Robust Enhancement of Tropical Convective Activity by the 2019 Antarctic Sudden Stratospheric Warming

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Abstract

Tropical tropospheric responses to a sudden stratospheric warming (SSW) event that occurred over Antarctica in September 2019 have been investigated by conducting a series of ensemble forecast experiments. Comparative examinations between the normal forecast and the partially nudged forecast, whose stratospheric circulation is constrained to a reanalysis, reveal a significant enhancement/suppression in the convective activity (upwelling/downwelling) over the northern/southern part of the tropics. Such an acceleration of the Hadley circulation is set up by thermal structural changes in the upper troposphere and lower stratosphere. The tropical cooling caused by the enhanced Brewer-Dobson circulation destabilizes the environment there and stimulates deep cumulus convections. In this case, the southern area of the Asian monsoon region is particularly sensitive. Although details of the triggered response depend on the adopted cumulus parameterization scheme, a boosting tendency of the convective upwelling via the SSW is robust.

Plain Language Summary

A rare Antarctic sudden stratospheric warming (SSW) event that occurred in September 2019 provides an opportunity to investigate its impact on convective activity in the tropics. By comparing the normal forecast and a “perfect stratosphere” forecast, this study confirmed the robust influence of the SSW on the cumulus convection over the Northern Hemisphere tropics. In other words, the Antarctic SSW could enhance the probability of extreme weather in boreal summer to early autumn, including the genesis and development of tropical cyclones. Therefore, this process of the teleconnection between the Antarctic stratosphere and the tropical troposphere has the potential to be a valuable source of extended-range predictability in practical seasonal forecasts.

1. Introduction

The stratospheric polar vortex in the 2019 austral spring was significantly distorted, although it did not record the second ever major sudden stratospheric warming (SSW) in the Southern Hemisphere (SH) after that of 2002 since observations began in the 1950s. The westerly zonal-mean zonal wind at 60°S 10 hPa (whose reversal is a measure of the major SSW) suddenly slowed about 90 to 10 m s\(^{-1}\) from late August to mid-September. This weakening magnitude is not far behind from that of the 2002 major event accompanying a change from about 60 to −20 m s\(^{-1}\) in late September (see, e.g., Lim et al., 2020). In fact, due to the very strong Brewer-Dobson (B-D) circulation enhanced by this extreme vortex weakening event of 2019, the polar warming and the equatorial cooling in the stratosphere showed the largest anomalies for September in the 40-year observational record of the satellite era, consistent with the record-breaking accumulation of upward propagating planetary wave activity (Figures S1–S3 and Text S1 in the supporting information).

Impacts of this extreme event on other parts of the Earth system, such as the smallest Antarctic ozone hole on record (since its discovery over three decades ago) and the extreme negative phase of the Southern Annular Mode (SAM) in the ensuing early summer season are of significant interest, as numerous researchers and forecasters already discussed (Hendon et al., 2019; Lim et al., 2020). As is well known, the SAM influences the hemisphere-wide tropospheric processes (e.g., Gillett et al., 2006; Thompson & Wallace, 2000). The downward propagation of SAM (e.g., Thompson et al., 2005) could become a source of seasonal predictability, as that in the Northern Annular Mode (NAM) (e.g., Baldwin & Dunkerton, 2001; Sigmond et al., 2013), which is an attractive theme in the recent dynamical forecast studies (e.g., Byrne et al., 2019; Sceviour et al., 2014). In particular, since the stratospheric downward coupling contributes to the hot and dry
extreme conditions in Australia (e.g., Lim et al., 2019), the effect of this minor SSW on the 2019–2020 Australian bushfires (Nolan et al., 2020) warrants further investigation. However, its attribution is not straightforward due to many other influencing factors, including the positive Indian Ocean Dipole mode (Doi et al., 2020; King et al., 2020; Saji et al., 1999) and the global warming trend (Phillips & Nogrady, 2020).

Simultaneously, the SSW impact on the tropical convective activity, as discussed in the past SH SSWs (Eguchi & Kodera, 2007, 2010; Kodera & Yamada, 2004), presents another attractive topic for investigation. Recent examinations of this process in individual cases in the Northern Hemisphere (NH) (e.g., Evan et al., 2015; Kodera, Eguchi, et al., 2011; Kodera et al., 2015; Resmi et al., 2013; Sridharan & Sathishkumar, 2011), in addition to analyses of the composite of multiple events (Bal et al., 2017; Kodera, 2006; Kuroda, 2008) and deterministic model integrations (Eguchi et al., 2015), suggests that the enhancement of the B-D circulation associated with SSWs is linked to the enhancement in the organized tropical convections and the Hadley circulation. It seems that the SSW event accompanies a seesaw of convective activity in the troposphere—an enhancement in the convective activity of the tropics in the opposite hemisphere but a suppression in that of the same hemisphere. Nevertheless, the robustness of the tropical response is unclear, since the previous investigations relied mainly on the analysis of limited samples of observations or free-evolving numerical integrations. One exception is the study by Kodera, Mukougawa, et al. (2011), who examined the impact of an Arctic SSW on the tropical convective activity by comparing numerical experiments with and without the SSW. They controlled the onset of SSW (the amplification of planetary waves) by introducing a tropospheric blocking-like anomalous field in the model's initial conditions and found significant differences as expected. Such a numerical approach would be appropriate to disentangle the SSW influence on the tropical convective activity. However, the prescribed tropospheric wave source may also control synoptic variations in the middle-to-low latitude, for example, cold surges that affect tropical convections including the tropical cyclone development (Chang et al., 2003; Wang et al., 2012). Therefore, the robust influence of SSW on the tropical convective activity has not been confirmed, despite its potential to be a promising source of extended-range predictability if its influence is robust and detectable in the practical forecast.

This study investigates the influence of the 2019 Antarctic SSW on the tropical convective activity through a series of ensemble forecast experiments in a practical setting. In particular, by conducting ensemble “nudged” integrations, whose stratospheric circulation is relaxed toward a reanalysis, and comparing them with normal ensemble forecasts that failed to reproduce the onset of the warming event (due to too early initialization), we successfully deduce a significant effect of the SSW on the tropical tropospheric circulation. Since the settings other than the nudging are identical between the two ensembles, any tropospheric difference seen in the following results, by experimental design, must ultimately be of stratospheric origin. Such a nudging approach has been successful in showing the probabilistic NAM response to virtual SSW events in the Canadian Middle Atmosphere Model (CMAM) (e.g., Hitchcock & Simpson, 2014; Maycock et al., 2020). By adopting this approach in a practical ensemble prediction system which has often been used in the SSW predictability studies (e.g., Noguchi et al., 2016, 2020), this study tries to disentangle the stratospheric influence on the tropical convections in a more sophisticated manner than Kodera, Mukougawa, et al. (2011).

2. Experimental Settings

We used an atmospheric general circulation model of the Meteorological Research Institute (MRI-AGCM; e.g., Mizuta et al., 2012) for forecasting, with similar settings to those used by Mukougawa et al. (2017) and Noguchi et al. (2016, 2020). The horizontal resolution of the MRI-AGCM used in this study is T159 (~110 km), and there are 60 vertical layers with the top boundary at 0.1 hPa. A modified Tiedtke-type mass-flux scheme (Yoshimura et al., 2015) was used for the parameterization of cumulus convection. As boundary conditions, we used the monthly climatological sea surface temperature (SST) with the addition of a constant SST anomaly from the climatology at the initial time. The concentration of ozone is specified by the zonal-mean climatological value, although the chemical impact on the forecast skill during the event might be one of another attractive investigations.

We prepared initial conditions by using the ensemble prediction system of the MRI (MRI-EPS; Yabu et al., 2014). The MRI-EPS generates initial perturbations by a breeding of growing modes (BGM) method (Toth & Kalnay, 1993). We produced 25 perturbations every day by using the Japanese 55-year reanalysis
By adding and subtracting these perturbations to JRA-55, 50 perturbed initial conditions were created besides the control initial condition. Therefore, we obtained 51-member initial conditions for every 12 Coordinated Universal Times. Sixty-day numerical integrations were conducted for all forecasts.

After confirming the poor deterministic predictability of the SSW onset from the initial conditions of early to middle August (see Text S2 and Figure S4 in the supporting information for details), we conducted two types of 51-member ensemble integrations starting from 10 August 2019: the normal forecast (FREE) and the partially constrained forecast (NUDGE). The stratospheric circulation of the latter is constrained to JRA-55 by applying an additional relaxation on the zonal and meridional winds (X) of the form $-K(p)(X - X_{JRA})/\tau$. Here, the $X_{JRA}$ is the JRA-55 field, $\tau$ is 0.1 day, and $K(p)$ is a height-dependent prefactor that varies between 0 and 1. The relaxation is applied only above the middle stratosphere, with a $K(p)$ that is 0 from the surface to 40 hPa, rising linearly to 1 at 1 hPa, so as not to constrain the lower atmospheric circulation directly (by considering the possible overshooting height; e.g., Sherwood & Dessler, 2001). Note that the nudging is applied in the grid space, unlike the CMAM setting (cf. Hitchcock & Simpson, 2014; Simpson et al., 2011, 2013) that relaxes only the zonal mean spectral components of temperature, vorticity, and divergence fields. Compared with the CMAM setting with $K(p)$ of 0 from the surface to 64 hPa and $\tau$ is 0.25 day, a more stringent constraint in the upper stratosphere with a wider transition region is adopted. This setting enables us to investigate the response of freely evolving tropospheric circulation even in the tropics, under the “perfect” stratospheric circulation including wave components. Considering other relaxation settings in various literature (e.g., Davis et al., 2020; Douville, 2009; Hitchcock & Haynes, 2016; Jung et al., 2010), further sophistication of the nudging methodology might be possible. However, the current setting works well, as shown in the following results. Therefore, we leave it for a future investigation.

3. Results

As shown in Figure 1, our experimental settings work well as designed. All ensemble members of the NUDGE forecast are well constrained around the reanalysis, while the FREE forecast misses the SSW. Although a few members follow the SSW, the majority members of the FREE forecast could not reproduce the southern polar warming at 10 hPa (Figure 1a). As a result, the ensemble mean shows a nearly climatological time evolution. Although it is the same with the equatorial cooling at 50 hPa (Figure 1b), it is worth noting that the NUDGE forecast follows the reanalysis despite this region being below the nudging layers and its temperature is not constrained directly. Note that the tropospheric circulation in both forecasts evolves freely, and their ensemble spreads of them are already saturated in early September (see Figure S5). Hereafter, we investigate how the difference between NUDGE and FREE forecasts grows in the tropical troposphere.

The enhancement of the B-D circulation, which caused the polar warming and equatorial cooling in the stratosphere, is prominent in the early half of September as the temperature variation peaked around that time. Therefore, we first examine how the difference of the transformed Eulerian mean (TEM) residual mass stream function (e.g., Andrews et al., 1987) varies before and after that, by dividing the period into the last half of August, the early and last half of September (Figure 2). The stream function difference (of the NUDGE forecast from that of FREE) in the stratosphere is largest, as expected, in the early half of September (Figure 2b). It exhibits that about half of the B-D (anticlockwise meridional) circulation in the southern midlatitude lower stratosphere in the NUDGE forecast is underrepresented in the FREE forecast.
due to the miss of SSW. Although the differences are already beginning to grow in the last half of August, those of the tropical troposphere are tiny and not judged to be significant as yet (Figure 2a). The difference in the tropical troposphere that accelerates the Hadley cell, an anticlockwise circulation accompanying the upwelling (downwelling) over 10°–20°N (10°–30°S), becomes significant in the early half of September. This Hadley cell difference grows further in the last half of September, although the difference in the B-D circulation is beginning to attenuate (Figure 2c). Therefore, we can say that the Hadley cell is accelerated in response to the enhancement of the B-D circulation with a little delay.

Details of this response and how it is delayed can be observed in the time-latitude and time-height cross sections focusing on the equatorial region (Figure 3). As shown in the TEM residual vertical velocity at 70 hPa (Figure 3a), the enhancement of the lower stratospheric tropical upwelling in the NUDGE forecast is latitudinally symmetric and statistically significant in the early half of September. However, in the upper troposphere (200 hPa), it becomes asymmetric and somewhat localized, although some are still judged as significant. In particular, we can find a sudden appearance of a dipole difference peak with strong upwelling (weak downwelling) at 10–20°N (10–20°S) around 20 September (Figure 3b). This response and subsequent upwelling in the NH tropics correspond to the accelerated Hadley circulation shown in Figure 2c. These tropospheric upwelling would accompany the deep convective activity over this region. In fact, the outgoing long-wave radiation (OLR) (whose low value indicates enhanced convection in the tropics) of the NUDGE forecast shows a consistent and significant decrease (about −5 W m⁻² even in the zonal-mean field around 20 September) compared to that of the FREE forecast (Figure 3c).

A look of thermal structure changes helps to understand how such deep convections occurred. As shown in the temperature difference in the off-equatorial NH region (Figure 3d), the significant cooling tendency in the NUDGE forecast reaches to the lower stratosphere by mid-September, and (although its magnitude is tiny but) it extends to the troposphere around 10–15 September. Correspondingly, the convective (static) stability decreases significantly at about 100 hPa (Figure 3e). It protrudes to the upper to middle troposphere around 15–20 September. This environmental change is consistent with the enhanced convective heating around 20 September (Figure 3f). Therefore, from the differences between the NUDGE and FREE forecasts, it is possible to think that the lower stratospheric cooling tendency, which penetrated to the troposphere from the stratosphere, triggered cumulus convections. Note that the near-tropopause stability changes may be enough as suggested by Chae and Sherwood (2010). In any case, this convective heating can compensate for the aforementioned temperature change. As a result, the cooling tendency in the troposphere is soon alleviated after mid-September. Note that the deep convection further destabilizes the environment (and promotes subsequent feedback) by the heating in the troposphere and the cooling in the lower stratosphere. In fact, the off-equatorial NH mean of the lower stratospheric temperature shows somewhat persistent cooling compared to the whole equatorial mean (see Figure 1b).

Figure 2. Latitude-height cross sections of the TEM residual mass stream function for periods of (a) the last half of August, (b) the early, and (c) last half of September. The ensemble mean of the NUDGE forecast is shown by contours with a logarithmic interval. The ensemble mean difference of the NUDGE forecast from the FREE forecast is shown by colors. The regions where the positive (negative) difference is significant at 90% confidence (estimated by Welch’s t test) are stippled by red (blue) points.
Finally, to find regions sensitive to the Antarctic SSW, we checked the horizontal distributions of the convective activity difference between the NUDGE forecast and the FREE forecast (Figure 4). The differences in OLR (Figure 4a) and the convective precipitation (Figure 4b) averaged for a period of the latter half of September show notably significant enhancements of convective activity over the southern Asian Monsoon (AM) region (e.g., Philippines islands and Indochina peninsula). The magnitudes of differences over the South China Sea are particularly high (over 10 W m$^{-2}$ and 1.5 kg m$^{-2}$ day$^{-1}$), although there are other many significant regions (e.g., the enhancement over the northern part of Africa and around the Mexican peninsula, and the suppression over the SH tropical part of South America). Note that this AM region is known for frequent occurrences of deep convections penetrating the tropical tropopause (e.g., Kim et al., 2018; Liu & Zipser, 2005; Paulik & Birner, 2012) and climatologically high convective activity (see Figure S6). The convective response to the enhanced B-D circulation mainly occurred in such an active region.

This convective response to the stratospheric constraint (i.e., a signal from the “perfect” stratosphere) is not small compared to the variable range of ensemble members (which can be regarded as a noise). The signal-to-noise ratios (calculated as the ensemble mean difference divided by the ensemble spread of the half monthly mean value) of the AM area-averaged quantities are more than 0.3 (0.71 for OLR and 0.57 for convective precipitation). Note that the signal-to-noise ratio of the daily values, which corresponds to that of the plotted histograms, is also shown in Figure 4. This value is smaller but not so far behind from the extratropical (~SAM) response to the nudged stratosphere (more than 0.8; see Figure S7 and Text S3 in the supporting information). Therefore, we can find a distinguishable rightward shift in the ensembles of the NUDGE forecast compared to that of the FREE forecast, even in the histogram of daily values of the AM average (Figures 4c and 4d), like the NAM response to SSWs (e.g., Figure 6a of Hitchcock & Simpson, 2014).
4. Discussion and Remarks

By adopting the nudging methodology in a practical ensemble prediction system, this study revealed a significant enhancement in the convective activity at the NH tropics as a response to the 2019 Antarctic SSW. This tropospheric response ultimately stems from the “perfect” stratospheric circulation in the NUDGE forecast; this is due to the experimental design that the same initial and boundary conditions are used in both the NUDGE and FREE forecasts. Therefore, an effort to improve the reproducibility of the polar vortex behavior in the Antarctic stratosphere leads to an improvement in the extended-range forecast of the tropical variability, which have been shown as differences in our study. This would also benefit the forecasting of the extreme weather conditions during midlatitude boreal summer to early autumn, including the genesis and development of tropical cyclones. Considering the rising demands for developing and sophisticated early warning systems for these phenomena (e.g., Robertson et al., 2020), the additional impact from the stratosphere might have to be considered.

In a mature phase of the equatorial lower stratospheric cooling due to the enhanced B-D circulation, the zonal-mean OLR drops by 1–5 W m\(^{-2}\) at 10–20°N (and rises by ~1 W m\(^{-2}\) in the SH tropics). This magnitude is almost comparable to the reported value in the composite result of Arctic SSWs (Bal et al., 2017). However, for the 2002 Antarctic SSW, Eguchi and Kodera (2007) and Kodera and Yamada (2004) reported about 10–20 W m\(^{-2}\) variations in the zonal-mean OLR. However, the sign of their reported zonal-mean OLR change is opposite to ours—the OLR in the SH/NH tropics decreases/increases during the 2002 SSW. The difference in enhanced regions of the convective activity might be just reflecting the diversity of SSWs (i.e., the enhanced B-D circulation during the 2002 SSW is narrower and stronger than that of the 2019 SSW). Another possible explanation for this inconsistency would be the difference of the focused periods: the previous studies pointed the convective response in the onset phase of the SSW, while our study extracted the convective enhancement in the mature phase of the lower stratospheric cooling. The enhancement of the tropical convective activity during the SSW would be divided into instantaneous responses and following feedback processes from the convection-promoting environment. The convective response in the previous studies could be considered as the former, which is contingent and sometimes involved with the equatorward propagation of waves through the upper troposphere and lower stratosphere (e.g., Albers et al., 2016; Kuroda, 2008; Yoshida...
& Yamazaki, 2011). Since our experimental setting is not designed to constrain such a transient process perfectly, the ensemble difference between the NUDGE and FREE forecasts mainly corresponds to the latter environmental response. In fact, the enhancement of upwelling in the NUDGE forecast (Figure 3a) does not completely follow the former response observed in JRA-55, although what should be expected as the former response is unclear. It is worth noting that we can find another OLR change in early October 2002, which is consistent with our result for the 2019 SSW (see Figure 2 of Kodera & Yamada, 2004). The difference in magnitude is explainable by the difference between one realization and the ensemble mean. Therefore, we believe that a pure tropical response to the stratospheric basic state change (in the mature phase of the lower stratospheric cooling by the enhanced B-D circulation) via Antarctic SSWs is the enhancement of upwelling/downwelling in the NH/SH tropics—the acceleration of the Hadley cell—as shown in this study. This is consistent with a mirror image of the dipole convective response to Arctic SSWs.

We acknowledge that this convective response has a somewhat weaker signal as compared to that of the annular mode response to SSWs in middle to high latitudes. This could be because not only of the weaker linkage with the stratosphere in nature but also of the insufficient and incorrect representation of convectons in the numerical prediction model. Unlike the large-scale dynamical coupling, there is high uncertainty in the cumulus convective parameterization. Therefore, tropical convective response might be highly dependent on the choice of cumulus parameterization schemes. Fortunately, the other two options of the cumulus schemes in the MRI-AGCM (the Kain-Fritsch and Arakawa-Schubert types; see details in Yukimoto et al., 2011) provides opportunities to check the sensitivity of the convective response. Results of the same NUDGE and FREE experiments for other cumulus schemes (Figure S8) show a similar tendency of enhancement of convections in the NH tropics (and the suppression in the SH tropics) in response to the SSW. This result further confirms the robust response of the tropical troposphere. However, details of the response vary among schemes; the Kain-Fritsch scheme shows a weaker and equatorward enhancement of the convective activity due to insensitive characteristics over the AM region (see Figure S9), while the Arakawa-Schubert scheme shows a response similar to the default (Yoshimura) scheme with its magnitude and timing being somewhat moderate and earlier. The superior performance of the Yoshimura scheme and the underestimating feature of the Arakawa-Schubert scheme are well known when predicting extreme precipitation in the MRI-AGCM climate simulations. Furthermore, the Kain-Fritsch scheme is known to show an equatorward biased precipitation response in the future projection experiments (e.g., Endo et al., 2012). Therefore, these diverse responses among the cumulus schemes are consistent with studies based on the response to global warming.

Running similar numerical experiments using cloud-resolving models are promising for reducing the uncertainty in the tropical convective response to SSWs. Advances in high-performance computers enable the nonhydrostatic model intercomparisons with horizontal resolutions <10 km (e.g., Nakano et al., 2017). Further investigations, possibly a comparison of ensemble cloud-resolving model simulations, are envisaged as an extension of this study.

**Data Availability Statements**

The JRA-55 data sets are available on the JMA Data Dissemination System (http://jra.kishou.go.jp/JRA-55/index_en.html). The numerical data used in this study are available from this site (https://doi.org/10.5281/zenodo.3786444). The GFD-DENNOU Library was used for graphics.

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