THE INTERNATIONAL REVIEW OF WEATHER, CLIMATE AND HYDROLOGY TECHNOLOGIES AND SERVICES

Meteorological Technology International

JANUARY 2024

A NEW ERA

The WMO's new chief, Prof. Celeste Saulo, talks equality, partnerships and building capacity as she becomes the first female to lead the UN organization

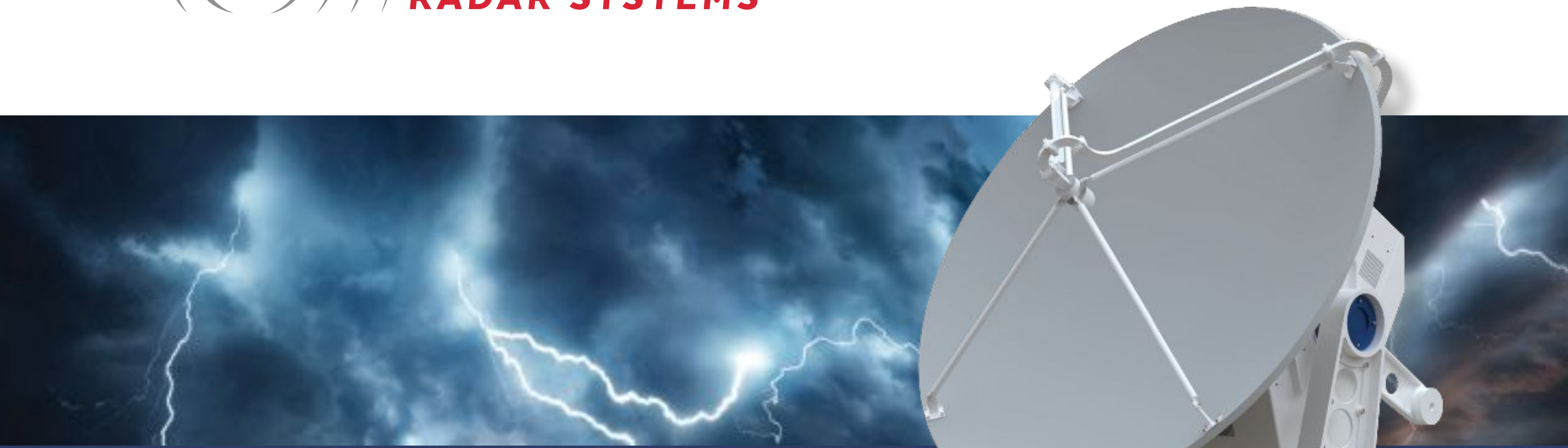
WILDFIRE EWS

A range of technologies including drones, sensors, satellites and AI models must be used to monitor fires to save lives and protect infrastructure

HYDROLOGY

More research and tools are needed to help predict the impact of climate change on data-sparse mountain cryosphere regions

RADAR SYSTEMS



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The Forecast

Welcome to the first-ever January issue of *Meteorological Technology International* magazine! This issue is also my first after a two-year hiatus from the meteorological world. And what an issue to be returning with. When I first started editing this magazine back in early 2016, I must admit that I felt a bit intimidated by the lack of other women at industry events. Men seemed to dominate, and even though I never had any gender-related issues and everyone I encountered within the industry was extremely helpful, I did at times feel like the odd one out.

But things are changing. This is thanks in part to the WMO's Policy on Gender Equality, which was adopted by the 17th World Meteorological Congress in June 2015, and the Gender Action Plan, which was set up to identify concrete actions to improve gender equality within all parts of the organization. This plan is the only one of its kind in the United Nations and has led to the average gender representation on the management groups of the technical commissions at the WMO more than doubling from 20% in the years 2012-2015 to 42% in 2020-2023.

The year 2024 will hopefully see this percentage grow even more as Argentina's Prof. Celeste Saulo becomes the first woman to take the helm at the WMO – an institution with roots dating back to 1879. Saulo won a landslide victory at the WMO Congress in June 2023, with many in the industry claiming that she will be a fantastic role model not just for women around the world but also for equality globally, being as she is from a developing country.

> "Saulo won a landslide victory at the WMO Congress in June 2023, with many claiming that she will be a fantastic role model"

MTI spoke to Saulo before she began her official work as secretary-general to find out her key aims for her first four-year term. "I have a huge opportunity to be a key role model for other women, younger generations, and for people from developing nations," she says in *Call for action* on page 10. "Nothing is easy in the developing world, but I am proof that following your dreams is possible if you are committed and passionate."

Saulo also took the opportunity to issue a call for action to the meteorological and hydrological sector to come together to address both the climate crisis and inequality in a collaborative way. "If we don't act now, the narrow window of opportunity to stop climate change, and the deadly impact it will have on vulnerable nations, will rapidly close," she says.

The impact of climate change on developing countries and small island developing states is increasing year-on-year. A recent Stanford University study found that, for example, it has increased economic inequality between developed and developing nations by 25% since 1960. The WMO's Early Warnings for All initiative is working to ensure that everyone on Earth is protected against hazardous weather by life-saving early warning systems by the end of 2027. Saulo hopes that it will help address inequality worldwide as it builds capacity at local levels to protect citizens from extreme weather events. "This is the WMO's overriding priority for the next four years," she adds.

As a fellow female in the meteorological sector, I would like to wish Saulo good luck in her new role. I'm looking forward to seeing more women in the room in the future.

Helen Norman, editor

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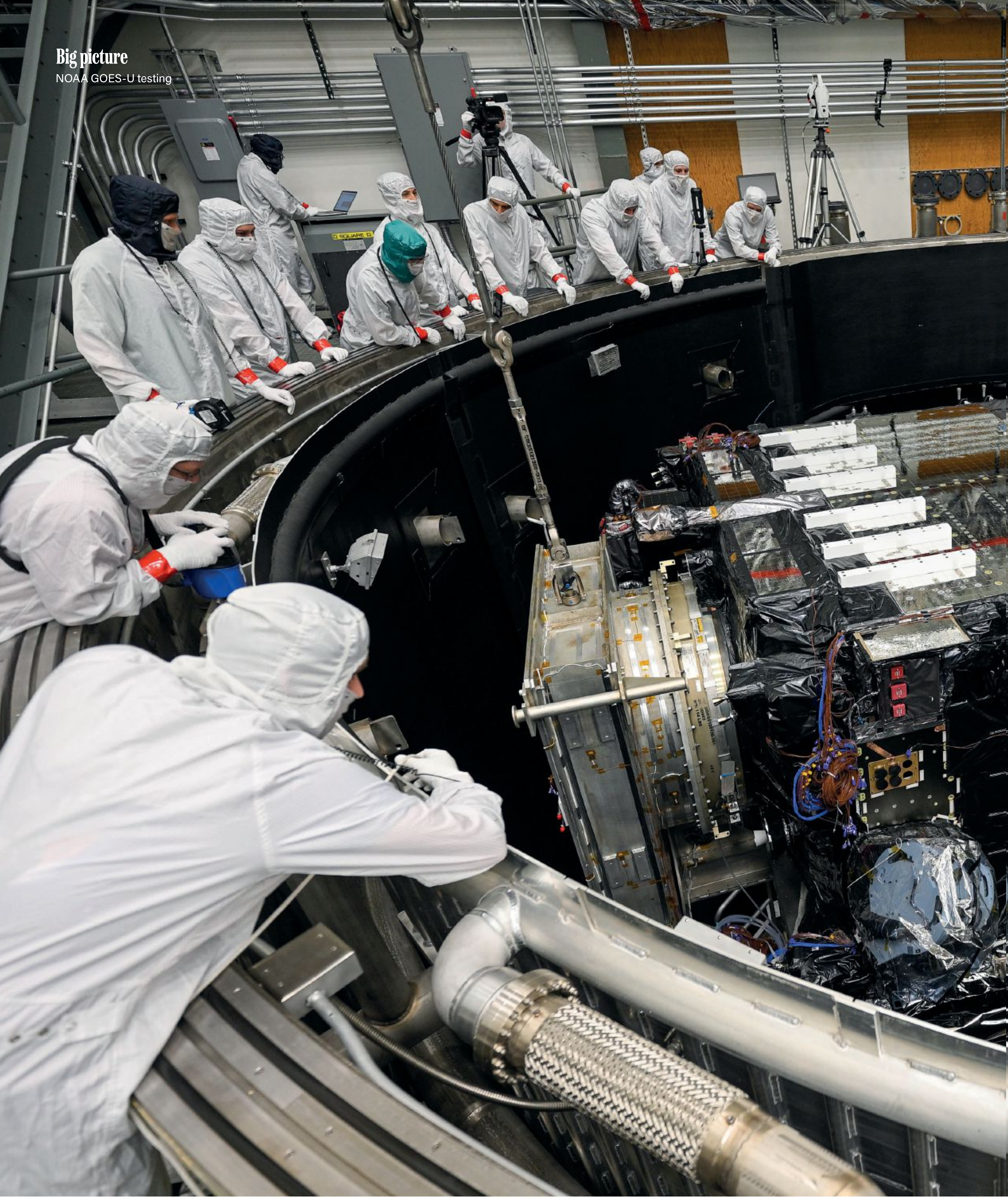

Image: Lockheed Martin

Testing, testing

GOES-U, the fourth and final satellite in NOAA's GOES-R series of advanced geostationary satellites, recently completed rigorous testing to ensure it can withstand the harsh conditions of launch and orbiting in space 35,785km above Earth. The testing process spanned nearly a year and included thermal vacuum, vibration, acoustic, shock, EMI/EMC and solar array deployment tests. During thermal vacuum testing (pictured), GOES-U was placed in an 8.8m-wide by 19.8m-deep chamber and subjected to a vast range of temperatures, soaring as high as +86.6°C and dropping as low as -55°C, to simulate the extreme temperatures of launch and the space environment.

The tests confirmed that the GOES-U satellite, and all of its instruments, can withstand the launch and maintain functionality in orbit. Lockheed Martin and SpaceX personnel conducted the testing at the Lockheed Martin facility in Littleton, Colorado, where the satellite was built.

The team also conducted testing to verify commands with the new Compact Coronagraph-1 (CCOR-1) instrument. This new space weather instrument will fly on NOAA's GOES-U and image the solar corona to detect and characterize coronal mass ejections.

GOES-U is on track for an April 2024 launch from Cape Canaveral Space Force Station in Florida on board a Falcon Heavy launch vehicle. The satellite will be renamed GOES-19 once it reaches geostationary orbit, approximately two weeks after launch. It will then undergo an on-orbit checkout of its instruments and systems, and validation of its data products.

NOAA's GOES-R series is the western hemisphere's most advanced weather observing and environmental monitoring system. The satellites provide critical data for weather forecasts and warnings; detection and monitoring of environmental hazards like fire, smoke, fog, volcanic ash and dust; and monitoring of solar activity and space weather.

NOAA-21 satellite becomes operational

The latest satellite in NOAA's Joint Polar Satellite System has become operational. NOAA-21 joins Suomi NPP and NOAA-20, each circling the globe 14 times a day, providing a continuous data stream to improve the accuracy of NOAA's three- to seven-day forecasts. This includes observations of extreme weather events and monitoring climate change.

NOAA-21 launched in November 2022 and now gives NOAA three spacecraft operating the most sophisticated technology the agency has ever flown in a polar orbit, capturing precise observations of the world's atmosphere, land and waters.

The satellite provides the US National Weather Service with global data for the numerical weather prediction models used to develop accurate US weather forecasts. In addition, high-resolution imagery from its Visible Infrared Imaging Radiometer Suite (VIIRS) will enable NOAA-21 to detect fog, Arctic Sea ice, volcanic eruptions and wildfires.

This advanced modeling information and imagery, shared with international and governmental partners, will help firms, emergency responders and communities and individuals make the best decisions possible in the face of weather-related hazards. ∎

https://tinyurl.com/3f4k2akv

NOAA-21 complements the operational on-orbit satellites in the JPSS constellation

Alan Turing Institute and UK Met Office to use AI for improved forecasting

The Alan Turing Institute and the UK Met Office have announced a new partnership to work together to develop AI models that will enable improved forecasting, including for extreme weather events, helping to save lives and protect critical national infrastructure.

Currently, the UK's national meteorological service uses information from satellites and observational data from weather stations on Earth and runs simulations on a supercomputer that generates forecasts for people all around the world.

The organizations state that they hope the collaboration will accelerate work to deploy machine learning (ML) technology alongside traditional techniques to improve the forecasting of some extreme weather events, such as exceptional rainfall or impactful thunderstorms, with even greater accuracy and detail, helping communities to increase their resilience.

Dr Scott Hosking, a senior research fellow at the Alan Turing Institute, speaks in more detail about this project to *Meteorological Technology International* in *Role Models*, page 64.

https://tinyurl.com/ynbftams

Scan the QR code for the full article

NOAA conducts first collocated drone mission into a hurricane

NOAA has conducted a collocated drone mission into a hurricane, collecting data in the lower levels of the storm that have been historically too hard to reach. The NOAA Hurricane Field Program team flew several operational and research missions into Hurricane Tammy in October 2023 on board the NOAA Hurricane Hunter P-3 aircraft and collected data sets from multiple different instruments. In addition to the first-ever Black Swift Technologies S0 drone launch into a storm, the missions resulted in the successful coordination of a low-flying drone (Anduril's Altius 600), an ocean-surface uncrewed vehicle from Saildrone, atmospheric profilers (dropsondes) and ocean profilers (bathythermographs).

By gathering data at different levels of the ocean and the atmosphere, NOAA continuously learns more about how storms form, build and intensify.

https://tinyurl.com/y8s9csr2

EUMETSAT and CSA to lead International Charter Space and Major Disasters

Europe's meteorological satellite agency EUMETSAT and the Canadian Space Agency (CSA) have taken up the rotating leadership of International Charter Space and Major Disasters, a global collaboration involving 17 member agencies, which provides satellite data to support responses to disasters worldwide.

For six months, EUMETSAT and the CSA will jointly lead the collaboration, with support from other organizations and contributors of satellite data.

The UK Space Agency was responsible for leadership of the charter from April to October 2023 and the German Aerospace Centre (DLR) will take over the reins in April 2024.

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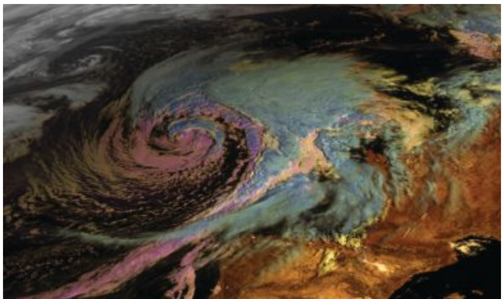


Kingdom of Tonga develops early warning systems for volcanoes and tsunamis

The Kingdom of Tonga has announced that it is further developing its early warning systems through the Tonga Mobile Applications Community MHEW and Response System (MACRES) to help it cope with natural disasters such as the volcano and tsunami disaster of January 15, 2022.

Through the Tonga Meteorological Services (TMS) and the Permanent Representative to the WMO, the people of Tonga have demanded an improved system for rapid and mass dissemination of warnings to communities. The Tonga MACRES will be developed to deliver on this demand through the Climate Risk and Early Warning Systems (CREWS) initiative Accelerated Support Window (ASW) – a financing mechanism dedicated to least developed countries (LDCs) and small island developing states (SIDS).

The Tonga MACRES will be established so that most smartphones can be used and warnings will need no internet data to reach people. Alerts or sirens and warning messages or flashing screens will attract users' attention (particularly useful for people living with disabilities). This also enables two-way communication of reports from communities (crowdsourcing) connected to a database to ensure both the TMS and the National Emergency Management Office can receive hazard and damage information for quick and targeted response.
https://tinyurl.com/9nnznr6s

When the Hunga Tonga-Hunga Ha'apai volcano erupted in January 2022, it sent a tsunami racing around the world and set off a sonic boom that circled the globe twice, according to NASA

NCAR study could improve predictions of dangerous storms

Scientists at the National Center for Atmospheric Research (NCAR) in the USA have used computer modeling techniques to identify two entirely different modes of hurricanes' rapid intensification. The findings may lead to better understanding and prediction of these dangerous events. One of the modes discussed occurs when a hurricane intensifies symmetrically, fueled by favorable environmental conditions such as warm surface waters and low windshear. This type of abrupt strengthening is associated with some of the most destructive storms in history, such as Hurricane Katrina.

The research also identified a second mode of rapid intensification that had previously been overlooked because it doesn't lead to peak winds reaching such destructive levels. In the case of this mode, the strengthening can be linked to major bursts of thunderstorms far from the storm's center. These bursts trigger a reconfiguration of the cyclone's circulation, enabling it to intensify rapidly, reaching category one or two intensities within a matter of hours.

The discoveries emerged after the researchers produced a very high-resolution, 40-day computer simulation of the global atmosphere, using the NCAR-based Model for Prediction Across Scales (MPAS).
https://tinyurl.com/4wasxwb5

Copernicus researchers say they are "virtually certain" 2023 will be warmest year on record

The Copernicus Climate Change Service (C3S) has found that October 2023 was the warmest October on record globally, with an average surface air temperature of 15.30°C, 0.85°C above the 1991-2020 average for October and 0.40°C above the previous warmest October, in 2019. With these findings, Copernicus researchers are now "virtually certain" that 2023 will be the warmest year on record.

Samantha Burgess, deputy director of the Copernicus Climate Change Service (C3S), said, "October 2023 has seen exceptional temperature anomalies, following on from four months of global temperature records being obliterated. We can say with near certainty that 2023 will be the warmest year on record and is currently 1.43°C above the pre-industrial average. The sense of urgency for ambitious climate action going into COP28 has never been higher."
https://tinyurl.com/9h7dn63z

Jack Roper

BLAZE A TRAIL

Is wildfire suppression leading to the accumulation of fuel loads and increasing the risk of catastrophic fires? A new modeling system has been developed to investigate this theory

In 2020 the state of California saw five of its seven largest wildfires since reliable records began in 1932. A total of 9,917 fires burned 1,780,000ha, or 4.4% of California's total land area, versus just 105,218ha burned in 2019. Yet prior to 1800, at least 1,821,085ha, and sometimes up to 4,856,227ha, burned in the region now known as California every year, according to UC Berkeley researchers.

"We know that fires happened frequently in western North America," says Susan Prichard, research scientist at the University of Washington College of Forest Resources. "It wasn't caused just by lightning but also by indigenous cultural burning. For the past century a grand experiment has removed fires from the landscape, allowing fuels to grow and creating a tinderbox."

Prichard believes decades of fire suppression have led to enormous fires recently ravaging the US. For wildfires, mature forests represent combustible fuel. Letting them burn limits fuel build-up and creates resilient landscapes. Putting them out means that when fires do come, they are far larger and less controllable. Reburn is a modeling tool that illustrates this principle.

UNDERSTANDING SPOT-FIRE SPREAD

Containing a wildfire can depend on understanding the spread of spot-fires ignited by embers transported downwind by plumes of hot, turbulent air shaped by forest canopies. As Californian wildfires raged in 2018, Stanford PhD researcher Hayoon Chung realized that her study of ocean currents flowing over seagrass could help to understand this process. "We saw some physics from our work on aquatic systems that could translate to the wildfire field," says Chung. "We modified our experiments in water to reflect parameters of interest in wildfire systems."

Experiments conducted in a 9m water-flume used wooden dowels in repeat patterns to represent forest canopies. As water flowed over them, a hot water jet directed upward through the dowels simulated fire plumes interacting with the canopy. Finally, microplastic rods and spheres representing embers were injected and their downstream dispersion observed.

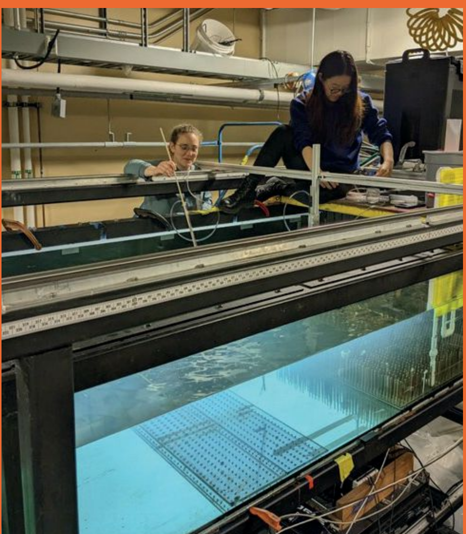
"In fluid dynamics we can model air flow around an airplane by putting it in water," explains Chung's colleague, Prof. Jeff Koseff. "We can model flows in water using air. We simply adjust the terms of force equations to compensate for the

303,500ha

The approximate area the Reburn system can iteratively model fire spread over landscapes

> **“We now know there’s no stopping fires, so we need to live with them better”**

Susan Prichard, research scientist, University of Washington College of Forest Resources



density and viscosity of the medium. It’s called the principle of similitude,” Koseff adds.

Chung’s work demonstrated that a canopy’s relative density determines the intensity of rollers, or vortices, that interact with the plume. This could inform strategic thinning of forest canopies to forestall violent and unpredictable wildfire plumes and reduce dispersion of embers.

“Fuel breaks created to contain fires and provide access to firefighters may have unintended effects,” comments Chung. “Our current project explores how rollers created by vertical canopy structures impact the transport and settling of embers. For fire managers, it’s bad news when they’re more widely dispersed.”

Chung’s work could enable models to better represent spot-fire spread, which fire managers today must attempt to predict using empirical methods. “People are trying to create accurate models using computational fluid dynamics,” she says. “Previous experimental modeling tended to focus on simpler ballistics models based on the background flow. We’re saying that there may be other physics, related to vertical structures and turbulence, which causes embers to settle very differently.”

Wildfire modeling

“Reburn is a modeling system that iteratively models fire spread over landscapes of, say, 750,000 acres [303,500ha],” Prichard explains. “It runs thousands of years of simulations in a couple of weeks. It grows fuels by one timestep every year, as fires are allowed to burn and bump into areas burned by past fires. Reburn provides a safe space to imagine an alternate reality where fires run wild and do the good work of limiting fuels.”

Prichard developed Reburn with colleagues at the US Forest Service’s Pacific Northwest Research Station, including Paul Hessburg and Brion Salter. It initially modeled the area of the Tripod Complex Fire, which burned 70,800ha of north-central Washington state in 2006. “Paul told me the Forest Service had extinguished 300 known fire-starts within Tripod Fire since 1940,” Prichard recalls. “That inspired the project. We’re now looking at similar study areas in northern California and British Columbia.”

Reburn shows how possible futures diverge according to the risks we accept. Wildfires represent a vivid and immediate risk anyone can see, to which suppression is a natural response. Forests overloaded with fuel present risks less tangible but potentially greater. “Anyone who’s lived through a wildfire, breathed the smoke and recognized the reality of Tolkien’s Mordor doesn’t want more fire,” says Prichard. “We’ve invested billions and continually increased firefighting forces, but managing short-term risk hasn’t worked. We now know there’s no stopping fires, so we need to live with them better.”

Change of direction

Prichard believes a shift in approach for wildfire management is needed. “Our messages are percolating through to Congress,” she says. “Republicans and Democrats are uniting around a common language of proactive versus reactive. California has shifted from 100% suppression to a prescribed fire program. We could also allow some wildfires to burn.”

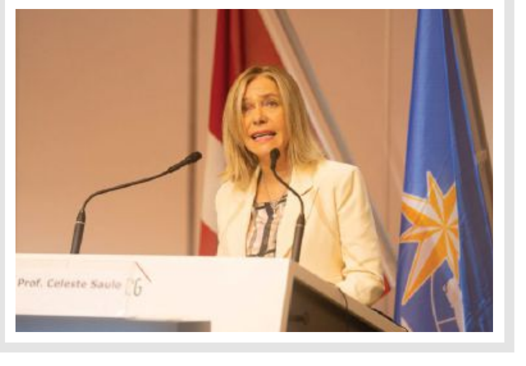
“Suppressing fires got us into this problem,” states Mike Falkowski, program manager for the Applied Sciences Wildland Fire program at NASA and lead for the NASA FireSense project. “Now we have climate change layered on top. Absolutely, we must put out fires that threaten communities. But we can be smarter about which fires we let go. If we can better understand fuel moisture content and predict air quality impacts, we may become more comfortable lighting prescribed fires.”

Reburn is intended to provide wildland and fire managers with means to understand the value of wildfires, but there are no plans to develop it into a smart and seamless operational application. “It’s really only a demonstration tool,” says Prichard. “It’s just on someone’s computer. We use ArcGIS, a common mapping tool, to layer on topography, fuel and other variables in geospatial pixels and then update the base landscape after each fire season.” ∎

Helen Norman

The WMO's first female secretary-general, Prof. Celeste Saulo, makes a call for action to the entire meteorological sector to address the unequal impact of extreme weather worldwide

CALL FOR ACTION



It is no secret that climate change is increasing the frequency of extreme weather around the world. Scientific studies indicate that events such as heat waves and large storms are likely to become more frequent and more intense with human-induced climate change. Extreme daily precipitation events, for example, are projected to intensify by about 7% for each 1°C of global warming, notes the Intergovernmental Panel on Climate Change.

This link between climate change and extreme weather has been thoroughly documented, but what is not often addressed is that the world's most vulnerable nations are suffering disproportionately. "Our world is becoming more and more unequal," says Prof. Celeste Saulo, who will become secretary-general of the WMO on January 1, 2024, taking over from Petteri Taalas, who has completed two terms in the role.

"People in developing countries and small island developing states [SIDS] are particularly vulnerable to the impact of climate change and extreme weather, and not enough is being done to address this," she continues. "I am very, very worried about this. The climate and inequality crises need to be addressed at the same time so that no one is left behind.

"We are far from solving this right now and that is why I am taking this opportunity to make a call for action to the entire meteorological and hydrological sector, including public and private organizations, governments, individuals, academic and any other stakeholders, to come together now to address both the climate crisis and inequality in a collaborative way. If we don't act now, the narrow window of opportunity to stop climate change, and the deadly impact it will have on vulnerable nations, will rapidly close."

> The climate and inequality crises need to be addressed at the same time so that no one is left behind"

2027

The year the Early Warnings For All (EW4All) initiative will ensure every person on Earth is protected by early warning systems

Career to date

Saulo's call for action comes a few weeks ahead of her taking up her new role as SG of the WMO – one of the most important positions in the meteorological sector and one that has never been held by a woman in the organization's 150-year history. "This is a great opportunity for me, for women worldwide and for the developing world," she says. Saulo is currently a WMO vice president and has headed the National Meteorological Service of Argentina (SMN) since 2014. In June 2023 she won a landslide vote for the role of SG at the 19th World Meteorological Congress in Geneva.

"My ambition is to lead the WMO toward a scenario in which the voice of all members is heard equally, prioritizing those most vulnerable, and in which the actions it undertakes are aligned with the needs and particularities of each one of them," she adds.

Saulo's passion for addressing the inequality issue alongside the climate crisis is rooted in her career to date, which has been in the developing nation of Argentina. Her enjoyment of both physics and mathematics led her to study meteorology at graduate level. "During my studies I developed a great love for meteorology and the combination of physics and models to generate tangible results," she says. "This love led me to join the academic sector, where I became a professor and researcher at the University of Buenos Aires.

"I have a love for teaching," she continues. "I especially enjoyed being with the students and learning from them, too. While working as a professor and researcher I learned about numerical weather prediction, atmosphere dynamics and thermodynamics, mesoscale meteorology, cloud dynamics and cloud microphysics. I became really interested in how we can improve the quality of forecasts, especially at a local level."

Following her professor role, Saulo became director of the Department of Atmospheric and Ocean Sciences at the University of Buenos Aires. "I was then asked by my government to take up the position of head of the National Meteorological Service of Argentina," she adds.

Under her leadership the SMN underwent a strong modernization process with sustained advances in observation, forecasting and communication methods, and the implementation of a new early warning system.

Saulo has been involved with the WMO since 2015, when she was elected as a member of the Executive Council. Then in April 2018 she was elected as second vice president for the WMO and, in June 2019, was elected first vice president, becoming the first woman to hold the office.

She has also been a member of various WMO expert scientific panels, including the Scientific Steering Committee for the World Weather Research Programme, the Working Group on Seasonal to Interannual Prediction, and the World Climate Research Program's Climate and Ocean Variability, Predictability and Change panel for the Variability of the American Monsoon Systems.

EARLY WARNINGS FOR ALL

The Early Warnings for All initiative – currently the WMO's top priority – will ensure that every person on Earth is protected by early warning systems by the end of 2027. Its Executive Action Plan is organized along the four pillars of a multihazard early warning system, including disaster risk knowledge, observations and forecasting, dissemination and communication, and preparedness and response. The WMO leads the implementation of the second of these and supports all the others.

According to the WMO, it is currently working alongside the UN Office for Disaster Risk Reduction, the International Federation of Red Cross and Red Crescent Societies, and the International Telecommunication Union to step up coordinated action, initially in 30 particularly at-risk countries, including small island developing states (SIDS) and least developed countries. "Additional countries are expected to be added as this vital work with partners gathers pace, scale and resourcing," according to the WMO.

Early warning systems have helped decrease the number of deaths resulting from hazardous weather, water and climate events. The latest data from the WMO's Atlas of Mortality and Economic Losses from Weather, Climate and Water-related Hazards revealed that mortality rates from extreme weather have fallen thanks to early warnings. In the decade 1970-1979 there were more than 556,175 reported deaths from weather-, water- and climate-related hazards. In 1980-1989 there were 666,000 deaths and in 2010-2019 the figure was down to 184,000.

However, major early warning gaps still exist, especially in SIDS and developing countries. Between 1970 and 2021, extreme weather-, climate- and water-related events caused nearly 12,000 disasters, with economic losses of around US$4.3tn and a death toll of two million, with 90% of these deaths in developing countries. "This is such an important initiative for the WMO, and one that will help save lives around the world and significantly address the global inequality issue," Saulo says.

Prof. Celeste Saulo's vast teaching experience has been mainly related to numerical weather prediction, atmosphere dynamics and thermodynamics, mesoscale meteorology, cloud dynamics and cloud microphysics

> "We need to build capacity at local and regional levels so that all these high-level initiatives, such as Early Warnings for All and GGGW, can be successful"

Building bridges

"The past 10 years have been a huge learning curve for me," Saulo says. "I learned about the operational aspects of the meteorological sector and expectations from society and stakeholders. It has been a wonderful experience and my background in academia has really helped me to understand what we could do and what we couldn't do with regard to forecasts. For example, I could identify tools that were available in academia, but they were isolated and not available for the national met service. I tried to build bridges and I believe I was rather successful at that."

This bridging of the academic and met service sectors has been one of Saulo's key achievements to date, she believes. "Being elected secretary-general of the WMO is certainly another highlight that I would never have dreamed of," she adds. "Besides this, however, bridging gaps between the different stakeholders in the meteorological sector is something I am very proud of, and I think this approach should be replicated around the world. After all, no one person can solve the climate crisis on their own.

"I also believe that national met services need to be more transparent with stakeholders and invite them to work with them," she continues. During her time at the National Meteorological Service of Argentina, for example, Saulo encouraged closer collaboration with sectors such as renewable energy and agriculture to address interdisciplinary problems.

"Thanks to this work we found that the met service in Argentina actually got more support from other government ministries than we did from our own. We built strong partnerships with the ministries of culture, transportation, agriculture, energy, etc, and with many other industries, and we gained the respect of colleagues, partners and stakeholders who were previously reluctant to work with us."

This idea of co-production led to the development of a new department the SMN called Meteorology and Society. "This provides a clear link between our services and information with general society and what they expect from us. Sometimes these two worlds can speak different languages, so the development of this new department was a great move to bridge the met service with the outside world," Saulo adds.

WMO key priorities

At the 19th World Meteorological Congress in Geneva in May/June 2023, three key priorities were identified for the WMO's Strategic Plan 2024-2027. The groundbreaking international campaign to ensure that everyone on Earth is protected against hazardous weather by life-saving early warning systems by the end of 2027 was recognized as the overriding priority, according to Saulo.

In October 2023, Prof. Saulo, in her role as director of the SMN, and colleagues kicked off construction of Clementina XXI, a new super-computer for SMN

The Early Warnings for All initiative is being conducted by the WMO alongside the UN Office for Disaster Risk Reduction, the International Federation of Red Cross and Red Crescent Societies, and the International Telecommunication Union. According to the WMO, currently only half of countries worldwide report having adequate multihazard early warning systems (see *Early Warnings For All*, page 13). "Meeting the 2027 deadline will be a huge challenge and one that will require coordinated action," Saulo says.

"Another priority for the WMO is the strengthening of the global observing system, which is currently weak. We need more observations. To achieve this, we need to make use of the Systematic Observations Financing Facility (SOFF), which is a financing mechanism that supports countries with the most severe shortfalls in observations to close the basic weather and climate data gap. SOFF is also a foundational element and delivery mechanism of the Early Warnings for All Initiative.

"We will also be working on the new Global Greenhouse Gas Watch (GGGW) initiative, which was approved at the 19th congress in Geneva," she continues. The GGGW aims to fill critical information gaps and provide an integrated, operational framework that brings under one roof all space-based and surface-based observing systems, as well as extensive modeling and data-assimilation capabilities.

GHG watch

The GGGW envisages a top-down approach to the flux evaluation, which builds on existing capabilities in surface- and space-based observations and modeling and ensures timely exchange of all observations and data, according to the WMO. In its initial configuration it is envisaged that the initiative will consist of four main components.

First will be a comprehensive, sustained, global set of surface- and satellite-based observations of CO_2, CH_4 and N_2O concentrations, total column amounts, partial column amounts, vertical profiles and fluxes, and of supporting meteorological, oceanic and terrestrial variables, internationally exchanged rapidly, pending capabilities and agreements with the system operators.

The other three components are prior estimates of GHG emissions based on activity data and process-based models; a set of global high-resolution Earth system models representing GHG cycles; and associated with the models, data assimilation systems that optimally combine the observations with model calculations to generate products of higher accuracy.

As an output, the infrastructure will produce gridded net monthly fluxes of CO_2, CH_4 and N_2O at a spatial resolution of 100km by 100km. These outputs can drive multiple applications, from contribution to the global stocktake to assessment of the fluxes from individual facilities or landscapes.

"On top of the key WMO priorities I also hope to empower the national meteorological and hydrological services providers," says Saulo. "We need to build capacity at local and regional levels so that all these high-level initiatives, such as Early Warnings for All and GGGW, can be successful. The 2027 target for Early Warnings for All, for example, will only be met if the local meteorological services are equipped with the tools and knowledge to produce and communicate timely warnings for extreme weather. A bottom-up approach is essential across all these initiatives."

> It's important to remember that diversity isn't just about gender but also about regional and cultural representation"

EQUALITY WITHIN THE WMO

On January 1, 2024, Argentina's Celeste Saulo will become the first woman to take the helm at the WMO – an institution that has roots dating back to 1879. The task at hand, Saulo notes, is daunting, but one that she is tackling head on in a bid not only to improve forecasting worldwide but also to address the wider equality issue.

"I have a huge opportunity to be a key role model for other women, younger generations and people from developing nations," she says. "I believe that I will be observed more closely just because I am female, but I plan on taking the opportunity to show what women are capable of. And with my background in Argentina I also hope that I can inspire colleagues from the developing world to follow their dreams of becoming leaders. Nothing is easy in the developing world, but I am proof that success is possible if you are committed and passionate."

Over its nearly 150-year history, senior positions in the WMO have been dominated by men. Saulo believes, however, that this is gradually changing and in some areas gender equality is "more or less balanced".

This gradual shift is thanks to the WMO Policy on Gender Equality, which was adopted by the 17th World Meteorological Congress in June 2015 to promote and facilitate gender equality across the WMO and to establish a mechanism to measure progress.

A Gender Action Plan was set up to identify concrete actions to improve gender equality in all parts of the organization, including constituent bodies, the secretariat, members' national meteorological and hydrological services, and other institutions. These actions included encouraging regional associations to include more women in their delegations, mentoring programs and training staff on gender bias. The WMO Gender Action Plan is the only one of its kind in the main bodies of the UN, as it includes constituent bodies while others only focus on the secretariat.

The plan has led to the average gender representation on the management groups of the technical commissions doubling from 20% in 2012-2015 to 42% in 2020-2023. Although less pronounced in the leadership of the regional associations, a considerable increase of 10% has also been observed in the same period. Furthermore, the share of female delegates to the Extraordinary Congress in 2021 reached 33%, marking a 5% year-on-year increase, WMO figures revealed.

"Bringing diversity into this organization will be a top priority for me," says Saulo. "It's important to remember that diversity isn't just about gender but also about regional and cultural representation. Currently the WMO is too biased toward men and the developed world, and I hope to encourage more balanced representation."

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LEAD BY EXAMPLE

As Argentina's Celeste Saulo takes up her role as the first-ever female secretary-general of the WMO, *Meteorological Technology International* speaks to six high-profile women in the industry inspiring the next-generation of female leaders

Diane Campbell

Dr Florence Rabier

Marianne Thyrring

Prof. Sue Grimmond

Dr Sarah Kapnick

Dr Sue Barrell

DIANE CAMPBELL

ASSISTANT DEPUTY MINISTER, METEOROLOGICAL SERVICE OF CANADA

Between her time with Natural Resources Canada and Environment and Climate Change Canada, Diane Campbell has spent more than 40 years in federal public service. Her current role sees her head up the Meteorological Service of Canada (MSC) and serve as Canada's permanent representative to the World Meteorological Organization (WMO).

Over the years Campbell has gained a strong love and passion for the met industry, especially its ability at WMO-level to work collaboratively for the greater good. Fifteen years since joining MSC she still "learns something new every day" in what she believes is the "best job ever".

"I have a degree in marine biology and the early part of my career was actually working in science-based programs with Environment and Climate Change Canada," Campbell explains. "Over the years I have worked on things like ecotoxicology studies in the Great Lakes, the impact of acid rain in Ontario, how metals are affecting the environment and remediation issues in the energy sector, plus many other projects.

"I quickly discovered that I loved the science environment and found it extremely motivating. I joined the met service 15 years ago, first leading a team to drive service transformation before managing different parts of the organization. Then in 2019 I became assistant deputy minister, succeeding David Grimes, who was an inspirational leader both in Canada and in his role as president at the WMO."

Campbell's role today sees her oversee all programs and people in MSC, including looking at current and future trends, technologies and challenges, such as the changing role of the private sector, machine learning's impact on forecasting, and emergency management.

"Like everywhere else in the world, Canada is being heavily affected by climate change and it is impacting citizens directly," she comments. "To tackle this we must evolve as an organization and better understand the needs of our clients and our citizens."

To do this, MSC is currently amid a "major transformation" project, notes Campbell. The organization has a services-based approach to forecasting at its core. "We are working toward an impact-based forecasting approach, and the integration of vulnerability information with traditional meteorological data, to better service our citizens' requirements for things like the record-breaking wildfires of 2023 and the deadly heat dome of summer 2022 in British Columbia. We want to provide the right information as far upstream of an event as possible."

Campbell believes that the WMO's new female secretary general, Prof. Celeste Saulo, will be a "fantastic role model" for women around the world. "There are now so many impressive women in leadership positions and represented at the WMO, including Dwikorita Karnawati, director of the Indonesian Agency for Meteorology, Climatology and Geophysics; Penny Endersby, chief executive of the UK Met Office; and Virginie Schwarz, head of Météo-France, as well as many others. Also, at the 2023 WMO Congress in Geneva there were so many more women in the room. We are seeing a shift toward gender equality in the sector.

However, there is still work to be done when it comes to gender equality, and equality in general, within the meteorological sector, Campbell notes. "Here at MSC just over 30% of our workforce is women but we are making tangible gains in attracting females to apply for jobs in the organization," she says. "But more needs to be done, especially concerning females in technical, engineering and management roles. I believe we need to partner with academic institutions to try to encourage women to take up careers in these areas. This will help generate a pipeline of talent."

40

The number of years Diane Campbell has spent in federal public service

> "We are working toward an impact-based forecasting approach, and the integration of vulnerability information with traditional meteorological data, to better service our citizens' requirements"

DR FLORENCE RABIER

DIRECTOR GENERAL, EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS (ECMWF)

Dr Florence Rabier first became inspired by the meteorological sector when she was a young girl living by the sea in southwest France. "There were a lot of storms rolling in off the sea and the weather was very variable," she says. "We always needed to be prepared for changeable weather conditions. That is where my interest in the weather and forecasting began."

Dr Rabier has been director general of ECMWF since January 2016, after two years leading the center's Forecast Department. Her career so far has taken her back and forth between Météo-France and ECMWF. "I studied mathematics, physics and meteorology before joining Météo-France in the 1980s. Since then I have switched roles between the French met office and ECMWF, working on wave modeling, data assimilation, numerical weather prediction, forecast verification and model diagnostics," she explains.

According to Dr Rabier, her career highlight is her role in the development of a data assimilation method, called 4D-Var, in 1997, which was a first worldwide. This contributed to the optimal use of satellite observations in weather forecasting and led to substantial improvements in ECMWF's forecasts. "This is what I worked on for my PhD and 25 years later it is still used today. Other meteorological centers are also using it as it really was a step change in the quality of the forecast."

In her current role as director general of ECMWF, Dr Rabier and her team are working on blending the use of machine-learning technology with physics-based modeling. "I hope that within the next few years we will have managed to incorporate machine learning at the right level so that we can really make the best of both traditional and new techniques to deliver high-quality services to our member states," she says.

She also highlights how "new space" – the emergence of the private space industry – and its contribution to Earth observation via private-sector satellites is set to disrupt the system. "We have to embrace this," she says. "At ECMWF we use all sorts of satellite data, including operational and research data, blended to create forecasts. We need to ensure that data coming from new space systems is accurate. This will mean we need to be much more flexible in the way we use data, which is a manual process now, but maybe machine learning could help us to characterize bias and do quality control in a cleverer way in the future."

In terms of gender equality, Dr Rabier notes that ECMWF is gradually becoming more balanced, with more members of the leadership team now female. "We have a gender, diversity and inclusion plan and we do a lot of training to ensure that there is no unconscious bias during recruitment or operations in the business," she explains.

MARIANNE THYRRING

DIRECTOR GENERAL, DANISH METEOROLOGICAL INSTITUTE (DMI)

Marianne Thyrring became director general of the Danish Meteorological Institute (DMI) in 2013 after many years working in the fields of climate and the environment for the European Commission as well as various ministries in Denmark, including the Ministry of Environment. "I was always curious about the scientific and operational parts of climate and environmental policies, which is what led me to DMI," she says.

During her earlier years at DMI, Thyrring was involved in making the organization more public-facing and making better use of the large stores of weather-related data it held. "This kind of work really fuels me," she explains. "In simple terms I like to make things better by implementing change. I am very proud of where DMI is today. DMI has been able to change its profile from a conservative monopoly to a modern public agency focusing on the societal value we can deliver."

Thyrring notes that during her career to date she has mainly worked in male-dominated environments. "Even though we are working to change this and make the playing field level, I believe that development in gender equality is rather slow. The main reason is that it is still difficult to get female candidates to apply for the very top positions."

Although the shift to gender equality is slow, Thyrring is seeing more females joining the met industry. "In the past 10 years we have recruited more female meteorologists than male, for example," she says. "We are also seeing an increase in female climate researchers at DMI, contributing to our diversity."

To help it achieve equality, DMI has established a network specifically for female leaders, which facilitates mutual support and the exchange of experiences. "By creating this network we aim to empower and inspire our female leaders while promoting an inclusive culture within the organization at DMI," Thyrring says. "We are convinced that diverse leadership will contribute to a more dynamic and innovative organization."

> "DMI has been able to change its profile from a conservative monopoly to a modern public agency focusing on the societal value we can deliver"

> "I hope that within the next few years we will have managed to incorporate machine learning at the right level so that we can really make the best of both traditional and new techniques to deliver high-quality services to our member states"

Looking at what the future holds for DMI in general, Thyrring continues, "I would like us to take a closer look at our work culture to try to increase productivity. We want to cultivate a culture marked by mutual trust and respect, where all team members can be themselves."

DMI is also preparing for the start of operation of its new supercomputer, which is being developed alongside met services in Iceland, Ireland and the Netherlands, and is due to come online in late spring 2024. "This will provide earlier and more accurate weather forecasts than ever before and enable us to deliver better weather warnings," comments Thyrring. "The collaboration, known as the United Weather Centres-West (UWC-W), will also bring changes in our respective organizations as there will be considerable economies of scale when four countries come together to share the same computer and data model.

"Another project that has been a major focus at DMI is that we have been tasked with predicting land-based flooding. We already issue warnings for heavy rainfall, as well as flooding from the sea, but we have not previously been authorized to develop a warning service for river and stream flooding. This initiative was prompted by the devastating floods that hit central Europe in 2021. One of the most important tasks is to give the public and the emergency services the opportunity through our warnings to react fast."

PROF. SUE GRIMMOND

PROFESSOR OF ATMOSPHERIC AND OCEANIC SCIENCE, UNIVERSITY OF READING, AND MET OFFICE JOINT CHAIR

Sue Grimmond's career to date has seen her installing mobile pneumatic towers in strong wind gusts in Tucson, Arizona; visiting weather stations in schools in Mexico City; installing a flux site in Ouagadougou, Burkina Faso; and standing on roofs in cities across the world – all as part of various fieldwork projects.

Starting out as a hydrologist with an interest in snowmelt, flooding and irrigation in New Zealand, she moved to Canada to complete an MSc and PhD before spending 17 years in the US at Indiana University and then moving to the UK for roles at King's College London and finally at the Meteorology Department at the University of Reading in 2013.

Grimmond's career has seen her travel the world and move from a focus on hydrology to one that incorporates meteorology and urban climates. A career highlight is when in 2021 she became the first female recipient of the Royal Meteorological Society's prestigious Symons Gold Medal.

> "We are aiming to incorporate humans and their behaviors into weather and climate forecasts and projections"

This award recognized her research in understanding urban climates, her contribution to improving the environment in cities around the world, and the selfless fostering of young researchers. "The award was a lovely recognition of the work my team has done, but even more so for the field of urban climatology," Grimmond says. "When I started out there were few people working explicitly on and in cities, but now it's mainstream. To know I have been part of that is very special."

The main project Grimmond is working on currently is called 'urbisphere', which aims to forecast dynamic feedback between weather/climate and cities. "We are aiming to incorporate humans and their behaviors into weather and climate forecasts and projections," she explains. "It's a multiyear project working in Berlin, Paris, Bristol, London, Freiburg, Stuttgart, Heraklion, Nairobi, Beijing, Colombo and Lahore. We're measuring, modeling, undertaking surveys and working with a broad group of stakeholders and end users. My team is focused primarily on the modeling."

Grimmond credits some of her success to the female support she has received along the way. "Right from the outset I benefited from great mentors, other female meteorologists and friends, who were all very generous with their guidance and support," she says.

Looking at what needs to be done to encourage more women to join the industry, she concludes, "Meteorology needs to be open to women who have come through a range of pathways and ready to support them in acquiring the skills they need. There's no question that gender – and other – inequalities still exist in some schools, and we need to make sure that women who haven't followed a traditional STEM training path can enter the sector."

DR SARAH KAPNICK

CHIEF SCIENTIST, NOAA

Sarah Kapnick's first job related to meteorological applications was structuring catastrophe bonds at a bank. This required using catastrophe models to quantify expected losses from windstorms in Europe and hurricanes in the US, and using that data to develop bonds with payouts when extreme weather occurred. It was this job that inadvertently led to her successful career in the met sector and to her current position as chief scientist at NOAA.

"I was fresh out of college when I started in the catastrophe bonds role in the mid-2000s," she explains. "I was curious about the science of the bonds and how it needed to evolve with climate change. I was completely obsessed with the problem. My boss at the time, however, told me my job was not science and didn't see climate change as an issue!

"When I argued with him, he said if I believed that much in the problem I should make it my career. I took his advice, believing in my intuition and curiosity, and that led to me getting a masters in atmospheric sciences and a PhD in atmospheric and oceanic sciences."

Kapnick's role today sees her focusing on policies and program direction for science and technology at NOAA and ensuring that the work at NOAA informs the future of innovation and commerce beyond the agency. "Currently I am working on encouraging innovation in climate modeling and the use of climate information to inform decision makers – from communities and small businesses to states, the federal government and multinational corporations," explains Kapnick. "We call this work building a climate-ready nation to manage our exposure to the current climate, and also to mitigate and adapt to climate change."

2022
The year Dr Kapnick was appointed chief scientist at NOAA

Speaking about the most important science and technology goals for NOAA over the next few years, she continues, "We want to improve our models for forecasts and predictions. This requires bringing in new data sets from us or third parties via data assimilation and targeted field campaigns to understand key processes in the Earth system. We are also building out our ocean observations for seasonal to decadal prediction to improve prediction skill and applications and develop social, behavioral and economic sciences to communicate the value and impact of our science and technology."

Alongside these projects, Kapnick is also playing a big role in encouraging gender equality within NOAA. "We have built plans for improving diversity in our workforce, including measuring where we are and where we hope to be in the future," she says. "I have also brought up the issue and had solutions brainstormed in different parts of NOAA. It's something that requires multiple solutions and strategies. It can't be solved in isolated areas but requires systematic cultural change."

To encourage more women to start a career in the met sector, Kapnick believes that mentorship can play a key role. "As I've risen through the ranks, I've focused increasingly on mentorship and sponsorship of those coming up behind me to make sure they get opportunities, develop critical skills, and hopefully not feel the loneliness I did as an early and mid-career scientist."

> "Currently I am working on encouraging innovation in climate modeling and the use of climate information to inform decision makers"

DR SUE BARRELL

SCIENCE LEADER, INDEPENDENT CHAIR, DIRECTOR, MENTOR

In 2022 Dr Sue Barrell was named Laureate of the International Meteorological Organization (IMO) Prize for her leadership in the international weather, water and climate community and for a career of commitment to the WMO. The prize (named after the WMO's predecessor, the IMO) came four years after she officially retired from her role as chief scientist at the Bureau of Meteorology (BoM) in Australia – an organization she was part of for 38 years.

Starting as a graduate meteorologist at BoM, Dr Barrell had a distinguished career spanning operational forecasting, research, science, climate, infrastructure and data policy, retiring from her final role as BoM chief scientist, with responsibility for research, international and national science relationships, innovation, STEM, diversity and inclusion, in 2018.

"I also represented Australia and led high-level activities at the WMO, the UN Framework Convention on Climate Change [UNFCCC] and the intergovernmental Group on Earth Observations [GEO]," she says.

It was her involvement with the WMO that led to one of her proudest career achievements. "My engagement with the WMO started as I was initiating the redesign of BoM's observing system strategy, and I became actively engaged in the development of the WMO Integrated Global Observing System [WIGOS] concept, going on to lead that process, through to its adoption and implementation, as the vice president of the Commission for Basic Systems," she explains.

"As we started to better understand the implications of integrated Earth system data across surface and space-based systems and all domains, as well as the growing requirements and opportunities of NWP, data policy became a more visible issue. I led initiatives first at the Bureau and then at the WMO to better articulate the need for national and international data coordination and exchange. Ultimately this culminated in the 2021 congress approval of the WMO Unified Data Policy, which was a significant achievement that I share with many others," Dr Barrell adds.

Following her retirement in 2018, Dr Barrell continued to work with the WMO on various projects, which focused on data policy and polar and high mountains, but over the past year she has relinquished responsibility. "My focus has now moved more to roles in Australia, with a special focus on research infrastructure and data. They span some exciting and diverse science challenges including deep oceans, the impact of climate change on coral reefs, and the search for dark matter – from 1km underground in a gold mine!"

38
The number of years Dr Barrell worked for the Bureau of Meteorology in Australia

Looking at what she believes the future holds for the met sector in general, Dr Barrell says, "Technological developments will never stop, from miniaturized sensors to AI, adding value to the information and services delivered. The pace of these changes brings risks as well, and it is critical for industry bodies, the WMO and national agencies to monitor and assess the risk, impact, benefit, cost, equity, ethics, etc of changes in the context of the need being met, the standards being applied and the genuine value being delivered."

> "The gender equality challenges lie not just within the industry, but also in having the right policies and practices in place to source, employ and retain qualified women"

Dr Barrell notes that throughout her whole career in the meteorological sector she has always "been treated with respect" despite sometimes being the only female in the room. "The gender equality challenges lie not just within the industry, but also in having the right policies and practices in place to source, employ and retain qualified women, and in the feeder pool itself, getting greater diversity into STEM education streams. The latter needs to start in school; university is too late," she explains. ∎

Jack Roper

EARLY AD

OPTERS

There is no single silver-bullet solution for the early detection of wildfires, according to leading meteorological experts. A toolbox of technologies including drones, ground-based sensors, satellites and AI models needs to be used to predict and monitor fires to save lives and protect infrastructure

Early wildfire detection

Early wildfire detection is critical. "Extinguishing a wildfire in the first five minutes requires a bucket of water," comments Grigoris Konstantellos, mayor of Vari-Voula-Vouliagmeni in Attica, Greece. "After 15 minutes it requires two fire trucks. After 30 minutes you need 10 airplanes to fight something uncontrollable."

In five years Attica has lost 38% of its forests to wildfires aided by heat and drought and abetted by intense winds. The coastal municipality of Vari-Voula-Vouliagmeni is surrounded by pine forests parched to tinder by heat waves of increasing frequency.

"This is climate change," adds Konstantellos. "We used to get maybe two days of 40°C heat. Now we have two weeks and see wildfires even in the winter. We're slowly transforming green, livable areas north of the Mediterranean into desert."

Drone-based EWS

His administration has responded by developing drone-based early wildfire detection. The drones are equipped with digital cameras, thermal cameras with lasers to capture spot temperatures, transponders for identification and even 200m directional microphones so that warnings can be communicated to people in restricted forests during high-risk periods.

"In the summer, one drone patrols the city boundaries 24/7, with a second on standby for emergency situations," Konstantellos explains. "Each drone is controlled remotely by a certified operator at our operations center and sends back real-time imagery. We obtained a license to fly remotely anywhere in the city, up to a 1,000ft [305m] operational ceiling."

The system was conceived after a fire nearly engulfed the municipality in 2022. Fanned by severe winds, it quickly climbed a neighboring mountain and entered a ravine, which became a savage funnel of concentrated flame. Only when winds died down at sunset could firefighters master the flames.

"Initially they chased the fire rather than cutting in front," Konstantellos recalls. "We fought the fire on the mountain. We lacked the situational awareness to make effective decisions. We ran behind the extinguishing forces to provide water, but they had moved elsewhere."

The drone system was developed with Vanguard, a security company using drones to deter theft of copper power lines from railways. Previously two fixed cameras at panoramic vantage points had been used to detect smoke, but were little help in fighting a fire. Now Konstantellos can direct the drones and view real-time footage on his iPhone as an emergency situation unfolds.

ABOVE: A drone monitoring a controlled-burn experiment by the University of California, Davis, autumn 2023 at Grouse Ridge

BELOW: Prescribed fires are an important tool used by Cal Fire and other forest management entities to reduce wildfire risk

> We use instruments similar to the infrared atmospheric sounding interferometer (IASI) on European Met-Op satellites to measure temperature and humidity"

Dave Turner, senior scientist, NOAA

Ground-based monitoring

In 2020, Californian wildfires burned 1,780,000ha, destroyed 10,000 structures and caused over US$12bn in damage. The California Department of Forestry and Fire Protection (Cal Fire) is evaluating detection technologies, but sees limited scope for drones.

"There is no determined need or immediately applicable solution for using unmanned aerial systems (UAS) in wildfire detection," explains Marcus Hernandez, deputy chief of wildfire technology research and development. "Technologies are being developed to allow crewed and uncrewed aviation to work harmoniously. Cal Fire uses UAS for some operations, but only incorporates additional technologies that are proved safe and reliable."

In Mendocino County, Cal Fire is testing networks of wireless ground-based sensors with infrared, gas and particulate detection capabilities. The trials will establish whether these sensors offer sufficiently reliable power and connectivity for dependable wildfire detection. Cal Fire sees promise in AlertCalifornia, a statewide network of more than 1,000 elevated pan-tilt-zoom cameras operated by the University of California, San Diego.

"The AlertCalifornia network has detected fires before they were reported via the 911 system," says Hernandez. "The technology detects anomalies in the captured video that may indicate the presence of smoke. It enables a professional to verify what is detected, which reduces false detections. We're assisting in training an AI model for automated detection of anomalies."

Space-based detection

NOAA provides actionable wildfire information from satellite imagery. GOES-R geostationary satellites 35,405km from Earth measure mid-wave infrared signals at moderate spatial resolution to capture diffuse heat from fires.

"Geostationary satellites are constant sentinels," says Mike Pavolonis, wildland fire program manager at the NOAA Satellite Service (NESDIS). "They enable detection of house-sized fires within 5 to 30 minutes of ignition. AI is a force-multiplier that can mimic a human expert checking imagery. We have a prototype real-time AI system to detect fires and issue alerts."

The NOAA

3km

High-Resolution Rapid Refresh model restarts with new observations every hour to produce 48-hour forecasts

But geostationary satellites cannot see fires concealed by cloud, and their coverage deteriorates over northerly latitudes. To see fires in Alaska, NOAA relies on low-Earth-orbiting satellites that overpass only periodically. Ground-based technologies have a complementary role and must become interoperable with space-based detection.

"Every technology has a detection latency, depending on conditions," Pavolonis says. "No single technology will address early detection completely. California's ground-based tower cameras have enabled some very early detections. Drones face complex logistical hurdles. It's unclear where you'd position them, and the concept of operations is still evolving."

"The challenge is how we routinely operate drones in a safe and automated manner," adds NOAA senior scientist Dave Turner. "Aviation authorities are not just concerned with mid-air collisions. If a drone unexpectedly comes down on a highway it could cause an accident. The western US is vast, but drones only see a relatively small area, depending on altitude."

PREDICTING SHORT-TERM WILDFIRE EVOLUTION AT HIGH RESOLUTION

The National Oceanic and Atmospheric Administration is deploying radar, lidar and infrared instruments across the western US to make long-term measurements of fire weather and determine how a wildfire interacts with the boundary layer.

"Thermal conditions, humidity and wind determine a fire's growth," says NOAA senior scientist Dave Turner. "If temperatures near the ground are colder than aloft, smoke becomes trapped in valleys, creating negative health effects. The fire itself modifies the boundary layer, so conditions upwind and downwind can look quite different."

NOAA will deploy sensors at sites in Arizona, California, Colorado and Idaho to capture these interactions close to active fires in four distinct climatological regimes. The sensors include radar wind profilers, ceilometers and infrared spectrometers. "We're using both active and passive sensors," says Turner. "We use instruments similar to the infrared atmospheric sounding interferometer (IASI) on European Met-Op satellites to measure temperature and humidity. It's like one pixel from IASI on the ground looking upward."

Data collection will begin in spring 2025 and will support ambitions for an on-demand, operational National Weather Service model to aid decision makers by predicting short-term wildfire evolution. Since fire behavior depends on complex and localized terrain, this may require 100m spatial resolution. "Doubling resolution makes a model eight times more computationally expensive," says Turner. "Going from a 3km to a 100m grid-spacing costs thousands more, so we make it affordable by using a small, perhaps a 50km by 50km, domain. As winds quickly move through that, so a second model must provide boundary conditions."

The 3km High-Resolution Rapid Refresh model, which NOAA restarts with new observations every hour to produce 48-hour forecasts, would provide boundary conditions to drive the 100m wildfire mode. Improving its accuracy is a central aim of Turner's measurements, he notes.

"We will collect data for up to 10 years," adds Turner. "Of course that depends on instrument health and continued funding, but it's hard to separate weather from climate events like El Niño and La Niña without a long data record."

Agile deployments

NASA's FireSense program aims to deliver operational technologies to partners tasked with managing wildfires. They address not just detection but also monitoring pre- and post-fire environments. FireSense will test novel sensors in flight campaigns with manned aircraft, typically over prescribed fires set to manage fire risk.

"We're flying radars and lidars to map fuel, hyperspectral sensors to observe fuel composition and synthetic aperture radars and L-band microwave radiometers to detect fuel moisture," explains FireSense program manager Michael Falkowski. "We're flying sensors to look at post-fire impacts. We're also pushing toward 24/7 detection and tracking with thermal sensors." This means taking an instrument such as NASA's spaceborne MASTER multispectral imager and reducing its form factor, weight and power requirements to enable more agile deployments.

"If we shrink those sensors we could potentially put them on high-altitude platform stations (HAPS), which hover in the stratosphere for 30 to 60 days, or on small satellites in low Earth orbit," comments Falkowski. "In five years, privately owned constellations of 50 smallsats the size of mini refrigerators in low Earth orbit could provide 12-minute wildfire detection."

The discontinuous snapshots of low Earth orbiters could thus be improved by having many passing over in a continuous carousel.

> "In five years, privately owned constellations of 50 smallsats the size of mini-refrigerators in low Earth orbit could provide 12-minute wildfire detection"
>
> **Michael Falkowski, program manager, NASA FireSense**

Proactive detection

If no single technology can solve early detection, University of California, Davis scientists are maturing ambitious plans for an integrated system using AI models, sensors, drones and cameras. It would predict areas of high wildfire risk to target drone-based detection.

"Factors that cause wildfire risk are temperature, humidity, and wind speed and direction," says Prof. Anthony Wexler, director of the Air Quality Research Center at the University of California, Davis. "California's complex topography means these conditions can vary wildly between valleys. Because conventional wind sensors are too expensive to put in every valley, we've developed US$25 prototype sensors with a 2D strain gauge to measure winds."

A statewide network of palm-sized temperature, humidity and wind sensors could identify wildfire-conducive conditions and feed a predictive model envisaged by Wexler's colleague, associate professor Zhaodan Kong. "We could fuse that sensor data, historic fire data and geographical understanding of where roads, campsites or power lines create a wildland-urban interface," says Kong. "We detect fires reactively

ON THE WEB

NCAR STUDY ON SIMULTANEOUS WILDFIRE FREQUENCY

The National Center for Atmospheric Research (NCAR) has found that simultaneous outbreaks of large wildfires will become more frequent in the western USA this century as the climate warms – putting major strains on efforts to fight fires.

The new study focused on wildfires of 404ha or larger. It found that wildfire seasons in which several such blazes burn concurrently will become more common, with the most severe seasons becoming at least twice as frequent by the end of this century.

"Higher temperatures and drier conditions will greatly increase the risk of simultaneous wildfires throughout the west," says Seth McGinnis, NCAR scientist and the lead author of the study. "The worst seasons for simultaneous fires are the ones that are going to increase the most in the future."

McGinnis says that decision makers can take steps to manage the future risk and impact of simultaneous fires. These range from thinning forests and conducting prescribed burns to increasing firefighting crews and equipment.

today, but a machine learning algorithm could proactively identify high-risk areas."

"Fundamentally, two things cause wildfires – lightning and humans," adds Wexler. "That's it. Human infrastructure adjacent to forest automatically elevates the risk of wildfires that could damage human habitations."

Drones equipped with chemical sensors would then be dispatched to at-risk locations to detect fires. Wexler argues that we often smell a fire before seeing it, and that wildfires producing visible smoke are already well advanced. Therefore, chemical sensors offer better odds than cameras of catching them in their infancy.

"Think of the drone with chemical sensors as a dog," says Kong. "It sniffs out and tracks the fire to its source, then switches to a camera to monitor it. We would need a swarm to cover larger areas. Our current octocopter rotorcraft can only fly for 30 minutes, but a hybrid vehicle that takes off like a rotorcraft then flies in a fixed-wing configuration could offer greater endurance."

There are some daunting obstacles, with little precedent for drones using their own sensors to decide where to fly. Currently Kong must obtain FAA approval for individual flights and each drone requires a dedicated pilot. This makes automated swarms a distant prospect, and a mission-tailored hybrid aircraft has yet to be built. "We have three drones equipped with the sensor package," says Kong. "We've collected data around prescribed burns conducted by Cal Fire, to build a model of how chemicals from a fire propagate temporally and spatially. By next summer we aim to demonstrate that a drone can track a plume to its source."

LEFT: NASA's FireSense project conducts airborne observations over wildland areas to collect data that can improve fire models

BELOW: Drones in Greece (below left) send back real-time imagery to an operations control room (below right), enabling authorities to better monitor wildfire spread

In five years, Attica in Greece has lost

38%

of its forests to wildfires aided by heat and drought and abetted by intense winds

Saving lives in Greece

At 5:00am on August 26, 2023, Konstantellos was woken by a call from the operations center advising him to check his camera feed. Beset by a rare and deadly dry thunderstorm, Vari-Voula-Vouliagmeni recorded 270 lightning strikes exceeding 1.5MV and six simultaneous wildfires. One drone provided situational awareness while a second patrolled in case new fires broke out.

"We extinguished six fires in 40 minutes," explains Konstantellos. "It was a textbook operation, wholly coordinated through the drones. We could see all six fires and the system directed the fire service where to proceed. It helped in critical decisions that could have affected lives. Sometimes those decisions are dressed with a lot of luck."

The system proved its worth and continues to evolve. Satellite guidance may soon allow drones to fly remotely and transmit imagery even behind mountains. New batteries could add 30 minutes of endurance. Vanguard has partnered with Intercom in developing an AI application to screen drone imagery and issue automatic alerts.

"We plan to have three drones flying continuously at 200m, tethered by a cable that provides continuous power and data transmission," says Konstantellos. "They can also be unhooked, fly and check, and then return."

Last year drones were twice scrambled to assist neighboring municipalities in combating wildfires and Konstantellos believes the system could be rolled out nationwide. Europe has faced crises before, but whereas wars eventually end, climate change is forever. "Everyone on the scale of authority must do something proactive," he says. "In Greece we saw a break in the bond of trust between citizens and the state. If you don't feel secure for yourself, your family and your property, we move to another scenario – one of criminality and social unrest." ∎

"We plan to have three drones flying continuously at 200m, tethered by a cable that provides continuous power and data transmission"

Grigoris Konstantellos, mayor of Vari-Voula-Vouliagmeni, Attica, Greece

Paul Willis

More research and tools are needed to help predict the effect of climate change on data-sparse mountain cryosphere regions globally, with experts predicting that rising temperatures and shifts in precipitation could have a severe impact on water availability

A TALL ORDER

With high temperatures, flooding, storms and wildfires becoming more frequent in many places around the world, the effects of climate change on human populations are increasingly apparent. But it is in the Earth's cryosphere that climate change has been most extreme.

According to NASA, Antarctica and Greenland are losing ice mass at an annual rate of about 150 billion tons and 270 billion tons, respectively. Glaciers, meanwhile, have been consistently shrinking, with the World Glacier Monitoring Service noting that leading up to 2020 there were 33 consecutive years in which glaciers lost, rather than gained, ice.

Many of these glaciers are in mountainous regions, such as the Himalayan glacier of Lirung in Nepal's Langtang basin, which Philip Kraaijenbrink, an associate professor in Utrecht University's department of physical geography, has been studying with the assistance of drones since 2013. According to Kraaijenbrink, the glacier has retreated hundreds of feet over the past decade, and there is even vegetation growing on the glacier now. "The situation is really changing," he comments.

A 2019 Intergovernmental Panel on Climate Change (IPCC) report on high mountain regions noted a general decline in low-elevation snow cover, glaciers and permafrost due to climate change in recent decades. According to the report, snow cover duration has "declined in nearly all regions, especially at lower elevations, on average by five days per decade".

Water supply issues

The loss of mountain cryosphere is likely to have serious repercussions for large swathes of the global population who rely on the water locked up in mountain snow and ice for their water supply.

There are currently 218 sensors, measuring different components of the water cycle, at 62 locations in the Langtang valley, that are running on 10-minute to one-hour temporal resolution

Mimi Hughes, a research meteorologist for hydrology at the US National Oceanic and Atmospheric Administration (NOAA), says that "all of the western US states use snowpack to some degree as a water resource". Meanwhile, the 10 major rivers that originate in the Himalayas supply freshwater to an estimated 1.3 billion people living in their watershed.

"We typically refer to mountains as the water towers of the world," says Caroline Aubry-Wake, a Canadian post-doctoral researcher currently studying cryosphere/groundwater/surface water interactions in the upper areas of the Langtang basin. "There's more precipitation in the mountains than in the lowlands, and there are also glaciers and snowpack that act as mini reservoirs for water storage."

In the case of snowpack, this water is stored over winter and then released as snowmelt in the spring. The agricultural communities that live downstream of these mountain ranges have come to rely on these melt cycles, which are becoming increasingly erratic due to climate change.

In the Indus basin, home to one of the largest irrigation systems in the world, there are several cropping seasons, comments Kraaijenbrink, "but one major cropping season coincides exactly with the glacier and snowmelt period." He adds, "So if you have less glacier and snowmelt right at the start of your cropping season to irrigate your crops, that's quite a big deal."

Ironically, the loss of mountain cryosphere may well increase the amount of downstream water in the short term, says Aubry-Wake, "As glaciers retreat at first, they can provide more water to downstream communities because they're melting more."

APPLYING THE SCIENCE: WYOMING CASE STUDY

Researchers in Wyoming have begun a project aimed at understanding the future impact of climate change on mountain farming communities there. "The Wind River Range is home to the largest glaciers in the US Rocky Mountains, but they are rapidly melting and are expected to diminish considerably in a warmer future climate," says Eli Boardman, who runs Mountain Hydrology, a research group based in the region.

Mountain Hydrology recently began a project to improve the quality of snow monitoring and runoff forecast information available to rural stakeholders living in the Wind River Range.

"The local agricultural communities are reliant on late-summer streamflow for sustained irrigation, but a coordinated response to drought or surplus water supply conditions has historically been limited due to a lack of reliable snow monitoring information," explains Boardman.

The project, which recently received funding from the US Bureau of Reclamation, will involve an airborne survey of the snowpack. "We will primarily be using airborne lidar to measure gridded snow depths over entire watersheds, which we can combine with fieldwork-based snow density models to estimate the volume and spatial distribution of snow water equivalent (SWE)," he adds.

According to Boardman, the project hinges on a collaboration with the Airborne Snow Observatories, an operational science group that began at NASA's Jet Propulsion Laboratory and specializes in delivering lidar-based snowpack measurements.

"The watersheds are mostly contained within a federal wilderness area, so existing in-situ snow monitoring instrumentation is limited to low elevations that are not representative of the overall snowpack conditions. By deploying airborne surveys, we can measure the full snowpack water volume upstream of important decision points like reservoirs and diversion canals," Boardman explains.

As part of the project, which will run until late 2026, Mountain Hydrology will acquire lidar elevation maps of the glacier surfaces at the end of the ablation season each autumn. Boardman says, "This is useful to improve the accuracy of the spring snow depth maps by accounting for changes to the glacier datums, and it is important scientifically for our endeavor to predict the resiliency of historical streamflow patterns to climate change.

"By comparing year-over-year glacier lidar surveys, we can estimate the volume of ice mass wasting that contributes to late summer streamflow and predict how this could change as the glaciers recede," he adds.

LEFT: The Mountain Hydrology Group at Utrecht University downloading data from a weather station at Yala glacier in the Langtang region of Nepal

BELOW: A software engineer climbs a weather tower to clean radiometers as part of the Sublimation of Snow (SOS) project

However, in the long term, water availability will drop sharply as the glacier ice dwindles to nothing. This means that downstream communities, which have grown in the past 30 years as glacier melt provided more water for irrigation, will be faced with a dramatic loss of water availability in the future.

Researchers are also trying to understand the possible impact on the 344 million-plus people who live in mountainous regions globally. According to the findings of an IPCC cross-chapter paper released in 2022, a wide range of human and natural systems in mountains have already been affected by climate change, including terrestrial and aquatic ecosystems, agriculture, tourism and energy production.

Comparing mountain environments to the "canary in the coal mine", the report's co-author, Dr Carolina Adler of the Mountain Research Initiative (MRI), noted that, "Mountains offer a specific context in which to observe complex and dynamic global change phenomena, such as climate change, manifesting in rapid and tangible ways."

Research challenges

Despite the serious impacts of mountain cryosphere loss, this is an area that remains under-researched. One of the reasons is the complex topography of mountains, which even the most high-resolution climate models are too coarse to capture, according to Aubry-Wake.

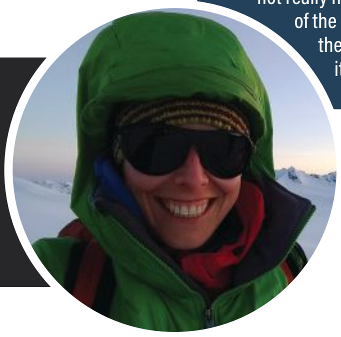
A DAY IN THE LIFE OF A MOUNTAIN RESEARCHER

"A typical day will begin with getting up, getting breakfast and shivering, because it's really cold!" says Utrecht University researcher Caroline Aubry-Wake of her fieldwork in Nepal's Langtang basin. "Then you start hiking. You'll spend a few hours hiking because it's at a high altitude – between 4,000 and 5,200m – so you move really slowly, or at least I do.

"We have more than 50 locations across the basin where we might be measuring soil moisture or rain or temperature. You go to all of those sites, you change the batteries on instruments, you clean them up and make sure everything works.

"Sometimes you replace sensors that have been giving problematic data. You install specific instruments, take specific measurements, you collect water samples, and then you hike back to camp or to a tea house where you are staying the night. In the evening you download and back up data.

"The days are really long, and you have headaches and you're not really hungry because of the high altitude. And the next day, you do it all over again!"



LEFT: An automatic weather station collecting data in the Langtang Valley in north-central Nepal

RIGHT: Dr Caroline Aubry-Wake is a postdoctoral fellow in the Mountain Hydrology group at the Netherlands' Utrecht University

"There's a product we're using that has a 12km resolution," she says. "But in the mountains, in 12km you can see a 2km vertical difference in altitude. So, a lot of the tools that are used to investigate climate change are not quite good enough to investigate what is going on specifically in the mountains, where temperature and precipitation are changing really fast."

Added to this is the remoteness of the mountain terrain, which makes conducting field research incredibly challenging. For example, the Langtang basin where Kraaijenbrink and Aubry-Wake have focused their research was chosen in part because it was considered "quite accessible", notes Kraaijenbrink, even though getting there requires a day-long journey by 4x4 followed by a hike of three to four days.

Moreover, the harshness of the mountain environment often leads to equipment breaking down, with instruments buried under snow, burned in bushfires or destroyed by curious wildlife. With field research in these regions carried out on a yearly basis at best, this can lead to some serious gaps in the data.

Aubry-Wake explains, "It's really hard to know exactly what's going on because, on the one hand, the models that we use that work quite well to predict global temperatures and averages don't work in the mountains. And we also don't have the data to prove that they don't work. So simple things like how much snow is in a valley is something that's really hard to know."

Measuring snowfall and groundwater

Despite the challenges, researchers are continuing their efforts to build up a picture of how climate

RIGHT: The three-pronged claws on this sonic anemometer used in the Sublimation of Snow (SOS) project are 3D wind sensors that use sound to measure wind direction and speed. These measurements are vital for understanding exactly how sublimation occurs

BELOW: Weather stations in the Langtang Valley are subject to extreme weather conditions

change is intersecting with mountain hydrology. Leading the way is Utrecht University's Department of Physical Geography, which, under the guidance of Professor Walter Immerzeel, has been collecting data in the Langtang basin in Nepal since 2012.

Much of the instrumentation used resembles traditional weather stations, with particular focus on precipitation gauges, which are important for measuring snowfall. Meanwhile, gamma sensors are used to measure a metric called the snow water equivalent (SWE), which is the amount of liquid water in the snow. Imagine taking a parcel of snow and melting it. The height of the water created would be the SWE metric. According to Kraaijenbrink, knowing SWE is important because the relationship between snowpack depth and water content is inexact as "all kinds of things happen to snow that can change the depth of the snowpack but not change the water content". Knowing the water:snow ratio is also key to understanding how much water is available for future snowmelt.

Another key part of the mountain hydrological cycle is the role played by groundwater. Although this was previously assumed to be trivial, it is now understood that mountain groundwater is a key water source, contributing more than 50% of the water discharge to downstream rivers during periods of low flow.

However, the loss of glaciers and snowpack is threatening the availability of this mountain groundwater, and along with it, its ability to sustain downstream rivers. "Low flows are often occurring when there's no rain and there's not a lot of glacier melt – in the Himalayas, during the dry season or in the winter after the monsoon," says Aubry-Wake.

During these periods, many rivers in the region are "really sustained by all the water that travels through the ground", she says. "So, if we don't have as much glacier snowmelt, does that mean that we're going to have less groundwater and our rivers are going to be drier in the dry season when we don't have any other water sources?"

Groundwater levels are measured using a variety of techniques, explains Aubry-Wake. To understand how much groundwater is available to begin with, wells are drilled in the field at altitude. (She notes that she chose the Langtang basin partly because the Utrecht team had already installed wells there and had groundwater data going back to 2017.)

To ascertain how much of this groundwater finds its way to rivers, Aubry-Wake uses modeling and hydro-chemical analysis of water samples collected downstream. Her project, which began in October 2022, will run until the end of 2024.

More data needed

Despite the tireless efforts of Aubry-Wake, Kraaijenbrink, Hughes and their peers, it is still too early to say what the future impact of climate change will be on the global mountain cryosphere and the countless millions who rely on it as a water source. Hughes says, "Because there's so much year-to-year variability in the snowpack, it becomes really challenging to see the long-term shift amidst those big swings."

But even without this yearly variability, the 10 years of data collected in the Langtang basin by Utrecht University's team isn't enough to say anything definitive yet about the impact, notes Kraaijenbrink. That said, none of the researchers are in any doubt that the impact will be far-reaching and serious. "I think climate change is changing everything in all aspects of life at this point," says Aubry-Wake. The world's mountain ranges are surely no exception to this trend. ∎

SUBLIMATION'S IMPACT ON WATER RESOURCES

The University of Washington and the Aspen Global Change Institute, in collaboration with the US National Center for Atmospheric Research (NCAR), have recently completed a field project measuring sublimation – the process of snow evaporating into the atmosphere instead of melting into water – in the Colorado mountains.

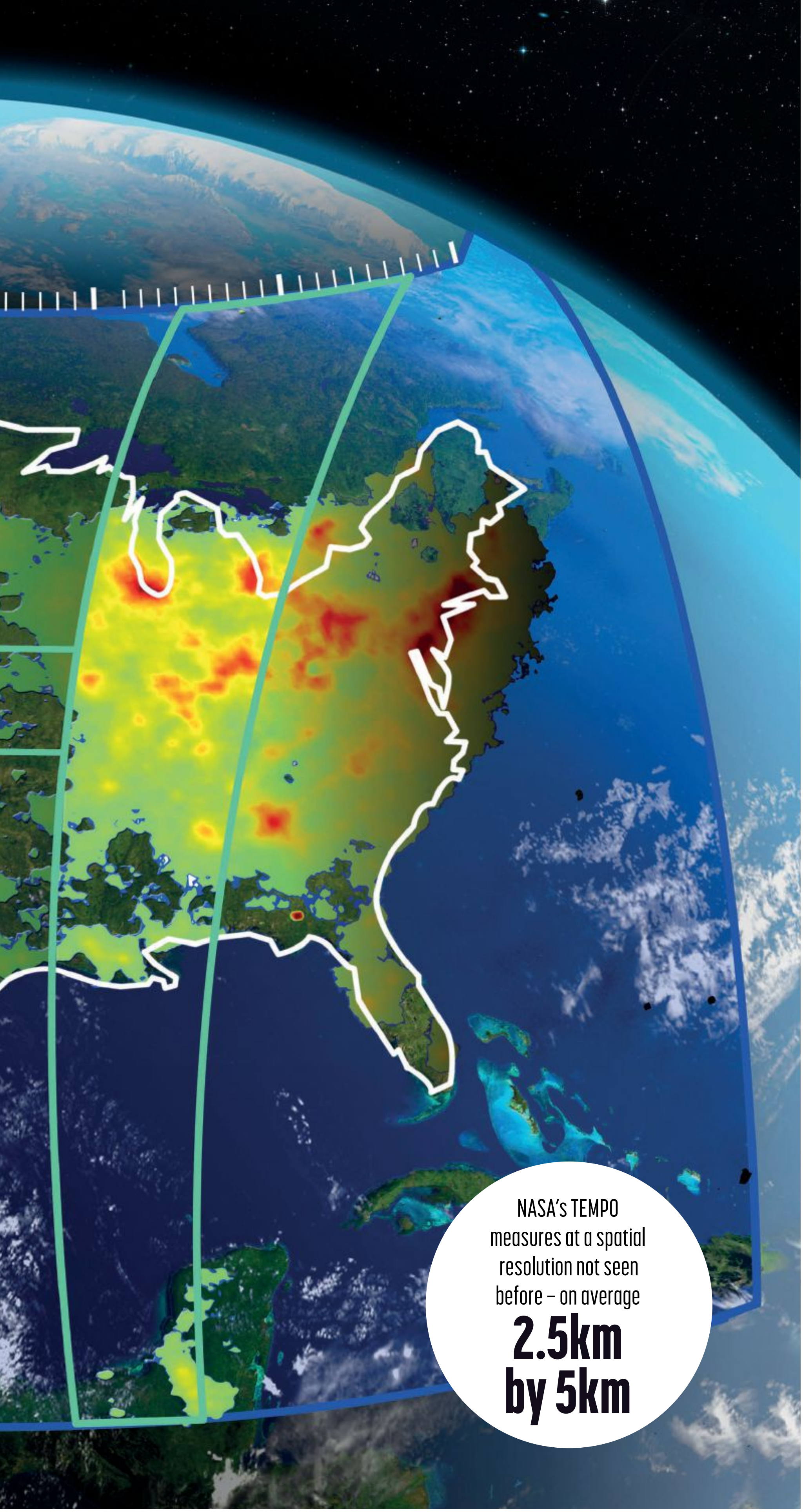
The aim of the Sublimation of Snow (SOS) project, which ran from October 2022 to May 2023, was to understand how much water is being lost to sublimation and the impact this has on water resources in the western United States. The team set up a field site near the Rocky Mountain Biological Laboratory outside of Crested Butte, consisting of four 10-20m-high towers loaded with instruments that collected data on wind speed, snowfall and blowing snow. The team measured the depth of the snowpack, the temperature of the snowpack surface and the intensity of the sun.

One of the early findings is that blowing snow is sublimating higher above the snowpack than previously thought. "As the wind lifts up the loose snow on the surface of the snowpack, the sensors are showing that a portion of the blowing snow is sublimating into the air rather than falling back down," says NCAR scientist Ethan Gutmann. "The 20m tower showed that wind is blowing plumes of snow higher than the instruments can measure, so it is likely that more sublimation is occurring even higher in the air."

The SOS research team will now analyze the data from the project to narrow the range of uncertainty around how much snow is sublimating.

Keri Allan

RAISE THE TEMPO



NASA's TEMPO measures at a spatial resolution not seen before – on average **2.5km by 5km**

How NASA's Tropospheric Emissions: Monitoring of Pollution mission is set to provide hyperlocal air pollutant monitoring at never-seen-before spatial resolutions

According to the WMO, air pollution is the world's leading environmental cause of illness and early death, responsible for seven million premature deaths a year. To reduce this figure, better understanding of the causes and movements of air pollution is needed to help develop improved forecasts and health warnings for vulnerable people, as well as to aid policymakers and leaders in taking the right steps to reduce pollutants.

Larger amounts of more detailed, hyperlocal data on air quality are therefore needed, especially in urban areas, which are particularly challenging for air quality forecasts because they are densely populated and contain many different pollution sources. Marko Torvinen, head of forecasting at Vaisala, says, "In these environments air quality can vary considerably within tens of meters and pollutant concentrations can accumulate suddenly and unexpectedly."

Coastal urban areas are particularly challenging to model, as the water interface can lead to some very complex and/or small-scale weather patterns. "Take somewhere like New York," says Laura Judd, a research physical scientist at NASA's Langley Research Center. "If the city's air pollution is blown out over Long Island Sound, for example, it will be stuck near the surface and cook secondary pollutants that are chemically produced, such as particulate matter and ozone. Then you get the sea breezes, which bring it back over land.

"Often beaches and coastal environments have the poorest air quality, but it's very shallow vertically, which is a challenge for satellites because they measure the amount of air pollution between the surface and top of the atmosphere, not what we're exposed to at nose level."

Introducing TEMPO

Today's air quality forecasts are around 12km resolution, but according to Judd, you don't really resolve what's going on until you get into much finer detail. There has therefore been a lot of work to push the boundaries of what's possible and improve on the standard resolution the meteorological sector is currently familiar with.

One of the results of this work is NASA's TEMPO – Tropospheric Emissions: Monitoring of Pollution, which measures at a spatial resolution not seen before – on average 2.5km by 5km.

This is also the first space-based instrument designed to continuously measure air quality across North America. Launched in April 2023 on a Maxar Intelsat 40e geostationary satellite, it became fully operational in October 2023 and during the day makes hourly scans of the lower atmosphere from the east to west coasts and from Mexico City to central Canada.

It forms part of a constellation of air pollution monitors for the northern hemisphere, which includes South Korea's Geostationary Environment Spectrometer and the European Space Agency's (ESA) Sentinel-4 satellite.

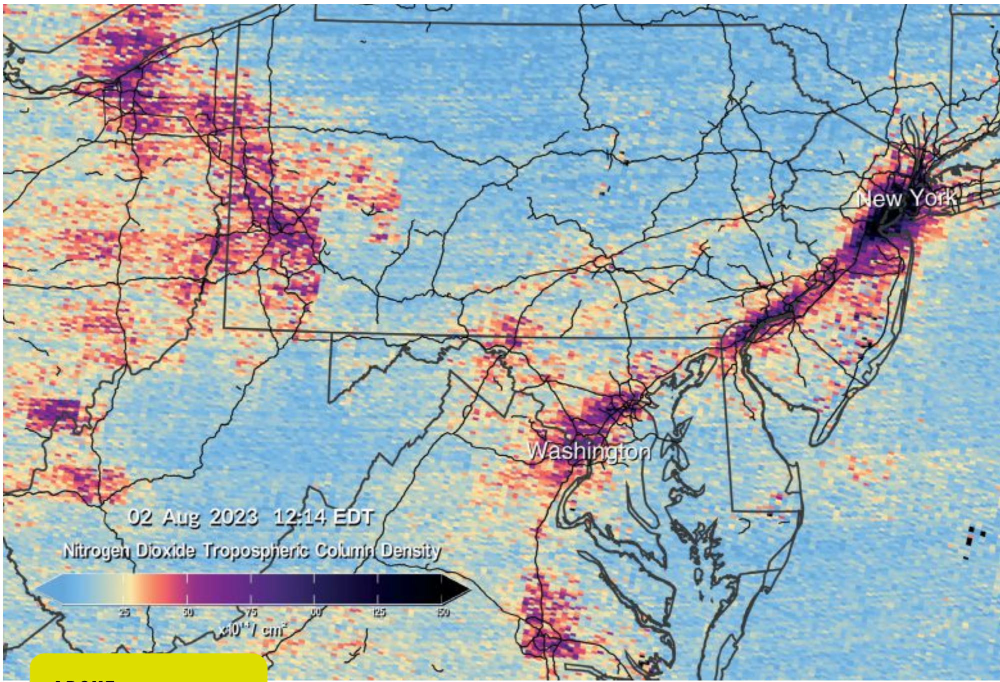
TEMPO's main instrument is an advanced spectrometer that detects pollution normally hidden within reflected sunlight, and it can measure concentrations of everything from ozone, nitrogen dioxide and sulfur dioxide through to aerosols, water vapor and several trace gases down to an accuracy of parts per billion.

"TEMPO's instrumentation measures ultraviolet and visible light that has traveled through the atmosphere and back up to the instrument," explains Judd.

These pollutants have been measured, albeit in less detail, by existing instruments for roughly 20 years, but TEMPO provides a new perspective scientists haven't had before.

A new perspective

Whereas the older satellites have been in low earth orbit, TEMPO is approximately 36,000km above the equator and is geostationary, enabling researchers to gather measurements of the same area at different times of the day and see how different periods of time, such as rush hour, affect air quality.



ABOVE: These images show nitrogen dioxide levels over the DC/ Philadelphia/New York region at 12:14 and 16:24 on August 2, as measured by TEMPO. Credit: Kel Elkins, Trent Schindler and Cindy Starr/NASA's Scientific Visualization Studio

"We do have models that try to simulate that, but we haven't had this top-down perspective before to evaluate if we are doing it right," says Judd. "The only data sets we had were from monitors on the surface – and we couldn't monitor everywhere. One of the challenges of the models is getting the right vertical distribution of the pollutants through the atmosphere, so having that whole column from TEMPO is very valuable."

One of the things unique to TEMPO is that it measures further out to the red wavelengths. It can combine ultraviolet and longer visible wavelengths, and the team is going to attempt to separate the lower atmospheric ozone amounts from the tropospheric and stratospheric column.

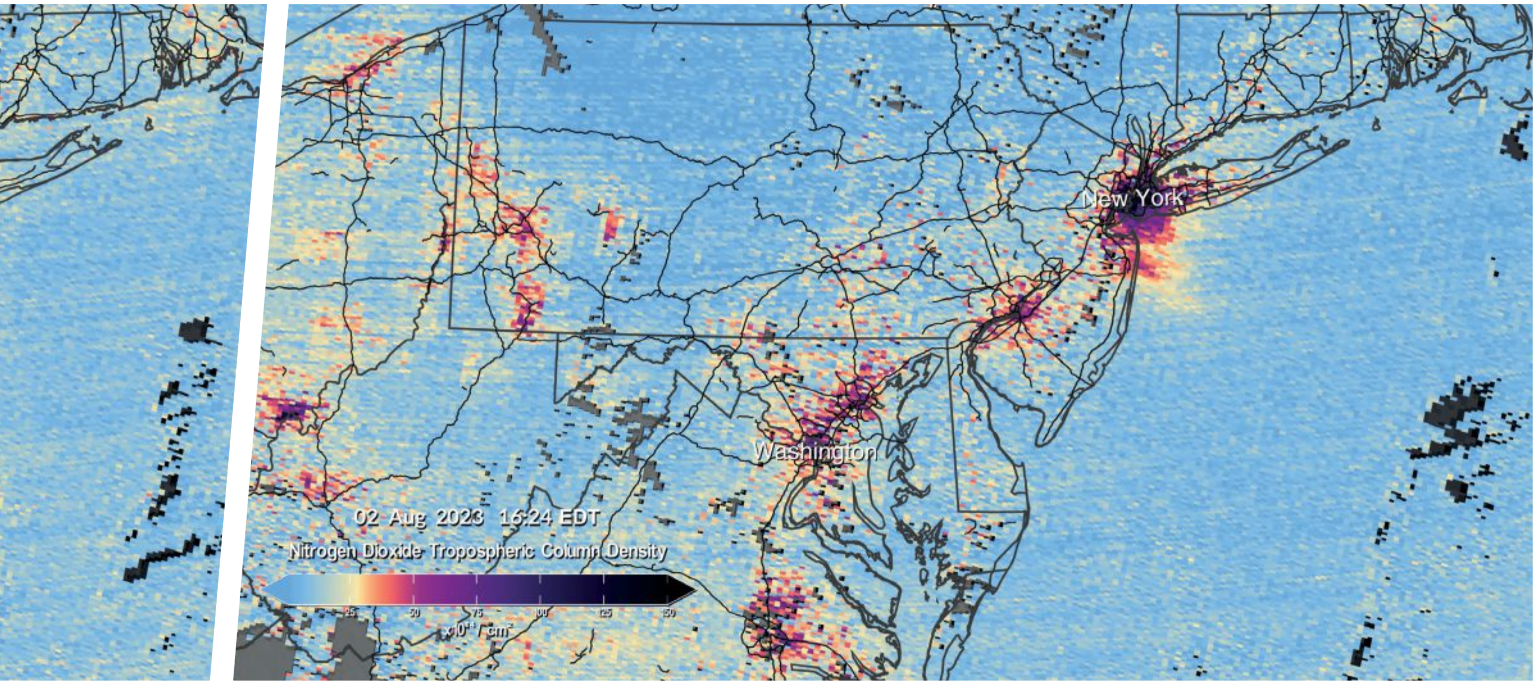
"That's not going to be an easy feat, but it will be really exciting if we can get this product validated and see if we can use it to understand the distribution of surface ozone," says Judd. "There's a lot going on in the different layers. Research has shown that we have to understand the different times of day and regionally and spatially how that relates to surface air pollution."

Time to validate

Over the summer, NASA, NOAA and partners at 21 universities undertook their most ambitious and sophisticated air pollution research campaign to date – AGES+. Their aim was to understand regional urban air quality issues and how air pollution sources have shifted over recent decades from fossil fuel emissions to volatile chemical products – consumer products derived from fossil fuels – and even wildfires.

> "TEMPO's instrumentation measures ultraviolet and visible light that has traveled through the atmosphere and back up to the instrument"

Laura Judd, research physical scientist, NASA Langley Research Center



Several coordinated research campaigns took place in June, July and August using multiple satellites, seven research aircraft, numerous vehicles, dozens of stationary installations and even instrument backpacks.

The largest of the projects was AEROMMA, in which 30 specialist instruments were put onto NASA's Gulfstream DC-8 flying laboratory, which collected chemical measurements from Los Angeles, Chicago, New York City and Toronto.

"This project had three goals," says Rebecca Schwantes, a research chemist at NOAA's Chemical Sciences Laboratory (CSL). "First, to better understand the marine boundary layer, particularly the sulfur cycle and how that affects climate; second, to improve knowledge of urban emissions and how pollutants are formed in the urban boundary layer; third, to validate TEMPO."

This will be achieved by comparing the measurements from all the summer's projects with those of TEMPO's high-resolution estimates of trace gas and aerosols, as well as with emission inventories and atmospheric processes.

To accelerate TEMPO's work further, another mission – Synergistic TEMPO Air Quality Science, or STAQS – took ground and airborne measurements to help evaluate TEMPO level 2 data products, such as NO_2 measurements, geophysically, spatially and temporally; interpret the temporal and spatial evolution of air quality events tracked by TEMPO; and assess the benefit of assimilating TEMPO data into chemical transportation models.

Advancing research

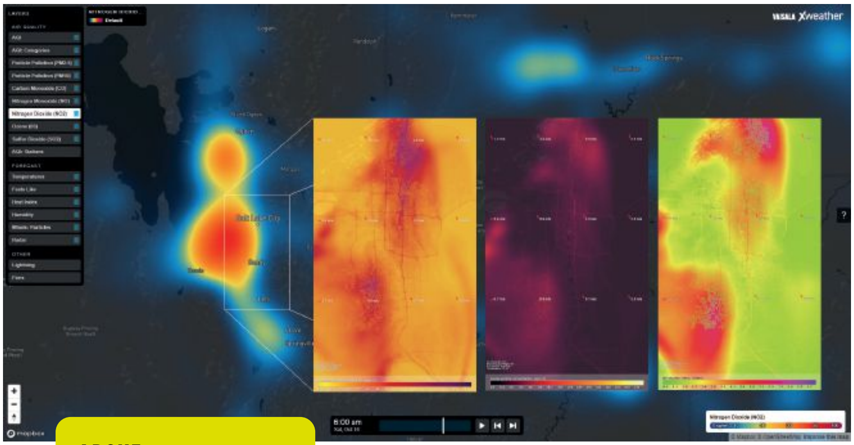
Lessons learned from all these projects will aid the interpretation of TEMPO data, which in turn will improve our understanding of urban air quality and advance research. "The data has so many uses," says Schwantes. "It will help us investigate why cities are plateauing in terms of air pollution reduction and how electrification of vehicles might benefit air quality. We can better understand what the other sources of air pollution are, which is something we've mostly ignored in the past because vehicle emissions were so dominant, but it will be important in the future.

"With this information we can inform policymakers on how they could target different regulations, but we also want to use the data to improve our operational models.

"We sampled a lot of wildfire smoke impacting the urban environment," Schwantes continues, "which is really interesting for operational air quality forecasting because there's a big initiative to understand how wildfires affect people's health

> Project AEROMMA saw 30 specialist instruments put onto NASA's Gulfstream DC-8 flying laboratory to collect chemical measurements from Los Angeles, Chicago, New York City and Toronto

BELOW: Collectively, the AGES+ campaigns represent the largest air quality-focused research campaign to date



ABOVE: Vaisala's Xweather solution showing nitrogen dioxide levels in Salt Lake City, Utah

and we need to make sure our operational systems represent that accurately."

Other projects and solutions

It's important to note that TEMPO isn't alone in its work to advance hyperlocal air quality. Academic research is underway at universities around the world, including Complutense University in Madrid (see *How Planetwatch's data can improve air quality monitoring*, below), and a pilot study called Air Inequality in New York was a part of this summer's coordinated research campaign in the US.

This entailed researchers walking and biking around the city wearing an instrument-laden backpack to gather data at a truly hyperlocal scale. "We're talking a scale of hundreds of meters," says Schwantes. "At the same time as they traveled around, we were flying above them. We hope that with this data we can bridge the gap and understand what information we're missing."

Much of the research into hyperlocal air quality forecasts is being done by the private sector, and solutions such as BreezoMeter, recently acquired by Google, and Vaisala's Xweather are already available. "Our enhanced hyperlocal air quality forecasting has a 13m resolution and provides a nowcast with one-hour updates and a long-term forecast up to 4.5 days ahead," says Laura Alku, air quality product manager at Vaisala. "You can monitor the air quality index, the level of pollutants and the impact of forest fires on your city."

The future of hyperlocal air quality monitoring

There's still much work to be done to improve hyperlocal air quality monitoring and Judd notes that there will always be a desire for higher-resolution data. However, that comes with its own challenges. "That's much more data to deal with and interpret, especially in a city, where air quality is dynamic and variable," she says.

Vladimir Kuzmanovski, data scientist at Vaisala, believes that striving for ever higher resolution may not bring much extra value because, "We're already at a point where the resolution is good enough for all practical needs." Instead, he believes the focus should be on improving the quality of the data.

"Reliable and precise forecasts require access to high-quality data from various sources – better sensor observations, satellite images, geographical data and dynamic emission data.

"We also need to improve the observation network by analyzing the existing air quality sensor network and recommending optimal locations for new sensors. In practice, this will allow the conversion of data into information that can be used in near real time, in a personalized manner, and offer insights for proactive air quality management and policies." ∎

HOW PLANETWATCH'S DATA CAN IMPROVE AIR QUALITY MONITORING

The Transport, Infrastructure and Territory Research Group (tGIS) at the Complutense University of Madrid has increasingly become drawn to the use of big data in the fields of mobility, transportation and urban dynamics.

In June 2023, during his work on local-scale spatial analysis of urban air pollution concentrations, group member Richard Hewitt came across PlanetWatch, which uses blockchain, advanced algorithms and sensors to deploy hyperlocal air quality monitoring networks to empower organizations with accurate data to fight air pollution. He was looking at how to use existing air pollution data from regional monitoring stations for air quality models. "The main importance of data provided by PlanetWatch is that it potentially enables the problem of interpolation based on very few points to be solved by providing sensor data at a higher spatial resolution and higher temporal resolution than existing public monitoring stations," he explains. "Potentially this means that much more accurate forecasting becomes possible."

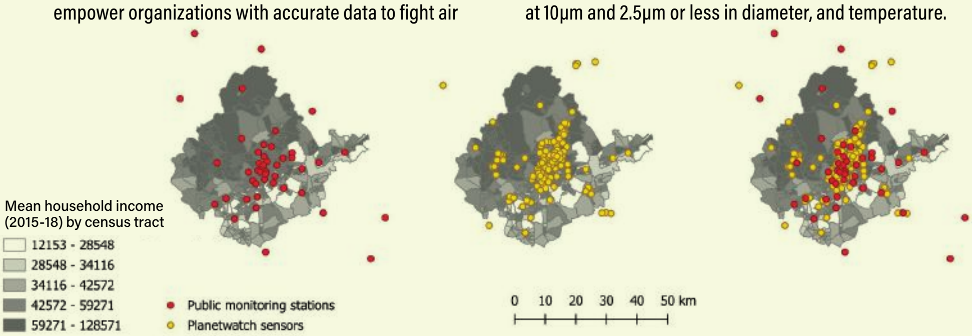
PlanetWatch sensors record humidity, particle matter at 10µm and 2.5µm or less in diameter, and temperature.

"The coverage is complementary to existing stations and the network is denser," notes Hewitt. "In this sense the PlanetWatch sensors clearly add value to existing public data sets for the monitoring of these variables."

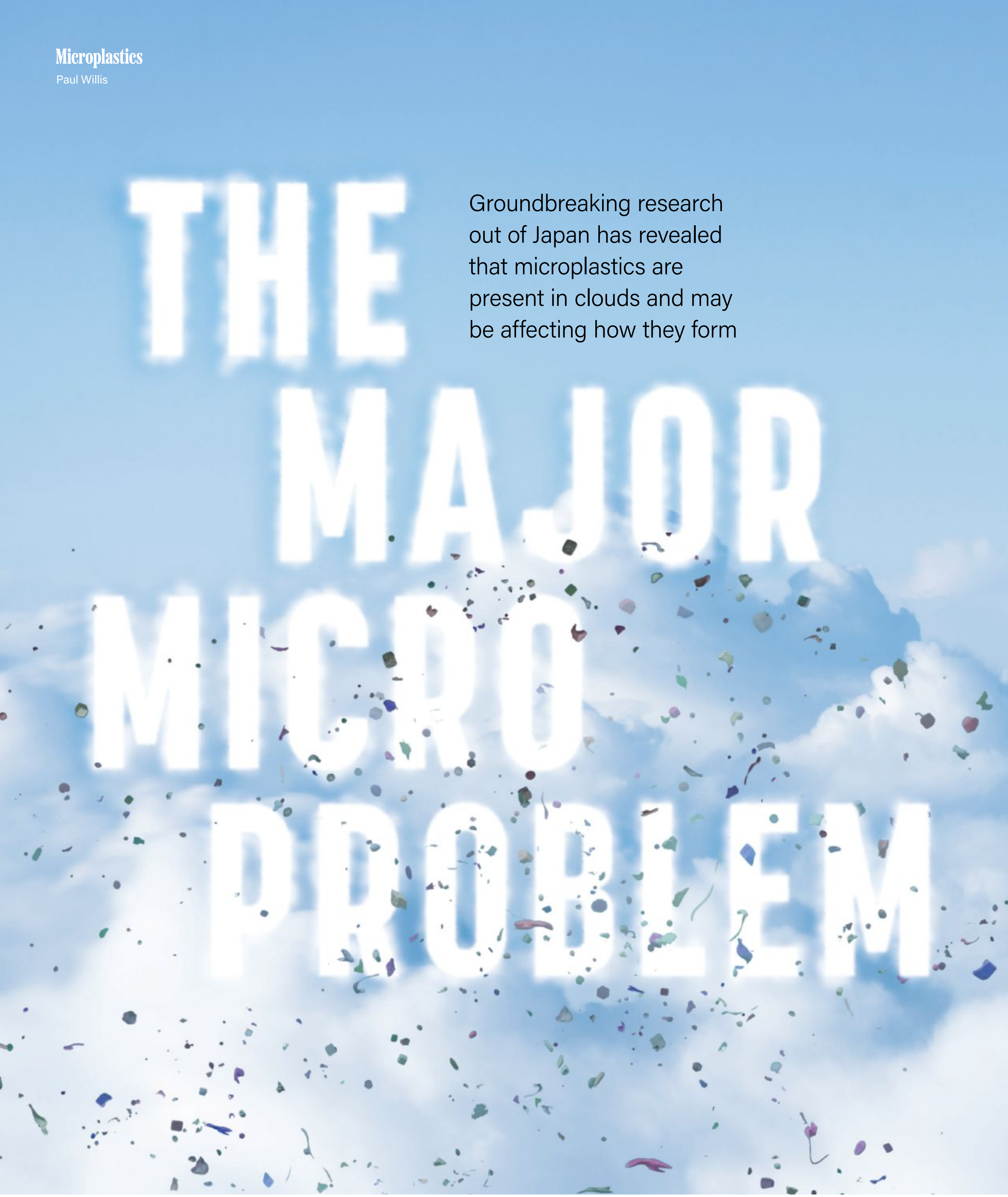
The group is now exploring how PlanetWatch's data can improve on existing approaches to air quality monitoring. By reviewing data on London, Munich, Madrid and Budapest, it aims to develop better-quality interpolations showing how air pollution varies over time and space, and compare PlanetWatch data with existing outputs from air quality simulation models.

"My personal interest relates to the use of air quality data to explore issues of social justice," says Hewitt. "Lower-income and disadvantaged neighborhoods tend to be in more contaminated areas, but it's very hard to demonstrate this at neighborhood level.

"The PlanetWatch data offers an opportunity to examine this. If statistically significant patterns do emerge, showing that marginalized communities are systematically more affected by air pollution, it becomes easier to persuade city authorities to enact measures to improve the situation. Without this evidence it's harder to enact policy, and without good-quality data we cannot collect the evidence," he concludes.



Paul Willis



THE MAJOR MICRO PROBLEM

Groundbreaking research out of Japan has revealed that microplastics are present in clouds and may be affecting how they form

> "Prior to our research there was no conclusive evidence to confirm the presence of AMPs in cloud water"

Microplastics – tiny particles of plastic most often formed from the degradation of bulkier plastic waste – are known to be widespread in the environment, including in oceans around the world. However, a new study in Japan has become the first to confirm their presence in clouds.

The study, led by Hiroshi Okochi, a professor at Waseda University in Tokyo, explored the path of airborne microplastics (AMPs) as they circulate in the biosphere. Through their analysis of cloud water samples taken from high-altitude mountains in Japan, the research team was also able to shed light on the influence of AMPs on cloud formation and their potential negative impact on the environment, particularly their contribution to climate change. *MTI* spoke to Prof. Okochi about his work and the technologies required for the research.

Why are your findings important?

Prior to our research there was no conclusive evidence to confirm the presence of AMPs in cloud water. Our findings are therefore groundbreaking. We successfully collected and analyzed samples of cloud water, revealing the presence of AMPs. While these findings are important, they represent only preliminary evidence. We must undertake further research to thoroughly understand the role of AMPs as cloud condensation nuclei and ice nuclei.

What field work did you conduct for this study?

Our study on AMPs in cloud water commenced in 2021 and we have been actively engaged in this research since. Our collection strategy involved a variety of tools and locations. Our study sites included the summit of Mt Fuji, the southeast foothills of Mt Fuji, and the summit of Mt Oyama [a 1,251m peak in the Kanagawa region of Japan]. The summit of Mt Fuji is in the free troposphere, while the southeast foothills of Mt Fuji and the summit of Mt Oyama in the Tanzawa mountain range are in the upper layer of the atmospheric boundary layer.

We used passive string-type cloud-water collectors at the summits of Mt Oyama and Mt Fuji. Additionally, for year-round data collection, an active string-type automatic cloud-water collector was sited at the base of Mt Fuji.

Cloud-water observation at the summit of Mt Fuji was conducted only during the two summer months when the Mt Fuji Research Station was accessible. During this intensive observation period (one week in July and one week in August), cloud water was automatically collected with each cloud event. Outside this period, cloud water collected by the automatic device was retrieved every two weeks. At the summit of Mt Oyama, observations were carried out throughout the year.

Why did you use passive cloud-water collection devices in your research?

In general, commercial power sources are not available at mountain summits and even if they are, there is a risk of lightning strikes traveling through power cables, making it advisable to avoid using outdoor power sources as much as possible. If there are no obstructions such as trees, the strong winds at mountain summits mean that passive samplers, which do not require power, can collect a sufficient volume of cloud water.

Did you notice any seasonal variation in the volume or types of microplastics you found in the clouds?

As this work has been ongoing only since 2021, we have a relatively small number of samples collected to date. Therefore specific details regarding the seasonal variation in the number concentration and polymer composition of AMPs in cloud water remain indeterminate. In our future work we aim to persist with our observations of AMPs in cloud water, with the goal of gaining a deeper understanding of their seasonal and annual variation, as well as identifying any distinctive regional features.

How do you ensure that your water samples contain cloud water and not rainwater?

The key distinction between cloud droplets and raindrops lies in their sizes. Raindrops are large and therefore have a high gravitational settling velocity, making them easily collectible in containers such as buckets. On the other hand, cloud droplets are small and have a slow gravitational settling velocity, making them impossible to collect in containers like buckets.

There are several devices for collecting cloud droplets, but the fine wire collection device used in this study, which uses the inertial collision of cloud droplets transported by the wind, is widely used. The disadvantage of passive collection devices that use natural wind is that they are constantly open and cannot clearly distinguish between clouds and rain during storms. However, at the summit of Mt Fuji rain rarely falls vertically and the summit is usually covered in clouds during bad weather.

Why should we be concerned about the presence of microplastics in clouds?

AMPs may significantly influence cloud formation, potentially causing major shifts in the global hydrological cycle by affecting rainfall patterns. Additionally, their role in altering the solar radiation budget through indirect radiative effects caused by cloud formation could lead to a global cooling phenomenon.

On the other hand, since AMPs are primarily composed of carbon and hydrogen, they are prone to emitting greenhouse gases such as CO_2 and CH_4 on degradation. This degradation is accelerated by the stronger ultraviolet radiation in the upper atmosphere compared with ground level. Moreover, the incorporation of AMPs into clouds

ABOVE & BELOW: Researchers at Mount Fuji Research Station – at 3,776m this is the highest research laboratory in Japan

100,000 metric tons

The estimated amount of microplastics the ocean is emitting each year according to Princeton and Cornell researchers

UP IN THE AIR

Researchers at Princeton and Cornell universities published a paper in October 2023 revealing that bubbles formed from breaking waves at the ocean's surface can launch microplastics into the atmosphere as they burst. Combining their observations with global estimates of microplastic concentrations, the researchers projected that the ocean might be emitting around 100,000 metric tons of microplastics each year.

For their study, the researchers set up a closed tank of water and filled it with plastic and glass pieces ranging in size from 10µm up to 280µm. They then used a syringe to create bubbles, which eject many smaller drops known as jet drops as they burst at the water's surface. By setting up high-speed cameras, the researchers could observe the rising bubbles scavenging microplastic pieces and flinging them out of the water in jet drops.

The researchers recorded around 100 pieces of plastic in a single drop. Given the enormous size of the ocean and the high frequency of breaking waves, the number of microplastics emitted to the atmosphere from the ocean can quickly add up, the researchers noted. "These bursting bubbles have been shown to transport salt crystals and bacteria into the atmosphere – enough to influence cloud formation and global climate dynamics," says Luc Deike, leader of the research team and associate professor in the mechanical and aerospace engineering department and the High Meadows Environmental Institute at Princeton. "Now we've shown that the same process is also capable of carrying microplastic particles out of the ocean and into the atmosphere."

According to the researchers, the work provides a reliable estimate of the size and number of microplastics that can be transported out of the ocean given a few known parameters, such as the size of the bubble and the concentration of microplastics at the ocean's surface. However, they note that there is still considerable uncertainty about how microplastics are distributed in time and space across the ocean. More work is needed, Deike notes, to sample microplastics at the sea's surface in order to refine their estimate of the ocean's contribution to the global microplastics budget.

Prof. Hiroshi Okochi from Waseda University on the summit of Mt Fuji in Japan during the microplastics research program

> "We must undertake further experimental research to thoroughly understand the role of AMPs as cloud condensation nuclei and ice nuclei"

suggests their subsequent transport to Earth's surface via rainfall, risking contamination of water sources with microplastics. This is particularly concerning for mountain water sources that contribute to our drinking water supply, raising the issue of increased microplastic consumption through drinking water.

In essence, the presence of airborne microplastics and nanoplastics in cloud water suggests the potential for widespread dispersion across land through precipitation. It could lead to the contamination of forests and soils with microplastics and nanoplastics, and ultimately contribute to the destruction of marine ecosystems via river systems.

Are you hoping to carry out follow-up studies?

To verify whether AMPs promote cloud formation, it is necessary to experimentally clarify the cloud-forming ability of AMPs in atmospheric aerosols. Our current results are only preliminary.

To measure AMPs we need to develop new cloud-water collection devices and conduct cloud-water sampling in mountainous regions domestically and internationally, using aircraft and drones, to elucidate the global presence of AMPs in cloud water. As the analysis methods for submicron-sized AMPs (0.1-1µm) and airborne nanoplastics smaller than 0.1µm are not yet established, the development of these methodologies is essential.

Moreover, from the perspective of public concern I believe the primary interest lies in health risks. Currently we are conducting cell and animal experiments to assess the impact on the respiratory system, but many aspects remain unclear. We intend to continue our research to elucidate the health and environmental risks of airborne microplastics and nanoplastics. ∎

Minttu Tuononen, team leader science, and Reijo Roininen, weather and road sensors product line manager, Vaisala

BREAKING boundaries

The latest weather measurement innovations from **Vaisala** are bringing advances in continuous high-resolution humidity profiling for early warning systems

The role of humidity in weather forecasting and its influence on the intensity and occurrence of extreme weather events is more pronounced than ever

Without early warnings in meteorology, protecting lives and property from extreme weather events is almost impossible. Providing advance notice of impending weather-related hazards like thunderstorms, heavy rainfall, flash floods and more, timely and accurate weather warnings allow individuals, communities, meteorological agencies and government organizations to take proactive measures, implement disaster preparedness plans and evacuate when necessary.

As climate change makes accurately predicting hazardous conditions more challenging – and more critical than ever – the role of humidity in weather forecasting and its influence on the intensity and occurrence of extreme weather events becomes even more pronounced. In fact, the WMO's Early Warnings for All initiative underscores the significance of continuous humidity monitoring through its top five prioritized disaster types: flash floods, drought/dry spells, riverine floods, tropical cyclones and thunderstorms/squall lines.

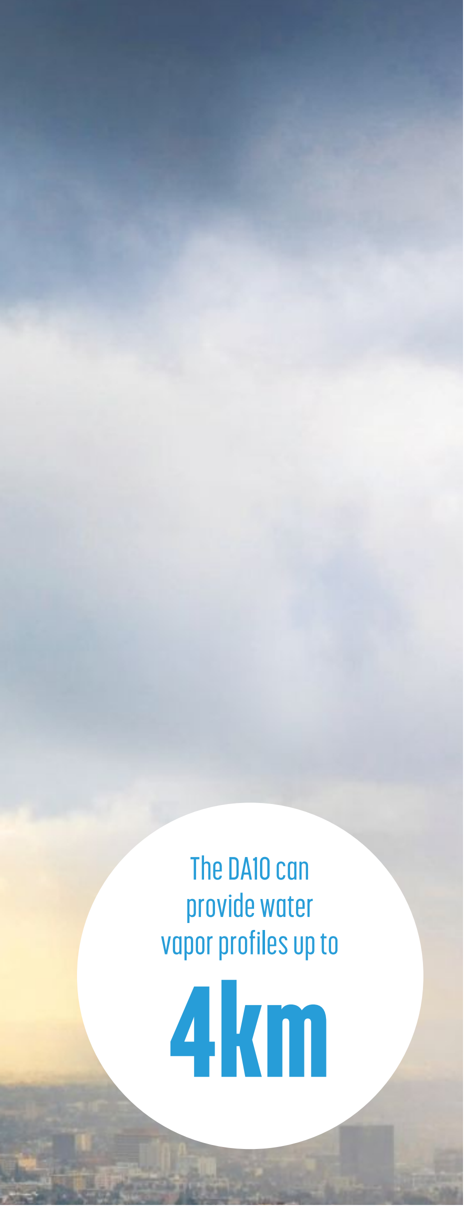
Unfortunately, given the dynamic and constantly changing nature of weather systems and the fact that radiosondes go up only twice a day, meteorologists often struggle to assess rapid humidity fluctuations in the boundary layer and effectively predict extreme weather events.

Enter real-time water vapor profiling. When combined with weather and climate modeling, continuous water vapor monitoring within the boundary layer provides access to highly accurate and reliable local observations, which are vital for issuing early warning alerts to local communities in advance of dangerous weather conditions.

Why water vapor measurements matter

In meteorology, two interconnected megatrends stand out: climate change, and the rise of extreme weather events. Our changing climate is seeing the disruption of traditional rainfall patterns, rising global temperatures and shifting weather patterns – all of which contribute to the intensifying frequency and severity of extreme weather events.

A fundamental component of the weather, humidity represents the amount of water vapor present in the atmosphere. As air rises and cools, its relative humidity increases, resulting in condensation and cloud formation. High humidity



The DA10 can provide water vapor profiles up to

4km

The DA10 differential absorption lidar (DIAL) is the industry's first continuous and autonomous water vapor monitoring solution created for observation networks

> "Advances in remote sensing technologies empower the meteorological industry to cost-effectively enhance severe weather forecasting and climate modeling capabilities with advanced, real-time water vapor profiles"

levels are essential for precipitation, including rain, snow, sleet and hail, and moisture availability helps dictate when and whether precipitation events occur.

High humidity also fuels instability in the atmosphere, leading to convection and thunderstorm development. Worse yet, rapid changes in low-level moisture content exacerbate severe storms that produce heavy rainfall, flash flooding, hail, tornadoes and other hazards, especially when combined with meteorological factors like slow-moving weather systems or orographic lifting. On the flip side, low humidity levels contribute to dry conditions, which can lead to droughts and escalate the likelihood of wildfires. Dry air accelerates the evaporation of moisture from soil and vegetation, making them more susceptible to ignition. Droughts and water shortages have severe economic and environmental consequences.

Complicating matters further, rapid changes in humidity in the boundary layer, the lowest part of Earth's atmosphere, can trigger convective storms and afternoon heavy rains that are challenging to predict. That's why the National Research Council's *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks* report notes that high-resolution humidity profiling within the boundary layer is essential for severe weather nowcasting.

Variations in humidity across different regions create humidity gradients that can intensify low-pressure systems and fronts that have the potential to precipitate extreme weather events. Consequently, meteorologists and government agencies must understand and monitor humidity levels to produce accurate forecasts and early warnings that help communities prepare for and respond to meteorological hazards.

From improved nowcasting and forecasting to severe weather prediction, accurate, real-time measurements of water vapor content in the atmosphere provide meteorologists with valuable data that enhances weather nowcasting and our understanding of atmospheric processes. However, as climate change alters established weather patterns, it also introduces greater complexity into the science of prediction.

Challenges predicting extreme weather

Meteorologists face immense challenges in predicting extreme weather events, especially those that develop rapidly, like afternoon thunderstorms and flash floods.

First, the predictive capabilities of meteorologists are challenged by the limitations of traditional observation methods when it comes to capturing rapid fluctuations in humidity that fuel storm development. Worse yet, with traditional weather patterns shifting and leading to erratic and unseasonal rainfall occurrences, deviations from historical norms can complicate weather nowcasting and forecasting.

Numerical weather prediction (NWP) is a weather forecasting method that translates into computer code the equations that describe the flow of fluids, and uses governing equations, numerical methods, parameterizations of other physical processes, and initial and boundary conditions to create low- and high-confidence models. But NWP is far from perfect and presents the following challenges, among others: sounding data from radiosondes is only collected twice a day, satellites miss the boundary layer data, and convective storms are hard to forecast with global NWP since these sub-grid phenomena must be resolved by parameterization.

The limited frequency of radiosonde launches means the instruments miss crucial short-term variability between soundings. Furthermore, the spatial coverage of radiosonde measurements is limited by sparse observation networks, in some areas more than others. Since convection initiation and cell propagation are poorly handled by NWP models, nowcasting based on extrapolation is difficult due to the rapid evolution.

Satellites typically measure humidity at different levels of the atmosphere, but their vertical resolution is also limited, particularly within the boundary layer. Even worse, satellites often fail to measure humidity close to Earth's surface because surface emissions can interfere with accurately detecting and measuring humidity levels in the lower atmosphere. Differences in spatial and temporal scales between satellite-derived humidity data and NWP models also create significant data assimilation concerns.

Convective storms can develop and dissipate rapidly, sometimes within minutes, challenging the limited spatial resolution of most NWP models. These storms often form in the afternoon (when heat from the sun is most intense) and dissipate in the evening, adding an unpredictable element of daily variation. Correct weather prediction depends heavily on the availability of reliable data, so any gaps in coverage, inaccuracies or errors in representing initial atmospheric conditions, or outdated observational infrastructure can hinder precise prediction. The challenge is that measuring water vapor in the atmosphere has always been manual, time-consuming and expensive – until now.

Continuous and autonomous water vapor monitoring

Advances in remote sensing technologies empower the meteorological industry to cost-effectively enhance severe weather forecasting and climate modeling capabilities with advanced, real-time water vapor profiles.

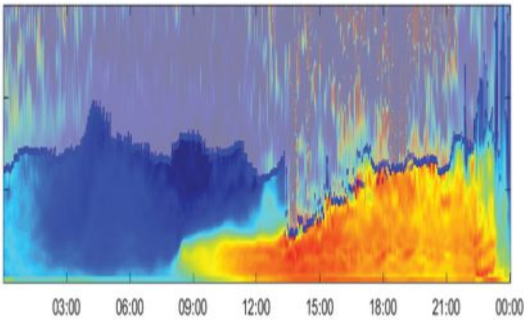
The Vaisala DA10 differential absorption lidar (DIAL) is the industry's first continuous and autonomous water vapor monitoring solution created for observation networks. It uses dual wavelengths to measure the water vapor mixing ratio in the boundary layer.

While globally coordinated upper-air observations provide an overall picture of humidity patterns, the DA10 continuously measures water vapor in the boundary layer, in any location, under any conditions to deliver previously unavailable research-grade data suitable for NWP modeling. Essentially a ceilometer and a water vapor profiler combined, the device creates two different profiles – one independent of water vapor and one dependent on water vapor – to determine the actual water vapor mixing ratio within the boundary layer. Combining the real water vapor mixing ratio profile within the boundary layer and the uncertainty profile for that measurement provides information readily available for assimilation.

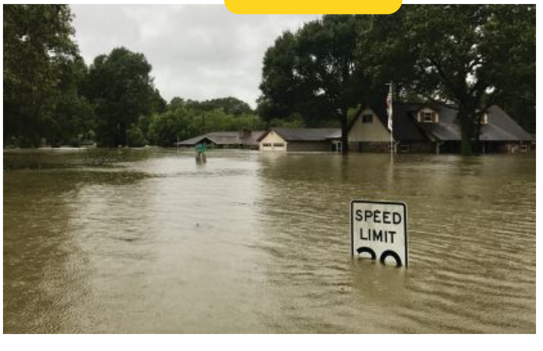
Designed to support nowcasting, forecasting, climate modeling and atmospheric research, the DA10 provides atmospheric profiling data, including information on water vapor mixing ratio profiles (g/kg), uncertainty for the water vapor mixing ratio (g/kg) and attenuated backscatter profiles (from the surface up to 18km); and atmospheric parameter data, including information on cloud base heights (up to five layers), cloud and penetration depth, precipitation/fog detection, sky condition and surface pressure, temperature and humidity.

The resulting information equips meteorological decision makers with time and height plots illustrating the changes in water vapor in the atmosphere and within the boundary layer.

Unlike traditional methods that rely on sporadic weather balloon launches, continuous humidity monitoring ensures meteorologists can access up-to-the-minute information and integrate it into numerical weather prediction models at all hours, minimizing the lead time for issuing weather warnings. Organizations can improve geographical data coverage by establishing or enhancing the forecasting capabilities of operational networks with real-time water vapor profiling.



The resulting data provides, for example, time and height plots where you can see the changes in water vapor both in the atmosphere and the boundary layer



Afternoon thunderstorms and flash floods develop rapidly and are hard to predict

Knowing the amount of water vapor in the atmosphere helps meteorologists predict the likelihood and intensity of precipitation and issue weather warnings and advisories, especially in the case of heavy rainfall events and severe storms.

Consider the UK Met Office and Deutscher Wetterdienst (DWD) as cases proving that the DA10 can help to improve NWP modeling and nowcasting capabilities.

The one-month UK Met Office measurement trial saw measurement error close to the 5% OSCAR breakthrough requirement and minimal overall bias, 0.1g/kg, with a correlation of 0.93 with the radiosonde measurement. The agreement between the radiosonde and the DA10 was better than the model versus the radiosonde, cementing that DA10 data should improve the model when it is assimilated.

For DWD's 2021 Field Experiment on Submesoscale Spatiotemporal Variability in Lindenberg (FESSTVaL) campaign, the German weather service DWD compared DA10 and radiosonde measurements. The pilot results showed that the DA10 successfully covered water vapor structure and evolution and captured mixing ratio profiles/gradients.

Fueling tomorrow's severe weather forecasting

With the frequency and severity of extreme weather events surging in the face of our changing climate, strengthening early warning systems through better observations and forecasts will only grow in importance.

Thankfully, continuous high-resolution humidity profiling provides the data needed to monitor water vapor profiles in real time, enabling more precise and earlier alerts for severe storms. By capturing previously unavailable variability in low-level moisture, innovative technologies like differential absorption lidar fill critical gaps in existing observation networks, unlocking the potential to significantly improve the numerical weather prediction models forecasting thunderstorms and heavy rainfall.

Solutions like the Vaisala DA10 are indispensable in the arsenal of meteorologists and forecasters tasked with keeping our communities safe in a changing climate. The future of adequate early warnings relies on transformative technologies and collaborative efforts to effectively prepare and respond to potentially life-threatening weather events. ∎

Julie Dauer, content specialist, OTT HydroMet

THE BIG melt

Climate change is hitting Greenland hard. To increase the quality of measurements, scientists are expanding their network with **OTT HydroMet** instrumentation

In the face of global warming, understanding the behavior of polar ice sheets has taken on new urgency. The Greenland ice sheet, the second-largest body of ice on the planet after the Antarctic ice sheet, plays a critical role in this context, contributing greatly to rising sea levels. If the entire Greenland ice sheet were to melt away it could contribute to a global sea level rise of up to 7m.

To unravel the intricacies of this dynamic ice sheet, the Geological Survey of Denmark and Greenland (GEUS) has deployed advanced monitoring methods and technology to paint a comprehensive landscape of the melting phenomena. Among the equipment being used is the Lufft WS401, a compact all-in-one weather sensor that supports research at monitoring stations across Greenland.

Quantifying the mass balance

The mass balance of the ice sheet, which determines the net gain or loss of ice, is a key indicator of its contribution to global sea level rise. The mass balance results from a complex interplay of various processes, including mass gain through precipitation and mass loss through surface melt, basal melt, evaporation, sublimation and calving.

To better understand the variations of the mass balance, the monitoring efforts are managed by two separate projects that divide the ice sheet into two distinct zones: the ablation zone, where ice is melting at the sheet's periphery, and the accumulation zone, where precipitation accumulates in the central region.

In 2007, Denmark launched the Program for Monitoring of the Greenland Ice Sheet (PROMICE) to assess the mass loss in the ablation zone. In the accumulation zone, GEUS recently took over the operation of the Greenland Climate Network (GC-Net), which was established in 1995. Lufft WS401 compact weather sensors are deployed in both zones to measure essential meteorological parameters that aid in understanding the ice sheet's mass balance.

Monitoring the ice flux

To gain a comprehensive understanding of near-surface climate in the accumulation zone, GEUS mounted two Lufft WS401 weather sensors at different heights at 16 of the 44 stations. This approach enables it to measure gradients and enhance the overall accuracy in determining the mass balance.

Additionally, GEUS employs other instrumentation, such as ice loss measurement systems, wind speed and direction sensors, solar radiation instruments and inclination sensors, to create a holistic view of the ice sheet's dynamics. The solar radiation instrumentation used to determine evaporation and other phenomena is also developed by OTT HydroMet under the product brand name Kipp & Zonen.

The Lufft WS401 is an all-in-one compact weather sensor that measures temperature, relative humidity, precipitation and air pressure. This instrument's ability to measure aspirated temperature improves data accuracy while providing other meteorological parameters for assessing energy changes on the ice sheet's surface.

The WS401's compact design and multifunctionality make it an ideal choice for the challenging conditions in the polar region. Lufft is one of OTT HydroMet's trusted product brands for environmental monitoring, along with Sutron and Kipp & Zonen.

Overcoming the elements

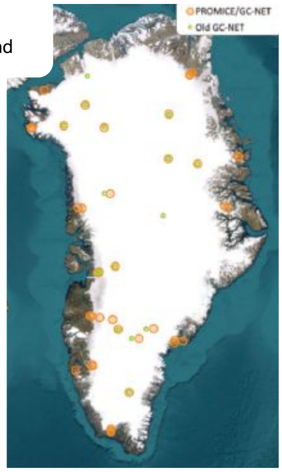
As you can imagine, monitoring the Greenland ice sheet in remote and harsh environments poses unique challenges. The extreme cold temperatures and variable winds require robust equipment. In the often transient ablation zone,

ALL IMAGES: Courtesy of GEUS

MAIN: Monitoring station equipped with two Lufft WS401 weather sensors

BELOW: Ice sheet margin in Greenland

RIGHT: A map of automatic weather stations in Greenland



the tripod-mounted stations can flip over due to strong winds; in the accumulation zone, sensors can be drilled into the ice. Snow accumulation can cover solar panels, leading to the stations losing power, and the frigid temperatures in the region often result in battery failures.

Transporting equipment to these remote locations is a logistical challenge. Ships are used as the primary mode of transportation to the port, and helicopters are used to access remote sites. Once on the ice sheet, researchers also use skis to cross the landscape. Most stations are visited annually, but some in the northern regions receive visits only every three years, hence the necessity for robust instrumentation.

Influencing climate action

The data collected by GEUS is instrumental in enabling data-informed decisions and supporting political action. By supplying the Danish Meteorological Institute with critical weather data, PROMICE is transitioning from research-based to operational-based measurements, necessitating standardized stations to meet global requirements. Additionally, the data provided by GEUS contributes greatly to the Intergovernmental Panel on Climate Change (IPCC) reports, further underscoring the relevance of the research on a global scale.

As we move into an uncertain future, the good news is that the PROMICE and GC-Net projects are being financially supported by the Danish government, ensuring a consistent source of funding for long-term monitoring.

Advancing mass balance models

According to GEUS, the Greenland ice sheet has now receded for 27 years in a row. In this year's melting season, it has shrunk by approximately 200 gigatons.

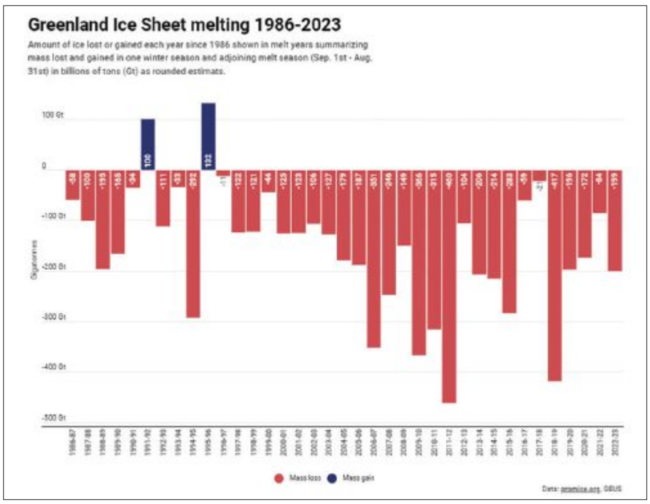
Predicting the precise impact on sea level rise over the next few decades remains a complex task due to the myriad of variables at play. While mass loss from the ice sheet is a critical parameter, the rise in sea temperature and its influence on water volume and other factors must also be considered.

Dr Jakob Jakobsen, glacier lab leader at GEUS, says, "The research results in one number for annual sea level rise, but this is just the tip of the iceberg. There is a lot of work, sensors and data processing that contribute to this number. We can pass this information along to decision makers and be a part of the climatologic discussion."

The future vision for PROMICE and GC-Net includes the deployment of new-generation stations, equipped with the Lufft WS401, alongside existing ones. As the sites are only frequented at most once a year, upgrading these sites can take time. The team is also focused on higher-precision positioning to compensate for station drift due to the floating ice surface, as well as wind-powered instrumentation to improve efficiency and reduce costs. Development efforts are ongoing to enhance maintenance processes and explore alternative methods for measuring accumulation and ablation.

The role of GEUS in monitoring the Greenland ice sheet is pivotal in the effort to understand and mitigate the impacts of global warming. The Lufft WS401 sensor and environmental monitoring technology provide crucial data for assessing the ice sheet's mass balance. As we continue to face challenges, these scientific endeavors play a vital role in realizing a climate-informed future. ∎

GEUS personnel following the completion of annual maintenance on a weather station



SAFETY first

Baron explores the importance of early warning systems and looks at how the right solutions and support can help countries better predict, detect and communicate potential weather disasters ahead of time, saving lives and livelihoods

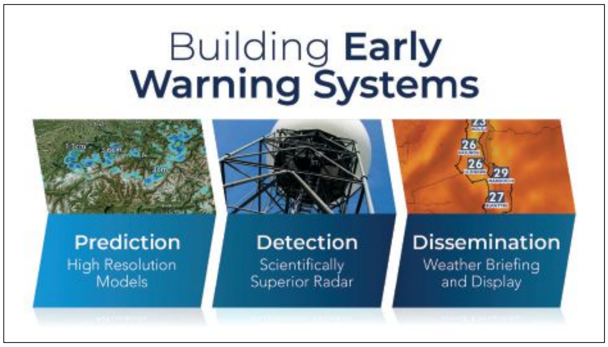
Climate- and water-related disasters are increasing in duration and frequency around the world. However, such calamities are less costly and deadly for countries with an adequate early warning system (EWS) and the necessary resources and infrastructure to support it.

Several recent events highlight the importance of an EWS capable of predicting, detecting and communicating how we should react when nature unleashes its fury, including the recent and deadly flooding in Libya, the Category 5 hurricane (Otis) on the southern Pacific Coast of Mexico, and extreme heat scorching Brazil in autumn 2023. For developing countries, investing in an EWS could prevent deaths and losses of US$3bn to US$16bn annually, according to the Global Commission on Adaptation.

A complete early warning system solution requires science-driven weather detection and monitoring, assessing and understanding weather hazards to reduce the loss of lives and protect communities

Leveraging modeling to minimize loss

Weather forecasting has made great strides in recent decades. At the heart of these advances is modeling, a crucial element of any EWS. Weather modeling employs cutting-edge algorithms and mathematical equations to simulate and predict weather patterns. The reliance on global models generated to cover large areas means localized information may be less relevant or detailed. However, thanks to technological leaps in computing capabilities we can now efficiently and cost-effectively run models tailored to specific regions, putting the control of forecasting resources in the hands of local meteorological and hydrological organizations.



These advanced, high-resolution models generate precision forecasts based on the weather dynamics of a country's operational area. Models specifically focusing on predicting weather conditions within a geographical area or region are called local or custom modeling. Alerts and warning messages are only effective when you caution the communities under the greatest threat of impact. Warning too large an area repeatedly risks notification messages becoming too frequent. High-resolution models give you the precision required for a successful EWS.

Focusing on the specific characteristics of an area, local domain modeling can provide more accurate and localized weather forecasts. Custom domain modeling benefits industries and applications requiring exacting weather information, such as agriculture, transportation and outdoor event planning.

Weather technology firm Baron works with customers to provide regional models within agreed-upon budgets, including integrating local land use, coastline and other geophysical data. Baron partners with several computer providers (Dell, HPE, etc) and can host on-site modeling, saving money on cloud computing costs.

Numerical weather prediction

NWP models should be tailored to meet user-specific requirements with a state-of-science, land-surface model. Baron recommends models

Modeling helps meteorologists and scientists understand and predict weather patterns. Baron provides visualization options, software to manage the model and extensive training for early warning systems officials

US$3-16bn

The value in losses that could be saved if developing countries had effective early warning systems

Source: Global Commission on Adaptation

Baron's proprietary technology provides for one- or two-way coupling between models for land surface, numerical weather prediction and others, thus improving application ranges and results

where forecast length, domain and resolution are configurable and specific needs are customized based on the urgency of weather updates, new input abilities and available computation resources. Baron offers standard NWP parameters and a variety of exclusive features. Models run at 15km, 3km and 1km resolution, accounting for local geographic variations. Baron also provides coupled hydrological models (flooding), ocean models (waves and currents), software to manage the models, visualization options and training.

Coupled ocean and waves model

The effect of weather is not only felt on land. Coastal communities also need decision support. A coupled ocean and wave modeling system is the only system that provides both ocean and wave forecasts. Working with an atmospheric NWP, sea surface wave and deep ocean circulation model improves fidelity at the atmospheric/ocean interface. Baron technology couples these distinct modeling components to provide forecasting capabilities that are otherwise unavailable.

When the Indonesian Meteorological, Climatological and Geophysics Agency (BMKG) wanted a state-of-the-art coupled atmospheric water and ocean (CAWO) modeling system, the organization chose CLS Group and Baron to provide the required capabilities.

Designed to meet the need for more reliable maritime forecasting worldwide, it serves as a blueprint for other nations looking to improve the safety of their coastal industries and populations. The coupled marine model is critical to Indonesia's Marine Meteorology System (MMS). It is designed to maximize the country's maritime economy by increasing weather awareness and safety on the seas and shorelines.

The system enables industries in Indonesia, including fishing, shipping and passenger ferries, among others, to better understand maritime conditions that could affect operational safety and efficiency. The model's data also creates a more effective EWS to alert citizens about dangerous sea or coastline weather.

"By dynamically computing ocean wave characteristics and circulation and exchanging this information with the atmospheric model, precipitation forecasting in the maritime environment improves along with the ability to track and forecast tropical cyclones," says John McHenry, chief scientist at Baron. "This provides a more accurate and complete forecast than a model relying on approximations or static data to represent conditions."

Radar for early detection

Building a reliable EWS requires a science-driven, accurate and reliable weather detection solution for monitoring, assessing and understanding weather hazards. Doppler radar technology is invaluable to a radar system as it detects weather hazards while tracking intensity, location and movement. Baron radars deliver the highest data quality on the market and can be the foundation of an effective and efficient meteorological operation. Baron's radar systems capture detailed atmospheric information, improving weather model accuracy, especially for localized and short-term forecasts.

Baron highly recommends assimilating the data from high-quality real-time Doppler weather radars to improve short-term forecast accuracy. With a history of innovation and global presence, Baron offers patent-pending, next-generation clutter-suppression technology, resulting in cleaner, easier-to-read radar data, auto-calibration capabilities, and advanced processor components.

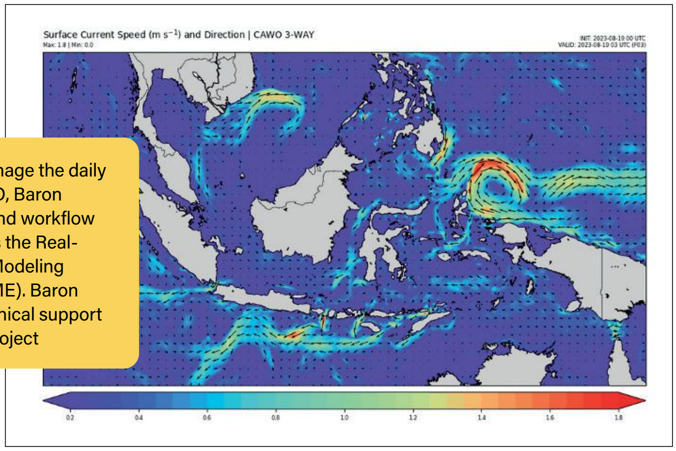
Designed for sustainability

Long-term planning of a radar system is critical to ensuring smooth operation. Radars need repairs from wear and tear and preventative maintenance. All three radars Baron offers – the X-, C- and S-band – have standardized components for increased accessibility and reduced maintenance. Multiple configurations ensure an organization can find the best solution for its needs.

Baron also works with customers to help determine the best path for extending equipment life based on needs and budget. Baron suggests securing a three- or five-year warranty to cover equipment with the highest wear and tear. Baron also offers a configurable warranty if needed.

When the Meteorological Services Department of the Zimbabwe government needed weather technology to improve public safety, it chose Baron's radar technology, enabling the department to detect weather events earlier and forecast more precisely. The country purchased five Baron Gen3 C-band dual-polarization weather radars installed nationwide and 10 Baron Lynx Advanced Forecaster Workstations.

"Timely evacuation of at-risk communities whenever there is a high possibility of flooding is critical to reducing the loss of lives and property," says Rebecca Manzou, director of the Zimbabwe Meteorological Services Department.



To help BMKG manage the daily operation of CAWO, Baron provided end-to-end workflow software known as the Real-time Operational Modeling Environment (ROME). Baron also provided technical support for the life of the project

"The Baron radars will help us better detect the areas and people in danger."

Effective weather communication

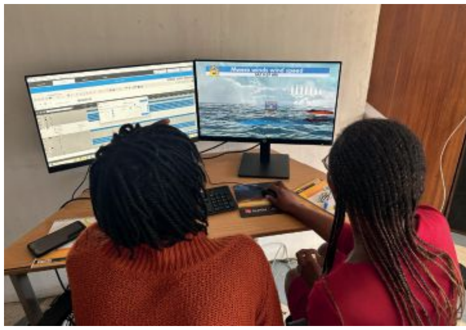
Conveying the severity of a weather threat and the necessary actions can be the most challenging aspect of creating an effective EWS. As 75% of the world's population have cell phones, many countries are extensively using social media platforms for warning dissemination.

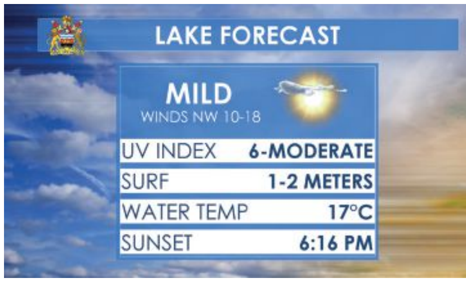
Baron Lynx, a software and communications tool, enhances ease of use when communicating alerts, warnings and everyday weather information to the public. Due to its ability to view all weather data with a single, end-to-end weather solution, Lynx is a powerful visual engine that seamlessly ingests and displays data from a country's entire meteorological network into one software display solution. Data sets typically include radar data (including dual-polarization products), value-added products, satellite imagery, forecast models and more, depending on user requirements.

On top of its powerful operational functionality, Lynx delivers advanced graphics capabilities for scientific and artistic presentation while empowering the operator to communicate and notify stakeholders and the public.

Investments for the future

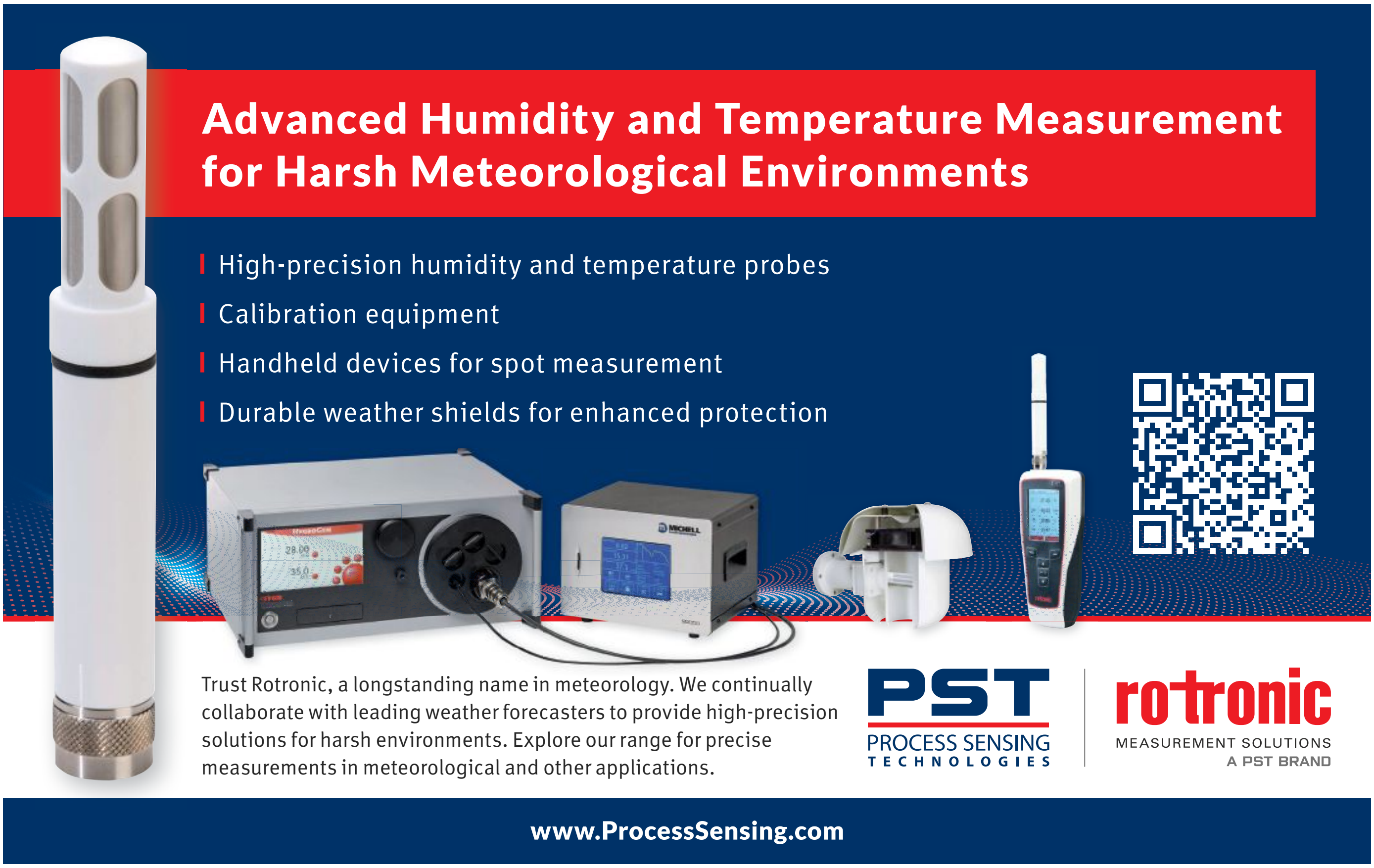
Keeping the public safe and healthy while maximizing quality of life and minimizing losses are clear benefits of a well-planned and implemented EWS. Meteorologists must have the best prediction, monitoring and communications tools to operate a successful EWS. While planning, designing and implementing these systems can be challenging, citizens will thank you later.





ABOVE: Baron systems are helping the country of Malawi keep people safe from flash flooding incidents

LEFT: All Baron Gen3 radar systems continuously monitor their performance, including voltages, temperatures, power levels, etc. Radar technicians can troubleshoot a system remotely, helping ensure continuous, sustainable performance



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Nikša Orlić, co-founder, Geolux

On the RADAR

Engineers at **Geolux** have developed the first radar-based snow-depth sensor, providing an accurate, compact and low-power solution for various sectors including transportation, agriculture and renewable energy

Snow-depth measurement holds much importance in meteorological and hydrological observations, affecting critical sectors such as transportation, agriculture and renewable energy, among others. The methods traditionally employed for snow-depth measurement have mainly revolved around in situ manual measurement or the use of remote sensing technologies such as ultrasound and lasers.

However, these methods come with constraints. Ultrasound accuracy can be compromised by temperature gradients, and laser technology is expensive. Furthermore, both methods tend to have degraded performance under precipitation and fogging conditions, which are common when dealing with snow.

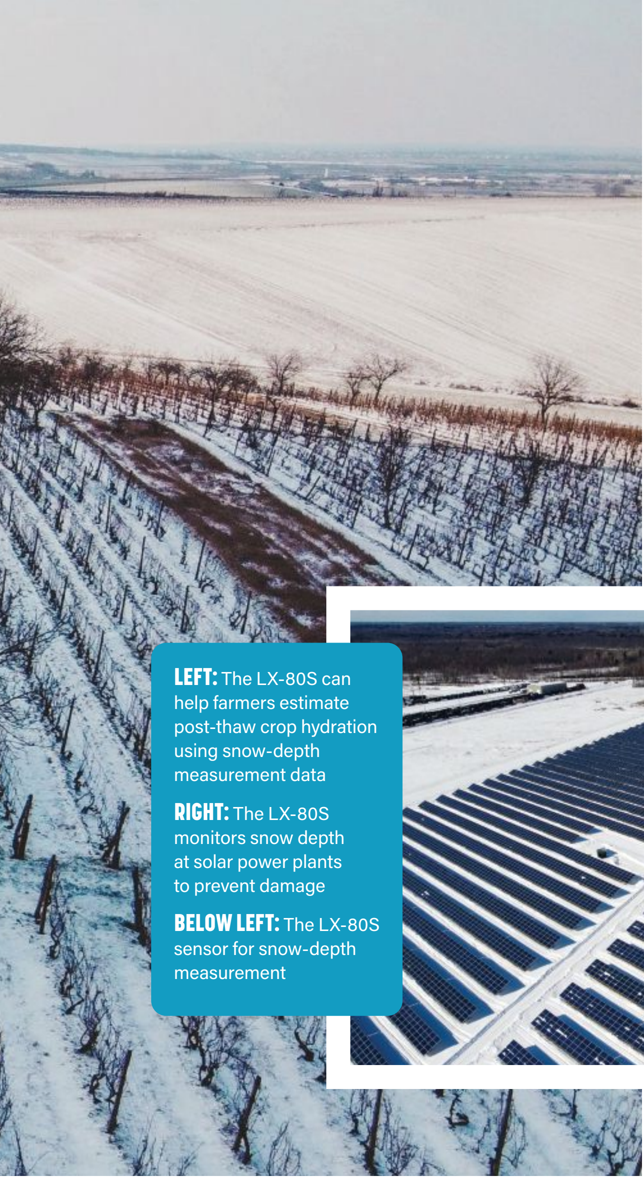
Geolux's groundbreaking LX-80S addresses these challenges. This sensor uses radar technology to measure the distance between the device and the snow surface, similar to how water-level radar sensors operate. However, the difference in density and structure of snow results in weaker radar signal reflections from snow than from a water surface. Overcoming these challenges, Geolux engineers have introduced the first radar-based snow-depth sensor to the market.

In any condition

The benefit of using radar technology for non-contact snow-depth measurement lies in the fact that the radar sensor will report the measurement regardless of the weather. Fog, air temperature gradient and precipitation do not affect radar measurements. Additionally, the 5° beam width ensures precise focus while minimizing errors influenced by nearby structures or wildlife. With its compact size, installation becomes simplified, eliminating the need for complex support structures.

Applications for the LX-80S span various sectors. In transportation, for example, understanding the snow depth near roads and railways is pivotal for

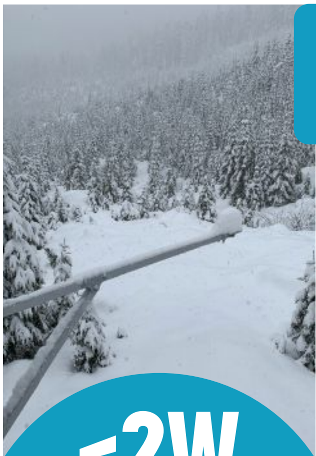
> **//** The benefit of using radar technology for non-contact snow-depth measurement lies in the fact that the radar sensor will report the measurements regardless of the weather"



LEFT: The LX-80S can help farmers estimate post-thaw crop hydration using snow-depth measurement data

RIGHT: The LX-80S monitors snow depth at solar power plants to prevent damage

BELOW LEFT: The LX-80S sensor for snow-depth measurement



A Geolux LX-80S snow-depth sensor installation in British Columbia, Canada

maintenance and safety protocols. The LX-80S delivers real-time data to guide snow removal efforts and travel advisories. In smart cities, meanwhile, the data provided by LX-80S streamlines snow removal management.

The impact of snow accumulation on solar power plants can be detrimental. The weight of snow can damage solar panels, leading to costly repairs and reduced efficiency. Employing the LX-80S enables active monitoring of snow build-up, facilitating timely actions to maintain energy production.

Agriculture relies on accurate snow-depth data to predict post-thaw crop hydration and prepare for potential flooding. The information provided by the LX-80S aids farmers in planning their operations, thereby contributing to food security.

Climatic shifts

Climate change is an urgent global challenge, and monitoring snow depth holds great importance in understanding its implications. Changes in snow-depth patterns offer critical insights into broader climatic alterations. In regions reliant on snowmelt for freshwater resources, shifts in snow depth and timing can affect ecosystems, water availability and various economic sectors. Additionally, alterations in snow cover influence albedo – the reflection of sunlight – thereby affecting regional climate and, in some instances, accelerating warming trends. Monitoring these changes and comprehending the relationship between snow depth and climate is vital in advancing our understanding of environmental shifts and their consequences.

The Geolux LX-80S has been designed and engineered with all these applications in mind. It also implements several industry-standard communication interfaces to enable simple and quick connection to various dataloggers, PLCs and modems. The LX-80S supports the Modbus and SDI-12 protocols, as well as proprietary data protocols over an RS-232 serial link. Analog 4-20mA output is also supported.

<2W

The power consumed by the Geolux LX-80S while operating. It can also enter sleep mode between measurements

The instrument is designed for low power consumption. It consumes less than 2W while operating and can enter sleep mode between measurements, when power consumption is less than 0.05W.

The LX-80S, with its ability to measure snow depth consistently and accurately, emerges as a crucial tool in observing changes. Its precise and reliable data collection under diverse weather conditions provides researchers with invaluable insights into alterations in snow-depth patterns and their relationship to broader climatic shifts, contributing greatly to our understanding of climate change. The LX-80S not only aids in real-time decision making but also plays a pivotal role in monitoring and comprehending the ramifications of climate change for snow depth, thereby advancing our knowledge of these critical environmental changes. ∎

Jakub Bartel, head of SW, AI and signal processing, Meteopress

SOLID report

Meteopress reports on the successful implementation and operation of a new solid-state radar in Australia following 12 months of reliable performance

Brisbane, in southeast Queensland, Australia, has historically been served by two S-band weather radars within the Bureau of Meteorology (BoM) of Australia network. However, a significant challenge arose when one of these required replacing in 2022.

This primary radar was scheduled for demolition and replacement, leading to an anticipated downtime of about six months. Recognizing the importance of uninterrupted weather data, authorities sought a cost-effective yet reliable temporary radar solution.

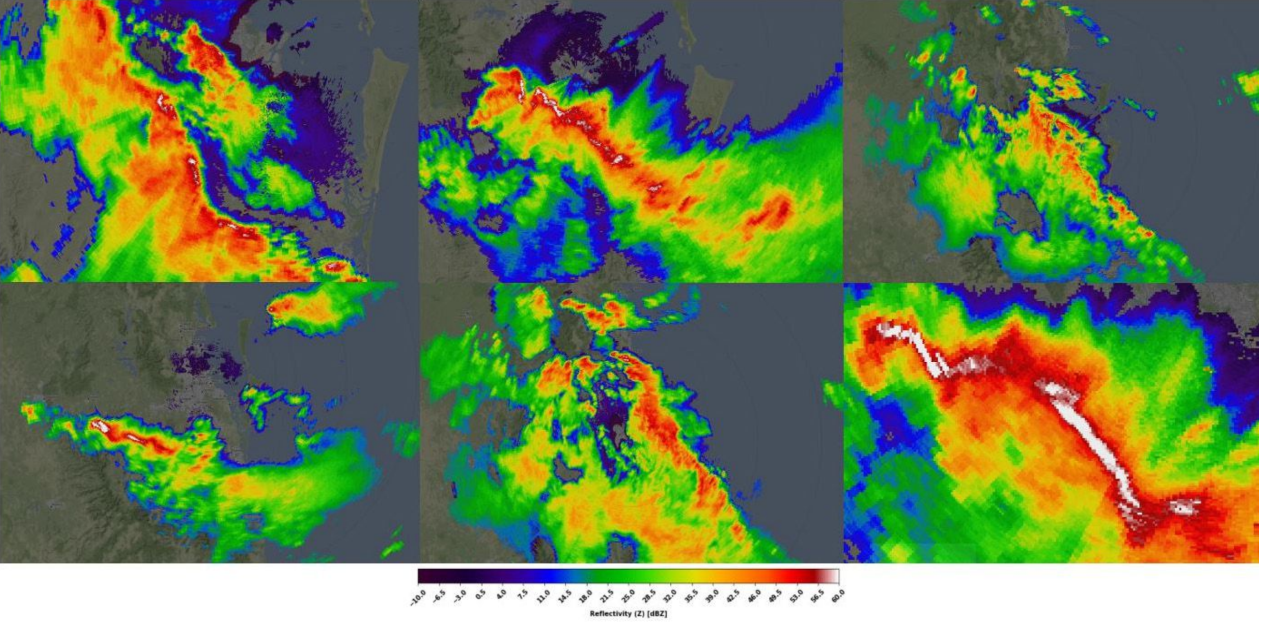
The aim was to maintain situational awareness, providing reflectivity data to forecasters and the public. After thorough consideration, an innovative Meteopress solid-state C-band Doppler radar system with dual polarization and a 2.4kW solid-state transmitter was chosen. This system, featuring a 1.7° beam width from a 2.4m antenna, met the essential requirement of delivering accurate reflectivity data.

The Meteopress Solid-state C-band installed at the Brisbane Airport Observing Office

Simplified installation

The Brisbane Airport Observations Office, previously a weather radar site until 2009, was selected for the installation of the temporary radar. It offered existing power and communication infrastructure, albeit with limitations due to new building developments affecting data quality for long-term use.

The installation process was streamlined due to several factors, including a low power requirement (15A circuit, 1.5kW maximum power load); compact design with radar transmitter and signal processing hardware integrated at the back of the antenna, eliminating the need for additional space for racks, etc; the option to forgo air-conditioning inside the radome; and operation within the existing C-band spectrum allocation, including necessary frequency modulation for close-range data.



ABOVE: Squall lines – narrow, elongated bands of intense thunderstorms – measured by Brisbane Airport weather radar during the first year of its operation

Integration with network

The new radar was seamlessly integrated into the BoM network, adhering to standard volume scan configurations and data formats. Communication was established via the existing BoM WAN at the Brisbane Airport Observations Office.

The radar's reflectivity data was also successfully ingested into BoM's data processing systems. This enabled the data to be displayed on the bom.gov.au website and smartphone app and incorporated into post-processing software for applications like gauge-adjusted rainfall accumulations.

Performance and reliability

The radar installation was completed within a week in July 2022, with data transmission beginning just four hours post-installation. Since its installation, the radar has experienced minimal outages. Most disruptions in the past year were due to external factors, like adjacent roof repairs, rather than the radar itself. Initial issues, including software resets and transmitter chain failures, resulted in approximately five days of outage over 12 months. However, subsequent upgrades have significantly improved reliability, approaching near 100% availability.

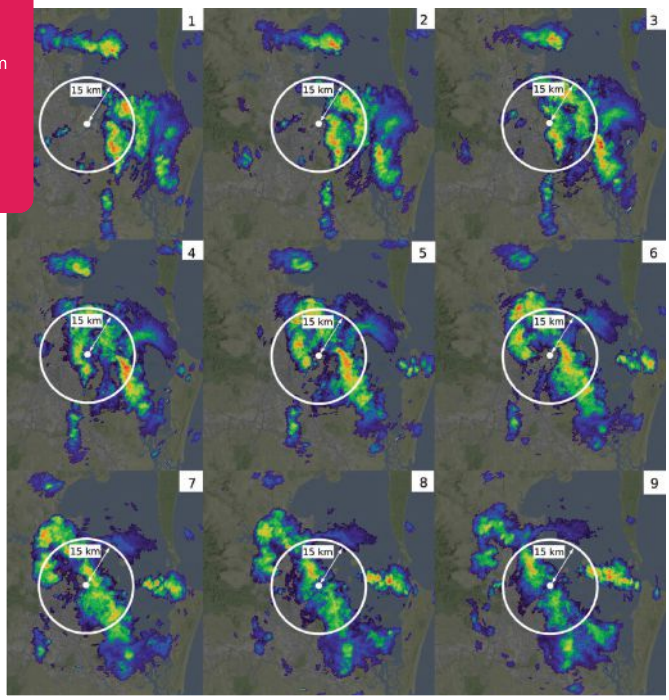
One-year of operations

The Meteopress solid-state radar installed at Brisbane Airport has now provided more than one year of reliable service for the Brisbane city and surrounding area. Originally serving as a backup data source, it has often been a single primary source of weather radar data over Brisbane due to outages of the other operational radar.

The project illustrates an innovative approach to maintaining critical weather monitoring services during significant infrastructure upgrades. It not only ensured uninterrupted weather data for Brisbane and southeast Queensland but also demonstrated the feasibility and effectiveness of rapidly deployable radar solutions in emergency or transitional scenarios.

The Meteopress solid-state radar is a mature technology with higher uptime than magnetron- and klystron-based radars, capable of operations even with the most demanding customers and in difficult climate conditions. ∎

Reflectivity measurements in so-called 'blind range' area of 15km around Brisbane Airport weather radar on April 24, 2023, proving no blind range issues



> // The project illustrates an innovative approach to maintaining critical weather monitoring services during key infrastructure upgrades"

Jean-Michel Fage, president, Remtech

CLUTTER free

Remtech explores how ground clutter influence can be removed from radar and sodar measurements to improve wind data quality

The antenna size of lidars corresponds to thousands of wavelengths, whereas radars and sodars typically have antenna sizes less than 20 wavelengths. The antennas of military phased-array airborne radars, for example, are typically 20 wavelengths, radar wind profilers are 10 wavelengths and sodars fewer than that. The result is that while lidars have negligible sidelobes, radars and sodars have significant sidelobes.

Ground clutter is caused by the antenna's side lobes, generating spurious reflections with an energy level that can be well above the useful signal. This is because although the emitted and received spurious signals are much attenuated by the relative level of the sidelobes versus the main lobe, the spurious reflections are generated by very efficient reflectors, such as buildings and trees, etc, while the useful signal is very poorly reflected by the air.

This ground clutter is generated by fixed obstacles that feed the acoustic spectrum in the receiving mode with an energy peak centered at zero Doppler shift. This can cause a dramatic underestimation of the measured wind speed.

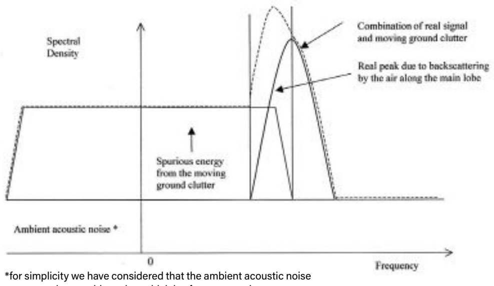
This signal processing problem is solved using the following techniques:

- No emissions below certain frequencies to generate antenna secondary lobes that are too sensitive to cause ground clutter;
- Cleaning of the ground clutter in the complex Fourier domain using a reference antenna;
- Using an angle of arrival approach to delete signals that come from too low an elevation;
- Applying a special erasing procedure of the spectra in the zero Doppler zone and a unique correction formula to avoid generating biases for the small real wind speed components.

TOP: Mid-range (700m average altitude) PA0 Sodar acoustic wind profiler in the Atacama Desert, South America

ABOVE: Remtech experts presenting the miniature PA-XS Sodar for wind energy applications at two field sites

An additional effect, still not documented in literature, is related to spurious reflections from moving obstacles. This is typically the case with reflections from tree branches. In such cases, the ground clutter effect is no longer a peak centered at zero Doppler shift in the received acoustic spectrum. As the movement of the branches reaches speeds similar to the wind speed itself (higher when the branch moves downwind than when it moves upwind) the received acoustic spectra look like this:



*for simplicity we have considered that the ambient acoustic noise corresponds to a white noise, which is of course not the case

This effect clearly causes an underestimation of the wind component. This underestimation will be a certain percentage of the real wind, so a scatter plot will show a regression-line slope below 1.0, depending on the site and the season. In recent investigations, slopes such as 0.85 have been obtained, leading to a 40% underestimation of the wind power. Moreover, as ground clutter depends on atmospheric stability there will be a diurnal variation that will affect the measurement error.

While fixed ground clutter is mostly a concern at low wind speeds – and in air quality applications – mobile ground clutter is highly relevant as any error in wind speed corresponds to a three-times-greater error in wind power. Remtech has solved this problem using two techniques: active calibration to characterize the backscatter from moving ground clutter, and special processing of the received spectra using a shape-recognition technique. These have been added to the company's previously mentioned techniques for ground clutter cleaning. ■

Yanick Ungricht, application manager, humidity, Rotronic

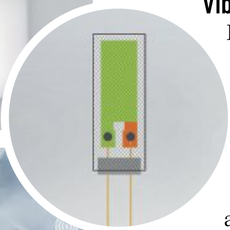
Rotronic's latest-generation humidity and temperature probes are providing stable and accurate measurements of climate conditions for the energy-efficient generation of artificial snow

Let it SNOW

To produce artificial snow, systems with nozzle technology are primarily used. Water is sprayed through nozzles into the air and forms water droplets. At the same time, a mixture of compressed air and water is sprayed through smaller nozzles. These microscopically small droplets immediately freeze into ice grains. The ice grains then serve as freezing nuclei for the larger water droplets. Thanks to this process of nucleation, it is possible to produce snow at a temperature of just below 0°C. (Normally the water would only freeze below -7°C, depending on the relative humidity.)

To meet the needs of maximum productivity, large propeller machines running on compressed air are generally used. However, the power consumption of such machines is up to 20kW/h, which is huge for large ski resorts that can have 1,000 snow guns. This means that the potential for saving energy is great.

Running snow cannons in the wrong climatic conditions can waste energy and produce unsafe icy conditions. Therefore before the snow cannons are sited throughout a ski area, a map of the climatic conditions is made and the supply shafts for the water pipes are installed. Vitally important here are the temperature and humidity reference probes, which are installed outside the snow cannon in a small weather shield. Measured data is transmitted to the main weather station. With additional software the individual snow cannons can be monitored and controlled to provide the best amount of snow.



MAIN & INSET: Rotronic meteo probes HC2A-S3(A)

TOP: A weather shield sample

ABOVE: Rotronic humidity probes measure climatic conditions to help efficiently produce artificial snow

Monitoring humidity and temperature is crucial for creating artificial snow and saving energy so that snow is only created when the necessary conditions are present.

Vibration resistance

During artificial snow production there are increased vibrations, which can influence the reference sensor itself. During the development of Rotronic's HC2A humidity and temperature probes, special consideration was taken to ensure that the sensors are vibration resistant and that the mechanical stability inside the sensing element was improved. Finally, the connecting legs of the sensor are made of gold-plated phosphor-bronze so that the probe can withstand even the toughest environments.

The Rotronic HC2A range of humidity and temperature probes and their predecessors have been well proved in these applications for nearly 60 years. These probes have supported the efficient production of snow to enable all winter sports enthusiasts to enjoy the longest-possible winter season.

Overall, Rotronic offers an advanced instrument range, precision crafted for meteorological and diverse applications. Its range includes high-precision humidity and temperature probes, calibration equipment, handheld measurement devices – for spot measurement – and robust weather shields. ∎

ROLE MODELS

Dr Scott Hosking, senior research fellow at The Alan Turing Institute, speaks to *Meteorological Technology International* following news that the institute is partnering with the UK Met Office to improve weather forecasting using AI

Please tell us more about your partnership with the UK Met Office.
This project aims to tackle the big hold-out problem in weather prediction – fast and accurate prediction of impactful weather events that sadly can bring devastating consequences to communities in the UK and worldwide.

Using the complex and rich meteorological data sets and expertise from the UK Met Office, and AI expertise from the Alan Turing Institute, we aim to save lives, protect infrastructure and push the boundaries of scientific understanding for the benefit of communities here in the UK and internationally.

What does the partnership hope to achieve?
It is hoped that the new collaboration will accelerate work to deploy machine learning technology alongside traditional techniques to improve the forecasting of some extreme weather events – such as exceptional rainfall or impactful thunderstorms – with even greater accuracy, helping communities to increase their resilience.

What are the key challenges associated with this project?
The key challenge will be closely embedding expert meteorologists and senior machine learning engineers in a team to develop advanced and fit-for-purpose AI solutions that consider the domain knowledge and state-of-the-art in spatiotemporal machine learning methods.

How will new AI models be tested?
Meteorologists have developed robust validation frameworks for their traditional physics-based models. We will be testing our models against those to ensure our AI models fit into place – in terms of the digital infrastructure and also the research culture of the weather community.

Do you see AI ever replacing traditional forecasting techniques?
We believe that using AI in combination with traditional computer models, based on the physics of the atmosphere, will provide the most detailed and accurate weather forecasting available.

How will AI technology improve over the next 5 to 10 years?
Through AI, we are witnessing a rapid shift in how scientists understand and predict changes in complex systems, reshaping the landscape of weather forecasting. The ability of AI models to blend large historical data while flexibly integrating real-time observations with ever-increasing accuracy and speed is astounding. As communities around the world look for solutions to become more sustainable, accurate weather forecasts are essential for maximizing our energy networks and agriculture. The test now for the AI and weather research community is whether we can produce highly localized and accurate forecasts. ∎

AI can be used to build next-generation forecast models to support the agricultural sector

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