

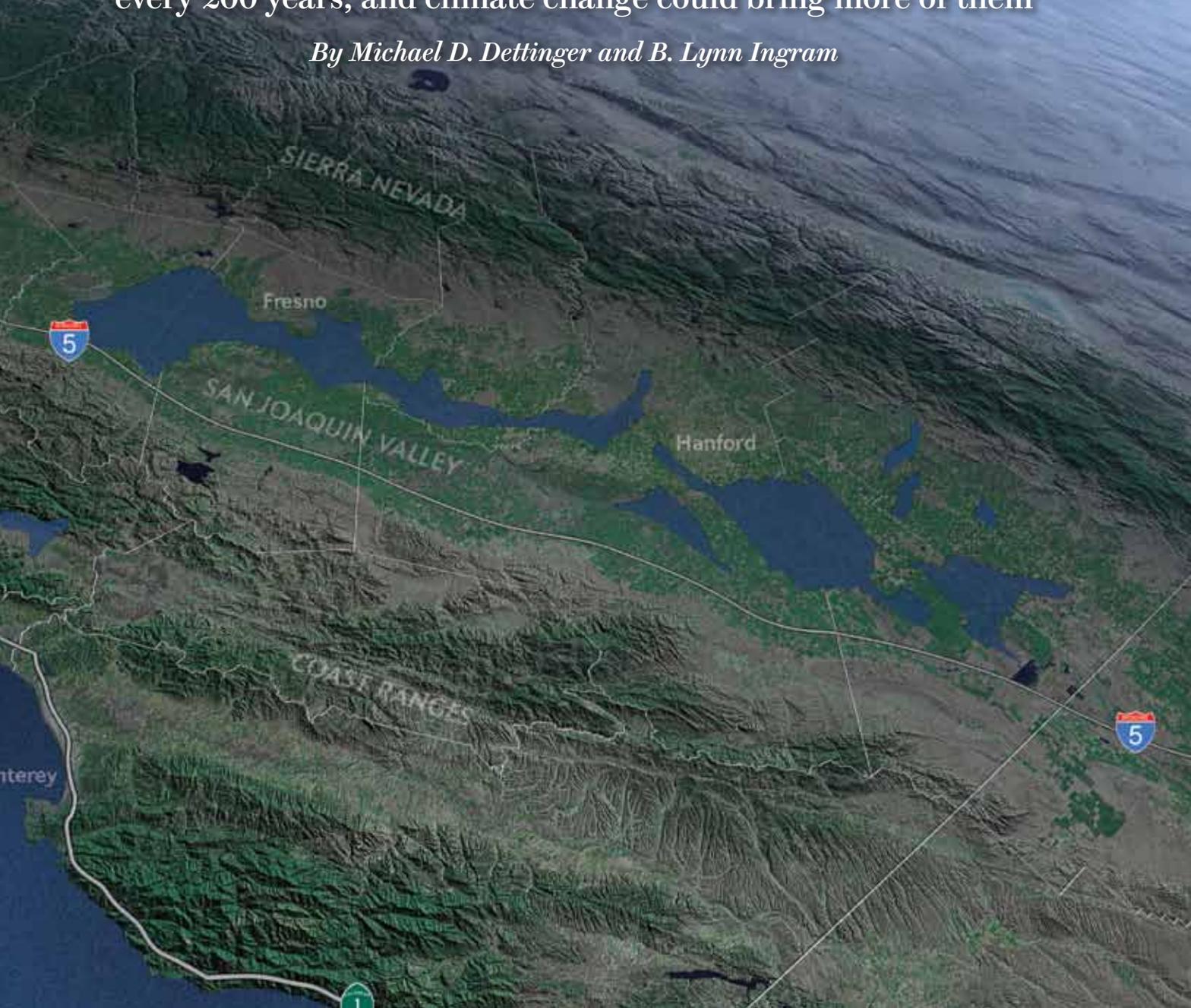
DROWNED: A 43-day atmospheric-river storm in 1861 turned California's Central Valley region into an inland sea, simulated here on a current-day map.

CLIMATE

THE COMING MEGAFLOODS

Huge flows of vapor in the atmosphere, dubbed “atmospheric rivers,” have unleashed massive floods every 200 years, and climate change could bring more of them

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THE INTENSE RAINSTORMS SWEEPING IN FROM

the Pacific Ocean began to pound central California on Christmas Eve in 1861 and continued virtually unabated for 43 days. The deluges quickly transformed rivers running down from the Sierra Nevada mountains along the state's eastern border into raging torrents that swept away entire communities and mining settlements. The rivers and rains poured into the state's vast Central Valley, turning it into an inland sea 300 miles long and 20 miles wide. Thousands of people died, and one quarter of the state's estimated 800,000 cattle drowned. Downtown Sacramento was submerged under 10 feet of brown water filled with debris from countless mudslides on the region's steep slopes. California's legislature, unable to function, moved to San Francisco until Sacramento dried out—six months later. By then, the state was bankrupt.

A comparable episode today would be incredibly more devastating. The Central Valley is home to more than six million people, 1.4 million of them in Sacramento. The land produces about \$20 billion in crops annually, including 70 percent of the world's almonds—and portions of it have dropped 30 feet in elevation because of extensive groundwater pumping, making those areas even more prone to flooding. Scientists who recently modeled a similarly relentless storm that lasted only 23 days concluded that this smaller visitation would cause \$400 billion in property damage and agricultural losses. Thousands of peo-

ple could die unless preparations and evacuations worked very well indeed.

Was the 1861–62 flood a freak event? It appears not. New studies of sediment deposits in widespread locations indicate that cataclysmic floods of this magnitude have inundated California every two centuries or so for at least the past two millennia. The 1861–62 storms also pummeled the coastline from northern Mexico and southern California up to British Columbia, creating the worst floods in recorded history. Climate scientists now hypothesize that these floods, and others like them

IN BRIEF

Geologic evidence shows that truly massive floods, caused by rainfall alone, have occurred in California about every 200 years. The most recent was in 1861, and it bankrupted the state.

Such floods were most likely caused by atmospheric rivers: narrow bands of water vapor about a mile

above the ocean that extend for thousands of miles. Much smaller forms of these rivers regularly hit California, as well as the western coasts of other countries.

Scientists who created a simulated megastorm, called ARKStorm, that was patterned after the 1861 flood but was less severe, found that such a torrent could force

more than a million people to evacuate and cause \$400 billion in losses if it happened in California today.

Forecasters are getting better at predicting the arrival of atmospheric rivers, which will improve warnings about flooding from the common storms and about the potential for catastrophe from a megastorm.

in several regions of the world, were caused by atmospheric rivers, a phenomenon you may have never heard of. And they think California, at least, is overdue for another one.

TEN MISSISSIPPI RIVERS, ONE MILE HIGH

ATMOSPHERIC RIVERS are long streams of water vapor that form at about one mile up in the atmosphere. They are only 250 miles across but extend for thousands of miles—sometimes across an entire ocean basin such as the Pacific. These conveyor belts of vapor carry as much water as 10 to 15 Mississippi Rivers from the tropics and across the middle latitudes. When one reaches the U.S. West Coast and hits inland mountain ranges, such as the Sierra Nevada, it is forced up, cools off and condenses into vast quantities of precipitation.

People on the West Coast of North America have long known about storms called “pineapple expresses,” which pour in from the tropics near Hawaii and dump heavy rain and snow for three to five days. It turns out that they are just one configuration of an atmospheric river. As many as nine atmospheric rivers hit California every year, according to recent investigations. Few of them end up being strong enough to yield true megafloods, but even the “normal” storms are about as intense as rainstorms get in the rest of the U.S., so they challenge emergency personnel as well as flood-control authorities and water managers.

Atmospheric rivers also bring rains to the west coasts of other continents and can occasionally form in unlikely places. For example, the catastrophic flooding in and around Nashville in May 2010—which caused some 30 deaths and more than \$2 billion in damages—was fed by an unusual atmospheric river that brought heavy rain for two relentless days up into Tennessee from the Gulf of Mexico. In 2009 substantial flooding in southern England and in various parts of Spain was also caused by atmospheric rivers. But the phenomenon is best understood along the Pacific Coast, and the latest studies suggest that these rivers of vapor may become even larger in the future as the climate warms.

SUDDEN DISCOVERY

DESPITE THEIR INCREDIBLE DESTRUCTION, atmospheric rivers were discovered only relatively recently and in part by serendipity.

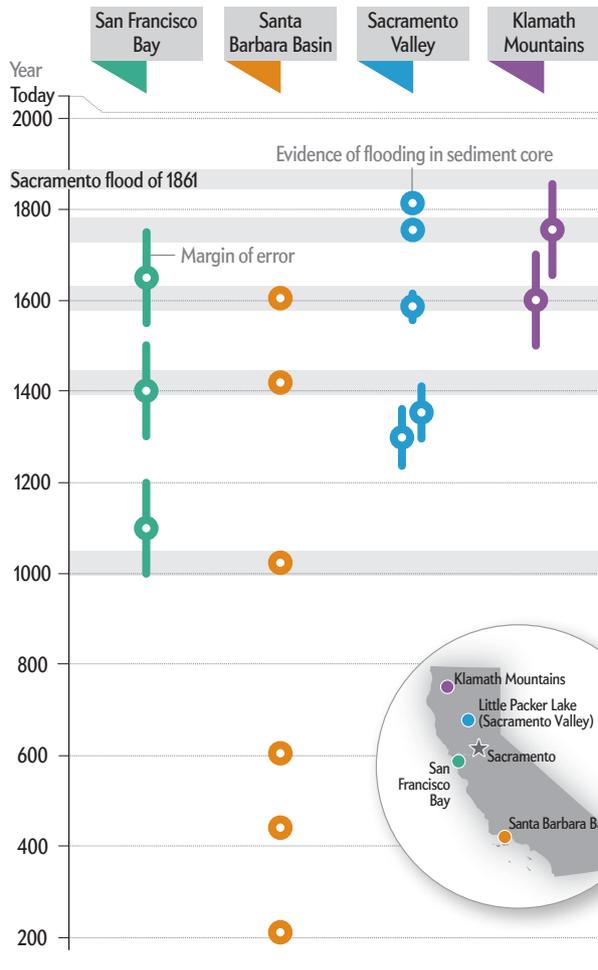
In January 1998 the National Oceanic and Atmospheric Administration’s Environmental Technology Laboratory began a project called CALJET to improve the forecasting of large storms that hit the California coast. The lab’s research meteorologist Marty Ralph and others flew specially outfitted aircraft over the North Pacific into an approaching winter storm to directly measure the conditions. That storm was described as a “jet”—a zone of high winds. The researchers found that the single storm, for several days running, was carrying about 20 percent of the atmosphere’s moisture that was moving poleward at middle latitudes. The jet was concentrated at about a mile above the ocean’s surface, high enough to have been difficult to identify using traditional meteorological observations from the ground.

Also in 1998 researchers Yong Zhu and the late Reginald Newell, then at the Massachusetts Institute of Technology, noticed an odd feature in simulations of global wind and water-vapor patterns that had been made by the European Center for Medium-Range Weather Forecasts. They found that, outside of the tropics, an average of about 95 percent of all vapor transport toward the poles occurred in just five or six narrow bands,

TIMELINE

California Megafloods, Every Two Centuries

Massive floods have struck California every 200 years or so, according to analysis of sediment deposits left by the torrents in four widely separated locations. Different dating methods used at the sediment sites have varying margins of error, but the mid-points align fairly well. If the pattern holds, the state could be due for another catastrophe; the most recent megaflood was in 1861, and it left Sacramento underwater for six months (photograph).



distributed somewhat randomly around the globe, that moved west to east across the middle latitudes. To describe these bands, they coined the term “atmospheric rivers.”

At about the same time, satellites carrying the new Special Sensor Microwave Imager were for the first time providing clear and complete observations of water-vapor distributions globally. The imagery showed that water vapor tended to concentrate in long, narrow, moving corridors that extend most often from the warm, moist air of the tropics into the drier, cooler regions outside the tropics. The tentacles appeared and then fell apart on timescales from days to a couple of weeks.

Needless to say, researchers soon put together these three remarkably complementary findings. Since then, scientists have conducted a growing number of studies to better characterize West Coast atmospheric rivers. New observatories with upward-looking radars and wind profilers have been established to watch for them. NOAA’s Hydrometeorological Testbed program is peering farther inland to find out what happens when atmospheric rivers penetrate the interior.

Using data from these networks, forecasters are getting better and better at recognizing atmospheric rivers in weather models and at predicting their arrival at the West Coast. In recent years some storms have been recognized more than a week before they hit land. Atmospheric rivers are also appearing in climate models used to predict future climate changes. Forecasters, feeling more confident in their prediction abilities, are beginning to warn the public about extremely heavy rains earlier than they would have in the past. This improvement is providing extra time for emergency managers to prepare.

A MEGAFLOOD EVERY CENTURY?

DESPITE GREATER SCIENTIFIC UNDERSTANDING, the 1861–1862 floods are all but forgotten today. Communities, industries and agricultural operations in California and the West have spent the past century spreading out onto many of the same floodplains that were submerged 150 years ago. Residents everywhere are unaware or unwary of the obvious risks to life and property. Meanwhile, though, anxious climatologists worry about the accumulating evidence that a megastorm could happen again and soon.

The concern grows out of research that is looking 2,000 years back in time to piece together evidence revealing the occurrence and frequency of past floods, like detectives returning to a crime scene of long ago. They are sifting through evidence archived in sediments from lake beds, floodplains, marshes and submarine basins. As floodwaters course down slopes and across the landscape, they scour the hills, picking up clay, silt and sand and carrying that material in swollen currents. When the rivers slow on reaching a floodplain, marsh, estuary or the ocean, they release their loads of sediment: first the larger gravels, then the sands, and finally the silts and clays. Nature rebuilds after such events, and over time the flood deposits are themselves buried beneath newer sediments left by normal weather. Scientists extract vertical cores from these sediments and, back at the lab, analyze the preserved layers and date what happened when.

For example, flood deposits have been found under tidal marshes around San Francisco Bay in northern California. Typically the inflowing river waters that spread across the marshes deposit only thin traces of the finest sediments—clays and silts.

The more vigorous flows of major floods carry larger particles and deposit thicker and coarser layers. The flood layers can be dated using the common radiocarbon-dating method, which in this application is accurate to within about 100 years. A study of the marsh cores by one of us (Ingram) and geographer Frances Malamud-Roam revealed deposits from massive flooding around A.D. 1100, 1400 and 1650. A distinct layer from the 1861–62 event is difficult to distinguish, however, because hydraulic gold mining in the Sierra Nevada foothills during the decade before and after the flood moved enormous volumes of silt and sand that essentially wiped out whatever traces the floodwaters might have left.

Sediment cores taken from beneath San Francisco Bay itself also indicate that in 1400 the bay was filled with freshwater (as it was during the 1861–62 event), indicating a massive flood.

Geologists have found more evidence in southern California, where two thirds of the state’s nearly 38 million people live today, along the coast of Santa Barbara. Sediments there settle to the seafloor every spring (forming a light-colored layer of algae known as diatoms) and again in winter (forming a dark-colored silt layer). Because the oxygen concentrations in the deep waters there are inhospitably low for bottom-dwelling

organisms that would usually churn and burrow, the annual sediment layers have remained remarkably undisturbed for thousands of years. Sediment cores there reveal six distinct megafloods that appear as thick gray silt layers in A.D. 212, 440, 603, 1029, 1418 and 1605. The three most recent dates correlate well with the approximate 1100, 1400 and 1650 dates indicated by the marsh deposits around San Francisco Bay—confirming that truly widespread floods have occurred every few hundred years. (In October, Ingrid Hendy of the

Ironically, smaller atmospheric rivers are not all bad; between 1950 and 2010 they supplied 30 to 50 percent of California’s rain and snow—in the span of about 10 days each year.

University of Michigan and her colleagues published a paper based on a different dating method; it found a set of Santa Barbara dates that were offset from the six specific dates by 100 to 300 years, but the same basic pattern of megafloods every 200 years or so holds.)

The thickest flood layer in the Santa Barbara Basin was deposited in 1605. The sediment was two inches thick, a few miles offshore. The 440 and 1418 floods each left layers more than an inch thick. These compare with layers of 0.24 and 0.08 inch near the top of the core that were left by large storms in 1958 and 1964, respectively, which were among the biggest of the past century. The three earlier floods must have been far worse than any we have witnessed.

Evidence for enormous floods has also been found about 150 miles northeast of San Francisco Bay, in sediment cores taken from a small lake called Little Packer that lies in the floodplain of the Sacramento River, the largest river in northern California. During major floods, sediment-laden floodwaters spill into the lake, and the sediment settles to the bottom, forming thick, coarse layers. Geographer Roger Byrne of the University of Cal-

Rivers in the Sky

An atmospheric river is a narrow conveyor belt of vapor that extends thousands of miles from out at sea, carrying as much water as 15 Mississippi Rivers. It strikes as a series of storms that arrive for days or weeks on end. Each storm can dump inches of rain or feet of snow.

Buoyancy

The warm, moist air mass easily rises up and over a mountain range; as it does, the air cools and moisture condenses into abundant rain or snow. The river eventually decays into random local storms.

Orientation

If a river strikes perpendicular to a mountain range, much of the vapor condenses out. If it strikes at an angle (shown), a "barrier jet" can be created that flows along the range, redistributing precipitation on the mountainside.

Origin

Atmospheric rivers usually approach California from the southwest, bringing warm, moist air from the tropics.

Duration

A megastorm can last up to 40 days and meander down the coastline. Smaller rivers that arrive each year typically last two to three days; "pineapple expresses" come straight from the Hawaii region.

Atmospheric river

Precipitation

Several inches of rain or feet of snow can fall underneath an atmospheric river each day. Moderate storms can bring more than 15 inches of rain.

Vapor Transport

Moisture is concentrated in a layer 0.5 to 1.0 mile above the ocean. Strong winds within the layer bring very humid air from the tropics, but the river can also pull in atmospheric moisture along its path.

250 miles

1 mile

Not to scale

ifornia, Berkeley, and his then graduate student Donald G. Sullivan used radiocarbon dating to determine that a flood comparable to the 1861–62 catastrophe occurred in each of the following time spans: 1235–1360, 1295–1410, 1555–1615, 1750–70 and 1810–20. That is, one megaflood every 100 to 200 years.

Certain megafloods have also left records of their passage in narrow canyons in the Klamath Mountains in the northwestern corner of California. Two particularly enormous deposits were laid down around 1600 and 1750, once again agreeing with the other data.

When taken together, all the historical evidence suggests that the 1605 flood was at least 50 percent greater than any of the other megafloods. And although the radiocarbon dates have significant uncertainties and could be reinterpreted if dating methods improve, the unsettling bottom line is that megafloods as large or larger than the 1861–62 flood are a normal occurrence every two centuries or so. It has now been 150 years since that calamity, so it appears that California may be due for another episode soon.

DISASTERS MORE LIKELY

IRONICALLY, ATMOSPHERIC RIVERS that set up over California are not all bad. The smaller ones that arise annually are important sources of water. By analyzing the amount of rain and snow that atmospheric rivers brought to the U.S. West Coast in recent decades, along with records about long-term precipitation, snowpack and stream flow, researchers have found that between 1950 and 2010, atmospheric rivers supplied 30 to 50 percent of California's water—in the span of only 10 days each year. They are finding similar proportions along the rest of the West Coast. In the same time period, however, the storms also caused more than 80 percent of flooding in California rivers and 81 percent of the 128 most well-documented levee breaks in California's Central Valley.

Because atmospheric rivers play such terrible roles in floods and such vital roles in water supply, it is natural to wonder what might happen with them as climate change takes firmer hold. Recall that Zhu and Newell first coined the term “atmospheric river” to describe features they observed in computer models of weather. Those models are closely related to models used to project the future consequences of rising greenhouse gas concentrations. Scientists do not program atmospheric rivers into weather and climate models; the rivers emerge as natural consequences of the way that the atmosphere and the atmospheric water cycle work, when the models are let loose to simulate the past, present or future. Thus, the rivers also appear in climate projection models used in Intergovernmental Panel on Climate Change assessments.

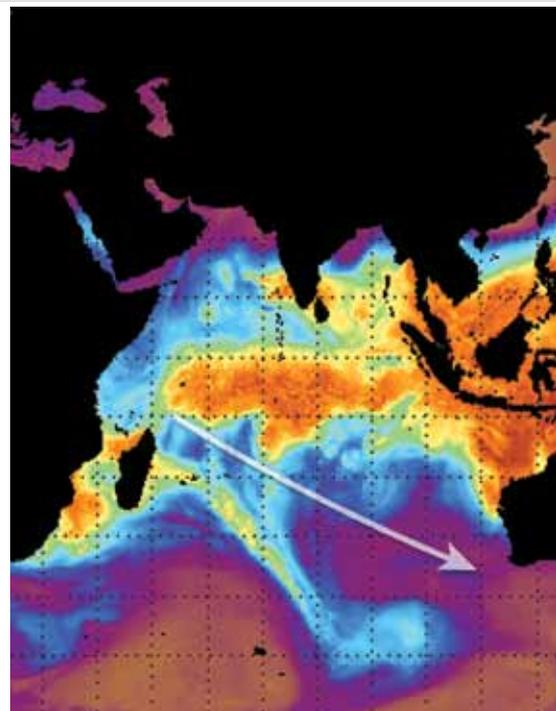
A recent review by one of us (Dettinger) of seven different climate models from around the world has indicated that atmo-

GLOBAL CONCERN

All West Coasts Can Be Hit

Atmospheric rivers form over tropical waters and flow poleward toward the west coasts of many continents (one hit England in November 2009). They are prominent along the U.S. Pacific Coast but can occasionally arise in unusual places, such as the Gulf of Mexico (one flooded Nashville in May 2010). Atmospheric rivers could become larger in the future as the climate warms.

Composite of atmospheric water vapor from December 17–19, 2010



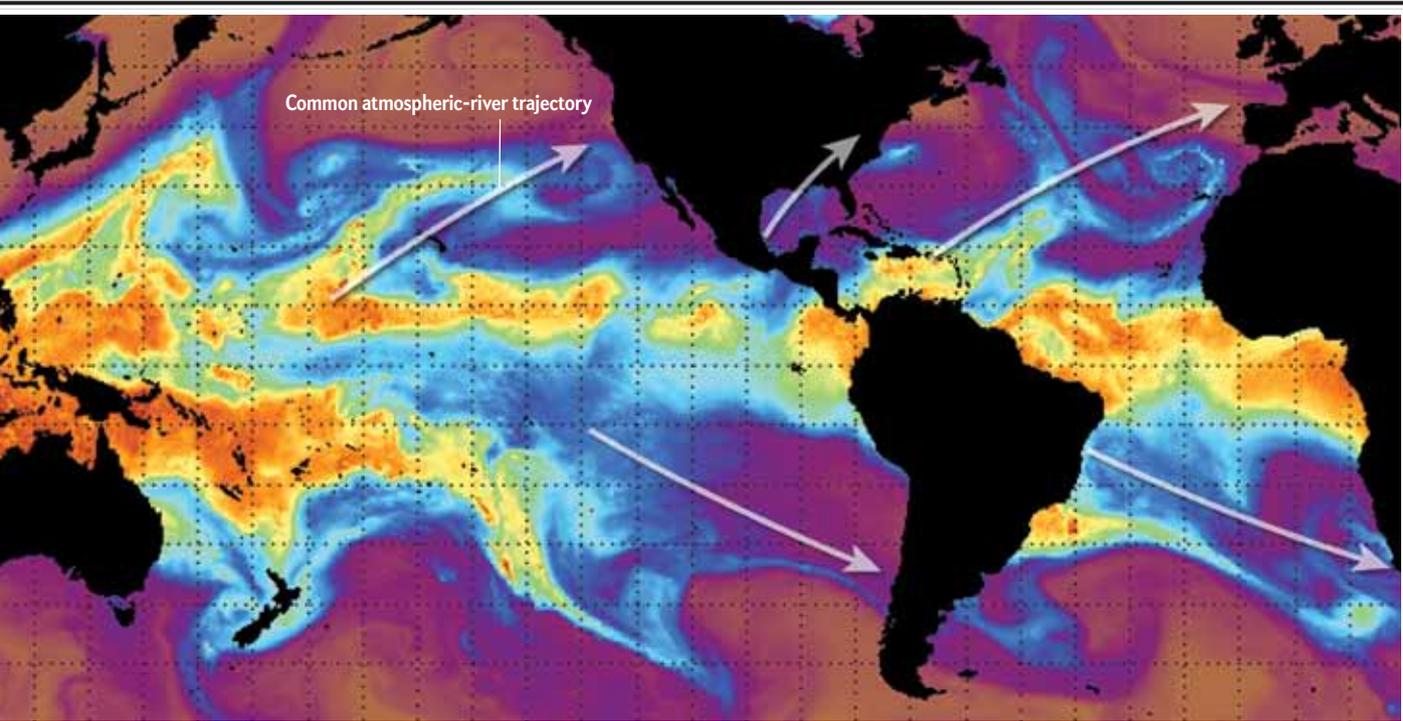
spheric rivers will likely continue to arrive in California throughout the 21st century. In the projections, air temperatures get warmer by about four degrees Fahrenheit on average because of increasing greenhouse gas concentrations. Because a warmer atmosphere holds more water vapor, atmospheric rivers could carry more moisture.

On the other hand, because the tropics and polar regions are projected to warm at different rates, winds over the midlatitude Pacific are expected to weaken slightly. The rain that atmospheric rivers produce is primarily a product of the amount of vapor they hold and how fast they are moving, and so the question arises: Will moister air or weaker winds win out? In six of the seven climate models, the average rain and snow delivered to California by future atmospheric rivers increases by an average of about 10 percent by the year 2100. Moister air trumps weaker winds.

All seven models project that the *number* of atmospheric rivers arriving at the California coast each year will rise as well, from a historical average of about nine to 11. And all seven climate models predict that occasional atmospheric rivers will develop that are bigger than any of the historic megastorms. Given the remarkable role that atmospheric rivers have played in California flooding, even these modest increases are a cause for concern and need to be investigated further to see if the projections are reliable.

TIME TO PREPARE

WITH ATMOSPHERIC RIVERS likely to become more frequent and larger and with so many people now living in their paths, society would be wise to prepare. To provide an example that California emergency managers could use to test their current plans and methods, scientists at the U.S. Geological Survey



recently developed the scenario mentioned at the start of this article: a megastorm that rivaled the 1861–62 storm in size but lasted 23 days instead of 43 (so no one could claim that the scenario was unrealistic). To further ensure that the scenario, which was eventually dubbed ARkStorm (Atmospheric River 1000 Storm), was as realistic as possible, scientists constructed it by stitching together data from two of the largest storm sequences in California from the past 50 years: January 1969 and February 1986.

When project leaders ran the events of ARkStorm through a variety of weather, runoff, engineering and economic models, the results suggested that sustained flooding could occur over most lowland areas of northern and southern California. Such flooding could lead to the evacuation of 1.5 million people. Damages and disruptions from high water, hundreds of landslides and hurricane-force winds in certain spots could cause \$400 billion in property damages and agricultural losses. Long-term business and employment interruptions could bring the eventual total costs to more than \$700 billion. Based on disasters elsewhere in recent years, we believe a calamity this extensive could kill thousands of people (the ARkStorm simulation did not predict deaths).

The costs are about three times those estimated by many of the same USGS project members who had worked on another disaster scenario known as ShakeOut: a hypothetical magnitude 7.8 earthquake in southern California. It appears that an atmospheric-river megastorm—California’s “Other Big One”—may pose even greater risks to the Golden State than a large-magnitude earthquake. An ARkStorm event is plausible for California, perhaps even inevitable. And the state’s flood protection systems are not designed to handle it. The only upside is that today, with improved science and technology, the mega-

storms could likely be forecasted anywhere from a few days to more than a week in advance. Proper planning and continuing efforts to improve forecasts could reduce the damage and loss of life.

The same promise, and warning, holds true along the western coasts of other continents. Scientists have studied atmospheric rivers in more depth along California’s coast than anywhere else in the world, but they have little reason to expect that the storms would be less frequent or smaller elsewhere. The next megaflood could occur in Chile, Spain, Namibia or Western Australia.

Californians, as well as people all along the West Coast, should be aware of the threats posed by atmospheric rivers and should take forecasts of storms and floods very seriously. Planners and city and state leaders should also take note as they decide on investments for the future. He who forgets the past is likely to repeat it. **SA**

MORE TO EXPLORE

Holocene Paleoclimate Records from a Large California Bay Estuarine System and Its Watershed Region: Linking Watershed Climate and Bay Conditions. Frances P. Malamud-Roam et al. in *Quaternary Science Reviews*, Vol. 25, Nos. 13–14, pages 1570–1598; July 2006.

Storms, Floods, and the Science of Atmospheric Rivers. Michael D. Dettinger and F. M. Ralph in *Eos*, Vol. 92, No. 32, page 265; 2011.

Design and Quantification of an Extreme Winter Storm Scenario for Emergency Preparedness and Planning Exercises in California. Michael D. Dettinger et al. in *Natural Hazards*, Vol. 60, No. 3, pages 1085–1111; February 2012.

NOAA atmospheric river page: www.esrl.noaa.gov/psd/atmrivers

USGS ARkStorm page: <http://urbanearth.gps.caltech.edu/winter-storm-2>

SCIENTIFIC AMERICAN ONLINE

For a historical account that details how extensively the 1861–62 megaflood devastated California, see ScientificAmerican.com/jan2013/atmospheric-rivers