CIRES COOPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES

SPHERES

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Water, Water, Everywhere...

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ON THE COVER:
A low aerial drone photo of Jaluit Atoll, Republic of Marshall Islands. Photo: Jeff Donnelly/Woods Hole Oceanographic Institution

CIRES, a partnership of the University of Colorado Boulder and NOAA, is dedicated to fundamental and interdisciplinary research targeted at all aspects of Earth system science and to communicating these findings to the global scientific community, to decision makers, and to the public. Our environmental scientists explore many aspects of Earth system sciences: the atmosphere, cryosphere, hydrosphere, geosphere, and biosphere. These spheres of expertise give our magazine its name.

SPHERES
Cooperative Institute for Research in Environmental Sciences

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99 percent

Sea surface temperatures in the Gulf of Maine have increased faster than **99 percent** of the global ocean, harming the cod fishery there. (see page 20)

60 days

By the 2050s, parts of the Arctic Ocean once covered by sea ice for much of the year will see an additional **60 days** a year of open water. (see page 22)

10%

Estimated amount of water that evaporates from Lakes Powell and Mead every year. That's **1.5 million** acre feet, enough for **~740,088** Olympic-sized swimming pools. (see page 4)

6 + 7

Epidemics of chronic kidney disease related to heat stress and dehydration are confirmed in **6 countries**, suspected in **7 others.** (see page 13)

13 years

The research vessel *Laurence M. Gould* crossed the Southern Ocean's Drake Passage **20 times a year** for **13 years** on Antarctic resupply trips, measuring ocean carbon along the way. (see page 24)

LOST LITERS

CIRES' Ben Livneh and colleagues seek to measure and conserve reservoir water lost to evaporation

by Laura Krantz

Lake Powell, Utah, USA (from plane). Note the prominent "bathtub ring" made visible by low water (May 2007). Photo: PRA/Creative Commons

Lake Mead and Lake Powell sit smack-dab in the middle of the American Southwest. The two reservoirs—the largest in the nation—provide water for communities throughout Utah, Arizona, Nevada, and California, not to mention Mexico, but the growing populations of nearby cities and continued drought have drastically lowered water levels in both lakes.

And then there's the problem of evaporation, an expected outcome when you site big expanses of open water in hot, dry deserts. Scientists don't know much yet about the role evaporation plays. "There hasn't been a lot of work done yet to quantify how much is being lost," says CIRES Fellow Ben Livneh. "And current reservoir estimations of evaporative are highly uncertain." So last October, Livneh and a group of scientists, including Katja Friedrich and Robert Grossman of the University of Colorado Boulder's Department of Atmospheric and Ocean Sciences, sat down to do a little math.

This team wanted to use the best science available to lessen losses from Western reservoirs and water systems. But first, they had to figure out how much water they were losing to evaporation. "We did some back-of-the-envelope calculations based on Lakes Mead and Powell," Livneh remembers. "Based on surveys, the water level had dropped more than 5 feet in a given year. That's about 1.5 million acre feet." (For reference, an acre foot is the amount of water you'd have if you covered a football field with a foot of water.) The annual flow of the Colorado River, the river that feeds these two reservoirs, is approximately 15 million acre feet. "So if 1.5 million acre feet are evaporating," says Livneh, "That's about ten percent."

Summer temperatures around Mead and Powell regularly climb into the triple digits, while precipitation and relative humidity tend to remain low. And other factors can drive reservoir evaporation, too: solar radiation (reservoirs at higher altitudes get more solar energy and therefore, have higher evaporation), the temperature of the water in relation to that of the air, wind speed, and barometric pressure.

Some places have already made efforts to reduce evaporation—in Arizona, for instance, the Central Arizona Project pumps water from the Colorado River into groundwater reservoirs, thus reducing the stored water's exposure to air and its evaporation rate. And Livneh suggests that future plans could involve keeping water closer to the source, for as long as possible, where reservoirs are smaller and evaporation could be less. "This is about conservation at the source, rather than at the spigot," says Livneh. "Whatever we can do to limit evaporation can help downstream."

> "Based on surveys, the water level had dropped more than 5 feet in a given year."
> —Ben Livneh

But what works for one area may not work for another. While some reservoirs are used exclusively for water supply, most have multiple uses, like hydropower, flood control, navigation, and recreation. So solutions for stemming evaporation are not one-size fits all. And, as scientists Peter Blanken and Justin Huntington are discovering, evaporation isn't uniform. Blanken is a professor of geography at CU Boulder; Huntington is a research scientist with the Desert Research Institute. Both are studying evaporation, in the Great Lakes and at Lake Tahoe respectively. Using buoys with instruments that measure changes in temperature and fluxes of energy and water, they've found that, as they move to different points in these lakes, the rate of evaporation changes.

With all that in mind, the scientists brought this research to a meeting with water managers from the West at a workshop, to discuss the needs of those water managers. Together, they also drew up a list of recommendations and questions they wanted to answer. They'll start by categorizing reservoirs from the lowest rate of evaporation to the highest, to see what factors might affect that.

Also in their plan is working with researchers using different methods to develop something of a crowd-sourced reservoir model. And they plan to develop more state-of-the-art methods and instrumentation to make measuring reservoir evaporation more accurate. Any findings and recommendations will have to keep existing infrastructure in mind. "If we could scrap and re-site reservoirs, great, but that's not a realistic option," says Livneh. "So what can we do with the existing system?" ■

Colorado’s Biggest Storms

Storms follow seasonal patterns in some regions, but not others

by Karin Vergoth

In a state known for its dramatic weather and climate, Colorado’s history of extreme precipitation varies considerably by season and location, according to CIRES and NOAA research. Decision makers typically turn to historical averages to understand when and where extreme rain, hail, and snow happen in this state. But those averages often are not reliable because they’re based on observations of events that don’t happen frequently and because the observations themselves are limited, especially in remote areas.

The September 2013 Colorado Front Range floods are evidence that big storms can happen out of season and don’t necessarily obey expected norms. The widespread flooding across northeast Colorado—when the city of Boulder saw just over 17 inches of rain in one week, close to the city’s typical total for the entire year—was unusual in that it happened more than one month after the state’s typical monsoon peak. Though atypical, the floods weren’t unprecedented. After 2013, researchers checked and found other big events in September, at the peak of the Atlantic hurricane season—including a big storm in 1938.

CIRES and NOAA researchers set out to improve understanding of the state’s extreme event climatology since “even in regions where you think you have a strong seasonal signal, the data actually show heavy precipitation events happening outside of the expected time, especially in the central mountains of Colorado,” said Kelly Mahoney, a scientist at NOAA’s Earth System Research Laboratory.

What’s the take-home message? It’s that Colorado’s extreme precipitation can occur anytime and at all elevations across the state. “Trying to assign extreme events to a certain season is not necessarily a good thing to do here in Colorado,” said Mahoney. Particularly along the Continental Divide, very big storms can happen during any season and it’s i`mportant for decision makers to understand that impacts such as flooding are a nearly year-round risk across the state. Mahoney’s parting advice: “We need to look at the critical ingredients that come together to produce an extreme event, because that can happen at any time during the year.” Having a better understanding of the weather pattern that produced the 2013 flood, for example, could be useful for predicting other similar events, regardless of the season. ■

The small mountain town of Jamestown, Colorado, population 300, was cut off by a flood in September 2013. FEMA Urban Search & Rescue teams deployed to the state to help out.
Photo: Steve Zumwalt/FEMA

RESEARCH PROFILE

Lisa Dilling

Director of the Western Water Assessment

Cities in the western United States stand at the front lines of a changing climate. Water managers in arid and semi-arid places like Las Vegas, Denver, and Phoenix have been grappling for decades with how to reduce waste and use water more efficiently. “They’re already at the forefront of adapting,” says Lisa Dilling, Director of the Western Water Assessment program within CIRES. “They have been experimenting with ideas like pumping surplus water into underground aquifers and negotiating water arrangements across the shared basin and with other sectors, such as agriculture.”

Dry times and warming temperatures can lead to tension, she points out, but water managers’ practical efforts to deal with these concerns have led to strong collaborations among cities and stakeholders. “People aren’t necessarily at each other’s throats–they’re working together in many cases to try to cope with change.”

Dilling’s research focuses on that space in which decision makers struggle with choices involving dynamic risks and vulnerabilities. Climate change is bringing hotter, drier conditions to the West, and she and her colleagues in the Western Water Assessment seek to better understand how people make decisions related to that change. In particular, Dilling studies:

1. **Adaptation**–building the capacity to adapt to variable and less predictable water availability, which involves innovative, flexible systems.
2. **Multilevel governance**–how water authorities at different levels (city, state, federal) work together and how they can build resilience to unexpected changes. In the West, especially, water systems are tied together, so water management is as well.
3. **Dynamics of vulnerability**–how decisions about one aspect (say, availability) might affect others (such as cost). For instance, water conservation policies can protect water supplies. But conservation can also mean reduced revenue, leaving utility managers struggling to maintain aging infrastructure. Effective adaptation strategies consider these kinds of links.

Increasingly, planners and other decision makers talk about responding to climate variability and change as a form of risk management, Dilling says. Her work aims to understand the decisions that are climate sensitive, and the tradeoffs involved in making decisions to reduce potential harm and increase opportunity. In some cases, she says, it’s impossible to fully characterize risks ahead of time. For example, as systems become more complex and interlinked, changes in environmental conditions or even changes in operating procedures can lead to unforeseen consequences. In such cases it’s important for decision makers to be both flexible and transparent, ready to shift strategies and explain why if the need arises. ■

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

The CIRES-based Western Water Assessment (http://wwa.colorado.edu) is funded by NOAA’s RISA program, Regional Integrated Sciences and Assessments: bit.ly/noaaRISA

Counting Every Snowflake

An early understanding of snowpack helps downstream water management

by Laura Krantz

Growing cities and thirsty farms slurp up lots of water, especially in the arid American West. While city planners and water managers have a pretty good sense of how much water they'll need from year to year, knowing how much water will actually be available is a little more complicated.

High up in the Rocky Mountains, where the headwaters of many American rivers get their start, the snow usually begins to settle in by December. Where it falls and how much water it actually contains will have a big effect on how much water is available in rivers downstream. The sooner water managers know what's up in those mountains, the better they can plan.

That's where snow hydrologists like Mark Raleigh come in. Raleigh, a CIRES Visiting Fellow working with the National Snow and Ice Data Center, spends a lot of time thinking about the Colorado River Basin. As a snow hydrologist, he wants to know how much snow is falling, where, and how much water it contains. Until very recently, that's been dependent entirely upon a boots-on-the-ground methodology—tramping through the mountains, digging deep snow pits, and taking measurements by hand.

But in 2012, NASA and the Jet Propulsion Laboratory in California developed the Airborne Snow Observatory (ASO), which lets scientists map the depth of snowpack using lidar—a system that works similarly to radar, but uses lasers instead. "ASO brings in a tremendous amount of data," where once there were only a handful of measurements, says Raleigh: "This is a game-changer for researchers and may be the way of the future for water management."

ASO is still in the early phases, which means there are some big limitations: For one, the ASO operates only in a limited area right now, including the Tuolumne River Basin of California and Colorado's Uncompahgre and Rio Grande River basins. Additionally, lidar can't tell the snow's density, which means Raleigh (happily) gets to be out on skis at least a few times a year, digging snow pits.

Water managers and others with a stake in water forecasting use ASO data to estimate snowpack and water content. "There are limits to the models that snow hydrologists use—there's no silver bullet for getting perfect forecasts," says Raleigh. "But the basic goals are to improve models and to tell water managers how much water is in the snow."

Raleigh's colleague, John Berggren, has interviewed those same water managers to see how the data they're getting from campaigns like ASO and scientists like Raleigh can be more helpful. Berggren, a graduate student with the Western Water Assessment, spent the past summer speaking with water managers in the Uncompahgre and Rio Grande River basins. "We wanted to find out how they used existing information, how they incorporated it, what their general concerns are," he says. "We were also trying to find out if there were specific times or years that were bad and whether, if they'd had different data, they could have reduced negative impact."

Berggren found water managers especially keen on getting two pieces of information as early as possible: how much water is in that snowpack and when it is going to melt. Both of those details inform water managers' decision about when to turn on irrigation ditches and how water should be allocated that year given the supply. "In the Rio Grande Basin, for example, the amount of water that must be delivered downstream from Colorado to New Mexico and Texas is governed by the Rio Grande Compact. The compact stipulates that the bigger the snowpack, the more water is owed downstream," says Berggren. "If water managers can get a more accurate April 1 forecast, that helps them apportion the right amount of water to users."

Unexpected amounts of water can throw a big wrench into the system. In May 2015, Colorado experienced a very wet month, which no one had predicted. More accurate snowpack data would have helped water managers deal with the unexpected rain and high elevation snow and its effects, including flood control and water distribution.

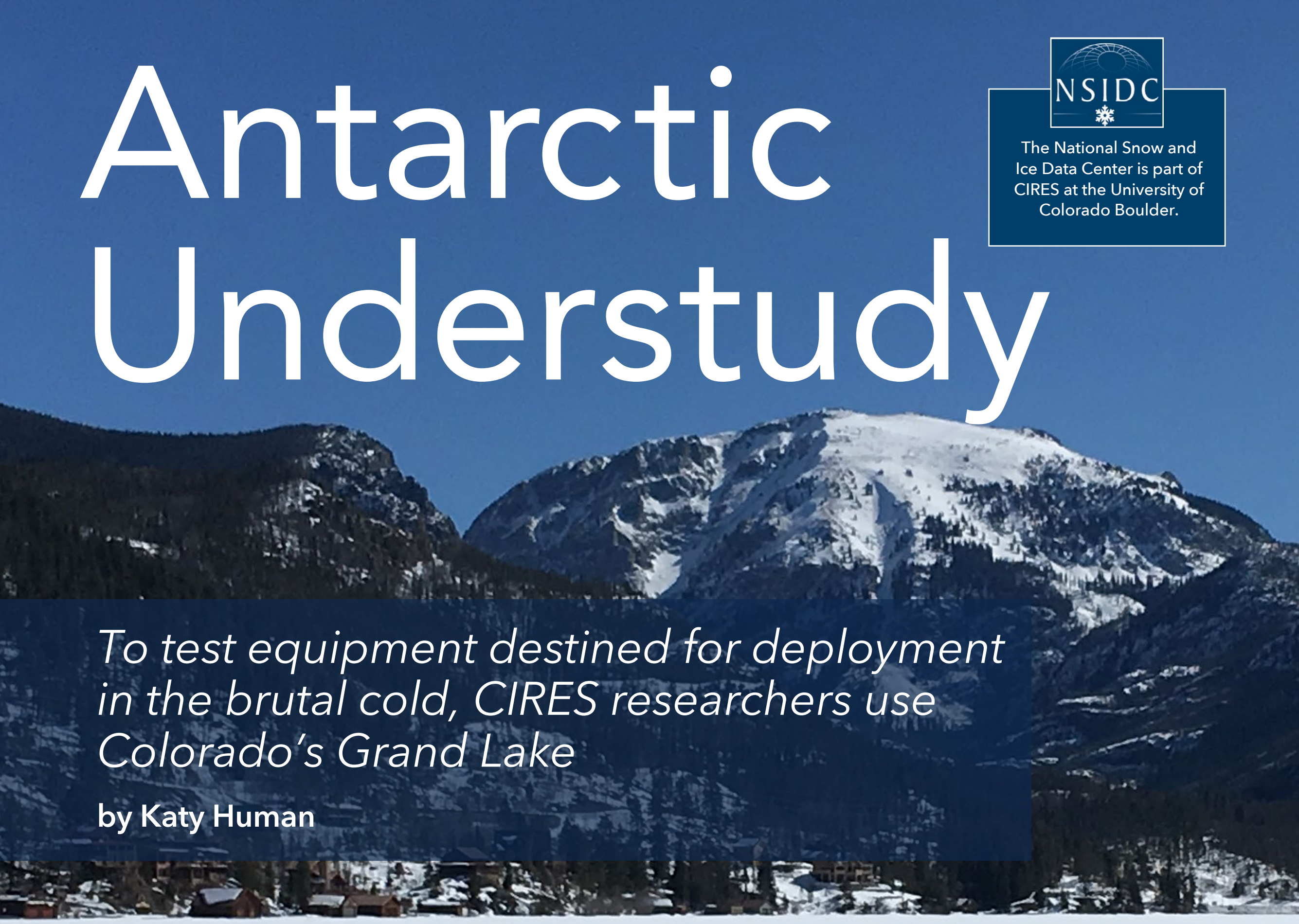
> "This is a game-changer for researchers and may be the way of the future for water management."
> —*Mark Raleigh*

The cool new science being used in ASO, as well as the work that Raleigh and other snow hydrologists do, helps develop a better understanding of the snowpack. "Improving snowpack monitoring data," says Berggren, "means we can better handle the severe weather events because we're already operating in a more accurate way." ■

Mark Raleigh downloading data from a ground-based GPS station in Niwot Ridge, Colorado. The GPS data are processed to derive variables such as snow depth and soil moisture. Photos: Courtesy of Mark Raleigh

Mark Raleigh installing a time-lapse camera that will monitor snow presence on the ground and in the forest canopy through the winter for the NASA SnowEx project in Grand Mesa, Colorado.

Mark Raleigh measuring the mass and density of snowpack layers in a snow pit in Fraser Experimental Forest, Colorado.



Antarctic Understudy

The National Snow and Ice Data Center is part of CIRES at the University of Colorado Boulder.

To test equipment destined for deployment in the brutal cold, CIRES researchers use Colorado's Grand Lake

by Katy Human

On Antarctica's ice shelves, floating atop the ocean, temperatures can plummet well below minus-50-degrees Fahrenheit and ice grows hundreds of feet thick. So if you want to get better information about changing ocean temperatures and currents or track the region's weather, you need very robust instruments. And you need to test them well.

To that end, a team of researchers in the National Snow and Ice Data Center spent a couple weeks camped out in Grand Lake, Colorado last winter, testing equipment in the high mountain lake. They drilled holes through the ice and dropped cable-bound instruments—part of a system called AMIGOS-II, or Automated Met-Ice-Geophysics Observing Systems II—through more than 100 feet of water.

"We learned that the basic idea works," said NSIDC's Ted Scambos. "Our sensors recorded water temperatures from from top to bottom, found a bottom layer of water close to three, four degrees C, the sensors talked with the computer… it was a good shakedown."

It was also a good shakedown for his colleagues, some of whom hadn't camped on noisy floating ice before or never had to troubleshoot challenges in real-time, in the cold and sometimes dark.

"Camped out on the ice one night, our air mattress collapsed," said NSIDC researcher Marin Klinger, "so it got very cold." The noises were surprising, too, loud creaks and sudden booms from the shifting ice. Klinger got little sleep that night, but she and her colleague did keep the instruments working throughout.

Antarctica in summer is a bit colder than Grand Lake in winter, Scambos said, and the differences grow from there: Antarctic ocean waters are salty, of course, and to reach them, researchers will have to melt through hundreds of feet of ice in some places. The water can be hundreds of feet deep, too, so researchers need much longer cables to capture data from the air above the ice all the way down to the water near the ocean bottom.

They need those data to better understand the role of ocean water in melting ice, Scambos said. In some parts of Antarctica, changing ocean circulation patterns periodically bring relatively warm water to the edges of ice sheets, where it can cause melting. This can lead to faster glacier ice flow off the continent, raising sea level.

Scambos and several colleagues developed and deployed some of the original AMIGOS stations on icebergs and in areas along the Antarctic Peninsula about a decade ago. In early 2017, he's heading with the latest instrument packages—similar to those tested at Grand Lake—to the Korean Antarctic base of Jang Bogo. For the expedition, a colleague is bringing a "hot water drill" to bore through thick ice, and the team hopes to install two AMIGOS-IIs on floating ice, he said.

Eventually, Scambos and his colleagues hope to get funding for a network of AMIGOS-II stations around the entire continent. That would help scientists to better understand how ocean currents and wind shifts in the far southern continent are affecting the ice sheet, and would support better predictions of how fast the ice will melt and contribute to sea level rise. ■

◀ Mount Craig, also referred to as Mount Baldy, from the middle of Grand Lake. Photos: Robin Strelow/CIRES

Marin Klinger, research assistant at the National Snow and Ice Data Center, clears ice from a metal frame used to support scientific equipment meant for Antarctic research, during a 2016 test at Grand Lake, Colorado.

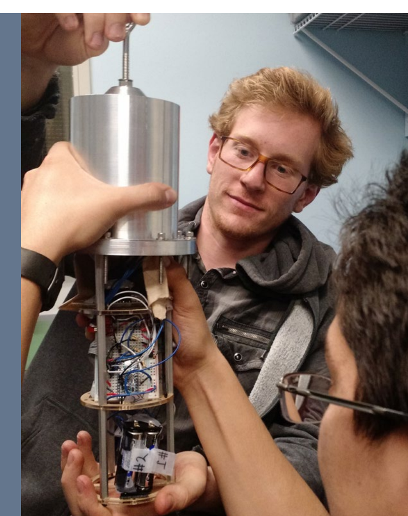
Ronald Ross, Polar66 Engineering, designed the AMIGOS-II system and helped test it out at Grand Lake in 2016.

Next-Gen

The CIRES Innovative Research Program is meant to fund small research efforts that can quickly provide concept viability or rule out further consideration. In 2015, the program supported work by NSIDC's Glenn Grant and colleagues, who aimed to develop a low-cost ocean current and temperature sensor for long-term deployment in polar ocean environments.

Grant worked with undergraduate and graduate engineering students on the project, and developed a package that cost only about $750, he said. That's by comparison to a similar instrument used with the AMIGOS-IIs, which cost roughly $17,000.

Although the instruments still need some finessing, Scambos said, "I was really impressed with what they were able to do. We're cold-testing in the laboratory at NSIDC right now. Who knows, maybe these will be part of the next version—AMIGOS-IIIs."



Engineering undergraduate students Drew Mario and Mario Medrano work on an early version of the low-cost ocean current and temperature sensor. Photo: CU Boulder

Breaking Down India's Monsoon

Studying El Niño and La Niña's effects in regions, sub-seasons, may improve rainfall forecasts

by Katy Human

Not enough rain fell across key breadbasket regions of India in the 2014 and 2015 monsoon seasons. And last year, while the monsoons were near-normal in many areas, crops still failed from lack of moisture in some regions.

"When rainfall deficits occur in areas where food grains are grown, that means hardships for many people," said Balaji Rajagopalan, a professor of civil, environmental and architectural engineering at the University of Colorado Boulder and a CIRES Fellow.

Inspired by the need to better understand and forecast India's monsoon rains, he and colleague Peter Molnar, also a CIRES Fellow and a professor in Geological Sciences, and their postdoctoral researcher Emily Gill, have spent several years dissecting the relationship between El Niño and La Niña and monsoonal rainfall in that country. The conventional wisdom has been that El Niños, characterized by relatively high sea surface temperatures in the central and eastern equatorial Pacific Ocean, bring dry times; La Niñas, with cooler equatorial Pacific waters, bring strong monsoon rains. But it's not so simple.

For example, the location of El Niño-related warming in the Pacific Ocean makes a serious difference, as Rajagopalan and his colleagues found a few years ago. During one of the biggest global El Niños on record, 1997-1998, India's monsoon season was nearly normal. That year, the El Niño signature warming over the Pacific was strongest in the east. "We found that if El-Niño-related warming is in the central Pacific, there's a much bigger drying impact on India," Rajagopalan said.

Led by Gill, an NSF-funded postdoctoral researcher, Rajagopalan and Molnar have further found that the impact of El Niño varies by region of India and sub-season. Specifically:

- Rainfall over the Indo-Gangetic plains and central India is more sensitive to Pacific sea surface temperatures during the early season (June).
- In parts of northern India, rainfall is sensitive to sea surface temperatures throughout the monsoon season.
- El Niño and La Niña do not have symmetric effects. During the peak of the monsoon season, for example, La Niñas tend to enhance rainfall, and El Niños tend to suppress it more intensely. By contrast, El Niños seem to suppress late-season rainfall, and La Niñas seem to enhance late-season moisture more.

The lush green valleys of central India. Photo: Rajarshi MITRA/Creative Commons

The research, published in the *Journal of Geophysical Research*, was possible, Gill said, because in recent years, Indian meteorologists have developed and made available detailed daily precipitation data combining station and satellite observations gridded at a resolution of 1 degree by 1 degree. "That let us look at these relationships spatially and sub-seasonally," she said.

"All-India rainfall may be an easy number to latch onto, but maybe it's time to move away from that metric, and use what we have learned about the spatial and sub-seasonal effects of El Niños and La Niñas to devise skillful spatial forecasting models," Rajagopalan said.

India is roughly one-third the size of the continental United States, so looking at the country as a whole can smear out important details. "It would be like looking at Florida and trying to make sense of what's happening in Illinois." ■

Kevin Alfonso Alas Enriquez, 24, used to cut sugarcane but now carries shade tents and water into a sugarcane field as part of a program designed to improve working conditions, minimize heat stress, and measure health outcomes. Photo: Tom Laffay/La Isla Foundation

Kidneys and Climate

Climate change likely to exacerbate epidemics of chronic kidney disease

by Katy Human

Global warming will likely exacerbate epidemics of chronic kidney disease seen recently in hot, rural regions of the world, according to a new assessment by an international team of researchers.

Chronic kidney disease caused by heat stress and dehydration appears to be increasing in communities in the Americas, Southeast Asia, Africa and the Middle East as regional temperatures rise, the authors wrote in a 2016 assessment published in the *Clinical Journal of the American Society of Nephrology*.

Chronic kidney disease, or CKD, means a loss in kidney function, which is problematic because kidneys filter waste and excess fluid from blood.

"Temperature increases add an additional dimension to this health issue," said CIRES Fellow Balaji Rajagopalan, a climate expert and engineering professor at the University of Colorado Boulder.

"In this paper, we find that in some places—mostly tropical countries where you have weak public health systems—temperatures are going up and people in farm sectors are vulnerable," Rajagopalan said.

Co-author Richard Johnson, a kidney disease expert and professor of medicine at the University of Colorado Anschutz Medical Campus, said CKD associated with heat stress and dehydration may represent "one of the first epidemics due to global warming."

Dr. Johnson estimates that CKD related to heat stress and dehydration in Central America likely killed more than 20,000 people between 2002 and 2015, most of them sugar cane workers who spent long hours in hot conditions.

For the new, global analysis, Rajagopalan and Henry Diaz, a now-retired CIRES research scientist and former Fellow, helped their medical colleagues assess the relationship between disease patterns and temperature trends in many parts of the world.

People at risk of heat-related CKD are often from "impoverished and neglected" rural communities, the authors noted, so the research team did not always have access to medical surveillance data. The new study relied on reports from a diversity of sources, including both papers and phone conversations with health experts in various parts of the world.

In some places, the scientists found higher levels of CKD in rapidly warming areas (e.g., the Pacific coasts of Nicaragua, El Salvador, and Costa Rica) compared to nearby areas with similar agricultural intensity but cooler temperatures.

The reports often contained other clues linking the disease to heat stress and dehydration: Male agricultural workers might have significantly higher disease rates, for example, than women and children in their communities who don't work in the fields.

The researchers recommended that governments and scientists begin better documenting the presence of CKD epidemics and developing interventions to improve outdoor worker hydration.

With climate change expected to worsen heat wave frequency and intensity in many parts of the world, the interdisciplinary team is continuing to work together, Rajagopalan said. "Our research communities are very different, so this kind of collaborative approach can offer rich insight as we think outside different boxes." ■

Ancient Drought

An environmental archaeologist examines the intersection of climate and politics in old Assyria

by Laura Krantz

In 657 B.C., an Assyrian astrologer named Akkulanu wrote a letter to the Assyrian king, Ashurbanipal, describing disasters, climate-related and political, that had rocked the Assyrian Empire (which included parts of modern day Egypt, Israel, Jordan, Palestine, Syria, and Iraq). That letter, or at least fragments of it, found its way into the hands of a 21st century ancient historian, Dr. Selim Adali, then at Koç University in Turkey. He wondered if there was any way to empirically corroborate the letter's account of a disastrous drought that ruined the harvest in that year.

So Adali turned to Adam Schneider, an environmental archaeologist who is now a CIRES Visiting Fellow, to ask if there was anything in the climate record that matched the astrologer's descriptions in the letter.

Turns out, there was. Around that time period, according to sedimentary records and stable oxygen isotope ratios, much of the Near East appears to have experienced a period of intense aridification. "It became clear that this was a rare instance where an ancient drought that could be seen in the paleoclimate record could also be confirmed on the ground by eyewitness accounts," says Schneider. "This was 2700 years ago. We were incredibly lucky to find this."

Schneider's path to becoming a CIRES Visiting Fellow is a little different than some of his peers. While no stranger to Boulder, having gone to CU Boulder as an undergrad, his background was in archaeology. But he has family connections with the world of climate science, so he delved into the field of environmental archaeology during his doctoral program at the University of California San Diego. "I was looking specifically at how changes of climate affected people in the Middle East and North Africa," he says. "One of the things I do is try to understand the context of why environment affects people. So I can look at pre-event history and see how that primes the pump for how a climactic event will affect a population."

Kkulanu letter: The letter written by Ashurbanipal's court astrologer, Akkulanu, in which Akkulanu attempts to put a positive spin on a major drought that evidently wiped out the Assyrian harvest in the spring of 657 B.C. Photo: Courtesy of the trustees of the British Museum

Adam Schneider in Damascus, Syria when he was part of an archaeological excavation. Photo: Courtesy of Adam Schneider

"One of the things I do is try to understand the context of why environment affects people. So I can look at pre-event history and see how that primes the pump for how a climactic event will affect a population."
– *Adam Schneider*

Now he's working under CIRES Fellow Balaji Rajagopalan in the Civil, Environmental, and Architectural Engineering Program, and what he's finding is that it's not just alterations in climate that brought about big political changes in the Middle East; it's climate in conjunction with human decisions. In the case of the Assyrian letter, a severe drought was certainly causing problems in the Empire, but the impacts of drought were greatly increased by the decision of Ashurbanipal's grandfather, Sennacherib, to move the Assyrian capital some 50 years earlier to the city of Nineveh, which was located in an area (near modern Mosul in northern Iraq) that was—and continues to be—particularly susceptible to drought, according to both paleoclimate and modern data. "There was no memory of severe drought in that area—there hadn't been a drought in hundreds of years," says Schneider. "It never occurred to them that they'd run out of water. But then, 50 years after the [new] capital is created, there's evidence of historical drought and then, five years later, revolution, civil war, and decline of the state."

Essentially, says Schneider, climate change can amplify social tension and force unpopular decisions. The Assyrian Empire is a lesson on what can happen when a society develops rapidly with no risk management and no forethought. "What's important for me about archaeological research and climate change," explains Schneider, "Is that we can take away some of the issues of uncertainty. We can look back at these kinds of events and show that there's evidence to demonstrate that climate has caused severe problems in the past. Even in these earlier cases, in which people like the Assyrians were impacted by comparatively minor climatic fluctuations, major problems occurred. So there's no reason that anthropogenic climate change won't cause huge problems." ■

Aerial photo of Mili Atoll, Republic of the Marshall Islands, taken from a drone during fieldwork in the western tropical Pacific. Photo: Jeff Donnelly/Woods Hole Oceanographic Institution

Water, Water, Everywhere…

Island nations face a drier future than was originally thought

by Laura Krantz

Island nations could be forgiven for feeling slighted. They already face the brunt of the effects of climate change: Rising sea levels, dwindling resources, threats to infrastructure and economic foundations. But to add insult to injury, thousands of these islands are too small to be accounted for in the global climate models (GCMs) used by scientists to measure the effects of climate change. That leaves the population of those islands—approximately 18 million people—in the position of being what CIRES Fellow Kris Karnauskas refers to as "computationally disenfranchised."

It's something that Karnauskas, also an assistant professor of atmospheric sciences at the University of Colorado Boulder, and his colleagues are hoping to remedy. The problem is that GCMs aren't all that fine-grained. These models divide the planet into a grid and each grid box is approximately 240 km by 210 km. That's a pretty big space and if there's a tiny island—or even an island chain like French Polynesia—alone in one of those grid boxes, it's too difficult to see them in the model. "Think of pixels," says Karnauskas. "If they're too big to resolve the freckles on someone's nose, you won't be able to see those freckles. You have to have super fine pixels to resolve it."

The "pixels" of the GCMs are too big and scientists don't have the computer resources to do something on a more refined scale. Take, for example, an island like Easter Island, which is 3,512 kilometres off the coast of Chile in the South Pacific. Easter Island is small and it's the only spot of land in its GCM grid box. Essentially, it's a freckle and the GCM can't get down to that level of detail. So, in the current GCMs, Easter Island doesn't exist—that whole grid square is just considered open ocean.

That's the case with islands all over the globe and it's a real problem when it comes to knowing what climate change will do to islands' freshwater supplies. Unlike continents or larger islands, the effects of climate change on freshwater for these smaller, isolated islands aren't being calculated. "Paper after paper in my field show changes in drought, aridity," says Karnauskas. "But my eye always looks at the maps and graphs in their papers and I don't see islands. It's so much harder to do this for islands than for places where there are big chunks of land."

To understand how climate change will affect freshwater, scientists have to understand what's happening with precipitation and evaporation. The first part is easy: Current GCMs can tell you all about precipitation over land or over the ocean. Even in a grid square like the one that's home to Easter Island, they know how much precipitation is falling.

But evaporation is another matter. When it comes to those same small islands, the models don't show how much water is evaporating because those islands don't exist in the models—it's all ocean there. Nor can it be calculated using the amount evaporating off the ocean, as ocean evaporation follows different physical principles than water evaporating off land. Without knowing how much water is evaporating off these islands, there's been no way to know exactly how the freshwater supplies are being affected. So Karnauskas and his former colleagues from the Woods Hole Oceanographic Institution in Massachusetts developed a way to get the information needed to know what's happening on islands.

Karnauskas draws a diagram of a cube on a white board. "This is a 3-D picture of an ocean grid cell," he explains. "Say there's an island in here. The climate model doesn't have the island but let's go to the location where there ought to be an island and use the information on the model from over that point." Essentially, they're looking at the climate above the surface of the island to make an approximation of the island's actual climate. They can do this because the islands are so small that climate above the island isn't any different from climate above the ocean. That's been verified even on islands as large as Maui, where data from weather stations at airports shows no difference from data from weather stations moored way offshore.

"We called it the blind pig test," explains Karnauskas with a grin. "If you were a blind pig flying in this area, would you know there was an island here? Could you feel a difference in the heat or the humidity?" A "successful" blind pig test means you can't tell if you're over land or over ocean. If that's the case, scientists don't need to know anything from the land itself to predict evaporation; they just need to know what's happening in the atmosphere right near the surface. From that information, they can glean how much water is evaporating and, thus, get a more accurate picture of the ratio of precipitation to evaporation in a particular area.

This, in turn, changes what's known about freshwater and climate change on islands. When just precipitation was used as a measure of how much freshwater was available, the GCMs showed that 50 percent of islands would become wetter and 50 percent would become more arid. But this new model shows that 73 percent of islands will actually become more dry as a result of increased evaporation. "Islands are already dealing with sea level rise," says Karnauskas. "But this shows that any freshwater they have is more vulnerable."

Karnauskas sees this work as extremely important, both for understanding climate change in these regions and in considering human health and safety. A vast majority of the people living on these remote islands rely on rainwater as the source of their drinking water. And for those that already have health issues due to water quality, increased pressure on freshwater systems will only exacerbate the problem. Already someone from the Cook Islands, an archipelago in the South Pacific Ocean, saw his research online and reached out for more details. "There's an opportunity to get important information out there," Karnauskas says. "This is a framework to provide more information on what to expect." ■

"We called it the blind pig test.If you were a blind pig flying in this area, would you know there was an island here? Could you feel a difference in the heat or the humidity?"
–Kris Karnauskas

Food Web Redesign

What a shift in the size of aquatic insects can mean for water quality

by Laura Krantz

While hiking in Rocky Mountain National Park, Tommy Detmer noticed a horde of fish schooling in what was supposedly a fishless lake. Closer inspection revealed that the swimmers were actually some seriously big insects. "I was up there doing research on another project," says Detmer, "but seeing that made me start thinking about lakes without fish."

Much of the research on the relationship between lakes and fish developed out of Wisconsin. It suggests that introducing fish into lakes without them causes something known as a trophic cascade. Essentially, fish eat bugs and bugs eat algae. If there are no fish in a lake, the theory goes, the bugs eat the algae and the water is clear. If you add fish, the fish eat the bugs, so there are fewer bugs to eat the algae, and the algae grows, clouding the water.

But what Detmer found in Rocky Mountain National Park veered away from this model. He realized that lakes there, both with fish and without, didn't differ in their algae content as would be expected based on the original models. So he started to look at what kind of bugs lived in each lake. Big bugs in lakes with fish didn't last long—they were gobbled up both near the shoreline, as well as further out.

But while the fish ate the larger insects, the smaller insects were thriving, possibly because they had less competition. So in lakes with fish, while the average size of the bugs is smaller, there's a higher turnover rate. Detmer explains it like this: "If you're comparing how much a moose and a mouse eats, it's obvious that the mouse eats less. But if you have the same quantity of mice in terms of mass as you do of moose, the mice would eat more."

In terms of insects, these lakes have smaller bugs but the amount that they eat in terms of their biomass goes up in comparison with larger bugs. That means it requires fewer smaller bugs to consume the same amount of algae. So even though the fish were devouring the larger bugs, the smaller ones still kept the algae down. "It was an exciting finding," says Detmer. "It has a lot of implications in terms of how we manage fisheries and aquatic ecosystems." His results were recently published in the journal *Limnology and Oceanography*.

As for why it worked this way in Rocky Mountain National Park and not in Wisconsin, Detmer thinks it has to do with the community there. If there is only one size of insects, be it large or small, there wouldn't be this shift in size distribution. "There's been a lot of debate over the past thirty years about influencing fish populations," says Detmer. "What we found is a piece in that puzzle but not the only answer." ■

Detmer's study: http://onlinelibrary.wiley.com/doi/10.1002/lno.10446/full

◀ Detmer preparing to use a specially designed benthic invertebrate sampler at Pear Lake in Rocky Mountain National Park, Colorado, in late October. Photos: Courtesy of Tommy Detmer

Detmer using a specially designed benthic invertebrate sampler at Sandbeach Lake in Rocky Mountain National Park, Colorado, in late October.

Greenback cutthroat trout at Lower Hutcheson Lake in Rocky Mountain National Park.

STUDENT PROFILE

Photo: Robin Strelow/CIRES

Michaela Brannum

An Arvada, Colorado, native, Michaela Brannum started school at Colorado Northwestern Community College, where research opportunities were limited. So she spent the summer of 2016 working doing fieldwork with CIRES limnologists, sampling streams and analyzing data. The NSF-funded program that supported her—Research Experience for Community College Students—is run by experts in CIRES' Education and Outreach program. Two years in, they've demonstrated success: Community college students in their program have applied for undergraduate and graduate programs in the sciences, and credit their summer at CIRES for giving them inspiration and experience. Brannum is now working on a bachelor's degree in Marine Biology at the University of Hawaii in Manoa.

More about the RECCS program: http://cires.colorado.edu/outreach/RECCS.

Warming Waters a Major Factor in Gulf of Maine

Cod Collapse

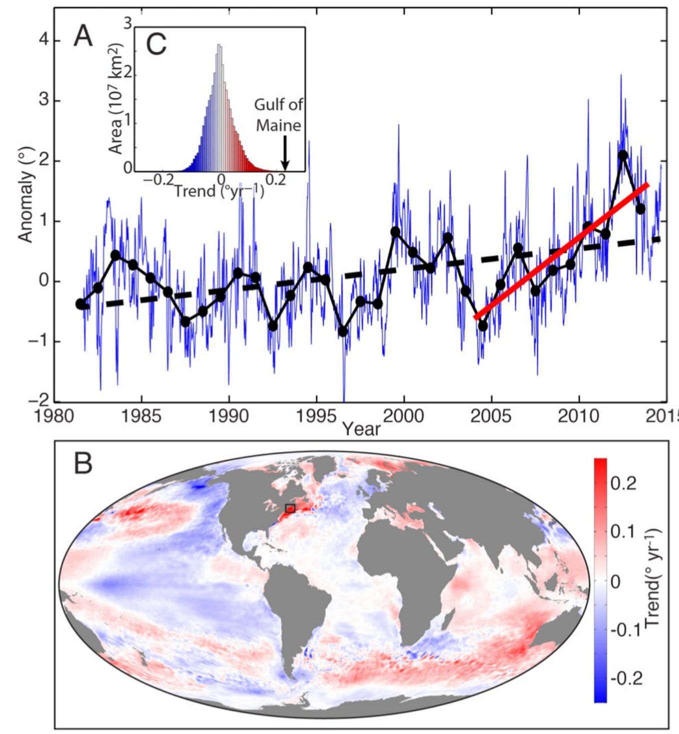
by Karin Vergoth

For centuries, cod were the backbone of New England's fisheries and a key species in the Gulf of Maine ecosystem. Today, those cod stocks are on the verge of collapse; even tighter limits on fishing failed to slow their rapid decline. Research by NOAA and CIRES scientists and partners concludes that rapid warming of Gulf of Maine waters—99 percent faster than anywhere else on the planet—has reduced the capacity of cod to rebound from overfishing, leading to collapse.

"Several processes contributed to the rapid warming off the coast of New England, including natural and manmade changes in the ocean and atmosphere," said Michael Alexander, a research meteorologist in the NOAA Earth System Research Laboratory and co-author of the analysis, published in *Science*.

The rapid warming is linked to decadal climate oscillations in the Atlantic and the Pacific and a northward shift in the Gulf Stream, which brings warmer waters into the region, according to Alexander and his co-authors, including James Scott, a CIRES scientist in NOAA. These factors accelerate the steady pace of ocean warming caused by global climate change.

A researcher from the Gulf of Maine Research Institute sampling cod for study. Photos: Gulf of Maine Research Institute



The Gulf of Maine sea surface temperature has been rising steadily over the last 35 years. In the most recent decade, the warming trend (0.23 deg C /year) was faster than 99 percent of the global ocean.

In the face of already depleted cod stocks, fisheries managers placed a series of restrictions on harvesting this key Gulf of Maine species. When strict quota limits on fishermen failed to help cod rebound, fisheries managers tightened catch limits even further. "The cod population kept declining," said Andrew Pershing, the study's lead author from the Gulf of Maine Research Institute. "It turns out that warming waters were making the Gulf of Maine less hospitable for the fish."

Increasing water temperatures reduced the number of new cod produced by spawning females and also led to fewer young fish surviving to adulthood, the researchers found.

Those conclusions square with the understanding of regional fisheries managers, said Bill Karp, director of the NOAA Fisheries Northeast Fisheries Science Center. "We are devoting significant resources to linking climate models and fish population models to better understand current status and better estimate what the stock will look like in the future," he said.

Recovery of Gulf of Maine cod depends on both sound fishery management and on future temperatures, according to the study. Cod are a coldwater species, and the Gulf of Maine is near the edge of their geographic range. As the ocean warms, the Gulf's capacity to support cod will decline, leading to a smaller fishery. ■

A cod fishing vessel in the Gulf of Maine.

The Arctic Ocean will experience more days of open water by the 2050s. Photo: Katy Barnhart/INSTAAR

LESS ICE, MORE WATER

New study: Parts of Arctic Ocean shifting rapidly to conditions very different from last century

by Laura Krantz

By the 2050s, parts of the Arctic Ocean once covered by sea ice much of the year will see at least 60 additional days a year of open water, according to a new modeling study led by researchers at the University of Colorado Boulder.

"We hear all the time about how sea ice extent in the Arctic is going down," says Katy Barnhart, who led the study while at CU Boulder's Institute for Arctic and Alpine Research (INSTAAR). "That's an important measurement if you are trying to understand broad impacts of climate change in the Arctic, but it doesn't tell us about how the changes in the sea ice in the Arctic are going to affect specific places."

So Barnhart and her colleagues, including CIRES Fellow Jen Kay and INSTAAR Fellow Irina Overeem, set out to investigate the very local impacts of open water expansion patterns in the Arctic. The researchers used climate computer model simulations from the National Center for Atmospheric Research to see how the number of open water, or sea-ice-free, days change from 1850-2100 in our planet's northernmost ocean.They also wanted to understand when open water conditions in specific locations would be completely different from preindustrial conditions.

Because most economic activity in the Arctic is along the coastline, the team focused on several coastal locations that demonstrated the range of sea ice change. Among them was Drew Point, along Alaska's North Slope where open water is already shifting from preindustrial conditions. Once present about 50 days a year, on average (~1900-2000), open water is now present about 100 days a year. By 2075, the modeling study concludes, there could be close to 200 days a year with no sea ice at Drew Point, which is likely to worsen coastal erosion.

For the study, Barnhart, Kay and their colleagues relied on climate projections from 1850 to 2100 and analyzed multiple runs or "realizations" from a single climate model.

According to the researchers' analysis, the entire Arctic coastline and most of the Arctic Ocean will experience an additional 60 days of open water each year by the 2050s, and many sites will have more than 100 additional days.

"The Arctic is undergoing some significant transitions, and we expect these to continue, with impacts on Arctic people and ecosystems, including polar bears," Kay said. "By the end of this century, assuming no major changes in our emissions of greenhouse gases, the Arctic will be in a new regime with respect to open water, fully outside the realm of what we've seen in the past." ■

The Flood that Changed Forecasts

1976's Big Thompson led to better weather warnings

By Theo Stein, NOAA Communications

Forty years ago, a brewing thunderstorm parked itself at the head of the Big Thompson Canyon in Colorado. Up to a foot of rain fell over the next three hours, unleashing a torrent of floodwater that swept 10-foot boulders down the canyon in the dark. One hundred forty-four lives were lost, and 570 homes and businesses were destroyed in the worst flood in Colorado history.

The Big Thompson flood of July 31, 1976, was one of three major flash floods during the span of five years in the 1970s that killed more than 450 people across the country—tragic events that helped spur the modernization of NOAA's National Weather Service flood forecasting system.

In the 21st century, Americans expect timely, accurate forecasts and instantaneous warnings of severe weather. But in 1976, forecasters had to manually assemble information, including radar and satellite information, to compile a forecast.

"In 1976, data was old by the time we got it," said Nezette Rydell, lead forecaster with National Weather Service's Denver-Boulder Forecast Office. "It took a long time to get observations transmitted to the forecast offices. The biggest change in my mind is we now have the ability to overlay radar on top of satellite imagery on top of surface readings and we can integrate it in front of us almost in real time."

Preventing tragedies such as these spurred Congress to fund research to develop better tools to provide more timely and accurate severe weather warnings. These three were a direct result of that initial research push.

- **Better Radar:** In the 1970s, the development of Next-Generation Radar (NEXRAD) Doppler technology gave forecasters the ability to monitor precipitation rates and develop more precise estimates of precipitation amounts to improve flood and flash flood warnings. More than 160 NEXRAD stations now in operation across the country provide blanket coverage of the continental United States and give forecasters a powerful tool to monitor severe weather.
- **Faster Processing:** NOAA's Advanced Weather Interactive Processing System (AWIPS) debuted in 1986, allowing forecasters to see integrated and animated meteorological and hydrological data along with satellite and radar imagery. It also generated simple, speedy severe weather warnings. AWIPS is still considered the cornerstone of NWS operations.
- **Automatic Observations:** In the early 1990s, the Automated Surface Observing System began providing real-time weather observations for forecasters. Today, the system gathers weather data from 900 sites across the country, and serves as the nation's a primary climatological monitoring network.

For Colorado, a big test of these new technologies came in 2013, when a massive storm dumped a year's worth of rain on the northern Front Range in a week. Despite significant widespread damage from flooding, fewer lives were lost. ■

The Big Thompson Flood in Colorado left this cabin lodged on a bridge in Larimer County. Photo by W. R. Hansen, August 13, 1976. Photo: USGS

SOAKING IT UP

Scientists find Southern Ocean removing CO_2 from the atmosphere more efficiently

by Karin Vergoth

Since 2002, the Southern Ocean has been removing more of the greenhouse gas carbon dioxide (CO_2) from the atmosphere, according to CIRES-led research. The research used millions of ship-based observations and a variety of data analysis techniques to conclude that the Southern Ocean has increasingly taken up more CO_2 during the last 13 years. That follows a decade from the early 1990s to 2000s, where evidence suggested the Southern Ocean CO_2 sink was weakening.

Global oceans are an important sink for human-released carbon dioxide, absorbing nearly a quarter of total CO_2 emissions every year. Of all ocean regions, the Southern Ocean below the 35th parallel south plays a particularly vital role. "Although it comprises only 26 percent of the total ocean area, the Southern Ocean has absorbed nearly 40 percent of all anthropogenic CO_2 taken up by the global oceans up to the present," says David Munro, a scientist at the Institute of Arctic and Alpine Research at CU Boulder involved in the study.

The study focused on a region of the Southern Ocean that extends from the tip of South America to the tip of the Antarctic Peninsula. "The Drake Passage is the windiest, roughest part of the Southern Ocean," says Colm Sweeney, lead investigator on the study and a CIRES scientist in the NOAA Earth System Research Laboratory. "The critical element to this study is that we were able to sustain measurements in this harsh environment as long as we have—both in the summer and the winter, in every year over the last 13 years. This data set of ocean carbon measurements is the densest ongoing time series in the Southern Ocean."

The team was able to take these long-term measurements by piggybacking instruments on the Antarctic Research Supply Vessel *Laurence M. Gould*. The *Gould* makes nearly 20 crossings of the Drake Passage each year, transporting people and supplies to and from Antarctic research stations. For over 13 years, it's taken chemical measurements of the atmosphere and surface ocean along the way. By analyzing more than one million surface ocean observations, the researchers could tease out subtle differences between the CO_2 trends in the surface ocean and the atmosphere that suggest a strengthening of the carbon sink. This change is most pronounced in the southern half of the Drake Passage during winter. Although the researchers aren't sure of the exact mechanism driving these changes, "it's likely that winter mixing with deep waters that have not had contact with the atmosphere for several hundred years plays an important role," says Munro.

Their study, published in *Geophysical Research Letters*, came out at roughly the same time as a paper in *Science*, also with Colm Sweeney as co-author. The *Science* analysis, which took a broader look at the Southern Ocean below the 35th parallel south, also showed that the Southern Ocean as a whole is more efficiently removing carbon from the atmosphere, said Sweeney.

Despite these research efforts, the Southern Ocean remains undersampled. "Given the importance of the Southern Ocean to the global oceans' role in absorbing atmospheric CO_2, these studies suggest that we must continue to expand our measurements in this part of the world despite the challenging environment," says Sweeney. ■

◀ The *Laurence M. Gould*, which supports research funded by the National Science Foundation (NSF) in the Antarctic, makes nearly 20 crossings of the Drake Passage each year. Photos: Colm Sweeney/CIRES & NOAA ▼

LEADERSHIP

Steven Nerem

CIRES Fellow Steven Nerem leads NASA's Sea Level Change Team, a group of national experts who have been collaborating since 2014 to better understand present-day and future global and regional sea level change. Follow the team's work here: http://sealevel.nasa.gov

Finding El Niño

In early 2016, a red slash of warmer-than-usual surface waters blazed across the tropical Pacific Ocean. Researchers from NOAA, CIRES, STC and elsewhere flew into action, planning a remote research mission—to the heart of an intense El Niño—with unprecedented speed. Data gathered during the El Niño Rapid Response Field Campaign, from the tropical Pacific to the west coast of the United States, is helping scientists better understand and predict how El Niño forms, develops, and affects U.S. weather thousands of miles from the Pacific.

El Niño is a recurring climate phenomenon characterized by exceptionally warm ocean temperatures in the central and eastern equatorial Pacific. That warmth can feed deep tropical convection, produce exceptional rainfall, heat the atmosphere, and shift wind patterns, affecting weather around the globe.

IN THE AIR...

1. 2. NOAA's Gulfstream IV aircraft flew south from Honolulu into the heart of the El Niño in 20-plus research flights in early 2016. Scientists aboard dropped parachute-topped instruments and used Doppler radar to gather weather data as they chased storms brewing in the central Pacific.

NASA's Global Hawk, a massive, 131-foot wingspan unmanned aircraft, carried meteorological sensors and dropped weather instruments through the atmosphere during three research flights in the eastern Pacific.

ON LAND...

3. 4. From Kiritimati Island, a remote atoll 1,340 miles south of Honolulu, NOAA-funded researchers and Kiribati Meteorological Service staff launched weather balloons twice a day to track changing conditions.

Scientists installed a temporary scanning X-band radar in the San Francisco Bay area to fill coverage gaps in the existing radar array and provide additional rainfall estimates for the region, in anticipation of predicted heavy precipitation from El Niño storms.

AT SEA...

5. Scientists aboard the NOAA ship *Ronald H. Brown* launched weather balloons up to eight times a day and took many other measurements from the eastern tropical Pacific.

Honolulu

Kiritimati Island

equator

FOR THE FUTURE...

Scientists will spend years learning from data gathered during ENRR, and initial analyses are promising: When they took the extra weather data gathered during the campaign and incorporated it into weather models, they made better forecasts—and scientists also got insight into how they might improve forecast models themselves. That's great news for western water planners and everyday people who want to know whether or not to grab the umbrella on the way out the door. ENRR also showed that NOAA can quickly plan and execute a mission to study a high-impact climate event—we'll see more of these in the future.

LEARN MORE: http://ciresblogs.colorado.edu/el-nino-rapid-response/

Photo: NASA/SnowEx

SNOWEX

Science supporting water management

Photo: NASA/SnowEx

Dozens of scientists headed into Colorado's high country by ski, snowshoe, snow machine, and aircraft in February 2017. The snow physicists, data experts, hydrologists, and others kicked off NASA's multi-year SnowEx mission with its singular overarching goal: Figure out the most accurate, reliable way to measure the water content in snow—from space. To support decisions around drinking water, agricultural water use, hydropower, and more, scientists need to better understand how much water the planet's snowpack holds and when it may melt out. Eventually, NASA hopes to launch a global snowpack satellite, but first, scientists need to understand what kind of data water managers need and how to get those data. Under consideration are a slew of snowpack-targeting devices: Radar and lidar, microwave devices, thermal infrared cameras, and more. CIRES' Jeff Deems (with the National Snow and Ice Data Center and the Western Water Assessment) spent SnowEx in the Senator Beck Basin near Silverton, Colorado, making ground-based measurements before, after, and while instrumented aircraft zipped above their heads. They installed meteorological stations and dug snowpits (shown here), dragged around radar units, and used scanning lidar to help them assess data from airborne instruments. NSIDC will host and distribute SnowEx data sets.

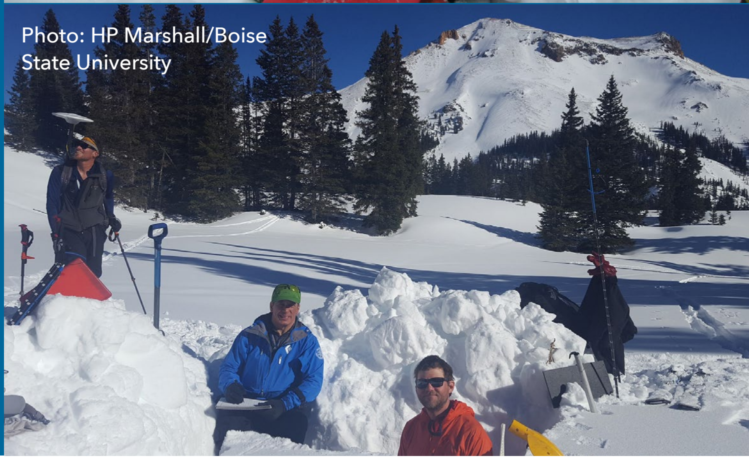


Photo: HP Marshall/Boise State University

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