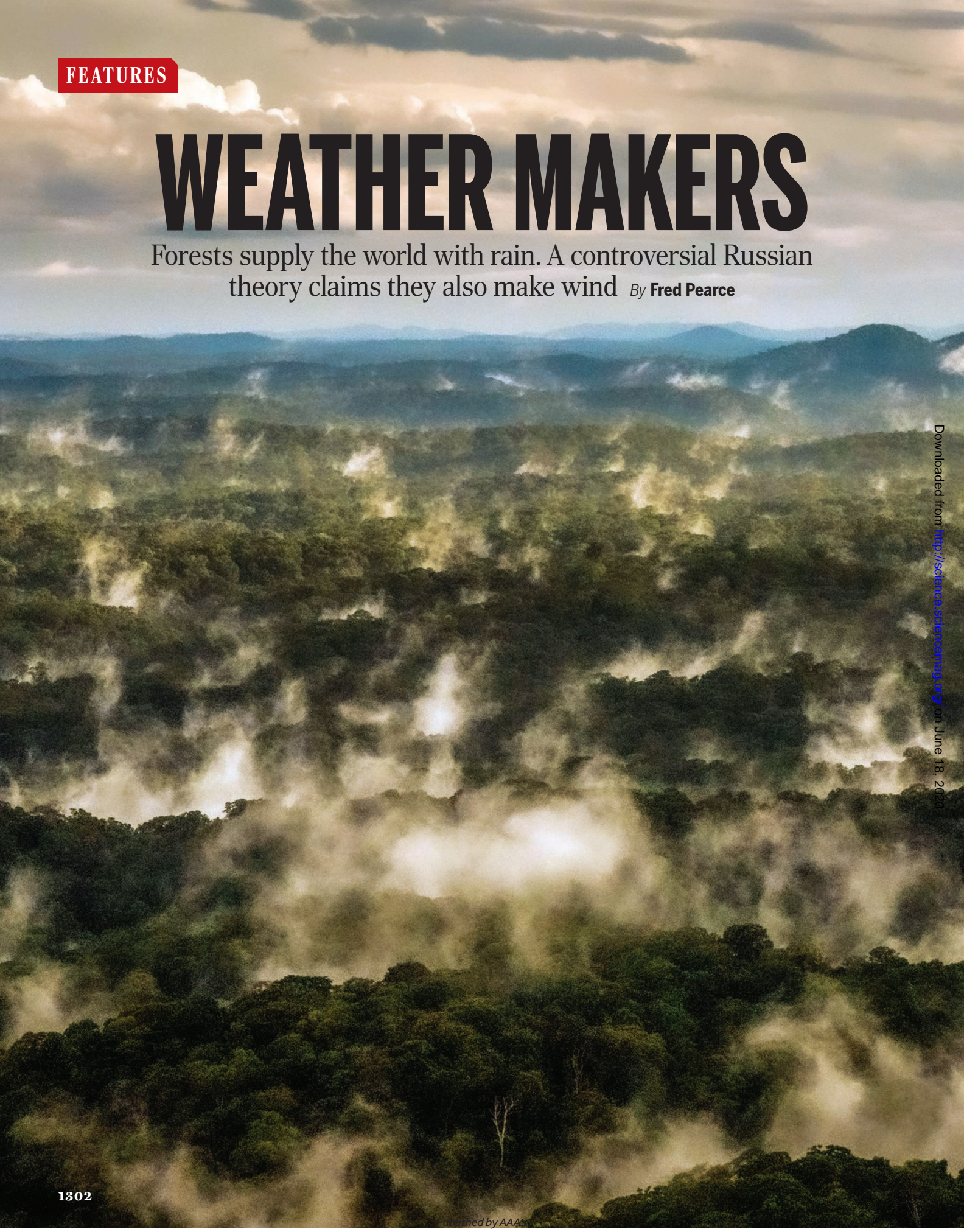


WEATHER MAKERS

Forests supply the world with rain. A controversial Russian theory claims they also make wind *By Fred Pearce*



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Every summer, as the days get long, Anastassia Makarieva leaves her lab in St. Petersburg for a vacation in the vast forests of northern Russia. The nuclear physicist camps on the shores of the White Sea, amid spruce and pine, and kayaks along the region's wide rivers, taking notes on nature and the weather. "The forests are a big part of my inner life," she says. In the 25 years she has made her annual pilgrimage north, they have become a big part of her professional life, too.

For more than a decade, Makarieva has championed a theory, developed with Victor Gorshkov, her mentor and colleague at the Petersburg Nuclear Physics Institute (PNPI), on how Russia's boreal forests, the largest expanse of trees on Earth, regulate the climate of northern Asia. It is simple physics with far-reaching consequences, describing how water vapor exhaled by trees drives winds: winds that cross the continent, taking moist air from Europe, through Siberia, and on into Mongolia and China; winds that deliver rains that keep the giant rivers of eastern Siberia flowing; winds that water China's northern plain, the breadbasket of the most populous nation on Earth.

With their ability to soak up carbon dioxide and breathe out oxygen, the world's great forests are often referred to as the planet's lungs. But Makarieva and Gorshkov, who died last year, say they are its beating heart, too. "Forests are complex self-sustaining rainmaking systems, and the major driver of atmospheric circulation on Earth," Makarieva says. They recycle vast amounts of moisture into the air and, in the process, also whip up winds that pump that water around the world. The first part of that idea—forests as rainmakers—originated with other scientists and is increasingly appreciated by water resource managers in a world of rampant deforestation. But the second part, a theory Makarieva calls the biotic pump, is far more controversial.

The theoretical foundation of the work has been published, albeit in lesser known journals, and Makarieva has received support from a small coterie of colleagues. But the biotic pump has faced a head wind of criticism, especially from climate modelers, some of whom say its effects are negligible and dismiss the idea completely. The dispute has made Makarieva an outsider: a

theoretical physicist in a world of modelers, a Russian in a field led by Western scientists, and a woman in a field dominated by men.

Yet, if correct, the idea could help explain why, despite their distance from the oceans, the remote interiors of forested continents receive as much rain as the coasts—and why the interiors of unforested continents tend to be arid. It also implies that forests from the Russian taiga to the Amazon rainforest don't just grow where the weather is right. They also make the weather. "All I have learned so far suggests to me that the biotic pump is correct," says Douglas Sheil, a forest ecologist at the Norwegian University of Life Sciences. With the future of the world's forests in doubt, "Even if we thought the theory had only a small chance of being true, it would be profoundly important to know one way or the other."

The importance of this recycled moisture for nourishing rains was largely disregarded until 1979, when Brazilian meteorologist Eneas Salati reported studies of the isotopic composition of rainwater sampled from the Amazon Basin. Water recycled by transpiration contains more molecules with the heavy oxygen-18 isotope than water evaporated from the ocean. Salati used this fact to show that half of the rainfall over the Amazon came from the transpiration of the forest itself.

By this time, meteorologists were tracking an atmospheric jet above the forest, at a height of about 1.5 kilometers. Known as the South American Low-Level Jet, the winds blow east to west across the Amazon,



Anastassia Makarieva and Victor Gorshkov developed the biotic pump theory at a nuclear physics institute.

Many meteorology textbooks still teach a caricature of the water cycle, with ocean evaporation responsible for most of the atmospheric moisture that condenses in clouds and falls as rain. The picture ignores the role of vegetation and, in particular, trees, which act like giant water fountains. Their roots capture water from the soil for photosynthesis, and microscopic pores in leaves release unused water as vapor into the air. The process, the arboreal equivalent of sweating, is known as transpiration. In this way, a single mature tree can release hundreds of liters of water a day. With its foliage offering abundant surface area for the exchange, a forest can often deliver more moisture to the air than evaporation from a water body of the same size.

about as fast as a racing bike, before the Andes Mountains divert them south. Salati and others surmised the jet carried much of the transpired moisture, and dubbed it a "flying river." The Amazon flying river is now reckoned to carry as much water as the giant terrestrial river below it, says Antonio Nobre, a climate researcher at Brazil's National Institute for Space Research.

For some years, flying rivers were thought to be limited to the Amazon. In the 1990s, Hubert Savenije, a hydrologist at the Delft University of Technology, began to study moisture recycling in West Africa. Using a hydrological model based on weather data, he found that, as one moved inland from the coast, the proportion of the rainfall that came from forests grew,

reaching 90% in the interior. The finding helped explain why the interior Sahel region became dryer as coastal forests disappeared over the past half-century.

One of Savenije's students, Ruud van der Ent, took the idea further, creating a global model of airborne moisture flow. He combined observational data on rainfall, humidity, wind speed, and temperature with theoretical estimates of evaporation and transpiration to create the first model of moisture flow at scales larger than river basins.

In 2010, van der Ent and his colleagues reported the model's conclusion: Globally, 40% of all precipitation comes from the land rather than the ocean. Often it is more. The Amazon's flying river provides 70% of the rain falling in the Río de la Plata Basin, which stretches across southeastern South America. Van der Ent was most surprised to find that China gets 80% of its water from the west, mostly Atlantic moisture recycled by the boreal forests of Scandinavia and Russia. The journey involves several stages—cycles of transpiration followed by downwind rain and subsequent transpiration—and takes 6 months or more. "It contradicted previous knowledge that you learn in high school," he says. "China is next to an ocean, the Pacific, yet most of its rainfall is moisture recycled from land far to the west."

IF MAKARIEVA IS CORRECT, the forests supply not just the moisture, but the winds that carry it.

For a quarter-century, she worked with Gorshkov, initially as his pupil, at PNPI—part of Russia's foremost civil and military nuclear research agency, the Kurchatov Institute. They were mavericks from the start, studying ecology in a place full of physicists who use neutron beams from nuclear reactors to study materials. As theorists, she says, they had "exceptional freedom of research and thought," pursuing atmospheric physics wherever it took them. "Victor taught me: Do not be afraid of anything," she says.

In 2007, in *Hydrology and Earth System Sciences*, they first outlined their vision for the biotic pump. It was provocative from the outset because it contradicted a long-standing tenet of meteorology: that winds are driven largely by the differential heating of the atmosphere. When warm air rises, it lowers the air pressure below it, in effect creating space at the surface into which air moves. In summer, for example, land surfaces tend to heat faster and draw in moist breezes from the cooler ocean.

Makarieva and Gorshkov argued that a second process can sometimes dominate. When water vapor from forests condenses

into clouds, a gas becomes a liquid that occupies less volume. That reduces air pressure, and draws in air horizontally from areas with less condensation. In practice, it means condensation above coastal forests turbocharges sea breezes, sucking moist air inland where it will eventually condense and fall as rain. If the forests continue inland, the cycle can continue, maintaining moist winds for thousands of kilometers.

The theory inverts traditional thinking: It is not atmospheric circulation that drives the hydrological cycle, but the hydrological cycle that drives the mass circulation of air.

Sheil, who became a supporter of the theory more than a decade ago, thinks of it as an embellishment of the flying river idea. "They are not mutually exclusive," he says. "The pump offers an explanation of the power of the rivers." He says the biotic pump could explain the "cold Amazon paradox." From January to June, when the Amazon Basin is colder

"We need new international hydrological agreements to maintain the forests of source regions."

Lan Wang-Erlandsson, Stockholm University

than the ocean, strong winds blow from the Atlantic to the Amazon—the opposite of what would be expected if they resulted from differential heating. Nobre, another early acolyte, enthuses: "They don't start with data, they start with first principles."

Even those who doubt the theory agree that forest loss can have far-reaching climatic consequences. Many scientists have argued that deforestation thousands of years ago was to blame for desertification in the Australian Outback and West Africa. The fear is that future deforestation could dry up other regions, for example, tipping parts of the Amazon rainforest to savanna. Agricultural regions of China, the African Sahel, and the Argentine Pampas are also at risk, says Patrick Keys, an atmospheric chemist at Colorado State University, Fort Collins.

In 2018, Keys and his colleagues used a model, similar to van der Ent's, to track the sources of rainfall for 29 global megacities. He found that 19 were highly dependent on distant forests for much of their water supply, including Karachi, Pakistan; Wuhan and Shanghai, China; and New Delhi and Kolkata, India. "Even small changes in precipitation arising from upwind land-use change could have big impacts on the fragility of urban water supplies," he says.

Some modeling even suggests that by removing a moisture source, deforestation could alter weather patterns beyond the paths of flying rivers. Just as El Niño, a shift in currents and winds in the tropical Pacific Ocean,

is known to influence weather in faraway places through "teleconnections," so, too, could Amazon deforestation diminish rainfall in the U.S. Midwest and snowpack in the Sierra Nevada, says Roni Avissar, a climatologist at the University of Miami who has modeled such teleconnections. Far-fetched? "Not at all," he says. "We know El Niño can do this, because unlike deforestation, it recurs and we can see the pattern. Both are caused by small changes in temperature and moisture that project into the atmosphere."

Lan Wang-Erlandsson, who researches interactions between land, water, and climate at Stockholm University, says it's time for water resource managers to shift their focus from water and land use within a river basin to land-use changes occurring outside it. "We need new international hydrological agreements to maintain the forests of source regions," she says.

Two years ago, at a meeting of the United Nations Forum on Forests, a high-level policy group on which all governments sit, David Ellison, a land researcher at the University of Bern, presented a case in point: a study showing that as much as 40% of the total rainfall in the Ethiopian highlands, the main source of the Nile, is provided by moisture recycled from the forests of the Congo Basin. Egypt, Sudan, and Ethiopia are negotiating a long-overdue deal on sharing the waters of the Nile. But such an agreement would be worthless if deforestation in the Congo Basin, far from those three nations, dries up the moisture source, Ellison suggested. "Interactions between forests and water have been almost entirely ignored in the management of global freshwater resources."

The biotic pump would raise the stakes even further, with its suggestion that forest loss alters not just moisture sources, but also wind patterns. The theory, if correct, would have "crucial implications for planetary air circulation patterns," Ellison warns, especially those that take moist air inland to continental interiors.

THE THEORY'S SUPPORTERS are a minority. In 2010, Makarieva, Gorshkov, Sheil, Nobre, and Bai-Lian Li, an ecologist at the University of California, Riverside, submitted what was meant to be a landmark description of the biotic pump to *Atmospheric Chemistry and Physics*, a major journal with open peer review. Titled "Where Do Winds Come From?" the paper faced a barrage of criticism online, and it took the journal many months to find two scientists willing to review it. Isaac Held, a meteorologist at Princeton University's Geophysical Fluid Dynamics Laboratory, finally volunteered—and rec-

ommended rejection. “This is not a mysterious effect,” he says. “It is small and included in some atmospheric models.” Critics said the expansion of air from heat released when water vapor condenses counteracts the space-creating effect of condensation. But Makarieva says the two effects are spatially separate, with the warming effect happening aloft, and the pressure drop of condensation occurring closer to the surface, where it generates the biotic wind.

The other reviewer was Judith Curry, then an atmospheric physicist at the Georgia Institute of Technology, who has long had concerns about the atmospheric dynamics at the core of climate models. She felt it was important to publish the paper and says the standoff was “very bad for climate science, which badly needs an infusion from hardcore physicists.” After 3 years of debate, the journal’s editor overruled Held’s recommendation and published the paper, saying it

was published “not as an endorsement” but “to promote continuation of the scientific dialogue on the controversial theory [that] may lead to disproof or validation.”

Since then, there has been neither validation nor disproof, but largely a standoff. Gavin Schmidt, a climate modeler at Columbia University, says, “It’s simply nonsense.” The authors’ responses to criticisms were “really just mathematics that gave no one any confidence that there was any point in continuing the dialogue.” Jose Marengo, a meteorologist in Brazil and head of the National Centre for Monitoring and Warning of Natural Disasters, says: “I think the pump exists, but it’s very theoretical right now. The climate model community hasn’t embraced it, but the Russians are the best theoreticians in the world, so we need proper field experiments to test it.” Yet no one, including Makarieva, has yet proposed clearly what such a test might look like.

For her part, Makarieva is building on the theory, arguing in a series of recent papers that the same mechanism can affect tropical cyclones, which are driven by the heat released when moisture condenses over the ocean. In a 2017 paper in *Atmospheric Research*, she and her colleagues proposed that biotic pumps set up by the forests on land draw moisture-rich air away from the cyclone nurseries. This, she says, might explain why cyclones rarely form in the South Atlantic Ocean: The Amazon and Congo rainforests between them draw so much moisture away that there is too little left to fuel hurricanes.

Kerry Emanuel, a leading hurricane researcher at the Massachusetts Institute of Technology, says the proposed effects “while not negligible are very small.” He prefers other explanations for the lack of South Atlantic hurricanes, such as the region’s cool waters, which send less moisture into the air, and its strong shearing winds, which disrupt cyclone formation. Makarieva is equally dismissive of the traditionalists, saying some of the existing theories for hurricane intensity “conflict with the laws of thermodynamics.” She has another paper on the topic under peer review at the *Journal of the Atmospheric Sciences*. “We are concerned that, despite the editor’s encouragement, our work will get rejected once again,” she says.

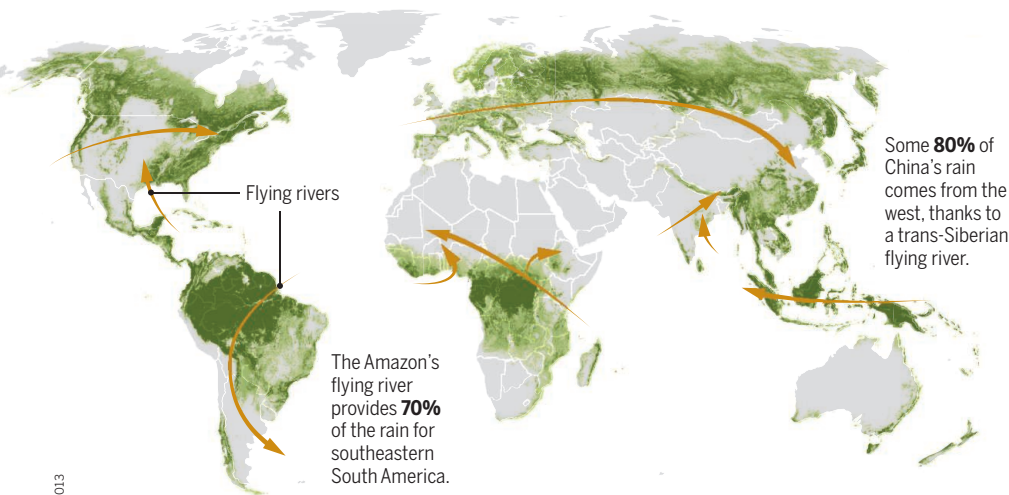
Even if Makarieva’s ideas are fringy in the West, they are taking root in Russia. Last year, the government began a public dialogue to revise its forestry laws. Aside from strictly protected areas, Russian forests are open to commercial exploitation, but the government and the Federal Forestry Agency are considering a new designation of “climate protection forests.” “Some representatives of our forest department got impressed by the biotic pump and want to introduce a new category,” she says. The idea has the backing of the Russian Academy of Sciences. Being part of a consensus rather than the perennial outsider marks a change, Makarieva says.

This summer, the coronavirus lockdown put the kibosh on her annual trip to the northern forests. Back in St. Petersburg, she has settled down to respond to yet another round of objections to her work from anonymous peer reviewers. She insists the pump theory will ultimately prevail. “There is a natural inertia in science,” she says. With a dark Russian humor, she invokes the words of the legendary German physicist Max Planck, who is said to have once remarked that science “advances one funeral at a time.” ■

Fred Pearce is a journalist in London.

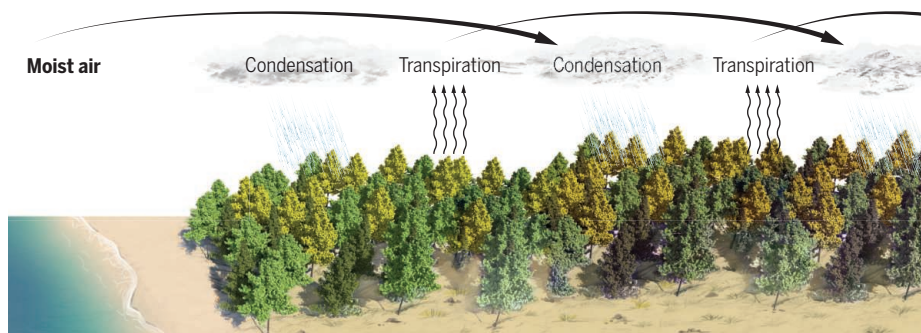
Rain parades

So-called flying rivers are prevailing winds that pick up water vapor exhaled by forests and deliver rains to distant water basins. A controversial theory suggests forests themselves drive the winds (bottom).



Sowing the wind

The biotic pump theory suggests forests not only make rain, but also wind. When water vapor over coastal forests condenses, it lowers air pressures, creating winds that draw in moist ocean air. Cycles of transpiration and condensation can set up winds that deliver rains thousands of kilometers inland.



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Weather makers

Fred Pearce

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