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CLIMATE CHANGE

A Shifting Band of Rain

By mapping equatorial rainfall since A.D. 800, scientists have figured out how tropical weather may change through 2100

By Julian P. Sachs and Conor L. Myhrvold

THE FIRST INDICATION THAT OUR EXPEDITION WAS NOT GOING AS PLANNED was the abrupt sputter and stop of the boat's inboard engine at 2 A.M. The sound of silence had never been less peaceful. Suddenly, crossing the open ocean in a small fishing vessel from the Marshall Islands in the North Pacific Ocean seemed an unwise choice. A journey to a scientific frontier had led us to a different frontier altogether, a vast darkness punctuated by the occasional lapping wave.

We are climate scientists, and our voyage (which ended safely) was one of many intended to help us do what at first glance seems impossible: reconstruct rainfall history back in time, across an ocean. By tracing that history, we can gain a better understanding of how the ongoing buildup of greenhouse gases in the atmosphere, rising air temperatures and changes in tropical precipitation are likely to alter future climate patterns. We have traveled far and wide to numerous islands across the Pacific Ocean.

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IN BRIEF

The tropical rain band that wraps the globe north of the equator migrates as atmospheric temperature changes, altering rainfall patterns worldwide.

Data from sediments in Pacific Island lakes show that the band is at 3°N to 10°N, as far north as it has ever been in at least 1,200 years.

At current warming rates, the band could shift north by five degrees by 2100, drying out farmland for millions of people in Ecuador, Colombia and elsewhere.

Multiyear drought conditions in the southwestern U.S. could persist as that area becomes more like the semiarid region of northern Mexico.

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Some present-day climate patterns are well known, such as the El Niño and La Niña circulations in the Pacific. A lesser known but equally important pattern is the primary precipitation feature on the planet: a band of heavy rainfall that circles the globe in the tropics and migrates north or south seasonally with the angle of the sun. The area in which it moves is known as the Intertropical Convergence Zone (ITCZ).

Any change in the earth's temperature, as a result of incoming solar radiation or greenhouse gases, can affect the rain band, which provides the precipitation that feeds equatorial agriculture. The band also plays a central role in the monsoons of Asia, Africa and India and the large convection cells that transport heat from the equator toward the poles. The frequency and intensity of El Niño and La Niña events and the strength and duration of hurricane seasons in the Pacific and Atlantic can all be influenced by variations in the band's position. Changes in rainfall resulting from a permanent shift of the band would dramatically alter the equatorial environment, with effects reaching worldwide. And we have good reason to believe the band is shifting.

Until recently, climate scientists did not know whether the current annual range of the band's midline—from 3°N to 10°N latitude over the Pacific Ocean—was its historical range. But now field measurements from latitudes bracketing the ITCZ have allowed our colleagues and us to define how the band has moved over the past 1,200 years. A large shift of five degrees northward—about 550 kilometers—occurred from about 400 years ago until today. Discovery of that shift led us to a startling realization: small increases in the greenhouse effect can fundamentally alter tropical rainfall. We can now predict where the ITCZ will move through 2100 as the atmosphere warms further. We can also predict whether rainfall may rise or fall across the world's equatorial zones, the probable effects across higher latitudes in Asia, Central America and the U.S. southern tier, and what those changes might mean for weather and food production. Some places are likely to benefit, but many others, we fear, will face dry times.

MEDIEVAL UNKNOWN

UNTIL WE BEGAN mapping rainfall history, scientists had little data about where the ITCZ had been during the past millennium. The band hovers near the equator, but it can be tens or hundreds of kilometers wide, depending on local conditions and seasonal sunshine. Because the zone is highly pronounced over the Pacific, that region is ideal for tracking its movement. And because the rain band girds the earth, Pacific trends indicate global changes.

Scientists can profile the sun's strength from isotopes such as carbon 14 in tree rings and beryllium 10 in ice cores and can reconstruct the historic profile of worldwide greenhouse gases from air bubbles trapped in tubular cores of ice extracted from polar regions. By comparing solar output and greenhouse gas levels with the ITCZ's position over centuries, we can infer how tropical rainfall might change in the 21st century in response to rising greenhouse gas emissions.

Clever investigators have identified many different indicators of global temperature during the past millennium. Two periods stand out. Around A.D. 800, global temperatures were similar to those in the late 1800s. Temperatures then rose during the Medieval Warm Period (A.D. 800–1200), reaching levels similar to 20th-century temperatures. They gradually settled and fell during the Little Ice Age (A.D. 1400–1850). In the past two decades the sun's output has remained essentially constant, yet both temperature and levels of carbon dioxide—the most abundant manmade greenhouse gas—have become significantly higher than at any point in the past 1,200 years.

Atmospheric scientists knew few specifics about past tropical climate, however, when we began our work. Seafloor sediments, which can provide exquisite records of climate on multithousand-year timescales, accumulate too slowly to record much information about the past 1,000 years. Many corals produce annual bands, but the creatures rarely live longer than 300 years, providing no records from 300 to 1,000 years ago.

Mapping rainfall would allow us to fill in the missing information about the ITCZ's position over the past millennium. Usually determining rainfall once it has hit the ocean is a lost cause. But small islands scattered across the Pacific have enclosed lakes and ponds that can reveal the history. In the past six years we have collected dozens of sediment cores from the bottoms

IN THE LAB

Algae: Rain Gauge of the Ages

Algae obtain all their hydrogen from the water in which they live. By measuring the two stable isotopes of hydrogen—deuterium and protium—in the lipids of algae that are preserved in sediment underneath tropical lakes, we can infer the amount of rainfall that occurred when they lived.

The deuterium/protium (D/H) ratio of many algae has a linear relation with the D/H ratio of the water. The water ratio, in turn, reflects the rate of precipitation relative to evaporation in a lake's area. Within the tropical rain band region, where rainfall is frequent and heavy, the D/H ratio of lake and seawater is low. Outside the region, where evaporation can exceed precipitation, the D/H ratio is high. So we can use the varying D/H ratios of algal lipids found deeper and deeper in sediment to infer past rainfall.

Fortunately for us, algae also adjust the D/H ratio of their lipids in response to salinity. Special conditions on Christmas Island created a natural experiment for us to calibrate this response. The island hosts a series of ponds that have similar temperatures, light levels, nutrient levels and water D/H ratios, yet they differ widely in their salinities. We found that as the salinity increased so did the D/H ratio of lipids produced by cyanobacteria, in a linear fashion. Because the salinity of saltwater ponds decreases when rain is abundant and increases when it is dry, the salinity effect on lipid D/H acts in the same direction as the rainfall amount effect, making lipid D/H ratios sensitive gauges of hydrologic change.

These results, alone, are like geeks at the prom: they need dates! A sediment's age is determined by two radioactive isotopes, carbon 14 and lead 210, which have half-lives of 5,730 and 22.3 years, respectively. By comparing the hydrogen isotope ratios at various dates, we have reconstructed the series of precipitation changes going back 1,200 years. *—J.P.S. and C.L.M.*

PRECEDING PAGES: COURTESY OF NOAA-NASA GOES PROJECT

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of such waters in some of the most remote, exotic Pacific islands. The locations span a range of latitudes above, below and within the current band and fully across the Pacific. We can define where the rain band was during a given time period by pinpointing places that experienced intense rainfalls in that period at various latitudes. Simultaneous rainfall increases and decreases, northward or southward, indicate a common, oceanwide shift in the band.

Fieldwork is an adventure fraught with setbacks, equipment issues, language barriers and difficulty getting to the sediment-coring locations. For example, by the time we arrived in the capital city of Majuro, the local airline, Air Marshall Islands (affectionately known to locals as "Air Maybe"), had two broken planes in its fleet of two. The two-day trip mentioned earlier to test a local entrepreneur's modified fishing boat that looked alarmingly unseaworthy ended when the engines died on our overnight return from a neighboring atoll.

A sediment core pulled from a lake bottom on Lib Island holds preserved algae that reveal past rainfall. Trees prove handy for keeping a core vertical as thin sections are cut for the lab.

COURTESY OF CONOR L. MYHRVOLD

To retrieve an undisturbed sediment core, we push, pound and screw long tubes into a lake's bottom. Just about every site we have cored has a unique sediment sequence. Sometimes we find bright-red gelatinous layers several meters thick made up of cyanobacteria, as in the Washington Island lake. Other times the sediment is brown mud rich in hydrogen sulfide (read: it stinks!), containing mangrove leaf fragments and the occasional layer of bivalve shells, as in Palau.

As we slog through mud on foot and row across shallow water, we push a long pole into the sediment to test depths and to see whether obstacles lurk. It is not unusual to abort a core attempt because it hits rocks, ancient coral, sand or roots.

Because the rate of sediment deposition is highly variable, we do not know how deep we need to go. Generally speaking, one meter of sediment stretches back at least several hundred years: nine meters of sediment from Washington Island, for example, spanned 3,200 years. When possible, we try to hit "bedrock" at the bottom of a core: deposited sand, coral or volcanic rock marking the time when the lake first began accumulating sediment, so that we can obtain the most complete record of the historical climate.

THE SECRET LIES IN LIPIDS

RECONSTRUCTING RAINFALL is our goal, but we have to measure the ecosystem's characteristics in the present climate to know what the same measurements of the past environment reveal about the past climate. We therefore collect water samples at different depths to determine the chemical composition and hydrogen isotope ratio of the water, as well as traits of the algal and microbial populations. We trap phytoplankton, zooplankton and microbes on fine, glass-fiber filters, then immediately store them on ice so we can later analyze their lipid composition. Vegetation samples are collected from the immediate vicinity to evaluate their lipids, too.

After we carefully raise the cores out of the lake bottom, we have to get the samples back to the lab without disturbing the sediment. To avoid mixing a core's layers, we painstakingly "section" the uppermost sediments that are particularly soft into one-centimeter slices and store each slice in labeled plastic bags.

Once we have sectioned cores on site, we journey back to Seattle to our lab at the University of Washington, hauling stacks of ice chests filled with sediment and water and long cardboard boxes filled with the segments of cores that did not require bagging. By measuring the two stable isotopes of hydrogen in the lipids of algae preserved in successively deeper layers of sediment, and dating the samples back in time, we can infer the amount of rainfall that occurred when the flora lived [*see box on opposite page*].

WET REGIONS BECOME DRY

OVER SUCCESSIVE YEARS we have added more data to an increasingly accurate map that pinpoints the ITCZ's historical locations, and we continually update it with our latest results. Although our findings from the most recent expedition—to Kosrae in Micronesia—will take a few more months to analyze, the results from many trips, combined with data from colleagues, indicate that small changes in atmospheric heat were accompanied by large changes in tropical rainfall during the Little Ice Age, drying previously wet regions such as Palau and bringing abundant rain to previously arid regions such as the Galápagos Islands. When solar energy reaching the top of the atmosphere decreased by just two tenths of a percent for about 100 years, the ITCZ migrated south toward the equator by 500 kilometers.

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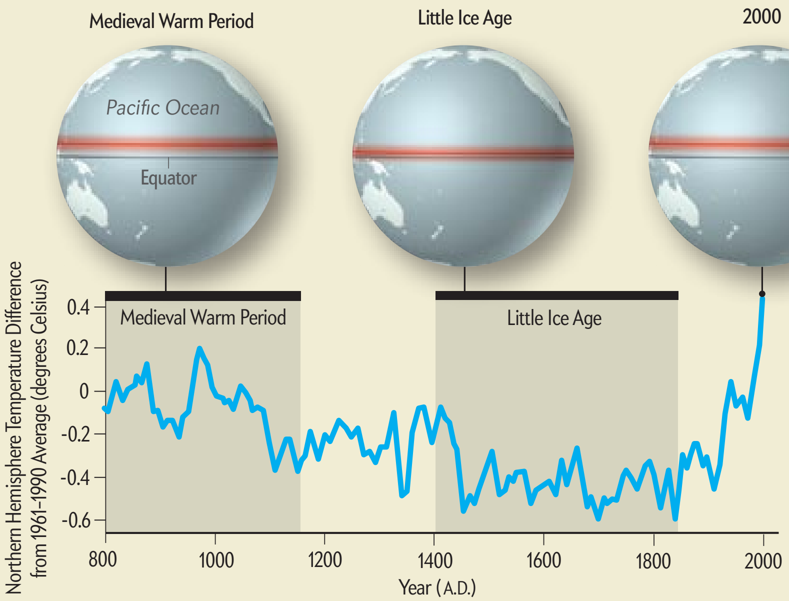
As Temperature Rises, So Does the Rain Band

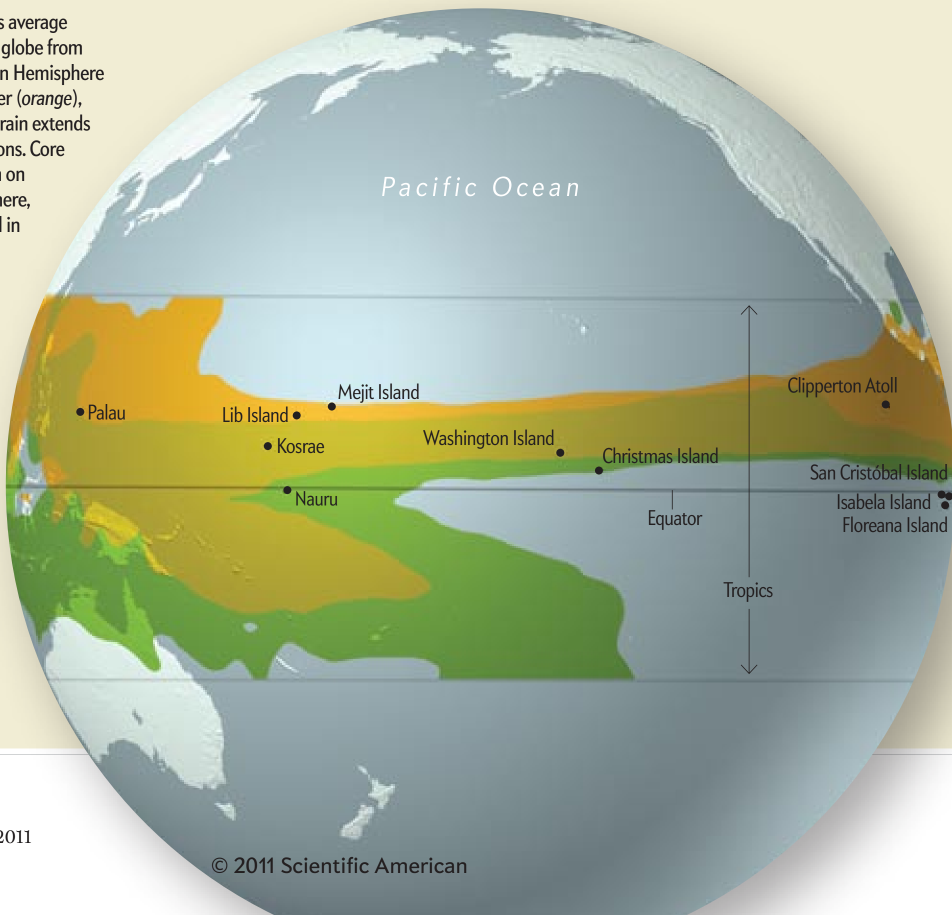
The Intertropical Convergence Zone (*red*), which circles the earth, is formed by opposing trade winds that create low pressure above equatorial water heated by the sun. The water evaporates, rises and condenses as rain—lots of it. The low pressure also creates adjacent, massive high-pressure cells that circulate atmospheric heat toward higher latitudes, driving weather systems there.

Elevated Northern Hemisphere temperatures moved the rain band north during the Medieval Warm Period (*left*); cooler temperatures shifted it south during the Little Ice Age. Today the band is as far north as it has ever been in the past 1,200 years. The projected rise in global greenhouses gases could bump it another five degrees northward by 2100.

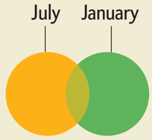


Implications: If the rain band travels another five degrees north, hundreds of millions of people near the equator would be left in its dry wake. Subsistence agriculture, coffee and banana crops, and tropical biodiversity would wither in places such as Ecuador, Colombia, northern Indonesia and Thailand. Locations in the band for the first time would receive much more rain, including Guam and El Salvador. Serious drought in the southwestern U.S. would likely become the new normal pattern.

Seasonal swing: The rain band's average latitude of 7°N varies across the globe from roughly 3°N during the Northern Hemisphere winter (*green*) to 10°N in summer (*orange*), stoked by the sun's heat. Heavy rain extends beyond the band in certain regions. Core samples of lake sediments taken on islands, including some shown here, reveal where and when rains fell in the past, indicating the band's position over time.



Average Monthly Precipitation in the Tropics from 1979–2005 (>200 millimeters)



SOURCES: NOAA (*precipitation*); "PROXY-BASED RECONSTRUCTIONS OF HEMISPHERIC AND GLOBAL SURFACE TEMPERATURE VARIATIONS OVER THE PAST TWO MILLENNIA," BY M. E. MANN ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 105, NO. 36; SEPTEMBER 2, 2008 (*temperature curve*)

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That sensitivity does not bode well for our future. The Intergovernmental Panel on Climate Change projects that because of primarily tailpipe and smokestack emissions, the atmospheric carbon dioxide concentration will rise to double preindustrial levels by midcentury and triple by 2100, causing an increase in atmospheric heating two to three times larger than changes that occurred at the end of the Little Ice Age from increased sunlight alone.

During the Little Ice Age the rain band's midline remained south of 5°N. Today it hovers between 3°N and 10°N. Recent increases in greenhouse gases threaten to move the band's center another five degrees northward—550 kilometers—by 2100. This new location (8°N to 15°N) would significantly change the intensity of rainfall in many regions [*see box on opposite page*].

Evidence for potential changes comes from our findings on the islands. Washington Island, located at 5°N, now receives three meters of rain a year, but 400 years ago it received less than one meter of rain and experienced more intense evaporation. Conversely, the highlands of San Cristóbal Island at 1°S in the desertlike Galápagos archipelago were substantially wetter during the Little Ice Age.

Evidence from archaeologists is also helpful. They have concluded that on islands across Indonesia and the South Pacific, a marked increase in the construction of fortifications coincided with the last large southward shift in the ITCZ's position. The bulk of fortifications—stone structures to fend off intrusions from neighboring societies—were built from the onset to the end of the Little Ice Age. As the rain band moved south, islands left in its northern wake dried out, perhaps forcing inhabitants to flee to more southern islands, raising fears of invasion among local peoples there.

Today desalination technology and shipping ease strict dependence on rainfall, but a move of the rain band five degrees further north would endanger the hundreds of millions of people who live near the equator and depend on subsistence agriculture, not to mention tropical biodiversity. Most nations in the current range are developing nations. They are likely to experience great population increases during this century and are unlikely to have the resources to successfully adapt. Rainfall declines, on one hand, and flooding, on the other, across decades or even a few years would reduce crop yields, leading to localized food shortages, political unrest and ultimately geographic displacement.

Areas directly in the ITCZ for the first time (10°N to 15°N), such as El Salvador and Manila in the Philippines, would receive more rain annually and would become more humid. Regions no longer under the rain band's direct influence (3°N to 8°N) would receive less rain and become more arid. Whether this drying effect would be countered in certain places by the strength of the Asian and Indian monsoons is subject to debate.

SLIDE SHOW OF PACIFIC RAINFALL RESEARCH
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LESS COFFEE, FEWER BANANAS

OVERALL, WET AREAS in northern Indonesia, Malaysia, the Philippines, Micronesia, Thailand and Cambodia would miss a good portion of the ITCZ rains they now receive. Crop varieties ideal for today's growing conditions would no longer thrive. For example, coffee plants, much like vineyards, need a lot of rain at the beginning of the growing season and require more than 1.8 meters in total to develop suitable beans.

In Central America, Ecuador and Colombia would be left in the ITCZ's wake and become drier. Colombia's increased urbanization may help it cope because its economy is no longer as highly dependent on agriculture. Colombia, however, is the world's third-largest coffee producer, and as in Indonesia, less precipitation could affect long-term coffee yields. Most growing regions for the bean, which are below 8°N latitude, would likely suffer by the mid- to late 21st century. Productive areas in the south and along the coast are most at risk because they will be the farthest from the rain band.

The future of Ecuador's banana industry may be bleak. Good bananas require warm temperatures and 2 to 2.5 meters of annual rainfall, but Ecuador is already well below the current ITCZ and barely meeting the minimum precipitation threshold. A shift would likely decrease rainfall to a meter a year or less by 2100, shutting down the country's banana industry. A large drop in banana yield can happen quite fast. In the Philippines at the beginning of 2010, roughly half of the plantations produced small and underweight bananas that were useless commercially, because of an abnormal dry season.

Subsistence agriculture would also be affected in all the aforementioned locations. Even if people gravitate toward cities, a lack of regional food sources is a recipe for disaster.

If the band continues migrating north at the average rate it has been over the past 400 years, substantial rainfall changes in the continental U.S. are likely, too. Some changes may have already begun. The southwestern U.S. is enduring a severe multiyear drought that is likely to represent the new normal pattern in the 21st century should greenhouse gas levels continue to rise apace. Higher temperatures, and a continuing northward shift of the rain band, threaten to shift the subtropical dry zone that lies to its north, which currently stretches across northern Mexico, into this part of the country.

Scientists are unclear whether a northward shift would affect the frequency or size of hurricanes or monsoons. We also have yet to determine any possible effects on the patterns of El Niño and La Niña.

BETTER MODELS COMING

MORE WORK needs to be done before alarm bells can be sounded with confidence. Computer-based climate models have not accurately reproduced past and present rainfall patterns in the tropics. If modelers can use data from sediment cores and other sources to produce patterns that more closely approximate those that are known, the world could have greater confidence in their projections of future rainfall. This type of experiment is being pursued by our colleagues at the University of Washington and elsewhere.

We will continue to study sediments from tropical islands in the ITCZ, and to its north and south, to more precisely define the rain band's position throughout the past millennium and to predict where it will be in generations to come. SA

MORE TO EXPLORE

Proxy-Based Reconstructions of Hemispheric and Global Surface Temperature Variations over the Past Two Millennia. Michael E. Mann et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 105, No. 36, pages 13252–13257; September 2, 2008.

Southward Movement of the Pacific Intertropical Convergence Zone AD 1400–1850. Julian P. Sachs et al. in *Nature Geoscience,* Vol. 2, No. 7, pages 519–525; July 2009.

Paleoclimates and the Emergence of Fortifications in the Tropical Pacific Islands. Julie S. Field and Peter V. Lape in *Journal of Anthropological Archaeology,* Vol. 29, No. 1, pages 113–124; March 2010.

Paleoclimate research at the Sachs Lab: **http://faculty.washington.edu/jsachs**

Illustration by George Retseck (globes) and Jen Christiansen (graph)

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