CLIMATOLOGY

Monsoon Melee

Peaks of contention. Modeling climate in the Himalayas and other mountainous regions is notoriously difficult.

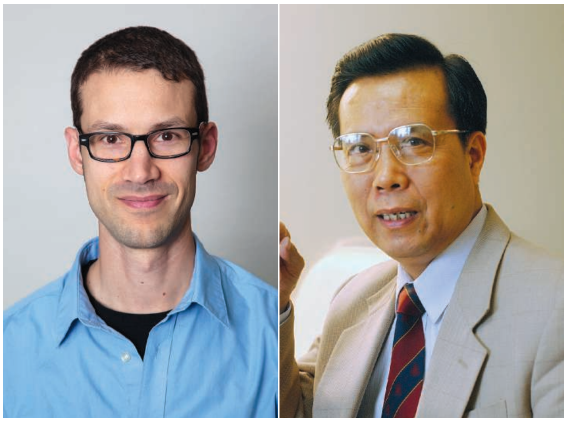
The rhythms of life across South Asia depend on the Indian monsoon. Climate scientists are locking horns over the cause of the summer deluges

BEIJING—The Tibetan Plateau is a study in extremes. It's the world's largest expanse of elevated terrain, covering 2.5 million square kilometers. Frigid in winter, it bakes in summertime: Because the average altitude tops 4000 meters, the vast landscape absorbs far more solar energy than land at sea level. As a result, models predict that in summer, the air layer above the plateau can be much warmer than air at a similar altitude over the oceans or over land lying at sea level.

It's like "having a gigantic heat pump at over 4000 meters," says Wu Guoxiong, an atmospheric scientist at the Chinese Academy of Sciences' Institute of Atmospheric Physics here. The temperature differential is the engine that drives the spectacular summer deluges in South Asia known as the Indian monsoon—or so say textbooks. A new spate of research is challenging existing dogma, sparking a debate over the Tibetan Plateau's role in the Indian monsoon. How it's decided could have effects reaching far beyond the climate science community.

At stake are how to "predict when [the monsoon] will start, how long it's going to last, and how it will respond to rising carbon dioxide and aerosols," says David Battisti, a climate scientist at the University of Washington, Seattle. "That matters hugely to millions of people." A resolution could prove elusive, however, because of the challenges of modeling climate in mountainous regions.

This much is agreed upon: In the summer, the air over and around Tibet is much warmer than air at the same altitude over the Indian Ocean. Consensus breaks down on whether that heating effect has broad consequences. In the 1950s, atmospheric scientists Ye Duzheng and Hermann Flohn independently proposed that the temperature differential creates winds that blow moist air from the sea into the interior of the Indian subcontinent. There, the air warms and rises, creating monsoonal rains. The hypothesis, which has stood for decades, is supported by climate modeling: The monsoon's strength—the total rainfall on the Indian subcontinent, that is—and how far north it reaches are greatly reduced when Tibet and the Himalayas are removed from climate models.



Dueling theorists. Wu (*right*) says the "heat pump" of the Tibetan Plateau drives the Indian monsoon. Boos (*left*) disagrees.

But those modeling studies have got it wrong, argues William Boos, a climate scientist at Yale University. They fail to "distinguish the role of the Himalayas from that of the Tibetan Plateau," he says. In 2008, he and Zhiming Kuang, then both at Harvard University, after examining temperature and humidity records in India and Tibet, uncovered what they claim are inconsistencies in the monsoon paradigm. One is that the upper atmosphere in the region is hottest over northern India and along the Himalayan ridge—not over Tibet. The finding "contradicts the view that Tibet is the heat center," says Peter Molnar, a geoscientist at the University of Colorado, Boulder. Secondly, Boos and Kuang showed that this hot air blankets the land surface with the highest energy level—a calculation based on temperature and the energy released by water vapor when it rises and condenses into liquid. That means heating of the Indo-Gangetic Plain, rather than Tibet, is driving the monsoon, Boos argues.

Supporters of a diminished role for the Tibetan Plateau also point to precipitation models, which hold that the hotter the surface is and the more moisture it contains, the more likely it is that water vapor will rise. Heat is released as water vapor condenses and rain falls, thereby transferring the energy of air near the surface to the upper atmosphere. More water vapor means a warmer upper atmosphere—exactly what Boos and Kuang saw.

In a series of papers, the most recent of which appeared in February in *Scientific Reports*, the two scientists argue that Tibet is irrelevant to the Indian monsoon. Instead, they say the monsoon is caused by a "barrier effect": the Himalayas blocking cold, dry winds from the north. In a global climate model, the duo showed that the Himalayas alone could generate a monsoon pattern that is largely similar to that pattern predicted when the Tibetan Plateau is included. When the mountain ranges were absent, they ended up with much lower energy in the air over northern India and got a weaker monsoon.

To further support their hypothesis, the researchers tweaked the model such that the Tibetan Plateau reflected all incoming solar radiation back into space, without heating the atmosphere. This "effectively turned off the heating source of Tibet without changing the Himalayas' blocking effect," Boos says. The result: The monsoon pattern hardly budged.

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Climate counterpoint

The new take on Tibet has shaken the foundation of how climate scientists understand the Indian monsoon, Molnar says. But not everyone is convinced. Wu, for one, argues that the reduced monsoon rainfalls that Boos and Kuang saw in their model could result from heating of the Himalayan slopes rather than from a barrier effect. To test this, Wu and colleagues performed another simulation in which they removed Himalayan heating. They came up with much less rainfall in the northern branch of the Indian monsoon—the rain belt stretching from the Bay of Bengal into Bangladesh, northern India, Myanmar, Nepal, and northern Pakistan. In a May 2012 report in *Scientific Reports*, the researchers concluded that the southern branch of the monsoon, which covers southern India, is mainly driven by land-sea thermal differences, while heating of the Himalayas is necessary for drawing moisture further inland.

Others have leapt to the defense of the plateau heating hypothesis. Peter Webster, a climate scientist at the Georgia Institute of Technology in Atlanta, questions whether the upper atmosphere over northern India is hotter than that over Tibet: The weather data that Boos and Kuang relied on are flawed, he asserts, but an equally fundamental issue is that "a hot surface isn't enough to give you a monsoon," he says. "The most effective way to heat up the upper atmosphere is through large, elevated land." The heat and moisture that give the air high energy levels over northern India, Webster says, come from the warm ocean near the equator. This depends on a big temperature difference between the equator and the elevated terrain in a midlatitude swath of Asia, Tibet included, which sets up the winds that blow inland. The high energy of air over northern India "is a result, rather than the cause, of the monsoon," Webster says.

To Brian Hoskins, a climate scientist at Imperial College London, the argument of Boos and Kuang rests too heavily on models of vertical air and energy flow in an idealized atmospheric column. It neglects the dynamics of air flow and monsoon structure in the real world, he says: "You probably would get a monsoon without Tibet, but it would look very different. The issue at stake is how the plateau affects monsoon onset, duration, and rainfall distribution."

Other critics say that the argument highlights fundamental problems of modeling climate in mountain regions like Tibet and the Himalayas—which is notoriously difficult because of their complex topography and the complicated ways it could affect climate. In addition, the models used by Boos and Wu have a resolution of 200 kilometers, which are too coarse to separate out the effects of the Himalayas and the Tibetan Plateau or to delineate the details of heat and moisture distribution, says Moetasim Ashfaq, a climate scientist at Oak Ridge National Laboratory in Tennessee. The models' coarseness means that the plateau can't be fully removed from simulations, Ashfaq says. "It's difficult to know exactly what you are seeing in such models," he says. Boos and Wu acknowledge that the coarse resolution is a major constraint.

Ashfaq says that the Weather Research and Forecasting Model, a relatively new regional model that uses massive computing power to simulate processes at 10-kilometer resolution, is superior to global climate models for such simulations. Moreover, the model is nonhydrostatic—meaning that it factors in vertical movement of air and moisture—and is more capable of simulating cloud formation, says Matthew Huber, a climate scientist at Purdue University in West Lafayette, Indiana. When Ashfaq removed the Tibetan Plateau in this model, leaving just the Himalayas, the monsoon's northern branch "is all gone," he says. "What the topography does is bring moisture from the equator further inland," says Ashfaq, who is writing up the results for submission.

Ground truths

Those in the barrier effect camp concede that Himalayan heating plays at least some role in monsoon formation, but maintain that the low-lying plains in northern India are the primary driving force for the downpours.

Molnar and colleague Balaji Rajagopalan, also at the University of Colorado, correlated heating of Tibet and monsoon characteristics in a report in February in the *Journal of Geophysical Research: Atmospheres*. "If you heat the Tibetan Plateau, the monsoon starts earlier and you get more rain," Molnar says. The effects are mostly at the beginning and at the end of the monsoon season. "But we don't see much of a correlation when we look at the main part, between June and August, when the rain is the heaviest," he says. According to their study, variations in heating over Tibet might affect a third of the monsoon season and account for only 30% of total rainfall.

Others say that the jury is still out on which model, if any, is correct. Yang Kun, a climate scientist here at the Chinese Academy of Sciences' Institute of Tibetan Plateau Research, notes that the plateau is notorious for its lack of climate observations, which cripples the predictive power of global climate models for the region. "Even basic weather stations are very sparse, let alone data on soil moisture, which is the most important parameter for energy exchange between land and atmosphere," he says. He thinks only high-resolution climate models, ground-truthed with robust long-term data, can hint at the correct answer.

Weather forecast. Unraveling the monsoon's cause should sharpen predictions of its start date and duration and how it will respond to climate change.

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In the past few years, Yang and his colleagues have been gauging soil moisture at more than 100 sites across Tibet. The measurements will be used to calibrate satellite data, allowing scientists to calculate energy flux on the plateau. In addition, China has earmarked $441 million for stepping up research and establishing state-of-the-art climate observatories and long-term research stations in Tibet and neighboring countries. The data, Yang says, will help elucidate climate processes and validate models. "Until then," he warns, "any conclusions about the role of the Tibetan Plateau in regional and global climate would be premature."

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