FEATURES

THE STORM KING

A mysterious tropical weather pattern called the Madden-Julian oscillation fuels El Niños and triggers rain, heat waves, and hurricanes around the globe

By **Eric Hand**

The clouds swelled over the Indian Ocean, forming a herd that lumbered east along the equator, bringing days of wind and rain wherever it went. By March, the clouds had reached the Pacific, east of New Guinea, and piled up to the stratosphere in a mass thousands of kilometers across. Westerly gusts, nearing the force of tropical storm winds, swept warm water into a mound that barely rose above the surface but jutted deeply into cold waters 100 meters down. The enormous bulge of tropical water rolled eastward toward South America, like an upside-down tidal wave.

In May, a second rain and wind event plowed into the western Pacific, shouldering another massive slug of warm water eastward. In July, yet another disturbance thundered through.

When this trio of weather events began early last spring, warm waters were already gathering on the far side of the Pacific, off the coast of Peru—the beginnings of the global weather phenomenon known as El Niño. But it was a weak start. The three extra pulses of warm water turned this El Niño into a beast: It is now the strongest since 1997 and may end up being the most severe on record. It has already boosted hurricane activity in the Pacific Ocean, tamped it down in the Atlantic, and set the stage for torrential rain in southern California and the U.S. South.

Yet, although everyone is bracing for a monster El Niño this winter, few know much about the phenomenon that triggered it. Fewer still know its name: the Madden-Julian oscillation (MJO). The bouts of tropical storminess that the MJO brings not only play an important role in fueling El Niño events, but also have striking weather effects in their own right. The MJO is the single biggest driver of weather in the tropics, and at higher latitudes it can lead to cold snaps, heat waves, rainy seasons, and hurricanes—just about everything El Niño does, says Adam Sobel, an atmospheric sci-

PHOTO: OWEN SHIEH

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Clouds grow in the early stages of a 2011 Madden-Julian oscillation event in the Indian Ocean.

entist at Columbia University. "The MJO is the most important [oscillation] about which we understand as little as we do," he says. Yet "people have never heard of it."

But scientists are making progress in understanding this hidden force in weather and climate. Computer models are finally mimicking the MJO, after decades of failure. That is allowing weather forecasters to push their predictions further into the future than ever before, while climate scientists are exploring how the MJO will behave in a warmer world. And after an intense field campaign in the Indian Ocean involving dozens of nations, researchers are starting to answer some of the most fundamental questions of all: Why does the MJO exist, and how does it form?

"I saw someone refer to it as the maddening Julian oscillation," says Tony Del Genio, a climate modeler at NASA's Goddard Institute for Space Studies in New York City. "We've been frustrated for so long. I think we're taking steps in the right direction. But I also think the story is not over yet."

SOME YEARS, no MJO events occur. Other years, there are more than half a dozen. Most often they form over the Indian Ocean during the northern winter, as tall rainclouds coalesce into clusters. This "active phase" of rain and wind is preceded by a zone of clear skies, the "suppression phase." The two phases march eastward in tandem at about 5 meters per second and cross Indonesia into the Pacific. There, the storms lose strength, but the system speeds up to as much as 15 meters per second. Some MJO events die when they hit the mountain wall of the Andes, but the seeds of others continue across South America, the Atlantic, and Africa. A few even circumnavigate the globe, winding up in the Indian Ocean 30 to 60 days after they started.

As the MJO's active phase proceeds around the equator, it shapes weather in distant latitudes. In the Indian Ocean, it can trigger and enhance the Indian and Australian monsoons. When it is over the Pacific, atmospheric ripples can peel off from the MJO and tilt the jet stream, sending humid air from the vicinity of Hawaii up to drench the Pacific Northwest in "Pineapple Express" events. Other "teleconnections" in the atmosphere lead to cold snaps and heat waves in North America and Europe. And when the MJO persists into the Atlantic basin, it can affect cyclone formation: A 2000 study found that hurricanes are four times more likely to form during an active MJO phase than during a suppressed one. In 2012, for instance, Hurricane Sandy formed just after a strong MJO passed through.

It took keen insight and one of the most powerful punch card computers of its time for Roland Madden and Paul Julian to discover the MJO in 1971, working with data from a scattering of island weather stations (see sidebar, p. 25). Soon the MJO was unmistakable in images from weather satellites, which revealed throngs of cumulonimbus clouds regularly circling Earth's belly. Yet the computer models that climate scientists and weather forecasters rely on could not reproduce the MJO, to the modelers' embarrassment. "We're not happy when something that shows up in the real world does not show up in our models," Del Genio says.

Those models work by dividing Earth's atmosphere up into millions of boxes. Weather observations provide the starting conditions of temperature, humidity, wind speed, and other variables for each box. Then the model is set in motion, evolving according to the laws of physics. Making the boxes smaller to sharpen the model's resolution quickly raises the computational cost to prohibitive levels. One of the best forecast models in the world, at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, U.K., uses boxes that are 16 kilometers on a side. That is still too coarse to model local phenomena, such as the billowing evolution of individual storm clouds; it will be a decade before computers will be capable of running global cloud-resolving models for daily forecasts.

In the meantime, modelers cheat: They apply "parameterizations," semiempirical computational shortcuts applied within grid boxes for processes such as cloud formations. These parameterizations were somehow fouling up the formation and movement of MJO events. The models did show storms gathering over the equatorial ocean, but they grew too fast in too many places, dumping their moisture as rain and preventing the formation of squadrons of small- and medium-sized rain clouds needed to assemble an MJO event.

A breakthrough came with a study published in 2008 and led by Peter Bechtold, a principal scientist at ECMWF. Bechtold realized that the parameterizations in the ECMWF model were not accounting for the turbulence along the edges of rising, moist cloud columns. With more turbulence, dry air can mix into the cloud, effectively stopping its rise—a process researchers call entrainment. Entrainment could slow the formation of the biggest storm clouds, keeping the MJO events from aborting themselves early. Bechtold showed that once cloud parameterization in the ECMWF model was altered to include more entrainment, MJO events began to appear.

Other major weather forecasting models in Europe, Japan, and the United States soon followed ECMWF's lead—and because MJOs have such far-reaching effects on weather, the models gained new forecasting power. ECMWF weather forecasts now have some predictive skill out to a world-leading 25 days. Other forecasters are finding new customers. Earlier this year, WSI, a division of The Weather Company, launched an MJO-based forecast that helps predict cold snaps and heat waves in North America and Europe up to 5 weeks in advance. So far, most of Ventrice's customers are hedge funds and traders who want to make bets on energy supplies such as heating oil or natural gas, says Michael Ventrice, a WSI scientist in Andover, Massachusetts. He says retailers are using MJO forecasts from other modelers to tweak the timing of seasonal clothing lineups.

Climate researchers have made less progress than weather forecasters in simulating the MJO. In a 2006 study, just two of 14 global climate models produced a reasonable MJO. Part of the problem was that the fix that worked so well for weather forecasters produced unwanted side effects for the overall long-term climate. Upping entrainment, which dries out the biggest storm clouds, left more moisture for medium-sized rainstorms around the globe, making the overall climate too wet. "Entrainment is the medicine to make the MJO, but it made the rest of the climate have an upset stomach," Del Genio says.

Some climate modelers are starting to find workarounds—either with further tweaks to parameterizations or with models that simulate clouds explicitly for small areas. But a study published in May found that even now, only eight of 27 global climate models produce good MJO events. Some poor performers even made MJOs that moved backward, from east to west.

Still, the models are already offering glimpses of how the MJO could change in a warmer world. A study published in July found that, if global temperatures rise 4°C by the end of the century—the likely outcome if greenhouse gas emissions continue to grow unabated—the MJO would increase in both frequency and intensity. That's both good news and bad, says Eric Maloney, an atmospheric scientist at Colorado State University, Fort Collins. "A stronger MJO in future climate is potentially going to exacerbate some [weather] extremes, but possibly allow us to better predict them on seasonal time frames," he says.

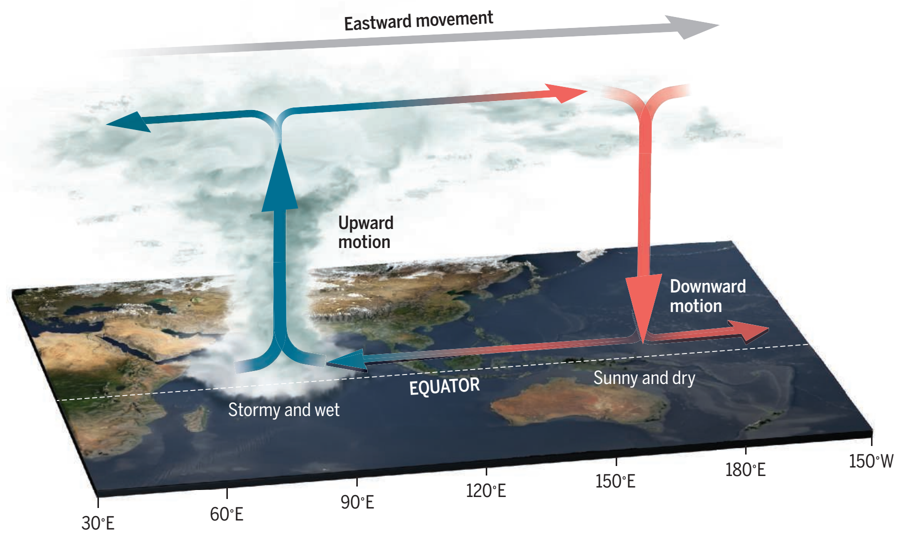
WHILE MODELERS STRUGGLE to predict MJOs, field researchers recently mounted a massive campaign to understand what gives birth to them in the first place.

The approximately $60 million campaign, called CINDY/DYNAMO, was led by Japan and the United States and concentrated on the place where the MJO begins. "We simply cannot explain why MJO would start from the Indian Ocean," says Chidong Zhang, who studies ocean-atmosphere interactions at the University of Miami in Florida and is the principal investigator for the U.S. portion of the project, which included universities and other research institutions from 14 countries.

From October 2011 to March 2012—a winter season in which they could reasonably expect to catch a couple of MJOs in the

Around the world in 30-60 days

The Madden-Julian oscillation (MJO) forms in the Indian Ocean as a pair of related wet and dry phases. In tandem, the system moves eastward at about 5 meters per second, circling the globe in 1 or 2 months.



Regional effects

The MJO not only drives weather in the tropics but can also trigger and strengthen phenomena such as monsoons and hurricanes elsewhere in the world.

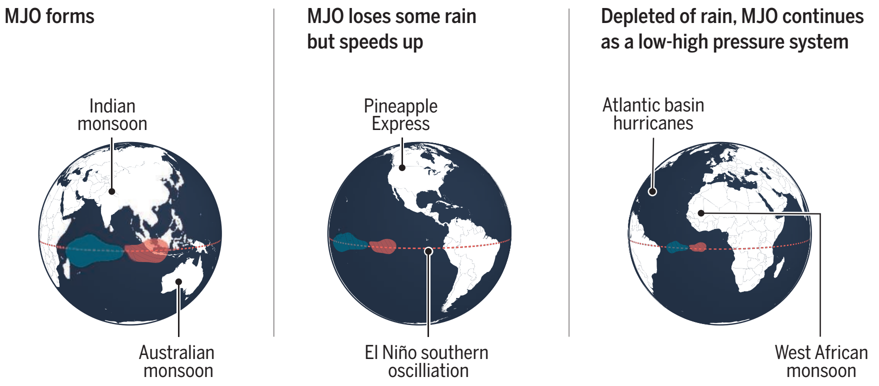


ILLUSTRATION: ADAPTED FROM CLIMIA V. ALTOUNIAN/SCIENCE; G. GRULLÓN/SCIENCE act—the CINDY/DYNAMO partners flooded the zone. Satellites can look down on the cloud tops that mark an MJO event. But to watch one take shape, researchers needed a vertical picture of all the cloud layers. They got it from radars operating at different frequencies from sites on land and ships, ocean measurements from ships and buoys, and atmospheric readings from more than 23,000 weather balloons and two dedicated aircraft.

All that data did not pin down the reason for the MJO's existence, but it did elevate a new candidate. For years, some theorists thought the MJO was a variation on a much swifter eastward-moving wave of atmospheric pressure called a Kelvin wave. But a Kelvin wave can exist in a dried-out atmosphere. Maloney says the CINDY/DYNAMO results suggest that the MJO owes its existence to moisture. He says the MJO is an example of a "moisture mode" that develops when humid air rises and circulates inside storm clouds.

Del Genio, who has followed the debates as an outsider, says that the moisture mode theory "seems to be gaining traction." But Zhang, who in 2005 wrote a review that identified a half-dozen explanatory theories, isn't quite ready to anoint it as the winner, although he says it is appealing.

Even if the MJO is a moisture mode, there remains the question of what mechanism brings the moist air to the Indian Ocean at the critical time. The CINDY/DYNAMO campaign appears to have stumbled on at least one answer. The Intertropical Convergence Zone (ITCZ) is a band of low pressure where the two hemispheres' trade winds collide, forming a pool of moist, hot air. In the Northern Hemisphere's winter, in the Indian Ocean, that band sits 500 to 1000 kilometers south of the equator. The field campaign found that, just before an MJO kicks off, the ITCZ shifts northward into the MJO's cauldron of formation, supplying it with moisture.

What pushes the ITCZ toward the equator, Zhang says, may be dry air moving in from the southern latitudes of the Indian Ocean. Maloney suggests that just as the MJO affects weather in higher latitudes through teleconnections, phenomena in the higher latitudes of the Indian Ocean exert the same kind of remote control over the MJO.

Even as it hinted at answers, the DYNAMO campaign underscored the mysteries that remain. For example, Zhang says, team members aren't even sure how many MJOs they saw. Everyone agrees that there were at least two. But a third event, which satisfied some criteria for an MJO but not others, left them divided. "I often joke that we wanted to find out how MJO initiates," Zhang says. "When we came out of the field, we did not how to define MJO. That's progress." ■

How two pioneers took the tropics' pulse

By **Eric Hand**

It was 1970, and two young scientists were hoping that their thick stacks of computer punch cards contained clues to the hidden rhythms of tropical weather.

Roland Madden, a former forecaster for the U.S. Air Force, was working at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, alongside Paul Julian, a scientist nearly 10 years his senior and an expert on a new computer-aided technique for finding patterns in data.

In the wake of World War II, island weather stations dotting the Pacific began to accumulate long-term data sets. Analysis of them revealed not just the obvious daily and seasonal changes, but, in 1960, a 26-month cycle of shifting stratospheric winds called the quasi-biennial oscillation. The discovery showed that tropical weather, long ignored for its seeming dullness, held more than balmy, blue skies.

At NCAR, Madden and Julian wanted to probe further. They had a fancy new computer to work with: a CDC (Control Data Corporation) 6600, with 64 kilobits of memory and a 10-megahertz clock. They also had a new way to sift that data for temporal patterns in wind speeds, temperature, or pressure: the fast Fourier transform, a technique invented by mathematicians in 1965. What they needed was a big data set.


Studies on Kanton Island yielded crucial data.

PHOTO: CHANUTE AIR MUSEUM

It would come from a lonely spit in the Pacific Ocean called Kanton Island. The coral lagoon sits about halfway between Hawaii and Fiji, close to the crosshairs of the International Date Line and the equator. An operator would release a weather balloon at 1 p.m. local time. A radio dish antenna, tracking the rising sphere, would gather temperature, humidity, and pressure data. Geometric calculations yielded the wind speed.

By 1970, that data had wound up on magnetic tapes at NCAR. Madden converted the tape into decks of computer punch cards that were fed into the maw of the CDC 6600. (Today, thousands of the cards sit in boxes in Madden's garage. "I use them for shopping lists," says Madden, now 77. "I suppose now they're museum pieces.")

The CDC 6600 churned through its punch card decks. The Fourier analysis showed that air pressures fell and winds peaked roughly every 44 days. Madden and Julian began to imagine a giant storm system passing over Kanton Island every month and a half. In a 1971 publication of the *Journal of the Atmospheric Sciences*, they called it the "40-50 day oscillation." But they did not yet have a mental picture of what it really was. "We only had that one station," Madden recalls. "Was this thing moving, or locally pulsing, or what?"

They accumulated data from other weather stations, islands with names like Eniwetok, Wake, and Yap. They folded in surface pressure data collected by ships crisscrossing the ocean during the International Geophysical Year, 1957–58. A piecemeal geography emerged. First, they confirmed that the oscillation was confined to the tropics—it didn't extend beyond 10° north and south latitude. But Madden still wanted to visualize its movement.

One night in 1971, he took home printouts of a data set: surface pressures for various longitudes, over time. He spread them out on his couch and set to work. By hand, he subtracted out the long-term mean, and found that each day, negative pressure anomalies popped out at a particular longitude. A day or two later, those anomalies shifted east. It was a "eureka" moment, the first glimpse of how the disturbance that would eventually bear his name marched along the equator. "All of a sudden, I saw this beautiful eastward movement," he recalls. "I remember telling my kids, 'We're going to be famous.'" ■