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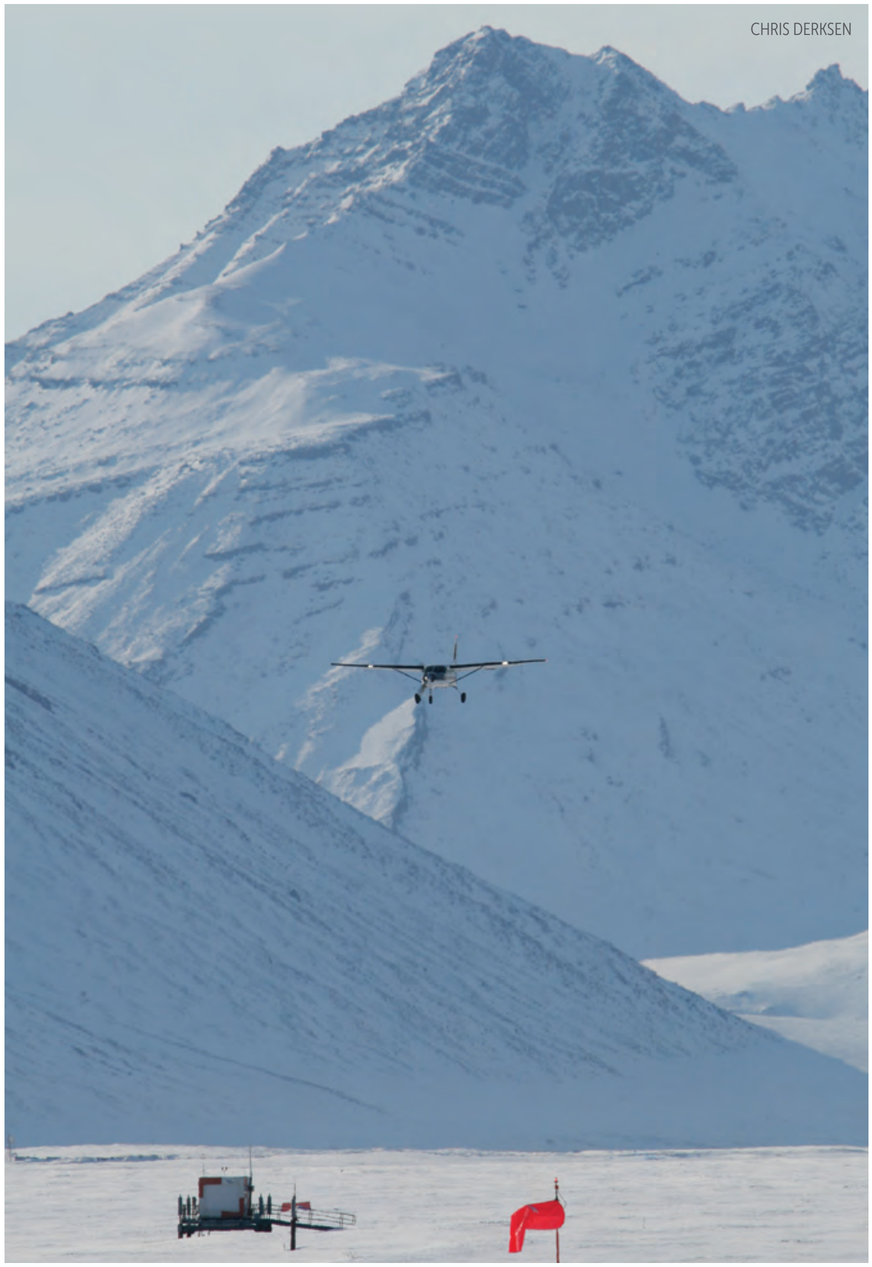
What do salmon, hydroelectric power, and agriculture have in common? They all depend on snowmelt. So do floods and wildfires. "We are seeing more fires because the snow is melting earlier," says Ana Barros, an engineering professor at the University of Illinois Urbana-Champaign, recalling how swaths of the US were shrouded in smoke from the record fires in Canada this past summer. Early melt can make soil soggy at the wrong time, and less snowmelt can leave soil dry; both force farmers to change their planting strategies to successfully grow crops.

The chief challenge in understanding and predicting seasonal snowmelt is measuring the snowpack. Snow accumulation varies spatially and temporally. It gets deep in mountains and remains shallower on prairies. Snow is porous, and its density varies with air, ice, and liquid-water content. Substrate, vegetation, sun, dust, soot, wind, snow grain size, and other factors affect how snow settles and melts and how sensors respond to snow.

Snow is a gap in the current understanding of the hydrologic cycle, says Barros. "Scientists don't have the understanding to really be able to assess and improve computer models." Hans-Peter Marshall, a snow physicist at Idaho's Boise State University, says that "we have to move to remote sensing, and monitoring snow will take more than one solution."

In the past 10 years or so, airborne remote sensing of snow has taken off. And for a couple of decades, scientists have been angling for a satellite dedicated to measuring the amount of water contained in snow, called the snow–water equivalent (SWE). A satellite could obtain global coverage every few days and complement other measurements and modeling to provide guidance on water consumption and risk management and to glean insights into Earth's hydrologic cycle, which becomes increasingly important as weather patterns morph because of climate change.



CHRIS DERKSEN

***IN SITU* MEASUREMENTS** paired with airborne ones in the Canadian high Arctic in 2016 were part of a US–Canadian effort to test methods for measuring water content in snow. The campaign was carried out in places with varied snow and terrain and is intended to ultimately help in satellite design.

TURLOCK IRRIGATION DISTRICT

TIMELY, HIGH-RESOLUTION SNOWPACK DATA help water managers avoid floods like one from the Don Pedro Spillway on New Year's Day 1997. When water managers for the Turlock Irrigation District in California released about 1700 cubic meters of water, the road below was damaged.

A major goal is to monitor the total amount of water stored in snow in the mountains, Marshall says. Mountain snowmelt supplies water to one-sixth of the global population, he adds. "Water security and food security are key issues."

Three satellite proposals—one in Canada and two in the US—are under review; the prospects for going forward are expected to become clear in the next year or two.

Snow courses and pillows

Snow has been monitored in mountain ranges around the world for more than 100 years. The simplest and cheapest method is to measure snow depth with a ruler at various spots during the winter months. Measurements might be collected monthly, daily, or even multiple times a day. Sometimes snow is dug out and weighed every few centimeters to assemble a profile of density as a function of depth. For bulk water content, the snow core extracted from plunging an aluminum tube into the snow is weighed to get the SWE. Typically, permanent manual-measurement sites, or snow courses, are located along paths above the snow line.

In the 1990s, many previously manual-monitoring sites in Canada were automated. "Human observers would weigh the snow to get density," says Chris Derksen, a research scientist for the government agency Environment and Climate Change Canada. "We lost that when we went to automated measurements. Depth on its own is useful, but without density, we can't know how much water there is."

In the US beginning in the 1960s and continuing for a few decades, large sacks of antifreeze were introduced to weigh snow. Called snow pillows, the roughly 3 m × 3 m waterbed-like containers are outfitted with pressure transducers. As snow piles up, the transducers weigh it and transmit the data. Some 150 snow pillows dot the Sierra Nevada, and there are more than 800 in mountains across the US; they don't work well in plains because winds blow the snow around.

But snow courses and snow pillows provide only spot measurements, snapshots in time and space. Water managers need estimates of when—and how much—melted snow will hit reservoirs and streams. Governments, municipalities, irrigation districts, and utilities need forecasts of water availability and risk associated with too much or too little water. "Snowpack varies over the length of a football field," says Marshall, "so stations are not representative of a watershed. And as soon as the snowpack moves up in elevation, you are left with dead sensors."

Predicting the volume of water that will flow into streams from the time of peak snowpack—traditionally 1 April in the Sierra Nevada—works "pretty well if the year is representative and close to the average over the past 30 years," says Marshall. "But we are having more extremes." For example, California had lower-than-average snowfall in the winter of 2019–20, but then three years later, this past winter, it had the most snow on record. Unusual weather patterns—rain on snow, early melt, excessive snow—challenge the traditional statistical approach. Traditional methods, Marshall says, have "no hope of getting measurements everywhere and estimating how much water you have. We need to go from statistics-based models to physics-based models."

Marshall adds, "We understand the physics well, but we need better inputs." Those inputs include snowfall, rainfall, condensation, absorption by the soil, evaporation, and albedo—the amount of the Sun's energy a surface reflects. Topography and meteorological variables such as temperature and wind speed and direction are also taken into account. "Put everything into a complicated model," he says, "and you can keep track of the energy and mass of the inputs and outputs."

Remote sensing

Snow is bright, so its extent is easy to map from satellites, says Derksen. "Getting more hydrologically significant measurements is the hard part." Snow depth and SWE can be measured by using remote sensing of microwaves or gamma rays emitted from Earth and comparing natural radiation at a given location with and without snow. Low-resolution passive microwave measurements can be made from space, while passive gamma signals are smaller and need to be measured closer to Earth, such as from towers or planes. Passive monitoring works best when the soil is frozen and the snow is shallow. "Passive gamma is more accurate than passive microwaves," says John Pomeroy, a professor at the University of Saskatchewan and director of its Centre for Hydrology. "It's not affected by ice layers or thawed snow."

Thomas Painter's company, Airborne Snow Observatories, flies planes over watersheds in the Sierra Nevada. The flights use lidar to obtain snow depth by comparing times for a laser signal to reflect back with and without snow coverage, and they use multiwavelength spectroscopy to measure albedo. By measuring multiple wavelengths, says Painter, the snow's grain size and the amounts of liquid, dust, black carbon, and biological matter in the snow can be discerned. "Those things affect how fast the snow melts." To get the SWE, he combines flight measurements of depth with modeled snow density constrained by data from existing snow courses and snow pillows. "The snow density doesn't change much across the mountain landscape compared with the change in depth," he says. (To learn how Painter's career has taken him from professor to NASA scientist to entrepreneur, see physicstoday.org/painter.)

"Ten years ago, we would take 17 snow course measurements over about 1500 square miles," says Wes Monier, chief hydrologist for the Turlock Irrigation District, which serves about 8500 farmers in California. "The sophistication we had was 'my aunt's cabin has snow to the eaves.' " Now, about a million data points from Airborne Snow Observatories feed into models. Without the technology, he says, "we wouldn't be able to adapt to the weather going from extreme to extreme. The information gives you time to develop a plan to use the water."

Satellites could help provide more accurate and refined measurements for water management, says Painter. "We may be able to use their inferences of SWE in dry snow." And indications from satellites that the snowpack "is melting could be helpful for modeling." The proposed satellites would use radar. But the problem with radar, says Painter, "is that, for the same reasons a microwave oven works, almost all of the microwaves will be absorbed in wet snow, so you have no signal. It only works if the snow is dry or has low liquid content."

Satellite monitoring of snowpack, Painter says, would be most valuable for hydrologic science and cryosphere science on the global scale—to understand glaciers, sea-level rise, and more. And, he adds, "the great thing about satellites is that they can cross geopolitical boundaries."

Dedicated snow satellites

Derksen is the principal investigator for Canada's proposed *Terrestrial Snow Mass Mission*, the satellite considered by the snow community to be closest to getting the nod. It would use radar scattering from snow volume to obtain the snowpack mass. The method has been demonstrated with instruments on towers and aircraft, Derksen says, but has yet to be tried from space. The concept is similar to a satellite proposal that didn't make the cut at the European Space Agency about a decade ago.

An advantage of radar is that it can be used at night and in cloudy weather. The plan is to use two frequencies, 13.5 GHz and 17.5 GHz (wavelengths of approximately 22 mm and 17 mm, respectively). The longer wavelength penetrates more deeply than the shorter one, and they scatter differently. With two frequencies, Derksen says, the SWE estimates will be better. "And it's not a huge cost to add the second frequency." The satellite would cover the globe every five to seven days and collect data at 500 m resolution.

In the US, two proposals are under review for satellites that would measure SWE. One, led by the University of Illinois Urbana-Champaign with NASA's Goddard Space Flight Center as a partner, is similar to the Canadian proposal, but at frequencies of 9.6 GHz (31 mm) and 17.2 GHz (17 mm). It would provide global coverage with a five-day revisit cadence and 250 m resolution.

All microwave techniques face limitations when the snow is wet, says Illinois's Barros, principal investigator for the US radar-scattering proposal. "But a combination of measurements at microwave frequencies can be used to infer snow conditions, including for melting and refreezing," she says. "And if we know the peak dry SWE, we can model the melt season."

The other US proposal would take advantage of existing signals, or "signals of opportunity." It is led by UCLA, with NASA's Jet Propulsion Laboratory as a partner. The approach relies on military communications signals at 260 MHz (1.2 m) and 370 MHz (0.81 m), and it is limited to lower latitudes (below about 60°) where those signals are found.

The longer wavelengths allow for seeing through forest cover and deeper snow, and they are less affected by liquid water in the snow than are millimeter signals, says principal investigator Steven Margulis of UCLA. It saves on transmitters, which at microwave frequencies can be bulky and expensive. "We would launch a constellation of receivers," he says. "The receivers are the eyes looking for signals that are reflected off Earth's surface. Measuring the change in reflected signal from snow-covered surfaces allows for retrieval of SWE at spatial resolutions of hundreds of meters every six days."

In competition with each other, the teams for the two US proposals are for now keeping mum on details. They are 2 of 14 proposals submitted last summer to NASA that target seven observables identified in the 2017 decadal survey on Earth system science: greenhouse gases, ice elevation, ocean surface winds and currents, ozone and trace gases, snow depth and SWE, terrestrial ecosystem structure, and atmospheric winds. Next spring, four of the proposals are to be selected for further study, and in 2025 two will be chosen to fly. NASA has said that one of the two final winners will likely focus on greenhouse gases.

Despite the competition between the US proposals, Boise State's Marshall says that "the snow community will rally behind either if one is funded." Barros agrees: "Everybody is hungry for data."

In the meantime, scientists will focus on getting relevant data from other, multipurpose satellites. They include *NISAR*, a collaboration between NASA and the Indian Space Research Organisation, set to launch early next year; it will collect data from which snow mass can be calculated. The European Space Agency plans to launch a similar satellite, *ROSE-L*, in 2028, and its *Copernicus Imaging Microwave Radiometer*, planned for launch within the next decade, will provide passive microwave data. Scientists expect to be able to extract changes in SWE every few weeks from those satellites' data, Marshall says, "but it is likely to only work some of the time due to the longer repeat intervals designed for other applications." NASA's *Surface Biology and Geology* mission will quantify global albedo when it flies later this decade.

Noah Molotch, of the University of Colorado Boulder, studies how stream flow will change as the quantity of snow and the timing of snowmelt changes. He notes that "simply from an accounting standpoint, our estimates of water stored in snow globally are at best within 40%." Studying SWE with a space-based instrument would help, he says. Without one, "we are flying blindly into the future when it comes to snow–water resources on the global scale. One of the big questions is, How does snowpack change as climate changes?"

Toni Feder

The future has arrived for securing confidential data

Though quantum computers are still a decade or more away, NIST is finalizing new encryption standards now to replace current vulnerable protections.

Breaches to data security are almost an everyday occurrence. Yet much worse could lie ahead: Cryptologists agree that quantum computers will be able to crack current encryption systems that now protect e-commerce transactions, mobile-device conversations, personal identifiers such as social security numbers, national security and industrial secrets, and other confidential information. And much of that information that already exists on networks could be saved and decrypted whenever quantum-decryption capabilities do arrive.

There's no consensus on when quantum computers will render current encryption obsolete. In a 2022 survey by the Global Research Institute and evolutionQ, a Canadian quantum security consulting firm, 20 of 40 academic and industry quantum computing leaders said they considered it more than 5% likely to happen within 10 years, while 9 respondents indicated that the likelihood was 50% or greater. For 20 years from now, 14 said there would be a 70% chance, and all but 5 gave the same odds within 30 years.

And if such computers become available within the next couple decades, much of the sensitive information that is being shared over networks today may be vulnerable. "Imagine you have classified information you want to keep safe for 30 years," says Dustin Moody, a NIST computer-security mathematician. "It is safe for now, but if a quantum computer comes in 15 years, someone can break [into] it and they will have access to it 15 years before you wanted them to."

Many experts are all but certain that intelligence agencies in the US and other