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ОРИГИНАЛЬНАЯ СТАТЬЯ **ORIGINAL PAPER**

Antarctic polar vortex dynamics in 2019 and 2020 under the influence of the subtropical stratosphere

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Abstract. The trend of strengthening of the Antarctic polar vortex in late spring and early summer (November–December) has been observed in recent decades. A good example of this trend is the dynamics of the Antarctic polar vortex in 2020 when it existed until the last week of December. In 2019, conversely, on the contrary, an unusually early breakup of the polar vortex occurred, a minor sudden stratospheric warming was recorded. Strengthening (or weakening) of the Antarctic polar vortex occurs as a result of an increase (or decrease) in the stratospheric meridional temperature gradient under conditions of growth (or decline) in the temperature of the lower subtropical stratosphere. We considered the temperature variations in the lower subtropical stratosphere in the spring of 2019 and 2020 and the corresponding response of the Antarctic polar vortex. The dynamics of the Antarctic polar vortex in September–October 2019 and November 2020 was largely synchronized with the temperature changes in the lower subtropical stratosphere relative to climatological means. Using correlation analysis, we show that the Antarctic polar vortex dynamics in December is largely due to the temperature changes in the lower subtropical stratosphere that occurred in the second half of November, which manifested itself in 2020.

Keywords: Antarctic ozone hole, Antarctic polar vortex, lower subtropical stratosphere, sudden stratospheric warming

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Introduction

The Southern Annular Mode (SAM), also known as the Antarctic Oscillation (AAO), largely determines the climate variability of the extratropical latitudes of the Southern Hemisphere [1, 2]. The SAM is a zonally symmetric mode of variability in the Southern Hemisphere with geopotential height perturbations of opposite signs over the Antarctic and a zonal band centered near 45° S [2, 3]. The positive phase of the SAM is associated with a decrease in the geopotential height over Antarctica and its increase over the middle latitudes of the Southern Hemisphere [2]. The SAM index in the stratosphere is a measure of the polar vortex strength [4]. The Antarctic polar vortex strengthening (in spring) and the subsequent increase in the SAM (in summer) have been observed in the last 3–4 decades [4]. The strengthening (or weakening) of the Antarctic vortex can also affect other aspects of the tropospheric circulation, including the occurrence of weather anomalies in the polar and subpolar latitudes [5, 6].

The Antarctic polar vortex usually forms in April, reaches its peak intensity in September and collapses in November–December [7, 8]. In the lower stratosphere inside the vortex, as a result of a significant decrease in temperature during the polar night, polar stratospheric clouds (PSCs) are formed, which act as surfaces for heterogeneous reactions between chlorine reservoirs, proceeding with the release of molecular chlorine [9, 10]. With the appearance of solar radiation over the polar region in the lower stratosphere, the chlorine cycle of ozone depletion begins inside the polar vortex, and proceeds until the collapse of the vortex [11, 12]. The earlier breakdown of the polar vortex occurs under the influence of planetary waves and is accompanied by sudden stratospheric warming (SSW) [13, 14]. SSWs are characterized by a sharp increase in temperature in the middle and lower polar stratosphere, which is observed as a result of a strong displacement (minor SSW) or splitting (major SSW) of the polar vortex [15]. SSWs were observed over Antarctica in the September of 2002 (major SSW) and 2019 (minor SSW) [16, 17].

Earlier weakening and breakdown of the Antarctic polar vortex in the spring of 2019 has been considered in several works [18–20]. The abnormal weakening of the polar vortex in 2019 was observed from September to October, after which it collapsed in the first half of November, about a month earlier than the average for 40 years. Although a minor SSW was recorded in 2019 (the polar vortex displacement was observed), the polar vortex weakening in 2019 was comparable to that in 2002, when a major SSW occurred as a result of the vortex splitting [18]. A significant displacement of the polar vortex was observed from 3–5 to 19–21 September, as the vortex area decreased to 24 million km^2 [19]. However, in 2020, an abnormal strengthening of the Antarctic polar vortex was observed in late spring [21, 22]. In 2020, anomalously high values of the average wind speed along the vortex edge were recorded throughout the entire period of its existence, and record values of the vortex area and ozone hole area were observed from mid-November to December. The polar vortex in 2020 existed until the last week of December, which is an unprecedented case [23].

The formation and strengthening of the Antarctic polar vortex occurs under conditions of an increase in the stratospheric meridional temperature gradient [24, 25]. The seasonal temperature variation of the lower subtropical stratosphere in the Southern Hemisphere provides favorable conditions for the formation of the strong polar vortex [26]. A gradual increase in temperature from March until reaching a maximum in September contributes to the gradual strengthening of the polar vortex from its formation in April to its peak intensity in September. Moreover, temperature variations in the lower subtropical stratosphere relative to its climatological means in October and November cause corresponding changes in the Antarctic polar vortex dynamics (a temperature increase relative to the means leads to vortex strengthening and a temperature decrease causes vortex weakening) [27]. This work aims to illustrate the influence of temperature changes in the lower subtropical stratosphere in the spring of 2019 and 2020 on the Antarctic polar vortex dynamics.

Data and methods

The geopotential, zonal and meridional winds, temperature and ozone mass mixing ratio data for 0–90° S on the 50 hPa pressure surface from 1983 to 2022 were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis data (https://doi.org/10.24381/cds.bd0915c6) [28]. The data on minimum temperature for 50–90° S on the 50 hPa pressure surface, PSC volume for 60–90° S and ozone hole area for 40–90° S from 1983 to 2022 were taken from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) data [29].

To analyze the dynamics of the Antarctic polar vortex in 2019 and 2020, we obtained the 40 year climatological mean seasonal cycles of zonal mean zonal wind at 60° S, minimum temperature for 50–90° S, PSC volume and ozone hole area in the Antarctic stratosphere over the period 1983–2022 with standard deviations (σ). To explore variations of lower subtropical stratospheric temperature in 2019 and 2020, we obtained the 40-year climatological mean seasonal cycles of temperature anomalies for 20–40° S over the period 1983–2022 with standard deviations. Climatological means and their standard deviations were smoothed with the FFT filter (fast Fourier transform filter) over 15 points. Time series of the characteristics studied in 2019 and 2020 were smoothed with a 5-point FFT filter.

To trace the Antarctic polar vortex edge in 2019 and 2020 (Fig. 1) we used the vortex delineation method, according to which the Antarctic vortex edge at the 50 hPa level is determined by geopotential value of 19.3·104 m^2/s^2 [30]. To analyze temperature changes in the lower subtropical stratosphere, taking into account its significant interannual variability, we used temperature anomalies. We obtained temperature anomalies by subtracting the annual mean values of the corresponding year from the daily mean values. To study the influence of temperature changes in the lower subtropical stratosphere on the polar vortex dynamics, we calculated the Pearson correlation coefficients between daily mean values of the zonal mean zonal wind at 60° S and the temperature anomalies for 20–40° S at the 50 hPa level from September to December over the period 1983–2022.

Results

Fig. 1 shows the geopotential, wind speed and ozone distributions in the lower stratosphere over the Antarctic from 15 September to 15 December of 2019 and 2020. The Antarctic polar vortex edge, characterized by a geopotential value of $19.3 \cdot 10^4$ m^2/s^2 (according to the vortex delineation method [30]), is highlighted in the geopotential distributions by a line. Prior to the vortex breakdown, the geopotential values of $19.3 \cdot 10^4$ m^2/s^2 accurately describe the edges of the Antarctic polar vortex in the lower stratosphere, since they correspond to the maximum wind speed values (characterizing the vortex edges) in the wind speed distributions and are in good agreement with areas of low ozone content (characterizing regions of the polar vortex) in ozone distributions (Fig. 1). In the wind speed distributions, the values of 20 m/s are marked with a line, at

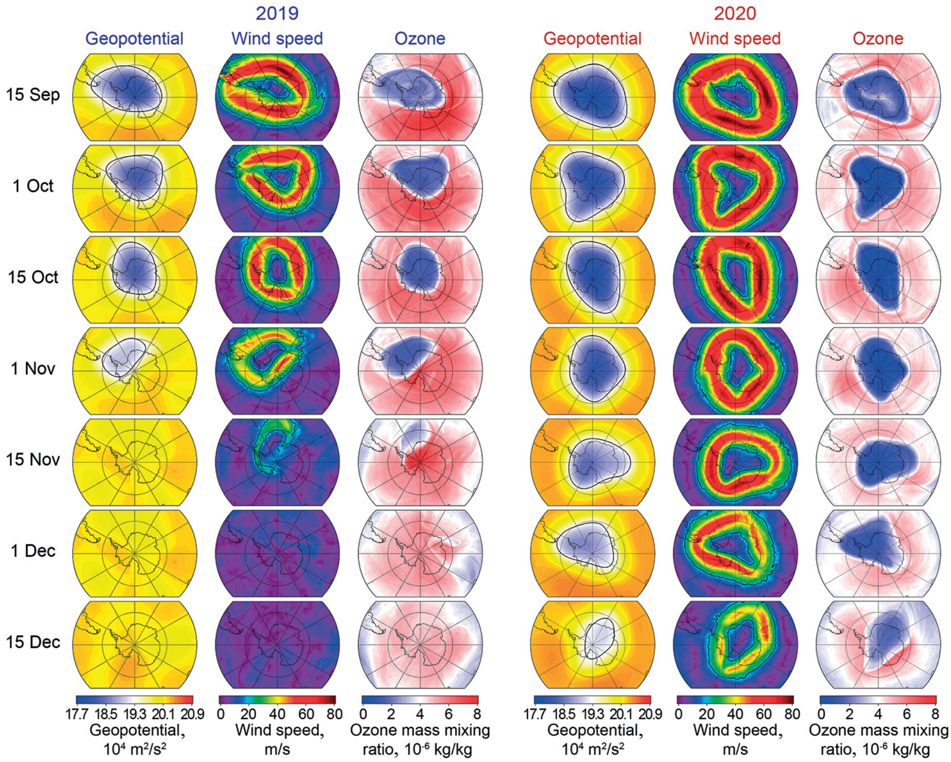

Fig. 1. Geopotential, wind speed and ozone distributions at the 50 hPa level over the Antarctic from 15 September to 15 December of 2019 and 2020

Рис. 1. Поля геопотенциала, скорости ветра и озона на уровне 50 гПа над Антарктикой с 15 сентября до 15 декабря 2019 и 2020 гг.

which the polar vortex edge becomes a dynamic barrier [31]. As seen from Fig. 1, in 2019 the polar vortex was much weaker than in 2020. The vortex displacement was observed in September 2019, accompanied by a minor SSW, and its breakdown occurred in the first half of November. In 2020 the Antarctic polar vortex was unusually strong, characterized by high wind speed along the vortex edge and a large area, with deep ozone depletion observed inside the vortex.

The spring strengthening (weakening) of the Antarctic polar vortex is usually due to an increase (decrease) in the stratospheric meridional temperature gradient under conditions of a growth (decline) in the temperature of the lower subtropical stratosphere [27]. Fig. 2 shows 40-year average intra-annual changes in mid-latitude temperature values in the range of 0–60° S and zonal wind in the range of 30–90° S at the 50 hPa level, as well as the intra-annual variation in the temperature values in the region of 20–40° S and zonal wind at 60° S with standard deviations (σ). The red and blue lines correspond to the maximum and minimum values in intra-annual changes for each latitude. The intra-annual temperature variation of the lower subtropical stratosphere is explained by the ongoing compensation between temperature changes in tropical and polar latitudes [32]. The seasonal maximum in the lower stratosphere of tropical and Antarctic latitudes is observed at the end of July and December, respectively. Seasonal temperature variations in the lower tropical stratosphere are due to the intra-annual variation of stratospheric ozone in the tropics: the temperature maximum is observed approximately 2–3 weeks after the formation of the ozone maximum [33]. As seen from Fig. 2, in the Southern Hemisphere, seasonal changes in the temperature of the lower subtropical stratosphere are in good agreement with changes in the zonal wind at 60° S (reflecting the dynamics of the Antarctic polar vortex): an increase in temperature in the autumn-winter period (from March to September) contributes to an increase in the stratospheric meridional temperature gradient and subsequent strengthening of the Antarctic polar vortex.

To illustrate the influence of the subtropical stratosphere on the Antarctic polar vortex dynamics, Fig. 3 shows the time series of temperature anomalies in the region of 20–40° S at the 50 hPa level from June to December 2019 and 2020 compared with

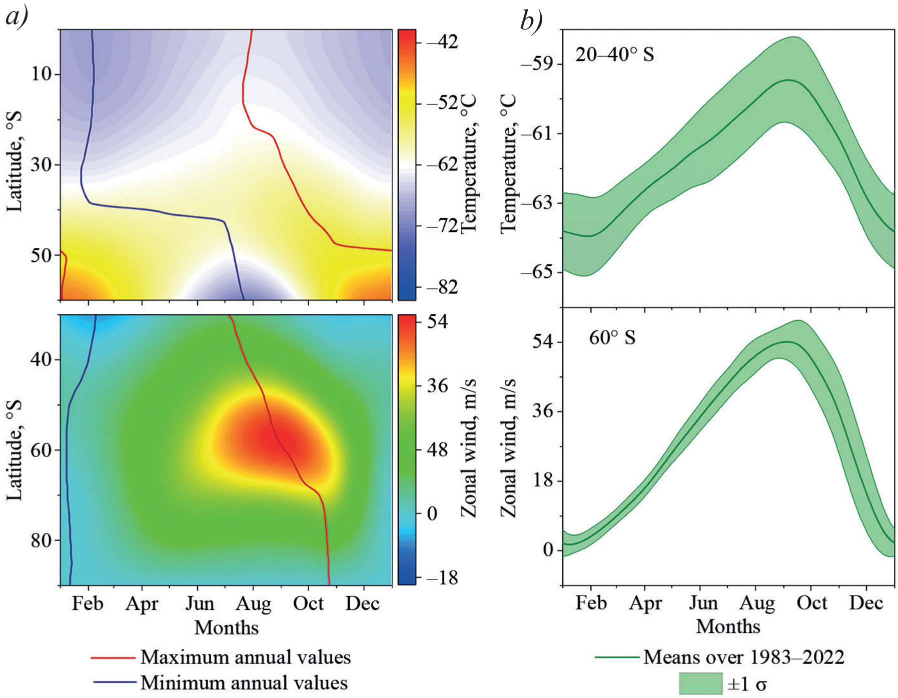

Fig. 2. The 1983–2022 climatological means of zonal mean temperature and zonal mean zonal wind: *a*) the climatological mean values of zonal mean temperature from 0° S to 60° S and zonal mean zonal wind from 30° S to 90° S at the 50 hPa level from January to December (the blue and red lines correspond to the minimum and maximum values over the year); *b*) the climatological means of zonal mean temperature for 20–40° S and zonal mean zonal wind at 60° S at the 50 hPa level from January to December with ±1 σ

Рис. 2. Внутригодовые изменения температуры и зонального ветра в среднем за 1983–2022 гг.: *а*) зональные средние внутригодовые изменения температуры в области от 0° до 60° ю. ш. и зонального ветра в области от 30° до 90° ю. ш. на уровне 50 гПа (синие и красные линии соответствуют минимальным и максимальным значениям во внутригодовых изменениях на каждой широте); *b*) внутригодовой ход температуры в области 20–40° ю. ш. и зонального ветра у 60° ю. ш. на уровне 50 гПа с СКО (±1 σ) the 40-year means. Fig. 3 also shows intra-annual changes in the zonal mean zonal wind speed at 60° S, zonal mean temperature in the area of 60–90° S and minimum temperature in the area of 50–90° S at the 50 hPa level, the PSC volume in the region of 60–90° S and the ozone hole area from July to December 2019 and 2020 compared with the 1983–2022 climatological means. An abnormal decrease in the temperature of the lower subtropical stratosphere in 2019 was observed from early September and was accompanied by an anomalous decrease in zonal wind at 60° S and an anomalous increase in the mean and minimum temperature in the lower polar stratosphere. At the same time, a rapid decrease in the PSC volume and ozone hole area was observed (Fig. 3). The temperature increase in the subtropical stratosphere, which began on 19 September

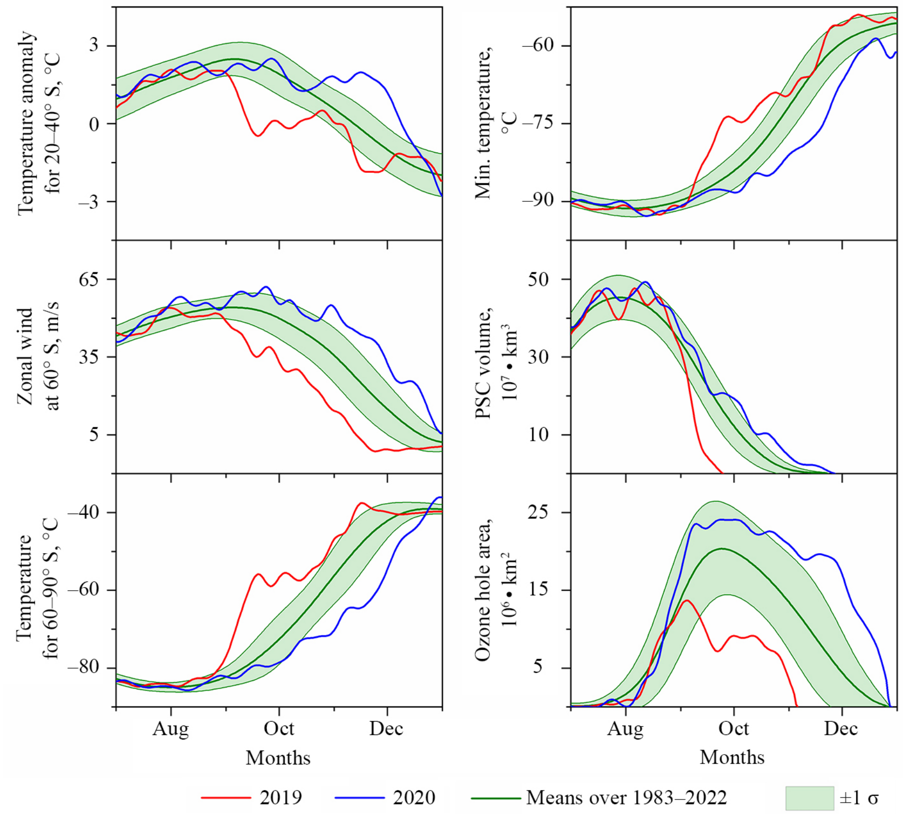

Fig. 3. Time series of temperature anomalies for 20–40° S, zonal mean zonal wind at 60° S, zonal mean temperature for 60–90° S, minimum temperature for 50–90° S at the 50 hPa level, PSC volume for 60–90° S and ozone hole area for 40–90° S from July to December of 2019 and 2020 in comparison with the 1983–2022 climatological means with ±1 σ

Рис. 3. Внутригодовой ход температурных аномалий в области 20–40° ю. ш., скорости зонального ветра на 60° ю. ш., средней температуры в области 60–90° ю. ш. и минимальной температуры в области 50–90° ю. ш. на уровне 50 гПа, объема ПСО в области 60–90° ю. ш. и площади озоновой дыры с июля по декабрь 2019 и 2020 гг. на фоне средних значений за 1982–2021 гг. с СКО (±1 σ)

2019, was accompanied by an increase in wind speed and a decrease in mean temperature in the polar region, as well as an increase in ozone hole area. Subsequent changes in the temperature of the lower subtropical stratosphere were also largely synchronized with the polar vortex dynamics until its breakdown in early November (Fig. 3). SSWs can contribute to an intensification of the Brewer-Dobson circulation, which can lead to a temperature decrease in the lower subtropical stratosphere [34], which in turn leads to a decrease in the stratospheric meridional temperature gradient and an additional weakening of the polar vortex. A temperature increase in the lower subtropical stratosphere in the second half of October 2020 was also accompanied by an anomalous increase in zonal wind at 60° S, a decrease in the mean and minimum temperatures in the polar region, and an increase in the PSC volume and ozone hole area. The temperature decrease since 30 October 2020 was accompanied by a decrease in zonal wind and an increase in mean temperature in the polar region. Subsequent changes are also largely correlated up to the second week of December (Fig. 3).

During the second and third weeks of December 2020, the characteristics of the polar vortex remained abnormally high, while the temperature of the lower subtropical stratosphere approached the climatological means. Fig. 4 shows the distributions of the Pearson correlation coefficients between the zonal mean zonal wind at 60° S and zonal mean temperature anomalies in the region of 20–40° S at the 50 hPa level from 1983 to 2022. Correlation values above 0.4 and 0.6 are outlined. Correlation coefficients get higher than 0.4 from 21 September, higher than 0.6 from 16 October and close to 0.8 from early November, with the highest values observed mostly day-to-day. According to Fig. 4, in December, changes in zonal wind at 60° S are largely due to temperature

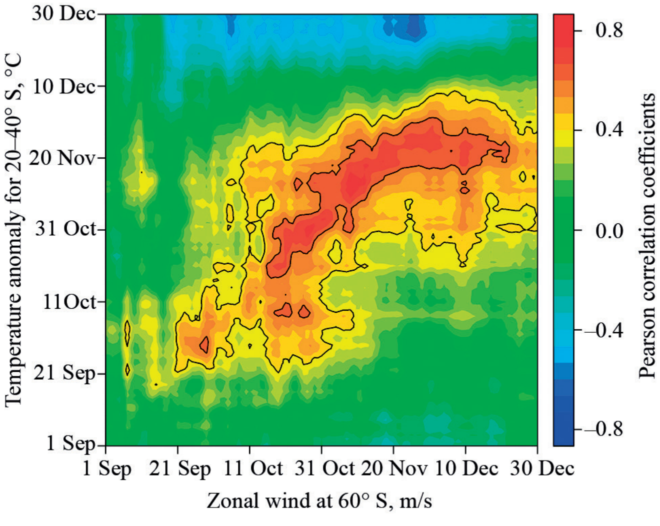

Fig. 4. The Pearson correlation coefficients between daily mean values of zonal mean zonal wind at 60° S and temperature anomalies for 20–40° S at the 50 hPa level from 1 September to 30 December over the period 1983–2022

Рис. 4. Коэффициенты корреляции между среднесуточными значениями зонального ветра на 60° ю. ш. и аномалиями температуры в области 20–40° ю. ш. на уровне 50 гПа с 1 сентября по 30 декабря за 1983–2022 гг.

variations in the second half of November. This explains the Antarctic polar vortex dynamics in December 2020, which was more correlated with the temperature variations of the subtropical stratosphere observed in the second half of November. Another explanation could be the influence of deep ozone depletion on temperature decrease inside the polar vortex in the second and third weeks of December (Fig. 3), which in turn could contribute to an increase in the stratospheric meridional temperature gradient and the persistence of the strong vortex.

Conclusion

In this work, using the ERA5 reanalysis data and the MERRA-2 data, we illustrated the influence of the temperature of the lower subtropical stratosphere on the Antarctic polar vortex dynamics in spring 2019 and 2020. The unusual weakening of the polar vortex was observed in September and October 2019, until its breakdown in early November. The unusual strengthening of the polar vortex and an unprecedented increase in the duration of its existence was observed in November and December 2020 (the polar vortex breakdown occurred in late December). The formation and strengthening of the Antarctic polar vortex occurs as a result of an increase in the stratospheric meridional temperature gradient under conditions of a seasonal temperature increase in the lower subtropical stratosphere. During spring, the temperature gradient begins to decrease and the polar vortex becomes more sensitive to temperature changes in the lower subtropical stratosphere relative to the climatological means. The Antarctic polar vortex dynamics in September–October 2019 and November 2020 was largely correlated with temperature changes in the lower subtropical stratosphere. An unusual weakening and subsequent breakdown of the polar vortex in the spring of 2019 was observed under conditions of an anomalous temperature decrease of the lower subtropical stratosphere. The 2019 SSW could have contributed to the intensification of the Brewer-Dobson circulation, which could have led to a decrease in the temperature in the lower subtropical stratosphere [34] and a subsequent weakening of the polar vortex. An unusual strengthening of the polar vortex from early November to the first week of December 2020 occurred under the conditions of an anomalous temperature increase of the lower subtropical stratosphere. Changes in the main characteristics of the polar vortex in the spring of 2019 and 2020 were largely synchronized with temperature variations in the subtropical stratosphere relative to the climatological means. At the same time, in December 2020, temperature changes in the subtropical stratosphere and the polar vortex dynamics were not consistent. Using correlation analysis, we have illustrated that in December the Antarctic polar vortex dynamics is largely determined by temperature changes in the lower subtropical stratosphere observed in the second half of November. It is also possible that deep ozone depletion may influence the decrease in temperature within the polar vortex, which could contribute to an increase in the stratospheric meridional temperature gradient and subsequent strengthening of the polar vortex.

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REFERENCES

1. Fogt R.L., Marshall G.J. The Southern Annular Mode: Variability, trends, and climate impacts across the Southern Hemisphere. *WIREs Clim. Change*. 2020; 11(4): e652. https://doi.org/10.1002/wcc.652
2. Gillett N.P., Kell T.D., Jones P.D. Regional climate impacts of the Southern Annular Mode. *Geophys. Res. Lett*. 2006; 33(23): L23704. https://doi.org/10.1029/2006GL027721
3. Limpasuvan V., Hartmann D.L. Eddies and the annular modes of climate variability. *Geophys. Res. Lett.* 1999; 26(20): 3133–3136. https://doi.org/10.1029/1999GL010478
4. Waugh D.W., Polvani L.M. Stratospheric polar vortices. Polvani L.M., Sobel A.H., Waugh D.W. (Eds.) The Stratosphere: Dynamics, Transport, and Chemistry. *Geophysical Monograph Series*. 2010; 190: 43–57. https://doi.org/10.1002/9781118666630.ch3
5. Lim E.-P., Hendon H.H., Boschat G., Hudson D., Thompson D.W.J., Dowdy A.J., Arblaster J.M. Australian hot and dry extremes induced by weakenings of the stratospheric polar vortex. *Nat. Geosci.* 2019; 12: 896–901. https://doi.org/10.1038/s41561-019-0456-x
6. Kidston J., Scaife A.A., Hardiman S.C., Mitchell D.M., Butchart N., Baldwin M.P., Gray L.J. Stratospheric influence on tropospheric jet streams, storm tracks and surface weather. *Nat. Geosci.* 2015; 8(6): 433–440. https://doi.org/10.1038/ngeo2424
7. Waugh D.W., Sobel A.H., Polvani L.M. What is the polar vortex and how does it influence weather? *Bull. Amer. Meteor. Soc*. 2017; 98(1): 37–44. https://doi.org/10.1175/BAMS-D-15-00212.1
8. Hurwitz M.M., Newman P.A., Li F., Oman L.D., Morgenstern O., Braesicke P., Pyle J.A. Assessment of the breakup of the Antarctic polar vortex in two new chemistry-climate models. *J. Geophys. Res.* 2010; 115(D7): D07105. https://doi.org/10.1029/2009JD012788
9. Solomon S. Stratospheric ozone depletion: a review of concepts and history. *Rev. Geophys*. 1999; 37(3): 275–316. https://doi.org/10.1029/1999RG900008
10. Newman P.A., Kawa S.R., Nash E.R. On the size of the Antarctic ozone hole. *Geophys. Res. Lett.* 2004; 31(21): L21104. https://doi.org/10.1029/2004GL020596
11. Vargin P.N., Nikiforova M.P., Zvyagintsev A.M. Variability of the Antarctic ozone anomaly in 2011–2018. *Russ. Meteorol. Hydrol*. 2020; 45(2): 63–73. https://doi.org/10.3103/S1068373920020016
12. Smyshlyaev S.P., Blakitnaya P.A., Motsakov M.A. Numerical modeling of the influence of physical and chemical factors on the interannual variability of Antarctic ozone. *Russ. Meteorol. Hydrol*. 2020; 45(3): 153–160. https://doi.org/10.3103/S1068373920030024
13. Charlton A.J., Polvani L.M. A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. *J. Climate.* 2007; 20(3): 449–469. https://doi.org/10.1175/JCLI3996.1
14. Charlton A.J., Polvani L.M., Perlwitz J., Sassi F., Manzini E., Shibata K., Pawson S., Nielsen J.E., Rind D. A new look at stratospheric sudden warmings. Part II: Evaluation of numerical model simulations. *J. Climate*. 2007; 20(3): 470–488. https://doi.org/10.1175/JCLI3994.1
15. Butler A.H., Seidel D.J., Hardiman S.C., Butchart N., Birner T., Match A. Defining sudden stratospheric warmings. *Bull. Amer. Meteor. Soc*. 2015; 96(11): 1913–1928. https://doi.org/10.1175/BAMS-D-13-00173.1
16. Charlton A.J., O'Neill A., Lahoz W.A., Berrisford P. The splitting of the stratospheric polar vortex in the Southern Hemisphere, September 2002: Dynamical evolution. *J. Atmos. Sci.* 2005; 62(3): 590–602. https://doi.org/10.1175/JAS-3318.1
17. Safieddine S., Bouillon M., Paracho A.-C., Jumelet J., Tencé F., Pazmino A., Goutail F., Wespes C., Bekki S., Boynard A., Hadji-Lazaro J., Coheur P.-F., Hurtmans D., Clerbaux C. Antarctic ozone enhancement during the 2019 sudden stratospheric warming event. *Geophys. Res. Lett*. 2020; 47(14): e2020GL087810. https://doi.org/10.1029/2020GL087810

18. Lim E.-P., Hendon H.H., Butler A.H., Thompson D.W.J., Lawrence Z.D., Scaife A.A., Shepherd T.G., Polichtchouk I., Nakamura H., Kobayashi C., Comer R., Coy L., Dowdy A., Garreaud R.D., Newman P.A., Wang G. The 2019 Southern Hemisphere stratospheric polar vortex weakening and its impacts. *B. Am. Meteorol. Soc*. 2021; 102(6): E1150–E1171. https://doi.org/10.1175/BAMS-D-20-0112.1

19. Roy R., Kuttippurath J., Lefèvre F., Raj S., Kumar P. The sudden stratospheric warming and chemical ozone loss in the Antarctic winter 2019: comparison with the winters of 1988 and 2002. *Theor. Appl. Climatol*. 2022; 149: 119–130. https://doi.org/10.1007/s00704-022-04031-6

20. Wargan K., Weir B., Manney G.L., Cohn S.E., Livesey N.J. The anomalous 2019 Antarctic ozone hole in the GEOS constituent data assimilation system with MLS observations. *J. Geophys. Res*. 2020; 125(18): e2020JD033335. https://doi.org/10.1029/2020JD033335

21. Yook S., Thompson D.W.J., Solomon S. Climate impacts and potential drivers of the unprecedented Antarctic ozone holes of 2020 and 2021. *Geophys. Res. Lett*. 2022; 49(10): e2022GL098064. https://doi.org/10.1029/2022GL098064

22. Klekociuk A.R., Tully M.B., Krummel P.B., Henderson S.I., Smale D., Querel R., Nichol S., Alexander S.P., Fraser P.J., Nedoluha G. The Antarctic ozone hole during 2020. *J. South. Hemisph. Earth Syst. Sci.* 2021; 72(1): 19–37. https://doi.org/10.1071/ES21015

23. Zuev V.V., Savelieva E.S., Pavlinsky A.V., Sidorovski E.A. The unprecedented duration of the 2020 ozone depletion in the Antarctic. *Dokl. Earth Sci.* 2023; 509(1): 358–362. https://doi.org/10.1134/S1028334X22601754

24. Stenchikov G., Hamilton K., Stouffer R.J., Robock A., Ramaswamy V., Santer B., Graf H.-F. Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models. *J. Geophys. Res.* 2006; 111: D07107. https://doi.org/10.1029/2005JD006286

25. Driscoll S., Bozzo A., Gray L.J., Robock A., Stenchikov G. Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. *J. Geophys. Res*. 2012; 117: D17105. https://doi.org/10.1029/2012JD017607

26. Zuev V.V., Savelieva E. The cause of the spring strengthening of the Antarctic polar vortex. *Dynam. Atmos. Oceans*. 2019; 87: 101097. https://doi.org/10.1016/j.dynatmoce.2019.101097

27. Zuev V.V., Savelieva E. The cause of the strengthening of the Antarctic polar vortex during October–November periods. *J. Atmos. Sol.-Terr. Phys*. 2019; 190: 1–5. https://doi.org/10.1016/j.jastp.2019.04.016

28. Hersbach H., Bell B., Berrisford P., Hirahara S., Horányi A., Muñoz-Sabater J., Nicolas J., Peubey C., Radu R., Schepers D., Simmons A., Soci C., Abdalla S., Abellan X., Balsamo G., Bechtold P., Biavati G., Bidlot J., Bonavita M., de Chiara G., Dahlgren P., Dee D., Diamantakis M., Dragani R., Flemming J., Forbes R., Fuentes M., Geer A., Haimberger L., Healy S., Hogan R.J., Hólm E., Janisková M., Keeley S., Laloyaux P., Lopez P., Lupu C., Radnoti G., de Rosnay P., Rozum I., Vamborg F., Villaume S., Thépaut J.-N. The ERA5 global reanalysis. *Q. J. Roy. Meteor. Soc.* 2020; 146(729): 1–51. https://doi.org/10.1002/qj.3803

29. Gelaro R., McCarty W., Suárez M.J., Todling R., Molod A., Takacs L., Randles C.A., Darmenov A., Bosilovich M.G., Reichle R., Wargan K., Coy L., Cullather R., Draper C., Akella S., Buchard V., Conaty A., da Silva A.M., Gu W., Kim G.-K., Koster R., Lucchesi R., Merkova D., Nielsen J.E., Partyka G., Pawson S., Putman W., Rienecker M., Schubert S.D., Sienkiewicz M., Zhao B. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *J. Climate*. 2017; 30(14): 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

30. Zuev V.V., Savelieva E. Stratospheric polar vortex dynamics according to the vortex delineation method. *J. Earth Syst. Sci*. 2023; 132(1): 39. https://doi.org 10.1007/s12040-023-02060-x

31. Zuev V.V., Savelieva E. Antarctic polar vortex dynamics depending on wind speed along the vortex edge. *Pure Appl. Geophys*. 2022; 179(6–7): 2609–2616. https://doi.org/10.1007/s00024-022-03054-4

32. Yulaeva E., Holton J.R., Wallace J.M. On the cause of the annual cycle in tropical lower-stratospheric temperatures. *J. Atmos. Sci.* 1994; 51(2): 169–174. https://doi.org/10.1175/1520-0469(1994)051<0169:OTCOTA>2.0.CO;2
33. Steinbrecht W., Hassler B., Claude H., Winkler P., Stolarski R.S. Global distribution of total ozone and lower stratospheric temperature variations. *Atmos. Chem. Phys*. 2003; 3(5): 1421–1438. https://doi.org/10.5194/acp-3-1421-2003
34. Noguchi S., Kuroda Y., Kodera K., Watanabe S. Robust enhancement of tropical convective activity by the 2019 Antarctic sudden stratospheric warming. *Geophys. Res. Lett*. 2020; 47(15): e2020GL088743. https://doi.org/10.1029/2020GL088743

Динамика антарктического полярного вихря в 2019 и 2020 гг. под влиянием субтропической стратосферы (расширенный реферат)

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В последние десятилетия наблюдается выраженная тенденция усиления антарктического полярного вихря в поздневесенний и раннелетний период (ноябрь–декабрь), проявляющаяся в удлинении периода его существования. Ярким примером этой тенденции стала динамика антарктического полярного вихря в 2020 г., когда он существовал вплоть до последней недели декабря. В свою очередь в 2019 г., наоборот, произошло необычно раннее разрушение полярного вихря, регистрировалось малое внезапное стратосферное потепление.

В работе с использованием данных реанализа ERA5 и данных MERRA-2 рассмотрено влияние температуры нижней субтропической стратосферы на динамику антарктического полярного вихря весной 2019 и 2020 гг. В 2019 г. наблюдалось аномальное ослабление полярного вихря в сентябре и октябре, вплоть до его разрушения в начале ноября. В то время как в 2020 г. наблюдалось необычное усиление полярного вихря в ноябре и декабре и беспрецедентное увеличение продолжительности его существования (полярный вихрь разрушился в конце декабря).

Формирование и усиление антарктического полярного вихря происходит в результате увеличения стратосферного меридионального температурного градиента в условиях сезонного роста температуры нижней субтропической стратосферы.

Весной температурный градиент начинает уменьшаться и полярный вихрь становится более чувствительным к изменениям температуры нижней субтропической стратосферы относительно климатической нормы. Показано, что динамика антарктического полярного вихря в сентябре–октябре 2019 г. и в ноябре 2020 г. была в значительной степени скоррелирована с изменениями температуры нижней субтропической стратосферы. Ослабление и последующее разрушение полярного вихря весной 2019 г. наблюдалось в условиях аномального понижения температуры нижней субтропической стратосферы. Усиление полярного вихря с начала ноября по первую неделю декабря 2020 г. происходило в условиях аномального увеличения температуры нижней субтропической стратосферы. Изменения основных характеристик полярного вихря весной 2019 и 2020 гг. были в значительной степени синхронизированы с вариациями температуры субтропической стратосферы относительно климатической нормы. При этом в декабре 2020 г. не наблюдалось согласованности в изменениях температуры субтропической стратосферы и динамике полярного вихря. С использованием корреляционного анализа показано, что в декабре динамика антарктического полярного вихря в большей степени обусловлена изменениями температуры нижней субтропической стратосферы, наблюдавшимися во второй половине ноября, что, в частности, проявилось в 2020 г.