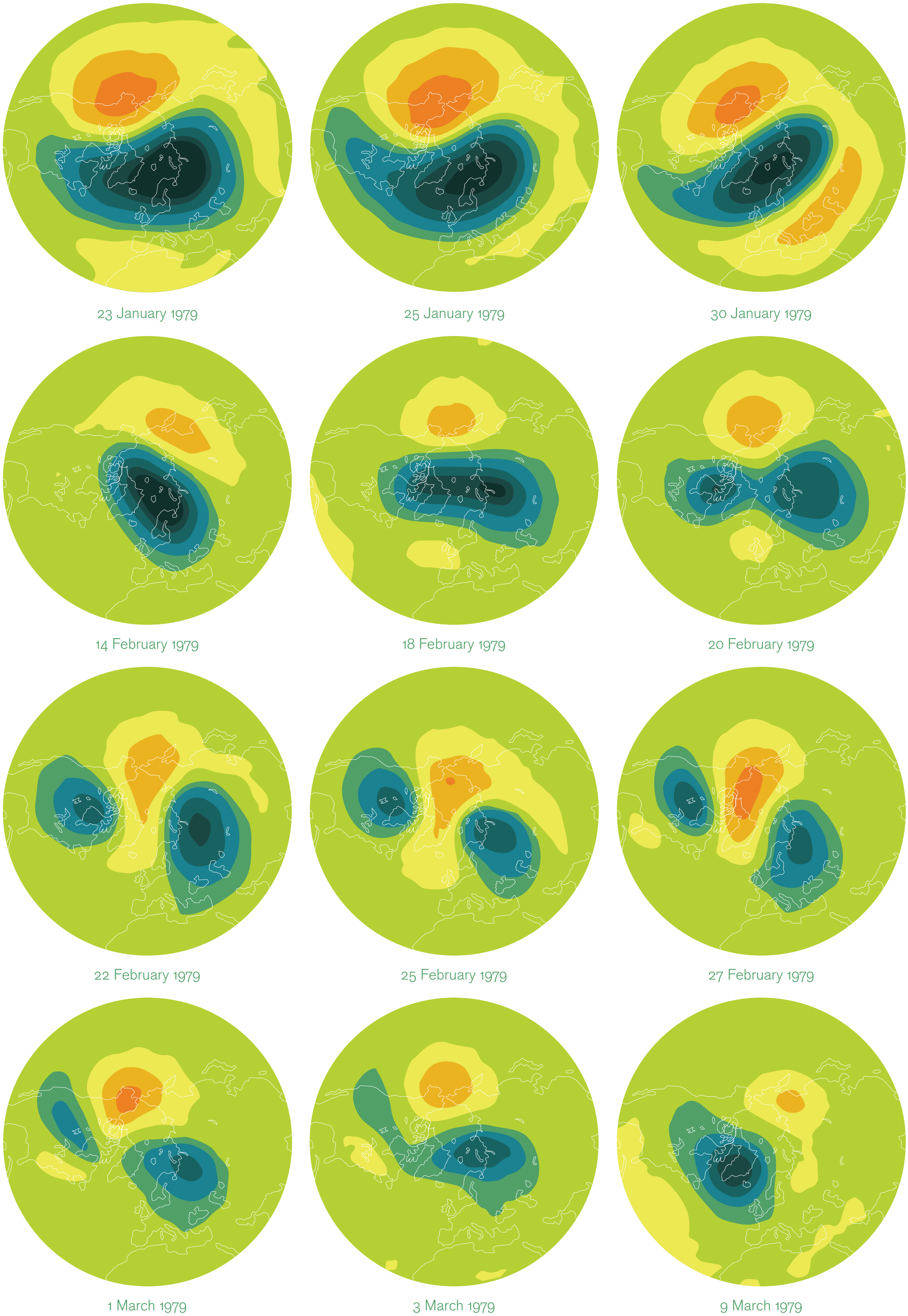
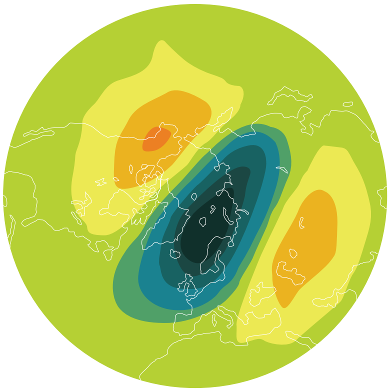


A series of images shows the development of the first Stratospheric Sudden Warming monitored by satellite, in early 1979. As the air warms, the winds that normally circle the North Pole counterclockwise switch direction. The low pressure area over the pole, in blue, distorts and splits. These warming events affect winter weather patterns on the ground. *Source: Lorenzo M. Polvani*



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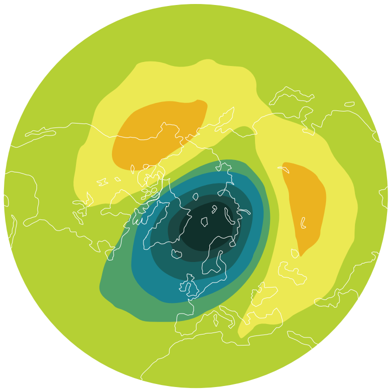

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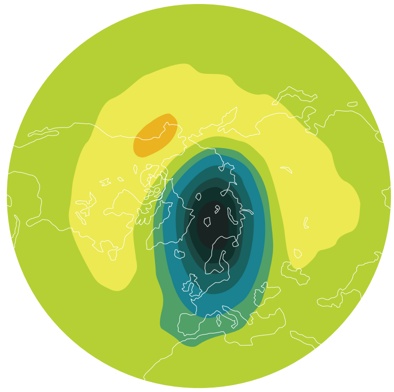
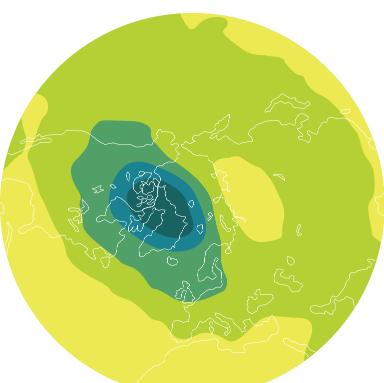


11 February 1979

Cosmic weather gauges

Particle physics joins forces with other fields to look at two important factors shaping weather: temperatures high in the atmosphere and the dampness of the dirt beneath our feet.

By Glennda Chui and Tona Kunz



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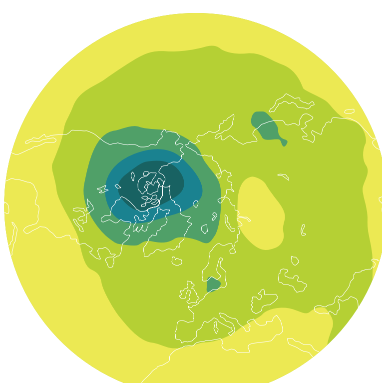

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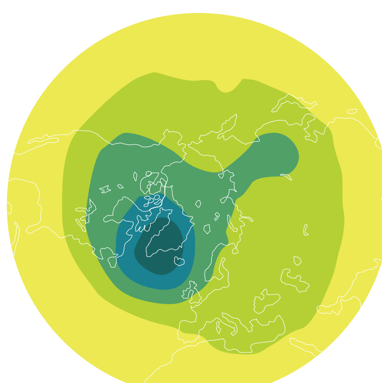


24 March 1979

Cosmic rays are everywhere and have been put to many uses. Zipping in from the far reaches of space, they bring news of some of the most explosive processes in the universe. They're a radiation hazard for astronauts, the basis of many a cool science project, and a tool for exploring ancient pyramids (see "Secrets of the Pyramids," Mar/Apr 08.)

Now they're being drafted for a new job: helping to monitor and forecast the weather.

In January, scientists announced they had found a new way to take the temperature of the lower stratosphere from a highly unlikely location: a former Minnesota iron mine half a mile underground. When they see a sudden increase in the number of cosmic ray particles arriving at a 6000-ton detector called MINOS, they know a heat wave has hit this layer of the atmosphere 20 miles above our heads—and that winter storm patterns may soon change for people on the ground.

MINOS Far Detector in Minnesota. ***Photo: Fred Ullrich, Fermilab***

"We're looking at the particles as a very strange thermometer," says particle astrophysicist Alec Habig of the University of Minnesota in Duluth, a senior scientist on the MINOS project. While taking the stratosphere's temperature is not new—it's been done for decades from weather balloons and satellites—the new technique may offer a way to independently validate those readings.

Two thousand miles away, just north of the Mexican border in Arizona's San Pedro River valley, a new type of instrument known as a "cosmic-ray soil-moisture probe" has been counting cosmic-ray neutrons that rebound out of the ground. Their intensity reveals the soil's dampness.

"Soil moisture basically controls the weather for short periods of time," says Marek Zreda, associate professor of hydrology at the University of Arizona. "It is an important prediction variable."

Based on a decade of previous research, he and other scientists plan to build COSMOS, a national network of 500 cosmic-ray detectors, starting this year. The goal is to increase the lead time for knowing when a storm or dry spell will strike from two days to as much as two weeks, and eventually to set up similar networks in other countries, linked up by 2015.

Both of these studies required the combined tools and expertise of particle physicists and scientists from other fields. The results are already feeding back into particle physics, Habig says, helping scientists understand the dynamics of cosmic ray showers.

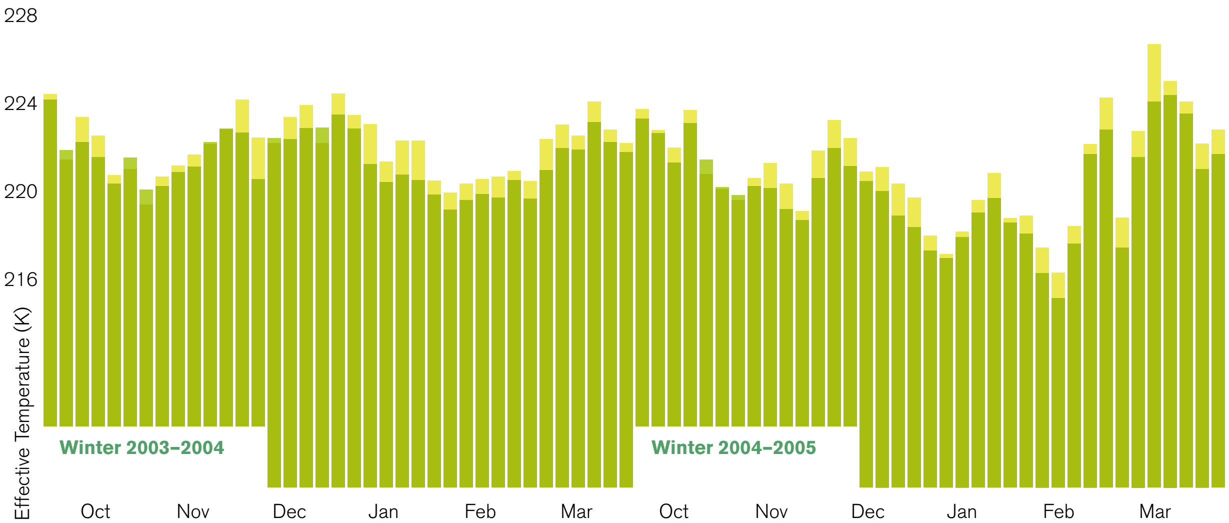
"This is something we think we can do better as result of this collaboration with atmospheric scientists than we could without them," he says. "Both the atmosphere guys and the particle guys come away with new stuff out of data that's been there all along."

Friends and foes

Cosmic ray particles originate from radioactive decay in stars, supernovae, and the sun. The most energetic ones appear to come from supermassive black holes in the centers of galaxies (see "On the trail of cosmic bullets," Oct/Nov 07.) When the rays strike our atmosphere, they create showers of other particles that pass through the average human body 600 times per minute.

From a science standpoint, cosmic rays can be a nuisance, a constant background patter of radiation

MUON RATE AND EFFECTIVE TEMPERATURE: The rate of muons coming into the MINOS detector, above, closely matches stratospheric temperatures obtained by satellites and weather balloons. The graph below compares the two types of measurement over four winters. *Source: NCAS-Climate Working Group and MINOS Collaboration*



that has to be taken into account in many measurements. On the other hand, they're a useful tool for calibrating particle detectors—something experimenters at the Large Hadron Collider on the Swiss-French border have been doing while they wait for the giant machine to start up again after repairs.

The same is true at MINOS, the Main Injector Neutrino Oscillation Search, which generates a beam of neutrinos at Fermilab in Illinois and aims it at the underground detector in Soudan, Minnesota, 450 miles away.

Eighteen months before their neutrino study started, MINOS scientists began calibrating their detector by recording the arrival of cosmic ray particles called muons.

Survival and decay

Muons don't enter deep underground detectors at a steady rate; instead the rate is slightly higher in summer and lower in winter.

The reason has to do with pions, cosmic ray particles that give rise to muons. When the atmosphere is warm it expands, leaving more space between air molecules, so pions slip through more easily and have a better chance of surviving long enough to decay into muons. When the atmosphere is cold and dense, more pions crash into other particles before they can decay, and fewer muons result.

While particle physicists have known about this seasonal fluctuation for about a decade, climate scientists were largely unaware of it, says Scott Osprey, an atmospheric scientist with the United Kingdom's National Centre for Atmospheric Science who is based at the University of Oxford. He specializes in studying the stratosphere and its impact on weather.

"My interest in this research goes back a couple of years," he says. "It came down to news reports about the effects of cosmic rays on climate. With our colleagues we discussed the flip side–what about the impact of climate on cosmic rays?"

One of Osprey's Oxford colleagues, particle physicist Giles Barr, happened to be a member of the MINOS collaboration and had access to its data. Led by Osprey, the atmospheric scientists and the particle physicists joined forces.

The MINOS Far Detector at Fermilab. ***Photo: Peter Ginter***

Trickle-down weather

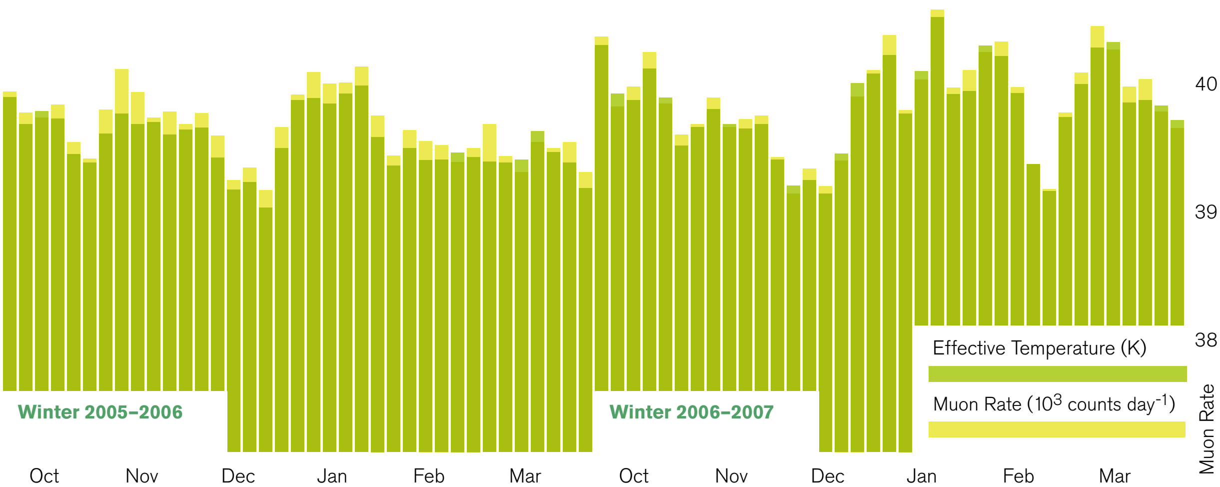
By the time they got together, MINOS had collected four years' worth of data on muons. To the scientists' surprise, the fluctuating muon rates matched the temperature of the lower stratosphere so closely that they served as a sort of long-distance thermometer.

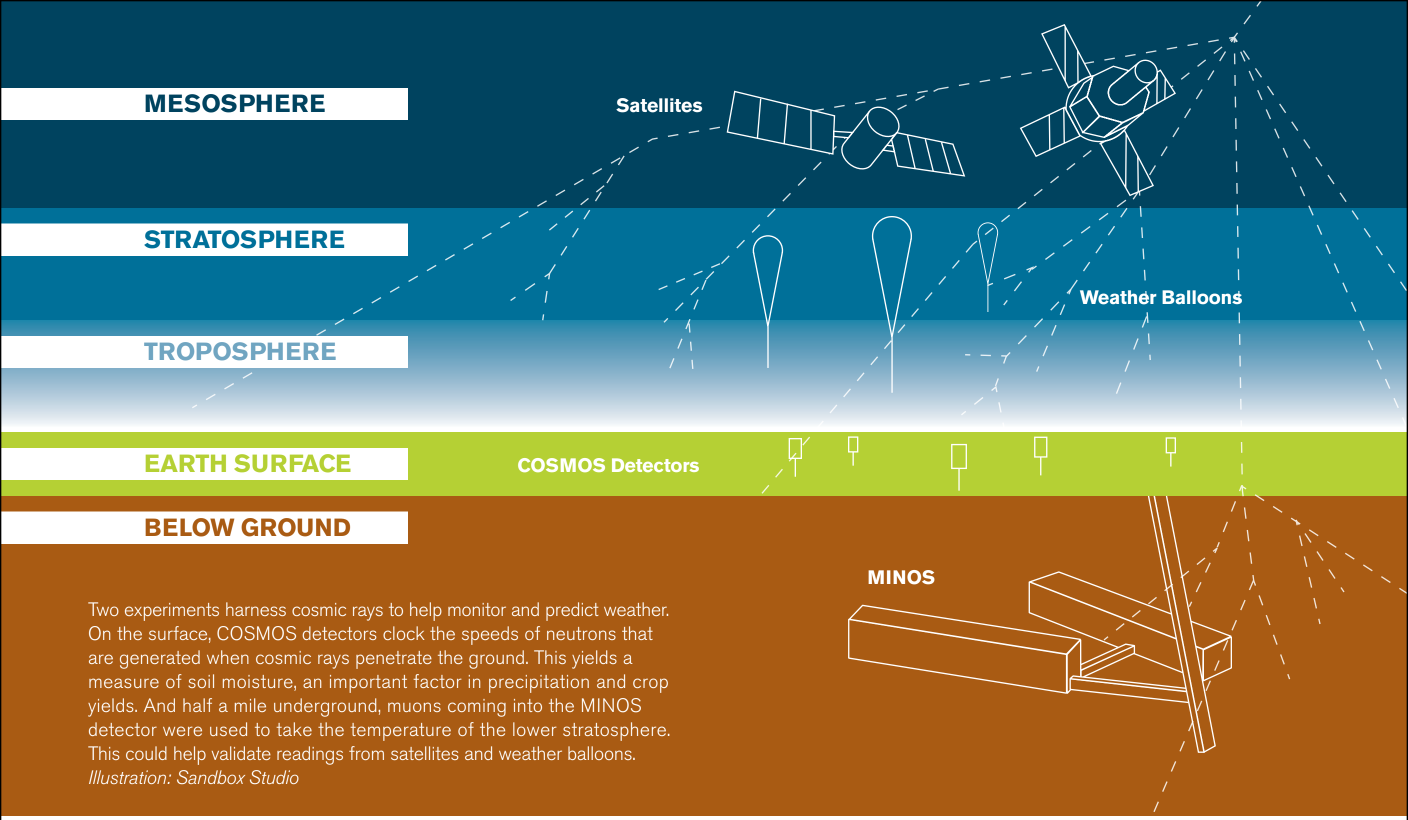
What's more, the researchers could instantly see from the data when this layer of the atmosphere warmed by as much as 40 degrees Celsius over the course of a few days, an event known as Stratospheric Sudden Warming or SSW.

These warmings occur roughly every other winter in the Northern Hemisphere; only one has ever been recorded in the South. Although each warming generally lasts about a week, its effects on weather can linger for a month or two.

The warming has a trickle-down effect on weather over a wide area.

The vortex of strong wind that normally circles the North Pole counterclockwise becomes chaotic, or even reverses direction. The blob of air over the





Two experiments harness cosmic rays to help monitor and predict weather. On the surface, COSMOS detectors clock the speeds of neutrons that are generated when cosmic rays penetrate the ground. This yields a measure of soil moisture, an important factor in precipitation and crop yields. And half a mile underground, muons coming into the MINOS detector were used to take the temperature of the lower stratosphere. This could help validate readings from satellites and weather balloons. *Illustration: Sandbox Studio*

pole—it's a low pressure area, similar to the eye of a storm—normally sits in the middle of the circling wind like the yolk of a fried egg. But in an SSW it gets pushed off to the side or even split in two.

As a result, powerful currents of air known as jet streams, which blow west to east at about the level that commercial jets fly, often shift southward, carrying storm tracks with them.

"You're shifting where the average storm would go, north or south," says Mark Baldwin, an atmospheric scientist with Northwest Research Associates in Seattle, who in 1999 published the first paper on the connection between SSWs and weather. "So it makes a big difference in whether the storms are all going to British Columbia, or whether they're going to Washington state."

Osprey says the most recent warming, an unusually strong one, started the third week of January. The temperature of the lower stratosphere shot up by 60 to 70 degrees Celsius. Meanwhile the vortex winds, which had been blowing counterclockwise at about 150 mph, switched to 70 mph clockwise. At least one forecaster, at the UK Met Office's Hadley Climate Center, has linked this stratospheric warming event to unusually cold, snowy weather in Britain.

Baldwin, who was not involved in the MINOS study, says weather is so complex, with so many interrelated factors and natural oscillations, that scientists have still not puzzled out the physics of the stratosphere-weather connection or how it might play into global climate change.

So far, though, SSWs appear to be a good thing for the Earth's protective ozone layer. The chemical reactions that destroy ozone take place in the spring, when the sun hits icy stratospheric clouds in polar regions. The colder the air, the faster those reactions bust ozone molecules apart. Sudden warming events slow this process and scatter the manmade chemicals that trigger ozone loss, promoting the healing of the ozone layer.

Finding a role

What can muons add to this picture?

"I don't particularly want to overstate what a cosmic ray detector could do," Osprey says, "because these other ways of monitoring the atmosphere are better in many respects. We'll never replace the networks of balloons and satellites" that take atmospheric temperatures today.

On the other hand, underground detectors can take data day and night, and in weather too stormy for a balloon launch. They might conceivably be used for other studies—for instance, measuring ionization levels in the atmosphere. And since scientists have been measuring various aspects of cosmic ray showers for 50 years, Osprey says, it might be possible to use those data to independently verify records of atmospheric temperatures and SSWs, which go back at least that far.

Lorenzo Polvani, an atmospheric scientist at Columbia University who was not involved in the study, says, "One of the key problems in all climate research is that we only started observing over the last few decades. If you go back 50 years, that could be useful. The more data we have the better, and if it comes from deep down in the earth, so what? It could be a validation."

As for the particle physicists, Habig says they already have a study under way that uses the muon results to get a better handle on the ratio of pions to kaons in cosmic ray showers.

Dirt, mud, and COSMOS

In a 2008 report "Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks," the National Research Council deemed one of its top priorities the establishment of a system of soil moisture and temperature probes on at least 3000 sites.

As water evaporates from the soil it cools the surrounding air; when it condenses into drops, it warms the air. This cycle affects humidity, rain and snowfall. So soil moisture is one of the factors that allow forecasters to predict short-term weather, as well as create less-definitive outlooks for precipitation and average temperatures over months or seasons.

Accurate measurements of moisture in various levels of the soil are also important for computer models that simulate how plants compete for water at different depths. This helps farmers optimize their yields and determine the most efficient irrigation patterns.

By tracking soil moisture patterns during the next 10 years and comparing them to air temperatures, researchers hope to build a data base that could help in the understanding of global climate change.

Until recently there have been two approaches to measuring soil moisture, "and both have deficiencies," says Xubin Zeng, an atmospheric scientist and director of the University of Arizona's Climate Dynamics and Hydrometeorology Center.

The COSMOS network, he says, will fill in the gaps.

A question of scale

Earth scientists now use probes stuck into the ground to measure soil moisture in small, shallow, widely scattered areas, just one meter square. At the other extreme, satellites measure average soil moisture over large areas, roughly 30 kilometers square. Neither approach provides accurate data at the in-between scale that is most useful for weather forecasting and climate prediction.

"In nature, 30 kilometers by 30 kilometers would more than cover the Tucson, Arizona, area, taking in everything from mountains to urban areas. Those areas have very different water concentrations," Zeng says. "An average over an area that size cannot be very accurate. And we have proven in studies that it is not."

In contrast, the COSMOS detectors are mounted in rectangular boxes on poles roughly four feet tall. Each one measures soil moisture over a circular area 700 meters across and 15 to 70 centimeters deep, depending on soil dampness.

Data from the COSMOS network will help NASA calibrate its Soil Moisture Active Passive satellite, or SMAP, scheduled to launch in 2012. The satellite will track global soil moisture levels and surface freezing and thawing patterns. The goal is to improve climate, flood, and drought predictions by better understanding how water, energy, and carbon cycles affect one another. The microwave emissions that SMAP uses for imaging are affected by moisture, Zreda says, so moisture data from COSMOS detectors can improve the resolution of the satellite's images.

From dates to drips

A geologist and hydrologist by training, Zreda had been using chlorine-36 isotopes to date rocks, with a goal of understanding glaciers, sand dunes, earthquakes, and other geological phenomena. These isotopes form when muons and neutrons from cosmic-ray showers hit the Earth's surface; the longer a rock is exposed, the more atoms of the isotope it accumulates. Zreda realized that any water in the rock affects the cosmic-ray neutrons, thereby affecting the rate of isotope formation.

A researcher works with a COSMOS detector at the University of Arizona's Biosphere 2 research facility. *Photo courtesy of: Marek Zreda*

That realization led him to a new way of measuring soil moisture.

It turns out that when cosmic rays penetrate the ground, they spawn another wave of particles, including so-called fast neutrons. These neutrons are slowed by water in the soil. By measuring their intensity as they escape back out into the atmosphere, it should be possible to gauge how much water the soil contains.

Zreda and colleagues have been testing that theory since 1998 with portable detectors in Hawaii, India, and the western United States. They describe one of these experiments, in Arizona's San Pedro River valley, in a November 2008 paper in Geophysical Research Letters.

A consortium of companies, including General Electric and Hydroinnova in New Mexico, is building the detectors for the US network, which will be installed during the next five years, Zreda says.

Just as in the work on stratospheric temperature, it took scientists from two normally distant fields to fully tap the information flow from soil moisture studies—and add one more job title to the resume of the cosmic ray.