Making waves

Pulses of energy called planetary waves traverse the globe, protecting the Arctic ozone layer and influencing weather and climate. Atmospheric scientists are now realizing just how important they are, says Larry O'Hanlon.


R. KAWA & P. NEWMAN

Planetary waves help to dispel the polar stratospheric clouds that contribute to ozone depletion.

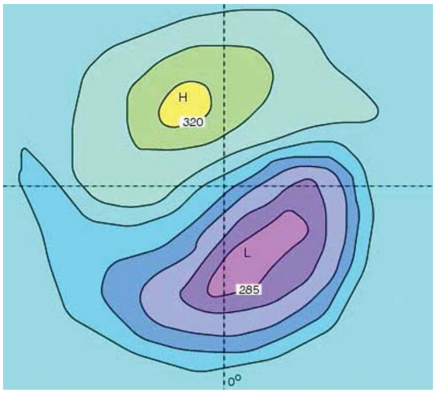
At their largest scale, they straddle the Earth. Without them, ozone depletion in the stratosphere would be worse and more frequent than it is now. They influence the weather that we experience, and are thought to be an important missing link in climate models. They are planetary waves: mammoth pulses of energy created when wind streams crash into mountains or collide with the steep temperature gradients in the air above coastlines.

These atmospheric Titans are certainly starting to make waves at scientific conferences. At meetings of the American Geophysical Union, for instance, the amount of time given over to planetary waves and related issues has tripled over the past three years. The subtleties of their behaviour remain mysterious, but if researchers can crack the waves' secrets, a better understanding of weather, climate and ozone depletion should follow. "There's no question that it's a hot topic," says Alex Hall, who studies climate dynamics at the University of California, Los Angeles.

Hot link: Paul Newman has helped to confirm the effects of planetary waves on temperature.

The Earth's atmosphere is full of waves, the smaller varieties of which provide our day-to-day weather. A ridge of high pressure that brings us sunshine for a day or two, for instance, is a wave — albeit a small one on the global scale.

Planetary waves reveal themselves over longer time and distance scales. For example, the high- and low-pressure fronts of the Northern Hemisphere are embedded in a giant wave. This has a low-pressure trough over central Asia and a high-pressure peak over North America — forming a huge 'yin-and-yang' pattern on plots of pressure centred on the North Pole (see right). Analyses of weather maps in the Northern and Southern Hemispheres reveal other such waves, some of which move across the Earth's surface.



ADAPTED FROM J. R. HOLTON

Grand-scale wave: high pressure over North America and a corresponding low over Asia.

Under pressure

Natural barriers to wind flow, such as the Rocky Mountains in North America, are one cause of such waves. Atmospheric pressure increases as the air piles up on the western side of the Rockies, and decreases as it expands after passing over the range. This creates a standing wave, fixed with respect to the Earth's surface. The wave is analogous to the patterns of water flow that form over rocks submerged in fast-moving streams, explains Paul Newman, an atmospheric physicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Some of the waves formed at mountain ranges move away from their sources. In the case of the Rocky Mountains, the high-pressure western side of the range emits waves of warm and less dense air, whereas cooler, denser waves leave the low-pressure eastern side. Some of the waves travel upwards, and the biggest — with wavelengths of tens of thousands of kilometres — can pass up through the troposphere, the lower 10–30 kilometres of the Earth's atmosphere in which weather patterns move, and into the overlying stratosphere.

Even a perfectly smooth planet would create planetary waves, provided it had land and sea. Both air pressure and temperature change rapidly at the boundary between the two. Wind streams hitting this sharp gradient send reverberations of changing pressure, temperature and density outwards from the collision zone.

Planetary waves have attracted interest in recent years because of the way in which they influence the polar climate, a relationship that ultimately has a beneficial effect on polar ozone levels. Ozone in both the Arctic and Antarctic is destroyed because the low temperatures in the upper atmosphere allow the formation of clouds containing crystals of nitric acid, which absorb stable chlorine compounds throughout the winter. The spring sunshine and warmth releases these chlorine compounds, which are further broken down by sunlight into highly reactive

Acting as barriers to wind flow, the Rocky Mountains are the source of a major planetary wave.

S. T. SMITH/CORBIS

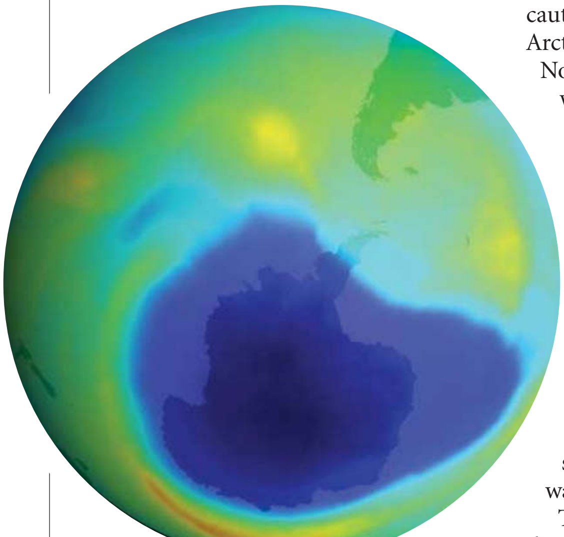
Understanding the effects of planetary waves could improve long-range weather forecasts.

chlorine molecules. It is these that go on to destroy ozone. In addition, ozone destruction is normally kept in check by nitrogen dioxide (NO_2), which mops up some of the chlorine molecules. But the nitric acid in polar clouds is formed from NO_2, which effectively removes it from circulation.

Crystals of nitric acid only form if winter temperatures in the stratosphere fall below −78 °C, and planetary waves limit this by raising the temperature. They do this in two ways, first by disrupting polar vortices — circular patterns of wind in the troposphere and stratosphere that isolate the poles from surrounding weather patterns, driving temperatures down. By disrupting the stratospheric vortex, incoming planetary waves allow warmer air from temperate latitudes to mix with and warm the polar stratosphere.

Upward-moving planetary waves also help to protect the polar ozone by 'breaking' when they enter the thinner stratosphere, much as water waves collapse and break when they hit shallower water. The breaking waves transfer their energy in the form of turbulence and heating to gases in the polar stratosphere.

Last September, Newman's team confirmed that the amount of energy deposited into the stratosphere by planetary waves in winter correlates with the subsequent temperature of the stratosphere — showing that the two are part of the same phenomenon[1]. "For the first time, we showed the relationship," he says.



Future shock: could the ozone hole above Antarctica (blue) be mirrored in the Arctic?

NASA/GODDARD SPACE FLIGHT CENTER

It has also long been suspected that upward-moving waves hitting the polar stratosphere drive the flow of ozone from the tropical stratosphere to the poles, which helps to top up polar levels[2].

But planetary waves benefit the two hemispheres to different extents. In the Northern Hemisphere, large land masses and high mountain ranges create high-amplitude waves. The south, with fewer mountains and smaller land masses, creates weaker waves and so gets less help. As a result, ozone over the Antarctic is largely wiped out for several months every spring, whereas only patchy holes form over the Arctic.

The Southern Hemisphere provides a cautionary tale of what could happen to the Arctic ozone layer if the influence of the Northern Hemisphere's planetary waves weakens — and the bad news is that the build-up of greenhouse gases in the atmosphere could have just that effect.

Greenhouse gases such as carbon dioxide and methane absorb various wavelengths of radiation and re-emit them as heat in all directions, ensuring that at least some of the heat is retained in the atmosphere rather than escaping into space. As heat radiated from the Earth's surface is trapped by the gases in the troposphere, less escapes into the overlying stratosphere. So, while the troposphere warms, the stratosphere cools[3].

This stratospheric cooling could cripple the ability of planetary waves to mitigate ozone destruction. Currently, it does not take much energy from a planetary wave to raise the stratosphere's temperature above the threshold for the formation of nitric acid crystals. But in 1998, Drew Shindell and his fellow atmospheric modellers at NASA's Goddard Institute for Space Studies in New York showed that if the stratosphere gets colder, the planetary waves may not contain enough energy to raise the temperature sufficiently to shut the process down[4].

A second blow comes from the effect of greenhouse warming on the westerly winds that stream across the Northern Hemisphere. These drive weather systems and feed into and reinforce the Arctic vortex. Together, the winds and the vortex form part of the Arctic Oscillation (AO). When the AO is in its positive phase, which can last for months or even years, barometric pressure drops over the polar regions and goes up at latitudes of around 55 degrees.

A tricky phase

Positive phases of the AO are more likely to occur during the winter, and the bigger the difference in atmospheric pressure between the pole and the lower latitudes, the stronger the westerly winds. The pressure differences have been getting bigger since the 1960s (ref. 5) and, although the reasons are unclear, greenhouse warming is a prime suspect. Whatever the cause, stronger positive phases of the AO could be a problem for the ozone layer, as the more powerful westerly winds that result would bolster the Arctic vortex and deflect planetary waves away from pole. If the pressure difference across the AO continues to increase over the years, the ability of planetary waves to rescue Arctic ozone will decline[6].

Planetary waves may also be influencing the polar vortex and the AO in more subtle ways. Last October, Mark Baldwin and Timothy Dunkerton, meteorologists with the research firm Northwest Research Associates based in Bellevue, Washington state, showed that the stratosphere could influence the AO

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N. JACOBS/AP

Twister: events in the stratosphere could provide clues to forthcoming freak weather conditions.

(ref. 7). They noticed that a weakening of the AO-strengthened vortex in the troposphere tends to be preceded, about two weeks earlier, by a weakening of the vortex above it in the stratosphere. The result was intriguing, as the low-pressure and virtually weather-free stratosphere was previously thought to have little impact on weather patterns below it.

Quite how this feat is accomplished is not known, but David Thompson, a meteorologist at Colorado State University in Fort Collins, suggests that planetary waves, one of the few messengers to cross between the two regions, could play a role. “No one understands this yet,” he says — but there is a lot of speculation.

Chain reaction

The chain of events may start when a planetary wave reaches the stable and non-turbulent airflow in the stratosphere. As the wave breaks, it transfers its energy to molecules in the stratosphere and deposits some tropospheric air. But on crossing into the stratosphere, some of the wave’s energy is deflected in a way similar to how light is refracted when it passes from water to air, explains Thompson. The direction of the deflection depends on the stratosphere’s temperature, and the direction and speed of its airflow.

Now comes the most speculative part, says Thompson: each wave that breaks within the stratosphere causes a disturbance and slows the stratospheric airflow. This, in turn, progressively alters the degree of deflection encountered by subsequent waves. That alone would seem to be a one-way, upwards effect. But the deflection also changes the airflow below the stratosphere in a process analogous to the way in which waters upstream of an obstruction in a stream can back up and slow down, as if they are ‘feeling’ the change ahead.

Another possible way in which the lightweight stratosphere may influence the troposphere does not involve planetary waves, but simply the moving about of stratospheric air — subtly lightening the load above the troposphere in some areas and weighing down over others. It is not a lot of air or mass, but under some conditions it might be enough to tickle the troposphere into responding in kind and even switching between positive and negative AO modes, says Thompson.

A better understanding of the link could help weather forecasters to make improved long-range forecasts. Baldwin and Dunkerton’s work suggests that changes to the weather in the troposphere could be foreseen weeks ahead of time by monitoring the behaviour of the stratosphere.

Baldwin has recently explored this connection with Wallace and Thompson[8]. “We wanted to see generally what was the scale of these effects on the hemisphere,” says Baldwin. The researchers also wanted to make clear the importance of the stratospheric connection with the weather, and to compare its effects to the temperature and pressure fluctuations of the El Niño/Southern Oscillation in the tropical Pacific Ocean.

They found that a pronounced weakening in winter of the Arctic’s stratospheric polar vortex was often followed for about two months by an unusual increase in the number of intense winter storms and severe cold outbreaks in North America, northern Europe and eastern Asia. But a strengthened wintertime vortex brought unusually warm surface temperatures to the same, highly populated areas. The weather signal, they found, was just as loud as that caused by El Niño, and so monitoring the stratospheric polar vortex could potentially be as useful as studying El Niño in predicting severe weather events, says Baldwin.

This top-down weather signal has also caught the attention of climate modellers, who until now have mostly ignored the stratosphere. “It’s the opposite of everything people have been learning for a decade,” says Shindell. Modellers usually assume that the stratosphere follows the cues of its bulky big brother below. To save time and money, they leave it out of their equations.

Predictive power

But Shindell and his colleagues are among the minority who have kept the stratosphere in their models. As a result, they have accurately reproduced the rising winter temperatures in the Northern Hemisphere over the past three decades[4], in addition to showing the stronger stratospheric polar vortices that set the stage for ozone destruction. Their model also recreates the way in which the stronger westerly winds deflect planetary waves.

On a shorter time scale, meteorologists are already used to keeping an eye on the joint influence of planetary waves and the tropospheric Arctic vortex. Planetary waves can disrupt the tropospheric vortex to an even greater extent than that in the stratosphere. Once weakened by the waves, the tropospheric curtain of winds that rings the pole and holds in the cold winter air can leak. Great masses of cold air are let loose, which can slide south along continental interiors. These leaks cause bizarre winter weather in temperate regions, such as freak snowstorms in Dallas, says Thompson. The extra-cold air masses can also collide with warm moist air, triggering the extreme storms seen in areas such as North America’s Tornado Alley, a north–south corridor centred on the lowland areas of the Mississippi and Ohio river basins.

With planetary waves having a hand in such a wide range of atmospheric processes, and with the details of their behaviour still elusive, much work remains to be done. But thanks to the upsurge of interest sparked by the discovery of their influence on Arctic ozone, researchers from across the spectrum of atmospheric science are now taking notice. For those involved, it is an exciting time. “A bunch of fields are coming together,” says Thompson. “It’s all one big jigsaw puzzle.” ■

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