Weather from the Stratosphere?

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Is the stratosphere, the atmospheric layer between about 10 and 50 km, important for predicting changes in weather and climate? The traditional view is that the stratosphere is a passive recipient of energy and waves from weather systems in the underlying troposphere, but recent evidence suggests otherwise. At a workshop in Whistler, British Columbia (*1*), scientists met to discuss how the stratosphere responds to forcing from below, initiating feedback processes that in turn alter weather patterns in the troposphere.

The lowest layer of the atmosphere, the troposphere, is highly dynamic and rich in water vapor, clouds, and weather. The stratosphere above it is less dense and less turbulent (see the figure). Variability in the stratosphere is dominated by hemispheric-scale changes in airflow on time scales of a week to several months. Occasionally, however, stratospheric air flow changes dramatically within just a day or two, with large-scale jumps in temperature of 20 K or more.

The troposphere influences the stratosphere mainly through atmospheric waves that propagate upward. Recent evidence shows that the stratosphere organizes this chaotic wave forcing from below to create long-lived changes in the stratospheric circulation. These stratospheric changes can feed back to affect weather and climate in the troposphere.

Throughout northern-hemispheric winter, air flowing over mountain ranges and continental landmasses induces large planetary-scale waves in wind patterns that propagate upward, refract, and reflect in the stratosphere. The waves break in the stratosphere and above, analogous to ocean waves breaking on a beach (*2*). They thereby create fluctuations in the strength of the polar vortex formed by high-latitude winds in winter (*3*). These fluctuations tend to move down to the lowermost stratosphere, where they can last 1 to 2 months (*4*).

Calm above the storm. This photo shows the dark blue, clear stratosphere above the cloudy, stormy troposphere. The boundary between troposphere and stratosphere, the tropopause, is near 10 km at mid-latitudes, approximately the height at which commercial aircraft fly.

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The Southern Hemisphere has fewer mountain ranges and less land surface. Hence, the planetary-scale waves there are smaller in amplitude, and wave forcing of the stratosphere is less influential than in the Northern Hemisphere. Consequently, the southern-hemispheric polar vortex is relatively undisturbed during winter and early spring, and large stratospheric vortex variations occur mainly during late spring.

In the cold southern polar vortex, human-made chlorine species are transformed into ozone-destroying species. Ozone is destroyed photochemically when sunlight returns in spring. The resulting ozone "hole" leads to a relative reduction in solar heating and a stronger vortex. Observations and recent model simulations (*1*) show that the strengthening of the polar vortex during spring leads to lower surface temperatures over Antarctica and higher temperatures in mid-latitudes of the Southern Hemisphere that persist into summer.

Variability in the tropical stratosphere is dominated by the quasi-biennial oscillation (QBO), in which vertically alternating westerly and easterly wind bands descend with time. The period of the QBO at any level varies from 2 to 3 years, and it is predictable for about 1 year. The QBO affects the global stratospheric circulation, modulating the strength of both polar vortices. Observations suggest that the QBO modulates the height of the tropopause in the tropics and subtropics, affecting convection, monsoon circulations, and hurricanes.

Recent observational analyses have shown a strong connection between the strength of the stratospheric polar vortex in the Northern Hemisphere and the dominant pattern of surface weather variability, the Northern Annular Mode (NAM, also called Arctic Oscillation) (*5, 6*). The NAM is also known as the sea-level pressure oscillation between Iceland and the Azores termed the North Atlantic Oscillation (*7*).

When the NAM is positive, pressures are lower than normal over the polar cap but higher at low latitudes, with stronger westerlies at mid-latitudes, especially across the Atlantic. Northern Europe and much of the United States are warmer and wetter than average, and Southern Europe is drier than average. Variations in the strength of the polar vortex in the lower stratosphere affect the sign and persistence of the NAM at Earth's surface. Hence, the slowly varying stratospheric signal may help to predict the NAM well beyond the 7- to 10-day limit of weather prediction models.

The connection between the stratospheric polar vortex and the surface NAM has important implications for predicting the climatic response to increasing concentrations of greenhouse gases. As the troposphere warms, the stratospheric polar vortex is expected to cool; as a result, a trend toward a more positive NAM would be expected. But climate models do not agree as to whether the stratospheric polar vortex will become colder and stronger with increasing greenhouse gas concentrations. The disagreement centers on the role of waves emanating from the troposphere: If the waves strengthen sufficiently, they could overwhelm the cooling effects of increasing greenhouse gases, resulting in a warmer, weaker stratospheric vortex.

Some volcanic eruptions cause large increases in sulfate aerosols that heat the stratosphere (*8*). The altered thermal struc-

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ture in the stratosphere appears to affect the NAM at Earth's surface. Changes in solar ultraviolet radiation as a result of the 11-year solar cycle also affect stratospheric ozone and temperatures, but it is not clear whether or how these changes are communicated to the surface.

Observational and modeling results (*1*) show that stratospheric processes affect tropospheric and surface climate on many time scales. However, existing theories cannot explain the underlying mechanisms. Anomalies in the lowermost stratosphere have nonlocal dynamical effects that change winds in the troposphere (much as an electric charge has nonlocal electrostatic effects that change the surrounding electric field) (*9*). This effect can cause changes at Earth's surface but is probably too weak to account for the magnitude of the observed surface pressure changes. Changes in stratospheric winds may also cause downward reflection of planetary-scale waves originating in the troposphere, but the magnitude of this effect on the NAM remains uncertain.

Whatever the mechanism, an amplifier appears to be needed. In the upper troposphere, weak changes to the winds could be amplified by interactions with "synoptic-scale" waves with wavelengths of 1000 to 5000 km. These waves are strongest in the upper troposphere but extend several kilometers into the stratosphere. Hence, there is a region where synoptic-scale waves can be affected directly by stratospheric wind anomalies. The altered waves could in turn affect tropospheric circulation and induce surface pressure changes corresponding to the NAM (*10, 11*). A complete explanation will require carefully designed modeling experiments and comparisons with observations.

The evidence presented at the workshop (*1*) suggests that, together with the tropical oceans, the stratosphere is a player in determining the memory of the climate system. It exerts its influence on tropospheric weather most strongly during northern winter and southern spring. At its maximum, the magnitude and geographic scale of this influence may be comparable to that of El Niño–Southern Oscillation. The stratosphere may play an important role in long-term variations in the polar ice pack (*12*), sea surface temperatures, and deep ocean circulation (*7*), because the mid- and high-latitude oceans are sensitive to persistent changes in the NAM.

The most pressing issue in stratosphere-troposphere coupling is to better understand the dynamical processes by which the tropospheric circulation responds to changes in the stratosphere. This understanding may help to better predict not only weather on monthly and seasonal time scales, but also the climatic effects of greenhouse gas increases, stratospheric ozone depletion, solar changes, and volcanoes (*13*).

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CIRCADIAN RHYTHMS

Clocks on the Brain

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Circadian oscillators are widely distributed among living things. They regulate the behavioral and physiological rhythms that underlie adaptive partitioning of an organism's activities throughout the day. Individual organs such as liver, lung, and kidney contain their own circadian oscillators and are capable of generating circadian rhythms when isolated from the organism and cultured in vitro (*1*). However, in the intact animal their rhythms are coordinated in adaptive synchrony by brain structures, in particular the suprachiasmatic nucleus (SCN) of the hypothalamus. The SCN is a major coordinator of internal circadian organization (*2, 3*) and is itself synchronized with the day:night cycle by direct neural input from specialized retinal photoreceptors (*4*). The molecular loops that generate circadian oscillations within cells of the SCN and peripheral oscillators have been partially characterized and no differences have been found among them. However, oscillators in the forebrain but not in the SCN appear to use NPAS2 (neuronal PAS domain protein 2; also called MOP4), a paralog of the transcription factor CLOCK, which is a major player in the SCN (*5*). NPAS2 may substitute for CLOCK in the forebrain, and so it is of considerable interest to determine if mice deficient in NPAS2 have specific circadian phenotypes. On page 379 of this week's issue, Dudley *et al.* (*6*) reveal that mice lacking NPAS2 show abnormalities in sleep, locomotor activity, and adaptive behavior. Their findings demonstrate that NPAS2 of the forebrain oscillator cooperates with CLOCK in the SCN to influence circadian behavior.

NPAS2 is expressed primarily in the mammalian forebrain and is a member of the basic helix-loop-helix–PAS class of transcription factors. Other members of this family include the circadian clock proteins CLOCK and BMAL1 (MOP3). These proteins form heterodimers and transcriptionally activate the *per* and *cry* genes, critical events in the circadian clock mechanism of many organisms (*7–10*). In the forebrain, NPAS2 forms heterodimers with BMAL1, which activate *per* and *cry* gene expression and are required for rhythmicity; CLOCK fulfills this role in the SCN (see the figure).

Dudley and colleagues used mice deficient in NPAS2 to examine the NPAS2-driven clock of the mammalian forebrain. Such mice are known to have defects in cued and contextual memory (*11*). In the new study, the investigators found that loss of normal NPAS2 produced defects in several aspects of the circadian system, even though the SCN clock was intact. This finding strongly suggests the involvement of the forebrain in the control of circadian behavior.

The NPAS2-deficient mice exhibited normal locomotor rhythms in cyclic light, and retained this rhythmicity when transferred into constant dark conditions. However, the period of the rhythms of the NPAS2-deficient animals was short, averaging only 23.5 hours compared with 23.7 hours for wild-type animals. In addition, the nocturnal activity patterns showed an intriguing difference: Whereas normal mice typically took a break from wheel running and spent a few hours sleeping during mid to late night, the NPAS2-deficient animals showed reduced and delayed

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