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LETTER

Recent weakening of the southern stratospheric polar vortex and its impact on the surface climate over Antarctica

Hataek Kwon[1], Hyesun Choi[2], Baek-Min Kim[3], Sang-Woo Kim[1] and Seong-Joong Kim[2]

[1] School of Earth and Environmental Sciences, Seoul National University, Seoul, Republic of Korea
[2] Division of Polar Climate Sciences, Korea Polar Research Institute, Incheon, Republic of Korea
[3] Department of Environmental Atmospheric Sciences, Pukyong National University, Busan, Republic of Korea

E-mail: seongjkim@kopri.re.kr

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Abstract

The variability in the southern stratospheric polar vortex (SSPV) and its downward coupling with the troposphere are known to play a crucial role in driving climate variability over Antarctica. In this study, SSPV weakening events and their impacts on the surface climate of Antarctica are examined using *in-situ* observation and reanalysis data. Combining criteria from several previous studies, we introduce a new detection method for SSPV weakening events. Based on the new criteria, the occurrence frequency of SSPV weakening events has exhibited a systematic increasing trend since the 2000 s. However, the weakened anomalies of individual SSPV events are not statistically different (95% confidence level) between the earlier (1979–1999) and later (2000–2017) periods examined in this study. The recent increase in the occurrence of SSPV weakening events is largely controlled by tropospheric mechanisms, i.e. the poleward heat flux carried by southern hemispheric planetary waves and associated vertical wave propagation. Among the various scales of planetary waves, the wavenumber 1 contributes most of the poleward eddy heat flux. We show that SSPV weakening events induce statistically significant cooling over the Antarctic Peninsula (AP) region and warming over the rest of Antarctica. Typically, surface air temperature anomalies with large negative values smaller than -0.6 °C and positive values larger than $+0.8$ °C are observed over the east coast of the tip of the AP and King Edward VII Land, respectively. The influence of an SSPV weakening event on the surface lasts for approximately three months with higher height anomalies off western Antarctica, providing favorable conditions for the atmosphere to transport cold air from the interior of Antarctica to the AP via the Weddell Sea. Distinct positive surface air temperature anomalies over the rest of Antarctica are associated with the northerly circulation anomaly from the eastern Weddell Sea to east Antarctica.

1. Introduction

The southern stratospheric polar vortex (SSPV) is known to play an essential role in driving climate variability at the Antarctic surface on a range of different time scales (Thompson and Wallace 2000, Kwok and Comiso 2002, Thompson and Solomon 2002, Thompson *et al* 2005). In particular, stratospheric polar vortex variations and their downward coupling to the troposphere are regarded as critical drivers of variations in the southern annular mode (SAM) in austral spring and summer (Thompson and Wallace 2000). As a possible driver of the strengthening of the SSPV, ozone depletion and associated vortex strengthening have been examined in several studies (Thompson and Solomon 2002, Polvani *et al* 2011, Thompson *et al* 2011, Sheshadri *et al* 2014, Sun and Robinson, 2014, Ogawa *et al* 2015, Kidston *et al* 2015, Hirano *et al* 2016). However, only a few studies have examined the downward coupling following a large SSPV fluctuation (Thompson *et al* 2005, Lim *et al* 2018, Byrne and Shepherd 2018, Wang *et al* 2019). This is partly due to the rare occurrence of major sudden stratospheric warming (SSW) events in the Southern Hemisphere (SH) when adopting the World Meteorological Organization (WMO) criteria. The major SSW is defined as a zonal-mean zonal wind reversal in the polar stratosphere associated with a reversal of the meridional temperature gradient in WMO criterion. Motivated by the first occurrence of a major SSW event in 2002, (Thompson *et al* (2005) examined the temporal evolution of the tropospheric circulation, including the Antarctic surface air temperature (SAT) after large-amplitude variations in the SSPV and showed that variations in the stratospheric polar vortex are followed by coherent changes in the SAT throughout much of Antarctica. As will be shown in our study, many weakened SSPV events can be identified since 2002 if we adopt similar detection criteria for weakened SSPV events to those used in Thompson *et al* (2005).

Here, we extend the study of Thompson *et al* (2005) and investigate the impacts of SSPV weakening on the SAT over Antarctica using *in-situ* observation and reanalysis data from 1979 to 2017. To analyze the role of SSPV weakening on the SAT over Antarctica, we introduce a new definition of an SSPV weakening event using the polar cap height (PCH) anomaly, which is the averaged geopotential height (GPH) anomaly over 65°S-90°S and normalized by its temporal standard deviation. Descriptions of the observational datasets and the identification method for an SSPV weakening event are given in section 2. The long-term trend and occurrence statistics are examined in section 3, as well as the downward coupling and surface impacts. A discussion and conclusions are presented in section 4.

2. Data and methods

2.1. Data

We used the European Centre for Medium-range Weather Forecasting (ECMWF) Interim reanalysis (ERA-Interim) data from 1979 to 2017 for the detection of the SSPV weakening events and the analysis of the tropospheric and surface responses to these events. The spatial resolution of the ERA-Interim data is ~0.75°, and the data are divided into 37 vertical levels from the surface up to 0.1 hPa (Dee *et al* 2011, Bracegirdle and Marshall 2012).

The monthly mean SAT observations (1979–2017) for 19 Antarctic stations obtained from the Scientific Committee on Antarctic Research (SCAR) Reference Antarctic Data for Environmental Research (READER) database (Turner *et al* 2004) were used to perform a composite analysis of the SAT over Antarctica. These monthly mean SAT values were produced via the mean of the 6-hourly synoptic observations, for which 90% of the data are available.

Daily and monthly mean SAT data derived from observations at 10-min intervals by the Automatic Meteorological Observation System (AMOS) at the King Sejong Station (KSJ) were used for the composite analysis. Note that, because the surface meteorological observations at the KSJ station are available since 1989, only datasets from 1989 to 2017 were used in this study. In this analysis, AMOS-1 was the primary dataset and any missing periods were supplemented using AMOS-2, which was installed and commissioned at a location 5 m from AMOS-1. AMOS-2 data were used for 2005–2008, years in which many of the AMOS-1 data were missing.

2.2. Identification method for SSPV weakening events

Even though, in the literature, there is no standard definition of an SSPV weakening event, definitions relying on zonal-mean zonal wind reversals (Charlton *et al*, 2007, Butler *et al*, 2015) and an increase in the GPH field anomaly (Baldwin and Dunkerton 2001, Thompson *et al* 2005, Baldwin and Thompson 2009, Byrne and Shepherd 2018) over specific regions have been widely used. In the SH, except in September 2002, no zonal wind reversals were observed during the austral winter and spring seasons because the zonal wind was too strong. Therefore, zonal wind reversal methods may not be appropriate candidates to formulate a definition of the SSPV weakening events in the SH. Methods based on GPH fields either employ an empirical orthogonal function (EOF) analysis (Baldwin and Dunkerton 2001, Thompson *et al* 2005, Byrne and Shepherd 2018) or adopt an average of the GPH anomaly over the polar cap region (Thompson and Solomon 2002) to examine the variability of the polar vortex. In this study, SSPV weakening events are defined based on the polar cap averaged GPH (PCH) anomaly due to its relative simplicity. The GPH anomaly is defined by the difference from 31-day running mean climatological value calculated from daily ERA-Interim GPH based on the period 1979–2019. The PCH anomaly was averaged over 65–90° S and normalized by its temporal standard deviation at each pressure level. Therefore, the PCH anomaly of 1 is the 1 standard deviation at a corresponding pressure level and is unitless. The positive PCH anomaly corresponds to a weak SSPV, and vice versa.

W(ia for SSPV weakening events by combining the criteria used in Thompson and Solomon (2002), Thompson *et al* (2005), and Black and Mcdaniel (2007).

- The onset date of an SSPV weakening event is defined as the first day when the PCH anomaly at 10 hPa is higher than the 95th percentile. The 95th percentile corresponds to the 1.65 PCH anomaly from the ERA-Interim data.
- If there is another onset date within 60 d following the first onset date, only the first date is used in the analysis (Thompson and Solomon 2002).
- A positive PCH anomaly needs to be maintained for at least 7 d after the onset date to prevent a event from being identified as a temporarily large anomaly.
- Southern Final Warming (SFW) events are excluded. Based on the definition in Black and

Mcdaniel (2007), SFW events are identified as the final time that the zonal-mean zonal wind smoothed by a 5-day running mean at 60°S and 50 hPa drops below 10 m s^{-1} until the following autumn.

- In this study, only robust SSPV weakening cases are analyzed to focus on strong stratosphere–troposphere coupling events. Robust SSPV weakening events are defined as cases in which a PCH anomaly at 10 hPa value greater than or equal to 2.8 is identified between the onset date and 60 d following the onset date. A PCH anomaly value of 2.8 is similar to a value corresponding to the 98.5th percentile in the ERA-Interim data.

Baldwin and Thompson (2009) showed that the PCH anomaly is an effective substitute for an index based on an EOF analysis. The events detected by our method include most of the events identified by the EOF-based index (Thompson *et al* 2005, Byrne and Shepherd 2018). We compare our identification to those of other well-known studies (Thompson *et al* 2005, Byrne and Shepherd 2018) that diagnose the variability of the polar vortex based on an EOF analysis of the GPH. Six out of eight stratospheric weakening events defined by (Thompson *et al* 2005) using data from January 1, 1979 to December 31, 2002, are found in our identification. The onset dates of the vortex weakening events identified in both (Thompson *et al* 2005) and this study are listed in table 1. In this study, two cases, the 1995 and 1996 stratospheric weakening events, are excluded. For the 1995 case, the stratospheric positive PCH anomaly do not meet the duration criteria (7 d) in our analysis, while for the 1996 case, the maximum positive PCH anomaly do not reach the 95th percentile (1.65). Both the 1995 and 1996 cases are defined as strong SSPV years in (Byrne and Shepherd 2018) using the ERA-Interim dataset for the period from March 1, 1979 to February 28, 2017. However, all of the SSPV weakening events identified in our study are included in the SSPV weakening years in (Byrne and Shepherd 2018). Therefore, our identification method appears to be effective for both the 1995 and 1996 cases; in addition, the identification of SSPV weakening events in this study is at least as reliable as that reported by (Thompson *et al* 2005) and (Byrne and Shepherd 2018).

3. Results

Table 1 shows SSPV weakening events based on the criteria described in the previous section. Only one SFW case is identified during the period, and in total, 15 SSPV weakening events are identified since 1979. The averaged onset date of the SSPV weakening events is September 22. All of the SSPV weakening events occur during late winter and spring (August–October), with the highest frequency of events occurring in October. SSPV weakening events occur more frequently since 2000 (71% of all cases), including a significant SSW event in 2002. However, the increasing frequency in recent decades does not indicate that the overall strength of the SSPV has weakened. Indicators related to the weakening degree of the SSPV, such as the peak value at 10 hPa in the earlier (3.70) period, are not statistically different (95% confidence level) from those in the later period (4.45, except for the extraordinary 2002 SSW, which had a value of 3.66).

Figure 1(a) shows the composite value of the PCH anomaly from days −90 to +90 for the onset dates of the 15 SSPV weakening events listed in table 1. Day 0 corresponds to the onset date. Ten days prior to the onset of the SSPV weakening events, positive PCH anomalies appeared in the upper stratosphere showing a maximum value (~2.25) shortly after the onset date. Subsequently, the positive anomalies gradually descended to the lower stratosphere and troposphere and lasted for ~90 d after the onset of the SSPV weakening events. Positive anomalies within the troposphere and near the surface showed significant values (95% confidence level) approximately 50 d after the onset date.

Figure 1(b) shows the composite PCH anomaly based on years when SSPV weakening events occurred (table 1). Comparing figures 1(a) and (b), we can conclude that SSPV weakening events tend to occur at similar times of the year, i.e. late September, and exhibit similar evolutions. The phase-locking characteristics of the SSPV weakening events are very different from those in the Northern Hemisphere (i.e. Charlton and Polvani 2007). Figure 1(c) shows the linear trend of the PCH anomaly. There appears to be an increasing PCH trend in the stratosphere and troposphere in austral spring. Because more frequent occurrences of SSPV weakening events have been observed since the 2000 s (table 1), changes in the SSPV weakening events in recent decades have likely contributed significantly to the recent trend toward a low SAM.

The weakening of the SSPV leads to a statistically significant GPH increase (95% confidence level) over the polar cap region and a GPH decrease in the mid-latitudes from the stratosphere to the troposphere (figure 2). This pattern resembles the general structure of the negative phase of the SAM. In particular, the tropospheric response to the SSPV weakening events is significant over the Amundsen Sea and exhibits a large positive value over 40 m.

To explain how the stratosphere–troposphere coupling associated with SSPV weakening events is statistically linked to the SAT over Antarctica, we present the composite daily mean sea level pressure and SAT anomalies during the 90 d after the onset dates of the SSPV weakening events in figure 3. The

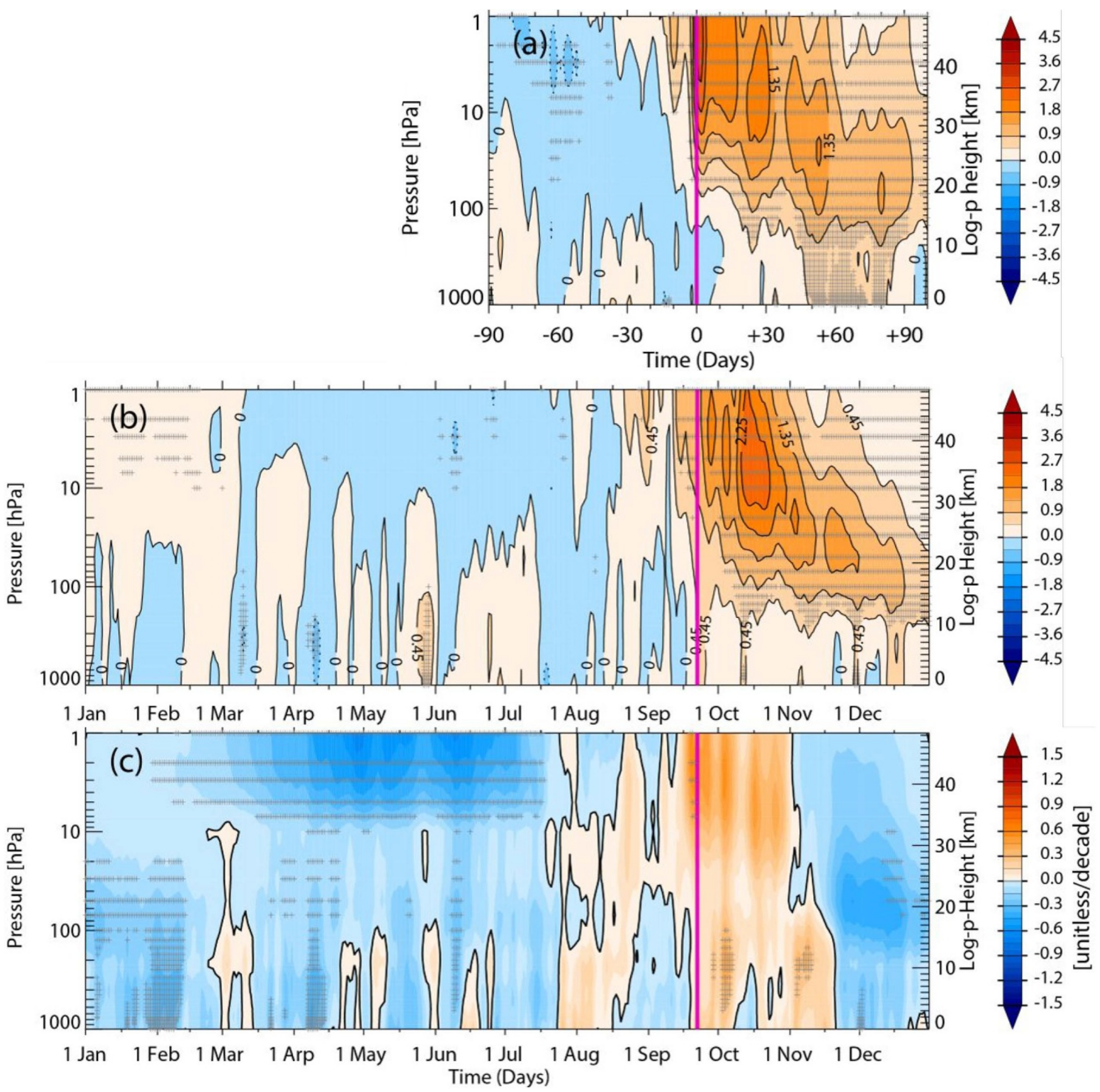

Figure 1. (**a**) Composite of the PCH anomaly based on the onset date for strong SSPV weakening events. (**b**) Same as panel (**a**) but based on January 1 of years corresponding to strong SSPV weakening events. (**c**) Linear trends of the PCH anomaly calculated for each calendar day and for each vertical level from January 1, 1979 to December 31, 2017. Gray crosses indicate regions statistically significant (95% confidence level). The black contour indicates zero values. The pink vertical line indicates the onset date in panel (**a**) and the average onset date (September 22) in panels (**b**) and (**c**).

Table 1. Onset date of the SSPV weakening events used in this study. The bold numbers represent the events that occurred after 2000. El Nino events corresponding to each SSPV weakening event are also displayed. EP and CP indicate the Eastern Pacific and Central Pacific ENSOs, respectively.

Number	Year	Onset date	Peak value of PCH at 10 hPa	(Thompson *et al* 2005)	El Nino events
1	1979	October 02	3.68	October 01	-
2	1982	October 08	3.75		EP
3	1988	August 03	4.83	August 01	-
4	1991	October 28	2.95	October 22	EP
5	1992	September 30	3.30	September 28	-
6	**2000**	October 10	3.47	October 17	-
7	**2002**	August 15	11.56	August 30	CP
8	**2003**	October 12	3.51		-
9	**2004**	September 26	3.51		CP
10	**2007**	September 18	3.63		-
11	**2009**	October 14	3.04		CP
12	**2012**	August 20	5.30		-
13	**2013**	September 18	4.38		-
14	**2014**	October 07	2.82		CP
15	**2017**	August 22	3.31		-

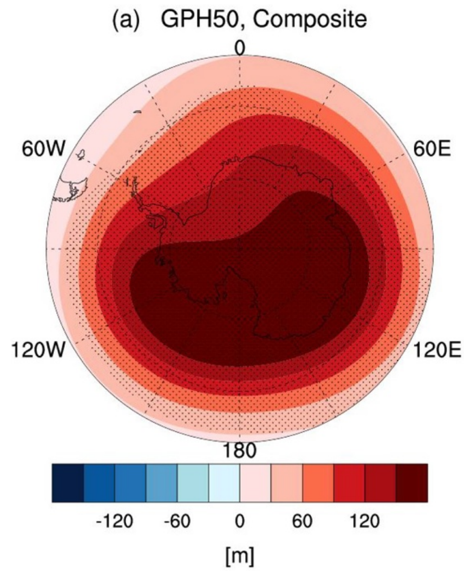

Figure 2. Composite map of the geopotential height anomalies at 50 hPa and 500 hPa during the 90 d after the onset date of the SSPV weakening events. The dotted area indicates regions statistically significant (95% confidence level).

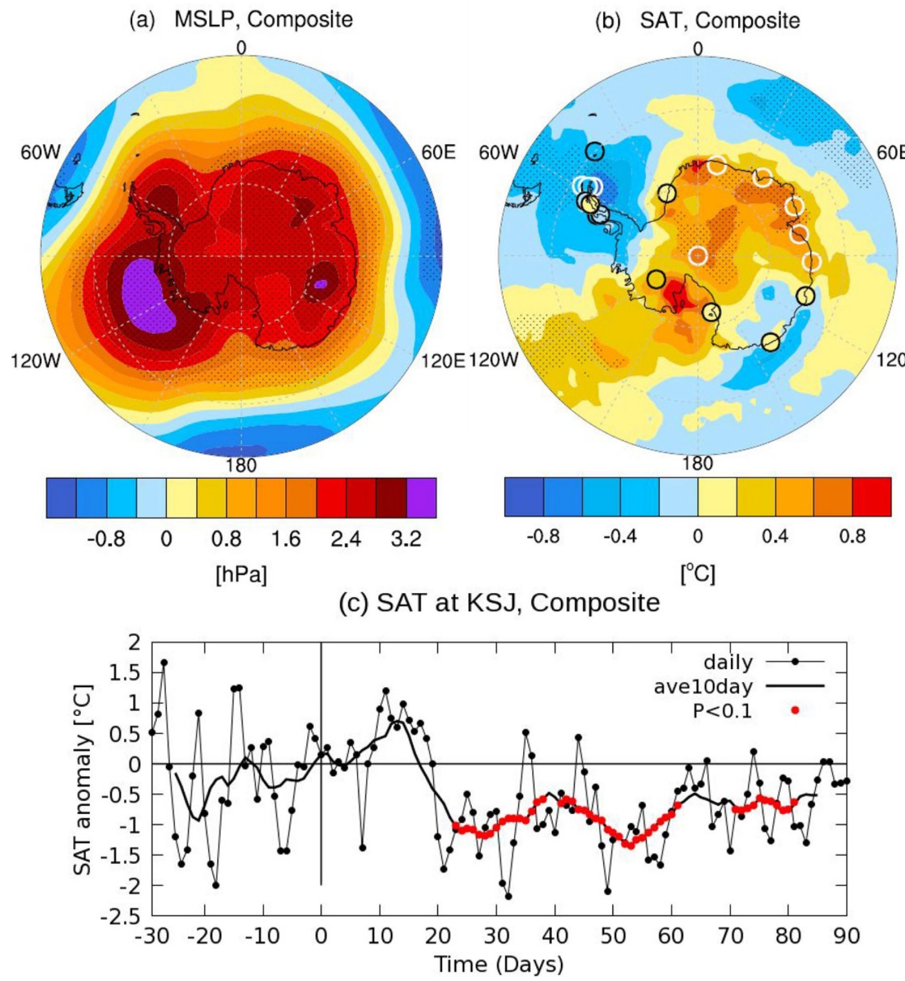

Figure 3. (**a**) Composite map of the mean sea level pressure and (**b**) SAT anomalies during the 90 d after the onset date of strong SSPV weakening events. (**c**) Temporal evolution of the daily SAT anomalies from a lag of −30 d to 60 d at the KSJ station for the period from 1989 to 2017. Lag 0 indicates the onset date of the strong SSPV weakening events. The circles in panel (**b**) indicate the composite SAT value from the monthly observations. The circles with white outlines denote stations where the results exceed the 90% confidence level. The dotted areas in panels (**a**) and (**b**) and the red circles in panel (**c**) indicate the results that exceed the 90% confidence level.

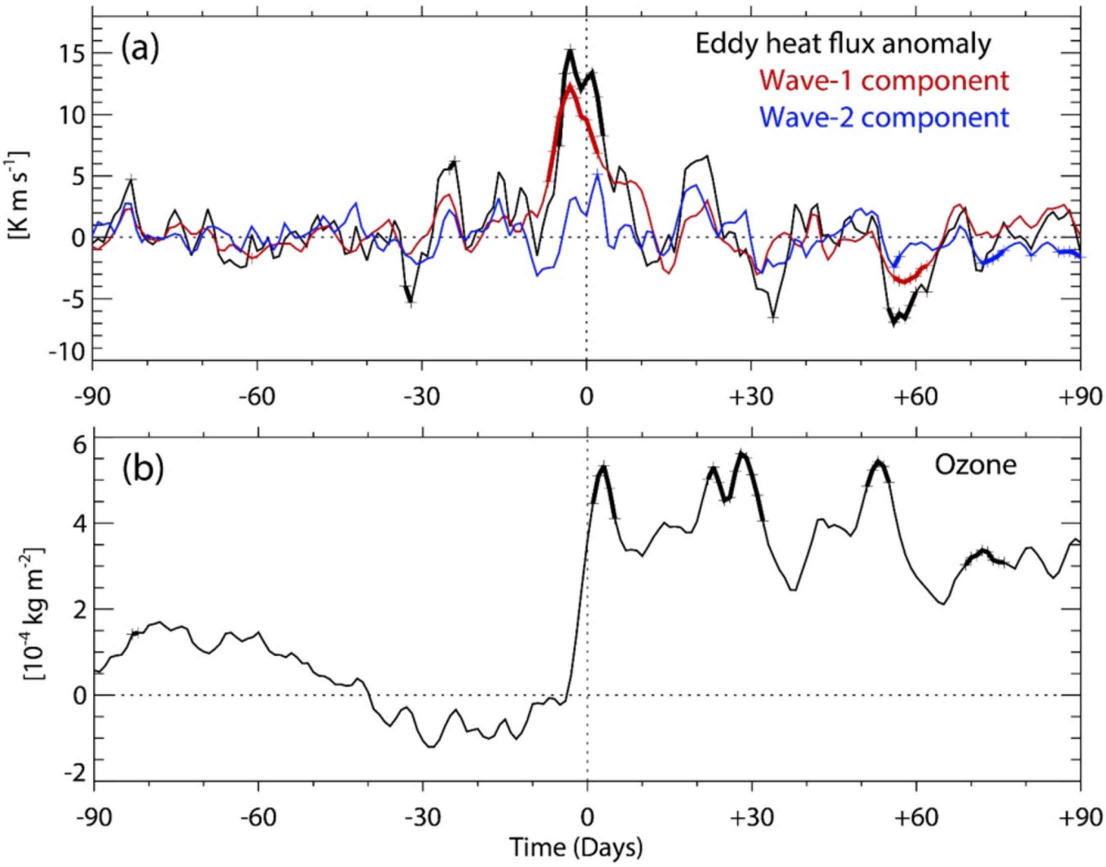

Figure 4. (**a**) Anomalies of the meridional eddy heat flux averaged over 45–75° S at 100 hPa. The black line denotes anomalies from the total eddies, and the red and blue lines denote contributions from the zonal wave components 1 and 2, respectively. The sign is reversed for the visualization. (**b**) Total column ozone anomalies averaged over 65–90° S calculated from the ERA-Interim reanalysis data. The solid bold part of each line indicates that the heat flux anomaly is significantly different (95% confidence level) from zero.

weakening of the SSPV in the stratosphere effectively influences the surface for approximately 90 d, as shown in figure 3. The composite map of the sea level pressure anomaly shows that, after the occurrence of the SSPV weakening, significantly higher height anomalies develop over the Amundsen Sea (figure 3(a)). The anticyclonic circulation anomaly over western Antarctica helps provide cold air to the AP region from the Antarctic continental interior via the Weddell Sea, resulting in strong negative SAT anomalies, while distinct positive SAT anomalies, associated with the northerly circulation anomaly from the eastern Weddell Sea to eastern Antarctica, are observed over the rest of Antarctica (figure 3(b)). SAT anomalies with large negative values (smaller than − 0.6 °C) and positive values (larger than +0.8 °C) are seen over the east coast of the tip of the AP and King Edward VII Land, respectively. The reanalyzed SAT results (shading) are in good agreement with the station observation data (the circles in figure 3(b)). This result suggests that SSPV weakening events drive the cold anomaly over the AP region and the warm anomaly over much of the rest of Antarctica. Note that, because only monthly mean SAT station observations are available, the monthly SAT is averaged over a three-month period from the first month following the onset date of the SSPV weakening events in the composite analysis. This SAT response pattern over Antarctica is similar to the SAT response pattern associated with negative polarities of the SAM (Thompson *et al* 2005). Figure 3(c) shows the daily SAT changes over time after the occurrence of the SSPV weakening events at the KSJ station, located in the AP region. Note that, because surface meteorological observations at the KSJ station are only available since 1989, only 11 SSPV weakening events were considered in the SAT composite analysis. Negative SAT anomalies are seen from approximately three weeks after the onset of extreme SSPV weakening events and last for ~75 d, with a mean value of −0.79 °C. The highest negative value of the SAT anomaly (approximately − 2.2 °C) occurs approximately 30 d after the onset of the SSPV weakening events. The daily observation data clearly show marked surface cooling after the occurrence of extreme SSPV weakening events.

4. Discussion and conclusions

The SSPV weakening events and their surface impacts on Antarctica were examined using the PCH anomaly, which is the averaged GPH anomaly over 65°S-90°S and normalized by its temporal standard deviation, based on previous studies. With the newly devised method, we found that (1) the occurrence frequency of the SSPV weakening events has exhibited a systematic increasing trend since the 2000 s and that (2) the SSPV weakening events have induced statistically significant cooling over the AP region and warming over the rest of Antarctica, which confirms the findings of (Thompson *et al* 2005). The surface influence of these events lasts for approximately three months, providing favorable conditions for the atmosphere to transport cold air from the interior of Antarctica to the AP via the Weddell Sea. This result could partially illustrate the cooling of the AP region since 2000 reported by (Turner *et al* 2016), even though further studies are required.

What has, then, caused the more frequent occurrences of SSPV weakening events in recent years? We examine two possibilities that could generate these SSPV weakening events: (1) upward propagation of large-scale tropospheric waves and (2) stratospheric ozone variability prior to initiation. As clearly shown in figure 4(a), prior to the onset date, there exists a large poleward heat flux at 100 hPa carried by southern planetary waves. This observation provides solid evidence of strong upward wave propagation from the troposphere to the stratosphere prior to the initiation of the SSPV weakening events. Therefore, for such events in the SH, wave propagation from the troposphere is essential. Of the various scales of planetary waves, the wavenumber 1 component contributes the majority of the poleward eddy heat flux (figure 4(a)). The importance of this contribution is further confirmed by its in-phase relationship with the preexisting climatological stationary wavenumber 1 component (not shown). These results are consistent with those of previous studies showing that planetary waves in the SH propagating upward from the troposphere play an important role in causing stratospheric temperature changes (Hartmann *et al* 1984, Black and Mcdaniel 2007). In particular, (Newman and Nash 2005) also emphasized the role of the wavenumber 1 component. Conversely, stratospheric ozone variability prior to the initiation of an event is very weak and the stratospheric ozone increases substantially after the onset of an event, indicating that the ozone responds to the temperature and related circulation changes caused by an SSPV weakening event (figure 4(b)). Therefore, it is not likely that the recent increase in the occurrence of SSPV weakening events since the 2000 s is controlled by ozone recovery; instead, it is likely controlled by tropospheric mechanisms, i.e. the poleward heat flux carried by SH planetary waves and associated vertical wave propagation.

Previously, Central Pacific (CP) El Nino events, i.e. El Nino events with a warm sea surface temperature anomaly center over the CP, were thought to reduce the strength of the SSPV (Yu *et al* 2015). In the case of SSPV weakening events, however, we find a relatively tenuous association with CP El Nino events (table 1).

Even though further studies are required, especially to understand the initiating mechanism of SSPV weakening events, we suggest that a proper estimation of the future strength of the SSPV is essential to understand changes in the surface Antarctic climate and glacier melting, which will likely lead to severe socioeconomic damage worldwide due to sea level rise.

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Data Availability

The model output is available on reasonable request from the corresponding author. The ERA-Interim analysis data is openly available from the ECMWF data server at the following URL/DOI: https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/. The READER data is openly available from the SCAR data server (http://dx.doi.org/10.5285/569d53fb-9b90-47a6-b3ca-26306e696706). The AMOS data at the KSJ station are available on request from the corresponding author.

ORCID iD

Baek-Min Kim https://orcid.org/0000-0002-1717-183X

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