FEATURES

THE OVERWORLD

A new NASA mission will probe threats to the ozone layer over the United States

By **Eli Kintisch**

PHOTO: SANTIAGO BORJA

Teenagers armed with AK-47s stood guard as Lockheed pilot Ron Williams taxied a NASA research jet down a runway in Punta Arenas at the southern tip of Chile. The long, gliderlike wings of the aircraft—a modified Lockheed U-2 spy plane known as the ER-2—were heavy with fuel and scientific instruments. Not long after he took off, Williams watched as the sky above his cockpit turned from blue to purple to black, with countless bright stars. Below, Earth's curvature appeared. Williams had climbed into the overworld, the heart of the frigid, dry lower stratosphere, some 18 kilometers up.

It was August 1987 and dictator Augusto Pinochet still ruled Chile. Williams had journeyed to Patagonia to help researchers probe a worrying development in the skies over nearby Antarctica: Reactions triggered by industrial chemicals appeared to be eating a hole in Earth's ozone layer, which protects life from harmful ultraviolet (UV) radiation.

The flights were dangerous, recalls atmospheric chemist James Anderson of Harvard University. He had a 150-kilogram instrument aboard the ER-2 that would sniff the overworld's thin air for ozone-destroying chemicals as Williams hurtled, for 8 hours, high over icy nothingness. If the single-engine jet went down, a rescue wasn't certain. And just landing the spindly plane at the notoriously windy Punta Arenas airport could be an adventure. "The worst was the thought that my instrument wouldn't work," Anderson says, "since the pilot was risking their life."

Ultimately, the measurements that Williams and other pilots collected over Antarctica in 1987 became iconic—and influential. Scientists and journalists called them "the smoking gun" proving that chlorinated compounds used in refrigerators, spray cans, and industrial processes were destroying stratospheric ozone. The findings helped clear the way for the approval for the Montreal Protocol, a global pact that phased out the worst ozone-destroying compounds. Since then, levels of the chemicals in the atmosphere have decreased, enabling the ozone layer over Antarctica to slowly recover.

More than 3 decades later, NASA's ER-2 is again preparing to soar to the overworld in search of a potential new threat to the ozone layer. And Anderson is again at the center of the investigation. But this time, the flights will take place far from the South Pole, over the U.S. Great Plains. There, scientists suspect, towering summer thunderstorms are lofting water and pollutants high into the stratosphere, where they can catalyze ozone destruction. And researchers worry the problem could worsen as the planet warms.

Some researchers say the fears are overblown. Satellites have yet to detect any reduction in the health of the ozone layer over the United States, and no evidence exists yet of either increased UV levels at ground level or an increase in human cancers related to UV exposure, such as skin cancer.

But for the past 2 decades, a steady drip of findings has suggested the hypothesis is worth investigating. One such finding was the discovery that pockets of the stratosphere over the central United States are unexpectedly cold and wet—creating prime conditions for ozone depletion. Last year, NASA announced it would fund a 5-year, $30 million effort, beginning this year, to probe whether Midwestern storms are altering the makeup of the stratosphere. The Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) project will seek to illuminate potential threats to the ozone

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Powerful overshoot storms can penetrate the stratosphere, injecting moisture and pollutants.

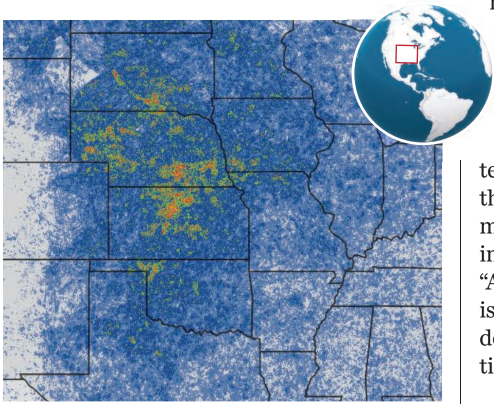
layer over the central United States, where it protects 100 million people from cancer-causing UV rays.

Scientists "have a fundamental responsibility to fully understand this problem," Anderson says. The implications for human health could be substantial, he adds, for residents of the Midwestern United States and beyond.

THERE'S A LOGIC to the order of the sky. The bottom 10 kilometers or so of the atmosphere, the troposphere, boasts warm temperatures, wet weather, and just about all life. But life also depends on the stratosphere, the layer above the troposphere, which includes Earth's roughly 20-kilometer-thick, UV-absorbing ozone layer.

Roughly half of the ozone, by mass, is found in the bottom 10 kilometers of the stratosphere. The air there is extraordinarily dry, with water vapor concentrations of just 3 to 5 parts per million—whereas tropospheric levels are thousands of times higher. Moisture rising from lower altitudes typically doesn't reach the stratosphere because air cools as it rises, causing water vapor to condense into clouds and rain well below the stratosphere. "It's like a cold trap," says atmospheric scientist Ken Bowman of Texas A&M University in College Station, the DCOTSS principal investigator.

Small amounts of water vapor do slip into the stratosphere near the equator. There, the cauldron of tropical heat propels some air through the tropopause, the boundary between the troposphere and the stratosphere. That air has been stripped of most—but crucially not all—of its moisture, which then drifts toward the poles. (Other water found in the stratosphere comes from the degradation of methane and hydrogen.)



Radar data show that more than 45,000 overshoots—storms that rise into the stratosphere (dots)—occur each year over the central United States.

Near the poles, that water freezes into ice crystals, found within bizarre mists called stratospheric clouds. Those crystals were long thought to be essential to initiating the chlorine-catalyzed reactions responsible for the Antarctic ozone hole. (In those reactions, chlorine radicals convert ozone's triplet of oxygen atoms into dioxygen.) But in 2000, during ER-2 missions over Sweden, instruments revealed that ozone-destroying reactions could also occur in the presence of ubiquitous droplets called sulfate aerosols, derived from both natural sources such as volcanoes and the burning of fossil fuels. Lab experiments later showed water vapor could aid the process by diluting the sulfate droplets, freeing them to catalyze more ozone-destroying reactions. The findings were a surprise, Anderson says. But, "At the time we thought it was an academic issue," he says, because researchers hadn't detected such wet, ozone-unfriendly conditions in the stratosphere.

Then, a series of chance discoveries hinted that the stratosphere over midlatitudes was wetter than scientists had thought. Balloon and satellite measurements, for example,

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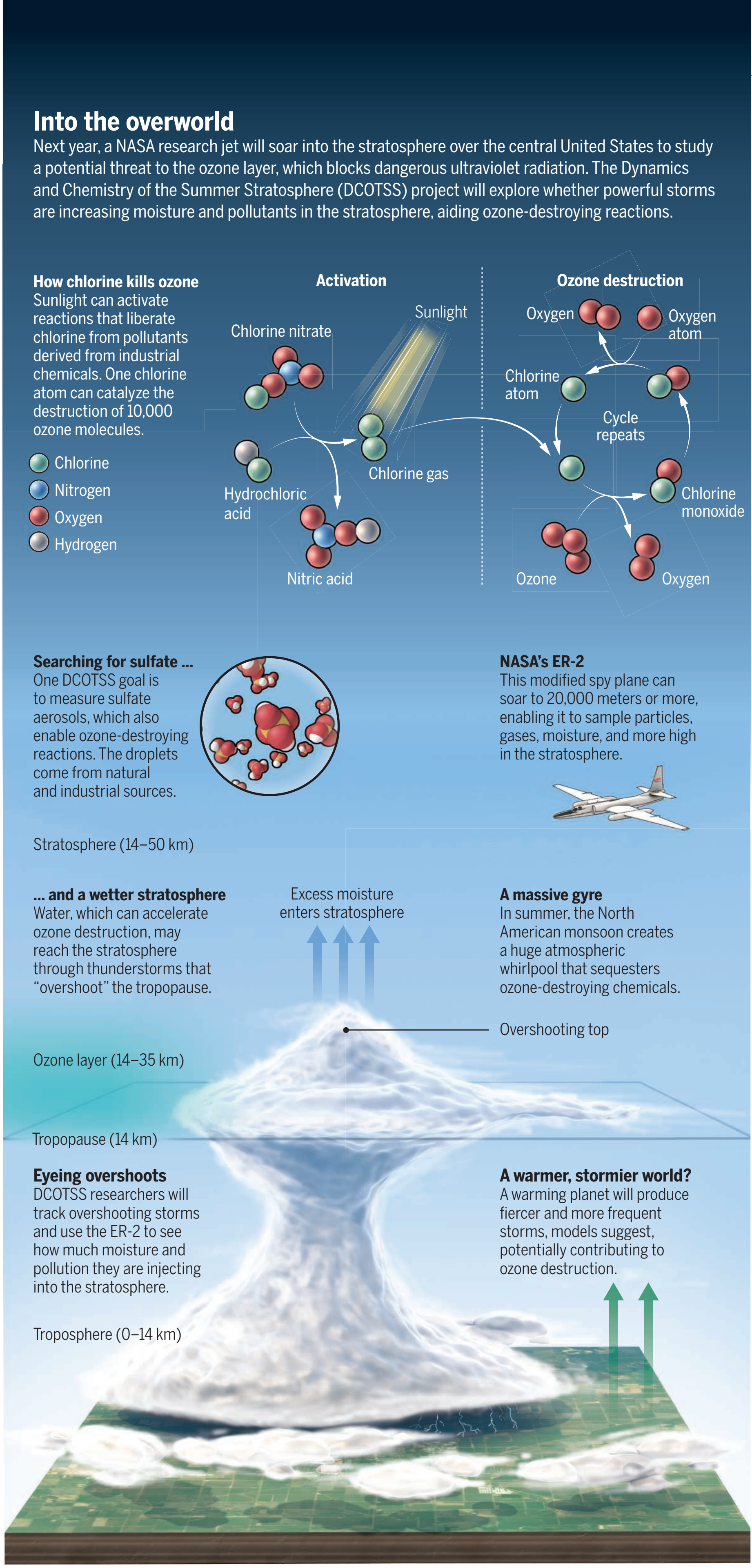

GRAPHIC: C. BICKEL/SCIENCE

suggested the stratosphere over Southeast Asia and North America contains a few parts per million more water than over anywhere else in the world.

Over North America, researchers suspected the source might be outsize thunderstorms. Although most thunderheads rise only to the top of the troposphere and then spread into the familiar anvil shape, some especially powerful storms overshoot, injecting moist air into the stratosphere.

In 2005, for instance, a converted bomber called a WB-57 was conducting research flights in the lower stratosphere over Texas when, within just a few weeks, its instruments detected several plumes of water vapor. "We had been flying [these flights] for decades and not seeing such plumes. … Suddenly, we saw three in a short campaign," says atmospheric scientist Thomas Hanisco of NASA's Goddard Space Flight Center in Greenbelt, Maryland. He later showed, by analyzing chemical isotopes in the water, that the vapor had recently been ice particles lofted by storms. Bowman made a similar discovery of stratospheric moisture in 2008 during an experiment studying large-scale circulation patterns—think the jet stream or continent-size atmospheric waves—aboard a G5 jet over Colorado.

Other studies revealed overshoots were more common than researchers realized. A decade ago, Bowman figured overshoots over the United States totaled "maybe a few each year." But the real number is more like 250 per day during spring and summer, says meteorologist Cameron Homeyer of the University of Oklahoma in Norman. Using a technique Homeyer developed, one of Bowman's students combined 3D radar data, generally used for weather forecasting, collected by 125 National Weather Service stations between 2004 and 2013. He tallied more than 400,000 overshoots over the continental United States during that 10-year period. "We've been surprised at every stage that these storms are more frequent and intense than we expected," Homeyer says.

A third line of research revealed patches of the lower stratosphere over the central United States that were much colder than expected, potentially creating ideal conditions for ozone destruction. In 2013, for example, ER-2 flights over the Great Plains measured summer temperatures in the overworld that were 73°C below zero, 15°C colder than a commonly used model had assumed. That temperature drop could speed up ozone-depleting reactions by a factor of 100, Anderson and colleagues reported in 2017 in the *Proceedings of the National Academy of Sciences*. That's partly because the cold causes more water vapor to condense into a liquid, enabling it to further dilute sulfate aerosols and catalyze reactions. A cooling of just 3°C, his research suggests, can trans-

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form the stratosphere from a safe haven for ozone into a killing zone. "This chemical reaction is the most sensitive to temperature I've ever confronted," Anderson says.

In 2017, such findings prompted Anderson and 14 other members of the U.S. National Academy of Sciences to ask NASA and the academy to make assessing the threat a priority. "The stratospheric system resides at the cusp of significant ozone reduction," the scientists warned in their letter to the academy.

Last fall, NASA announced it had chosen the DCOTSS project as one of five missions, selected from 30 proposals, for its suborbital research program. Three 8-week field campaigns by the high-flying ER-2—which can reach 20,000 meters—are the centerpiece of the project. From a base in Salina, Kansas, the aircraft will crisscross the Great Plains in 2020 and 2021, enabling researchers to document conditions in the overworld and at lower altitudes in unprecedented detail. "The irony," Bowman says, is that "we know the stratosphere over the poles better than over the midlatitudes."

FOR NASA'S FOUR ER-2 PILOTS, the flights will mean more risky journeys. Pilots have nicknamed the jet's predecessor, the U-2, the Dragon Lady, a sexist moniker that refers to the craft's difficult temperament. To prevent the plane from stalling or creating destabilizing shock waves, for instance, ER-2 pilots must stay within a narrow range of speed dubbed the "coffin corner." Even experienced pilots can lose control; during the Cold War, several of the finicky U-2s fell from the sky.

In polar regions, the stratosphere's extreme temperatures and winds added to the hazards. Before Williams flew over Antarctica in 1987, for instance, a U.K. meteorologist predicted he would face winds of 231 kilometers per hour and temperatures of –92°C—far outside the ER-2's usual operating environment. Williams was skeptical and bet the scientist half a bottle of scotch that he was wrong. The pilot lost the bet in spectacular fashion, ending at least one flight early after encountering cold so extreme he feared his fuel would freeze.

The pilots in the DCOTSS project should see milder conditions. But the project's scientific findings could prove just as important. A central focus will be collecting data on the North American monsoon anticyclone, a continent-size atmospheric gyre that partially confines moist summer air over North America. The gyre is fed by warm, wet air from the Gulf of Mexico, which pours across the Midwest, fueling thunderstorms that feature some of the world's most intense rain, lightning, and convection strong enough to puncture the tropopause. "North America really is unique in terms of intense convection," Anderson says. In the stratosphere, he hypothesizes, the result is a potential "photochemical batch reactor" for destroying ozone.

Within the gyre, DCOTSS researchers want to quantify how much water and other substances are entering the stratosphere and trace their fate. To do so, the ER-2 will carry instruments for measuring water, trace chemicals, ozone, aerosols, and physical parameters such as air pressure and temperature. Researchers will use radar and satellite data to track overshoots and then send the ER-2 to chase them. The planes won't be allowed to fly directly into the strong updrafts, but "we can predict where that air is going after it enters the stratosphere, and we can go sample it," Bowman says.

ER-2 pilots must wear pressurized suits to survive at the very high altitudes reached by the research jet.

PHOTO: NASA/STU BROCE

Researchers will search for ozone-destroying chemicals, such as chlorine and sulfur, which have been lofted into the stratosphere. By taking the express train to high altitude, those chemicals may be sidestepping cleansing processes in the lower atmosphere, where sunlight and compounds called hydroxyl radicals can break them apart. "We don't know much about the meteorology and chemistry of the stratosphere here because we haven't gone up before looking," Bowman says.

MANY ATMOSPHERIC SCIENTISTS agree about the value of the DCOTSS project. "We know too little about the stratosphere, so it should be studied," says David Fahey, who runs a division of a National Oceanic and Atmospheric Administration laboratory in Boulder, Colorado. But he and others are skeptical that the ozone layer above midlatitudes faces imminent risk. In a study published in *Geophysical Research Letters* in 2013, for example, researchers failed to replicate the earlier findings of the wet, cold stratospheric conditions over North America necessary to trigger ozone depletion. The study, based on 8 years of daily moisture and temperature data collected by NASA's Aura satellite, also reported low amounts of ozone in the tropospheric air lifted by overshoots. If DCOTSS scientists find reduced ozone in the wake of overshooting storms, those injections of ozone-poor air could be the reason—not destructive chemistry.

The authors of the 2013 paper stated that work by Anderson and others "suggested" there could be what the authors characterized as "alarming reductions" in summer ozone levels. But those reductions "are not seen in the current climate," the authors concluded. And Fahey says that if midlatitude ozone depletion is "going to get worse, it's got a long way to go."

Anderson notes he has never used the phrase "alarming reductions," and he says the satellite data used in the 2013 paper are not sensitive or detailed enough to reveal the relevant mechanisms. But he is worried about the future. "It will be too late," he fears, if action is delayed until "we actually have measurable decreases in ozone [and] increases in UV radiation [over midlatitudes]." And global warming could speed any losses. Warming has caused moisture in both the lower and upper atmosphere to increase, a trend expected to intensify, and it could mean more powerful thunderstorms pumping that moisture into the stratosphere. In addition, research has shown that although the dominant warming gases, carbon dioxide and methane, warm the lower atmosphere, in the stratosphere they radiate solar energy to space, cooling that part of the sky—which could also favor ozone destruction. The data collected by the DCOTSS project should help determine whether that scenario is already occurring.

Public health officials would be smart to keep an eye out for the results, says dermatologist Paul Nghiem of the University of Washington in Seattle, a skin cancer expert who recently began to collaborate with Anderson. If the findings suggest local weather, such as big storms, can drive short-term drops in stratospheric ozone and peaks in UV exposure, then warnings to limit sun exposure might "have to be linked better to real-time direct measurement of weather," Nghiem says.

Veterans of the 1980s effort to convince governments that the Antarctic ozone hole demanded attention are also watching DCOTSS with interest. The "data from Punta Arenas are probably the best example of fundamental science … going into policy," says Robert Watson, the retired NASA scientist who led the 1987 expedition in Chile. Now, he and Anderson say, the question is whether policymakers will again be willing to listen if researchers find evidence of a new danger lurking in the overworld. ■

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