U.S. DEPARTMENT OF ENERGY (DOE)
NATIONAL NUCLEAR SECURITY ADMINISTRATION (NNSA)
DEFENSE NUCLEAR NONPROLIFERATION (DNN)

DNN Sentinel

DEFENSE BY OTHER MEANS

VOL. XI, NO. 3

IN THIS ISSUE:

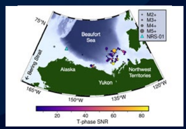
3 Addressing a Critical Nexus: The Inaugural Year of NC²

4 Using the International Monitoring System to Evaluate Climate Change: An NC² Project

5 Argonne's AMIS Beamline Aims to Accelerate Development of New Nuclear Materials Quickly and Efficiently

6 How Electron Beam Technology Can Safely and Securely Support Climate Initiatives

7 Promoting the Responsible Expansion of Nuclear Power to Fight Climate Change: ICONS Atoms4NetZero Side Event and Joint Statement

9 Nuclear Explosion Monitoring in the Changing Arctic


When Existential Threats Meet: Climate Change and Nonproliferation

DNN SENTINEL:
DEFENSE BY OTHER MEANS

VOL. XI, NO. 3

https://www.energy.gov/nnsa/
missions/nonproliferation

From the Principal Assistant Deputy Administrator

I am immensely proud and inspired by the dedication and diligence of our DNN team. Amid the growing number of global threats, DNN programs have remained steadfast in their commitment to nonproliferation and our national security mission. We do not have the privilege of looking at one threat at a time; we must address a multi-threat landscape simultaneously. Geopolitical events, international politics, and environmental risks must be integrated into how we address our mission.

The existential threat of climate change has more intersections with the DNN mission than one might expect. DNN strives to prevent the further spread of nuclear weapons and prevent terrorist acquisition of nuclear weapons or nuclear or radioactive material, technology, or expertise. At the same time, nuclear and radiological technologies have incredible potential for addressing some of the planet's growing needs as we combat climate change, and DNN is working to help facilitate that with the highest standards of nonproliferation and nuclear security.

Across the board, the DNN programs have leveraged their partnerships with the U.S. National Laboratories and international organizations to come up with innovative solutions. These programmatic initiatives demonstrate DNN's perseverance to manage the impacts of climate change while simultaneously pursuing a path toward the sustainable and safe usage of nuclear technology. This edition of the Sentinel highlights several of DNN's ongoing projects at the intersection of nonproliferation and climate change.

The Office of Global Material Security works internationally to promote the use of non-radioscopic electron beam (eBeam) technologies to create crops resilient to climate change. Technologies that use radioactive sources can be misused or stolen for nefarious purposes. Instead, eBeam technologies can yield better results and pose no risk of theft, misuse, or a release of radioactive materials.

The DNN Office of Research and Development (DNN R&D) sponsors research by scientists at Los Alamos National Laboratory (LANL) to study how the changing arctic climate will impact hydroacoustic monitoring, one of the primary methods for detecting underground nuclear explosions. DNN R&D also sponsors research at Argonne National Laboratory aiming to accelerate the development of new nuclear fuels and materials for nuclear reactors to help in decarbonizing the electrical grid.

The Office of Nonproliferation and Arms Control (NPAC) supports policy analysts and scientists at Pacific Northwest National Laboratory (PNNL) to investigate how the International Monitoring System (IMS), a structure operated by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, can be leveraged to collect climate data to aid in an understanding of climate science.

These are only a few of the numerous and inventive projects that DNN staff have been working on to understand climate science and its intersection with nonproliferation. DNN is proactively paving the path toward a future that focuses on the safe usage of nuclear technology to meet climate goals.

We are constantly faced by multiple global existential and evolving threats, which at times call for conflicting solutions. This Sentinel demonstrates DNN's efforts to address climate change within the lens of our nonproliferation mission. DNN staff have shown ingenuity and resolution on these projects, and I am truly grateful to serve alongside such a talented team.

Karla R. Mendelsohn

Addressing a Critical Nexus: The Inaugural Year of NC²

By Kate Doty, Lindsey Gehrig, Aubrey Means

After a year of foundational research, DNN's NPAC launched the Nonproliferation and Climate Change Program (NC²) in 2023. NC² is close to completing its first full year of programmatic activities. These activities have included engaging with international organizations such as the International Atomic Energy Agency (IAEA) and collaborating with DNN's program offices and the National Laboratories. Additionally, NC² funded a study that was published in the Journal of Environmental Radioactivity on the "Impacts of Future Nuclear Power Generation on the International Monitoring System," and in October 2023, NC² team members participated in a panel at the IAEA Conference on Climate Change and the Role of Nuclear Power. PNNL's Lindsey Gehrig presented an overview of NC² and the driving concepts behind our program, while Kathleen Doty moderated the ensuing panel discussion.

NC² aims to prepare DNN to manage the impacts of climate change and to support a secure and sustainable pathway for nuclear technology to support global Net Zero emissions goals. NC² is a program designed to meet the moment: it is responsive to the Biden administration's call for agencies across the U.S. government to consider the impacts of climate change. It exemplifies the ability of DNN and its National Laboratory partners to tackle both highly technical and complicated policy issues of paramount concern to the United States and international partners through work on a broad and interrelated suite of issues at the nexus of nonproliferation and climate change.

NC² project research was featured at the IAEA's 2nd International Conference on Climate Change and the Role of Nuclear Power, and the Workshop on Signatures of Man-Made Isotope Production. Additionally, climate and nonproliferation experts from the National Laboratories came together in March 2024 for an interdisciplinary workshop—hosted by LANL with support from Lawrence Livermore National Labortory and PNNL—to identify gaps in the research and future opportunities for the program.

DOE/NNSA recognizes that climate change is expected to have cross-cutting impacts on the nonproliferation regime because of the physical changes to the environments where current and future nuclear facilities may be sited, the anticipated increase in both the pace of deploying of nuclear technology and the end-use scenarios for which they are being use, and the geopolitical tensions that arise from the impacts of climate change. NC² will continue to expand its engagement with government, industry, and international organizations to ensure that DNN equities are represented in climate and other forums where nuclear deployment is under consideration.

In FY 2024, multidisciplinary teams including policy analysts, nuclear engineers, climate scientists, international legal experts, physicists, and others worked together on a range of projects. Examples of NC² research activities include:

- Evaluating the future requirements for global governance to enable the sustainable, safe, and secure deployment of new civil nuclear technologies in the context of climate change, as well as the incentive structures that would encourage relevant entities to practice responsible nuclear behavior.
- Using climate modeling to improve understanding of where, how, and under what conditions nuclear technology is best suited to expand in pursuit of decarbonization goals, allowing better alignment between nonproliferation policy, regulatory requirements, and climate mitigation goals.
- Evaluating the extent to which civil nuclear expansion and the corresponding emission of radionuclides may interfere with monitoring and verification efforts supported by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization's (CTBTO PrepCom) International Monitoring System.

Using the International Monitoring System to Evaluate Climate Change: An NC² Project

By Dr. Micheal Foxe

This year, senior scientists and policy analysts at PNNL, supported by DNN/NPAC's Nonproliferation and Climate Change (NC²) program, are working to bridge the gap between nuclear nonproliferation and the climate science community. They are doing this by investigating the potential use of the data and infrastructure from the International Monitoring System (IMS), operated by the CTBTO PrepCom, for climate change analysis/applications. The IMS includes over 300 monitoring stations around the world that record seismic, hydroacoustic, infrasound, and radionuclide data and collect air and particulate samples to detect nuclear explosions. Importantly, many of these stations could potentially be used to support the advancement of climate science.

CTBTO radionuclide monitoring stations. Credit: CTBTO Public Information, www.ctbto.org.

The objective of this project is to investigate how the IMS's worldwide network of 80 radionuclide sensors could be leveraged to better understand climate indicators and other climate phenomena over time. The project team is investigating how data collected by the IMS may contribute to a better understanding of climate change and its impacts through an analysis of the hundreds of thousands of high-resolution gamma ray spectra made on radionuclide samples over the last 20 years.

In addition, the team is investigating how IMS itself may be negatively affected by climate change. For example, some radionuclides detected by the IMS, such as radioactive iodine, may be impacted by heavy precipitation occurring between the source and the monitoring station, reducing its ability to detect radionuclides of interest.

The project's initial findings have provided an understanding of the ability and limitations of assessing the impact of utilizing weather station data alongside IMS data. This analysis method is enabling the team to identify specific radionuclides that are most correlated to weather and climate phenomena in the area.

Correlations between carbon dioxide and methane are being studied using data from a network of greenhouse gas sensors around North America. While no direct correlations and trends have been identified, the combination of the data may allow for a better understanding of the potential for linkages between radionuclides and greenhouse gas detection.

Alternatively, the inverse problem is being studied by evaluating the impact of climate change on IMS stations themselves. Station locations are being binned into a subset of climate types to allow for targeted climate change models to evaluate the trends for a subset of climate change indicators (e.g., heat, flood, precipitation, typhoons). This, combined with correlations identified in the first two tasks, may provide the ability to decrease the uncertainty of climate change models. It would bring the work full circle by improving the prediction of the impact of climate change scenarios on IMS stations.

This study exemplifies the cross-cutting nature of the NC² program, involving both nonproliferation and climate tools, as well as collaboration between NPAC offices. The study's final report will provide NNSA with potential pathways for the additional use of signals and samples normally reserved for nonproliferation and arms control purposes. It will also identify how climate indicators may impact future operation of IMS stations to enhance the CTBTO PrepCom's ability to effectively address maintenance, replacement, or modification requirements in support of its mission.

Argonne's AMIS Beamline Aims to Accelerate Development of New Nuclear Materials Quickly and Efficiently

By Peter Mouche

Scientists in search of new materials for use in nuclear energy generation can now study potential options more quickly and efficiently, thanks to a new beamline at the Argonne Tandem Linac Accelerator System (ATLAS) at DOE's Argonne National Laboratory.

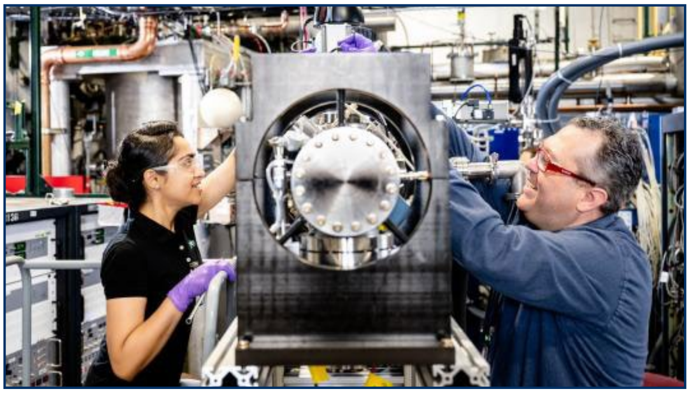
The beamline, made available through the recently commissioned ATLAS Material Irradiation Station (AMIS), uses heavy ions at the accelerator's lowest energy levels to displace high volumes of atoms in potential nuclear fuels and structural materials. This process prompts a degradation of their properties similar to that caused by fission fragments or neutrons inside a nuclear reactor. As fuels and materials evolve, it's important to fundamentally understand how they are deviating from their initial performance to establish their usability. This improved understanding will help inform the nuclear energy industry as it pursues advanced reactor designs that can contribute more clean, green power to the U.S. energy grid.

The NNSA-funded AMIS beam could significantly accelerate and increase the pace and number of such studies. It can produce as much degradation in the properties of target materials in one day as a typical nuclear reactor does in a year—all without making those materials radioactive. This lets scientists study the effects of degradation on potential materials more rapidly and without the complications of handling activated materials.

"The high energy heavy ion beams are the key to the process," said Abdellatif Yacout, senior nuclear engineer. "You really can't create this amount of degradation this fast in material properties without them."

Scientists measure the degradation of material properties by the number of displacements per atom (DPA) caused by irradiation. Thermal nuclear reactors in the United States produce neutron degradation of a structural material's properties at an approximate rate of 10 DPAs or less per year. This relatively slow rate of degradation limits the pace of research into advanced nuclear materials.

By contrast, the heavy ion beams delivered to AMIS can quickly cause hundreds of DPAs in structural materials and thousands in nuclear fuel materials. This can cause the same amount of degradation in hours that it takes irradiation in a nuclear reactor to cause over the course of years—again without making the sample radioactive. The results provide fundamental data to inform models, act as screening studies, and help guide planning of test-reactor irradiations.



Argonne scientists adjust the AMIS beamline prior to its commissioning.

"AMIS provides a faster and safer process for everyone involved," Yacout said. "Scientists can use the beam to produce data and conduct analysis that would have taken years to do before. And the materials don't require special handling or operating procedures when they are used in subsequent analyses."

Jerry Nolen, an Argonne Distinguished Fellow and physicist, and others first proposed the idea for AMIS more than a decade ago. Yacout and his materials research group led the project and developed the materials test station, while accelerator physicist Brahim Mustapha led the beamline design, construction, and commissioning.

Prior to AMIS, Argonne scientists would set up equipment to conduct brief experiments at the primary ATLAS beamline. The experiments required lengthy preparation and loading of samples, such as, opening up a vacuum, and complete disassembly when they were over. This all had to happen during allocated beam time—time that the scientists would have rather used to conduct experiments.

The dedicated beamline has allowed for better use of time, an increased versatility in irradiation conditions, and a wider range of experimentation.

"With AMIS, more scientists will get more irradiation time as well as access to these unique heavy ion beams, which can accelerate their work and open the door to more studies," Yacout said. "Both outcomes can help enable the development of new fuels and materials for nuclear reactors, which can play a critical role in our efforts to decarbonize the electrical grid in the face of climate change."

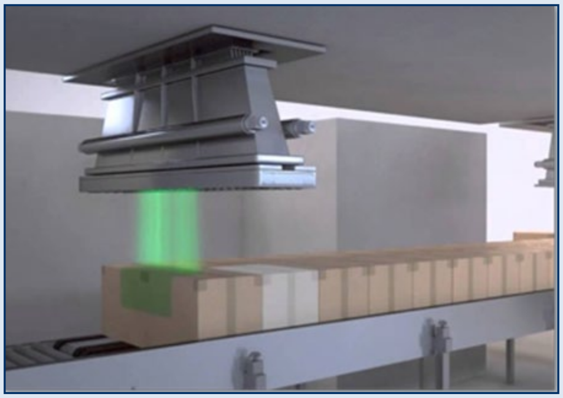
How eBeam Technology Can Safely and Securely Support Climate Initiatives

By Matthew Keskula

Radiation technologies have tremendous potential to help offset impacts of climate change. They can be used to create more resilient crops, limit the spread of harmful pests, and remediate a range of waste plastics in water and in flue gases. In the wrong hands, however, certain gamma radiation technologies can be used in an act of radiological terrorism. DNN's Office of Radiological Security (ORS) works around the world to promote the development and adoption of alternatives to gamma devices, such as eBeam technology, to prevent radiological terrorism while ensuring continued availability of these important technologies to fight climate change.

The IAEA notes that radiation technologies can be used for nine of the 17 United Nations Sustainable Development Goals such as Zero Hunger, and Clean Water and Sanitation. Although radioactive cobalt-60 and cesium-137 can be used for these applications, non-radioisotopic machine-based technologies like eBeam and X-ray can achieve the same or better results. Importantly, eBeam and X-Ray do not pose a risk of misuse, theft, or accidental release of radioactive materials. ORS promotes the use of non-radioisotopic technologies where feasible, as part of a global radiological risk reduction strategy. The use of eBeam and X-ray technologies supports both ORS's radiological security mission and a range of climate goals.

For example, a major global climate challenge is how the expansion of biomes for insect populations will impact human health and agriculture. One tool for stopping the unchecked growth of these insects is the sterile insect technique (SIT), where insects and their pupae are sterilized through irradiation and released into the environment to competitively mate with the wild population with the goal of significantly reducing the insect population. While cobalt-60 and cesium-137 have been traditionally used for SIT, self-shielded X-ray irradiators have become more prominent among researchers and governmental pest control organizations, and interest in eBeam for SIT is growing. ORS and its partner laboratories work with researchers in the United States, South Africa, and Mauritius to conduct comparison studies between current gamma systems and both eBeam and X-ray on a range of insects, including disease vectors and agricultural pests. ORS, in partnership with DNN R&D, has also supported the development of new SIT irradiation machines and the replacement of gamma-based systems with X-ray irradiators which directly reduces radiological risk.



A representation of an electron beam sterilization system.

Many partners throughout the world reliably use radiation technology to induce mutations and select beneficial traits in crops as part of plant and seed breeding programs. These new crops can have a range of beneficial characteristics, including improved yields, enhanced pest resistance, and better resilience in the face of adverse weather conditions, such as droughts. Much like SIT, gamma irradiators have traditionally been used successfully for mutation breeding projects, but research on the use of self-shielded X-ray irradiators is promising. ORS supports global efforts to compare the effectiveness of X-ray and eBeam-induced mutagenesis to gamma in the irradiation of several crops, with the goal of promoting more mutation breeding with X-ray and eBeam technologies.

There is growing international interest in the use of radiation technologies for remediating biological and chemical environmental wastes. For example, eBeam can disinfect wastewater and break down simple and complex compounds in liquid and gaseous waste streams. It can also improve the physical properties of compounds and wastes, allowing them to be reused or recycled more effectively. Wastes can be broken down in an efficient manner, limiting their harmful impact on the environment. To promote eBeam use for environmental applications, ORS has supported partners conducting studies on feasibility and optimization of waste treatments with this technology. ORS has also contributed $2 million to the IAEA's Nuclear Technology for Controlling Plastic Pollution initiative, which aims to use radiation technologies for remediating plastic wastes and enabling wider reuse.

Matthew Keskula is a contractor supporting the Office of Radiological Security's alternative technology efforts.

Promoting the Responsible Expansion of Nuclear Power to Fight Climate Change: ICONS Atoms4NetZero Side Event and Joint Statement

By Anagha Iyengar, Katherine Holt

In November 2022, at COP27, Director General of the IAEA Rafael Grossi launched the "Atoms4NetZero" initiative. The proposal aims to harness the power of nuclear energy to achieve net zero carbon emissions and energy security. The responsible use of nuclear power infrastructure and its planned expansion requires consideration of nuclear security as early as possible to fulfill the commitments of meeting climate change targets and ensuring nuclear security. The IAEA's Milestones Approach lays out 19 infrastructure issues that a country needs to consider when establishing a nuclear power program, including nuclear security, safety, and safeguards.

The U.S. Government Delegation at ICONS

These three considerations, the so called "3S" approach, where safety, security, and safeguards are prioritized early in the development of a nuclear power program, have become central to U.S. Government (USG) efforts to support the responsible global expansion of nuclear energy.

Over the past few years, DNN has established multiple programs to support the responsible expansion of nuclear energy by highlighting the important role nuclear security and nonproliferation play in enabling access to peaceful uses of the atom. The 2024 International Conference on Nuclear Security (ICONS) in Vienna called attention to the nexus of nuclear security and nuclear energy. It provided the United States, which has the largest nuclear power program in the world and a proven track record in operating nuclear power with the highest standards for safety, security, and nonproliferation standards, the opportunity to highlight how government resources and efforts have evolved and expanded to support the expansion of nuclear energy globally.

The ICONS side event took place on May 21, and brought together leaders across the USG for the first time to discuss the importance of linking nonproliferation and security equities to the climate change and energy security conversation in an important international forum focused on security. The event showcased the major USG resources available to support the responsible global expansion of nuclear power with an emphasis on prioritizing 3S approaches from the outset and provision of related capacity building.

U.S. Deputy Secretary of Energy David M. Turk, kicked off the session, followed by an introduction to the panel and facilitated discussion led by U.S. Ambassador to the U.S. Mission to International Organizations in Vienna (UNVIE) Laura Holgate. The Ambassador facilitated an interactive discussion with questions posed to the audience via e-polling and sought reflections on the answers from the panelists on stage. U.S. panelists included Ambassador Bonnie Jenkins, the Under Secretary of State for Arms Control and International Security at the U.S. Department of State, who set the framework of nuclear security and highlighted recent major announcements at COP28 such as the Declaration to Triple Nuclear Energy, Group of 7 statements, and resources for nuclear newcomer countries. Nuclear Regulatory Commission Chair Christopher Hanson, spoke about the importance and role of a strong, independent regulator. He provided perspectives on how critical it is to consider security along with safety, and

"All of us are excited at the expansion of nuclear power to address the climate crisis. However, this is also a critical time for all to address the threats and challenges associated with any nuclear facility," said Corey Hinderstein. "The National Nuclear Security Administration is prepared to assist states in addressing nonproliferation and security considerations to work towards promoting a regime which supports the responsible global expansion of nuclear power."

– Atoms4NetZero Initiative DOE/NNSA article

continued on page 8

ICONS Atoms4NetZero Side Event– *Continued*

Panelists participating in the U.S. Atoms4NetZero event at ICONS. From left: Jeana Lee Sablay, Philippine Nuclear Research Institute; Seth Debrah, Head of Ghana's Nuclear Power Institute, Ghana's Atomic Energy Commission; Acting Principal Deputy Administrator of NNSA Corey Hinderstein; Ambassador and Under Secretary of State for Arms Control and International Security Bonnie D. Jenkins; Nuclear Regulatory Commission Chair Christopher Hanson; Henri Paillere, Head of the Planning and Economic Studies Section at the IAEA, and U.S. Ambassador to the United Nations International Organizations in Vienna Laura S.H. Holgate.

how countries can establish competent regulatory bodies and national infrastructure to support new nuclear power programs. Acting Principal Deputy Administrator of NNSA Corey Hinderstein highlighted the agency's capacity-building programs and technical resources available via the National Laboratories, including capacity-building support on 3S for new nuclear power program development under the Office of International Nuclear Security.

Henri Paillere, Head of the Planning and Economic Studies Section at the IAEA, spoke about the IAEA's Atoms4NetZero initiative, the recent focus on financing, and the important role nuclear security plays. The event was rounded out by representatives providing testimonials from two embarking countries – Seth Debrah, Head of Ghana's Nuclear Power Institute from Ghana's Atomic Energy Commission, and Jeana Lee Sablay from the Philippine Nuclear Research Institute. Both underscored the importance of linking nuclear security, safety, and nonproliferation with ambitions to build nuclear power capacity, and how partnership with the United States, the IAEA, and other established resources is needed to support their burgeoning programs.

"The IAEA has joined multilateral efforts that highlight and promote the role of nuclear technologies to meet climate change goals, whether through nuclear power or other non-power applications. Security is essential for the use and expansion of these technologies, which alongside safety, are key to the public confidence that is required for their application."

– Ambassador Holgate at the Opening remarks at Atoms4NetZero Event

Hinderstein announced a Joint Statement that DNN spearheaded on The Role of Nuclear Security in Harnessing the Power of Nuclear Energy, which was one of the deliverables for the United States at ICONS. The statement was signed by 28 countries including the United States and outlined five recommendations the signatory countries commit to in developing and strengthening nuclear security infrastructure at the national and site levels. It calls on them to consider 3S early in the decision-making process.

This Joint Statement, now officially known as Information Circular 1217, shows a global commitment to maintaining the highest standards of nuclear security in the development of nuclear power capacity. DNN will continue to work internally and across the USG to harness its resources in supporting the development of secure and safe new nuclear power programs and maintain the highest nonproliferation standards in this new era of global nuclear power program expansion.

Katherine Holt currently serves as the Program Director for Analytics & Innovation in the Office of International Nuclear Security (INS), responsible for developing new capabilities to reduce the risk of nuclear terrorism and anticipate emerging threats for global nuclear security, including advanced and small modular reactors (A/SMRs). She has held previous positions in Congress, the Department of State, and NNSA, including the Office of Congressional Affairs, and later as Policy Advisor to the Administrator. Katherine spearheaded the organization of the ICONS side event on the Role of Security in Supporting the Atoms4NetZero Initiative and the development of the Joint Statement.

Anagha Iyengar is the Deputy Program Director for Analytics & Innovation in INS. In this role, she oversees programs responsible for developing capabilities and tools to reduce risk of nuclear terrorism and other security challenges posed by emerging threats and technologies to include A/SMRs. In the lead up to ICONS, she served a detail to the U.S. Mission to International Organizations in Vienna (UNVIE) as the Deputy Nuclear Energy Attache to help promote U.S. interests at the IAEA on matters related to A/SMRs and fusion energy. She led the campaign to get signatories from partner countries for two joint statements from the United States, including the Joint Statement on the Role of Nuclear Security in Harnessing the Power of Nuclear Energy, which was announced by DOE/NNSA at the Atoms4NetZero side event.

Nuclear Explosion Monitoring in the Changing Arctic

By Siobhan Niklasson, Charlotte Rowe

As the Arctic warms and loses its perennial ice cover, it attracts new attention as a locus for resource extraction, commerce, communication, and defense. The region previously had a relatively low priority in global geopolitics due to operational challenges but is quickly attracting interest for economic growth, competition, and potential conflict. Future years and decades will see a transformation of the Arctic's place in global geopolitics. In this context, monitoring both human and natural activity in the Arctic is increasingly critical.

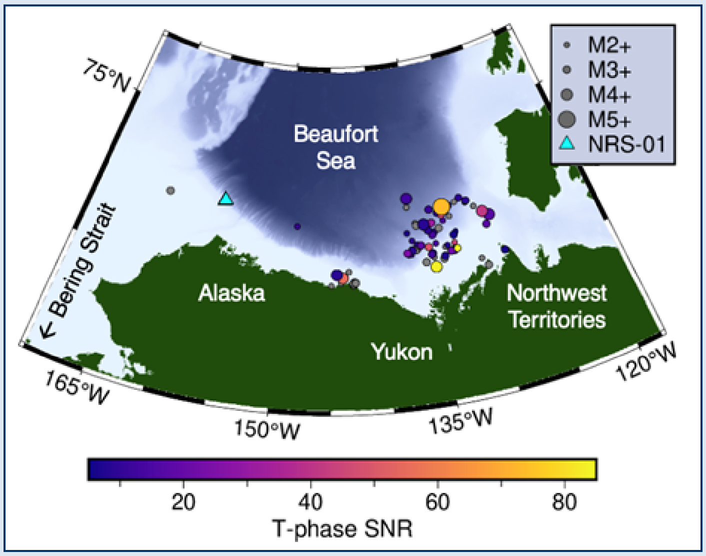


Figure 1. Submarine earthquakes observed at the NOAA NRS-01 hydrophone located at ~500 m depth in the Beaufort Sea. Circle size represents earthquake magnitude, and color shows the signal-to-noise ratio (SNR) of the water-borne wave generated by the earthquake (the "T-phase"). Gray circles represent known earthquakes that were not observed with the hydrophone. SNR generally increases with earthquake magnitude, but its relationship to distance from the sensor is more complex.

The changing Arctic climate modifies how the physical environment affects sound wave propagation under water, in the atmosphere near the ocean's surface, or near a coastline. This affects hydroacoustic monitoring capabilities in this region in ways that are still poorly understood.

Hydroacoustic monitoring is one of four primary methods for detecting underground nuclear explosions; the other methods being seismic, infrasound (acoustic), and radionuclide monitoring. Hydroacoustic technologies are used to identify sounds of interest in the ocean — explosions, the movement of vessels, and marine mammal migration — amid persistent environmental noise. To detect signals of interest, we need knowledge of their signatures, and of the background noise and its expected variations.

The Arctic is changing much more rapidly than lower latitudes (Meredith et al., 2019), affecting both environmental noise sources and sound propagation. For example, as sea ice freeze and thaw dates shift (Lin et al., 2022), seasonal patterns of cryogenic noise are also changing. Ice-free waters are also more amenable to shipping, and both the length of the shipping season and speed of transit are expected to increase through the 21st century (Melia et al., 2016). Therefore, shipping noise is expected to increase.

The sound speed structure of the ocean depends on temperature and salinity. Warmer, fresher water entering the Beaufort Sea through the Bering Strait *(Fig. 1)* modifies stratification of the western Arctic, strengthening a subsurface sound duct (Duda et al., 2021), which allows for enhanced transmission of sound from distant sources. The strength of the duct has increased over the past two decades (Niklasson et al., 2023), which changes how existing sensor networks record hydroacoustic signals in this region.

At LANL, we are using a multi-modal approach to understand how changes in the complex and dynamic Arctic system impact acoustic monitoring. LANL analysis of passive acoustic data collected by the National Oceanic and Atmospheric Administration's Ocean Noise Reference Station Network is revealing detection thresholds for regional submarine earthquakes *(Fig. 1)*. In addition, representatives from several divisions at LANL participated in the U.S. Navy's Operation Ice Camp in March 2024 to conduct an experiment designed to test how ice cover affects acoustic transmissions, a factor that is incompletely understood.

While observations illuminate current and past conditions of sound propagation in the Arctic, ultimately, we must turn to Earth system models to make projections of future conditions. LANL is a leader in development of DOE's Energy Exascale Earth System Model (E3SM; Golaz et al., 2022). E3SM produces estimates of Arctic temperature and salinity

continued on page 10

Nuclear Explosion Monitoring in the Changing Arctic– *Continued from page 9*

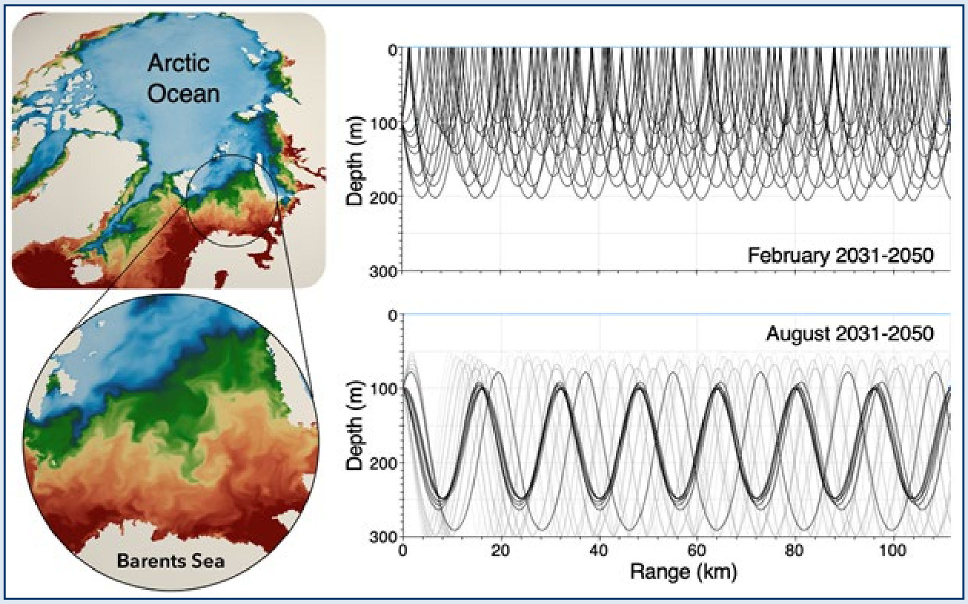


Figure 2. (Left) Sea surface temperature from E3SM. Inset shows the high-resolution mesh in the Barents Sea. (Right) E3SM projections of temperature and salinity in the Barents Sea during the period 2031-2050 give starkly different patterns of sound propagation in winter (top) vs. summer (bottom). Tracking the seasonal and decennial changes in these patterns has implications for acoustic monitoring and operational security in the area.

changes at spatial resolution down to kilometer scales, and sound emission due to ice dynamics and concentrations of marine fauna can be inferred from E3SM's sea ice and biogeochemical modules. We couple these estimates to acoustic models to investigate the effects of the changing climate on sound propagation in the coming decades *(Fig. 2)*.

Changes to the Arctic environment impact our ability to detect marine sounds of interest and to leverage the soundscape for operational security. At LANL, a cross-disciplinary team is using multiple modalities to assess our capabilities for regional acoustic source detection in this evolving soundscape. These results increase our confidence in hydroacoustic monitoring of the ever changing and increasingly important Arctic region.

Acknowledgment

This Ground-based Nuclear Detonation Detection research was funded by NNSA's DNN R&D and the Nuclear Testing Limitations Program in the NNSA Office of Nuclear Verification. LA-UR-24-28582.

References

Duda, T. F., Zhang, W. G., & Lin, Y.-T. (2021). Effects of Pacific Summer Water layer variations and ice cover on Beaufort Sea underwater sound ducting. The Journal of the Acoustical Society of America, 149(4), 2117–2136. https://doi.org/10.1121/10.0003929

Golaz, J.-C., Van Roekel, L. P., Zheng, X., Roberts, A. F., Wolfe, J. D., Lin, W., Bradley, A. M., Tang, Q., Maltrud, M. E., Forsyth, R. M., Zhang, C., Zhou, T., Zhang, K., Zender, C. S., Wu, M., Wang, H., Turner, A. K., Singh, B., Richter, J. H., … Bader, D. C. (2022). The DOE E3SM Model Version 2: Overview of the Physical Model and Initial Model Evaluation. Journal of Advances in Modeling Earth Systems, 14(12), e2022MS003156. https://doi.org/10.1029/2022MS003156

Lin, L., Lei, R., Hoppmann, M., Perovich, D. K., & He, H. (2022). Changes in the annual sea ice freeze–thaw cycle in the Arctic Ocean from 2001 to 2018. The Cryosphere, 16(12), 4779–4796. https://doi.org/10.5194/tc-16-4779-2022

Melia, N., Haines, K., & Hawkins, E. (2016). Sea ice decline and 21st century trans-Arctic shipping routes. Geophysical Research Letters, 43(18), 9720–9728. https://doi.org/10.1002/2016GL069315

Meredith, M., Sommerkorn, S., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, G., Kofinas, A., Melbourne-Thomas, J., Muelbert, M. M. C., Ottersen, G., Pritchard, H., & Schuur, E. A. G. (2019). Polar Regions. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (pp. 203–320). Cambridge University Press. https://doi.org/10.1017/9781009157964.005

Niklasson, S. M., Veneziani, M., Rowe, C. A., Worcester, P. F., Dzieciuch, M. A., Bilek, S. L., Price, S. F., & Roberts, A. F. (2023). Estimating Arctic Ocean Acoustic Travel Times Using an Earth System Model. Geophysical Research Letters, 50(7), e2022GL102216. https://doi.org/10.1029/2022GL102216