Correction

CORE CONCEPTS

Correction for "Core Concept: To improve weather and climate models, researchers are chasing atmospheric gravity waves," by Adam Mann, which was first published September 24, 2019; 10.1073/pnas.1912426116 (*Proc. Natl. Acad. Sci. U.S.A.* **116**, 19218–19221).

The editors note that reference 2 appeared incorrectly. The last name of the author should have appeared as Holton, not Horton. The corrected reference appears below. The online version has been corrected.

2. J. R. Holton, The role of gravity wave induced drag and diffusion in the momentum budget of the mesosphere. *J. Atmos. Sci*. **39**, 791–799 (1982).

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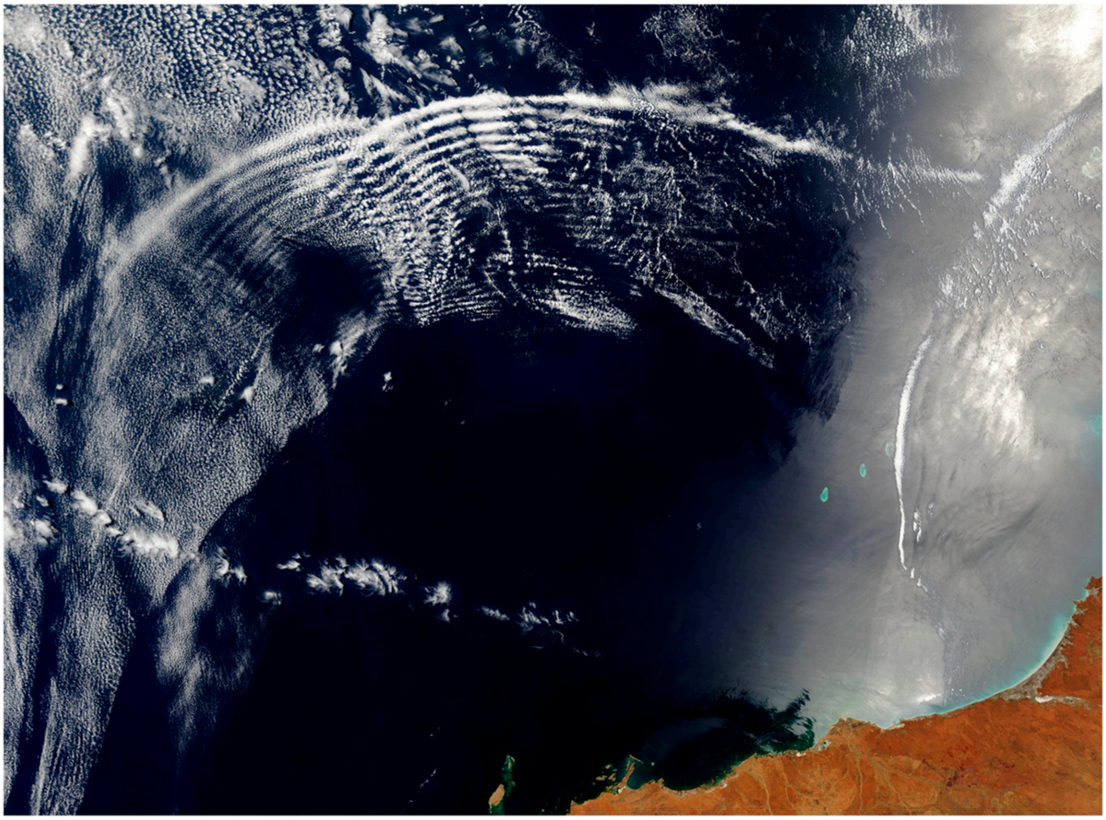
To improve weather and climate models, researchers are chasing atmospheric gravity waves

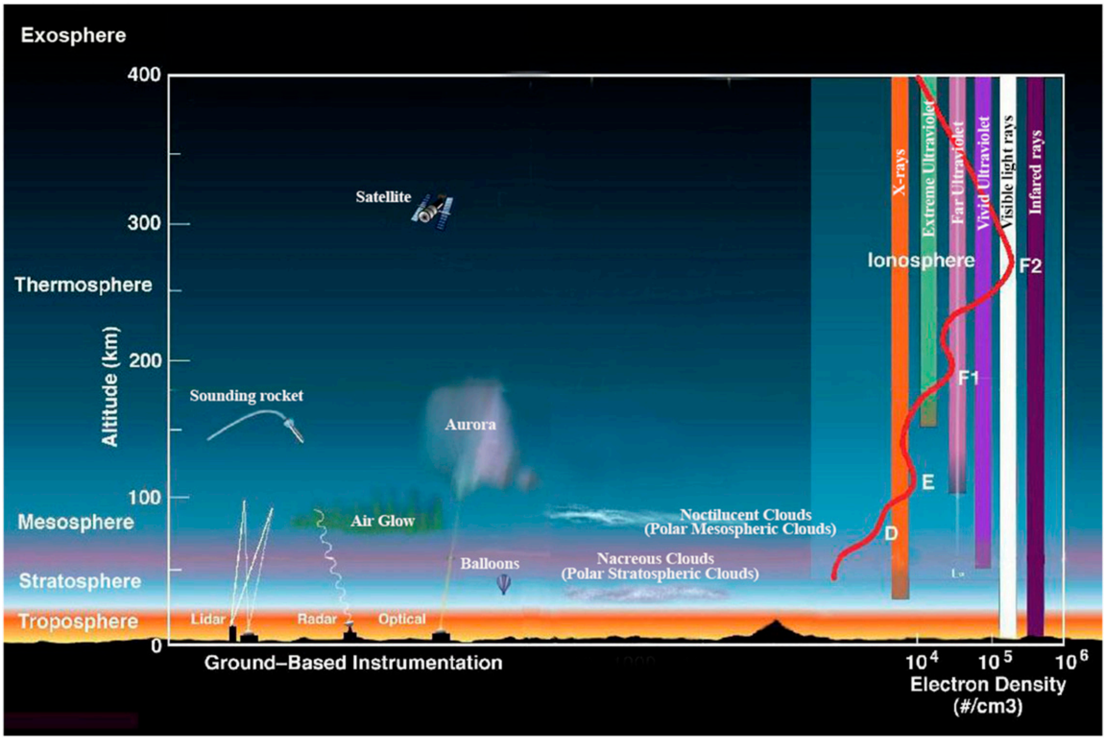
Adam Mann, *Science Writer*

On September 3, 2018, an unpowered experimental sailplane made history by flying into the stratosphere. After leaving from El Calafate, a town near the Southern Patagonian Ice Field in Argentina, glider pilots Jim Payne and Tim Gardner surfed on enormous airborne waves emanating from the Andes Mountains. They achieved a world record height of 23,203 meters—higher than a Lockheed U-2 spy plane's cruising altitude. No other unpowered aircraft has ever achieved such elevation. It was a feat made possible by not just human ingenuity but also the incredible strength of a phenomenon known as atmospheric gravity waves.

Unlike the similarly named (and perhaps more famous) cosmic gravitational waves, which are ripples in the fabric of space-time, atmospheric gravity waves are a wholly terrestrial occurrence. They emerge when parcels of air are forced upward, for instance, by a tall mountain range, moving from a dense atmospheric layer to a thinner one. The heavier blobs of air then succumb to the force of gravity and fall back down, resulting in a periodic oscillation that can carry energy and momentum over vast distances. They are the smallest atmospheric waves that researchers study, generally between a few hundred meters and a few



Atmospheric gravity waves—seen here over the Indian Ocean via the Moderate Resolution Imaging Spectroradiometer housed in NASA's Terra satellite—emerge when parcels of air are forced upward. Image credit: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC.



The actions of atmospheric gravity waves bring energy from the troposphere out past the edge of space, 500 or more kilometers above Earth's surface. Image credit: NASA.

hundred kilometers in size. But their cumulative effects can be dramatic.

The actions of atmospheric gravity waves bring energy from the troposphere—the lowest atmospheric layer, which ends at an altitude of about 10 kilometers—out past the edge of space, 500 or more kilometers above Earth's surface. They play important roles in daily weather as well as long-term climate fluctuations, decelerating powerful jet streams and affecting the circulating polar vortexes that appear over our planet's poles. They influence atmospheric turbulence, temperature, and chemistry, yet limited computing power continues to prevent their direct inclusion in most atmospheric simulations.

Although researchers believe they have a fairly good handle on the basics of atmospheric gravity waves, a more detailed and realistic look at the waves' behavior would provide increased accuracy for simulations predicting both local weather and potential adverse effects from climate change. In recent years, new efforts have sprung up to provide better observations and modeling of these important players in our planet's dynamic atmosphere.

"They seem small," says atmospheric researcher Joan Alexander of NorthWest Research Associates in Boulder, CO. "But they're affecting forecasting and predictions on many timescales, and if we don't include them we get big biases in our models."

A Rock in a Pond

Researchers have known about atmospheric gravity waves since the 19th century, but the waves remained obscure until 1960. Around then, atmospheric researcher Colin Hines of the Canadian Defense Research Board began wondering why the trails left by meteors, as they whooshed through the part of the ionosphere that sits at 80 to 110 kilometers above the surface, often contained irregular wave-like distortions. His calculations showed how gravity waves from below were crashing like ocean waves on the shore of the upper atmosphere, inducing the strange meteor trail patterns. Hines developed the first widely accepted theory on how gravity waves worked and how they influenced other events in the atmosphere (1).

Atmospheric gravity waves can be generated in a variety of ways, such as when air flows up and over mountains or in the updraft from a powerful thunderstorm. The air parcels may generate ripples that travel horizontally over the planet in a process similar to ocean waves rising and falling at the surface of the sea. More often, the undulations climb vertically, rising into different layers of the Earth's atmosphere, which becomes exponentially thinner as altitude increases. Conservation of energy forces the waves to grow in amplitude in the lower-density air, allowing them to travel to distant elevations where they impart energy and momentum.

"It's like dropping a rock in a pond," says climate researcher Julio Bacmeister of the National Center for Atmospheric Research in Boulder. "When a parcel hits the stratosphere, it generates oscillations that propagate in all directions."

Atmospheric gravity waves were first put into global weather forecasting models in the 1980s. Before that, numerical simulations that included the mesosphere—an atmospheric region between 50 and 85 kilometers—had produced temperature patterns that didn't match our planet's actual fluctuations. The mesosphere is particularly tricky to model because it gets unexpectedly colder in the summer and warmer in the winter, and at the time nobody could figure out why. Researchers realized that atmospheric gravity waves from near the surface were crashing against airstreams in the mesosphere, changing their normal flows. The effect forced winds in the mesosphere to pour from the Earth's summer hemisphere toward the winter one, creating the anomalous temperature inversion (2).

But these early models were too coarse-grained to resolve the small-scale oscillations of relatively tiny atmospheric gravity waves. Instead, theorists relied on what is known as a parameterization—essentially a workaround in which researchers use their knowledge of the gravity waves' actions to tell the simulation how to react to their influences, even while the researchers were unable to include the waves themselves (3, 4). Parameterizations have proven successful in reproducing most of our planet's real-world activities and are still used in most cases for modeling the effects of atmospheric gravity waves. But Bacmeister says that the basic methods haven't changed much since the first schemes were put together more than 30 years ago, and many in the field are now looking to improve their simulations.

> **"As in all things in meteorology, you have models and observations. You improve the models with observation, and there's an interplay between the two."**
>
> **—Marvin Geller**

Butterfly Effect

It's relatively easy to parameterize the effects of stationary topographic features such as mountains. But winds can sometimes travel around mountains rather than over them, so a simplistic treatment might induce too much or too little change. The results of transient phenomena such as storm fronts and clouds are even harder to parameterize accurately because such events arise sporadically from complex causes. Gravity waves can also generate turbulence or smaller secondary waves, but state of the art computing power still isn't sufficient to resolve such subtleties.

"It's kind of like the butterfly effect," says atmospheric researcher David Fritts, founder of the Colorado division of the aerospace company GATS, referring to the idea that tiny actions, such as a butterfly flapping its wings, can snowball into major consequences. "If you don't allow for the butterflies, it's hard to get the effect."

At the International Space Science Institute in Bern, Switzerland, Alexander has recently brought together a team of experts in data assimilation and global weather and climate forecasting models to figure out how to best advance atmospheric gravity wave simulations. Although the small waves don't affect the overall prediction that the Earth will warm in the coming decades, their actions can be crucial in determining whether some particular part of the globe will experience a greater potential for droughts, flooding, or other detrimental outcomes. The group hopes that getting a better handle on atmospheric gravity waves' sources, increasing the resolution of their models, and producing improvements in parameterization schemes will help provide crucial information for planners seeking to minimize weather-related damage from routine events such as rain and temperature extremes, as well as from major incidents such as hurricanes, tsunamis, and tornadoes, which have been estimated to impact 30% of the global economy (5).

For the past decade, Earth-observing satellite missions have assisted with such missions, producing a golden era in climatologic and atmospheric data. Mostly invisible to the human eye, atmospheric gravity waves have historically been difficult to observe. Weather balloons launched twice a day from hundreds of locations around the planet provide information about atmospheric temperature and pressure and wind speeds and directions for researchers but do not provide full coverage over the oceans or throughout the entire vertical height of the atmosphere. From their perch in space, instruments such as NASA's Atmospheric Infrared Sounder (AIRS) and the European Space Agency's Atmospheric Dynamics Mission Aeolus (ADM-Aeolus) can watch for changes in winds, temperature, and humidity around the entire Earth, allowing researchers to build complex predictive weather models.

So far, there have been no satellite missions devoted specifically to atmospheric gravity waves, and researchers often rely on incidental data gathered by instruments on satellites designed for other purposes. But earlier this year, NASA green-lit the Atmospheric Waves Experiment (AWE), an observatory that will monitor how gravity waves high in the ionosphere interfere with radio and Global Positioning System (GPS) communications. The AWE is expected to fly to the International Space Station in August 2022.

Ground-based detectors such as radar and Light Detection and Ranging (LIDAR) instruments that can spot atmospheric shifts are also being deployed to gather gravity wave data. Combined with satellite observations, information from these campaigns is helping answer remaining questions in the field. For instance, global circulation models often fail to correctly replicate the behavior of the Antarctic polar vortex, an organized swirl of air over our planet's South Pole. The simulations predict much stronger and colder winds than meteorologists have observed; researchers suspect that this is partly because of gravity waves originating from 60 degrees latitude south—a particularly windy region of our planet that does not get much observational coverage.

At the British Antarctic Survey, atmospheric physicist Tracy Moffat-Griffin is helping lead the Drake Passage Southern Ocean Wave Experiment (DRAGON-WEX), which will use radar and satellites to measure atmospheric gravity waves over the Southern Ocean and the Drake Passage at the tip of South America to investigate how they might be contributing to this discrepancy. Moffat-Griffin has also helped organize the Antarctic Gravity Wave Instrument Network (ANGWIN), an international effort to provide more comprehensive coverage of gravity waves over the South Pole. In their undulations, atmospheric gravity waves can create cold spots where clouds form. The surface of polar stratospheric clouds often induces ozone-destroying chemical reactions, contributing to the Earth's ozone hole, so monitoring the waves is an important part of predicting its size and behavior.

Atmospheric gravity waves aren't only an Earthly phenomenon. Observations from Japan's Akatsuki mission currently orbiting Venus have revealed a 10,000-kilometer-wide bow-shaped structure in the planet's upper atmosphere, which periodically appears and remains stationary for days at a time despite the turbulent Venusian clouds (6). Researchers believe the structure is caused by updrafts coming from mountains on the surface. Other gravity wave effects have been spotted from probes orbiting Mars, Jupiter, and Saturn (7–9). Studying such events can help inform researchers' general understanding of gravity waves, although thus far researchers have relatively little data with which to scrutinize these off-world cases, notes Moffat-Griffin.

Together with improved simulations, better monitoring will help atmospheric researchers gain a much greater understanding of gravity waves on Earth and beyond. "As in all things in meteorology, you have models and observations," says atmospheric researcher Marvin Geller of Stony Brook University in New York. "You improve the models with observation, and there's an interplay between the two."

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