Several storms merge into a “mesoscale convective system” over the resort town of Villa Carlos Paz, Argentina, December 2018. Mitch Dobrowner for The New York Times

What’s Going on Inside the Fearsome Thunderstorms of Córdoba Province?

Scientists are studying the extreme weather in northern Argentina to see how it works — and what it can tell us about the monster storms in our future.

By Noah Gallagher Shannon
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When he thought back to the late-December morning when Berrotarán was entombed in hail, it was the memory of fog that brought Matias Lenardon the greatest dread. He remembered that it had drifted into the scattered farming settlement in north-central Argentina sometime after dawn. Soon it had grown thicker than almost any fog the young farmer had seen before. It cloaked the corn and soybean fields ringing the town and obscured the restaurants and carnicerias that line the main thoroughfare. He remembered that the fog bore with it the cool mountain air of the nearby Sierras de Córdoba, a mountain range whose tallest peaks rise abruptly from the plains just to the town's northwest. Like any lone feature in flat country, the sierras had long served as lodestar to the local agricultural community, who kept a close watch on them for signs of approaching weather. But if Lenardon or anyone else in Berrotarán thought much of the fog that morning in 2015, it was only that it obscured their usual view of the peaks.

At the time, Lenardon was at the local radio station, where he moonlighted as the town's weather forecaster. It was a role the 22-year-old had inherited, in some sense, from his grandfather Eduardo Malpassi, who began recording daily weather observations in a family almanac almost 50 years before. Like many farmers in Córdoba Province, Lenardon had learned from older generations how to read the day's advancing weather according to a complex taxonomy of winds and clouds that migrated across the pampas — the vast pale grasslands that blanket much of the country's interior. If the winds turned cool as the day wore on, Lenardon knew it meant rain, brought north from Patagonia. More troubling were the winds that blew in wet and hot from the northwest — off the sierras.

As forecaster, Lenardon's chief concern was identifying weather patterns that might breed a thunderstorm, which on the pampas are notoriously swift and violent. Few official records are kept in Córdoba and the surrounding regions, but over the previous two years alone, newspapers reported that hail, flooding and tornadoes had damaged or razed thousands of acres of cropland, displaced more than five thousand people and killed about a dozen. Locals described barbed hailstones, shaped like medieval flails, destroying buildings and burying cars up to the hoods. Lenardon’s own family had lost their entire harvest to flooding three of the last five years, forcing them at one point onto state assistance. People in Berrotarán spent much of their summer bracing for the atmosphere to explode; the fire department had recently taken to standing at the ready with rescue equipment and heavy machinery, in hopes of getting a jump on digging people out of debris. Even so, Lenardon didn’t think much of the fog when he first saw it. The cool, moist air didn’t indicate anything, as far as he knew, except a welcome relief from the heat.

A supercell thunderstorm forming over ranchland near La Carlota, Argentina. Mitch Dobrowner for The New York Times

As Lenardon prepared to leave the station, he pulled up the feed from the region's lone radar dish in the nearby city of Córdoba, more out of habit than anything else. When the radar completed its 15-minute sweep, a massive red splotch flashed on the screen — a powerful storm appeared to be bearing down on them. Convinced it was a glitch, Lenardon raced outside to check the sky — forgetting in his panic that it was shrouded by fog. While the fog had little meteorological effect on the storm, it had nonetheless ensured that it would be maximally destructive. "No one could feel the wind," he said. "No one could see the sierras." Though he rushed to go live on the radio, it was already 9 a.m. by the time he issued a severe storm warning for 9:15.

The storm descended quickly. It engulfed the western side of Berrotarán, where winds began gusting at over 80 m.p.h. Soon, hail poured down, caving in the roof of a machine shop and shattering windshields. In 20 minutes, so much ice had begun to accumulate that it stood in the street in mounds, like snowdrifts. As the hail and rain continued to intensify, they gradually mixed into a thick white slurry, encasing cars, icing over fields and freezing the town’s main canal. With the drainage ditches filled in and frozen, parts of the town flooded, transforming the dirt roads into surging muddy rivers. Residents watched as their homes filled with icy water.

At home, Lenardon went back over his forecast, searching for what he had missed. “When you don’t have a sophisticated forecast system,” he said, “everyone is afraid of future storms.”

Lenardon and I met in early December 2018, at the height of summer storm season, in the resort town of Villa Carlos Paz, about a two-hour drive north of Berrotarán. A short and friendly man with large, inquisitive black eyes and the molded frame of a rugby player, he wore a polo shirt and carried with him a backpack full of weather books and records. We were seated together in a hotel suite, where Lenardon was spending the day meeting with a group of government and university scientists who are funded by the National Science Foundation, NASA and the Department of Energy. The group was in the midst of a two-month field campaign chasing the storms of the Sierras de Córdoba, and asked for Lenardon to join them.

The invitation had come specifically from the study’s leader, a 43-year-old severe-weather expert named Steve Nesbitt, who after learning of Lenardon’s story had driven several hours to meet him. A veteran of storm-chasing campaigns in Nepal, India and the Pacific, Nesbitt had developed a habit over the years of enlisting local sources.

He found their stories often contained information that satellites missed or couldn’t perceive — how the contour of the land influenced clouds, how a storm might suddenly change directions in open country. In the case of the sierras, Nesbitt also knew that stories like Lenardon’s represented some of the only existing in-situ data on the storms. Few, if any, scientists had ever observed them up close.

Wisps of “scud,” a sign of a developing thunderstorm near Canals, Argentina. Mitch Dobrowner for The New York Times

Nesbitt, who is a professor at the University of Illinois at Urbana-Champaign, had dedicated much of the last 15 years to studying the freakish storms of this sleepy agricultural region. He first became fascinated by them in the early 2000s, when a NASA satellite tentatively identified them as the largest and most violent on Earth. “We knew about the Great Plains, the Sahel,” Nesbitt said. But this appeared to be another world. Radar images suggested cloud structures dwarfing those of Tornado Alley or Ganges Plain, many of them materializing in as little as 30 minutes. (Thunderstorms typically develop over the course of several hours.) And yet in the years since, little reliable data had emerged. Many in the meteorological community felt the storms were simply too remote and too dangerous for controlled study. “The only thing the science community knew for certain,” Nesbitt said, “was that these things were monsters.”

Nesbitt had traveled to Córdoba Province because he felt the weather patterns might offer clues into the enduring riddle of why certain storms grew unexpectedly into cataclysms. In the United States, which is home to the most extensive weather forecasting infrastructure in the world, around a third of severe weather predictions still prove wrong — not only about timing and location but also size, duration and intensity. The false-alarm rate for tornadoes continues to hover at about 70 percent, while the average warning time has only increased from about 10 minutes in the mid-1990s to 15 minutes today. Satellites and supercomputer modeling have greatly improved the detection of large-scale phenomena — uncertainty about a hurricane’s path at 48 hours out, for example, has decreased by 30 percent since Katrina — but the more routine, and nevertheless destructive, storms that impact rural provinces and towns continue to erupt with little warning. Today few countries outside the United States and Western Europe even attempt to forecast extreme weather. In a place like Córdoba, prediction has often fallen to amateurs like Lenardon, who, tasked with the safety of their communities, must puzzle from the air what the sparse and unreliable infrastructure misses.

But it was a job that had grown considerably more difficult in recent years. As Lenardon explained to Nesbitt, the region was beginning to see ever more storms escalate in both size and intensity. “Before, it was impossible for me to imagine more than one damaging storm a year,” he said. “Now I expect three or four.” For Nesbitt, it was exactly these abnormal qualities of growth and destructiveness that made the sierras instructive. He believed that if he could chance a closer look inside one of the superstorms — mapping its internal wind structure and the conditions that gave it life — he might be able to produce a blueprint for predicting others like it, in Argentina and worldwide. “Climate-change models are predicting all this bad weather," Nesbitt said. "But no one knows exactly what that weather will look like." In Córdoba, he thought he'd discovered a laboratory for studying it — a rugged, poorly mapped swath of ground the size of Wisconsin, which might offer a glimpse of the storms to come.

If storm forecasting may seem the province of banal TV broadcasts, it's only because its routine accuracy now underpins so much of modern civilization's stability and abundance — not just in the evasion of disasters but also the preservation of the mundane. The World Meteorological Organization estimates that preventive road closures, supply-chain rerouting and the like save the world economy more than $100 billion annually. At any given moment, our expansive global infrastructure of satellites and weather stations is working to predict around 2,000 or more storms. It is a system that, at its best, promises some semblance of order amid chaos.

Every storm is composed of the same fundamental DNA — in this case, moisture, unstable air and something to ignite the two skyward, often heat. When the earth warms in the spring and summer months, hot wet air rushes upward in columns, where it collides with cool dry air, forming volatile cumulus clouds that can begin to swell against the top of the troposphere, at times carrying as much as a million tons of water. If one of these budding cells manages to punch through the tropopause, as the boundary between the troposphere and stratosphere is called, the storm mushrooms, feeding on the energy-rich air of the upper atmosphere. As it continues to grow, inhaling up more moisture and breathing it back down as rain and hail, this vast vertical lung can sprout into a self-sustaining system that takes on many different forms. Predicting exactly what form this DNA will arrange itself into, however, turns out to be a puzzle on par with biological diversity. Composed of millions of micro air currents, electrical pulses and unfathomably complex networks of ice crystals, every storm is a singular creature, growing and behaving differently based on its geography and climate.

With so many variables at play, it became apparent to modern meteorologists that predicting storms required sampling as many as possible. The perfect repository, as it turned out, existed in the Great Plains, where many of the world's most dangerous storms are born. Here, in the spring and summer months, moist air off the Gulf of Mexico pools with dry air from the Arctic and southwestern deserts, which is all then corralled by the Rocky Mountains, forming a massive eddy. For meteorologists, this sustained volatility has made the plains the de facto national laboratory, where about 30 National Weather Service offices, tens of thousands of private radars and weather stations and hundreds of airports are sampling the air conditions before, during and after storms. Each sample, whether taken by radar or wind gauge, is a snapshot of that particular storm's behavior and composition — such as air density, pressure, temperature, humidity and wind velocity — providing meteorologists a profile to look for in the future.

Until the launch of global weather satellites in the 1990s, this level of sampling and detection wasn't widely available outside North America. When NASA deployed its Tropical Rainfall Measuring Mission in 1997, the satellite offered the first comprehensive look at the entire world's weather. And part of what it revealed was an enormous regional variability in the size and intensity of storms. In Argentina, in particular, around the Sierras de Córdoba's sliver of peaks, T.R.M.M. data detected anomalous cloud formations on a scale never seen before: 225 lightning flashes a minute, enormous hail and thunderheads reaching almost 70,000 feet.

But data from T.R.M.M. and other satellites also revealed that storms throughout the world shared many of the same microphysical properties — some of which appeared to be changing. In the last few decades, as humans have poured more and more carbon into the atmosphere, heating the land and oceans, the air has become infused with greater levels of evaporated moisture, wind shear and what meteorologists call "convective available potential energy," or CAPE — a measure of how much raw fuel for storms the sky contains. And with ever more heat, moisture and unstable air available to feed on, storms in many parts of the world have begun to exhibit increasingly erratic behavior. Since 1980, the number of storms with winds topping 155 m.p.h. — the speed at which wind starts to tear walls from buildings — has tripled; over the last few years, parts of India and the American South have flooded, with anywhere from 275 to 500 percent more rain than usual. In the oceans, where there is now 5 percent more water aloft than there was in the middle of last century, the odds of a storm spinning into a major hurricane have shot up substantially in the last 40 years. In the Eastern United States, which is projected to see a 15 percent increase in days with high CAPE values over the next century, the 2011 "super outbreak" saw 362 tornadoes kill an estimated 321 people in four days.

Still, the most disturbing trend for meteorologists isn't the violence of these supercharged storms; it's the deeper concern that entire weather patterns are becoming distorted as storms stray into new latitudes and seasons. When Cyclone Idai hit Mozambique in March 2019, hundreds of thousands were caught unprepared by its late arrival in the season. Six weeks later, when Cyclone Kenneth slammed into the same coast, becoming perhaps the strongest storm to hit Mozambique, evacuation routes and shelters were still choked with people.

But if meteorologists could broadly infer that a wetter, hotter planet was contributing to these outbreaks, what they struggled to grasp was how each storm was reacting to it. Some storms appear to metabolize changes in the climate as faster sustained wind speeds, which is why researchers at M.I.T. and Princeton now consider a Category Six hurricane a realistic possibility; others as heavier deluges of rain. Even if some basic trends appeared to be emerging, the relative rarity of extreme events, coupled with their remoteness and the fact that usable satellite data dates to only 1960 or so, meant that it was still mostly impossible to project what extremes might materialize from place to place — much less in the years to come. In 2019, a study conducted by Stockholm University found that one of the only uniform impacts of climate change was on forecasting, which has become more difficult. It all of a sudden seemed possible that humankind was losing not only the comfort of a future that looked dependably like the present, but the reliability of a stable tomorrow.

For Nesbitt and a growing cohort of young meteorologists, the chaos wrought by climate change requires radically rethinking some of meteorology’s core concepts. As a discipline, meteorology is based on the idea that the climate is a constant; within each year, season or day, only a certain number and range of variable weather events are possible. But because that constant has itself become a variable, Nesbitt thinks the field needs to take a big step back and begin again with the basics: close observations of how storms develop and behave. “We thought we knew how the climate and weather operated,” he told me. “But now we have to think more like astronomers — like we don’t know what’s out there.”

Graduate students launch a weather balloon, or a “sounding,” in the foothills of the Sierras de Córdoba, in central Argentina. Mitch Dobrowner for The New York Times

The makeshift headquarters of the study — named RELAMPAGO, an English acronym that also means “lightning” in Spanish — occupied an array of outbuildings and conference rooms spread between a sprawling white estate and high-rise hotel in downtown Villa Carlos Paz. The sierras, which loom over the west end of town, are visible from almost anywhere on the study’s two sites, impeding the horizon. When I arrived at the hotel ops-center, one afternoon in mid-December, I found Nesbitt hunched over a swirling computer model in a narrow glass-enclosed room. He is tall and thickset, with a round, dimpled chin and boyish flop of hair, and he wore cargo shorts, a short-sleeve tropical shirt and sandals. He led me through a crowded office lined with servers and computers, where grad students stood monitoring satellite images, and into a crumbling courtyard that served as an office. It had now been four or five weeks since the last rash of major storms, and the sky above us stood huge and empty, save an occasional, lonely cumulus cloud that came drifting over the sierras, carried on the unseasonably pleasant breeze.

Nesbitt had come to Argentina with the goal of chasing the region’s storms so he could get advanced imaging technology deep within them. “In every storm there are fingerprints you can see of changing processes,” he said, and if he could find them, he could begin assessing how the storms are transforming in a warmer climate. But as he began scouting the study around 2012, he quickly realized that sampling one of the most dangerous and unpredictable phenomena on Earth, in a faraway region of scattered farm towns and mountain forests, would require as much of an infrastructural endeavor as a scientific one. The National Science Foundation had at various times funded armored airplanes to penetrate storms, but its most recent iteration was plagued by technological problems, and the project was eventually scuttled; the interior dimensions of these storms remained essentially unmapped. When Nesbitt started to think about what else might be able to get him close enough to the innermost abyss of one of the sierra’s superstorms, the name of one organization came immediately to mind: the Center for Severe Weather Research.

Founded in the 1990s, by the meteorologist Joshua Wurman, C.S.W.R. is a seminomadic 11-person research institution that over the years has earned a reputation for pushing boundaries in chasing technology. In the mid-90s, Wurman built the first truck-mounted doppler radar system, nicknamed the “doppler on wheels,” or DOW. By 1999, a DOW had recorded the fastest wind speed in history within a tornado, in Moore, Okla., at 301 m.p.h. Since then, perhaps no other organization has ventured as far into the world’s deadliest tempests as C.S.W.R., whose fleet of four trucks has now transmitted data from inside 15 hurricanes and about 250 tornadoes. Piloted directly into the path of a storm, the DOWs work as any other radar does, like atmospheric flashlights: An antenna casts a conical beam outward, inching upward typically one degree at a time, to eventually produce a 3-D image of the surrounding storm, like a spelunker lighting up a cave. Raised off the ground on hydraulic feet, the trucks are able to scan in winds that might otherwise peel asphalt off a road.

As technologically advanced as the DOWs are, however, Wurman and his team are still subject to the mercurial whims of each storm; he likened the work, at times, to a wildlife biologist scouting the best time and place for an encounter with a rare species. One of Wurman's most significant contributions to the field, in fact, happened one night in Kansas when something went wrong and one of his DOWs was hit by a tornado, exploding one of its windows. It was one of the best data sets they'd ever collected. In the sierras, Wurman and Nesbitt didn't know if they would be so lucky. Given the limited information about conditions upstream in the Pacific, South Atlantic and Amazon — which are all relative blank spots on the weather map — the chasers were left somewhat blind downstream. It was a challenge that, while complicated and potentially dangerous, didn't necessarily faze the seasoned Wurman. "If we could forecast these storms perfectly," he said, "there'd be no point in chasing them."

A few days later, the doldrums finally relented. The forecasters began to pick up on something promising in the Pacific: For the last several days, a trough of low-pressure air had been amassing, rolling steadily eastward toward the Andes. At the same time, humidity levels from weather balloons in the province indicated a low-level jet stream was bringing moisture out of the Amazon. On the morning of Dec. 12, the study forecasters reported that the two systems, along with another pocket of dry air moving north from Patagonia, seemed poised to converge over Córdoba sometime in the next few days. By the evening, values of CAPE and humidity started to spike in ominous ways. With many of the scientists getting ready to head home, the coming storm would in all likelihood be the study’s last big chase. That evening, as many retired for the long day ahead, a few drank wine and watched “Twister.”

Steve Nesbitt in front of the Center for Severe Weather Research’s C-band doppler on wheels, possibly the largest mobile radar system in the world. Mitch Dobrowner for The New York Times

In the morning, teams were on the road well before 7 o’clock, headed for a rural grid of farm roads four or five hours south of Villa Carlos Paz. The three DOWs stationed themselves at the points of a roughly 1,500-square-mile triangle — the hope being that their overlapping scans would form a vast enough atmospheric net to catch the storm. The remaining six trucks fanned out, positioning to launch weather balloons and drop off pods: ruggedized weather stations that resemble an air-conditioning unit. Most parked in dirt pull-offs along irrigation ditches, or in vacant gravel lots, careful to avoid depressions that might flood, as well as silos and trees, which might block radars, snag balloons or splinter into debris. With little to do but wait, the teams passed the next hours texting photos of clouds and making runs for gas-station empanadas.

Around 6 p.m., Angela Rowe, an assistant professor at the University of Wisconsin-Madison who was running the day’s operations, radioed from the ops center that several storms were tracking on a northeast bearing toward the triangle. Soon those of us who were in the field watched as the skies before us transformed. Clouds along the leading edge of the northernmost storm flattened, sending down graying tendrils of haze that brushed along the ground. Far above, the blackening core of the storm started bubbling, roiling skyward like an overflowing pot of pasta. The temperature plummeted and spiked wildly, the air detonating with erratic blasts of dust and rain. As night fell, lightning began coursing through the approaching sky, outlining the storm’s contorting shape in stenciled flashes. By 9 p.m., the wind began to pitch team members sideways, forcing them to dart back and forth between trucks, screaming to be heard as they wrestled to inflate balloons and place pods.

For the next few hours, as the teams worked to stay ahead of the wind and hail, all the storms appeared to push steadily northward, as predicted. But at some point, currents of swollen black clouds overtook us, rippling outward in every direction. Soon no one could tell exactly where each storm began or ended, or in what direction they were moving. Parts of the sky seemed to be eddying in place, flashing a ghostly pale green, the color of a dirty aquarium; while others appeared to be streaming back the way we came, pouring rain in steady, even sheets. By 11 p.m., the power in much of the province had gone out, and the sky’s seething black mass had all but collapsed the horizon, making it impossible to navigate except during the most brilliant flashes. At one point, we sped away from a tangle of lightning, which lit up the forest around us in noonday light, only to find another road impassable with windblown debris, another with standing water.

An hour or so later, we were on an empty four-lane highway, making our way to another team, when it was suddenly raining and hailing much harder. The whirling core of the storm appeared to be bearing down on us: The corkscrewing center had been drawing up millions of pounds of moisture until, around 30,000 feet, it froze, eventually hurtling back to earth as mammoth hail. The stones started reporting on the vehicle's steel frame so loudly they momentarily drowned out the wind in a concussive drumming. Then another massive downpour erupted, obscuring even the nearest taillights. It sounded like an airliner and, when it subsided, a stream of murky water was rushing over the highway. Inching along, I watched as the blinking shapes of floating cars, like ducks, were swept into the median and shoulder.

At 1 a.m., the order came to evacuate. One of the support trucks had already been winched out of a field in the mountains; another's antenna bent 90 degrees. Over the next four hours, the teams made their way carefully over roads washed-out and clotted with debris. Downed electrical wires whipped frantically. A roof lay upside down in a cornfield. People stood huddled under tollbooth awnings warning of stones falling from the sky. As we passed over a bridge in Córdoba, the sky lit up, illuminating a neighborhood heaped with fallen trees. Further out in the province, a hospital and three schools had been damaged by a tornado, which also threw two trucks into an outbuilding. One woman, who was 23 and eight months pregnant, was later reported to have died in her flooded home. In our vehicle, we hardly spoke. There was the sense, after witnessing the unforeseen, of the unimaginable expanding.

Cloud-Inflow. A supercell thunderstorm punches into the stratosphere, outside Monte Maíz, Argentina.
Mitch Dobrowner for The New York Times

In the hours after the storm passed, Nesbitt, Wurman and the others tried to figure out what they had seen. By the time the last trucks pulled in, around 5:30 a.m., the storm had raged unabated for more than six hours. At its peak, it stretched from the Andes to the Atlantic. Parts of it, now already drifting into Brazil, were so powerful they’d briefly become self-sustaining, the clouds feeding on their own heat and moisture — a destructive phenomenon meteorologists call “back-building.” Local agencies would spend the next few months trying to assess the extent of the damage, but it appeared to already include entire neighborhoods across the province. In the hotel, the mood among the meteorologists, many of whom were in their 24th hour of monitoring, was delirious. Unable to return to their flooded rooms, a few retired to the hotel restaurant, where distant lightning fields stood visible out the windows.

One event in particular drew the meteorologists' attention. For most of the evening, scans had shown a staggered line of storms marching steadily northward. Then, around 11:15 or so, something strange flashed on the satellite feed: a single, bulbous mass, which appeared suddenly, covering much of the image field. "This whole huge line just popped up," said Kristen Rasmussen, one of the principal investigators of RELAMPAGO and an assistant professor at Colorado State University. "It could tell us a lot," she said. "It was exactly what we were hoping for."

To elaborate, Nesbitt explained that as a storm travels along hot, saturated ground, its base tends to spread out and flatten, sucking up all available energy. The more it draws in, the faster and stronger the vacuum becomes, forming a narrow shaft of rushing air at the center of the storm, or updraft. An updraft, as Nesbitt went on, is essentially the storm's piston, drawing heat and moisture in like gas into a crankshaft, before firing it upward, fueling the storm's growth and movement. From what the team could gather, each of the storms had generated such large, powerful updrafts that they'd eventually merged together and begun to spawn other, smaller updrafts, creating what's called a "mesoscale convective system" — in short, a giant, organized complex of perhaps 50 or more updrafts, which becomes self-sustaining as it germinates more and more offspring. Most M.C.S.s on the Great Plains take about four or five hours to form; this one, according to time stamps, materialized in less than 30 minutes.

When Nesbitt and the others began combing through the scans and data, they found that several of the other storms they'd observed in Argentina had formed similarly strong updrafts — many of them as much as 60 percent larger than those in North American storms. One had reached over 69,000 feet, among the tallest ever documented. Others covered more than 15 square miles — a massive plume of air surging upward at more than 150 m.p.h. Based on the initial DOW scans, Nesbitt could infer that the scale and strength of the updrafts were a major source of the storms' violence. As winds within the updrafts began to widen and intensify, they not only gathered more moisture and heat, feeding the storms' growth, but also held that volatile mixture aloft, potentially turning it deadly. Suspended this way, at 30,000 feet or so, for several minutes or longer, the mixture froze, forming vast fields of tumbling ice crystals, which, given enough space and time, collided repeatedly, sparking lightning, or gradually congealing into enormous hailstones.

Maria Natividad Garay holds a hailstone she recovered outside her home in Villa Carlos Paz, Argentina.
Mitch Dobrowner for The New York Times

This finding seemed to suggest that something in the atmosphere was supercharging updrafts — wrenching heat and moisture off the ground so violently that it spun into unusually broad and towering pillars of air. To Nesbitt, the obvious culprit, at least in theory, was the heat and moisture itself — the storm’s fuel. As the atmosphere has continued to warm, lofting ever more moisture into the air, it has also begun to expand, increasing the air’s capacity to absorb ever greater volumes of moisture, not unlike a gas tank that grows in size as you pump more gas into it. And because water produces heat as it condenses at altitude, the added moisture accelerates the process further. Based on the study’s local weather stations — one of which was erected on the farmer Lenardon’s land — Nesbitt knew that the atmosphere in the province was already demonstrating signs of this cycle, including spikes in evaporative moisture. But as he pointed out, moisture and heat are merely values of potential energy. They tell us that the sky, like our drying forests, is rapidly becoming an ocean of fuel, but they don’t tell us where and when it might ignite — much less what, exactly, might spark it.

Finding answers to those questions, as Nesbitt saw it, required mapping updrafts in much more intricate detail. For years, the most prevalent models used to forecast global weather patterns, he explained, had relied on relatively simple mathematic calculations — or “parameterizations” — to predict where and when a storm might form. Programmed to predict some of the largest and most damaging effects of a storm, such as wind and rain, the parameters often failed to render the full complexity of a storm’s development, including the formation of its updraft, resulting in a loss of overall accuracy. “Now we’re having to go back,” said Nesbitt, “and try to add some additional realism to the calculations, so they can represent the full stages of a storm’s life cycle.”

By the time RELAMPAGO left Argentina, the study had collected nearly 100 terabytes of data from 19 separate chases. To begin the process of improving how storms are represented in models, the scientists would first have to create a profile of each storm they studied, along with all its minute microphysical features, digging through millions of points of data to separate out the effects of the landscape and natural fluctuations of weather from those features that might be unique to the storm. What the work amounted to was the rough meteorological equivalent of the parable of the blind men and the elephant: By July 2020, some 20 papers were in various stages of publication, each of them offering insights into different aspects of Córdoba’s storms. Ultimately, by looking at them in aggregate, the goal for Nesbitt would be to isolate what amounted to a fingerprint from a few molecules of air — air that, heated by the sun and bonded with evaporation, became the first disastrous breaths of an updraft.

Already, a simple version of RELAMPAGO's model had helped Servicio Meteorológico Nacional open the predictive window in the Córdoba Province by roughly 48 hours, Nesbitt says. Eventually, he hoped a higher-resolution version could provide similar warnings throughout the warming world — especially in the United States, where air conditions are poised to resemble those in the province in the next few decades. But for now, he contented himself with having provided families like Lenardon's a few more hours of readiness — though he wondered how long it would be until these models were rendered, once more, obsolete.

One day shortly before the end of the study, the meteorologists took me into the foothills of Villa Carlos Paz to visit a woman named Maria Natividad Garay, who had in her possession what may be one of the largest hailstones ever recovered. Her residence, which lay wedged between an apartment complex and repair shop, included a modest ranch home as well as several apartments and guesthouses, a few of which were rented to Argentine meteorologists affiliated with the study. When we arrived, Garay was sitting out back in a chair, her door left slightly ajar to the cooling breeze.

Garay is a carefully spoken woman in her mid-50s, with short brown hair and the mild, composed smile of someone long conversant with the punctuated boredom of life on the plains. Asked about the storm that produced the hail, she called up the precise date — Feb. 8, 2018 — and told me that the storm had lasted exactly 15 minutes; it was etched in her mind. She had lived in the area for nearly 30 years now, she explained, and though the region was known for storms, that was merely a thing people knew. "You have to experience it firsthand," she said.

She pointed out several long scars on the building next door, places where whole columns of bricks had been peeled away. "That was the first thing I saw," she said; "hail was hitting the wall sideways." The next instant, her skylights shattered, ice pouring into the house. The noise was incredible, she said, like a train coming through your yard — thin and distant at first, then roaring overtop of you. After the deluge stopped, she peered outside to find the yard blanketed in what looked like shards of milky glass. "It didn't rain at all until the hail stopped," she said, still surprised by the observation a year later. The meteorologists guessed this was why the stone had been so remarkably well preserved.

She held it before us. It was spherical and nearly the size of a grapefruit. She'd kept it wrapped in a Ziploc bag at the rear of her freezer. She couldn't say why, exactly, only that it had struck her as an object worthy of preservation. Its frightening size and appearance, buried there in her yard — it seemed of unearthly provenance. She leaned in and showed us the many thousands of crystals spidering through the stone, some of which were already beginning to fracture and melt in her hand.

But then again, she continued, it was just air and water. It was, in other words, composed of the same things we breathe.

The Great Climate Migration
The Teenagers at the End of the World
Destroying a Way of Life to Save Louisiana
The Fearsome Thunderstorms of Córdoba Province
Learning From the Kariba Dam

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