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HOW SUDDEN STRATOSPHERIC WARMINGS AFFECT THE WHOLE ATMOSPHERE

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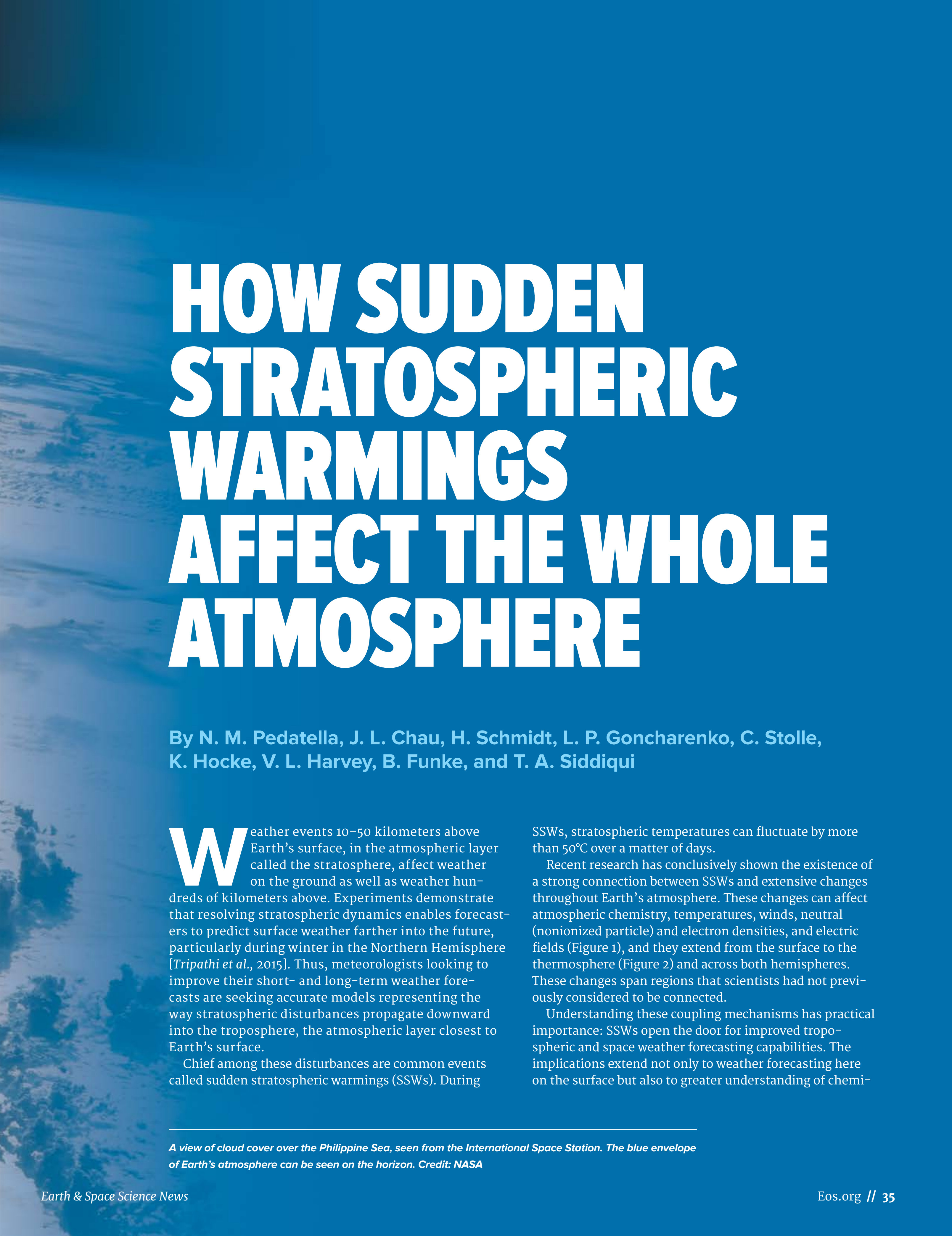
Weather events 10–50 kilometers above Earth's surface, in the atmospheric layer called the stratosphere, affect weather on the ground as well as weather hundreds of kilometers above. Experiments demonstrate that resolving stratospheric dynamics enables forecasters to predict surface weather farther into the future, particularly during winter in the Northern Hemisphere [*Tripathi et al.*, 2015]. Thus, meteorologists looking to improve their short- and long-term weather forecasts are seeking accurate models representing the way stratospheric disturbances propagate downward into the troposphere, the atmospheric layer closest to Earth's surface.

Chief among these disturbances are common events called sudden stratospheric warmings (SSWs). During SSWs, stratospheric temperatures can fluctuate by more than 50°C over a matter of days.

Recent research has conclusively shown the existence of a strong connection between SSWs and extensive changes throughout Earth's atmosphere. These changes can affect atmospheric chemistry, temperatures, winds, neutral (nonionized particle) and electron densities, and electric fields (Figure 1), and they extend from the surface to the thermosphere (Figure 2) and across both hemispheres. These changes span regions that scientists had not previously considered to be connected.

Understanding these coupling mechanisms has practical importance: SSWs open the door for improved tropospheric and space weather forecasting capabilities. The implications extend not only to weather forecasting here on the surface but also to greater understanding of chemi-



A view of cloud cover over the Philippine Sea, seen from the International Space Station. The blue envelope of Earth's atmosphere can be seen on the horizon. Credit: NASA

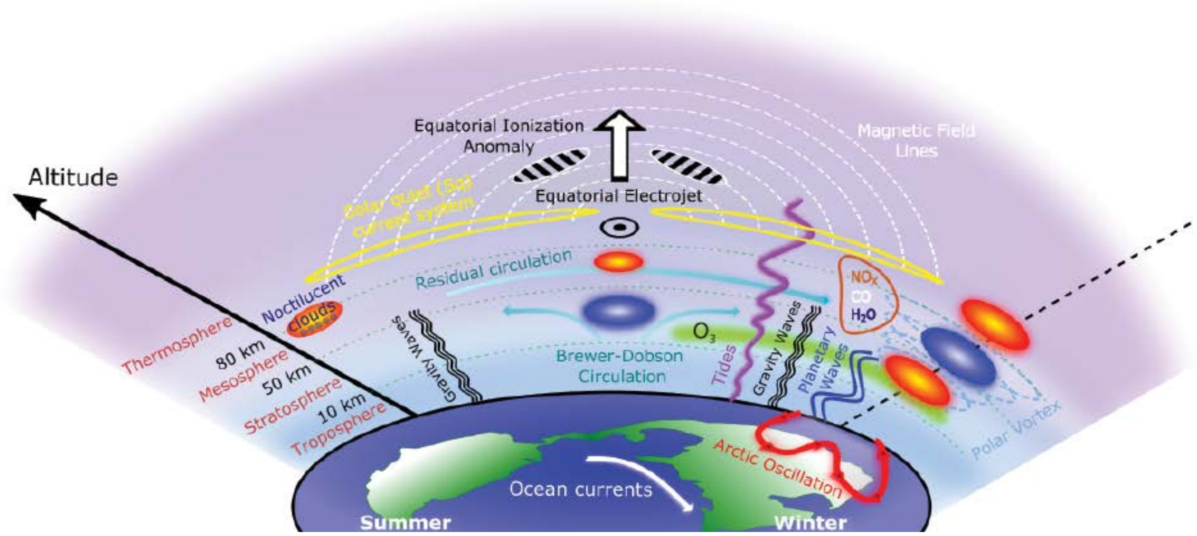


Fig. 1. Schematic of the coupling processes and atmospheric variability that occur during sudden stratospheric warming events. Red and blue circles denote regions of warming and cooling, respectively.

cal processes in the atmosphere, the sources of adverse effects on satellite navigation systems (e.g., GPS) and telecommunications, and possibly even the study of atmospheres on other planets.

How Sudden Stratospheric Warmings Begin

SSWs were first detected in the 1950s, when observations using balloon-borne instruments called radiosondes revealed that temperatures in the Northern Hemisphere wintertime stratosphere go through periods of rapid increase [*Scherhag,* 1952]. These periods spanned several days and were followed by a decrease toward typical climatological values over the next 1–3 weeks.

Further research showed that despite their name, SSWs actually start in the troposphere. *Matsuno* [1971] proposed a mechanism for the occurrence of SSWs that is still considered largely valid today: At altitudes of less than 10 kilometers above Earth's surface, planetary-scale waves form and propagate upward into the stratosphere, where they dissipate. This leads to a weakening of the polar vortex, a confined region of strong eastward winds that forms during wintertime at high latitudes. As the polar vortex weakens, polar stratospheric temperatures increase.

SSW Patterns

The planetary waves that drive the formation of SSWs tend to have larger amplitudes in the Northern Hemisphere compared with the Southern Hemisphere. This is partly because of differences in the distributions of mountains, land, and sea in the hemispheres—tropospheric planetary waves are fed by temperature contrasts between land and ocean as well as by mountains that channel wind flow, factors more prevalent in the north. Thus, SSWs occur primarily in the Northern Hemisphere, although a single strong SSW in the Southern Hemisphere was observed in September 2002.

Although the magnitudes of SSWs can vary, scientists are particularly keen to understand very strong midwinter warmings, referred to as "major" warmings. A variety of definitions exist, but the criteria for what constitutes a major warming in the Northern Hemisphere often include the reversal from eastward to westward of the longitudinal mean winds at 60°N latitude and about 30 kilometers in altitude.

Major SSWs occur in the Northern Hemisphere winter about six times per decade [*Charlton and Polvani,* 2007], depending upon the long-term variations in tropospheric and stratospheric winds, such as those driven by the El Niño–Southern Oscillation, quasi-biennial oscillation, and solar activity [*Labitzke,* 1987].

Surface Effects and Weather Prediction

Hemisphere-scale weather patterns in the wintertime Northern Hemisphere troposphere and stratosphere are associated with changes in an index called the Northern Annular Mode (NAM) [*Thompson and Wallace,* 1998]. In the troposphere, the NAM is characterized by a pressure anomaly over the polar region, with an opposite-signed anomaly near 50°–55°N. That is, high-pressure anomalies over the North Pole are coupled with low-pressure anomalies farther south and vice versa. This pattern is related to stronger eastward winds during positive NAM phases (i.e., for a negative polar pres-

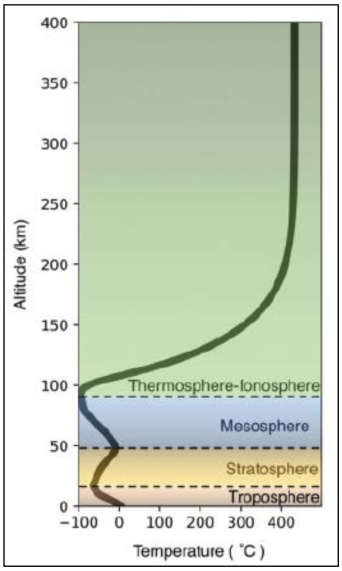


Fig. 2. Vertical profile of atmospheric temperature indicating the different layers of the atmosphere.

sure anomaly) and westward wind anomalies during negative NAM phases. In the stratosphere, the NAM describes the strength of the polar vortex. Negative NAM phases are associated with weak stratospheric polar vortices, like those that occur during SSWs.

NAM anomalies often move downward from the stratosphere to the tropopause (the boundary between the troposphere and the stratosphere) over the course of about 10 days and can then significantly alter extratropical weather patterns during the following 2 months. Knowledge of this downward movement can extend the range of weather forecasts.

Outside the tropics, an SSW can displace extratropical cyclonic storm tracks toward the equator, among other consequences. This displacement increases the probability that storms will pass over the United Kingdom and southern Europe, and it increases the probability of record-breaking cold temperatures and snowfall in eastern North America [*Kidston et al.,* 2015]. Although atmospheric reanalyses and climate model simulations clearly illustrate the downward propagation of the NAM anomalies, we do not yet fully understand the mechanism responsible for the stratospheric control of tropospheric weather patterns.

The downward influence of SSWs extends even to the ocean by providing a persistent forcing to surface winds, which modulate large-scale ocean circulation [*Reichler et al.,* 2012]. However, unlike the relatively short term atmospheric effects, SSWs contribute to variability in the ocean on timescales of 5–10 years. Such variability on longer timescales arises because of the clustering of SSW occurrences, leading to a consistent, multiyear forcing at the ocean surface.

Upward and Outward

Stratospheric wind changes during SSWs kick off a chain of events that lead to anomalies in the stratosphere and up into the next layer, the mesosphere, in both hemispheres. The stratospheric circulation changes during SSWs modulate the spectrum of atmospheric waves that propagate upward into the mesosphere, leading to changes in the daily average wind speeds and temperatures in the upper mesosphere and lower thermosphere (80–120 kilometers above the surface).

The mesospheric wind changes are related to the ways that winds in the stratosphere influence the filtering of atmospheric gravity waves. The mesospheric anomalies often, although not always, initially appear a week or more prior to the peak stratospheric disturbances. This timing gives the appearance that the SSW anomalies propagate downward all the way from the mesosphere to the troposphere, although we do not presently know whether the mesosphere has any control over stratospheric variability.

Warming of the Southern Hemisphere (summer) polar mesosphere also occurs during SSWs. This warming is related to wave-driven circulation changes in the Northern Hemisphere, which lead to a warming of the tropical mesosphere. The altered temperature gradient between the tropics and the southern pole alters the midlatitude summer circulation, changing the filtering of atmospheric gravity waves. With a different gravity wave spectrum reaching the mesosphere, polar summer mesosphere temperatures increase [*Körnich and Becker,* 2010]. This, in turn, modulates the formation of polar mesospheric, or noctilucent, clouds [*Karlsson et al.,* 2007].

Much of the high-altitude variability is driven by a phenomenon called atmospheric tides. Like ocean tides, these are periodic, global-scale oscillations in the atmosphere based on the 24-hour day and the effects of the Sun and the Moon on the atmosphere. Changes in stratosphere–mesosphere winds during SSWs lead to a change in atmospheric tides in both the Northern and Southern Hemispheres, demonstrating the global influence of SSWs on the mesosphere.

We also see surprisingly large changes in modes of the gravitationally driven lunar tide. Although generally relatively small, during SSWs the lunar tide meets or even exceeds the amplitude of the normally much larger thermally driven solar atmospheric tides [*Pedatella et al.,* 2014].

Chemistry Effects

Effects from SSWs are not limited to warming and cooling mechanisms. The variability in the stratosphere and mesosphere also modifies the atmospheric chemistry in these regions. This variability includes altering the distribution of atmospheric trace gases, including stratospheric ozone.

In the stratosphere, the descending motion of air within the polar vortex leads to a sharp gradient in trace gas concentrations across the vortex edge. The vortex edge is essentially a barrier between large trace gas concentrations within the vortex and small concentrations outside the vortex, or vice versa. The vortex breakdown during SSWs removes this barrier, increasing the mixing of air between midlatitudes and the polar region. This leads to more homogeneous concentrations throughout the Northern Hemisphere stratosphere during and after SSWs. In addition, SSW-induced temperature changes can modify chemical reaction rates, which is particularly important for upper stratospheric ozone.

Following certain SSW events, the polar stratopause (the boundary between the stratosphere and the mesosphere) re-forms at an altitude of 70–80 kilometers, which is approximately 20 kilometers higher than its usual position. Interaction between the wave forcing and mean winds causes the stratopause and strong wave forcing to descend in altitude. These changes cause chemical species that typically reside in the upper mesosphere to be transported downward into the lower mesosphere and upper stratosphere during the weeks following an SSW. This downward transport results in anomalously large concentrations of, for example, nitrogen oxides (NO_x) and carbon monoxide (CO) in the lower mesosphere and upper stratosphere. The transport of these gases to a lower location in the atmosphere has implications for the chemistry in the polar winter stratosphere, including enhanced levels of NO_x that increase the destruction of ozone.

The Space Weather Connection

Space weather—which describes conditions in the area between the Earth and the Sun—is determined not by the Sun alone, despite popular impressions. SSWs are a considerable source of variability in Earth's thermosphere and ionosphere and are thus an important component of near-Earth space weather.

This is especially true in the equatorial and low-latitude ionosphere, where high ionospheric conductivity in the low-latitude equatorial region causes the most significant SSW-induced variability. SSW events modify large-scale electron density structures within about 20° of the geomagnetic equator in a phenomenon known as the equatorial ionization anomaly [*Chau et al.,* 2012]. The electron density variability during SSWs is of a magnitude similar to that of a moderate geomagnetic storm [*Goncharenko et al.,* 2010], demonstrating that SSWs are a potentially important contributor to adverse space weather.

Tidal changes during SSWs additionally alter the equatorial electrojet, a narrow band of electric current along the geomagnetic equator at an altitude of about 100 kilometers, as well as the global solar quiet current system. Researchers have yet to determine the effect that the variability of the electric field and vertical plasma motion has on the day-to-day occurrence of equatorial postsunset ionosphere irregularities. These irregularities affect communication and navigation signals, so understanding how SSWs induce electric field variability, which would enable us to improve our predictions of these events, is of considerable importance.

SSWs also drive variations in the composition, density, temperature, and winds of the upper thermosphere (about 400 kilometers above Earth's surface). On global scales, satellite drag observations have revealed a reduction in the thermosphere density and temperature during SSWs [*Yamazaki et al.,* 2015]. The roughly 5% reduction in neutral density can have an appreciable impact on satellite drag and orbital debris.

Future Opportunities

The large atmospheric anomalies during SSW episodes allow a better understanding of whole-atmosphere coupling processes. This coupling presents a practical opportunity to improve both atmospheric and space weather forecasting. Detailed knowledge of how stratospheric anomalies influence tropospheric weather will open the door to improved forecasts. The effects of SSWs on the upper atmosphere will enable scientists to improve space weather forecasting, especially for determining the day-to-day variability in the ionosphere.

The physical processes that contribute to the variability of the Earth's atmospheric layers also operate in other planetary atmospheres and define their dynamics and energy budgets. Information gained from the study of coupling between Earth's atmospheric layers is potentially applicable to atmospheres of other planets.

It is unclear what, if any, effect climate change has on the frequency of occurrence and characteristics of SSWs. Moreover, current definitions of SSW events may not be appropriate in a drastically different climate [*Butler et al.,* 2015]. But it is crucial to understand that in a complex and evolving Earth system, any change in SSWs will invariably involve changes throughout the whole atmosphere.

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