: THE MORE THE MERRIER FOR OBSERVATIONS

The area where the ocean and atmosphere meet and exchange heat or the "boundary layer", is a place where hurricanes gain or lose energy, and still poses many unanswered questions for scientists. This area is being observed with uncrewed systems, such as small aerial drones and saildrones–that autonomously sail along the surface of the water–providing critical observations used by the HAFS to fill in the gaps about the forces driving hurricanes.

> "The more we understand about how the ocean fuels tropical storms, the better the forecast will be," said Frank Marks, Former Director of NOAA Atlantic Oceanographic & Meteorological Laboratory's Hurricane Research Division.

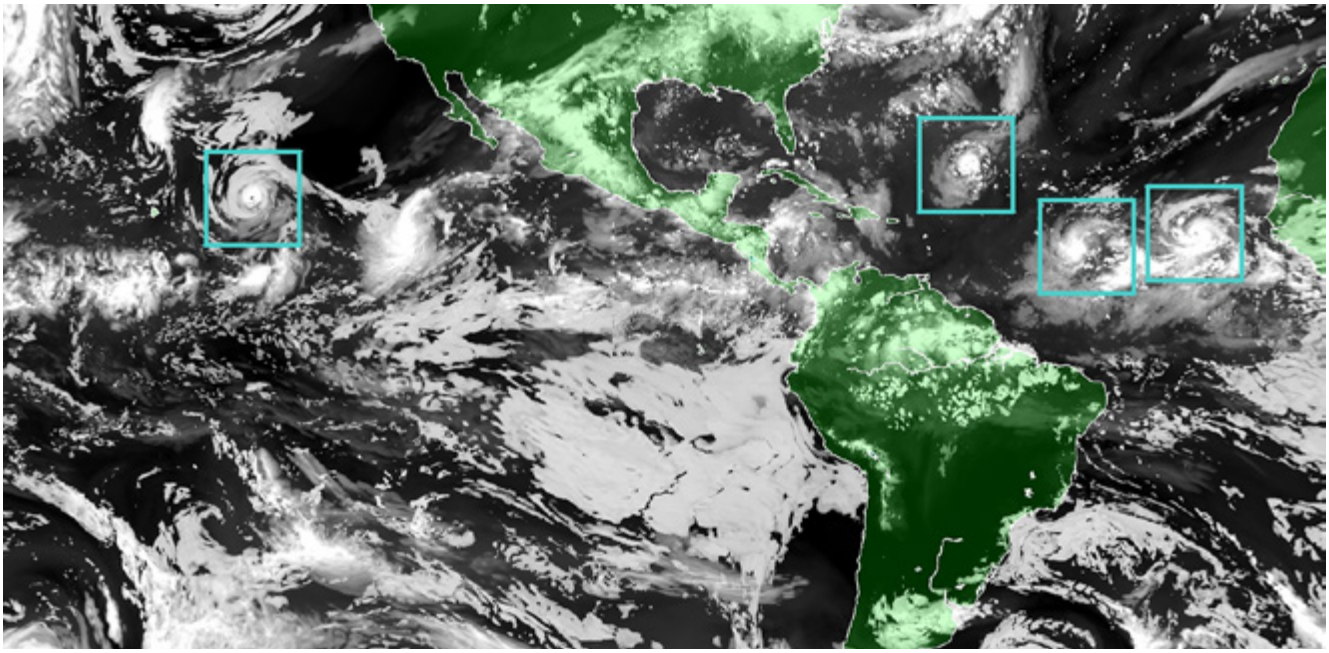
Through innovations like the HAFS, NOAA has improved storm track forecasts by nearly 70% over the last 40 years, but storm intensity and rapid intensification still require a better understanding. Drifters, gliders, and floats, operating below the surface of tropical cyclones, collecting ocean data, are crucial for improving storm intensity forecasting. The Extreme Events Ocean Observations Task Team, composed of members internal and external to NOAA, are connecting the ocean and atmospheric observing and modeling communities to better integrate ocean observations into hurricane monitoring and forecasting.

PUTTING THE HAFS TO THE TEST

With more observations comes the need to manage and analyze more information. NOAA has tackled this challenge by expanding the capacity of its operational supercomputing system by 20%, enabling more complex and upgraded forecast models to run. The HAFS uses a high resolution "moving nest"–similar to a high definition TV picture–to zoom in on unique features like the hurricane eyewall and use observational data to better represent the storm's structure. These improvements allow scientists to examine the storm for any triggers that may lead to rapid intensification such as bursts of thunderstorms, heat from oceans

and atmosphere to fuel the storm, and winds swirling in the direction of the storm or "low wind shear".

HAFS transitioned to operations in June 2023 after more than four years of R&D, replacing the Hurricane Weather Research and Forecasting (HWRF) model as NOAA's flagship hurricane model. An important stage of the R&D process, and HFIP-supported activity, was to test experimental versions of HAFS in near-real-time during the 2019-2022 North Atlantic hurricane seasons. When compared to HWRF, the latest pre-operational version of HAFS improved tropical cyclone track predictions by 10-15% at all forecast lead times and intensity predictions by 10-15% at days four and five. HWRF and other hurricane models will continue to run operationally in a limited capacity through 2024 to facilitate the transition to HAFS.



The Hurricane Analysis and Forecast System "moving nest" model. Global map showcasing land mass in green and water in black, clouds in white and tropical storms outlined in green boxes representing the moving nest model. Credit: NOAA

1.5 NOAA MAKES CRITICAL MODEL UPGRADES TO REDUCE IMPACTS OF STORM WATERS

Accurately anticipating the impacts of storm surge and rainfall can help inform life-saving decisions about storm preparation, evacuation or other measures to take prior to a hurricane's arrival. In 2022, Hurricane Ian made landfall in Southwestern Florida causing a total of 66 direct deaths. Its catastrophic storm surge was the most deadly hazard, claiming 41 lives, while significant freshwater flooding occurred due to record rainfall, including 26.95 inches of storm total rainfall recorded just north of landfall in Grove City, FL.

NOAA acted promptly to upgrade the Probabilistic Storm Surge model—the primary model for predicting storm surge associated with high-impact weather—in May 2023, just prior to the start of the 2023 hurricane season beginning June 1. Version 3.0 advanced storm surge modeling for the contiguous U.S. and provided new forecasts for surge, tide and waves for Puerto Rico and the U.S. Virgin Islands. Modeling can now run for two storms simultaneously, providing the likelihood of various flooding scenarios over different types of land surfaces, including a near worst-case scenario to help communities prepare for all potential outcomes.

NOAA is using critical satellite observations to improve models for 3D flood mapping. The 3D flood mapping can help users see floodwaters occurring over different types of terrain and flood depth to help identify when flooding may be considered hazardous. This additional information can support rescue efforts and damage assessment.

Giving communities more time to prepare for excessive rainfall is crucial for saving lives from flooding–a deadly hazard from heavy rainfall. NOAA has extended the Excessive Rainfall Outlook an additional two days, now providing forecasts up to five days in advance. The outlook shows general areas at risk for flash flooding due to excessive rainfall.

With these advancements, NOAA is delivering on, and exceeding, its promise to Congress and the American people, outlined in the HFIP and *Weather Research Forecasting Innovation Act of 2017*, to provide an advanced Hurricane Analysis and Forecast System, to save lives and property.

NOAA is now embarking on a new challenge while continuing to advance hurricane forecasts: what is the best way to communicate hurricane warnings so people can act and safeguard their families and homes from the risks and hazards of approaching storms?

1.6 A STORM IS COMING – NOW WHAT?

NOAA IMPROVES RISK COMMUNICATION, GUIDANCE, AND SERVICE FOR EXTREME WEATHER

Advancing hurricane forecast models is critical for progressing hurricane research, but this alone is not enough to fully improve the Nation's response in the face of tropical cyclones and related weather hazards. What we do with this information, in a timely manner, and what it takes to get people to sufficiently prepare for storms is another piece of the puzzle for improving our ability to face extreme weather. One of NOAA's strategies, outlined in the HFIP, is to apply social, behavioral, and economic research to improve tropical cyclone hazard guidance, warnings, products, and services with a focus on risk communication.

NOAA funded social and behavioral science research to understand how various groups use forecasts, warnings, and other tropical cyclone information, placing a particular emphasis on understanding how people consume and process evolving forecasts over time, as well as how people navigate NOAA's hurricane webpage and associated tropical products. A major research takeaway that emerged from all four projects is that these groups find NOAA's tropical cyclone products and services useful and important.

NOAA's research shows that providing short explanations on how to interpret weather graphics can significantly improve people's comprehension of uncertainty and probabilistic information in a weather forecast. The research findings further indicate that tropical cyclone forecast information should be specific and local to people's areas (where possible), include timing information for all possible hazards as early as possible, and that the tropical cyclone product suite would benefit from other improvements to address identified gaps and enhance risk communication.

NOAA is making progress in these areas, including improvements in 2023 to the Tropical Weather Outlook graphic by expanding the time range covered by formation forecasts from five to seven days. With an expanded time range to show tropical cyclone formation potential, this updated graphic can help provide more time to prepare for storms. In addition, a new generation of forecast flood inundation

mapping for portions of Texas, the Mid-Atlantic, and the Northeast became operational in September 2023, providing specific and localized information about flooding extent at street level. These forecast maps are on track to extend to the rest of the U.S. by 2026.

NOAA has also worked with partners to advance algorithms used for multi-hazard county and U.S. Census tract multi-risk mapping. The Billion-Dollar Disaster and Risk Mapping tools expand on the Federal Emergency Management Agency National Risk Index and U.S. Census tract data incorporated to provide an integrated view of U.S. hazard risk, exposure, and vulnerability across more than 100 combinations of weather and climate hazards. These hazards can include severe storms, flooding, drought events, heatwaves, extreme cold and freeze events, among other events.

The enhanced interactive maps provide data for over 72,000 U.S. Census tracts, which are small subdivisions of counties that average about 4,000 inhabitants. The new maps also provide select socioeconomic vulnerability information using the Center for Disease Control and Prevention Social Vulnerability Index, which is derived from the U.S. Census Bureau's American Community Survey data. Users can now visualize combined physical exposure, socioeconomic vulnerability, and markers of resilience to natural hazards on a finer scale than ever before.

In the summer of 2023, NOAA conducted research for three projects with goals to establish a process for improving forecast graphics, investigate communication of compound hazards during hurricanes, and develop a graphical product prototype for the communication of tropical cyclone intensity probability or likelihood. The results of this research will continue to inform how NOAA can fine-tune the suite of extreme weather products and services to safeguard the American people.

Whether experiencing a busy or slow season for hurricanes, it only takes one devastating hurricane to cause vast destruction and upend lives. With lessons learned from past storms, NOAA has made great advances and upgrades to forecast and warning products for extreme weather. NOAA remains committed to supporting the American people to understand the risks of hazardous weather and the steps they can take to prepare and protect their families and communities from the impacts of extreme weather events and phenomena.

NOAA's R&D is advancing the science of hurricanes and the HAFS is a great example of that. It was jointly created by NOAA's Atlantic Oceanographic & Meteorological Laboratory (AOML) Hurricane Modeling and Prediction Program and NOAA's National Weather Service Environmental Modeling Center (EMC) in collaboration with NOAA's Geophysical Fluid Dynamics Laboratory and NOAA's Cooperative Institute for Marine & Atmospheric Studies at the University of Miami. A major component of the physics used to represent the boundary layer relies on observations from NOAA Hurricane Hunter P-3 aircraft. The testing and evaluation was jointly done by EMC and AOML. The National Hurricane Center was involved from the developmental stages of the model all the way to its evaluation and implementation.

The Saildrone Surveyor in Alaska's Dutch Harbor at the beginning of the Aleutians Uncrewed Ocean Exploration expedition. NOAA Ocean Exploration Cooperative Institute led this expedition to collect ocean mapping and environmental data in unexplored waters around the Aleutian Islands. The work in these waters is a high priority for NOAA, partners, the broader federal Interagency Working Group on Ocean Exploration and Characterization, and contributes to the Seascape Alaska regional mapping campaign. Image courtesy of Saildrone

2. SUSTAINABLE USE AND STEWARDSHIP OF OCEAN AND COASTAL RESOURCES

The ocean covers about 70% of the planet's surface yet the vast majority of it remains unexplored with a limited understanding. Acting as our natural buffer to impacts of climate change, the ocean provides key indicators for changes affecting the entire planet. The ocean brings tremendous value to the U.S. economy. Approximately 40% of the U.S. population lives in coastal regions, which provide access to tourism and recreation, food sources, transportation, and exciting new medical remedies. NOAA is a trusted leader in ocean research, driving efforts for sustainable use and stewardship of our oceans and coastal resources. Amidst a warming planet, now more than ever, the stakes are raised to continue building a better understanding of the ocean and ensure that marine resources are managed sustainably, so they will last for future generations. Advancements in ocean observations are critical to provide the foundation to better understand the ocean and improve models and forecasts that inform sustainable use and stewardship. In 2023, NOAA made great progress in this area, using cost-effective technology to map seafloor areas that had never been explored, observing unique deep-sea coral communities, improving models and forecasts that anticipate how important marine species will respond to impacts of climate change, and developing better ways to harvest lobster that present less risk to the marine ecosystem.

One of the first steps in scientific investigation to better understand the ocean is observation. Making observations of the sea surface and what lies beneath is challenging, expensive, resource-

intensive, and part of why many areas have yet to be explored.

NOAA has made great strides in advancing ocean observations with the combination and use of innovative observation techniques like environmental DNA sampling, autonomous sampling, and the use of uncrewed systems to supplement traditional methods. The road to scientific success is not always a straight path forward and sometimes "failure" can mean progress when it comes to testing and developing new technology such as autonomous underwater and surface vehicles used for biological sampling in the Great Lakes. In 2023, after setbacks and successes of field testing, NOAA put into action a plan to guide the advancement of NOAA autonomous 'omics capabilities and further develop technology critical to unlocking new means for environmental research. These tools and techniques ultimately help us better understand biodiversity, population distributions, food web function, and organism abundance for life in our oceans and Great Lakes.

Emma Graves, Intern at NOAA's Atlantic Oceanographic & Meteorological Laboratory (AOML), holds a deep ocean sediment sample collected from the northern Gulf of Mexico. Environmental DNA was extracted from the sample to provide biological information associated with ocean particulates and better understand how they contribute to the global carbon cycle. Credit: NOAA AOML

Environmental DNA or "eDNA" are traces of genetic material shed by an organism into its environment. Environmental DNA can be collected and analyzed from a sample of water to detect what species may be present nearby. Environmental DNA sampling is part of a suite of cutting edge 'omics tools used to analyze DNA, RNA, proteins, or metabolites. Many 'omics approaches can be faster, less invasive, and more comprehensive than traditional methods, revolutionizing biological study. Learn more about advances in NOAA 'Omics R&D at the new NOAA 'Omics website.

2.1 SAILING THROUGH UNCHARTED WATERS TO OBSERVE AND MAP SEAFLOOR COMMUNITIES

In 2017, only 6% of the global seafloor had been mapped. As of 2023, 24.9% has been mapped, supporting national and international goals such as the National Strategy for Mapping, Exploring, and Characterizing the U.S. Exclusive Economic Zone and the global Seabed 2030 initiative.

Through a public-private partnership, NOAA and its partners mapped 17,375 square miles of seafloor in one of the most remote and understudied parts of the U.S. The innovative Saildrone Surveyor, the world's largest uncrewed ocean mapping vehicle, collected high resolution ocean mapping and environmental data in high priority areas around Alaska's Aleutian Islands and off the California coast. Piloted safely from shore, the Saildrone Surveyor, powered primarily by solar and wind energy, sailed along the surface of "uncharted waters", often otherwise dangerous for humans, sending a sonar signal to ping the ocean floor, measuring depth and unique

features of the seafloor. The data collected revealed unprecedented detail in ocean floor structures, such as potential hydrothermal vents on the Aleutian seafloor and an unknown seamount rising approximately 3,200 feet off the seafloor off the California coast. These ocean "discoveries" provide a better understanding of the physical processes of the ocean and critical marine habitats to further explore.

NOAA is not only supporting the exploration and mapping of the physical terrain of the ocean floor, but also gaining a better understanding of what marine life resides in these remote areas. During the expedition, the Saildrone Surveyor was equipped with a "lab in a can," known as an Environmental Sample Processor. This revolutionary technology collects and processes water samples containing traces of genetic material left behind by marine life present in or passing through the water column, called "environmental DNA" or "eDNA." Through analysis of these genetic "fingerprints," scientists can get a snapshot of life in these ecosystems, avoiding some of the challenges associated with more invasive survey methods. Pairing the collection of environmental DNA with uncrewed robotic technologies expands observing capabilities in ways that are cheaper, more environmentally friendly, and safer. This work represents a large leap forward to improve our understanding of the ocean and its biodiversity in areas that are difficult to access with crewed vessels.

2.2 SHEDDING LIGHT ON DEEP-SEA CORAL AND SPONGE HABITATS

When thinking of corals, vibrant, colorful, shallow water tropical reefs are often the first thing that come to mind. There are also abundant communities of deep-sea corals living in dark, cold Alaska waters at depths of 20 to more than 3,000 feet that we know far less about. These corals and sponges are habitats for commercially important fish such as rockfish, shrimp, and crab and have led to new discoveries for medicines. The full value of these deep-sea habitats is yet to be realized and holds potential to uncover exciting new advances in biomedical research and identification of new marine species. Arctic and Subarctic regions are undergoing major changes related to climate change making research in these waters crucial for understanding how these seafloor communities are being impacted and what management decisions can be made to support sustainable, climate-resilient Alaskan fisheries.

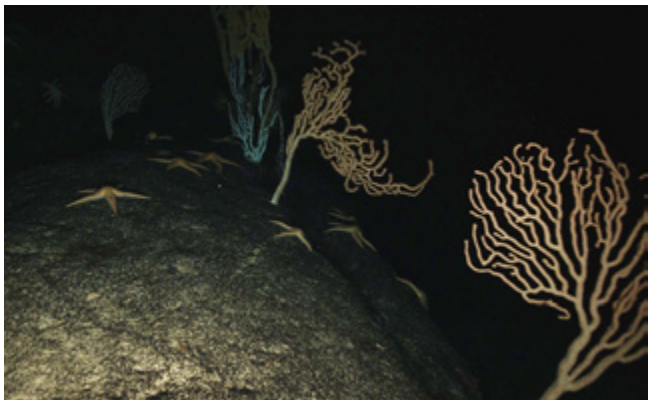
A high-density coral and sponge garden in the Aleutian Islands. Credit: NOAA Fisheries

CORALS IN ALASKA?

In 2020, NOAA launched a multi-year research initiative to study deep-sea coral and sponge communities in Alaska waters. NOAA collaborated with an international group of researchers and resource managers to inform a science plan prioritizing the observation and collection of new information about deep-sea coral and sponge habitats. This research aims to help scientists learn how natural processes and human activities such as fishing, affect these communities.

EXPLORING "UNDERWATER MOUNTAINS"

Since then, NOAA and partners have made great progress collecting valuable observations and data to improve models of deep-sea coral and sponge habitats in three major regions of Alaska—the eastern Bering Sea, Aleutian Islands and Gulf of Alaska. They have also explored and characterized several unmapped deep seamounts in the Northeast Pacific along the coast of British Columbia from Washington to Alaska. Seamounts result from marine volcanic hotspots in which magma from Earth's mantle rises and cools when it hits ocean water, forming "underwater mountain" structures. The variability in habitat structure in an otherwise monotonous seafloor provides increased biodiversity, making it an important area to explore. Additionally, scientists are working to better understand the geological connections and potential distribution pathways for corals and sponges along the seamount chain extending from the Aleutian Islands to the Pacific Northwest.



An otherwise bare rock face populated with corals creating vertical structure to this habitat. Warwick Seamount, depth approximately 1,738 feet. Credit: NOAA Fisheries

DIVING DEEP: DROP CAMERAS AND DNA UNLOCK MYSTERIES OF DEEP-SEA HABITATS

Scientists at NOAA found ways to increase sampling coverage while minimizing the environmental impact and cost of fisheries research through the use of innovative stereo drop-camera technology and environmental DNA sampling. The stereo camera system, submerged in the water hanging below the vessel, captures imagery, reconstructing the 3D environment. Scientists use the images to identify species, count animals in a certain area, measure animal size, determine distances between animals, measure their height off the seafloor, and learn how close other animals are to particular species of coral or sponge. Environmental DNA samples complement visual observations but also help detect rare or cryptic species that might be present but were unable to be observed with visual samples. The combined observations are being used to improve models for coral and sponge distributions and inform ecosystem-based fisheries management decisions such as where fishing closures can be most effective at protecting vulnerable habitats like dense and diverse coral and sponge communities.

Deploying the stereo camera system over the starboard side of the Canadian Coast Guard vessel *John P. Tully*. Credit: NOAA Fisheries/Paul Hillman

2.3 RESEARCH CRUISE EXPANDS OBSERVATIONS WITH ENVIRONMENTAL DNA SAMPLING

NOAA ship *Ronald H. Brown* at sea. Credit: NOAA

In March 2023, NOAA and international partners set out aboard the NOAA Ship *Ronald H. Brown* on a 55-day research cruise from Suape, Brazil to Reykjavik, Iceland, to study the Atlantic Ocean basin. Scientists made important observations to understand how the warming ocean impacts movement of ocean water across the entire planet, influencing our climate, and the health of marine ecosystems. For the first time on the A16N GO-SHIP research cruise track (a transect that gets sampled every 10 years) scientists collected environmental DNA along with other important biological measurements.

Widespread shifts in nutrients such as nitrogen, phosphorus, and iron uniquely shape diversity, distribution, and functioning of marine life and biogeochemical cycles in the Atlantic Ocean. Data collected from this cruise helps track the biological changes of the Atlantic Ocean, and increases our general understanding of the diverse life inhabiting this ocean. Other measurements along the A16N cruise track included heat, freshwater, carbon, oxygen, and nutrients taken from the ocean's surface to the seafloor, at depths greater than three miles in some cases. Additionally, cruises like this one provide a critical platform for testing, launching, and calibrating ocean observing technologies that will support improved models and enable a more holistic understanding of the ocean environment.

2.4 NOAA DIVES IN TO UNDERSTAND HOW MARINE SPECIES ARE RESPONDING TO A CHANGING OCEAN

Climate change is affecting the distribution of marine species in many areas across the globe, resulting in species moving outside of their usual boundaries to find food and environmental conditions suitable for survival. Food webs, made up of interconnected food chains, help us understand who eats whom in an ecological community. Changes to ecosystems such as shifts in the availability of prey, predators, or the addition of nutrients can affect different species directly or indirectly. Changes in aquatic food webs and ecosystems can have large-scale impacts on species that are valuable food sources for humans, contribute to commercial and recreational fishing, and support other areas of the U.S. economy.

HOW'S THE DIET? DNA ANALYSIS PROVIDES CLUES IN MARINE FOOD WEB DYNAMICS IN THE CENTRAL NORTH PACIFIC

With the help of innovative DNA technology, NOAA scientists are getting a closer look at the diets of marine species across food webs, from prey to predators, in the Central North Pacific. Scientists analyzed short sequences of DNA from the stomach contents of different fish and compared them with a reference library of known species–an approach called "DNA metabarcoding." This information combined with traditional diet analysis from stomach contents helps scientists better understand diets of top predators (bigeye tuna, swordfish, mahi-mahi) and forage fish such as midwater lanternfishes.

With climate change, species distribution shifts are expected, which in turn affect food availability, leading to further changes in species distributions. This is important to consider as distributions of commercially important fish such as tunas and billfishes will be impacted by changes in phytoplankton, zooplankton, and forage species distributions that provide food sources for them. Understanding the ecological links between prey and predators is crucial for supporting climate-ready fisheries. NOAA's research will help inform changes in pelagic food webs, estimates of prey and predator distributions, and ecosystem modeling of a changing climate in the Central North Pacific.

NOAA'S NEW INTEGRATED MODEL SUPPORTS CLIMATE-READY STRATEGIES TO MANAGE CHALLENGES FOR WEST COAST FISHING COMMUNITIES

As part of a new climate, ecosystems, and fisheries initiative, NOAA is collaborating with a diverse group of partners on a pilot project to link high-resolution ocean models of the California Current System with ecological and social models to assess options for climate-ready management strategies. The range of sardines, swordfish, and albacore tuna off the West Coast will shift north in coming decades as climate warming moves their habitat in that direction. Another recently published study by NOAA and partners revealed through analysis of archived eDNA spanning a 23 years time series, major changes in fish assemblages in the California Current Large Marine Ecosystem during and after the 2014–2016 Pacific Marine Heatwave.

Models simulating future conditions show that increasing sea surface temperatures will change ecosystems in unprecedented ways with one of the main drivers being the redistribution of species in coastal waters. That will influence fishery dynamics including openings and closures, catch allocations, and the ports where fishing fleets are based. The new analysis shows that ecologically and economically valuable species of sardines, swordfish, and albacore tuna, will shift north towards the pole and colder waters with impacts on local ecosystems and fishing fleets. This is especially challenging for smaller vessels that rely on local species like albacore tuna and have less flexibility to travel long distances to find other fish. These analyses will help deliver on the NOAA's Climate Science Strategy and support long-term projections of how climate change will affect fisheries, which fisheries and communities may be most vulnerable, and which are most resilient. This information is crucial to help identify climate-ready management strategies and overcome challenges.

In 2022, commercial landings of Pacific albacore tuna totaled 16 million pounds and were valued at $36 million, according to the NOAA Fisheries commercial fishing landings database. The majority of Pacific albacore tuna is landed in Washington and Oregon. Future climate-driven distribution shifts are likely for albacore tuna, moving from a warmer ocean to northern waters along the U.S. and Canadian west coasts. Credit: NOAA Fisheries

MAKING DAILY PREDICTIONS FOR WEST COAST TOP PREDATORS DURING CHANGING OCEAN CONDITIONS

The largest and warmest marine heatwaves on record have occurred in the last decade with cascading effects on marine ecosystems. NOAA scientists are working to predict how top predators living in ocean ecosystems will respond. Top predators have ecological,

cultural and economic significance and play a crucial role in supporting commercial fisheries. Understanding how they move during marine heatwaves can help managers adapt and be proactive with climate-ready strategies. A new study found that marine heatwave impacts on top predators such as sharks, tuna, and mammals vary widely, and can redistribute species across international boundaries. Scientists developed models that track ocean temperatures and other environmental factors to make daily predictions of how top predators shift during marine heatwaves and other environmental conditions affecting the U.S. West Coast. These predictions can provide an early warning system for fisheries and other marine resource ocean managers, alerting them to ecological changes affecting these valuable marine ecosystems.

NOAA'S UPGRADED DATA VISUALIZATION TOOL SHOWS NEW SHIFTS IN COD AND POLLOCK IN THE NORTHERN BERING SEA

Newly launched in 2022, NOAA's Distribution Mapping and Analysis Portal (DisMAP), has now undergone important upgrades in 2023 including additional years of data, new filtering features, and data from a new region—the Northern Bering Sea. DisMAP provides public access to information to track and understand distributions of marine species and is instrumental in visualizing population shifts related to climate change. Through data integration from various surveys, including NOAA Fisheries bottom trawls, DisMAP can now be used to see important shifts in cod and pollock populations and other species in the Northern Bering Sea, a region experiencing major effects from climate change. Decreases in winter sea ice production, related to climate change, has lessened the "cold pool" extent that occurs in the Eastern Bering Sea during the summer months. With less of a cold pool barrier between the Eastern and Northern Bering Seas, cod and pollock have likely been able to move farther north than they normally would. As climate change continues to impact ocean conditions and large-scale shifts in many marine species populations searching for their preferred environmental conditions, (e.g. temperature), DisMAP can help fisheries managers and the fishing industry better plan and respond to these changes.

SCIENTISTS CAN PREDICT TRAITS FOR ALL FISH WORLDWIDE FOR THE FIRST TIME

Scientists have developed a new model that can now predict growth, survival, and reproductive strategies for all known fish in the world. Different species have different strategies to survive and the combination of traits they have to adapt to their environment make up their life history strategy. The new model uses 33 traits—describing size, growth, reproduction, parental care, lifespan and more— to classify more than 34,000 fish species among three dominant life history strategies. Evolutionary information and data from well-studied species are incorporated into the model to predict strategies for data-poor species. The predictions of this model will inform ecosystem-based fisheries management, help forecast consequences of climate change, and advance our understanding of evolutionary relationships.

NOAA SCIENTISTS, PARTNERS, AND ANGLERS WORK TOGETHER TO SOLVE A SALMON MYSTERY

NOAA led a multi-agency team of scientists and resource managers to monitor, detect, and mitigate the negative impacts of thiamine (vitamin B1) deficiency on California's salmon

and steelhead. Based on the team's findings, several actions have been taken to reduce threats of this newly emerged stressor on California's endangered winter run Chinook salmon. Thiamine Deficiency Complex (TDC), which is a nutritional deficiency of thiamine, was first linked with high mortality of juvenile Chinook salmon in California's Central Valley hatcheries in 2020. Thiamine deficiency in marine systems is recognized as a globally-significant emerging threat to marine life.

Scientists initiated a survey to monitor salmon eggs and detect thiamine deficiency. Scientists also teamed up with anglers to collect parts of salmon (head, stomach, eggs) caught off the coast of California to better understand what the fish were eating, what might have caused the deficiency, and how to remedy it. These observations helped scientists demonstrate effective methods to prevent mortality of young salmon and predict impacts on young salmon and returning adults. Gut content analysis found that northern anchovy were the dominant prey item for Chinook salmon captured in California's ocean fisheries from 2020-2022. High abundances of northern anchovy off central and southern California have been observed in recent years with the highest in 2021. Anchovy contains an enzyme that breaks down thiamine that may have contributed to the deficiency in the salmon studied. Research suggests that California's salmonids are likely to remain at risk of TDC as long as their forage-base is dominated by northern anchovy.

In recent years anchovy have dominated salmon diets, with fishermen finding salmon stomachs almost entirely full of anchovy, as shown. Credit: John Field/NOAA Fisheries, Southwest Fisheries Science Center

2.5 IMPROVING TECHNOLOGY FOR FUTURE AND SUSTAINABLE USE OF FISHERIES AND MARINE RESOURCES

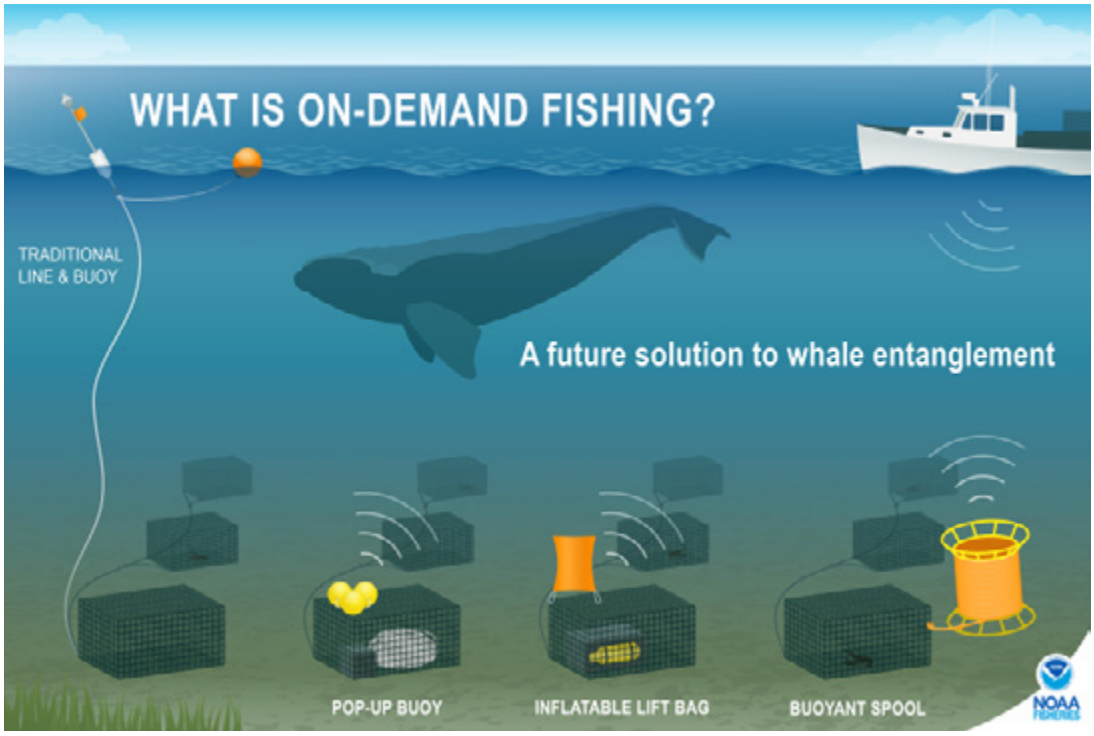
Ocean observations, predictions, and models help us better understand what is in the ocean, how the ocean works, and how it is changing. This important information informs decision-making and strategies to manage these valuable resources in ways that are sustainable through a changing climate and ocean. NOAA is taking steps to better protect marine resources and sustainably use them to benefit the Nation for years to come.

NOAA IS FINDING BETTER WAYS TO FISH: TESTING ROPELESS LOBSTER FISHING GEAR TO DECREASE RISKS TO WHALES

NOAA is studying how climate related impacts of warmer temperatures and more acidic oceans are affecting the reproduction of American lobsters in the Gulf of Maine and surrounding areas. The American lobster supports one of the largest and most economically valuable single-species fisheries in the U.S., but its ocean habitat is changing drastically. The results of this research will support the goal of increasing the American lobster industry's resilience to the biological, economic, and social impacts of ecosystem change.

NOAA is also testing out better ways to use on-demand, ropeless gear to fish for lobster that will present less risks to the marine ecosystem. NOAA has a gear library

consisting of approximately 400 systems from nine manufacturers with potential to grow. Fishermen are able to use this library to identify problems with the gear, identify which type of system is preferred by individual fishers, and to help familiarize the operation and utilization of on-demand gear. Presently, NOAA is working with 45 fishermen to trial this gear. In addition, NOAA collaborated with fishermen in the commercial trap/pot fishery to complete 2023 Northeast Experimental On-Demand Gear System Trials in both state and federal waters that were closed to fishing with static vertical lines. Participants completed over 500 hauls in several restricted areas as part of the gear trials and development. On-demand gear systems remove the vertical line in the water column to reduce the risk of large whale entanglement in American lobster and Jonah crab fisheries. NOAA continues to work with the Atlantic States Marine Fisheries Commission, state fisheries agencies, the fishing industry, and other partners on a number of initiatives to innovate, demonstrate and accelerate opportunities around on-demand fishing and expand the scope and effectiveness of on-demand fishing gear.



On-demand, also called “ropeless”, systems use far less rope in the water than traditional gear designs. To locate and retrieve gear, traditional methods tether gear to a rope attached to a buoy at the water’s surface. The main characteristic of on-demand gear is that it does not need this gear-to-buoy tether. Credit: NOAA Fisheries

Audrey Gaudel, Yoshira Ornelas Van Horne, and Isabella Vicenza walk the streets of New York City in August 2023, taking detailed readings of air pollutants from a simple backpack. It's an effort the team hopes will provide residents of New York with the tools they need to fight for better air. Credit: Lauren Lipuma, University of Colorado/Cooperative Institute for Research in Environmental Sciences

3. BUILDING A CLIMATE READY NATION

If the summer of 2023 had a theme song, the 1980s hit, "Cruel Summer" would be it, telling the story of extreme heat–by land and sea, hazardous weather, and environmental events made worse by climate change.

Record breaking land and ocean temperatures, flooding, and poor air quality from wildfires were some of the main events triggering warnings to keep people indoors this past summer. Sea surface temperatures were so warm that 48% of the global ocean was experiencing marine heatwaves in August of 2023, coral reefs were bleaching, and many marine species were on the move searching for cooler waters. Overall in 2023, there have been 28 individual billion dollar weather and climate disasters in the U.S., which is a new record.

As outlined in the NOAA FY22-26 Strategic Plan, building a Climate Ready Nation is a key priority in which NOAA is helping to create a thriving nation whose prosperity, health, security and continued growth benefit from and depend upon a shared understanding of, and collective action to reduce the impacts of climate change. In 2023, NOAA made great strides in this area conducting critical research around climate-related impacts to corals, expanding forecasts of marine heatwaves, engaging communities in nationwide urban heat island mapping campaigns, and collaborating with partners on the Nation's largest-scale air quality research campaign to date, among other accomplishments.

What is the difference between weather, climate, and climate change?

Weather and climate describe the same thing—the state of the atmosphere—but at different time scales. Weather is the short-term state of the atmosphere in a particular place and time. Climate refers to the averages of weather data over time. Significant changes in climate over an

extended period of time are considered "climate change." High temperatures, heavy precipitation, increased flooding, drought, more frequently occurring large wildfires, retreating sea ice, and rising seas that are becoming increasingly acidic are some of the powerful side effects of climate change, impacting life on Earth.

If climate change is not addressed, more extreme weather and climate-related events will continue impacting global economies, human lives, and the overall health of the planet. Scientists at NOAA lead an international effort to observe, monitor, and better understand climate conditions around the globe. This science and knowledge is openly shared through the annual *State of the Climate* report and the *Fifth National Climate Assessment* (NCA5), unveiled at the White House. The NCA5, a congressionally-mandated report, provides a roadmap to a better future through science-based information, data, and real world examples of ways to reduce greenhouse gas pollution and develop resilience strategies. NOAA made significant contributions to the NCA5, including 35 authors and 13 chapter leaders, reflecting the agency's critical role in observing, predicting and working with communities to build resilience to the effects of climate change.

NOAA's research is crucial for identifying and understanding the impacts and risks associated with potential future climate intervention approaches powerful enough to offset climate change impacts. In 2020, in response to a congressional mandate, NOAA established a comprehensive research effort to investigate natural and human activities that might alter the reflectivity and radiative balance of the atmosphere and their potential impacts on Earth's climate system. In 2023, NOAA contributed to a congressionally mandated research plan to identify knowledge gaps and potential research areas for better understanding risks and benefits posed by solar radiation modification. NOAA also launched exciting research, sending a high-altitude aircraft into the polar stratosphere to collect detailed observations of gases and aerosols, and to better understand how our current atmosphere might respond to climate interventions.

Various techniques of removing carbon dioxide and greenhouse gases from the atmosphere and permanently securing them in reservoirs, such as the ocean, forests, soils, and geologic formations, are being researched for potential use in climate mitigation. In 2023, NOAA released a Carbon Dioxide Removal Strategy, outlining the feasibility and possible impacts of several carbon dioxide removal techniques, and potential research contributions. NOAA also monitored and tracked greenhouse gas levels from stations around the world, committing monitoring, modeling, and data analysis capabilities to support a government-wide effort to reduce greenhouse gas emissions.

Human activities and natural causes contribute to climate change. Human activities include the emission of heat-trapping greenhouse gases, such as carbon dioxide and methane, into the atmosphere and changes in land-use patterns, such as agriculture and urbanization. Natural causes range from regular shifts in the dynamics of our oceans and atmosphere, such as El Niño/ La Niña, to volcanic eruptions that release gases and aerosols in the atmosphere, to variations in the amount of energy from the Sun that reaches Earth.

"Global warming" usually refers to "human-caused warming" from the increase in heat-trapping pollutants, such as carbon dioxide and greenhouse gases added from humans to the atmosphere, primarily by burning fossil fuels. Recent and ongoing rises in Earth's land surface and ocean global average temperatures is

one symptom of overall climate change. Carbon dioxide is being added at a much larger rate than it is removed by natural processes, creating a long-lived reservoir of gas in the atmosphere and oceans, leading to a warmer climate and unprecedented changes to the planet.

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Glacial silt pictured in Glacier Bay National Park, 2022. The natural addition of glacial silt colors coastal waters and is a potential analog for ocean alkalinity enhancement, a Carbon Dioxide Removal technique, as it increases the alkalinity in the marine environment. Increasing ocean alkalinity shifts natural air-sea CO2 exchanges in favor of enhanced ocean storage. Credit: Marina May, University of Washington / NOAA

3.1 OUR CARBON FOOTPRINT IS LEAVING A MARK ON CORALS

Greenhouse gases that have trapped and contributed to extreme heat on land, also affect the ocean. The ocean interacts with the atmosphere and absorbs about 30% of atmospheric carbon dioxide emitted from human activities. While the ocean plays a vital role as a "carbon sink," this "service" doesn't come without a "cost," resulting in chemical changes to the water, making the ocean more acidic. Ocean acidification affects corals, oysters, and other calcifying organisms making it harder to build and maintain their shells and skeletons.

In order for coral reefs to grow, they need to generate calcium carbonate (the coral skeleton material), providing foundational structure for the reef to build upon, at a rate faster than the reef erodes. Ocean acidification slows coral's ability to make calcium carbonate, making it more difficult to develop the foundation it needs to sustain growth.

NOAA IS IMPROVING PREDICTIONS FOR FUTURE CORAL REEF CONDITIONS IN A CHANGING OCEAN

Scientists at NOAA have now operationalized a census-based carbonate budget survey for assessing and quantifying the net rate of carbonate production within coral reef environments in the Pacific. How a reef persists through time based on how much reef material is produced compared to how much is being eroded determines the net rate of carbonate production. This survey is being used with other existing assessments and linked with co-located biogeochemical and ecological data to improve the modeling and predictions of future coral reef conditions. With a better understanding of how coral reefs are responding to a changing ocean, potential management solutions can be evaluated for future climate change scenarios that affect marine ecosystems and fisheries.

WHY ARE CORAL REEFS SUCH A BIG DEAL?

Coral reefs are some of the most diverse and valuable ecosystems on Earth, providing $3.4 Billion in economic value to the U.S. per year in services that include coastal storm protection, supporting fisheries, recreation, and tourism. Healthy coral reefs act as barriers, buffering coastlines from 97% of wave energy, helping to prevent loss of human life, property damage, and erosion. Fisheries depend on coral reefs for habitat and about 25% of all marine species utilize coral reefs at some point in their life cycle. Impacts of climate change, such as more extreme marine heatwaves, ocean acidification, and bleaching events are all major threats to these ecosystems.

Ian Enochs, Ph.D., Research Ecologist and head of NOAA Atlantic Oceanographic and Meteorological Laboratory's coral program, surveyed Cheeca Rocks corals on July 31, 2023 and found it severely bleached. Cheeca Rocks Sanctuary Preservation Area is located within the Florida Keys National Marine Sanctuary. Credit: NOAA

SURGING OCEAN TEMPERATURES ARE "COOKING" CORALS

In the Atlantic Ocean, the Florida Coral Reef, the only living coral barrier reef system in the continental U.S., has undergone dramatic decline since the 1970s due to impacts of

warming waters and climate change. Coral bleaching events due to ocean warming have become more frequent and severe. Eight mass bleaching events have impacted the Florida Keys since 1987. When corals are exposed to water that is too warm for an extended period of time, they become stressed and expel the algae living inside them that generate their energy and give them color. This may leave the coral with a white or "bleached" appearance and can lead to starvation and death of the coral.

Research by NOAA and partners has found that 70% of Florida's coral reefs are eroding and experiencing a net loss in habitat. In addition to the concerning loss of coral cover, a marine heatwave began in waters around the Gulf of Mexico and South Florida between February and March 2023, causing record-breaking sea surface temperatures around South Florida, resulting in coral bleaching. These sustained periods of unusually warm ocean temperatures called "marine heatwaves" occur naturally but are becoming more frequent and extreme due to climate change.

3.2 NOAA GETS AHEAD OF MARINE HEATWAVES: NEW FORECAST AND PREDICTIONS PROVIDE EARLY WARNINGS

NOAA has developed a new experimental forecast to predict marine heatwaves globally. In recent decades the ocean has absorbed an estimated 90% of excess heat associated with global warming. A warming ocean, made even warmer during a marine heatwave, impacts fragile marine ecosystems that are already under stress. Prolonged periods ranging from weeks to years of unusually warm waters can cause mass die-offs of fish, marine mammals, and seabirds. Marine heatwaves can also disrupt food webs and fisheries, bleach corals, and prompt harmful algal blooms in and around coastal waters and oceans across the Nation. One such example occurred along the coast of the U.S. Pacific Northwest from 2013-2016 known as the three-year "Blob" extreme heat event that devastated fisheries and disrupted marine populations.

3.3 HOPE FOR CORALS IN UNLIKELY PLACES

With the many challenges climate change brings, there is hope for corals. Scientists at NOAA collaborated with partners in a new study and found that corals are living and persisting in "tough" conditions in an urbanized environment near the Port of Miami. The Port of Miami includes a busy waterway with active coastal development, as well as a high volume of commercial shipping and recreational boating activity. Challenging water conditions in this area include poor water quality, excess nutrients, extreme temperatures, low salinity, and acidification that can be more extreme than conditions in the open ocean.

A knobby brain coral is pictured growing on the limestone boulder riprap at the Port of Miami exposed to the elements at low tide. This site is near NOAA's Coral Urban Research Experimental Site and the Coral City Camera where NOAA scientists are working to unlock the secret to the resilience of these corals. Credit: Colin Foord, Coral Morphologic

Scientists used underwater camera technology to observe strong and diverse coral communities living on man-made materials, such as seawalls and discarded objects. Scientists visited the Port of Miami over a three-year period to monitor environmental conditions and measure coral community dynamics. The team used a suite of state-of-the-art instruments that included sub-surface automated samplers and coral photomosaics, to characterize their coral cover, spread, and species diversity.

These observations are surprising and indicate that there may be genetic and molecular mechanisms of resilience at play, as the stressors that these corals are experiencing are harming reefs world-wide. The interaction between the environment and genetics of the coral species and algae living inside them may play a role in their persistence to survive.

Scientists at NOAA are presently using molecular techniques to examine the underlying resilience mechanisms of these corals, and evaluating their unique capabilities in the Experimental Reef Lab. Studying and identifying resilient coral reefs inform restoration efforts, risk assessment, and conservation and stewardship of these essential habitats. This exciting research provides hope that with suitable stewardship strategies in place, threatened corals may be able to coexist in environments that are changing and impacted by natural and human-caused stressors.

NOAA'S LANDMARK RESEARCH REVEALS OCEAN'S CAPACITY TO STORE CARBON IS WEAKENING

In 2023, scientists at NOAA published a study indicating that the ocean's ability to store human-caused carbon dioxide may be weakening. This knowledge is critical for planning efforts to reduce greenhouse gas emissions. If the ocean is absorbing a smaller proportion of carbon dioxide, then more will be left over in the atmosphere and on land, exacerbating climate change and impacts such as extreme heat, storms, and air pollution. Larger reductions in emissions will be needed to account for the ocean's decreased capacity to absorb carbon dioxide and buffer against future global climate change. NOAA's research is crucial for anticipating the impacts of heat-trapping atmospheric carbon and informing decisions about emission reduction solutions.

3.4 THE HEAT IS ON!...LAND AND IN THE AIR

While marine heatwaves swept through the ocean in 2023, the Nation also experienced extreme heat on land. 2023 had the hottest summer on record with the June–August global surface temperature reaching 2.07°F above the 20th-century average of 60.1°F, ranking as the warmest June-August period in the 174-year record. Global marine heatwaves and El Niño contributed to additional warming in an already warming climate.

Besides making us sweat, extreme heat can be deadly and is the leading weather-killer in the U.S. It also contributes to dangerous heatwaves, drought, wildfires, and extreme precipitation. The ocean and atmosphere exchange heat back and forth and humidity can make temperatures feel brutally warmer than they actually are. Urban communities can become "urban heat islands" that are significantly warmer than surrounding areas with more plant cover. In June 2023, Texas, the southern U.S. and Mexico experienced a deadly heatwave lasting three weeks. Within the same month, wildfires burning in Canada had far reaching impacts, leading to dangerous air quality across many states along the U.S. East Coast. Heatwaves are expected to become more frequent and extreme with climate change. NOAA has been working

around the clock to monitor, predict, and provide warnings for extreme heat events.

After more than 10 years of research, NOAA has developed the Global Land Surface Temperature Anomaly analysis using real-time NOAA satellites. With this system, NOAA supports a climate-ready nation by providing public monthly reports identifying land surface temperature changes that are significantly different from average readings. Trapped heat and warming from greenhouse gases contribute to the energy stored at Earth's surface. Land surface temperature is a key indicator of Earth's surface energy. Excess energy and significant changes in average land surface temperature can impact vegetation and crop productivity, as well as exacerbate events like heatwaves which pose health-risks for many Americans. NOAA's monthly reports and analysis of temperature changes help the Nation better prepare for the impacts of extreme temperatures on drought, agriculture, wildfire management, water use, energy management, human health, and other impacts.

In addition to understanding climate trends on a global and national scale, NOAA is committed to better understanding the impacts of weather and climate at a local level. Emissions from vehicles, heat-trapping buildings, and other sources in urban areas can cause big differences in temperatures from one neighborhood to the next. These differences present challenges for urban communities and impact how each community should prepare. NOAA's R&D efforts are critical to reducing the societal impacts of a warming climate.

NOAA EMPOWERS THE PUBLIC IN SCIENTIFIC EFFORTS ADDRESSING HEAT INEQUITIES IN URBAN COMMUNITIES

During the 2023 summer, NOAA harnessed the power of the public to participate with scientists in mapping the hottest parts of 18 communities in 14 states across the U.S. and in one international city, Santiago, Chile. U.S. communities included Chicago, Salt Lake City, Dallas, Asheville, NC; and Scranton, PA just to name a few. Identifying these hotspots, called "urban heat islands", helps local decision-makers take actions to reduce the health impacts of extreme heat.

Urban areas with a lack of vegetation, heat absorbing surfaces, and heat trapping buildings can become "urban heat islands" that are 15°F to 20°F warmer than surrounding areas with more trees and foliage. Residents in these city hotspots are more likely to experience heat-related illnesses and even death, along with worse air quality and a higher cost burden of air conditioning bills. Heat island inequities disproportionately affect low income populations and populations of people of color often living in the areas of the city most susceptible to the urban heat island effect.

Kyra Woods, Policy Advisor for the city of Chicago, hands out sensors that volunteers will attach to their cars to collect data along established routes in the city. The sensor records temperature, humidity and location every second. The data are then used to create a detailed map of urban heat pockets in the city. This work is part of the National Integrated Heat Health Information System. Credit: 2023 Chicago Urban Heat Island Mapping Campaign

Local partners in each participating city led volunteers from the public or "citizen scientists" to move through their neighborhoods in the morning, afternoon, and evening on one of the hottest days of the year with heat sensors

mounted on their own cars and bikes. The sensors recorded temperature, humidity, time and the volunteers' location every second.

The heat island maps and visualization tools will help inform equitable cooling solutions for the participating communities. Cities from past campaigns have already put their heat island maps to use, implementing tree planting strategies, informing the public of where to find transit shelters for cooling relief, and making heat action plans. Urban Heat Island Mapping Campaign data are open access and available on the federal website Heat.gov.

NOAA IMPROVES CLIMATE MODELS AND FORECASTS TO BETTER PREPARE FOR EXTREME PRECIPITATION

A warmer climate doesn't only lead to extreme temperatures, but can also fuel extreme precipitation. Heat trapping carbon emissions warm the atmosphere, allowing it to hold and eventually release more water. Major storms that battered California and parts of the U.S. West Coast in December 2022-January 2023, showed the need for forecasters to have better technology and more detailed information to help communities with decisions regarding storm preparedness, infrastructure operations, resource allocations, and public safety.

Standard weather radars are limited and don't provide the full picture of what is happening above California's coastal mountain ranges, where precipitation can be heaviest. A series of atmospheric rivers — long narrow regions in the atmosphere that transport water vapor — fueled the storms that battered the West Coast during the winter of 2022 and into 2023. Atmospheric rivers are naturally occurring events, but as a result of climate change, have led to more extreme precipitation along the West Coast.

In 2023, NOAA's Advanced Quantitative Precipitation Information (AQPI) project led to better predictions of two big atmospheric river events that affected the San Francisco Area. For this project, NOAA is developing a network of advanced weather radars and new surface meteorology stations along the West Coast that will feed into numerous meteorological and hydrologic models used by NOAA and U.S. Geological Survey. AQPI helps fill observational gaps by improving monitoring and forecasts of precipitation, streamflow, and coastal flooding in the San Francisco Bay Area. NOAA is also in the process of developing multi-seasonal atmospheric river frequency forecasts for longer-term preparation for water resources.

NOAA-FUNDED RESEARCH INSPIRES ACTION: LOS ANGELES USES FLOOD RISK FINDINGS TO ADDRESS INEQUITIES AND STORMWATER SYSTEM

NOAA supported impactful research that provided evidence and transparency around flood risks and inequities in Los Angeles, leading to the county's prompt action to improve planning for flood mitigation systems. The study examined a more comprehensive range of flood risk factors than ever before, quantifying the magnitude of flood risk and characterization of populations impacted within a 100-year flood zone in Los Angeles.

The study found that between 197,000 and 874,000 people and between $36 and $108 billion in property value would be exposed to more than 12 inches of flooding within the 100-year flood zone. This represents a flood risk level as severe as some of the most damaging hurricanes in U.S. history. Risks were disproportionately higher for some populations and communities burdened by greater challenges recovering, reinforcing

socioeconomic inequities.

Six weeks after the study was published, the Los Angeles County Board of Supervisors referenced the study's findings in a motion to assess and address inequities in its stormwater infrastructure and system. The motion was immediately and unanimously adopted. This research is a testament to the power of open science and NOAA's efforts to help transparently and equitably reduce flood risks, save lives, and protect property.

3.5 TEMPERATURES ARE BLAZING AND SO ARE FIRES: OBSERVING, MODELING, FORECASTING AIR QUALITY IN A WARMING CLIMATE

Rum Creek fire near Merlin, Oregon in August, 2022. Credit: Robert Hyatt, NOAA's National Weather Service

Climate change is exacerbating the frequency and intensity of extreme heat, drought, and wildfires, contributing to impacts on the air we breathe. Wildfires are spreading across larger areas and becoming more severe in recent years, with many blazing out of control during dry conditions of drought and extreme heat. These fires pose a serious risk to life and property, causing destruction and the release of dangerous pollutants into the air and environment. Small particles and gases make up smoke and can impair lung and cardiovascular function and have severe health impacts when breathed in. Many urban areas are already at a tipping point when it comes to local pollution and poor air quality. Smoke from wildfires are making air quality even worse, pushing many cities out of compliance for federal ozone and air quality standards.

The impacts of wildfire smoke in the U.S. have largely affected the western and mid-western states, where residents have suffered very high levels of pollution. More recently, the effects of wildfire smoke have spread to the eastern U.S., no longer spared from the hazy skies and smoky air that the western U.S. has endured.

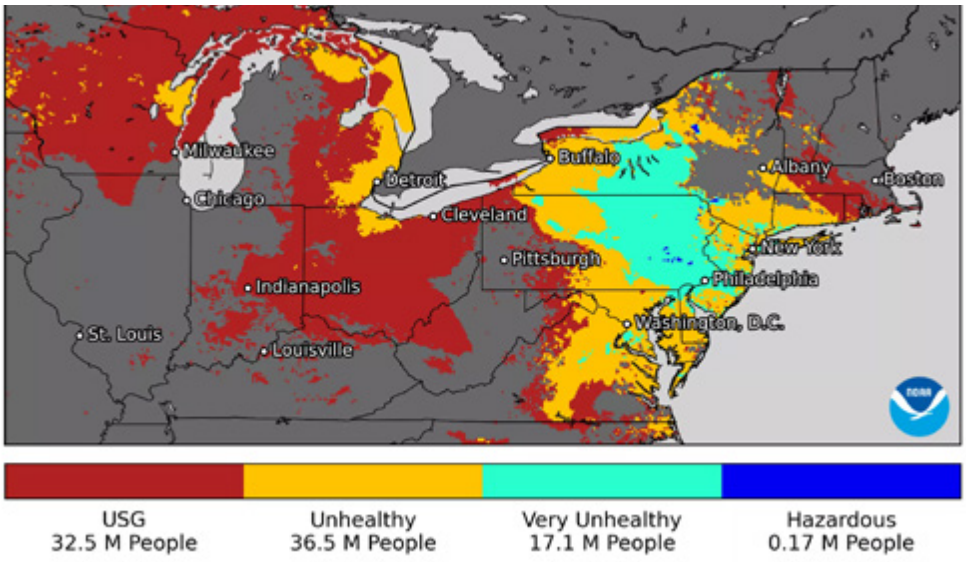
A smoke-filled New York City skyline is pictured in June 2023. Credit: Ahmer Kalam on Unsplash

NOAA SATELLITES PROVIDE CRITICAL DATA TO WARN THE NATION OF HARMFUL SMOKE AND AIR QUALITY

When wildfires burned in Quebec, Canada sending billowing plumes of smoke over the eastern U.S. in June 2023, NOAA's observations provided critical data for air quality forecasters, informing air quality alerts to protect public health. Instruments used on NOAA satellites collect visible and infrared images and global observations of the Earth systems. These data allowed scientists at NOAA to estimate that more than 86 million people experienced fine particulate pollution levels higher than the federal health standard.

NOAA satellite observations of wildland fires provide critical input to forecast models on fire locations and the amount of smoke and other pollutants emitted by wildfires that impact air quality downwind. Operational air quality forecast models use these satellite observations as input to predict the impact of wildfires on air quality. Fine particulate pollution data, observed with NOAA's geostationary satellites, are now used in short-term forecasts up to six hours out called "nowcasting." State and local forecasters use this information to inform decisions to issue air quality alerts to states and 360 cities and counties nationwide to help protect people from harmful exposure to smoky air. Air quality forecasts and current nowcast observations are available on AirNow.gov.

Satellite resources, such as NOAA's AerosolWatch website, provide operationally critical, real-time information on smoke content in the atmosphere and vital lead time for communicating warnings and impending impacts to air quality for the public. NOAA's smoke forecasting models predict the transport of wildfire smoke and the smoke's impact on weather and visibility over the U.S. NOAA has also established a new fire weather testbed to evaluate a wide range of experimental fire weather products and services, aiming to accelerate their transition for use by operational fire weather forecasters, their partners, decision makers, and stakeholders, and guide future research.



Millions (M) of people in the U.S. were exposed to harmful particulate pollution on June 3-10, 2023, broken down by Air Quality Index level, estimated from measurements of aerosol optical depth made by NOAA's Visible Infrared Imaging Radiometer Suite on NOAA satellites; gray indicates regions not impacted or no data. "Unhealthy for Sensitive Groups" (USG) includes children, senior citizens, and people with respiratory and/or cardiovascular diseases. Regions in Canada were not part of the analysis. Credit: NOAA

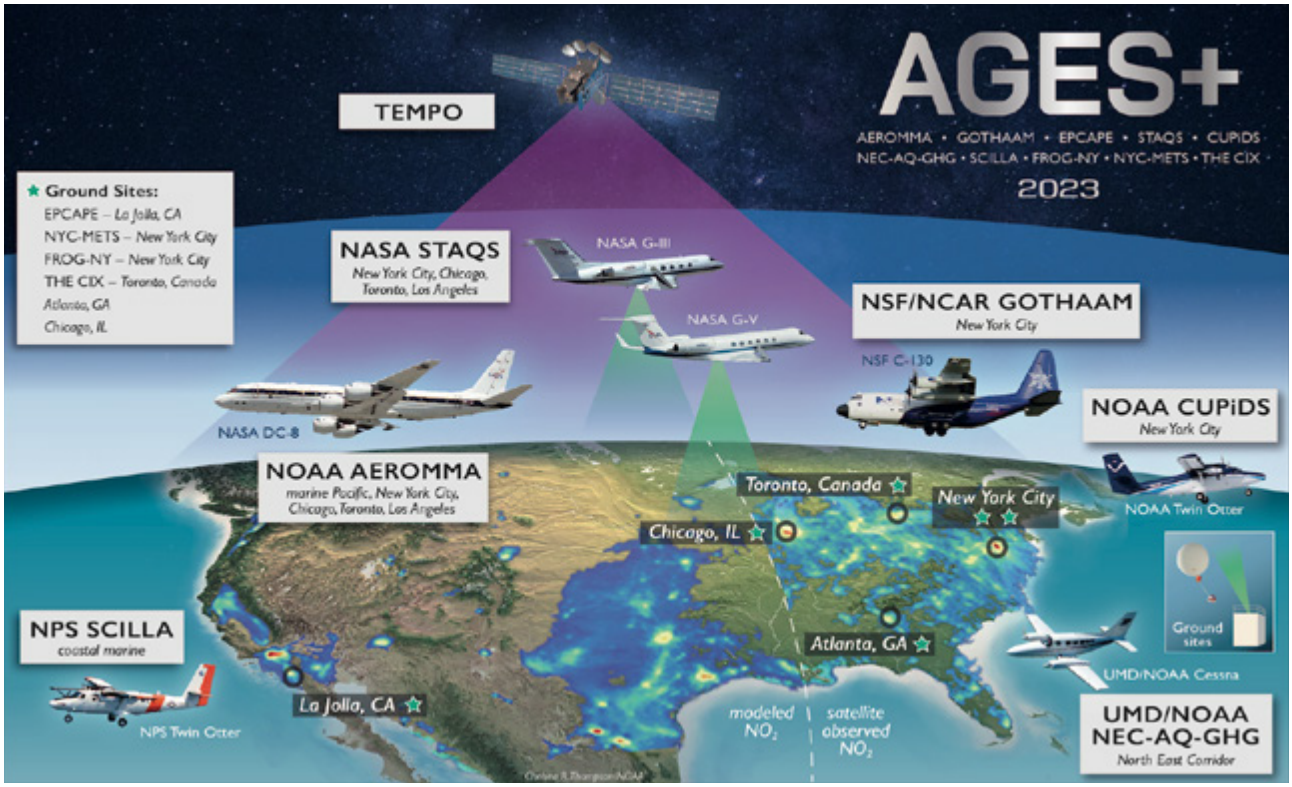
NOAA AND PARTNERS LEAD LARGEST AIR QUALITY RESEARCH CAMPAIGN YET

Air quality in major U.S. cities remains a significant public health threat and the effects of climate change and extreme heat can exacerbate the impacts of air pollution. NOAA, NASA, and other partners from numerous academic institutions and agencies embarked on a massive air quality research campaign during the summer of 2023 to help reduce air pollution. This effort impacts the entire Nation, especially urban areas where over 80% of the American population live.

Scientists from NOAA, NASA and 21 universities from three countries deployed state-of-the-art instruments in multiple, coordinated research campaigns to investigate how air pollution sources have shifted over recent decades. Using multiple satellites, research aircraft, vehicles, dozens of stationary installations — even instrumented backpacks — scientists measured air pollution from sources of transportation, industrial facilities, agriculture, wildfires and consumer products such as paint, pesticides and perfumes.

Scientists at NOAA and partnering agencies analyzed and ran the data through chemical and weather models to improve air pollution forecasts. NOAA will share research findings with state and local environmental officials to inform decisions about the most effective ways to reduce air pollution and protect public health.

> "This is an unprecedented scientific investigation — in scope, scale and sophistication — of an ongoing public health threat that kills people every year," said NOAA Administrator Rick Spinrad, Ph.D. "No one agency or university could do anything like this alone."



NOAA collaborated with several partners to conduct multiple, coordinated research campaigns investigating how air pollution sources have shifted over recent decades. Learn more about the 2023 AGES+ coordinated field activities at the project page. GOTHAAM was rescheduled to 2025. Image Credit: Chelsea Thompson/NOAA

The high-altitude operational return unmanned system (HORUS) glider and balloon prepared for a test flight on May 17, 2023 in Colorado's Pawnee National Grasslands. Credit: NOAA

4. A ROBUST AND EFFECTIVE R&D ENTERPRISE

NOAA supports a robust and effective R&D enterprise by continuously improving and advancing observations, models, forecasts, and the application and transition of research to help improve real-world issues affecting the Nation. Emerging fields such as AI, uncrewed systems, and other science and technology areas are accelerating and optimizing the use of economic, social science, physical, and ecological data for NOAA's R&D Enterprise. In 2023, NOAA leveraged AI to make beaches safer for swimmers through improved detection of rip currents, expanded forecasts for harmful algal blooms that affect public health, seafood, and recreation, and revolutionized the process for estimating fish age to better manage fisheries. NOAA also used satellites to gather critical space weather data to protect our technology-dependent society, uncrewed systems and other instruments to better assess tornado damage and collect observations that can help save lives, and used ice-tolerant robots to better understand ecosystems of the Great Lakes — just to name a few.

4.1 AN EVOLUTION OF AI

Just like new species of plants and animals evolve over long periods of time, AI has managed to do the same thing, but in a very short period of time. AI, although not a living, breathing organism, has undergone its own kind of "evolution" since its "birth" in the 1950's. AI

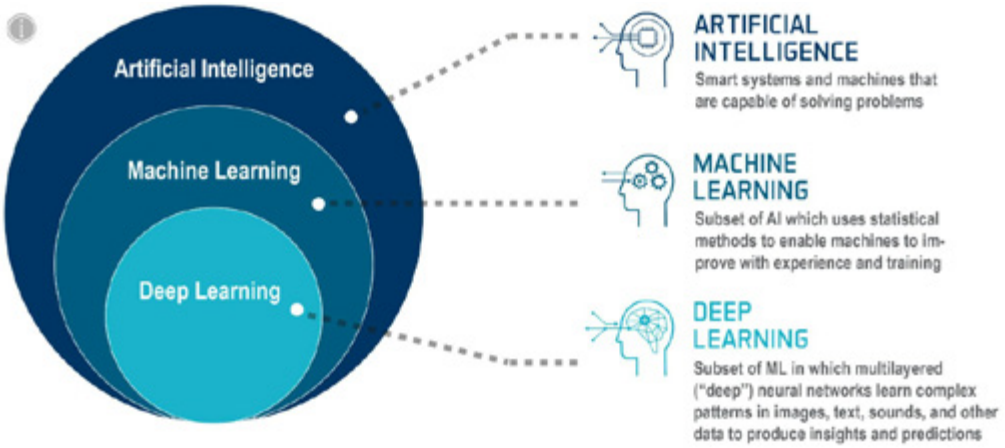
was once portrayed as a far-fetched futuristic technology, or a villainous power taking over humankind in sci-fi movies. Since then, times have changed and real-world AI capabilities have rapidly improved. Now in 2023, AI can be used to supplement scientific research to better understand the environment and our place in it. These advances in technology are now making research possible in places humans cannot safely access on their own and to efficiently analyze data and discern complex patterns beyond human capability.

NOAA has a long history of using AI and in the 1980s was one of the first organizations to use it to analyze satellite data and improve weather forecasting models. Since then, NOAA has continued to invest in R&D utilizing AI to improve accuracy and timeliness of weather and climate predictions, as well as to better understand the impacts of environmental changes on our planet.

In 2020, Congress passed the National AI Initiative Act, which formalized the mandate for NOAA's pioneering coordination of AI application across climate, ocean, Earth, and space sciences. NOAA has since established a Center for AI to support ongoing projects and to propel new uses of responsible AI technology to support environmental knowledge and study. The NOAA AI Strategic Plan 2021-2025 outlines the goals for expanding the application of AI across the agency to deliver improved performance and cost-effectiveness to support a better understanding of climate, weather, the ocean, and coasts.

The application of AI and machine learning (ML) has already helped advance NOAA's R&D with improved performance at greatly reduced costs and computational time. These exciting advancements are occurring in many areas spanning NOAA's mission, such as deep-sea exploration, habitat characterization, fisheries assessments, environmental modeling, and interpretation of Earth science observations. In 2023, NOAA continued to advance R&D through the use of AI, uncrewed systems, and other emerging technologies to help save lives and property and support NOAA's mission overall.

Artificial intelligence (AI) is the development of smart systems and machines that are task-oriented and capable of solving problems, such as recognizing speech, finding patterns, and making predictions based on data— sometimes better than humans can. The science of AI is dedicated to enabling machines to mimic human behavior with increased efficiency, precision, and objectivity. The goal of AI is not to replace the human element, but rather for humans and machines to work together to improve our environment.



Graphic explaining what artificial intelligence, machine learning, and deep learning are. Credit: NOAA National Centers for Environmental Information

In this image, green dye is used to visualize a rip current. Rip currents are powerful, narrow channels of fast-moving water that can move up to eight feet per second, which is even faster than an Olympic swimmer. Credit: NOAA National Ocean Service

4.2 USING MACHINE LEARNING TO DETECT AND VISUALIZE RIP CURRENTS

A relaxing swim at the beach can quickly become life-threatening in dangerous conditions. Rip currents are responsible for 80% of beach rescues and approximately 100 deaths in the U.S., annually. Rip currents are dangerous, strong currents that can drag beachgoers out to sea and are prevalent along the U.S. coastline and shores of the Great Lakes.

NOAA and partners have developed a new AI method to detect rip currents in low-cost coastal web camera video. This upgrade improves NOAA's national rip current forecast model, helping to better prepare lifeguards and warn swimmers when currents are dangerous, ultimately saving lives. The method combines ML with analysis of ocean water flow to detect when the path of water flow deviates from normal ocean flow in coastal areas. Using this detection method, rip currents can automatically be found and visualized from stationary webcam footage along the shoreline.

Validation of earlier versions of the rip current model relied solely on lifeguard observations, which are very useful and informative, but are also subjective, requiring supplemental validation. Low-cost shoreline web cameras provide a great alternative with their many locations and near-constant data streams. NOAA's new AI method and cutting-edge ML technology will help train and validate forecast models, supporting improved predictions of rip currents. Swimmers will be better warned when currents are dangerous, saving lives.

4.3 TINY TOXIC ALGAE, BIG BLOOMING PROBLEMS

If rough waters weren't enough to worry about at the beach, tiny plants making a toxic takeover of the water might be another. No need to fear, NOAA is here to investigate, detect, forecast, and help mitigate impacts of these toxic events — "harmful algal blooms" — that can close beaches, impact drinking water supplies, affect coastal recreation, and the Nation's seafood

supply.

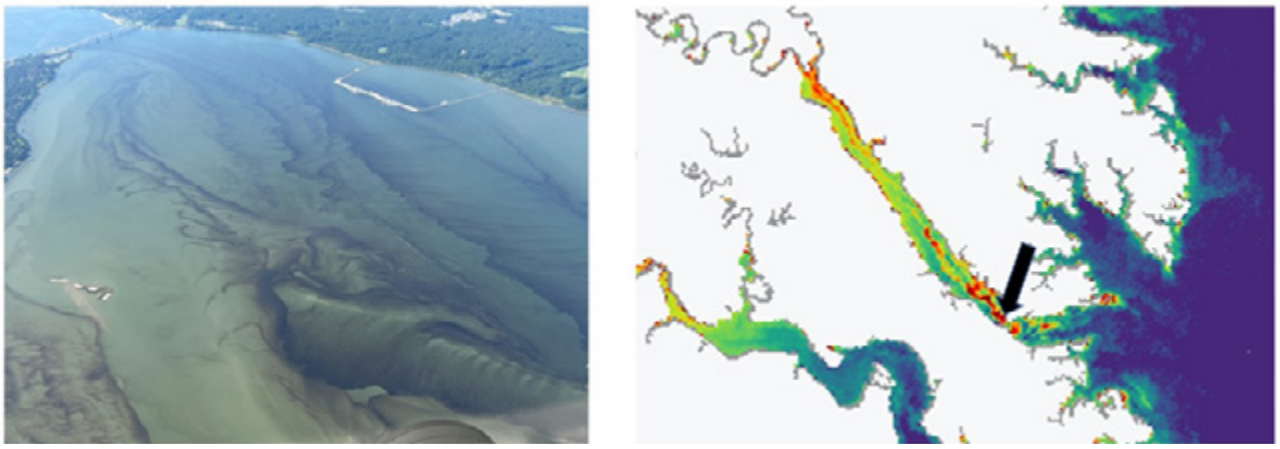
Harmful algal blooms occur when algae — simple plants that live in the sea and freshwater — grow out of control while producing sometimes toxic or harmful effects on people, fish, shellfish, marine mammals, and birds. Effects can be severe for coastal resources, local economies, and public health.

In 1998, Congress recognized the severity of these threats and authorized the Harmful Algal Bloom and Hypoxia Research and Control Act which was amended in 2004, 2014, and 2017 reaffirming and expanding the mandate for NOAA to advance the scientific understanding and ability to detect, monitor, assess, and predict harmful algal blooms and events of hypoxia (detrimentally low Oxygen levels in water). NOAA has made great progress leveraging AI with research to better understand what causes and sustains harmful algal blooms and develop tools, predictive models, forecasts, and prevention strategies. NOAA's research is crucial to help guide the management of coastal resources to reduce the development, impacts, and future threats of harmful algal blooms.

Razor clamming on Washington coast, October 20, 2021. Credit: Washington Department of Fish and Wildlife

NOAA HELPS DETERMINE THE ECONOMIC IMPACT OF HARMFUL ALGAL BLOOMS AND THE VALUE IN FORECASTING THEM IN THE PACIFIC NORTHWEST

In the Pacific Northwest, harmful algal blooms can contaminate razor clams and lead to closures of recreational harvests and significant local economic impacts. A new NOAA-funded study on the economic impact of these closures found that recreational harvests generate over $50 million annually for local communities. Long Beach, WA, the state's most popular beach for recreational clam diggers faced at least $840,000 in lost revenue if a bloom caused a razor clam season closure. This research highlights the value in the Pacific Northwest Harmful Algal Bloom Bulletin, a forecast that provides early warning of toxin blooms, and minimizes the need for widespread harvest closures.



(Left) Aerial view of the algal bloom (*Margalefidinium polykrikoides*) August 9, 2022 in the York River, VA. Credit: Savannah Mapes, Virginia Institute of Marine Science. (Right) Sentinel satellite image of the algal bloom (*M. polykrikoides*) on August 9, 2022. The black arrow indicates the location of the aerial image shown on the left.

In 2022, NOAA's satellite imagery and aerial photos captured the formation of a very intense harmful algal bloom in the York River, VA. This historically leads to the spread of other harmful algal blooms throughout the lower Chesapeake Bay which can adversely affect juvenile oysters, finfish, and other commercially important seafood. Virginia ranks second in the nation for production of farmed oysters, and first in clam production. This makes intense blooms a major cause for concern regarding ecological and economic impacts on valuable aquaculture and fishing industries throughout the Chesapeake Bay.

SUSTAINING OUR SEAFOOD: NOAA USES AI TO HELP DETECT, MONITOR, AND FORECAST HARMFUL ALGAL BLOOMS IN NEW AREAS

NOAA has now established a satellite-based monitoring system for algal blooms in Chesapeake Bay, developing a prototype forecast model for toxic blooms in the York River, and is establishing a community-based network of volunteers to help monitor algal species through the Phytoplankton Monitoring System. These efforts help NOAA and partners expand the current HABscope network to the Chesapeake Bay and develop AI that uses water samples to train the HABScope software to detect toxic algal species in that area. The HABscope is a portable microscope system that uses video and AI to quickly analyze Gulf of Mexico water samples for harmful algae and is now being deployed in other regions to detect other species of harmful algae. These critical advancements in monitoring and forecasting help support the valuable aquaculture industry, sustainable seafood, and reduce impacts of harmful algal blooms on the Chesapeake Bay.

4.4 MURKY WATERS AHEAD?

NOAA STIRS THINGS UP TO BETTER UNDERSTAND WATER QUALITY AND CONTAMINANTS IN THE GREAT LAKES

Felipe Arzayus (NOAA's National Centers for Coastal Ocean Science) briefs the NOAA Thunder Bay National Marine Sanctuary's Advisory Council members on the objectives of the Mussel Watch survey of the Great Lakes, and its expected findings. Credit: NOAA Thunder Bay National Marine Sanctuary

As the largest body of freshwater on earth, the Great Lakes are a vital source of drinking water for millions of people, and support multi-billion dollar fisheries and recreation industries. Thousands of chemical contaminants from a wide range of pollution sources accumulate in the Great Lakes every day, compromising water quality and food webs, which, in turn, threaten human and ecosystem health. NOAA and partners conducted a basin-wide survey to better understand the impact of these chemical stressors, assessing the magnitude and distribution of various contaminants in the Great Lakes.

Researchers collected thousands of samples of dreissenid mussels (invasive mussels) — an indicator of chemical contamination — from 70 sites, and sediment samples from 25 sites across the major lakes (Erie, Huron, Ontario,

Michigan, Superior, and St. Clair). The samples are being analyzed for a suite of more than 550 chemical contaminants, including legacy toxic compounds such as DDT, PCB, PAH, mercury, as well as contaminants of emerging concern, such as per-and polyfluoroalkyl substances (PFAS), pharmaceuticals, and chlorinated paraffins.

Results of this ongoing study will support a better understanding of sources, transport dynamics, and impacts of contaminants in the Great Lakes Ecosystem. These efforts will help fill critical data gaps in Great Lakes water quality information, support ongoing projects investigating environmental health implications of contaminants, and use ML and AI tools to better understand how contaminant distribution may, or may not, disproportionately affect under-resourced Great Lakes communities.

4.5 NOAA REVOLUTIONIZES THE PROCESS TO ESTIMATE FISH AGE WITH AI

What do trees and fish have in common? You can tell a lot about a tree's lifetime by examining its inner rings and the same is true for an otolith — the inner ear bone of a fish. The layers of an otolith, which are visible like tree rings, grow incrementally over the lifetime of a fish, recording a timeline of information about the fish's biology and environment. Scientists at NOAA successfully applied a novel approach, using near-infrared spectroscopy technology coupled with AI, to more quickly produce reliable estimates of fish age, and improve the accuracy of estimating ages of older fish. In other words, aim a beam of near-infrared light at an otolith, and it reflects a spectrum of information on the biological and environmental history of a fish which is correlated with its age. Rapid and reliable age estimation is crucial for effectively and efficiently managing fish stocks. This new approach revolutionizes a century-old approach using microscopes to count otolith ring layers to estimate fish age.

Now, scientists can process each otolith in 30–50 seconds to estimate fish age, which is more than 10 times faster than traditional methods and is more accurate for estimating ages of older fish. In Alaska, scientists at NOAA used AI models to speed the processing of diverse data sets. To train and test the models, scientists scanned a total of 8,617 walleye pollock otoliths collected during 2014–2018. With this and other information, scientists will be able to improve critical data needs in stock assessments that can help determine whether overfishing is occurring or if a fish stock is being overfished. NOAA has unlocked the potential to use these advanced technologies and data products in stock assessment models and fully integrate them into regular operations to better manage fisheries.

Otolith pairs (two per individual fish) from an assortment of Bering Sea fish species are pictured. Walleye pollock (top left) and Pacific cod (top right) are among the species shown. Note: otolith sizes are not on a relative scale. Credit: NOAA Fisheries

4.6 EXPANDING R&D CAPABILITIES WITH UNCREWED SYSTEMS, SATELLITES, AND OTHER TECHNOLOGY

Uncrewed systems are vehicles — aerial, terrestrial, or marine — and associated elements, such as sensors and communications software, that can conduct data-collection missions without a human presence aboard. They are typically controllable or programmable, self-powered, untethered, and operate on a continuum from attended to fully autonomous.

NOAA has committed to using cloud services, AI, uncrewed systems, satellites, and other cutting-edge technology and instruments to advance R&D that uses timely and accurate scientific information reaching from the surface of the sun to the depths of the ocean floor, and in between, increasing scientific knowledge vital to saving lives, property, and the planet. In 2023, NOAA made significant progress developing and procuring uncrewed aerial, surface, and underwater systems carrying novel instrument packages to fulfill mission goals; by storing and processing data from these systems in Microsoft's Azure cloud environment; and by applying commercially available AI to translate data from these systems into information.

NOAA used advanced technology, instruments, satellites, and uncrewed systems to make critical observations, reach new research milestones, and discover new knowledge in space weather, Earth's upper atmosphere, near and around tornadoes and storms, and below the frozen surface of icy waters in the Great Lakes. While there is still work to be done, these exciting advances have increased NOAA's technical capacity to respond to a growing list of challenges related to hazardous weather and space weather, climate, oceans, and coastal issues facing the planet.

NOAA'S R&D IS OUT OF THIS WORLD: SATELLITES CONVEY CRITICAL INFORMATION TO HELP PROTECT EARTH FROM SPACE WEATHER IMPACTS

The Earth's geomagnetic field is an invisible shield that envelops the planet and protects it from harmful solar and cosmic radiation. It protects various technologies from harmful radiation, especially satellites. So much of our daily lives are dependent on data from, and communication with, these satellites. The magnetosphere is constantly impacted by space weather, which can result in temporary changes to our geomagnetic field, known as geomagnetic storms, that have the potential to disrupt satellites, power grids, Global Positioning System (GPS), and communications systems. December 14, 2023 marked the one of the largest solar flares the Earth has seen since 2017. The intense burst of radiation, from the release of the Sun's magnetic energy, led to temporary radio signal and communication blackouts for parts of the Earth. An event like this serves as a reminder for the importance of NOAA's space weather prediction efforts for our technologically-dependent society.

In 2015, NOAA launched its first operational satellite to the point in space (1st-Lagrange or "L1") where solar wind data is measured. Solar wind involves the release of particles from the Sun into the solar system and data about solar wind is vitally important for space weather forecast, warnings, model development and scientific research. In a recent study, NOAA validated this satellite data against other satellites at this space point, showing a good correlation between hourly averaged solar wind data and the satellite. Solar wind observations

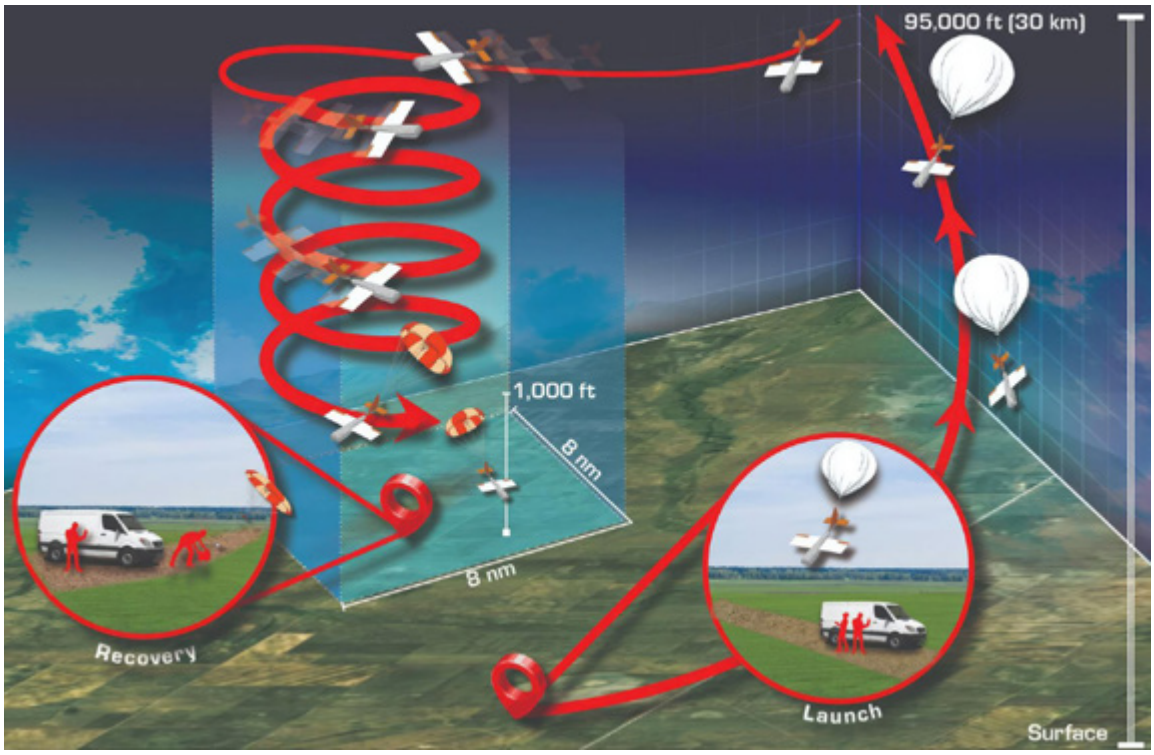
at L1 are the most used space physics data in research publications and crucial for better understanding space weather and how it affects our planet.

The Earth's geomagnetic field is an essential component of our planet's ability to sustain life. NOAA's ongoing R&D of models that can forecast changes in the magnetic field are critical to mitigating the effects of space weather on our technological infrastructure and improving the lives of people worldwide.

NOAA USES UNCREWED AERIAL SYSTEMS TO GUIDE BALLOON-BORNE INSTRUMENTS IN FOR A SOFT LANDING

NOAA has not thrown caution to the wind when it comes to atmospheric research and won't be throwing balloon-borne instruments to the wind either. NOAA has developed a reliable, cost-effective way to retrieve balloon-borne instruments from the stratosphere. In May 2023, over the eastern Colorado plains, NOAA used a weather balloon to lift a glider with a scientific sensor package to an altitude of 90,000 feet in controlled airspace and successfully returned it to the original launch location. This milestone is a major achievement for weather and climate research, which has long depended on balloon-borne measurements but has been limited by the dynamic forces and elements of the upper atmosphere.

Advancements in balloon-borne measurement technologies have been a challenge due to the need to track and recover their data and instrument package. While balloons can easily surpass typical aircraft altitudes of 45,000 feet on the way up, they drift with the wind, resulting in instruments landing up to 100 miles from the launch point, or being lost. This risk of equipment loss and lack of control often dictates the type and quality of instruments used.



This illustration depicts how the high-altitude operational return unmanned system (HORUS) autonomous instrumented atmospheric sampling system collects high-altitude measurements and then returns to the launch site. Credit: NOAA

NOAA has solved this problem by combining the weather balloon with a modern uncrewed aerial system. The balloon lifts a remote-controlled glider with an instrument package installed in its belly to altitudes up to 90,000 feet. The glider is programmed to release from the balloon at a specific altitude and then navigate back to a point above the landing spot, where it circles until the launch crew takes over to control its safe landing.

The high-altitude operational return unmanned system, developed by NOAA and partners, is dubbed "HORUS" after the falcon-headed Egyptian god of the sky, and provides a predictable and trackable trajectory back to its launch location. This allows for FAA air traffic control to ensure the safety of other aircraft.

The potential to deploy the HORUS system to locations where balloon retrieval would be nearly impossible or the instrument package would be lost is a major advancement and new opportunity to expand critical observations of the upper atmosphere.

NOAA TEAMS UP WITH PARTNERS IN ONE OF THE LARGEST TORNADO FIELD CAMPAIGNS TO DATE

If you noticed funny looking trucks with lots of equipment in the Southeast U.S. during the Spring of 2023, you may have spotted a NOAA PERiLS scientist. "PERiLS" is short for a big name (Propagation, Evolution, and Rotation in Linear Storms) of an even bigger project that involves NOAA's collaboration with several universities and partners in one of the most comprehensive severe storm field projects to date. Teams of scientists deployed dozens of instruments across seven states in the Southeast U.S. to measure the atmosphere near and inside storms to better understand how tornadoes form from lines of storms (squall lines). These types of tornadoes, more common in the Southeast U.S., pose a significant challenge to meteorologists and emergency managers, due to their rapid development.

High-wind damage to a rural area in Alabama. Credit: NOAA

Storms in this region can pose a higher risk to people and property than in other parts of the country because of their rapid development, making them difficult to predict in advance, and unique scientific and socioeconomic factors associated with the region.

Scientists work on developing an uncrewed aerial systems-based approach to better characterize high-wind damage to vegetation and in rural areas to improve disaster response and recovery. Credit: James Murnan/NOAA

About 30 teams used a variety of equipment including mobile radars, uncrewed aerial systems, trucks with instruments attached, and different kinds of portable devices designed to measure lightning and the atmosphere within and around storms. Various sites in Alabama, Louisiana, and Mississippi were set up with wind and temperature profiling radars and

other technology that scanned large areas for environmental data, gathering key information about storm development during severe weather outbreaks.

Uncrewed aerial systems can be deployed almost immediately after a high-wind event, capturing damage information in remote or inaccessible areas, and better documenting damage to vegetation and in rural areas.

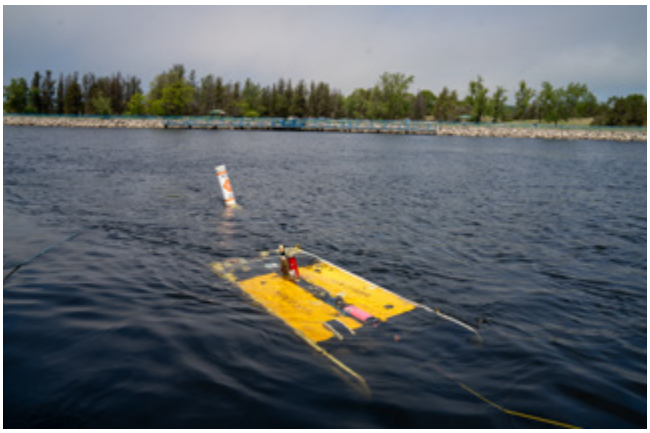
Damage information from uncrewed aerial systems is also used to better correlate storm signatures observed in radar and to understand the role of land cover and topography in tornado intensity and evolution. Better understanding of how tornadoes produce damage can help decision-makers and engineers develop more resilient strategies and designs to withstand high winds, saving lives and property.

ROBOTS BREAK THE ICE TO GET A FRESH GLIMPSE INTO WINTER WATERS OF THE GREAT LAKES

NOAA's efforts to advance new under-ice observing capabilities could lead to new discoveries in the Great Lakes. NOAA and a team of partners have conducted test deployments of an autonomous underwater vehicle in Lake Michigan. The goal is to use this robotic vehicle under lake ice, during winter, to collect ecological and water quality data. Cold temperatures and icy conditions can make fieldwork in the winter especially challenging compared to warmer seasons. For these reasons, observations of winter ecology and the hunt for winter data are especially important.

Most research buoys, ships, and instruments are not built to tolerate winter conditions and must be pulled out to avoid damage in winter, at least until recently. The new autonomous vehicle, tested by NOAA, uses an acoustic imaging system to gather data that can be transmitted into the lab's observing network. The robotic vehicle can be operated remotely, but during initial tests was also able to autonomously dock itself at a pier, using acoustic beacons to confirm its location. It can also successfully remain underwater yearlong and recharge its battery from a hydrogen fuel cell — a first for powering robotic vehicles like this one.

In future winter seasons, researchers plan to use the vehicle to collect data about water quality, life at the bottom of the lakes, and fish and zooplankton. It could also potentially be used to investigate or respond to oil spills in various locations. Water intake managers in the Western Basin of Lake Erie have also been using data from the observing network to monitor for the development of harmful algal blooms and other issues that might impact drinking water systems in cities such as Toledo, OH. Ice cover is a key variable in the regulation of biological processes in the Great Lakes during winter — an understudied area in which we have a lot to learn. Improving our understanding of these biological processes is critical now and in years to come as climate change impacts seasonal ice cover and may further impact lake ecosystems.



NOAA Great Lakes Environmental Research Laboratory and a team of federal, university, and industry partners conduct test deployments of an autonomous underwater vehicle in Lake Michigan, with the goal of using it under lake ice during winter to collect ecological and water quality data. Credit: NOAA