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USING SATELLITE INFORMATION ABOUT THE EARTH

VERTICAL STRUCTURE OF THE ANTARCTIC POLAR VORTEX DURING SUDDEN STRATOSPHERIC WARMINGS IN 1988, 2002 AND 2019 ACCORDING TO SATELLITE OBSERVATIONS

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Abstract. Using the MERRA-2 satellite data and ERA5 reanalysis data, we examined the vertical structure of the Antarctic polar vortex during the sudden stratospheric warming events (SSWs) of 1988, 2002 and 2019. The significant displacements of the polar vortex were observed in 1988 and 2019, and the vortex splitting occurred in 2002. Differences in the vertical dynamics of the Antarctic polar vortex during SSWs recorded due to displacement (1988 and 2019) or vortex splitting (2002) are shown. The weakening, displacement and subsequent breakdown of the polar vortex in 1988 and 2019 was observed first in the upper stratosphere, and then gradually spread into the middle and lower stratosphere within a month. Thus, the SSW in the lower stratosphere was preceded by a significant displacement of the polar vortex in the upper stratosphere a month before the event. While in 2002, before the split, the polar vortex was strong and stable at all stratospheric levels, the split was observed simultaneously in the middle and upper stratosphere, after which the vortex collapsed in the upper stratosphere, and existed for another month in the lower and middle stratosphere. In all cases, a decrease in wind speed along the vortex edge, an increase in temperature inside the vortex, melting of particles of polar stratospheric clouds and a decrease in ozone hole area were observed starting in late August. The earlier recovery of ozone hole occurred on 30 October 1988, 9 November 2002 and 6 November 2019, respectively.

Keywords: *Antarctic polar vortex, sudden stratospheric warming, polar stratospheric clouds, dynamic barrier*

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INTRODUCTION

Stratospheric polar vortices formed over polar regions in late spring are large-scale cyclonic formations propagating from the tropopause into the mesosphere and existing through spring (Waugh and Polvani, 2010; Waugh et al., 2017). The persistence of the polar vortex during the winter-spring period determines the extent and depth of the spring polar ozone depletion (Newman et al., 2004). The boundaries of the polar vortex represent a dynamic barrier preventing the meridional transport of stratospheric ozone from tropical and middle latitudes to the polar region (Manney et al., 2022). At the same time, polar stratospheric clouds (PSCs) are formed inside the polar vortex at extremely low temperatures (< −78 °C), on the surface and in the volume of which heterogeneous reactions with the release of molecular chlorine occur. When solar radiation appears over the polar region, molecular chlorine photodissociates to form chlorine radicals, which enter the catalytic cycle of ozone destruction (Solomon, 1999).

Sudden stratospheric warming (SSW) is an abrupt warming in the polar stratosphere as a result of strong displacement or splitting of the stratospheric polar vortex by vertically propagating planetary waves (Ayarzagüena et al., 2019). Planetary waves propagate into the middle stratosphere where they move in an easterly direction opposite to the westward motion of the polar vortex, resulting in perturbation of the polar vortex and its subsequent displacement or splitting accompanied by SSW (Kuttippurath and Nikulin, 2012). The Arctic polar vortex is almost annually affected by planetary waves, marked by SSW (Ageyeva et al., 2017). In turn, in the Antarctic, during the period from 1979 to 2023, the SSW was recorded only three times. SSW was recorded only three times — in 1988, 2002, and 2019 (Roy et al., 2022). The first of these is often not taken into account in the statistics of SSW events over Antarctica, because the significant displacement of the polar vortex in 1988 was observed during its weakening phase with decreasing area. However, the polar vortex dynamics in 1988 and 2019 have many similarities, with the second one being a recognized SSW event (Safieddine et al., 2020; Kogure et al., 2021; Noguchi et al., 2020).

An earlier weakening and destruction of the Antarctic polar vortex in the spring of 2019 was considered in a number of papers (Goncharenko et al., 2020; Klekociuk et al., 2021; Eswaraiah et al., 2020; Shen et al., 2022). An anomalous weakening of the polar vortex in 2019 was observed from September through October, followed by a recorded SSW in early November and subsequent vortex collapse in the first half of November, about a month earlier than the 40–year average (Wargan et al., 2020; Milinevsky et al., 2019). The dynamics of the weakening of the polar vortex in 2019 was comparable to the dynamics of the vortex in 2002, when its splitting occurred (Lim et al., 2021). In 2002, the Antarctic polar vortex splitting and subsequent SSW were observed on September 25 (Newman and Nash, 2005; Stolarski et al., 2005; Hoppel et al., 2003; Grooß et al., 2005). An irreversible character in the dynamic changes of the polar vortex in spring 2002 was observed from the second part of September, with the first signs of subsequent changes observed already from the end of August (Charlton et al., 2005; Feng et al., 2005; Manney et al., 2005). The dynamics of the polar vortex in the spring of 1988 had a similar nature of weakening as in 2019, with the vortex shift signaled by the SSW observed in the first days of November (Hirota et al., 1990; Grytsai et al., 2008). The aim of this work is to investigate the vertical structure of the Antarctic polar vortex during the 1988, 2002 and 2019 SSWs, as well as the dynamics of the PSCs and ozone hole from satellite observations.

DATA AND METHODS

Daily averages of zonal wind speed at 60°S, minimum temperature in the 50–90°S region at 50 hPa, PSC volume in the 60–90°S region, and ozone hole area (an area characterized by total ozone content (TOC) values below 220 DU) in the 40–90°S region from 1983 to 2022 are obtained from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) archive created by the Goddard Earth Observing System Data Assimilation System (GEOS DAS) based on NASA Goddard Space Flight Center (GSFC) satellite data, http://ozonewatch.gsfc.nasa.gov. MERRA-2 is the first long-term global reanalysis that assimilates space-based observations of aerosols and represents their interactions with other physical processes in the climate system (Gelaro et al, 2017). Daily mean geopotential and zonal and meridional wind speed data for the region 30–90°S with a horizontal resolution of 0.25° × 0.25° at levels between 100 and 5 hPa for 1988, 2002, and 2019 were obtained from the ERA5 European Centre for Medium-Range Weather Forecasts reanalysis (Hersbach et al., 2020), https://doi.org/10.24381/cds.bd0915c6. To analyze the vertical dynamics of the Antarctic polar vortex during the SSW 1988, 2002 and 2019, the fields of geopotential and wind speed at the levels from 100 to 5 hPa were considered in indices. The indices were calculated using the formula (x–y)/y, where x is the value of geopotential (wind speed) at a point, y is the value of geopotential characterizing the polar vortex boundary (the value of wind speed at which the dynamic barrier is formed) at the considered level (Zuev and Savelieva, 2024). The dynamics of the considered parameters in the studied years was compared with the 40–year climatic averages for 1983–2022, obtained with standard deviations of mean (SD, σ) and smoothed FFT-filter for 15 points.

RESULTS, THEIR ANALYSIS AND DISCUSSION

Fig. 1 presents the dynamics of the Antarctic polar vortex characteristics during the winter-spring period of 1988, 2002 and 2019. In all cases, one observed a decrease of the zonal velocity, the minimum temperature increase, a decrease of the PSC volume and the area of the ozone hole beginning from the end of August. Earlier "collapse" of the ozone hole occurred on October 30, 1988, November 9, 2002, and November 6, 2019, respectively. Table 1 shows the averaged September, October and November characteristics of the Antarctic polar vortex in 1988, 2002 and 2019. There was a more significant weakening of the polar vortex in 2002 and 2019 than in 1988: wind speed and PSC volume were on average 40% and 30% lower, despite higher ozone hole area values (Fig. 1, Table 1). Figures 2–7 show the geopotential and wind speed fields in indices at levels from 100 to 5 hPa for dates before, during, and after the 1988, 2002, and 2019 SSW events. In the geopotential fields, the contour marks the inferred polar vortex boundary, and in the wind speed fields, the dynamic barrier (corresponding to the value "0" on the scale in the indices). Table 2 summarizes the values of vortex area and mean wind speed along the vortex boundary for the considered dates before, during, and after the 1988, 2002, and 2019 SSW events at levels from 100 to 5 hPa.

Table 1. Monthly averages of zonal wind speed near 60°S, minimum temperature in the 50–90°S region at 50 hPa, PSC volume in the 60–90°S region, and ozone hole area in the 50–90°S region from September through November 1988, 2002, and 2019

	Zonal wind, m/s			Minimum temperature, °C			PSC volume, 10^7 km^3			Ozone hole area, 10^6 km^2		
	1988	2002	2019	1988	2002	2019	1988	2002	2019	1988	2002	2019
September	48.7	34.4	40.4	−84.2	−85.9	−81.8	14.4	12.8	9.3	9.2	14.3	10.4
October	32.5	22.0	24.9	−73.6	−71.1	−71.6	0.9	0.1	0.2	6.4	7.7	7.9
November	11.0	6.1	4.9	−59.0	−62.7	−62.7	0.0	0.0	0.0	0.0	0.5	0.5

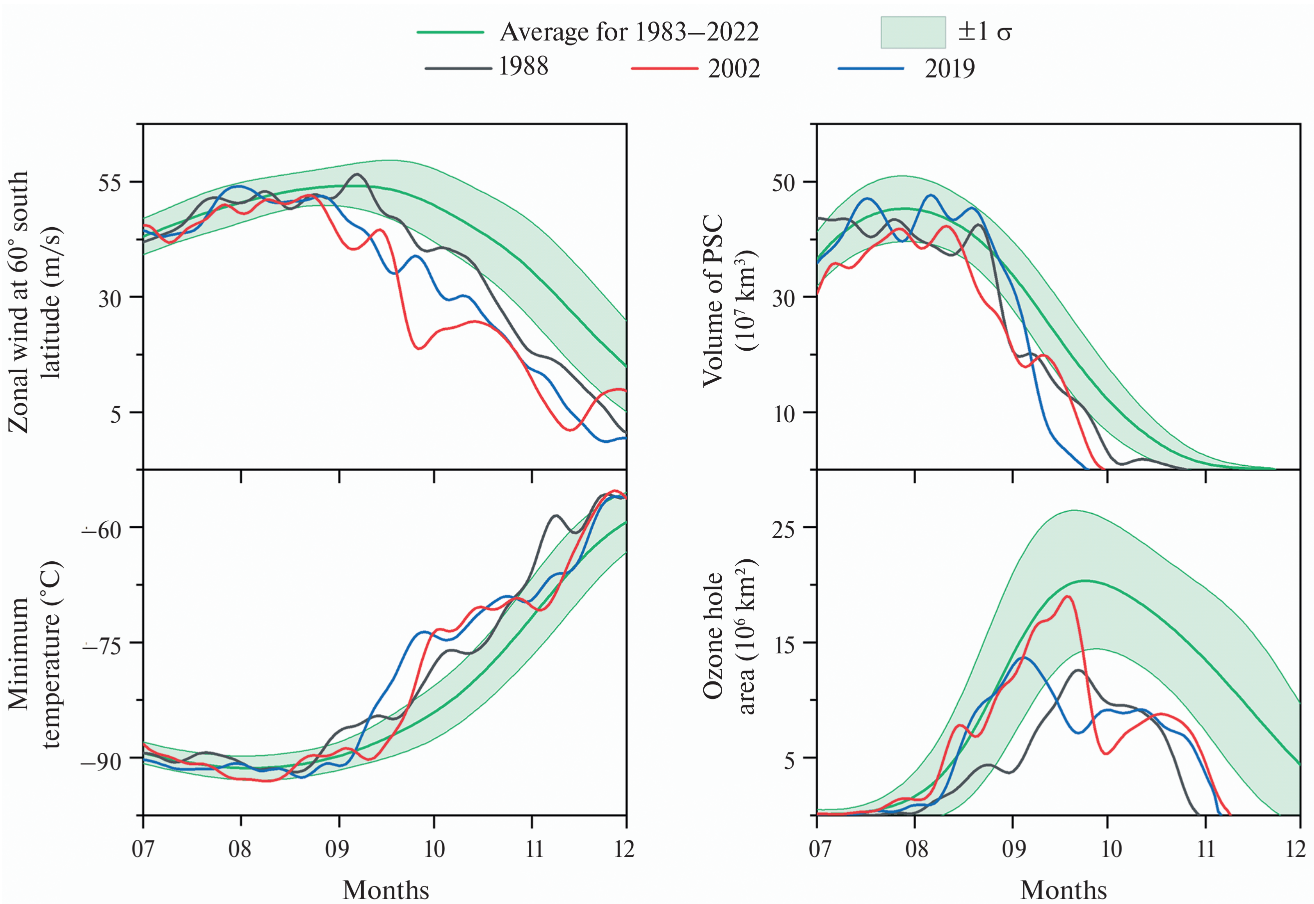

Fig. 1. Intra-annual variations of zonal wind speed near 60°S, minimum temperature in the 50–90°S region at 50 hPa, PSC volume in the 60–90°S region, and ozone hole area in the 40–90°S region from July to November 1988 2002, and 2019 against the 1983–2022 averages with SD (±1 σ).

In spring **1988,** a significant displacement of the polar vortex marked by the SSW was observed on November 1 in the lower stratosphere (Figs. 2, 3). In the middle and upper stratosphere, a significant displacement of the vortex was manifested already in the second part of October, while in early November at the levels of 10 hPa and higher, the polar vortex was no longer traced (Table 2). The weakening of the polar vortex in 1988 began in the first days of October in the upper stratosphere. One can see in Figs. 2, 3 how the displacement and weakening of the polar vortex, which began in the upper stratosphere, gradually

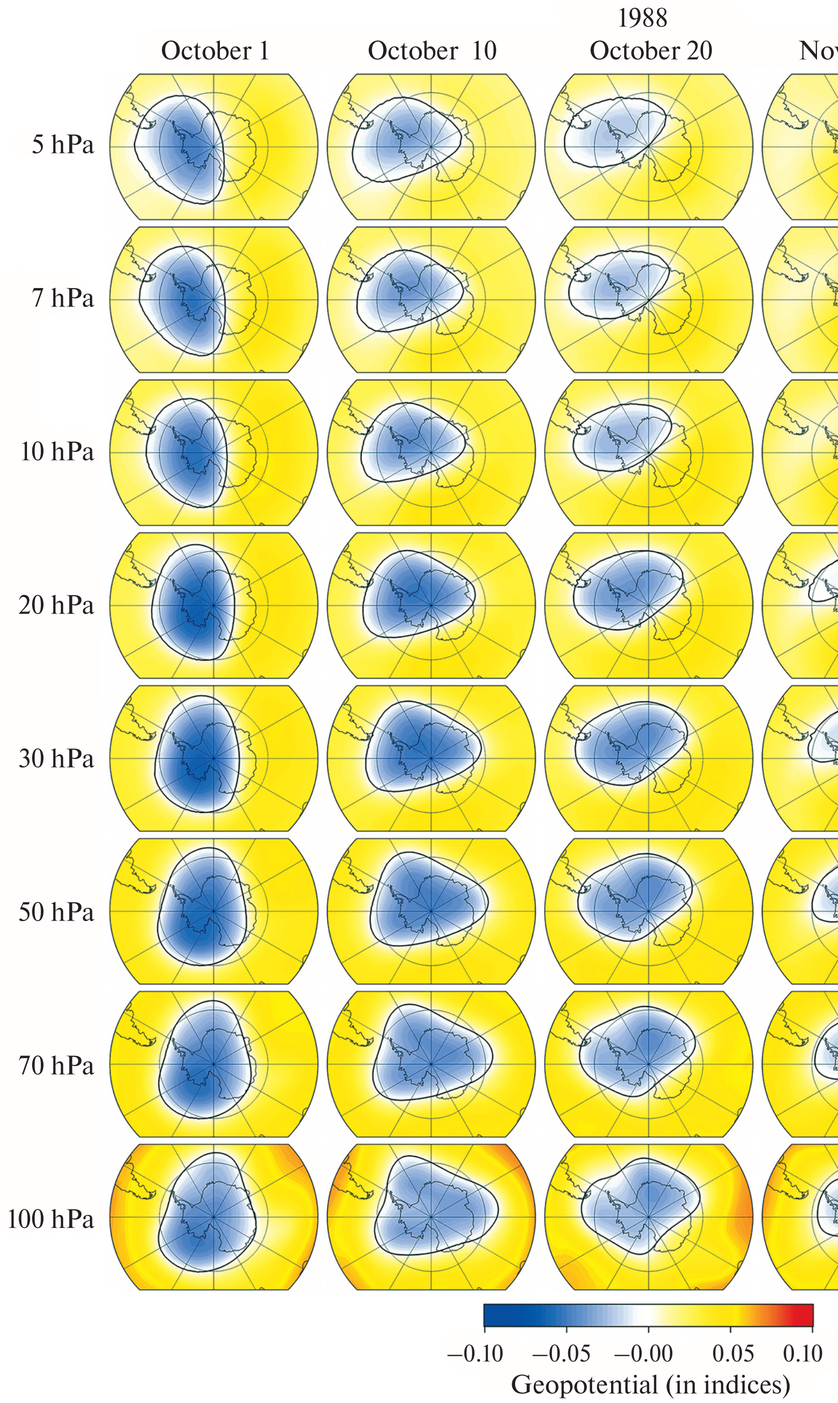

Fig. 2. Geopotential fields at the levels from 100 to 5 hPa over the Antarctic from October 1 to November 10, 1988.

manifested at the levels below until it reached the lower stratosphere in early November.

In the first part of September **2002,** the polar vortex was sufficiently strong and stable and was characterized by a greater area and wind speed along the vortex boundary in the upper and middle stratosphere as compared to the lower stratosphere (Table 2, Figs. 4, 5). On September 25, the vortex splitting occurred in the middle and upper stratosphere (at the levels from 20 hPa and above), with the polar vortex in the lower stratosphere taking the form of a “figure eight”. After splitting in the upper stratosphere, a small anticyclone was formed, one of the parts of the polar vortex “dissolved” and the second part gradually collapsed. In its turn

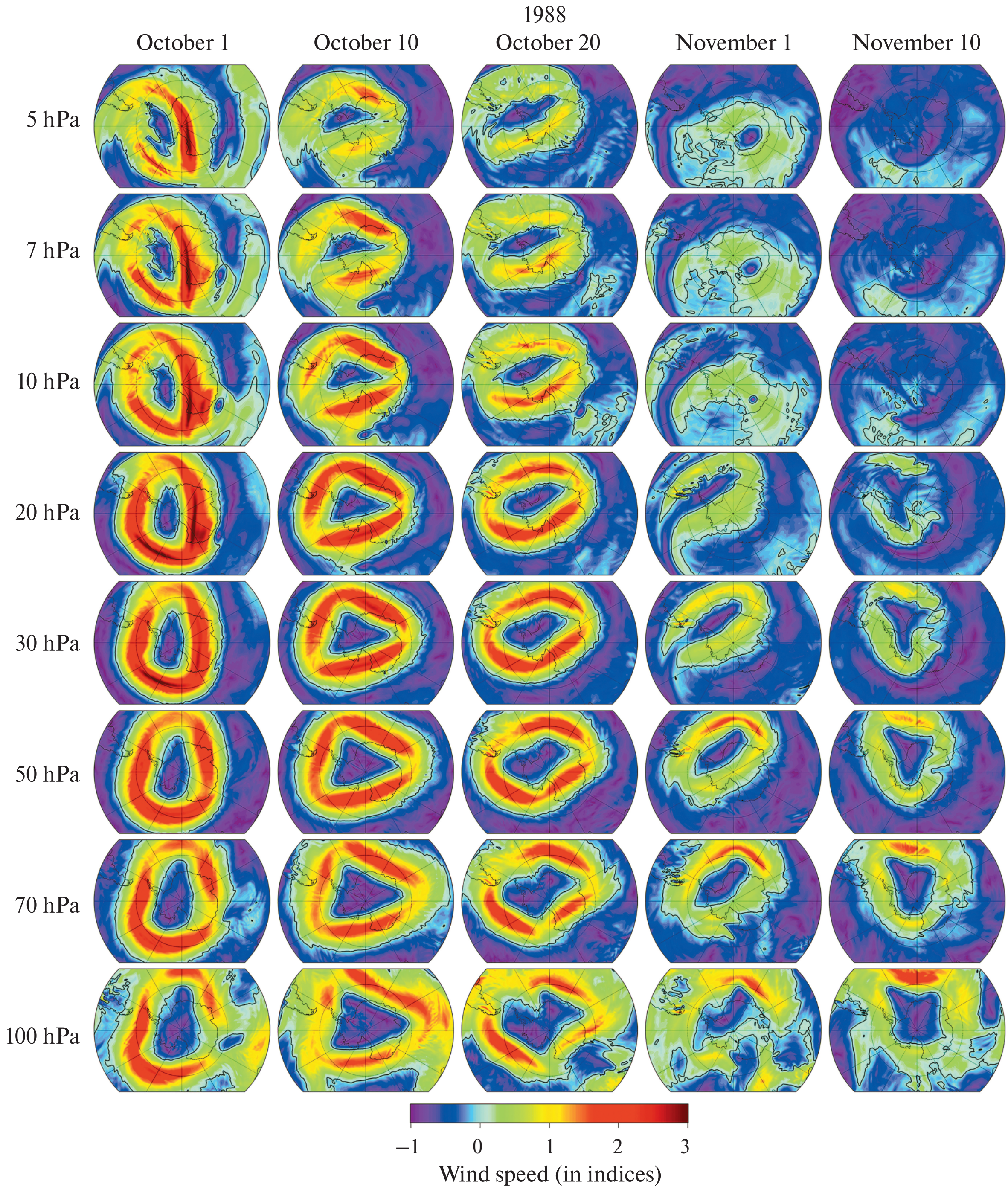

Fig. 3. Wind speed fields at the levels from 100 to 5 hPa over the Antarctic from October 1 to November 10, 1988.

in the lower and middle stratosphere, the polar vortex was partially restored and existed for another month.

The vortex dynamics in the spring of **2019** was to a large extent similar to the dynamics at the SSW of 1988. The vortex weakening and displacement began to manifest in the upper stratosphere as early as in early October and gradually spread to the middle and lower stratosphere (Figs. 6, 7). The SSW was observed on November 1 at the levels of 20 hPa and below, while at the levels from 10 hPa and above a significant displacement of the polar vortex was observed as early as in the second part of October (Table 2, Figs. 6, 7).

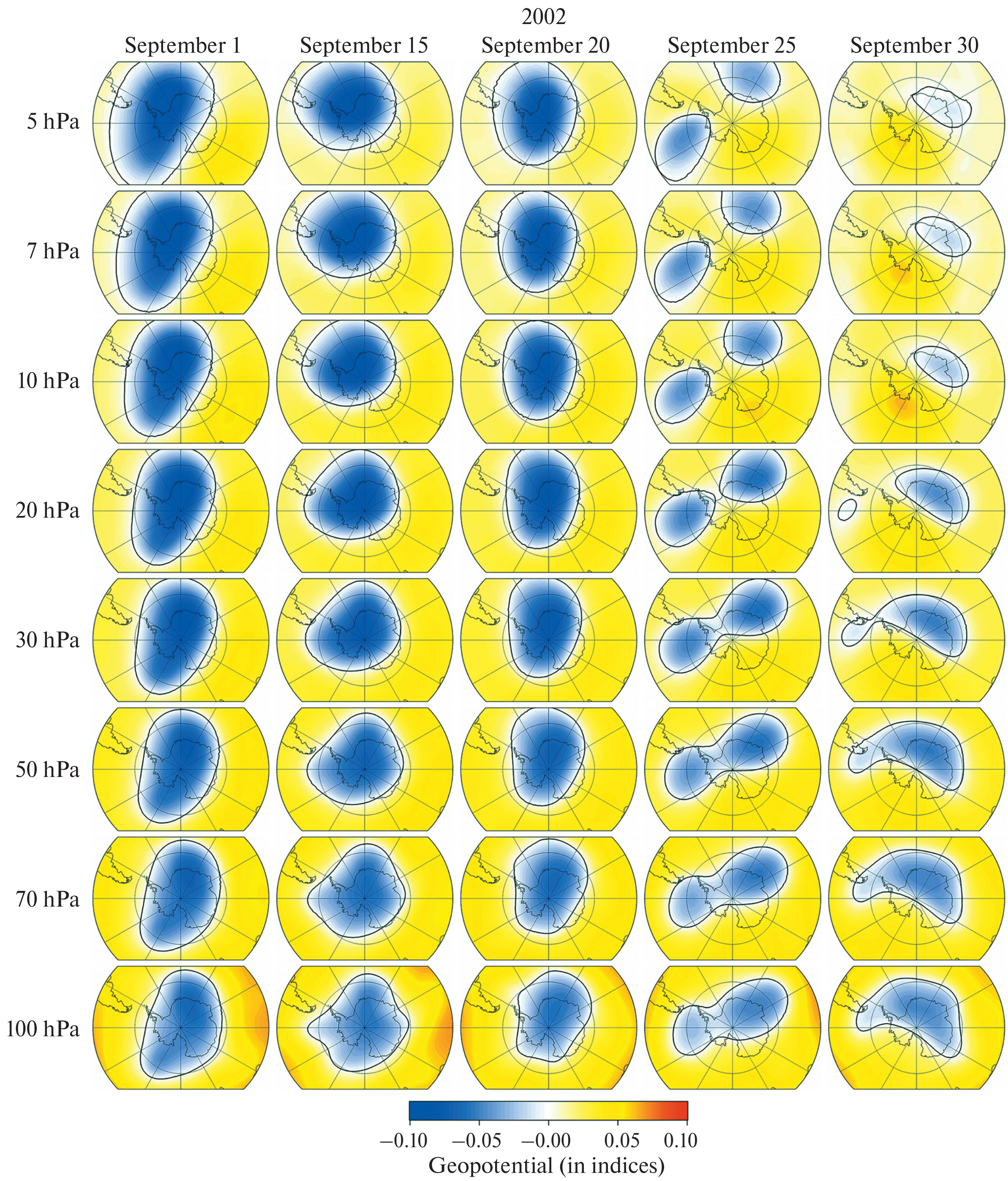

Fig. 4. Geopotential fields at the levels from 100 to 5 hPa over the Antarctic from September 1 to 30, 2002.

CONCLUSION

The paper considers the vertical structure of the Antarctic polar vortex during the SSW 1988, 2002 and 2019 and the dynamics of the PSC volume and the ozone hole area from satellite observations. A significant displacement of the polar vortex was observed in 1988 and 2019, and a cleavage in 2002. The volume of the PSC and the area of the ozone hole are indirect characteristics of the polar vortex dynamics. In the years under consideration, one observed almost simultaneously beginning from the end of August a decrease of wind speed along the

Table 2. Vortex area and mean wind speed along the vortex boundary before, during, and after the 1988, 2002, and 2019 SSWs

	Vortex area, mln. km^2					Wind speed at the vortex boundary, m/s				
	01.10.1988	10.10.1988	20.10.1988	01.11.1988	10.11.1988	01.10.1988	10.10.1988	20.10.1988	01.11.1988	10.11.1988
5 hPa	28.8	26.1	20.7			66.8	49.5	46.4		
7 hPa	28.0	24.8	20.1			66.4	56.7	52.9		
10 hPa	27.1	23.8	19.4			72.3	65.8	54.7		
20 hPa	30.2	28.4	25.3			70.3	69.9	60.8		
30 hPa	31.2	30.2	27.2	11.5		66.1	66.8	60.0	33.8	
50 hPa	32.4	31.7	28.4	14.9	11.7	57.5	57.0	53.6	35.3	22.1
70 hPa	32.9	32.7	28.8	16.5	15.2	50.8	48.6	46.4	31.1	24.3
100 hPa	50.8	50.5	45.4	37.8	36.3	37.9	37.5	35.5	27.8	28.0
	01.09.2002	15.09.2002	20.09.2002	25.09.2002	30.09.2002	01.09.2002	15.09.2002	20.09.2002	25.09.2002	30.09.2002
5 hPa	56.8	40.7	39.2	29.6		59.7	65.8	64.7	66.6	
7 hPa	50.6	38.4	35.3	27.5		62.6	67.9	71.4	70.4	
10 hPa	44.0	35.3	32.2	25.5		69.8	72.5	80.3	72.0	
20 hPa	42.0	35.5	33.7	29.6	16.2	66.8	67.2	75.3	62.4	56.7
30 hPa	40.6	35.2	33.6	30.6	22.2	63.2	63.7	69.2	60.4	57.0
50 hPa	38.9	34.7	32.2	29.8	26.5	56.8	55.0	57.2	54.3	56.6
70 hPa	37.8	34.3	30.5	29.1	27.3	51.3	47.7	49.5	46.9	50.8
100 hPa	54.3	52.1	45.4	46.7	47.1	38.0	35.0	30.8	31.1	30.8
	01.10.2019	10.10.2019	20.10.2019	01.11.2019	10.11.2019	01.10.2019	10.10.2019	20.10.2019	01.11.2019	10.11.2019
5 hPa	22.6	18.2	12.6			45.8	42.7	32.3		
7 hPa	19.3	16.9	12.6			51.8	47.1	37.1		
10 hPa	17.5	15.8	12.2			57.6	53.4	43.0		
20 hPa	21.5	19.9	17.2	11.7		59.7	58.4	52.5	41.1	
30 hPa	23.4	22.1	19.5	14.4		59.3	57.3	51.7	45.0	
50 hPa	25.1	24.6	21.7	16.1	9.2	56.0	54.3	48.9	44.5	31.2
70 hPa	26.0	26.3	23.0	16.3	10.7	52.3	50.2	43.6	37.4	33.0
100 hPa	42.0	42.8	42.1	34.6	27.7	33.2	34.3	28.4	25.4	25.9

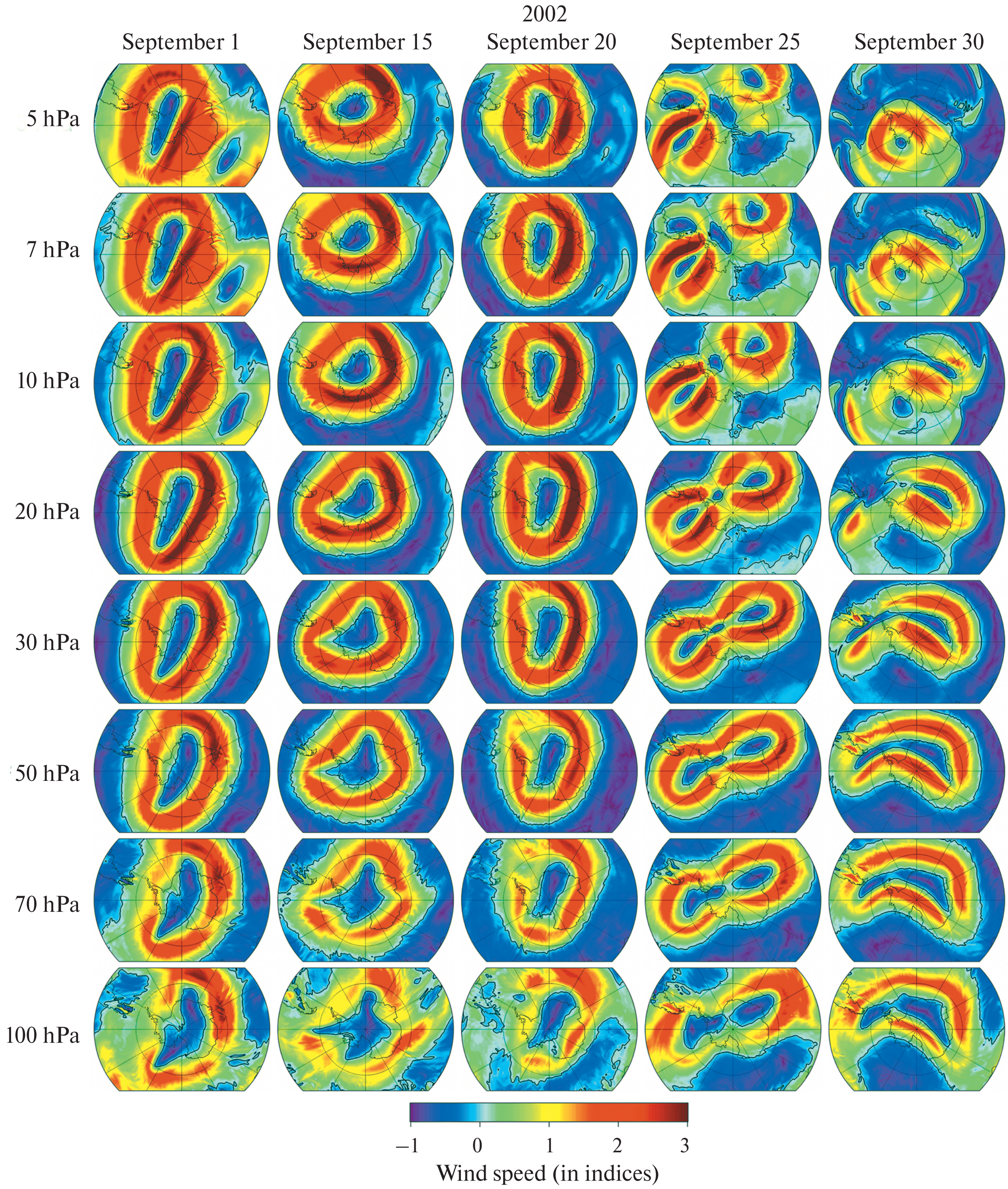

Fig. 5. Wind speed fields at the levels from 100 to 5 hPa over the Antarctic from September 1 to 30, 2002.

vortex boundary, an increase of temperature inside the vortex, destruction of PSC particles and decrease of the ozone hole area. The earlier tightening of the ozone hole occurred on October 30, 1988, November 9, 2002 and November 6, 2019, respectively. At the same time in 2002 and 2019, a more significant weakening of the polar vortex was observed: the wind speed and the PSC volume were on average by 40% and 30% lower than in 1988.

Different trends in the vertical dynamics of the Antarctic polar vortex at SSW recorded due to the displacement (1988 and 2019), or vortex splitting

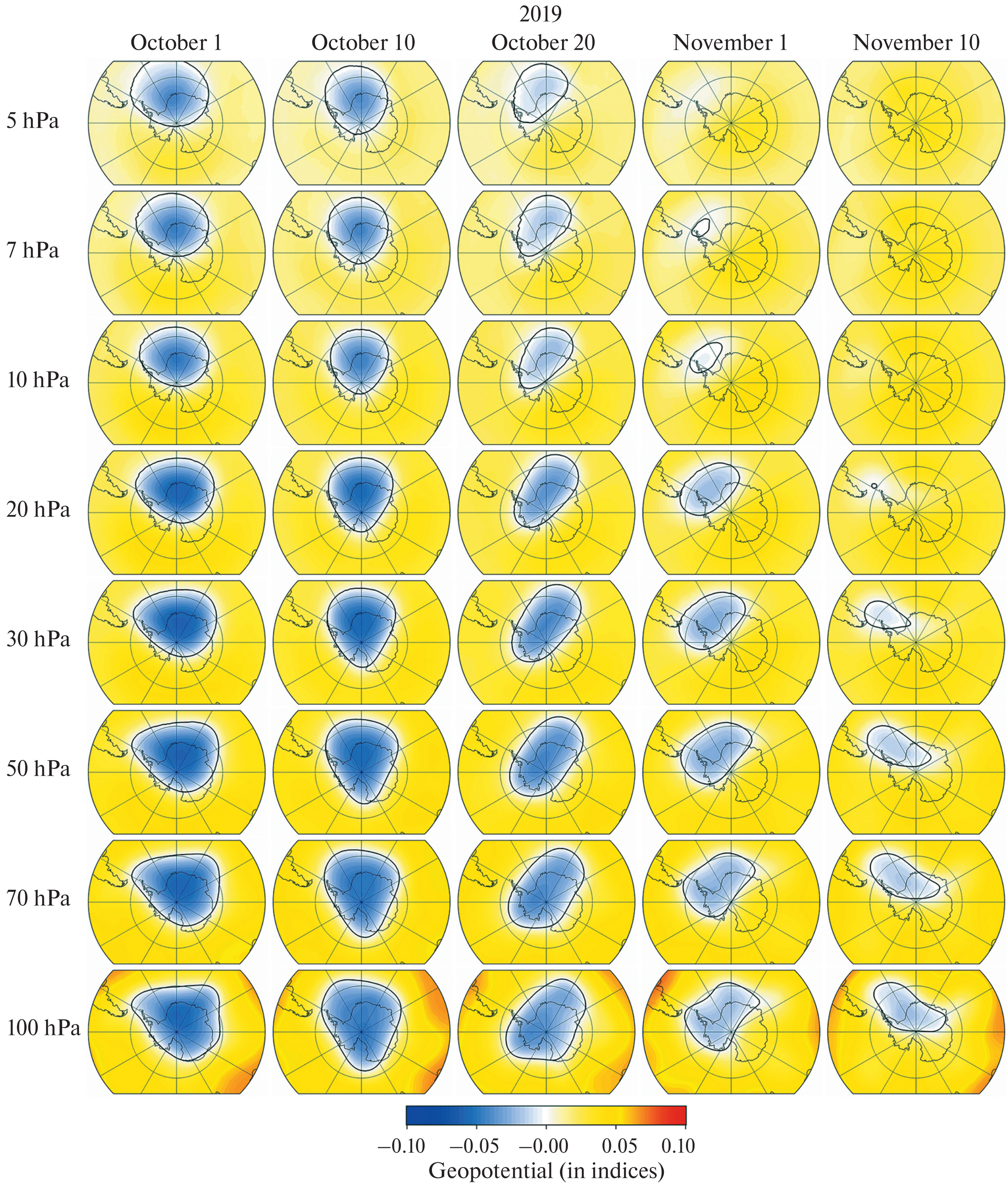

Fig. 6. Geopotential fields at levels from 100 to 5 hPa over Antarctica from October 1 to November 10, 2019.

(2002) were revealed. Weakening, displacement, and subsequent polar vortex breakup in 1988 and 2019 were observed first in the upper stratosphere and then gradually propagated into the middle and lower stratosphere over the course of a month. At the same time, the SSW in the lower stratosphere was preceded by a significant vortex displacement in the upper stratosphere one month before the event. In its turn in 2002 before splitting the polar vortex was sufficiently strong and stable at all stratospheric levels, splitting occurred in the middle and upper stratosphere, after which the vortex collapsed in the upper stratosphere

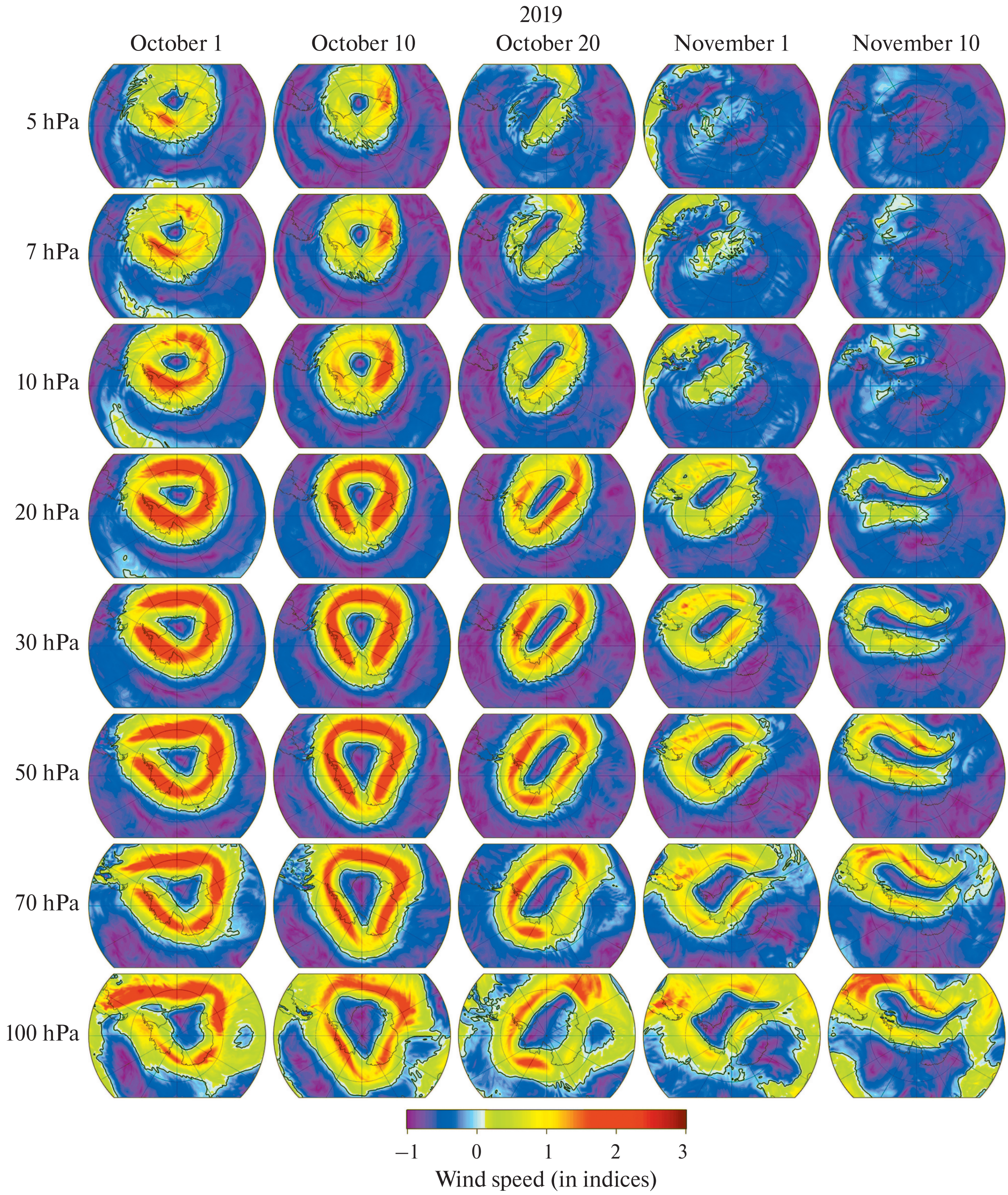

Fig. 7. Wind speed fields at levels from 100 to 5 hPa over Antarctica from October 1 to November 10, 2019.

and existed in the lower and middle stratosphere for another 1 month.

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