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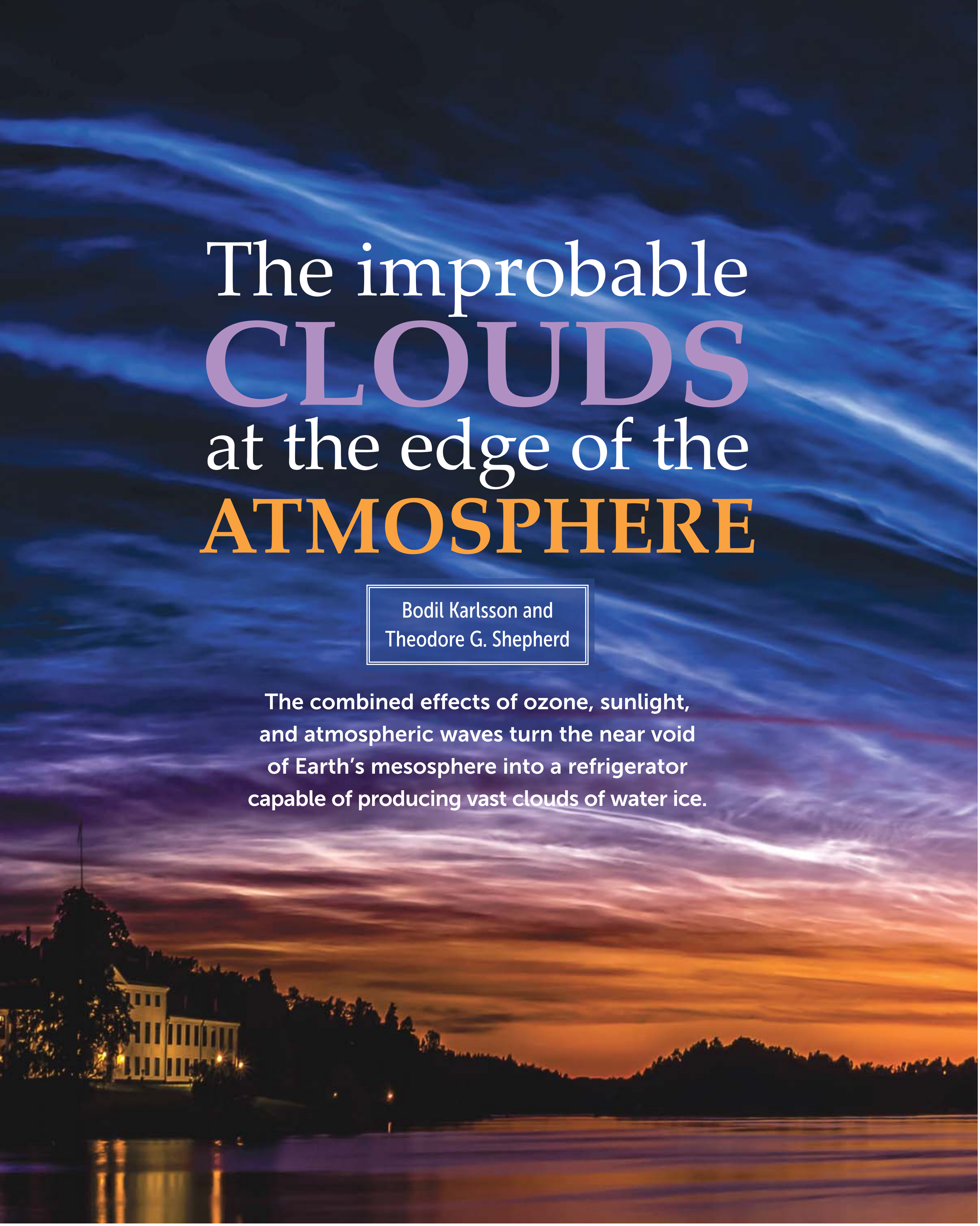

The improbable CLOUDS at the edge of the ATMOSPHERE

Bodil Karlsson and
Theodore G. Shepherd

The combined effects of ozone, sunlight, and atmospheric waves turn the near void of Earth's mesosphere into a refrigerator capable of producing vast clouds of water ice.

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In July 1885, two years after a massive eruption on Indonesia's Krakatoa island cast a haze of volcanic dust that would linger in Earth's skies for years, painter Robert Leslie, writing from the UK, described a peculiar observation to the editor of *Nature*:

> Ever since the sunsets of 1883 and last year there has been at times an abnormal glare both before and after sundown. But I have seen nothing in the way of twilight effect so strange as that of Monday evening, the 6th, when about 10 p.m. a sea of luminous silvery white cloud lay above a belt of ordinarily clear twilight sky, which was rather low in tone and colour. These clouds were wave-like in form, and evidently at a great elevation, and though they must have received their light from the sun, it was not easy to think so, as upon the dark sky they looked brighter and paler than clouds under a full moon. A friend who was with me aptly compared the light on these clouds to that which shines from white phosphor paint. This effect lasted for some time after 10 p.m., and extended from west to north, the lower edge of the clouds, which was sharply defined, was about 12° above the horizon.[1]

The phosphor-like clouds recurred, and two years later photometric techniques revealed that they were situated 82 km above Earth's surface, in what at the time was considered empty space. It was that extraordinary altitude—less than 20 km below the Kármán line that's commonly taken to mark the beginning of outer space—that allowed the clouds to catch the light of the Sun hours after it had disappeared below the horizon. They came to be known as noctilucent, or night-shining, clouds.[2]

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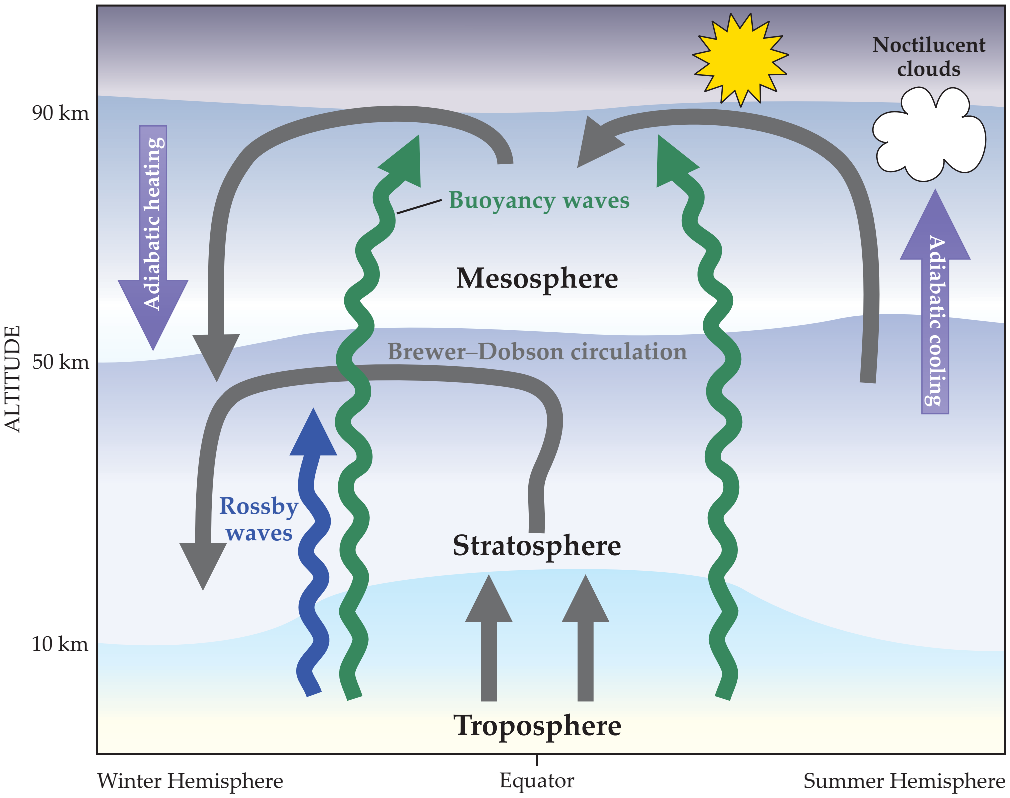

FIGURE 1. THE TROPOSPHERE, STRATOSPHERE, AND MESOSPHERE exhibit a rich and robust pattern of global currents. In the winter hemisphere, Rossby waves—generated when tropospheric winds interact with mountain ranges, weather systems, and temperature gradients at land–sea boundaries—drive a poleward flow known as the Brewer–Dobson circulation. Buoyancy waves, generated by smaller-scale disturbances such as thunderstorms, can propagate to the mesosphere, where they drive a poleward circulation in the winter hemisphere and an equatorward circulation in the summer hemisphere. The resulting upwelling and adiabatic expansion of polar air in the summer hemisphere chills the upper mesosphere to temperatures low enough to form noctilucent clouds, which, because of their high altitude, can remain visible through the night.

In the decades that followed, summer sightings of noctilucent clouds became commonplace at high latitudes. But the mystery of how the clouds formed took about a century to solve.

Atmospheric scientists now know the recipe. The ingredients are spare—just space dust and water vapor. But they must be prepared via an intricate combination of ozone photochemistry, sunlight, and atmospheric-wave phenomena. The relevant physical processes and interactions span the entire atmosphere, from Earth's surface to the edge of space.

One Earth, many spheres

Earth's atmosphere is customarily categorized into shells, or spheres, according to how temperature changes with altitude. In the lowermost shell, the troposphere, temperature decreases with altitude. The troposphere—whose name is derived from the Greek "tropos," meaning "turning"—is constantly stirred by convection and weather. At middle and high latitudes, it extends about 10 km above the surface. But near the equator, deep convection and the dynamically forced ascent of air push the top of the troposphere, the tropopause, to an altitude of nearly 20 km. All told, the troposphere holds ¾ of the atmosphere's mass and 99% of its water vapor.

Above the tropopause is the stratosphere, where UV absorption by ozone causes temperature to increase with altitude. Unlike the actively stirred troposphere, the stratosphere is stably stratified—hence the name—with warmer, thinner air situated above cooler, denser air.

The stratosphere culminates in a stratopause at about 50 km, above which the temperature profile inverts yet again: Radiative cooling in the overlying mesosphere causes temperature to decrease with altitude. The temperature reaches a minimum at the mesopause, around 80–85 km. It is there, at high latitudes in the summer hemisphere, that noctilucent clouds form (see figure 1).

From a purely radiative-thermodynamic perspective, the high-latitude summer mesosphere, exposed to sunlight day and night, is an odd place for clouds to form. Moreover, the mesopause is exceedingly dry; above about 80 km, what little water vapor exists is efficiently destroyed by solar Lyman-alpha photons. The water content near the mesopause is roughly one part per million, about 1/10 000 that in the troposphere. How can clouds form where water molecules are so scarce? The unraveling of that mystery began a century ago, with a puzzling ozone observation.

High and dry

In the 1920s Gordon Dobson, a British physicist and meteorologist, suggested correctly that ozone was responsible for heating the "high atmosphere," the region above the tropopause. Aware that ozone production requires sunlight and thus mainly occurs near the Sun-drenched equator, he must have been quite surprised when, one spring, he discovered an abundance of ozone in the Arctic. In a 1929 publication, he and his colleagues speculated that a slow poleward flow transported ozone from the tropics to high latitudes.[3] The ozone-rich tropical air could concentrate through descent to denser regions of the atmosphere, they argued, so the altitude of the ozone layer should be lower near the poles than in the tropics. At the time, however, there was no evidence of such an altitude variation, and Dobson dismissed his own hypothesis as unlikely.

Some 15 years later, during World War II, Dobson asked his student Alan Brewer to investigate when high-altitude aircraft would leave condensation trails. Brewer's subsequent measurements, taken at 11 km altitude aboard a Boeing B-17 bomber, revealed the stratosphere to be unexpectedly dry. "I would not have believed before I had started that the air could be so dry, but I saw it with my own eyes," he would later recall.[4]

In 1949 Brewer published an explanation for the dryness.[5] The high altitude of the tropopause in the tropics was known to cause the tropopause to be considerably cooler there than at higher latitudes. Brewer conjectured that air ascends to the stratosphere via that cold tropical tropopause, and because cold air saturates at very low water-vapor pressures, most of the air's moisture falls out as ice crystals. The "freeze-dried" air is then transported through the stratosphere to high latitudes, where it sinks.

Not only would Brewer's conjecture explain the dryness of the stratosphere, it would explain the high levels of ozone observed by Dobson. Decades would pass before the atmospheric-science community reached consensus around this unexpected north–south, or meridional, circulation. Today it is referred to as the Brewer–Dobson circulation.[6]

Brewer's findings led researchers to largely dismiss a proposal by US physicist William Humphreys that noctilucent clouds "are produced by condensation of water vapor just as are all the clouds of the lower atmosphere."[7] Stratospheric air, already bone dry, would be parched even further by Lyman-alpha radiation as it ascended into the mesosphere. Although a small amount of water vapor is produced in the middle atmosphere by methane oxidation, it seemed unrealistic that temperatures could fall low enough for so few water molecules to condense. More likely, researchers argued, the night-shining clouds consisted purely of space dust.[8] As the intricacies and implications of the Brewer–Dobson circulation came into clearer focus, however, those opinions would dramatically shift.

The "surf zone"

In the Brewer–Dobson circulation, air rises at the equator as it is heated by the Sun, and it sinks at higher latitudes as it cools by thermal emission to space. Yet the circulation is not thermally driven. The true driving force is mechanical, and the radiative heating and cooling are consequences, not causes, of the circulation. To understand why, one first needs to consider Coriolis forces.

Because Earth rotates, atmospheric flows are constantly accelerated by a Coriolis force that acts at a right angle to the flow direction. Near the winter pole, where cold, low-pressure polar air meets warm, high-pressure subpolar air, those Coriolis forces give rise to a circumpolar flow: As the air moves from high to low pressure, Coriolis forces spin the flow into a vortex that circulates eastward around the pole. During the polar night, temperature gradients in the stratosphere sharpen and the vortex intensifies.

Meanwhile, in the sunlit summer stratosphere, where ozone is vigorously heated by solar radiation, temperatures and pressures are higher at the poles than at the equator. The direction of the Coriolis force is therefore reversed, and a weak westward circumpolar wind prevails.

An east–west circumpolar wind experiences a north–south, or meridional, Coriolis force, directed equatorward for eastward winds and poleward for westward winds. Under steady flow, that Coriolis force is exactly balanced by an opposing pressure-gradient force. But that so-called geostrophic balance can be disrupted by localized disturbances known as atmospheric waves.

Among the most common atmospheric waves are planetary-scale waves, known in meteorology as Rossby waves after meteorologist Carl-Gustaf Rossby. (See the article by Jim Fleming, PHYSICS TODAY, January 2017, page 50.) Typically generated by flow interactions with mountain ranges, weather systems, or temperature gradients at land–sea boundaries, Rossby waves have wavelengths of thousands of kilometers and propagate upward from the troposphere.

Particular to fluids on a rotating spheroid, Rossby waves have the special property that they can propagate only if the

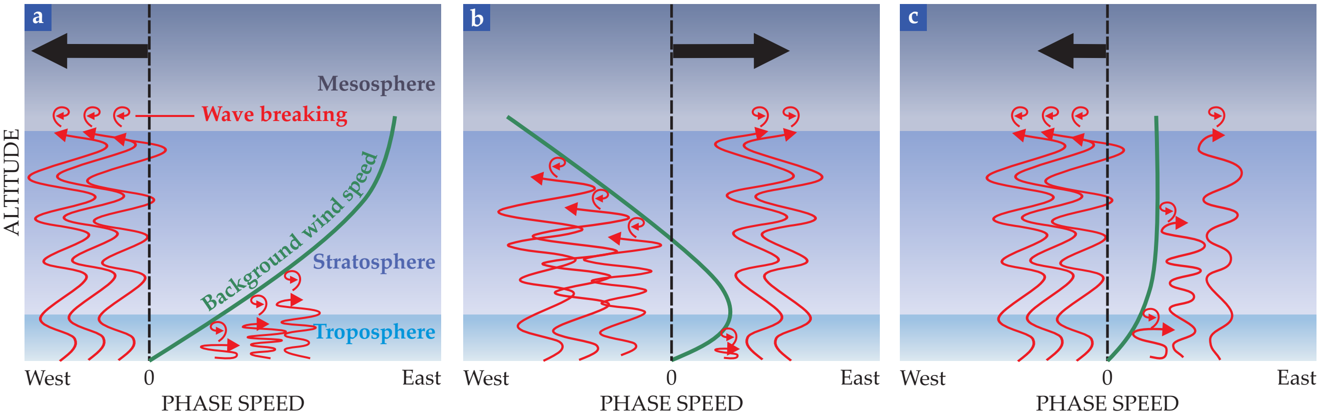

FIGURE 2. AS BUOYANCY WAVES (red) propagate up from the troposphere, they grow in amplitude and eventually break, like ocean waves on a beach, and transfer their collective momentum (thick black arrows) to the background flow. However, if a wave's east–west, or zonal, phase speed matches the background wind speed (green), it breaks prematurely. As a result, the spectrum of buoyancy waves driving the mesospheric circulation is determined by the velocity profile of the stratospheric background wind. **(a)** In the winter hemisphere, where strong, eastward stratospheric winds prevail, the mesospheric circulation is driven primarily by westward-propagating buoyancy waves. **(b)** In the summer hemisphere, where stratospheric winds flow westward, eastward-propagating buoyancy waves drive the mesospheric circulation. **(c)** The occasional weakening of the stratospheric circulation in the winter hemisphere allows some eastward-propagating waves to reach the mesosphere, which diminishes the westward buoyancy-wave forcing.

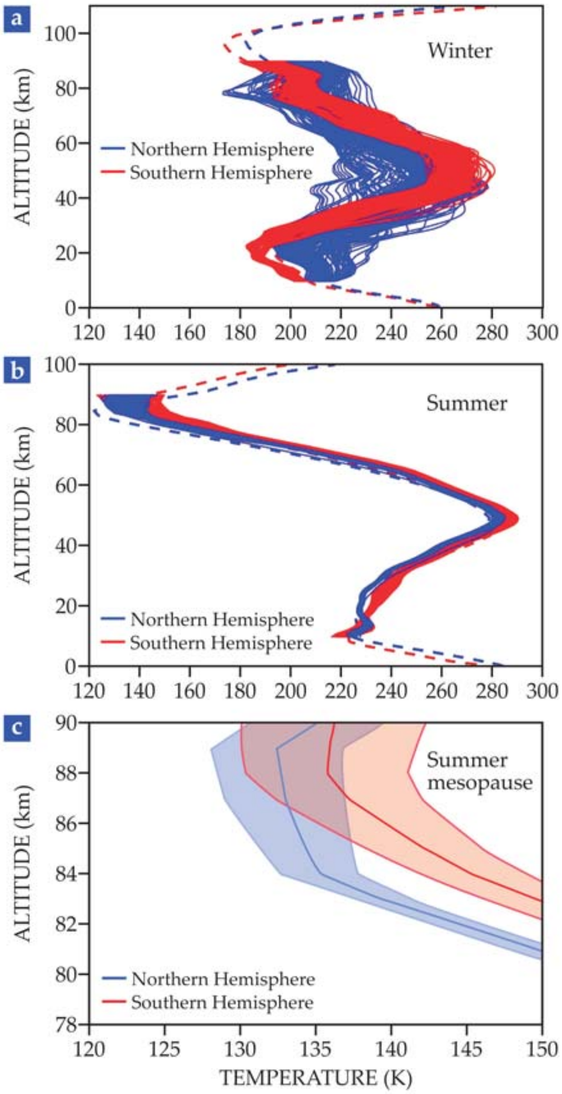

FIGURE 3. ATMOSPHERIC TEMPERATURE PROFILES measured by the *Aura* satellite's Microwave Limb Sounder during the winter polar night **(a)** and the summer polar day **(b)** reveal that winter temperatures are much more variable than corresponding summer temperatures, especially in the Northern Hemisphere. Counterintuitively, the coldest atmospheric temperatures are found in the summer, at the top of the mesosphere. In that region, known as the mesopause, **(c)** summer temperatures are more variable in the Southern Hemisphere than they are in the Northern Hemisphere. (The shaded areas denote standard deviations.) Data are averaged over latitudes of 68° and higher and are considered over the time range 2005–12; dashed curves in panels a and b correspond to simulated data produced with the Canadian Middle Atmosphere Model. (Data are available at http://climate-modelling.canada.ca/climatemodeldata/cmam/cmam30.)

east–west, or zonal, component of their phase speed is westward relative to the background wind speed.[9] Meanwhile, because the Rossby-wave-generating disturbances tend to be pinned to Earth's surface, they preferentially excite modes with a zonal phase speed of zero relative to the ground. It follows that Rossby waves can propagate only in eastward background winds.

In the winter hemisphere, where eastward winds are ubiquitous, Rossby waves can propagate well into the stratosphere. As they rise into less dense air, however, their amplitudes grow as a consequence of energy conservation. Eventually the waves grow so large that they break and dissipate turbulently, much like ocean waves on a beach. Thus the midlatitude winter stratosphere, where the breaking mainly occurs, is sometimes referred to as the stratospheric "surf zone."[10]

According to the first Eliassen–Palm theorem,[11] the momentum transferred from a breaking wave to the background flow is proportional to the wave's intrinsic phase speed—that is, its phase speed relative to the background wind. The breaking Rossby waves therefore exert a westward drag on the circumpolar winds, which disrupts the geostrophic balance. The restoration of geostrophic balance requires a weak poleward flow accompanied by an eastward Coriolis force. That poleward flow is the Brewer–Dobson circulation. Because Rossby waves can't propagate into the westward winds of the summer stratosphere, the Brewer–Dobson circulation is primarily a winter phenomenon (see figure 1).

The middle-atmosphere refrigerator

The atmospheric waves and circulation patterns we've discussed so far all unfold tens of kilometers beneath the mesopause. What have they to do with noctilucent clouds? To answer that question, we must consider a second class of atmospheric waves: buoyancy waves.

Generated in the troposphere by convection, thunderstorms, frontal systems, and flows over small-scale topography, buoyancy waves typically have horizontal wavelengths of tens of kilometers, much smaller than Rossby waves. Their restoring force is gravity—the same force that holds sway over waves on the surface of water. Yet they can propagate vertically through the atmosphere as a result of the stable stratification.[12]

Unlike Rossby waves, buoyancy waves do not have a preferred propagation direction relative to the background wind speed. Moreover, because many buoyancy waves are excited by moving sources, their phase speeds needn't be zero relative to the ground; a broad spectrum of buoyancy-wave phase speeds is generated in the troposphere. To a first approximation, a wave's zonal phase speed remains constant as it propagates upward through the atmosphere, and the different parts of the wave spectrum can be treated independently.

Because the amplitudes of buoyancy waves generally start off small, the waves can propagate all the way up to the mesosphere before they become large enough to break. However, if a wave encounters a so-called critical layer, in which the local background wind speed matches the wave's phase speed, the wave will break prematurely.[12] Background zonal flows such as the circumpolar winds therefore act as a spectral filter on the ascending buoyancy waves; the specific range of filtered phase speeds depends on the vertical profile of the background zonal flow, as illustrated in figure 2.

Waves that survive the stratosphere must eventually break in the mesosphere. There, the dissipating wave tends to drag the background flow toward its own phase speed.

We are now in a position to put together the pieces to explain the origin of noctilucent clouds. In the winter stratosphere, the eastward circumpolar flow filters out the eastward

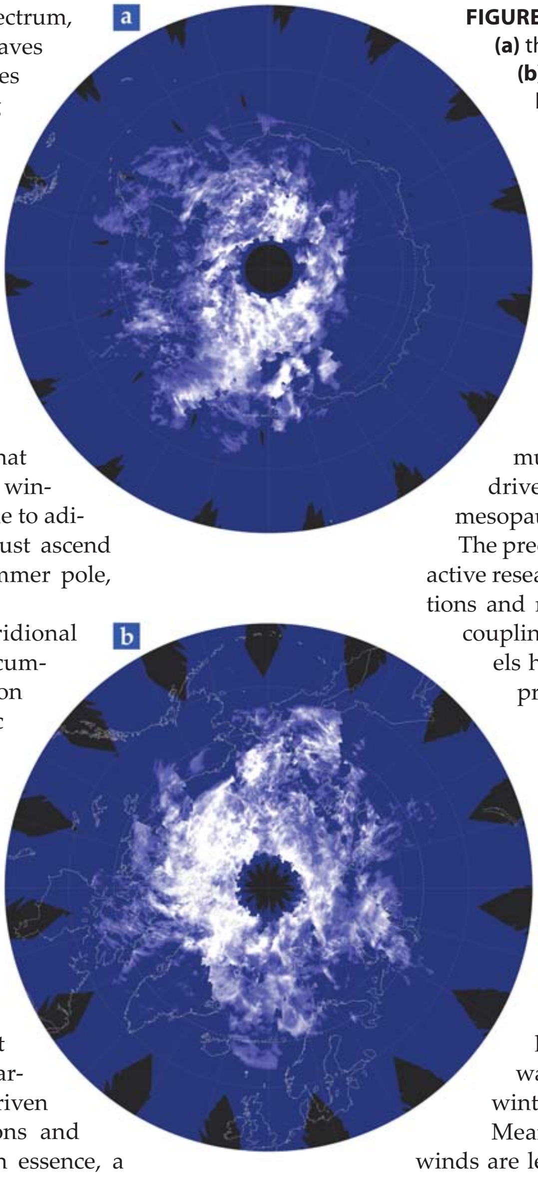

FIGURE 4. NOCTILUCENT CLOUDS above **(a)** the South Pole on 2 December 2009 and **(b)** the North Pole on 1 July 2009, as imaged by the Cloud Imaging and Particle Size instrument on NASA's *Aeronomy of Ice in the Mesosphere* satellite. The imaged regions correspond to latitudes of 50° and higher. Noctilucent clouds in the Northern Hemisphere tend to be larger and brighter than their Southern Hemisphere counterparts. (Images courtesy of the Laboratory for Atmospheric and Space Physics at the University of Colorado Boulder.)

component of the buoyancy-wave spectrum, so that only westward-propagating waves reach the mesosphere. As those waves break, they exert a westward drag that—as in the case of Rossby waves—must be balanced by a poleward flow. In the summer hemisphere, the situation is essentially the opposite: The westward circumpolar winds in the stratosphere filter out westward-traveling buoyancy waves, and the eastward-propagating waves that reach the mesosphere induce an equatorward flow (see figure 1).

Mass conservation then implies that mesospheric air must descend at the winter pole, which results in warming due to adiabatic compression. Likewise, air must ascend and adiabatically expand at the summer pole, which leads to cooling.

Although the mesosphere's meridional flow is much weaker than the circumpolar flows that induce it, the effect on temperature is dramatic: Mesospheric temperatures at the winter pole are driven far above expected values for a pitch-dark environment. At the same time, mesospheric air at the summer pole is intensely cooled. Counterintuitively, the Sun-drenched region becomes the coldest place in the Earth–atmosphere system (see figure 3). Temperatures there can fall to near −150 °C, cold enough to coax vast clouds of water ice from the dry, rarefied air. Because the mechanically driven circulation cools already-cold regions and heats already-warm regions, it is, in essence, a classical refrigerator.

Global connections

Rocket measurements from the 1960s confirmed the existence of extremely low temperatures in the summer mesopause,[13] and recent satellite measurements have confirmed that noctilucent clouds are indeed made up of water-ice nanoparticles presumably nucleated by dust from meteoric material.

Although noctilucent clouds form during summers in both the Northern and Southern Hemispheres, the Northern Hemisphere's cloud cover is brighter, extends to lower latitudes, and exhibits less day-to-day and year-to-year variation than its Southern Hemisphere counterpart (see figure 4). Those observations turn out to be related.

While searching for mechanisms behind the year-to-year variability of noctilucent cloud cover, a team that included one of us (Karlsson) discovered unexpectedly strong correlation between cloud variability and temperatures at high latitudes in the winter stratosphere—about as far from the noctilucent clouds as one can get.[14] Mass considerations suggest that the much denser winter stratosphere must drive the variation at the rarefied summer mesopause, rather than vice versa. But how? The precise mechanism remains the subject of active research, but middle-atmosphere observations and models suggest the interhemispheric coupling is robust (see figure 5). Those models have also helped identify the relevant processes.

The phenomenon starts in the polar winter stratosphere and is related to the fluctuating nature of Rossby-wave generation and breaking. Consider, for example, a sudden increase in Rossby-wave breaking in the winter stratosphere. The increased drag on the eastward circumpolar winds results in an intensified poleward stratospheric flow. That, in turn, leads to increased compression—and warming—of stratospheric air at the winter pole.

Meanwhile, the weakened circumpolar winds are less efficient at filtering out eastward-propagating buoyancy waves. As a result, more of those waves make it to the mesosphere, where they partially offset the drag exerted by the unfiltered westward-propagating buoyancy waves (see figure 2c). That weakens the poleward mesospheric flow and downwelling, and diminishes the adiabatic heating in the winter mesosphere. The result is an inverse correlation between stratospheric and mesospheric temperatures at the winter pole—a vertical coupling that's long been established in observations.

By mass conservation, increased (or decreased) downwelling and adiabatic heating at the poles implies an increase (or decrease) in upwelling and adiabatic cooling in the tropics. That gives rise to a quadrupole structure of temperature correlations at high and low latitudes in the winter stratosphere and mesosphere, as shown in figure 5b.

In turn, the tropical response to fluctuations at the winter pole—which is mediated both by stratospheric and by mesospheric meridional circulation—affects meridional temperature and pressure gradients in the summer hemisphere. Depending on the sign, those effects either weaken or strengthen the

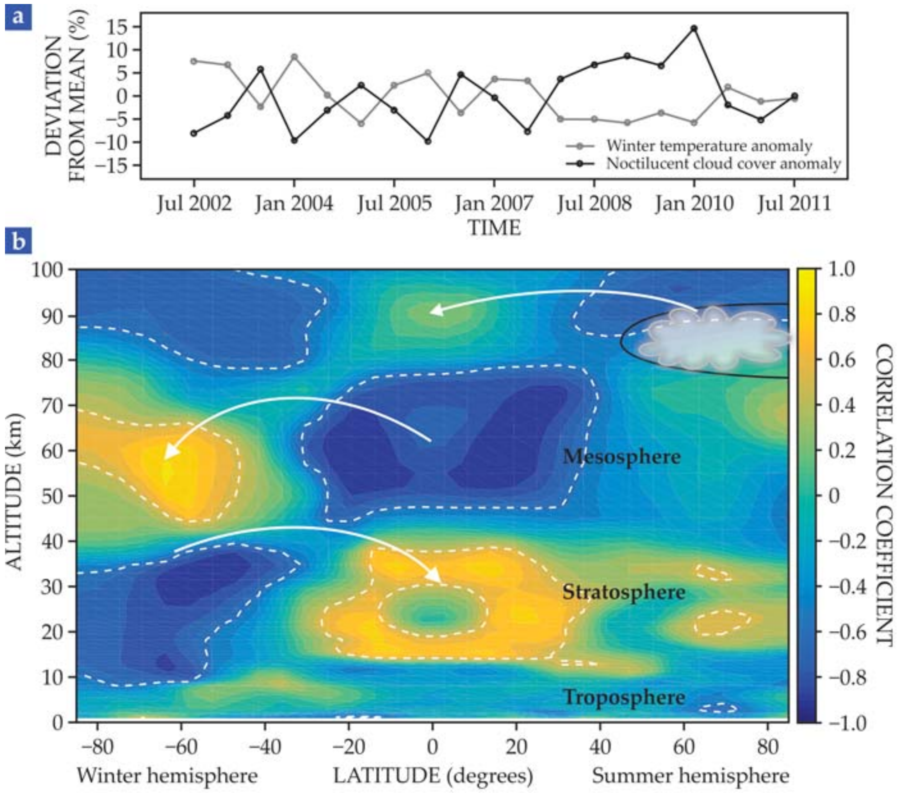

FIGURE 5. STUDIES OF NOCTILUCENT CLOUD VARIABILITY reveal rich inter-hemisphere correlations. **(a)** A plot of seasonal variations in noctilucent cloud cover in the summer mesosphere and corresponding temperature variations in the winter polar stratosphere suggests that the two quantities are correlated, with a correlation coefficient, *r*, of −0.86. The plot includes both July and January data, corresponding to peak noctilucent cloud cover in the Northern and the Southern Hemispheres, respectively. Cloud-cover data are from the Optical Spectrograph and InfraRed Imager System on the *Odin* satellite; temperature data are from the European Centre for Medium-Range Weather Forecasts reanalysis product ERA-Interim, accessible at http://apps.ecmwf.int/datasets. **(b)** Simulated data from the Canadian Middle Atmosphere Model further suggest that cloud-cover variability is correlated with temperature across a range of latitudes and altitudes. In particular, positive and negative correlation coefficients at high and low latitudes in the winter stratosphere and mesosphere exhibit a quadrupole structure, which is mirrored in the summer mesopause region. Those regions are linked by meridional circulation and associated upwelling and downwelling. White arrows denote the anomalous meridional circulation when the Brewer–Dobson circulation, described in the text, is anomalously weak. (Here, data from summers in the Northern and Southern Hemispheres have been combined, as have data from the winters; data are available at http://climate-modelling.canada.ca/climatemodeldata/cmam/cmam30.)

summer hemisphere's westward circumpolar flow, which, in turn, influences the critical-layer filtering of buoyancy waves in the summer hemisphere. In that way, a perturbation of the winter polar stratosphere can reach the summer polar mesopause.

Such stratospheric perturbations tend to be weak in the Southern Hemisphere winter, where there are relatively few longitudinal surface asymmetries capable of generating strong Rossby waves. The Southern Hemisphere's winter stratosphere is therefore calmer than its northern counterpart, and the Southern Hemisphere's Brewer–Dobson circulation is comparatively weak, which leads to a colder and stronger polar night vortex. Efficient critical-layer filtering by the southern stratosphere's strong, steady circumpolar winds results in stronger, less-variable buoyancy-wave forcing in the overlying mesosphere.

That strong buoyancy-wave forcing causes stronger cooling in the tropics, which results in a lowering of the summer mesospause temperatures as well. In that way, the calmness and coldness of the Southern Hemisphere's winter stratosphere is communicated all the way to the Northern Hemisphere's summer mesopause, causing the Arctic's noctilucent clouds to be brighter, larger, and more stable than their Antarctic counterparts. Likewise, the more dynamically active Northern Hemisphere winter stratosphere communicates its variability to the Southern Hemisphere's summer mesopause.

Such global-scale correlations demonstrate that Earth's middle atmosphere is a highly coupled system, with many nonlocal connections. That fluid dynamics concepts can explain those connections, and the improbable night-shining clouds they spawn, is a testament to the power of basic physical principles to unravel mysteries of Earth's atmosphere.

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