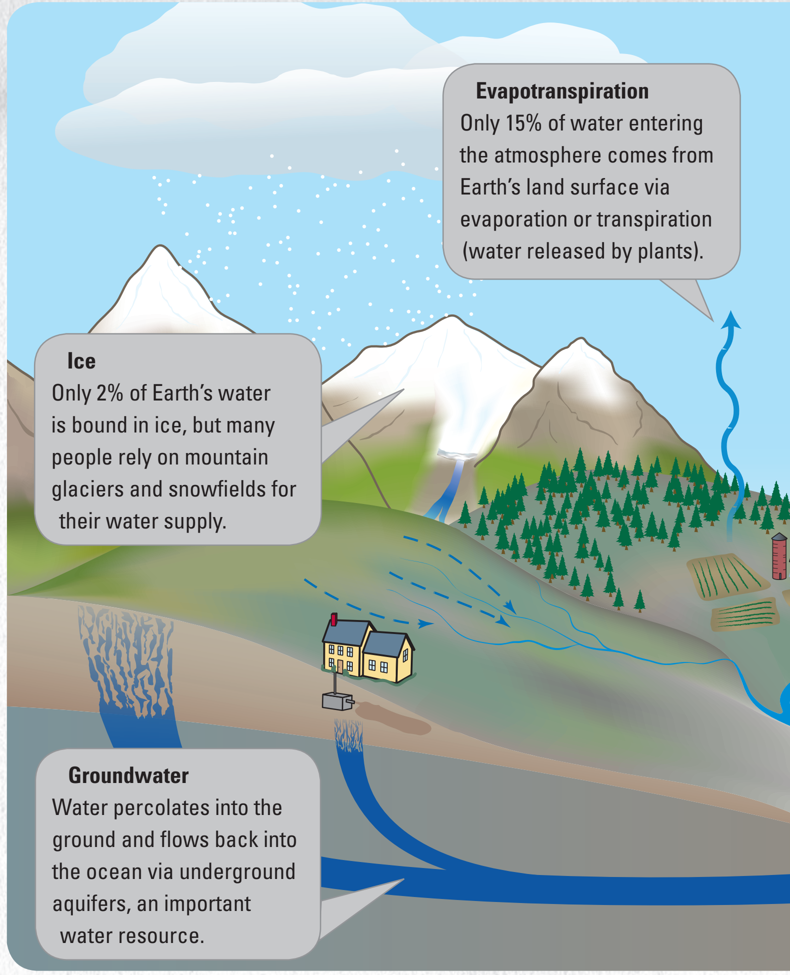
Storms, Floods, & Droughts

The delicately balanced cycle that transports water around the globe is intensifying

by Lonny Lippsett



The source of the rain that filled your town reservoir, or flooded your nearby river, or never arrived to water your crops, is most likely the ocean.

The ocean contains 97 percent of the free water on Earth, and it acts like a massive water pump. Heat powers the pump, evaporating water into water vapor. The atmosphere transports water vapor far and wide, until it condenses into rain or snow and completes the cycle—falling back on the ocean directly or returning to the sea via land, rivers, glaciers, and underground aquifers.

Now, there is strong evidence that the ocean water pump has been revving up as a consequence of climate change.

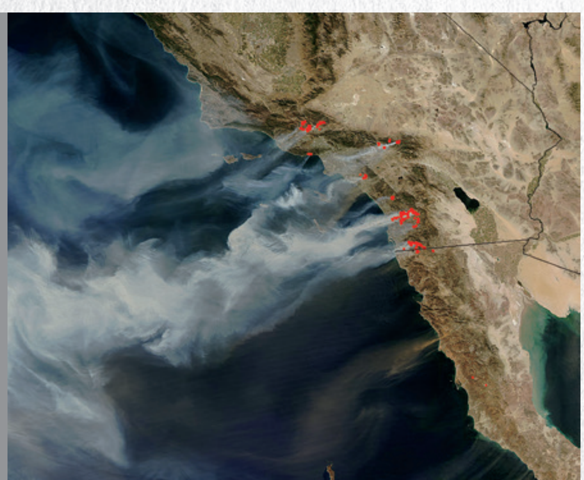
"As the planet continues to warm, more heat means more evaporation, and that means more precipitation, and more extreme weather," said Ray Schmitt, a scientist at Woods Hole Oceanographic Institution (WHOI).

You need only look at recent headlines: Superstorm Sandy in October 2012 killed at least 253 people and caused an estimated $65 billion in damage. The scorching drought across the continental United States in 2012 resulted in crop failures and soaring food prices. In 2011, a "super" tornado outbreak devastated Joplin, Mo., and caused more than $10 billion in damage, while the wettest spring in 117 years in the Ohio Valley region caused major flooding of the Mississippi River. Farther south, Texas had its hottest summer on record (with some towns registering more than 60 days over 100°F), leading to widespread drought and wildfires.

Extreme weather events have also become more frequent across the globe. Tremendous floods in 2011 wreaked havoc in South America, Southeast Asia, and Australia, where the worst flooding in decades caused $30 billion in damage. In 2010, flooding in Pakistan killed 1,400 people and displaced 200,000 others. The 2010 heat wave in western Asia caused major crop failures and

An increase in extreme weather events is a predictable outcome of warming temperatures that intensify Earth's water cycle.

WILDFIRE CALIFORNIA 2007



NASA/MODIS Rapid Response

DROUGHT TEXAS/MIDWEST 2011

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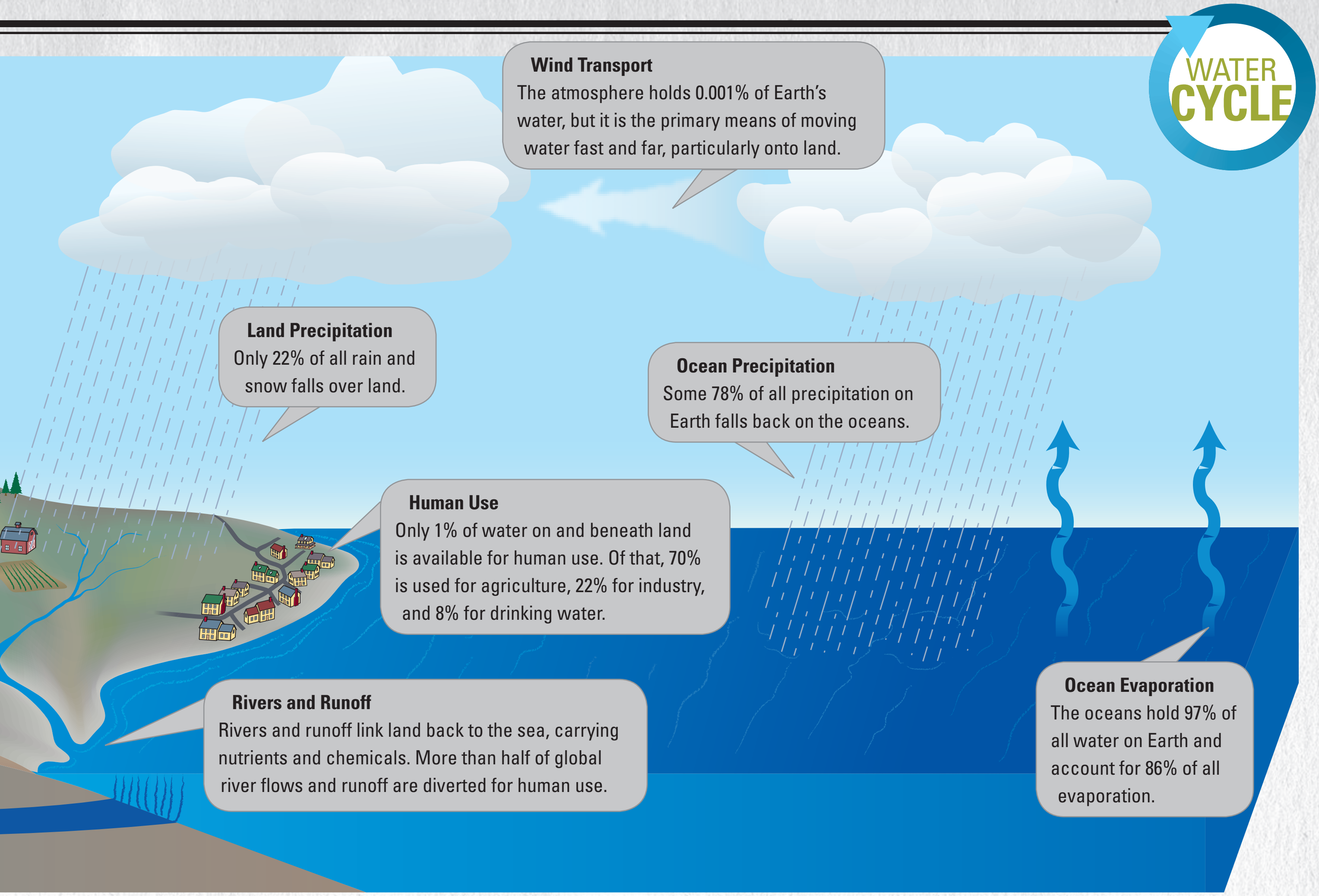

Illustration by Jack Cook, WHOI

wildfires across Russia, causing at least 56,000 deaths and $15 billion in damage, including 2,000 buildings destroyed. The 2010 heat wave was even implicated in the food riots that grew into the political uprisings of the "Arab Spring."

"The water cycle is intensifying, and areas where it usually does rain will get more rain and snow, and the areas where it usually doesn't rain will get even drier," Schmitt said. "Warming global temperatures will cause problems, but changes in the water cycle, *caused* by warming temperatures, will have even more important impacts on society."

To explore these issues, Schmitt invited researchers from diverse scientific fields, along with water resource managers and other policymakers, to a two-day meeting at WHOI in May 2012. This was the eighth in a series of Elisabeth and Henry A. Morss Colloquia, which bring experts to WHOI to exchange and foster ideas on important issues that confront society today. This one was titled "Drought or Deluge?"

"Drought or deluge? The answer is, 'Yes,' " said Kevin Trenberth from the National Center for Atmospheric Research in Boulder, Colo. "We will have both—at different times, or both at the same time but in different places. We can expect more and more intense storms, hurricanes, and perhaps tornadoes."

TORNADO
MISSOURI 2011

ASSOCIATED PRESS

STORM AND FLOOD
NEW JERSEY SHORE 2012

EPA/MICHAEL REYNOLDS

Annual growth rings in trees offer records spanning centuries of a region's rainfall and droughts. Such information is invaluable to policymakers devising long-term strategies to maintain water supplies, says WHOI dendrochronologist Kevin Anchukaitis (at right, taking a core sample from a tree).

Tree Rings: Copyright Daniel Griffin; Inset: Courtesy of Kevin Anchukaitis, WHOI

Earth's temperature has risen 1.4°F in the past century, mostly due to rising levels of heat-trapping carbon dioxide from fossil fuel burning. "Rising temperatures are sucking more moisture out of the land and ocean," Trenberth said at the Morss Colloquium.

A warmer atmosphere also can hold more water vapor, said WHOI oceanographer Lisan Yu. She has estimated that evaporation over the ocean, where 86 percent of all evaporation on Earth occurs, has increased by 4 percent over the past three decades. With scientists predicting temperatures rising another 3°F to 5.5°F during the 21st century, the rate of evaporation will increase significantly, Paul Durack, a scientist at Lawrence Livermore National Laboratory, told participants at the colloquium.

"And when water condenses from water vapor into rain, it releases heat into the atmosphere, and that drives stronger motions in the atmosphere," Schmitt said. "That's why thunderstorms are more intense and more tornadoes develop."

"It rains harder than it used to mainly because there's more water in the atmosphere," Trenberth said. When rainfall comes in deluges, it doesn't soak into the ground where it's most useful for agriculture; instead, it runs off quickly and causes flooding.

"There was major flooding of the Mississippi River in 1993, 2008, and 2011," he said. "Each of these was called a once-in-500-years flood. Obviously, they are not once-in-500-years floods anymore. What used to be a once-in-500-years flood is more like a once-in-50-years flood, and what might have been a once-in-100-years flood is more like a once-in-30-years flood."

Rising temperatures have also dramatically altered the timing of the spring melt of the snowpack, leading to earlier peak stream flows, said Richard Palmer, a professor of engineering at the University of Massachusetts. That affects all the competing users of the rivers. Water resource managers "are diverting water from streams to refill reservoirs in spring when spawning fish need it most," he said. Earlier snow melt also means less moisture for later in the summer, increasing the risk of droughts and wildfires.

As wet regions become wetter, normally dry regions will get drier. "The sun beats down, there's less moisture in the soil, it gets hotter, and there's no moisture to provide evaporative cooling," Trenberth said. "So drought begets more drought and heat waves."

Drought and the fall of civilizations

Drought is hardly a new phenomenon. It punctuates all of human history, often as a period signaling the end of civilizations. To learn from the past, Kevin Anchukaitis studies the history of climate written in trees.

The widths of trees' annual growth rings reveal what the climate was like in the years they formed, said Anchukaitis, who joined WHOI in September as its first dendrochronologist, or tree-ring specialist. Wider rings signal years with abundant rain; narrower rings indicate limited growth caused by drought. Many long-lived and fallen but preserved trees harbor records spanning thousands of years. Over the decades, dendrochronologists have sampled trees at thousands of sites throughout the world, divulging forgotten droughts that had profound impacts on humans.

In Asia, the rise of the ancient Khmer Empire, centered around Angkor Wat, paralleled the Khmers' ability to divert and store water for agriculture. Tree rings showed that monsoons ferrying moisture from the ocean began to shift in 1345, bringing extreme weather. A 20-year drought from 1345 to 1365, followed by a period of flooding and then a coup-de-grace drought from 1401 to 1425, led to the empire's collapse in the 1430s.

In China, the Ming Dynasty fell following food shortages and peasant revolts after a major drought from 1638 to 1641. Across the ocean, the ancient Ancestral Puebloan culture that built cliff dwellings in the U.S. Southwest abandoned the area and relocated farther south after the Great Pueblo Drought from 1276 to 1297.

"In the late 1500s, there was more than a decade of reduced rainfall in what is now the New York City region," Anchukaitis said. "Imagine such a drought occurring today. Everywhere we look not too far in the past, we see droughts that lasted longer and were more severe than those observed in the last century. That's what the climate system can do all on its own. Now add in anthropogenic climate change."

Data from tree rings and other indicators of past climate can give water resource managers "a good sense of their typical range of conditions on the thousand-year scale," Anchukaitis said. "With that knowledge, planners can design strategies based realistically on history, not simply on the recent climate."

Water, the bottom line for life

Managing water, and the food that depends on water, goes way back. The first famous policy planner might have been Joseph in the Book of Genesis, who dreamed of seven fat cows emerging from the Nile River, followed by seven gaunt ones. He urged Pharaoh to take advantage of the seven years of plenty that he foresaw and to store surplus grain. During the seven subsequent years, "there was famine in all lands; but in all the land of Egypt there was bread," as the Bible says.

In lieu of prophesies, water managers today rely on limited recent historical data that doesn't take into account the full range of possible climate and water fluctuations.

A case in point is the Colorado River, the major water resource in the arid U.S. West, which seven states now depend on for irrigation and drinking water. Michael Gritzuk, who recently served 17 years as director of Phoenix's Water Services Department, told the tale.

In 1922, Arizona, California, Colorado, Nevada, New Mexico, Wyoming, and Utah negotiated the Colorado River Compact, which apportioned a total of 15 million acre-feet (maf) of water per year among the states. A 1944 treaty allotted another 1.5 maf to Mexico downstream "in a normal water supply year."

"But what's a normal water supply year?" Gritzuk asked. Over previous decades, the Colorado's average annual river flow was 13.5 maf—so even at the start, the policymakers had overpromised. But a longer-term perspective shows that the river flow is highly erratic, ranging from 4.4 maf to more than 22 maf per year.

Today's managers must factor in additional pressure from skyrocketing population, Gritzuk said. In 1920, the combined population of the seven states was 5.7 million people; in 2010, it was 56.7 million; in 2050, it is projected to be 123 million.

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Not only will regions and nations battle over insufficient freshwater supplies, so will industries, Paul Faeth, a fellow at CNA Corp., told Morss Colloquium participants. A little-known fact is that 40 percent of our fresh water is used to cool power plants. More people require more energy plants that require more water. The recent surge in hydraulic fracking may offer new, cheap natural gas supplies, but it also requires abundant water supplies to get the gas out of the ground, Faeth said.

Nations will also incur higher costs to adapt to changes in the water cycle, said Anthony Patt, a researcher at the International Institute for Applied Systems Analysis in Austria. Developing countries with fewer resources to avoid catastrophes will suffer far more than richer ones.

Natural and human factors

"The lifetime of carbon dioxide in the atmosphere is more than 100 years," said Trenberth. "So even if we start to reduce carbon emissions now, it won't help us for 20 to 30 years, but in 60 years, two or more generations from now. We're already going to have to live with the consequences of what we've already done."

So what can we do to alleviate water problems in the short term? One strategy, Schmitt suggests, is to follow the water—back to the ocean, the ultimate source of rainfall on land. "As we increase our understanding of oceanic conditions, we are going to do a better job of predicting changes in the water cycle," he said.

For example, every major drought in southeastern Australia in the past 120 years coincided with a shift in conditions in the Indian Ocean, according to research presented by Caroline Ummenhofer, a climate scientist who recently joined WHOI from the University of New South Wales in Australia. The Indian Ocean experiences a phenomenon, similar to the El Niño-Southern Oscillation in the tropical Pacific Ocean, called the Indian Ocean Dipole. During opposite phases of the dipole, regions of unusually warm and cold ocean temperatures alternately appear in the western and eastern Indian Ocean. These changes in Indian Ocean water temperatures affect the overlying atmosphere and the passage of rain-bearing systems onto the Australian continent.

Individual years of severe drought in Australia are linked to El Niños. But prolonged droughts are robustly tied to Indian Ocean Dipole temperature patterns that don't bring rain to western and southeastern Australia for a decade or more, Ummenhofer said.

Across the globe, cooler-than-usual (La Niña) conditions in the tropical Pacific can explain droughts in the U.S. Southwest, including the recent drought in Texas, said Richard Seager, a climatologist at Lamont-Doherty Earth Observatory in Palisades, N.Y. He presented evidence that tropical Atlantic Ocean conditions also influence rainfall inland in North America, either softening a La Niña drought or amplifying it into a catastrophe. That happened in the 1930s, he said, when a cooler-than-usual La Niña coincided with a warmer-than-usual Atlantic to trigger the Dust Bowl, the worst drought in U.S. history, which devastated the nation's agricultural heartland and displaced a million or more people.

But Seager pointed out that a variety of factors, both natural and human, combine to create catastrophes. Making the Dust Bowl drought even worse were the mammoth dust storms depicted in classic photographs from the period. In March of 1936, for example, dust storms struck an area comprising about half of Texas and most of Kansas, Oklahoma, and New Mexico over ten to 25 days. The airborne dust interacted with solar and long-wave radiation, intensifying the drought and moving it as far north as Canada, he said.

Much of this resulted from land-use changes. During droughts in the 1800s, the landscape was dominated by ranches with unplowed grazing land. By the 1930s the area had been turned mostly to farmland, with native grasses and trees removed, few shelterbelts, and deep-till plowing that laid soil open to the wind.

"Human influence on droughts and floods is not confined to the impact that rising greenhouse gases have on atmospheric circulation and water vapor transport," Seager said.

Humans also have had significant impacts on all watersheds on land through damming, irrigation, groundwater depletion, and deforestation, Schmitt said. So the clearest way to see through these confounding factors and learn how the global water cycle is changing is to understand what is happening in the ocean.

The most direct way would be to see if evaporation is increasing over the ocean. But that's a dauntingly complex measurement for scientists to make (see article below). Instead, they can calculate evaporation rates indirectly by measuring what it leaves behind in the ocean: salt. More evaporation leads to higher ocean salinity.

"Over the past 50 years, in general, the salty regions of the ocean are getting saltier, and the fresher regions are getting fresher," Durack said. "That's the best evidence that the water cycle has been intensifying."

Only recently have scientists had the tools to monitor salinity in the vast ocean with much precision. Over the past decade, oceanographers have deployed some 3,500 Argo floats throughout the ocean. Equipped with sensors to measure temperature and salinity, the floats transmit their data back to shore every ten days. "They are like ocean weather balloons," Schmitt said.

CALCULATING OCEAN EVAPORATION

Scientists strive to unravel a host of dynamic interrelated factors

Imagine you turn on the tap in the morning and water pummels out and spills over your sink. Later you go out to your garden, but water trickles feebly out of the hose. The water pump in your house is definitely not working the way it used to.

Scientists say something like that is probably happening in our planetary home. Climate change is gunning the motor of Earth's water pump, driving more rainfall to already wet areas and less to drier regions.

To understand how things will change, it would help if we could get a handle on how the motor is driving more moisture from the ocean to the atmosphere. But figuring out how and why water molecules move between air and ocean is a formidable challenge for scientists.

"It's the boundary between two turbulent fluids, the ocean and atmosphere; each is its own thing, basically chaotic and hard to calculate," said Carol Anne Clayson, an oceanographer at Woods Hole Oceanographic Institution.

"Then the two are coupled: If something changes the sea surface temperature, for example, the atmosphere responds to it, and every atmospheric response changes the sea surface temperature," she said. "We don't have the computational power to simulate in a model all the physics that goes on—even if the interface between them were flat and never-changing."

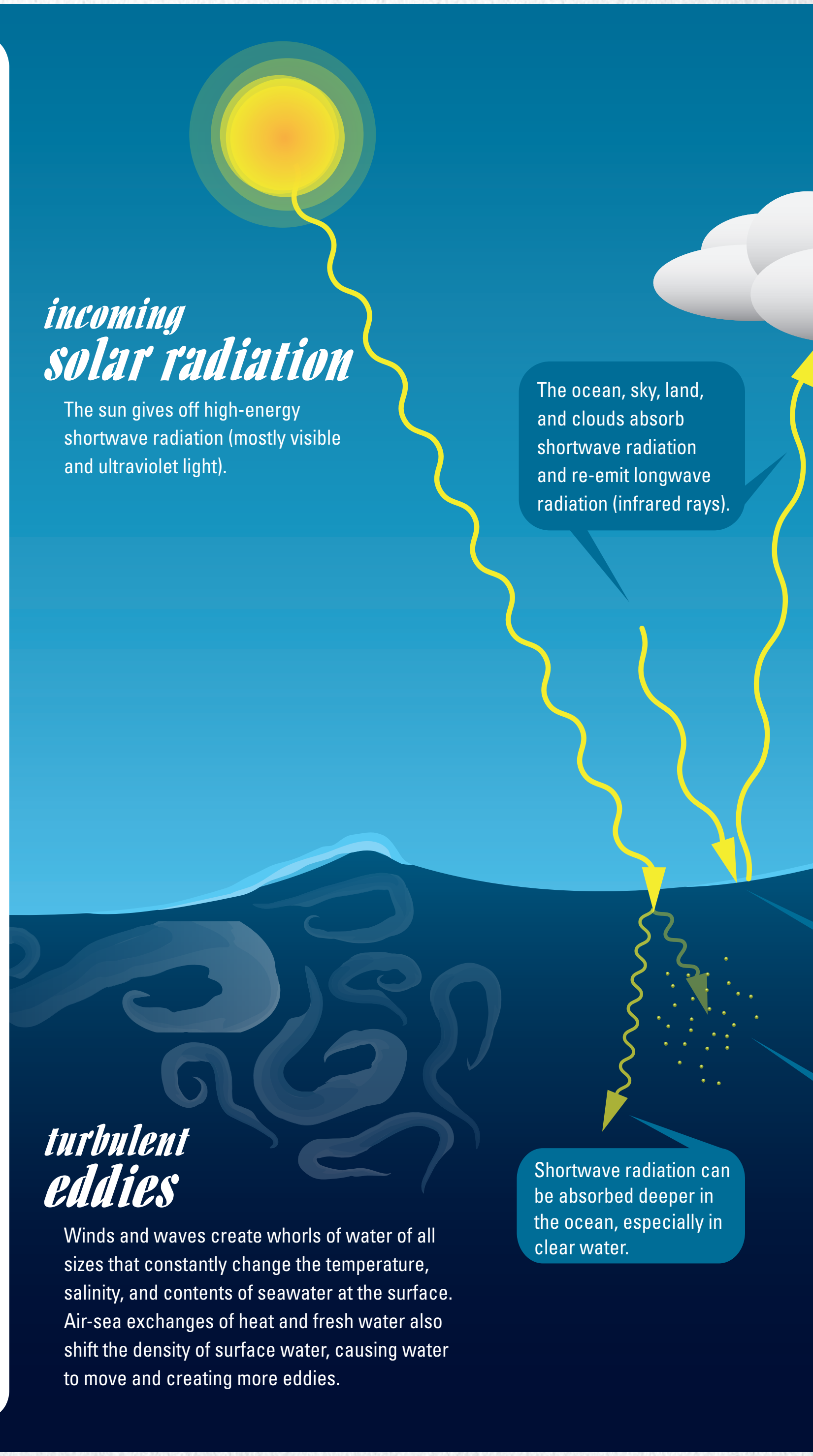
Which it most definitely isn't. The air-sea interface "is typically the most turbulent part of the ocean," Clayson said. A dizzying mix of factors are constantly interacting: Waves, winds, water temperature and salinity, bubbles and spray, solar radiation, and other phenomena all affect one another over various timescales (seconds to seasons) and space (millimeters to miles). See the illustration at right.

"Getting observations of what's going on at the air-sea interface is not trivial, especially in extreme conditions such as high winds," Clayson said. "It's also difficult to simulate the air-sea interactions, especially in extreme conditions, in laboratory experiments in a wave tank. Current computers don't have enough computational capacity to incorporate all the processes occurring, on all the spatial and temporal scales involved, to produce realistic simulations."

Clayson uses satellite measurements in an effort to improve estimates of ocean evaporation rates. "But the problem is going to be solved by large groups of people applying a range of methods," using more and improved data from satellites, sensors deployed in the ocean, and lab and at-sea experiments, she said. All of these will feed more details into models that can provide insights into how the climate and ocean are working and improve predictions of where and when rain will, or will not, fall in the future.

—Lonny Lippsett

Carol Anne Clayson's research is funded by NASA and the National Science Foundation.



In 2011, NASA launched Aquarius, a new salinity-sensing satellite, to provide continuous measurements of ocean salinity patterns over the entire globe, said another colloquium speaker, Gary Lagerloef, head of the Aquarius mission.

In September 2012, Schmitt and WHOI oceanographers Dave Fratantoni and Tom Farrar sailed aboard the WHOI research vessel *Knorr* to the saltiest region of the Atlantic Ocean off Africa to take part in an expedition with scientists from a dozen institutions. The Salinity Processes in the Upper Ocean Regional Study, nicknamed SPURS, used an array of oceanographic technology, including gliders, floats, and drifters, to collect high-resolution salinity measurements that can be coupled with data from the Aquarius satellite.

The scientists were surprised to discover that ocean salinity levels in the region were much higher than they had expected. They appear to be reaching record high levels, supporting the trends forecast by Durack and others.

Such data are crucial to provide a more accurate view of how ocean salinity patterns and the water cycle are changing—and how that might be affecting us on land, Schmitt said.

"Despite budget pressures, we can't reduce satellites and ocean sensors. When they asked the famous criminal Willie Sutton why he robbed banks, he said, 'That's where the money is.' That's why we study the ocean—that's where the water is."

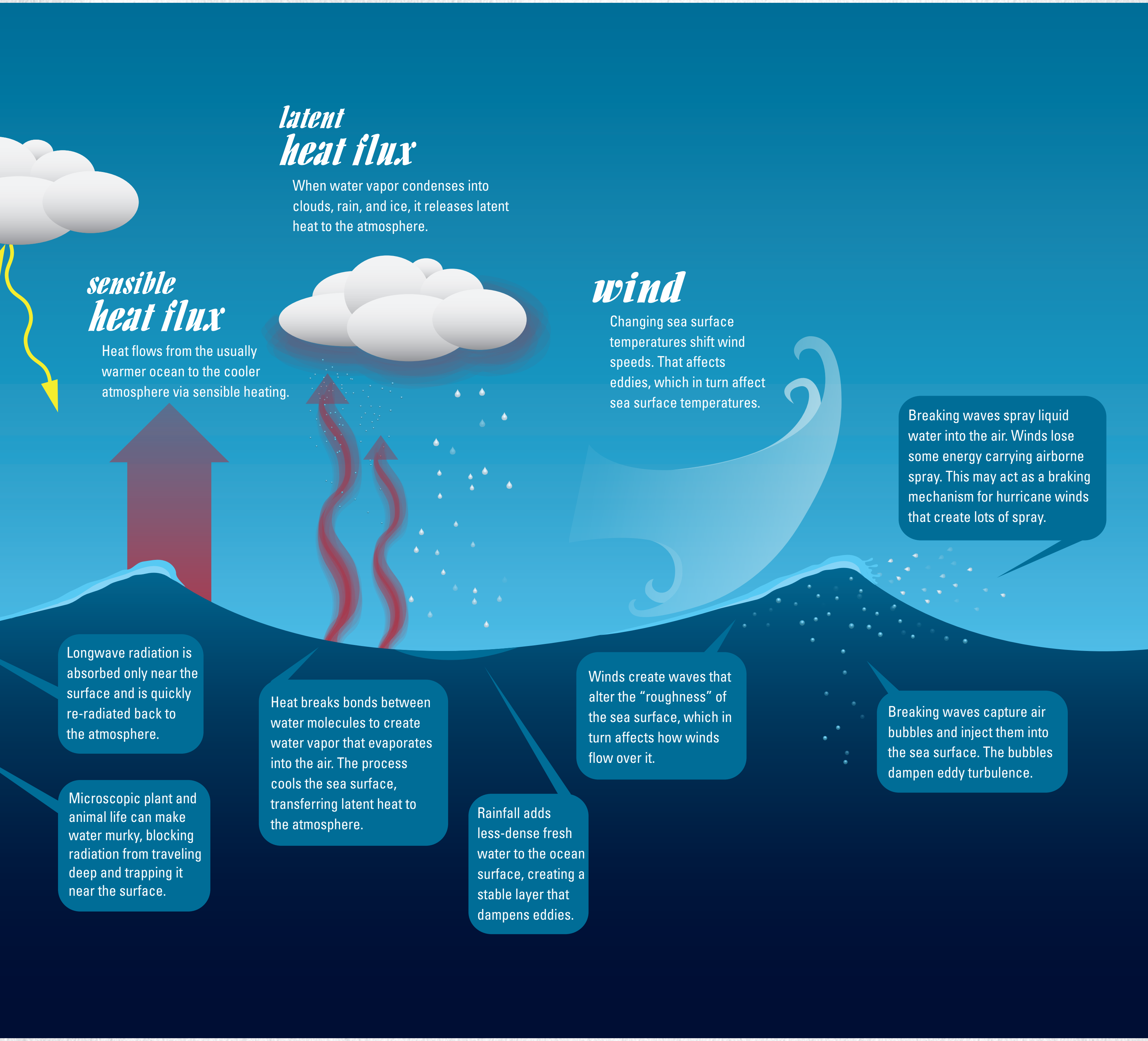


Illustration by Amy Caracappa-Qubeck, WHOI