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Arctic polar vortex dynamics during winters 2015/2016 and 2016/2017

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Abstract

In this work, we considered the role of the dynamic barrier weakening in winter in polar ozone depletion from late winter to spring with the example of the Arctic polar vortex dynamics in 2015/2016 and 2016/2017 by the vortex delineation method using geopotential. The main characteristics (vortex area, wind speed along the vortex edge, temperature and ozone mass mixing ratio inside the vortex) were calculated using the ERA5 reanalysis data based on the fact that the Arctic polar vortex edge at the 50, 70 and 100 hPa levels is determined by the geopotential values 19.5×10^4, 17.5×10^4 and 15.4×10^4 m^2/s^2, respectively. The geopotential values characterizing the polar vortex edge were determined from the maximum temperature gradient and maximum wind speed on average for 1979–2021. The dynamic barrier of the polar vortex contributes to lowering the temperature inside the vortex in the lower stratosphere and prevents the propagation of air masses into the vortex, creating conditions for ozone depletion from late winter to spring with the appearance of solar radiation. The polar vortex is characterized by the presence of a dynamic barrier, when the wind speed along the entire edge of the vortex is more than 20, 18 and 16 m/s at the 50, 70 and 100 hPa levels, respectively. In the winter-spring 2015/2016, almost no weakening of the dynamic barrier was observed, which contributed to a temperature decrease inside the vortex, the formation of polar stratospheric clouds and the subsequent occurrence of heterogeneous and photochemical reactions of ozone destruction, while in the winter 2016/2017, a frequent weakening of the dynamic barrier was observed in the lower stratosphere at the 50, 70 and 100 hPa levels, accompanied by an increase in temperature and ozone content inside the vortex as a result of the penetration of warm, ozone-rich air masses into the vortex.

Keywords: Arctic polar vortex, polar ozone depletion, dynamic barrier, vortex area, wind speed at the vortex edge, polar stratospheric clouds

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1 Introduction

The Arctic and Antarctic stratospheric polar vortices, which annually form in autumn over the winter hemisphere and breakdown in spring, create conditions for ozone depletion from late winter to spring inside the vortex in the lower stratosphere (Waugh and Randel, 1999; Waugh et al., 1999; Waugh et al., 2017). Inside the polar vortex at extremely low temperatures (below 78°C), absorption and crystallization result in the formation of stable aerosol particles, polar stratospheric clouds (PSCs) (Varotsos et al., 2012). They are formed as a result of the joint condensation of water vapor and nitric acid on a sulfuric acid aerosol (von der Gathen et al., 1995). There are two types of PSCs. Type II PSCs form at temperatures below 85°C and consist of water ice. PSCs of type I, formed in the temperature range from –78 to –85°C, consist mainly of nitric acid hydrates ($HNO_3.3H_2O$ and $HNO_3.2H_2O$), or a supercooled solution of $H_2SO_4/HNO_3/H_2O$ (Finlayson-Pitts and Pitts, 2000). In an upper layer of PSC particles, heterogeneous reactions of interaction of stable compounds of chlorine, hydrogen chloride HCl and chlorine nitrate $ClONO_2$ (and their radicals) occur with the release of photochemically active molecular chlorine Cl_2. In late winter, with the appearance of solar radiation over the polar region, the chlorine cycle of ozone depletion begins (Varotsos, 2002; Varotsos et al., 2020).

The dynamic barrier along the vortex edge contributes to a temperature decrease inside the vortex in the lower stratosphere and prevents the propagation of air masses into the vortex (Manney et al., 1994; Sobel et al., 1997). The dynamic barrier which is a characteristic of the strength and persistence of the polar vortex, largely determines the probability of ozone depletion (Zuev and Savelieva, 2019, 2020). When the dynamic barrier is weakened in winter, the temperature inside the vortex rises, accompanying by the melting of PSCs (Newman et al., 2001; Solomon et al., 2005). Since PSCs in winter contribute to the accumulation of chlorine reservoirs (HCl and $ClONO_2$) on their surface, followed by heterogeneous reactions with the formation of photochemically active molecular chlorine, their existence in winter determines the possibility of ozone depletion reactions in the period from late winter to spring (Solomon, 1999; Manney et al., 2011; Solomon et al., 2015). The weakening of the dynamic barrier of the polar vortex in winter indicates the weakening of the polar vortex. Not a single case of weakening of the dynamic barrier in winter was observed in the Antarctic polar vortex dynamics from 1979 to 2022. While this happens quite often with the Arctic polar vortex, ozone depletion is usually not observed in these cases.

The weakening of the dynamic barrier of the polar vortex often occurs when the vortex is weakened under the influence of wave activity (Limpasuvan et al., 2004). A significant displacement or splitting of the vortex, which occurs under the influence of planetary waves, is accompanied by a sudden stratospheric warming (SSW) (Charlton and Polvani, 2007; Charlton et al., 2007; Matthewman et al., 2009; Kuttippurath and Nikulin, 2012; Butler et al., 2015). SSWs usually indicate a significant disturbance of the polar vortex, while weakening of the dynamic barrier can be observed with a slight weakening of the polar vortex that is not accompanied by a SSW (Zuev and Savelieva, 2019). The work is devoted to comparing the dynamics of the Arctic polar vortex in the winters of 2015/2016 and 2016/2017. In both cases, no SSW events were recorded in winter, while ozone depletion was observed only in 2016 (Khosrawi et al., 2017; Voigt et al., 2018).

2 Data and methods

The daily mean data on zonal and meridional wind, geopotential, air temperature and ozone mass mixing ratio in the region of 40-90°N with a horizontal resolution of 0.25°× 0.25° at the 50, 70 and 100 hPa levels for 1979-2021 were obtained from the ERA5 reanalysis data (https://doi.org/10.24381/cds.bd0915c6; Hersbach et al., 2020). To analyze the dynamics of the Arctic polar vortex, we used the vortex delineation method using the geopotential (Zuev and Savelieva, 2022). On average, for 1979-2021, the values of the geopotential Φ^* in the region of the maximum temperature gradient along the vortex edge are $\Phi^* = (19.50 \pm 0.15) \times 10^4$ m^2/s^2 at the 50 hPa, $\Phi^* = (17.50 \pm 0.15) \times 10^4$ m^2/s^2 at the 70 hPa and $\Phi^* = (15.40 \pm 0.15) \times 10^4$ m^2/s^2 at the 100 hPa. Vortex area, mean and minimum wind speed along the vortex edge, mean temperature and mean ozone mass mixing ratio inside the vortex were calculated using the ERA5 reanalysis data, based on the fact that the Arctic polar vortex edge at the 50, 70 and 100 hPa levels is determined by geopotential values of 19.5×10^4, 17.5×10^4 and 15.4×10^4 m^2/s^2, respectively. The dynamics of the studied characteristics in the winter-spring of 2015/2016 and 2016/2017 was considered in comparison with 30-year means and their standard deviations (SD, σ) obtained as a result of selecting 30 cases with the strongest vortex for 1979–2021 (during averaging, the data of the period from July to June of the following years were removed: 1983/1984, 1984/1985, 1986/1987, 1987/1988, 1998/1999, 2000/2001, 2001/2002, 2003/2004, 2005/2006, 2008/2009, 2011/2012, 2012/2013, 2018/2019). When obtaining climatological means for the Arctic polar vortex, which is characterized by significant variability, it is especially important to filter out cases with a weak polar vortex. Climatological means and their standard deviations were smoothed with the FFT filter (fast Fourier transform filter) over 15 points. Time series of the studied characteristics in the winter-spring of 2015/2016 and 2016/2017 were smoothed with a 5-point FFT filter.

3 Results and discussion

Figure 1 shows the geopotential, wind speed and ozone distributions from December to March of 2015/2016 and 2016/2017 at the 70 hPa level. Figure 2 shows the time series of the vortex area, mean wind speed along the vortex edge, mean temperature and ozone mass mixing ratio inside the Arctic polar vortex from December to March of 2015/2016 and 2016/2017 at the 50, 70 and 100 hPa levels, obtained by the vortex delineation method. The main dynamic characteristics of the polar vortices (in addition to the presence of a dynamic barrier) are the vortex area of more than 10 million km^2 and the mean wind speed along the vortex edge of more than 30, 27 and 24 m/s at the 50, 70 and 100 hPa levels, respectively (Zuev and Savelieva, 2022a), marked with a blue dashed line in Figure. 2. The polar vortex is characterized by the presence of a dynamic barrier when the wind speed along the entire edge of the vortex horizontally is more than 20, 18 and 16 m/s at the 50, 70 and 100 hPa levels, respectively (Zuev and Savelieva, 2022b).

The values of 17.5×10^4 m^2/s^2, describing the polar vortex edge, are connected by a line in the geopotential distributions in Figure 1, and the values of 18 m/s, which characterize the dynamic barrier, are connected by a line in the wind speed distributions. As seen from Figure. 1, the polar vortex edge (outlined in geopotential distributions) coincides well with the maximum values of wind speed (in wind speed distributions). Despite the fact that in both periods under consideration the polar vortex was quite disturbed, in 2015/2016 it is stronger and more stable, which in particular manifests itself in lower values of the geopotential inside the vortex. In the 2015/2016 winter, practically no weakening of the dynamic barrier was observed: in Figure. 1, the wind speed exceeds

18 m/s along the entire edge of the vortex in all distributions, while in 2016/2017 a frequent weakening of the dynamic barrier was observed (Figure. 1, wind speed distributions). As a result, in 2015/2016, a gradual decrease in ozone content inside the vortex was observed, and in 2016/2017 a high ozone content appears in the polar region (due to the weakening of the dynamic barrier, air masses rich in ozone from the middle and subpolar latitudes penetrated inside the vortex).

The greater strength and stability of the Arctic polar vortex in 2015/2016, compared to 2016/2017, is manifested in a larger area, higher wind speeds along the vortex edge, lower temperatures and ozone inside the vortex throughout the winter (Figure. 2). As noted above, the weakening of the dynamic barrier is observed with a local decrease in wind speed along the vortex edge below 20, 18 and 16 m/s, at the 50, 70 and 100 hPa levels, respectively. At the same time, a decrease in mean wind speed along the vortex edge below 30, 27 and 24 m/s, at the 50, 70 and 100 hPa levels usually indicates a local decrease in wind speed below 20, 18 and 16 m/s at these levels, i.e., indirectly indicates a weakening of the dynamic barrier. As seen in Figure. 2, at high wind speeds along the vortex edge in 2015/2016, in 2016/2017 these values were often so low that they approached 30, 27 and 24 m/s, at the 50, 70 and 100 hPa levels, respectively or even fell below them. The constant weakening of the dynamic barrier in 2016/2017 contributed to a significant increase in temperature inside the vortex throughout the winter, especially compared to that in 2015/2016 (Figure. 2).

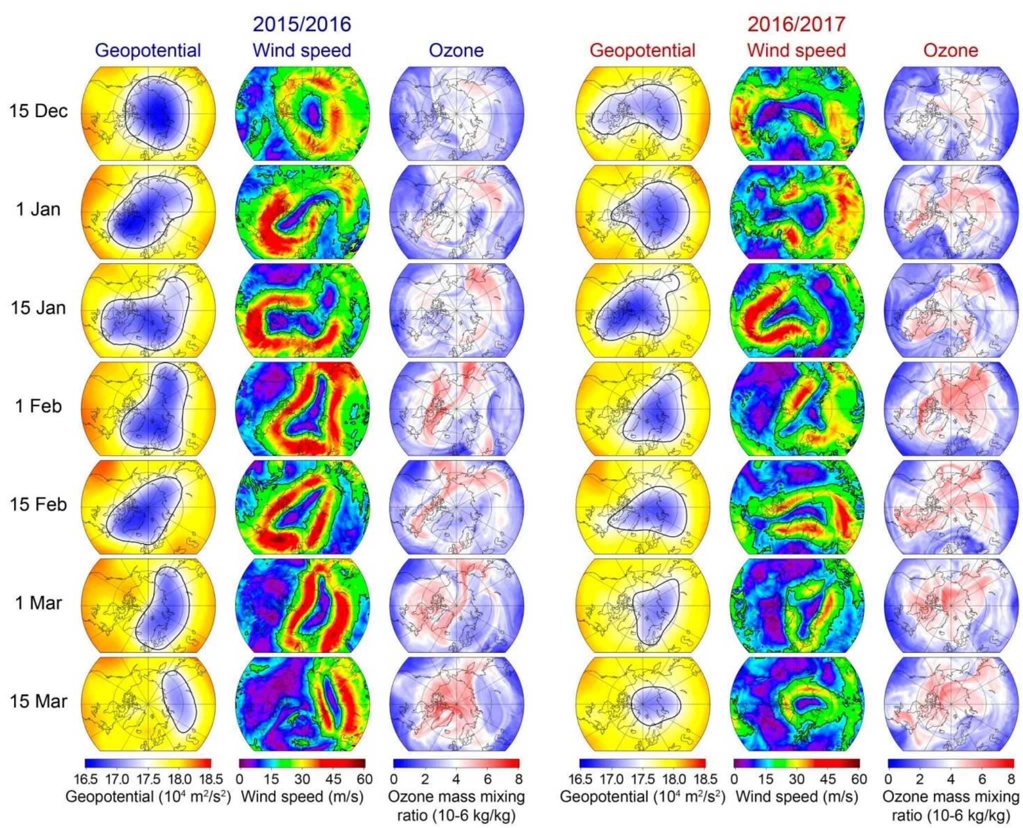

Figure 1. Geopotential, wind speed and ozone distributions at the 70 hPa pressure level over the Arctic from 15 December to 15 March of 2015/2016 and 2016/2017.

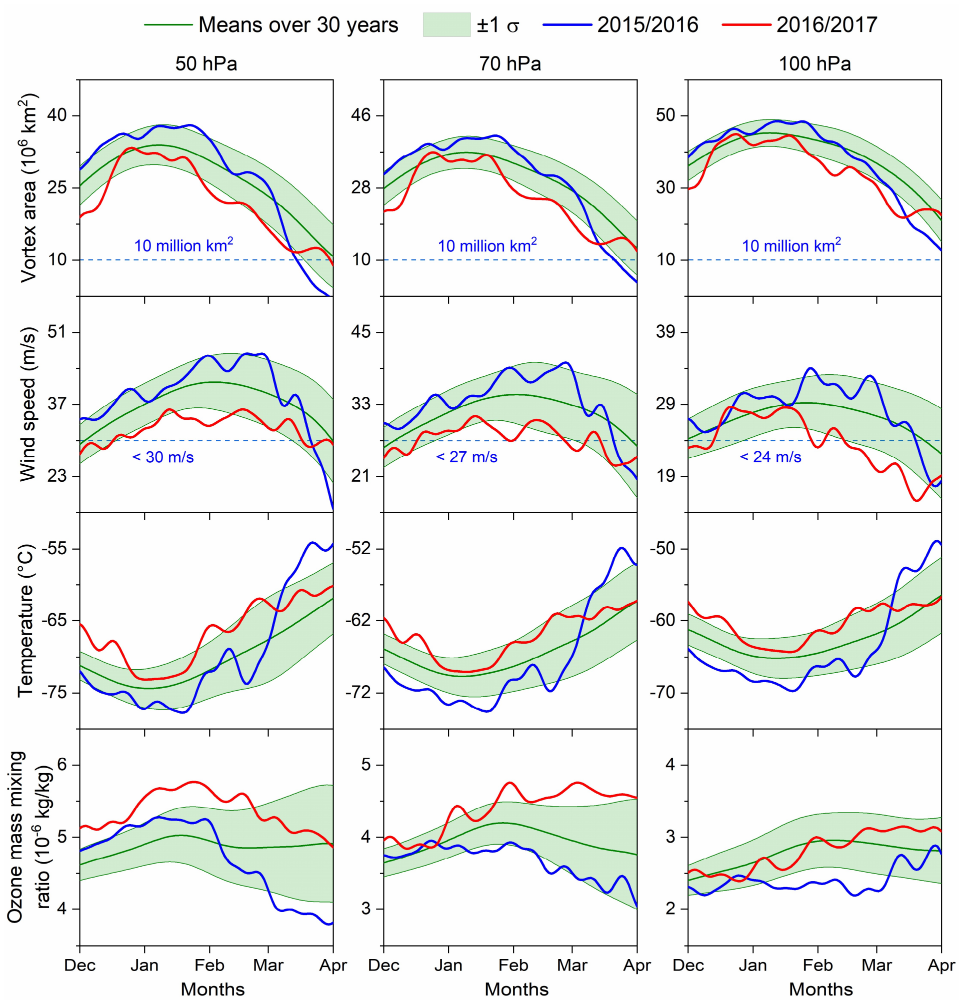

Figure 2. Time series of the Arctic polar vortex area, mean wind speed along the vortex edge, mean temperature inside the vortex and mean ozone mass mixing ratio inside the vortex at the 50, 70 and 100 hPa pressure levels from December to March of 2015/2016 and 2016/2017 in comparison with the 30-year means with ±1 σ.

4 Conclusions

In this work, we considered the role of the weakening of the dynamic barrier in winter in polar ozone depletion from late winter to spring using the Arctic polar vortex dynamics in 2015/2016 and 2016/2017 as an example by the vortex delineation method using geopotential. The dynamic barrier of the polar vortex contributes to lowering the temperature inside the vortex in the lower stratosphere and prevents the propagation of air masses into the vortex, creating conditions for ozone destruction in the period from late winter to spring with the appearance of solar radiation. The polar vortex is characterized by the presence of a dynamic barrier when the wind speed along the entire edge of the vortex horizontally is more than 20, 18 and 16 m/s at the 50, 70 and 100 hPa levels, respectively. In the winter-spring of 2015/2016, almost no weakening of the dynamic barrier was observed. As a result, the temperature inside the vortex decreased, PSCs existed throughout the winter, contributing to the accumulation of chlorine compounds on their surfaces. Moreover, the occurrence of heterogeneous reactions with the formation of molecular chlorine and ozone depletion was observed in February. In the winter of 2016/2017, a frequent weakening of the dynamic barrier was observed in the lower stratosphere at the 50, 70 and 100 hPa levels. It was accompanied by an increase in temperature and ozone content inside the vortex as a result of the penetration of warm, ozone-rich air masses into the vortex.

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