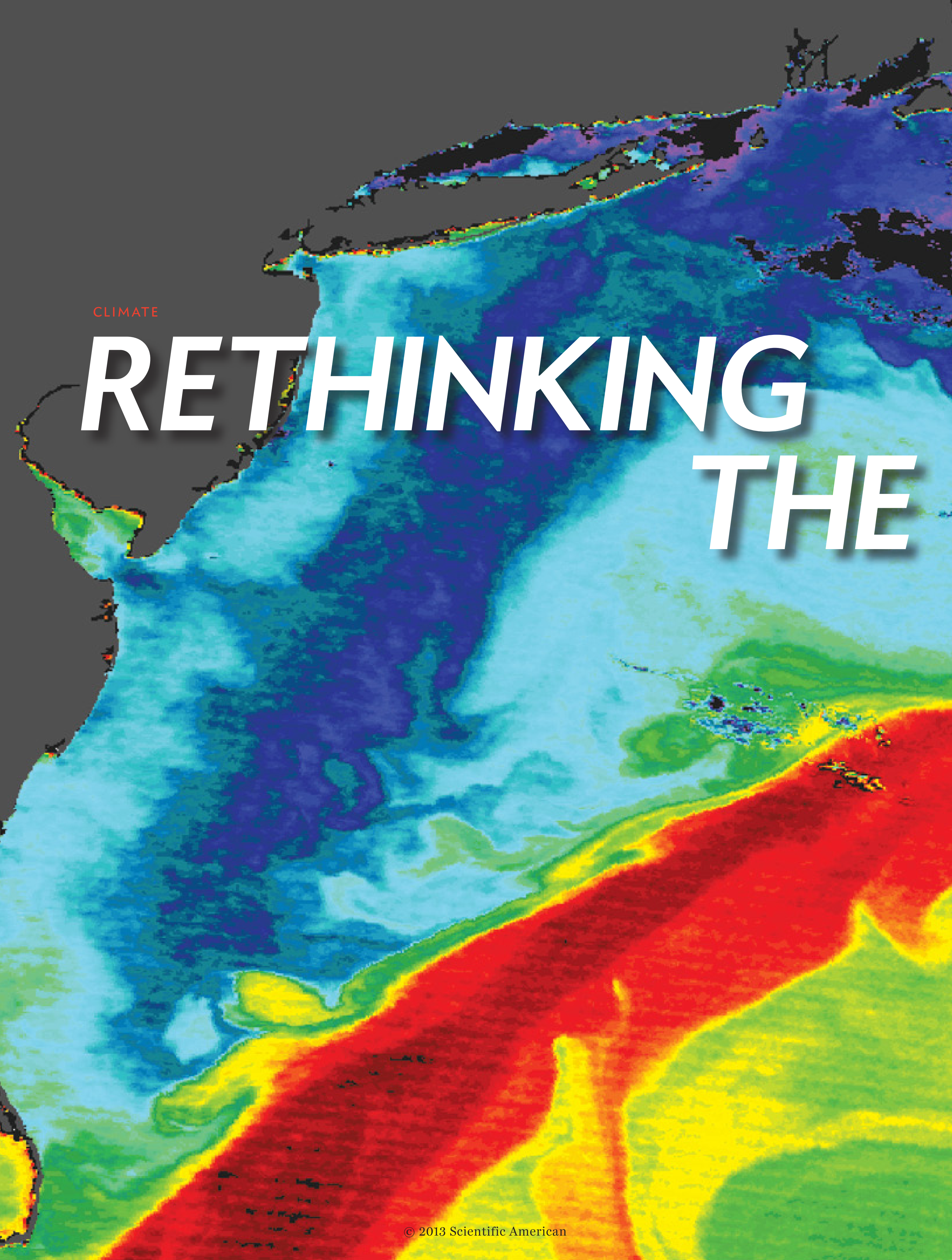
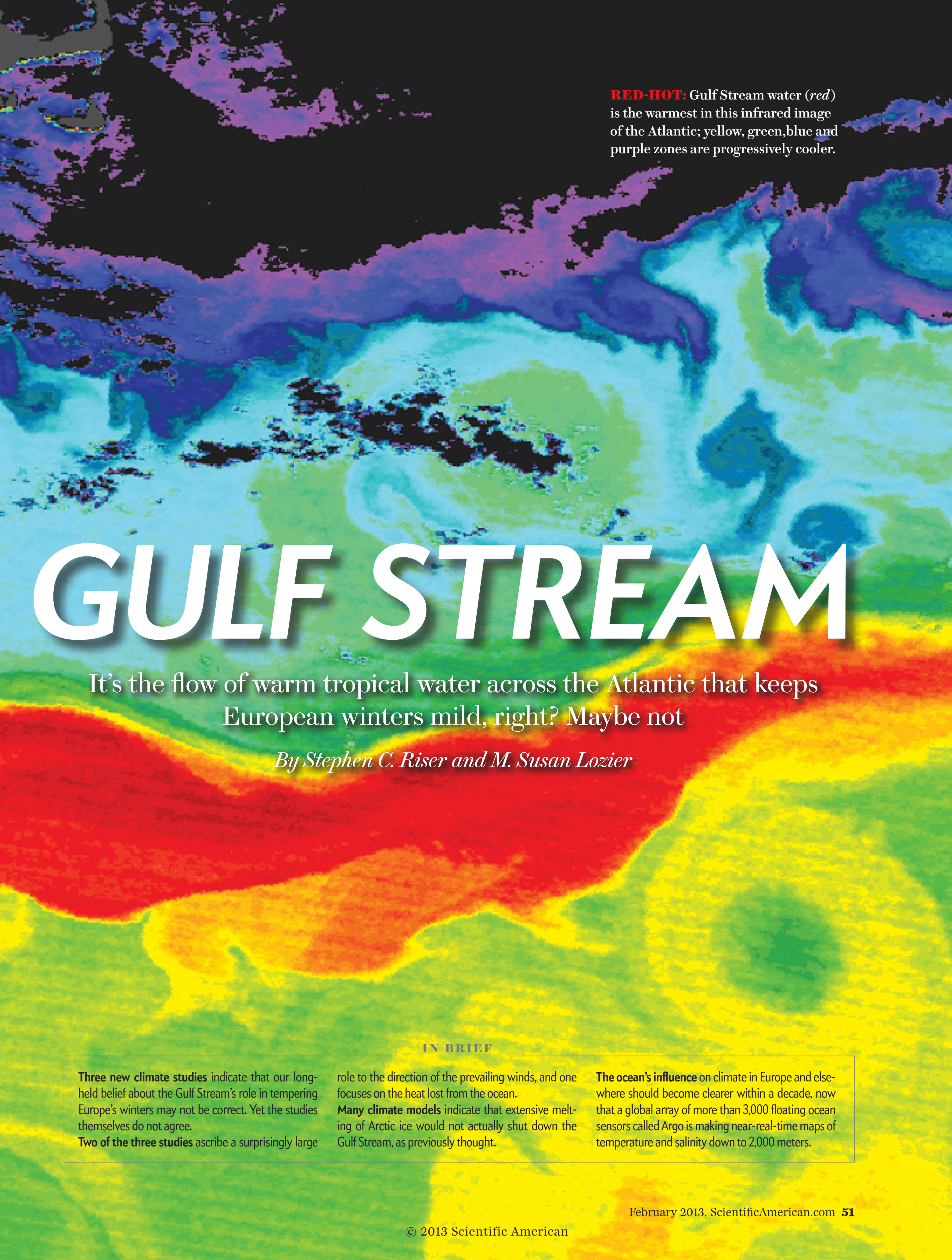
CLIMATE

RETHINKING THE





RED-HOT: Gulf Stream water (*red*) is the warmest in this infrared image of the Atlantic; yellow, green,blue and purple zones are progressively cooler.

GULF STREAM

It's the flow of warm tropical water across the Atlantic that keeps European winters mild, right? Maybe not

By Stephen C. Riser and M. Susan Lozier

IN BRIEF

Three new climate studies indicate that our long-held belief about the Gulf Stream's role in tempering Europe's winters may not be correct. Yet the studies themselves do not agree.

Two of the three studies ascribe a surprisingly large role to the direction of the prevailing winds, and one focuses on the heat lost from the ocean.

Many climate models indicate that extensive melting of Arctic ice would not actually shut down the Gulf Stream, as previously thought.

The ocean's influence on climate in Europe and elsewhere should become clearer within a decade, now that a global array of more than 3,000 floating ocean sensors called Argo is making near-real-time maps of temperature and salinity down to 2,000 meters.

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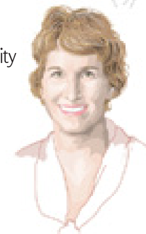


FOR A CENTURY, SCHOOLCHILDREN HAVE BEEN TAUGHT THAT THE MASSIVE OCEAN CURRENT KNOWN AS THE GULF STREAM

carries warm water from the tropical Atlantic Ocean to northwestern Europe. As it arrives, the water heats the air above it. That air moves inland, making winter days in Europe milder than they are in the northeastern U.S.

It might be time to retire that tidy story. The explosion of interest in global climate has prompted scientists to closely study the climatic effects of the Gulf Stream only to discover that those effects are not as clear as conventional wisdom might suggest. Based on modeling work and ocean data, new explanations have emerged for why winter in northern Europe is generally less bitter than winter at the same latitudes in the northeastern U.S. and Canada—and the models differ on the Gulf Stream's role. One of the explanations also provides insight into why winter in the U.S. Northwest is warmer than it is across the Pacific in eastern Russia.

At the same time, recent studies have been casting doubt on the popular conjecture made a few years ago that melting of Arctic ice could "shut down" the Gulf Stream, thereby wreaking havoc with Europe's weather. Yet the studies do suggest that climate change could at least affect the *strength* of the Gulf Stream, which could lessen the impact of global warming on northern Europe.

COMPETING THEORIES

CLIMATE VARIATIONS ACROSS the globe stem primarily from the earth's spherical shape. Because the sun's rays are more perpendicular to the earth's surface at lower latitudes, they impart more heat per unit area there than at higher latitudes. This differential heating leads to the prevailing atmospheric winds, whose instabilities redistribute that heat from the tropics to the poles. The oceans, covering 70 percent of the earth, also play a major role in this redistribution. The upper two meters of the oceans store more solar heat than the entire atmosphere above the seas because the specific heat (a property that determines the capacity to store heat) of a cubic meter of water is about 4,000 times greater than the same volume of air (and about four times larger than it is for soil). Water temperatures in the upper 100 to 200 meters of the oceans at midlatitudes might vary by 10 degrees Celsius over a year, storing and releasing an immense amount of heat compared with the atmosphere or the land. And because ocean currents, such as the Gulf Stream, move water around the globe, heat gained in the summer at one locale can later be released to the atmosphere thousands of kilometers away.

Given that movement and the oceans' ability to store heat, it is easy to hypothesize that ocean currents might be responsible for the fact that winter air temperatures in Ireland, at about 50 degrees north latitude, are nearly 20 degrees C warmer than they are at the same latitude across the Atlantic in Newfoundland. Similarly, air temperatures at 50 degrees north latitude in the eastern Pacific, near Vancouver, are about 20 degrees C warmer than they are at the same latitude at the southern tip of Russia's Kamchatka Peninsula.

In the 19th century geographer and oceanographer Matthew Fontaine Maury was the first to attribute the relatively mild climate of northwestern Europe to the Gulf Stream. This powerful ocean current flows northward along the southeastern U.S. coast, a product of warm waters from the subtropics and tropics. At about the latitude of Cape Hatteras, N.C., the Gulf Stream turns to the northeast and flows out into the Atlantic. Maury surmised that the Gulf Stream supplies heat to the overlying westerly winds that move across the Atlantic toward northwestern Europe. He also speculated that if the Gulf Stream were somehow diminished in strength, the winter winds would be much colder and that Europe would experience Arctic-style winters. Over the years Maury's idea became almost axiomatic—and until recently, it also remained largely untested.

PRECEDING PAGES: COURTESY OF PETER MINNETT AND BOB EVANS *University of Miami/MODIS/NASA*

A decade ago, however, Richard Seager of Columbia University's Lamont-Doherty Earth Observatory and his colleagues produced an explanation for Europe's warmer winter that had nothing to do with the Gulf Stream. Seager's modeling study indicated that when the atmospheric jet stream, which flows around the earth from west to east, hits the Rocky Mountains, it begins to oscillate north and south. The oscillation produces winds that flow from the northwest over the western side of the Atlantic basin and from the southwest over the Atlantic's eastern side. The northwesterly winds bring cold continental air to the northeastern U.S., whereas the southwesterly ones bring warm maritime air to northwestern Europe.

In this view, it is not heat carried by the Gulf Stream that moderates the European climate. Instead heat that is stored off the shores of Europe, in the upper 100 meters of the ocean during the summer, is released to the atmosphere in winter when the southwesterly winds mix the surface ocean waters. In this scenario, the classic conjecture of Maury is incorrect: large-scale wind patterns directed by mountain ranges, plus local storage of heat by the ocean near Europe, set the temperature differences between the western and eastern sides of the Atlantic [*see box on next two pages*].

It is important to keep in mind that Seager's model simulations did not explicitly take into consideration the transport of heat by the ocean, a point addressed in a study released soon after Seager's by Peter Rhines of the University of Washington and Sirpa Häkkinen of the NASA Goddard Space Flight Center. They put forth a counterargument that offered some modern support for Maury's historical ideas. After examining archived sea-surface temperature data, the two oceanographers concluded that the amount of heat stored in the upper layer of the eastern Atlantic Ocean at the latitudes of northern Europe is enough to maintain mild air temperatures only through December of an average year. The additional heat required to moderate the climate over the remainder of the winter had to be imported from elsewhere. The most likely source: the northeastward-flowing Gulf Stream.

Measurements showed that at 35 degrees north latitude—roughly the latitude of North Carolina—the North Atlantic transports about 0.8 petawatt of heat northward, mostly by the Gulf Stream. Yet at 55 degrees north latitude—the latitude of Labrador in Canada—this poleward heat transport is negligibly small. Where does all the heat go? Rhines and Häkkinen suggested that it is released by the ocean into the atmosphere along the path of the Gulf Stream. The prevailing winds then carry the heat eastward, where it moderates the European climate. Rhines and Häkkinen essentially argued for Maury's Gulf Stream conjecture, and Seager argued against it, focusing on the role of the atmospheric jet stream.

In 2011 Yohai Kaspi, now at the Weizmann Institute of Science in Rehovot, Israel, and Tapio Schneider of the California Institute of Technology unveiled a third idea, based on novel numerical experiments of the atmosphere and the ocean. They suggested a degree of truth in both the Seager and Rhines scenarios but concentrated mostly on patterns of atmospheric pressure. Kaspi and Schneider's model indicated that the loss of heat from the ocean to the atmosphere along the path of the Gulf Stream where it leaves the U.S. East Coast generates a stationary, atmospheric low-pressure system to the east—on the European side of the Atlantic. It also creates a stationary high-pressure system to the west—over the eastern edge of the North American continent. For complex reasons, the net result of this pattern is that the stationary low-pressure system delivers warm air to western Europe via the jet stream's southwesterly winds, which pick up heat released all winter long by the Gulf Stream. The stationary high pulls in cold air from the Arctic, cooling eastern North America and increasing the contrast in temperature between North America and Europe.

Thus, the difference in the climate across the Atlantic arises not only because western Europe warms but also because eastern North America gets colder. Both regions have their characteristic temperatures because of the atmospheric circulation pattern established by heat loss from the ocean in the vicinity of the Gulf Stream.

The amount of heat loss from the Gulf Stream that is required to establish this circulation cannot be sustained only from heat that the mid-Atlantic gains during the summer, however. Heat transported by the Gulf Stream, from lower latitudes, is also needed. In this sense, Kaspi and Schneider lend some credence to Maury's earlier ideas. Although the atmospheric low- and high-pressure systems are created without any need to invoke the influence of the Rockies on the jet stream, this new work does highlight the importance of the southwesterly winds in bringing warmth to Europe.

Interestingly, the Kaspi-Schneider model can also explain why western Oregon, Washington State and British Columbia have much milder winters than what Kamchatka endures. This transpacific contrast has never been attributed to the presence of the Kuroshio, the counterpart of the Gulf Stream in the Pacific, primarily because the Pacific is a much larger ocean and the Kuroshio is a considerably weaker current than the Gulf Stream across much of it. Yet the Kaspi-Schneider result would suggest that heat lost over the Kuroshio could induce a stationary, atmospheric-pressure system similar to the one near the Gulf Stream in the Atlantic. The system would deliver cold polar air to northwestern Asia via northwesterly winds there, and southwesterlies would deliver warmer air to the northern U.S. Pacific Coast.

SHUTTING DOWN THE GULF STREAM

THE JURY is still out on which model is correct, although the Kaspi-Schneider scenario seems plausible. The second part of Maury's conjecture—that a cessation of the Gulf Stream would lead to more intense winters over northwestern Europe—has also recently generated considerable interest. For many years the nature of the Gulf Stream's role in climate change has been framed as this question: If a warmer climate melts Arctic ice, will the excess freshwater that enters the ocean in the northern Atlantic decrease the overturning circulation there, shut down the Gulf Stream and rob northwestern Europe of an important source of heat?

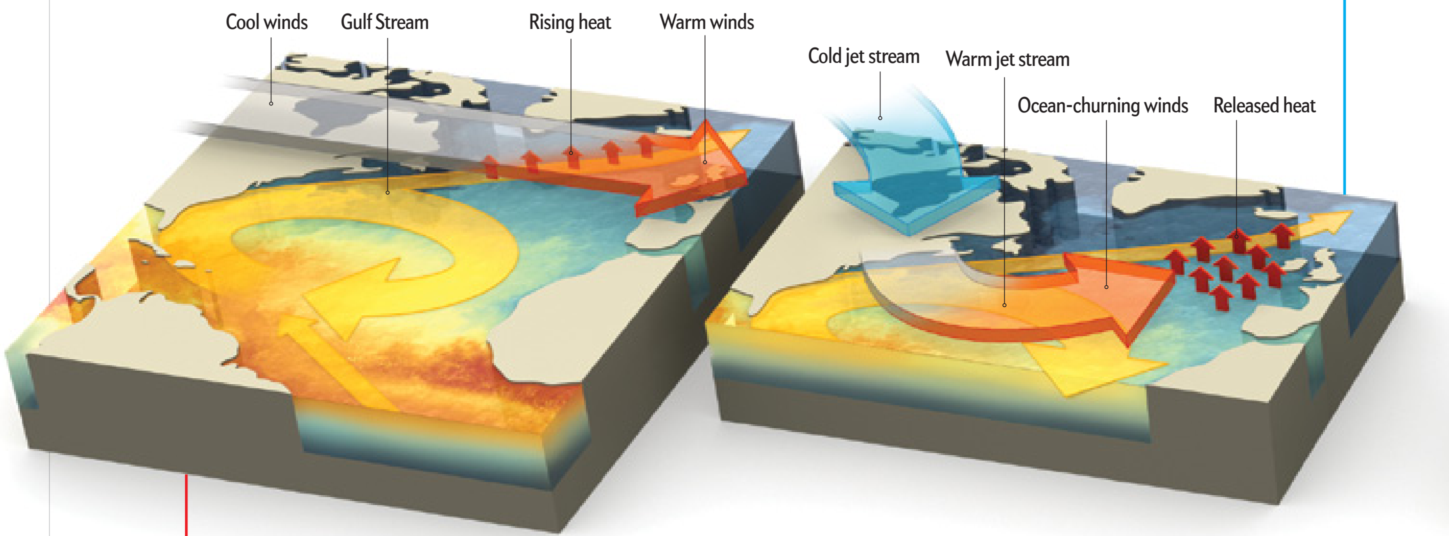
The overturning circulation consists of warm upper waters in the North Atlantic that move northward toward the pole and of cold deep waters that move southward toward the equator. These shallow and deep currents link to form something of a conveyor belt by the sinking, or downwelling, of surface waters at high latitudes in the Labrador and Nordic seas and by deep water elsewhere in the global basin that rises, or upwells, to the surface. In

ALTERNATIVE THEORIES

Why Winter Is Warmer in Europe

A century-old explanation says that warm Gulf Stream water makes Europe's winters milder than those at the same latitude on the North American side of the Atlantic. But competing new explanations emphasize the jet stream (prevailing winds) and Arctic air.

New Theory 1: Jet Stream
An oscillating jet stream heads from the southwest toward Europe. The winds churn the ocean's warm surface, releasing heat that was stored in the water during the summer.



The Classic Story, Incorrect
The Gulf Stream carries warm tropical water toward the southeastern U.S. and then crosses the Atlantic Ocean toward Europe. According to the old theory, as the water arrives near Europe, it heats the air above it. Winds move that mild air inland.

essence, the cold waters that sink in the northern North Atlantic are replaced by relatively warm surface waters that upwell elsewhere in the global ocean.

In many climate-warming scenarios, the melting of Arctic ice would add a large quantity of freshwater to the ocean at high latitudes. Because freshwater is less salty (and thus less dense) than seawater, it might not sink—so the downwelling that feeds the deep currents of the overturning circulation would be inhibited. In this case, there would be no physical requirement for warm deep waters to rise up elsewhere because there would be no downwelling to compensate for; in consequence, with no new warm water rising to the surface, the northward flow of such water—the Gulf Stream—might be diminished. Alternative scenarios hold that freshwater additions at high latitudes would divert the Gulf Stream farther south or diminish its strength. In either case, a weakened or diverted Gulf Stream would provide less heat for European winters. Many models strongly predict that a decrease in the overturning circulation correlates with a subsequent cooling in the North Atlantic and northwestern Europe.

Yet recent modeling studies with higher resolution of ocean currents suggest that fresh Arctic meltwater may pour mostly into currents that are more restricted to the coastlines and therefore have less influence on the open ocean, where downwelling primarily occurs. Even if freshwater significantly affected the amount of waters downwelled in the North Atlantic, it turns out to be highly unlikely that this change would effectively shut down the Gulf Stream. A shutdown is unlikely because the path and the strength of the Gulf Stream depend largely on the speed and direction of the large-scale midlatitude winds. In most climate change scenarios, the general direction of the large-scale winds does not change significantly as Arctic ice melts, so the general path and strength of the Gulf Stream do not change much either. The northeastward extension of the Gulf Stream—the relatively small branch that brings the warm upper waters to the subpolar regions—could potentially be disrupted, however. Thus, the weight of evidence indicates that the Gulf Stream would persist, but it is unclear how much Gulf Stream water would be carried northward under different climate scenarios.

MORE DATA, BETTER RESOLUTION

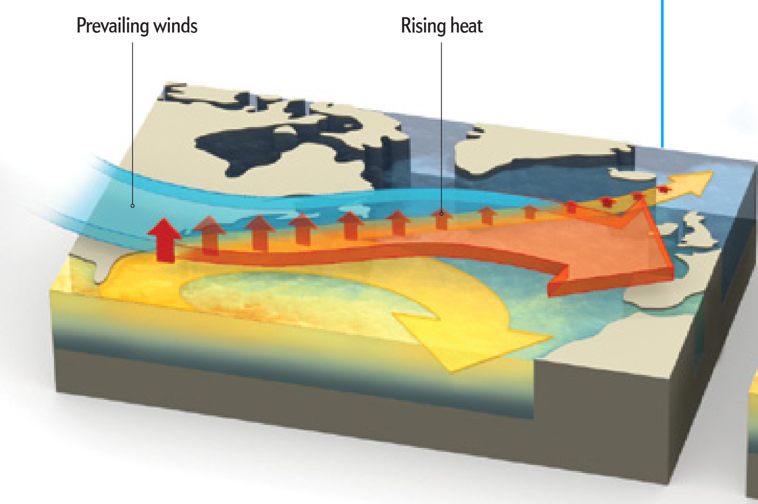
AT PRESENT, answers to how climate change would affect Europe's weather come largely from modeling experiments. Still, the experiments have considerable uncertainties that can be reconciled only with more extensive data from the oceans. Few observations from the open oceans are older than a century, and we have satellite data for just the past 30 years or so.

Scientists have recently been making considerable progress

Illustration by Emily Cooper

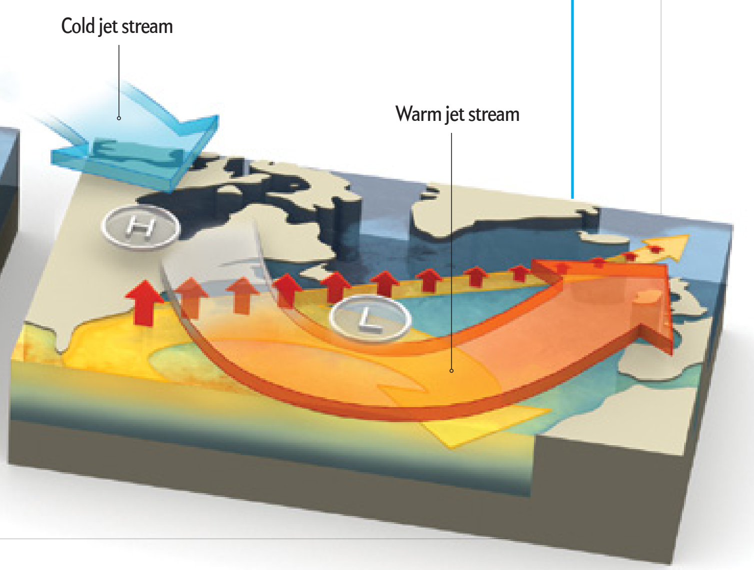
Theory 2: Heated Winds

The Gulf Stream releases heat to the atmosphere along its path across the Atlantic. The jet stream carries the heat eastward, where it moderates Europe's temperatures.



Theory 3: Pressure Systems

Heat released along the Gulf Stream generates stationary atmospheric high-pressure (H) and low-pressure (L) systems. The pressure systems direct warm prevailing winds toward Europe and also draw in cold prevailing winds from the Arctic that cool eastern North America, which accentuates the temperature difference between the continents.



in improving the oceanic database through the Argo project, an ongoing global collection of temperature and salinity measurements from more than 3,000 floating sensors scattered worldwide. The Argo array, deployed and operated by the U.S. and more than 30 other countries, allows scientists to make near-real-time maps of temperature and salinity in the upper 2,000 meters of the world's oceans. The complete array has been in place for less than a decade, and we are just beginning to use it to effectively examine the connection between atmospheric variability and changes in the large-scale ocean.

For example, a comparison of the Argo data with ocean observations from the 1980s, carried out by Dean Roemmich and John Gilson of the Scripps Institution of Oceanography, shows that the upper few hundred meters of the oceans have warmed by about 0.2 degree C in the past 20 years. Upper-ocean salinity also increased globally by a small 0.1 percent—yet below a few hundred meters, ocean waters appear to be considerably fresher than in previous decades. Whether these changes are enough to alter the climate in Europe or anywhere else remains an open question, but the data we are now getting from Argo offer some clues. For the earth to neither warm nor cool, the input of heat from the sun must equal the amount of heat radiated from the earth back into space. Accumulating greenhouse gases in the atmosphere are apparently upsetting this equilibrium. The observed warming of 0.2 degree C in the upper ocean is consistent with an excess of incoming solar radiation over outgoing radiation of approximately one watt per square meter.

Early results from our improved ocean observatory provide a powerful input for climate theories and models. The results also offer a hint at what will be possible in the coming decades. In the next 10 years, as scientists examine, in tandem, the sea-surface data from satellites, computer models and longer, subsurface data records from Argo, they should be able to assess the role of the ocean in climate with new precision. At that point, we may finally be able to determine how the Gulf Stream will affect climate change on our watery planet. SA

MORE TO EXPLORE

Is the Gulf Stream Responsible for Europe's Mild Winters? R. Seager et al. in *Quarterly Journal of the Royal Meteorological Society,* Vol. 128, No. 586, pages 2563–2586; October 2002.

The 2004–2008 Mean and Annual Cycle of Temperature, Salinity, and Steric Height in the Global Ocean from the Argo Program. Dean Roemmich and John Gilson in *Progress in Oceanography,* Vol. 82, No. 2, pages 81–100; August 2009.

Winter Cold of Eastern Continental Boundaries Induced by Warm Ocean Waters. Yohai Kaspi and Tapio Schneider in *Nature,* Vol. 471, pages 621–624; March 31, 2011.

SCIENTIFIC AMERICAN ONLINE
For more details about the Argo ocean array of 3,000 floating sensors worldwide, see **ScientificAmerican.com/feb2013/riser**