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Short Communication

The Southern Hemisphere sudden stratospheric warming of September 2019

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Sudden stratospheric warmings (SSW) are extreme cases of stratospheric polar vortex weakening [1]. They are termed minor when a reversal of the stratospheric meridional temperature gradient in the subpolar region at 10 hPa and poleward of 60° occurs, or major when this is accompanied by a complete reversal of the stratospheric circumpolar westerly jet [2]. Although SSWs occur in both hemispheres, major SSWs are usually observed in the Northern Hemisphere, with a frequency of approximately six per decade. In contrast, only one major SSW has been recorded in the Southern Hemisphere, which occurred in 2002 [3].

Despite the lower frequency of SSWs in the Southern Hemisphere, they can exert remarkable impacts on both the stratosphere and troposphere [3, 4]. The Antarctic SSW increases polar stratospheric temperature and suppresses the formation of polar stratospheric clouds, slowing down the catalytic chemical reactions in the polar stratosphere that facilitate ozone depletion [5]. It also decelerates the circumpolar westerly jet and increases meridional mixing between polar air with low ozone density and mid-latitude air with high ozone density [6]. Both effects promote a reduced Antarctic ozone hole [3]. The Antarctic SSW-related stratospheric circulation anomalies can descend into the troposphere in the form of Southern Annular Mode and persist for three months, which is more persistent than its Northern Hemispheric counterpart [4]. The resultant tropospheric circulation anomaly sometimes facilitates severe hot and dry conditions in Australia in the following seasons, increasing the likelihood of wildfire risks [7].

In early September 2019, the mid-stratospheric air temperature increased sharply over the Antarctic (Fig. 1a [8]), and the circumpolar zonal-mean westerlies weakened but did not reverse to easterlies (Fig. 1b). These results identify the occurrence of a so-called minor SSW event in the Southern Hemisphere in September 2019. Though the SSW is classified as minor, according to the standard World Meteorological Organization (WMO) definition [2], it was accompanied by the smallest Antarctic ozone hole on record [9], breaking two previous records set in 1988 and 2002 [3]. Considering the rarity of these events in the Southern Hemisphere, this unusual SSW in 2019 deserves further investigation and comparison with the previous two in 1988 and 2002 to understand their common features.

The reanalysis data used in this study are from the Japanese 55-year (JRA55) reanalysis dataset, which has a 1.25°×1.25° horizontal resolution and extends from 1000 to 1 hPa with 37 layers [10]. The date when the 2019 minor SSW reached its peak 10 hPa air temperature is 19 September, which is ~10 d earlier than the timing of the 1988 minor SSW (28 September) and the 2002 major SSW (29 September) (Fig. 1a). The change in 10 hPa polar air temperature is similar to 1988 and 2002 SSW, with an increase of ~45 K from the middle to late September. In contrast, from late August to mid-September in 2019, the comparative change was 70 K, suggesting that the 2019 SSW has the strongest 10 hPa polar cap warming in the JRA55 reanalysis from 1979 to 2019. The zonal mean air temperature at their respective times of peak 10 hPa warming reveals different altitudes of the three SSWs (Fig. S1a-c online). The maximum polar temperature in 2019 and 2002 was centered in the middle stratosphere between 5 and 10 hPa, whereas in 1988, the maximum was mainly located in the upper stratosphere above 5 hPa. This feature can also be seen in the polar temperature anomalies (Fig. S1d-f online). In regard to possible connections with the troposphere, the anomalous polar warming in both the 1988 and 2019 minor

SSWs was confined above 100 hPa during their peak days, whereas that in the 2002 major SSW extended downward to about 300 hPa (Fig. S1d-f online).

An inspection of the 10 hPa zonal mean zonal wind ($\bar{u}_{10}$) suggests that the 2019 SSW exhibits the second strongest circumpolar westerly deceleration (75 m/s, Fig. 1b), defined as $\bar{u}_{10}$ on the first date when $\bar{u}_{10}$ falls below its climatology and does not exceeds its climatology before the SSW minus the minimum $\bar{u}_{10}$ before the SSW. The only stronger event on record is the 2002 major SSW, which featured a reversal of the circumpolar westerly jet and deceleration of 103 m/s (Fig. 1b). Besides, the stratospheric equatorial winds were all easterly at 10 hPa during the three SSWs (Fig. S1a-c online). The altitudes of the equatorial easterly were quite similar in 2002 and 2019, and that in 1988 was a bit lower (Fig. S1a-c online), suggesting that the three SSWs occurred in a similar (westward shear) phase of the quasi-biennial oscillation (QBO) [11]. This coincidence implies a plausible role of the descending easterly phase of the QBO in the occurrence of the three SSW events via weakening the Antarctic stratospheric polar vortex [11].

The occurrence of SSWs can be well explained by the dynamical forcing of planetary waves propagating from the troposphere into the stratosphere [1]. The right panels in Fig. 2 show the evolution of the 45°-75°S averaged zonal mean eddy heat flux across 100 hPa, denoting the planetary wave energy entering the stratosphere. The negative eddy heat flux, i.e., upward planetary wave energy, was significantly stronger than the climatology and lasted for about one month before the peak of the 2019 SSW

(Fig. 2c). In contrast, peak heat-fluxes were stronger in the 2002 SSW and much shorter-lived for both the 2002 and 1988 SSWs (Fig. 2b, c). The resultant overall time-integrated (e.g., 25, 30, 35, or 40 d prior to the peak warming) eddy heat flux of planetary wave during the 2019 SSW is stronger than those during the 2002 and 1988 SSWs because of its long duration. These results suggest the crucial role of the troposphere-originated planetary wave forcing in the occurrence of the three SSWs despite some differences in their duration and strength.

Atmospheric blocking can alter the strength and upward propagation of tropospheric planetary waves [12], and often precedes the occurrence of SSWs in the Northern Hemisphere [13]. This motivates an examination of the three Antarctic SSWs for a possible association with atmospheric blocking. Other factors, such as oceanic forcing, may also alter the planetary waves [14], but we will focus on the role of the atmospheric blocking in this study. The left panels in Fig. 2 show the Hovmöller diagram of the blocking index during the three SSWs. The blocking index is a one-dimension version of [13] for the Southern Hemisphere:

$$GHGS(\phi_0) = \frac{Z500(\phi_S) - Z500(\phi_0)}{\phi_S - \phi_0}, \quad (1)$$

$$GHGN(\phi_0) = \frac{Z500(\phi_0) - Z500(\phi_N)}{\phi_0 - \phi_N} \quad (2)$$

where *Z*500 is the geopotential height at 500 hPa, $\varphi_S = \varphi_0 - 15°$, $\varphi_N = \varphi_0 + 15°$, and the central latitude ϕ_0 ranges from 30°S to 75°S. An atmospheric block is detected if $GHGN(\phi_0) > 0$ and $GHGS(\varphi_0) < -10\,\mathrm{m/lat}$ are both satisfied. It is interesting that the blocking index shares close similarities among the three SSWs. Periodic blocking events were observed between approximately 120° and 90°W before the maximum stratospheric polar warming occurred. Moreover, the occurrence of the blocking corresponded well with pulses of the negative eddy heat flux. This consistency suggests that the atmospheric blocking between 120° and 90°W is essential for the three SSWs.

In the climatological mean, the major ridge of planetary wave in September is located between 180° and 30°W in the Southern Hemisphere (Fig. S2 online). Hence, the blocking between 120° and 90°W can efficiently increase the amplitude of planetary waves and facilitate upward propagation of planetary waves into the stratosphere via linear constructive interference [12, 15]. Meanwhile, the negative geopotential height anomalies between 30° and 120°E can deepen the climatological trough and thereby enhance the upward propagation of planetary waves, too. This mechanism is further confirmed by the evolution of the 500 hPa geopotential height field before the three SSWs (Figs. S2-S4 online). The blocking before the SSW has a larger zonal extent in 2002 (Figs. 2b and S3d-f online) than in 1988 and 2019, which accounts for the strong pulses of eddy heat flux in 2002. The pattern is more continuous with a longer duration in 2019 (Figs. 2c and S4 online) than in 1988 and 2002, which explains the long duration of eddy heat flux in 2019.

This study documents a rare SSW observed in the Southern Hemisphere during September 2019 and compares it with two previous SSWs observed in 1988 and 2002.

The 2019 SSW is a minor SSW according to the standard definition of the WMO but caused the most substantial stratospheric polar cap warming and the second strongest circumpolar westerly deceleration since 1979. The polar-cap temperature rose by 70 K within approximately three weeks, exceeding that of the 2002 major SSW and the 1988 minor SSW. As a result, the 2019 SSW led to the smallest Antarctic ozone hole on record. The dynamical forcing of upward-propagating planetary waves from the troposphere well explains the three SSWs. Of the three SSWs examined peak forcing was strongest in 2002 but was longest in 2019, by the measure of eddy heat flux. The abnormal planetary waves during the three SSWs can be attributed to atmospheric blocking between 120° and 90°W, which amplified the ridge of climatological planetary waves and facilitated enhanced upward propagation of planetary waves into the stratosphere via linear constructive interference. Future studies should further elucidate the role of atmospheric blocking, especially near South America, during Antarctic polar vortex extremes.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Lin Wang, Xiaocen Shen, and Scott Osprey initiated the study. Lin Wang designed the scheme, Xiaocen Shen analyzed data and drew figures, Xiaocen Shen and Lin Wang wrote the manuscript. All the authors interpreted results and revised the manuscript.

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Figure Captions

Fig 1. Evolution of the stratospheric polar cap temperature and circumpolar westerly jet. (a) Daily evolution of the 80°-90°S averaged 10 hPa air temperature from 1 June to 1 October in 2019 (Red), 2002 (blue), 1988 (green), other years from 1979 to 2018 (grey), and their climatology (black). Red, blue, and green dashed vertical lines indicate 19 September 2019, 29 September 2002, and 28 September 1988, respectively, the date when the maximum 10 hPa warming was observed. (b) is the same as (a), but for the 10 hPa zonal mean zonal wind at 60°S.

Fig 2. Evolution of the tropospheric blocking and quasi-stationary planetary wave propagating into the stratosphere during the three Southern Hemispheric SSWs. (a) Hovmöller diagram of the blocking index (left panel) and the 45°-75°S averaged zonal mean eddy heat flux at 100 hPa (right panel) from 1 August to 1 October in 1988. (b) and (c) are the same as (a), but for 2002 and 2019, respectively. Red lines in (a-c) indicate 28 September 1988, 29 September 2002, and 19 September 2019, respectively, the date when the maximum 10 hPa warming was observed. Thick blue line on the right panels indicate values exceeding the 99.9% percentile estimated from 10,000 bootstraped samples.

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