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Weakening of the Arctic polar vortex dynamic barrier in 2006, 2010 and 2014

Vladimir V. Zuev[1], Ekaterina Savelieva[2*] and Alexey V. Pavlinsky[2]

[1] *Professor., Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia*
[2]*Ph.D., Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia*

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Abstract
The Arctic polar vortex is characterized by significant interannual and intraseasonal variability, causing instability of processes occurring in the winter-spring period in the polar stratosphere of the Northern Hemisphere. The dynamic barrier in the lower stratosphere leads to a decrease in temperature within the polar vortex, which is necessary for the formation of polar stratospheric clouds involved in the chlorine cycle of ozone depletion. In the middle and upper stratosphere, the dynamic barrier prevents air masses from the subpolar region from penetrating into the vortex, isolating the atmosphere inside the vortex from the outside. Using the vortex delineation method, based on the ERA5 reanalysis data, we examined the criteria for the weakening of the dynamic barrier in the middle and upper stratosphere and the features of the vertical dynamics of the Arctic polar vortex in 2006, 2010 and 2014. In 2006 and 2010, sudden stratospheric warmings were observed: on 21 January 2006, as a result of a significant displacement of the vortex, and on 9 February 2010, as a result of the vortex splitting. During the winter of 2014, the polar vortex was strong and persistent, taking on an elliptical shape in January and February. In the studied years, the breakdown of the Arctic polar vortex occurred in January 2006, February 2010 and March 2014, respectively. Despite the different time periods of the polar vortex breakdown, in each case it was observed after the weakening of the dynamic barrier. A weakening of the dynamic barrier (accompanied by a change in temperature inside the vortex) was observed with a local decrease in wind speed along the vortex edge below 27, 28 and 29 m/s at the 10, 7 and 5 hPa levels, respectively. The polar vortex breakdown occurred simultaneously with or shortly after the decrease in mean wind speed along the vortex edge below 41, 43, and 45 m/s at the 10, 7, and 5 hPa levels, respectively. The weakening of the dynamic barrier in the studied years was often not observed along the entire vertical extent of the polar vortex. In all cases, the weakening and subsequent breakdown of the Arctic polar vortex was first observed in the upper stratosphere and then spread into the middle and lower stratosphere.

Keywords: Arctic polar vortex, dynamic barrier, vortex area, wind speed at the vortex edge

*Corresponding author: esav.pv@gmail.com

1 Introduction

The Arctic polar vortex forms annually in November, usually strengthening in January and breaking down between February and April. The dynamic barrier of the polar vortex prevents the penetration of warm, ozone-rich air masses from mid- and subpolar latitudes into the vortex and, thus, contributes to a decrease in temperature inside the vortex, which is necessary for the formation of polar stratospheric clouds (PSCs) (Manney et al., 1994). In conditions of the stable polar vortex, characterized by the presence of a dynamic barrier, PSCs usually exist throughout the winter. When the dynamic barrier in the lower stratosphere weakens due to a local decrease in wind speed along the vortex edge below 20 m/s, the temperature inside the vortex increases to values above –78 °C, accompanied by the PSC melting (Zuev and Savelieva, 2023). Polar ozone depletions, which form within polar vortices from late winter to spring, are caused by the catalytic chlorine cycle of ozone destruction, which begins with heterogeneous reactions on the PSC surfaces (Solomon, 1999; Varotsos et al., 2012; Varotsos and Tzanis, 2012). Strong El Niño events can lead to a temperature increase in the tropical lower stratosphere, in particular, due to an increase in the amount of water vapor in the lower stratosphere during strong El Niño (Garfinkel et al., 2018). Heating of the tropical stratosphere from late winter to spring may lead to an increase in the stratospheric meridional temperature gradient and the subsequent strengthening of the polar vortex, resulting in strong ozone depletion in this period (Varotsos and Tzanis, 2012; Varotsos et al., 2020).

Weakening of the dynamic barrier is often observed due to the disturbance of the polar vortex under the influence of wave activity (Limpasuvan et al., 2004). A significant displacement or splitting of the polar vortex, occurring 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; Butler et al., 2015). In 2006 and 2010, SSW events were observed: on 21 January 2006, as a result of a significant displacement of the vortex, and on 9 February 2010, as a result of the vortex splitting (Ageyeva et al., 2017). Some studies (Berthet et al., 2007; Seppälä et al., 2007; Manney et al., 2008; Wright et al., 2010; France et al., 2012) examined the dynamics of the Arctic polar vortex in the winter of 2005/2006. Manney et al. (2008) showed that in January 2006 an unusual change in the stratopause height was observed, in which it dropped to 30 km. After the polar vortex breakdown, the stratopause cooled, became fuzzy, and with the recovering of the polar vortex in the upper stratosphere/lower mesosphere, the stratopause formed again at 75 km, then dropped and warmed (Manney et al., 2008; Wright et al., 2010). Some studies (Kuttippurath et al., 2010; Vargin, 2015; Wang and Chen, 2010; Khosrawi et al., 2011; Li et al., 2012; Pitts et al., 2011; Dörnbrack et al., 2012; Wetzel et al., 2012; Weigel et al., 2014) examined the dynamics of the Arctic polar vortex in the winter-spring period of 2009/2010. During the winter of 2009/2010, the polar vortex was strong and characterized by low temperatures from mid-December to mid-January. In early February, the strengthening of wave 1 led to the polar vortex splitting, accompanied by a SSW (Kuttippurath and Nikulin, 2012). In the winter of 2013/2014, the Arctic polar vortex was strong and persistent, with high wind speeds along the vortex edge, and took on an elliptical shape in January and February (Lawrence and Manney, 2018; Manney et al., 2022). The aim of this work is to consider the criteria for weakening the dynamic barrier of the Arctic polar vortex in the middle and upper stratosphere using the example of 2005/2006, 2009/2010 and 2013/2014.

2 Data and methods

The daily mean data on zonal and meridional wind, geopotential and air temperature in the region of 40–90° N with a horizontal resolution of 0.25°x0.25° at the 70, 20, 10, 7, 5 and 1 hPa levels for 1979–2023 were obtained from the ERA5 reanalysis data (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, 2023). On average for 1979–2023, the value of the geopotential Φ^* in the region of the maximum temperature gradient along the vortex edge equal $\Phi^*=(29.50\pm0.30)\cdot10^4$ m^2/s^2 at the 10 hPa, $\Phi^*=(31.80\pm0.32)\cdot10^4$ m^2/s^2 at the 7 hPa and $\Phi^*=(33.90\pm0.35)\cdot10^4$ m^2/s^2 at the 5 hPa. Vortex area, mean and minimum wind speed along the vortex edge and mean temperature inside the vortex were calculated using the ERA5 reanalysis data, based on the fact that the Arctic polar vortex edge at the 10, 7 and 5 hPa levels is determined by geopotential values $29.5\cdot10^4$, $31.8\cdot10^4$ and $33.9\cdot10^4$ m^2/s^2, respectively. The dynamics of the studied characteristics in the winter-spring of 2005/2006, 2009/2010 and 2013/2014 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 for the following years were removed (the period from July to June of the following year): 1984/1985, 1986/1987, 1987/1988, 1998/1999, 2000/2001, 2001/2002, 2003/2004, 2008/2009, 2011/2012, 2012/2013, 2018/2019, 2020/2021). 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 2005/2006, 2009/2010 and 2013/2014 were smoothed with a 3-point FFT filter.

3 Results and discussion

One of the dynamic characteristics of the polar vortices at the 50 hPa level is the mean wind speed along the vortex edge of more than 30 m/s, while locally along the vortex edge the wind speed values should not be lower than 20 m/s, otherwise the dynamic barrier weakens (Zuev and Savelieva, 2023). Taking into account the pressure difference, corresponding values were determined for the 10, 7 and 5 hPa levels. Figs. 1, 2 show the time changes in the area of the Arctic polar vortex, the mean wind speed along the vortex edge and the mean temperature inside the vortex from December to March 2005/2006, 2009/2010 and 2013/2014 at the 10 and 5 hPa levels, obtained using the vortex delineation method. The minimum mean wind speed along the polar vortex edge equals more than 41, 43 and 45 m/s at the 10, 7 and 5 hPa levels, respectively (shown as a red dashed line in Figs. 1, 2). At the same time, the dynamic barrier is observed at wind speed greater than 27, 28 and 29 m/s at the 10, 7 and 5 hPa levels, respectively (continuously along the vortex edge in horizontal projection). In Figs. 1, 2 the color of the wind speed curve changes from blue to red when the dynamic barrier of the polar vortex weakens. Fig. 3 shows the geopotential, wind speed and temperature distributions from December to March of 2005/2006, 2009/2010 and 2013/2014 at the 7 hPa level. The values of $31.8\cdot10^4$ m^2/s^2, describing the polar vortex edge, are connected by a line in the geopotential distributions, and the values of 28 m/s, which characterize the dynamic barrier, are circled in the wind speed distributions (Fig. 3). Fig. 4 shows wind speed distributions at the 70, 20, 5 and 1 hPa levels over the Arctic for 1 January, 1 February and 1

March of 2006, 2010 and 2014; the dynamic barrier is highlighted by a line (on the scale it corresponds to a value of 0.25 arbitrary units).

The 2005/2006 event. A weakening of the dynamic barrier (a decrease in the local wind speed along the vortex edge below 27, 28 and 29 m/s and the mean wind speed below 41, 43 and 45 m/s, respectively, at the 10, 7 and 5 hPa levels) in the period from December 2005 to March 2006 was observed on 4–5 January and starting from 21 January at the 10 and 5 hPa levels, as well as on 3–4 December at the 5 hPa level (Figs. 1, 2: wind speed curves turned red). As seen from Fig. 3, the dynamic barrier is present in all wind speed distributions in December and January (on 20 January the vortex was partially outside the figure field, but in the missing part, the dynamic barrier remains). As a result of a significant displacement of the polar vortex on 21 January (the SSW event), the dynamic barrier weakening at the 10–5 hPa levels occurred, followed by the vortex breakdown at these altitudes. On 24 January, a decrease in the mean wind speed along the vortex edge was observed below 41 and 45 m/s at the 10 and 5 hPa levels, respectively (Fig. 1, 2). The curves in Fig. 1, 2 are shown with 50% transparency from the moment of the dynamic barrier weakening. In Fig. 3, 4 it is evident that since February the polar vortex is no longer traceable (after its breakdown): in Fig. 3 the distributions are shown before February 1, in Fig. 4 the wind speed distributions for 1 February and March 2006 are shown with 50% transparency and reflect the formation of a zonal flow, mainly in the upper stratosphere, after the polar vortex breakdown.

The 2009/2010 event. The dynamic barrier weakening in the period from December 2009 to March 2010 was observed at the 10 hPa level (4–10 December, from 26 January to 2 February and from 7 February until the vortex breakdown) and at the 5 hPa level (1–6 December, from 27 January to 2 February and from 5 February until the vortex breakdown) (Figs. 1, 2). In Fig. 3, the dynamic barrier weakening at the 7 hPa level is evident on 1 February and in all subsequent wind speed distributions. A significant increase in temperature inside the polar vortex occurred with the dynamic barrier weakening in late January (Fig. 1, 2). The decrease in mean wind speed below 41 and 45 m/s at the 10 and 5 hPa levels occurred on 15 and 8 February, respectively, during the vortex splitting period on 9 February (the SSW event). The curves in Figs. 1, 2 are shown with 50% transparency from the moment of decrease in the mean wind speed along the vortex edge below 41, 43 and 45 m/s at the 10, 7 and 5 hPa levels, respectively. In Fig. 3 the distributions are shown up to 20 February, while on 10 and 20 February the polar vortex at the 7 hPa level had already breakdown. In the upper stratosphere, the polar vortex breakdown was already observed on 1 February (Fig. 4), and on 1 March the vortex was not observed at all stratospheric levels (wind speed distributions for 1 March 2010 are shown with 50% transparency).

The 2013/2014 event. In the winter of 2013/2014, the Arctic polar vortex was the strongest, especially compared to the 2005/2006 and 2009/2010 events. The changes in the vortex area did not fluctuate significantly and were generally within the standard deviation. Temperature variations were significantly lower than in the other two cases. High wind speeds along the vortex edge were observed, especially in mid-winter. The dynamic barrier weakening in the period from December 2013 to March 2014 was observed on 17–22 March and from 25 March at the 10 hPa level and from 16 March at the 5 hPa level (Figs. 1, 2). In Fig. 3, the dynamic barrier is present in all wind speed distributions, but weakens below the stratopause (Fig. 4). The decrease in mean speed below 41 and 45 m/s at the 10 and 5 hPa levels occurred on 25 and 17 March, respectively (after which the curves in Figs. 1, 2 are shown with 50% transparency). As seen from Fig. 4, the weakening of the dynamic barrier of the polar vortex is not always observed at all levels; in this case, it was observed only in the upper stratosphere on 1 February and March.

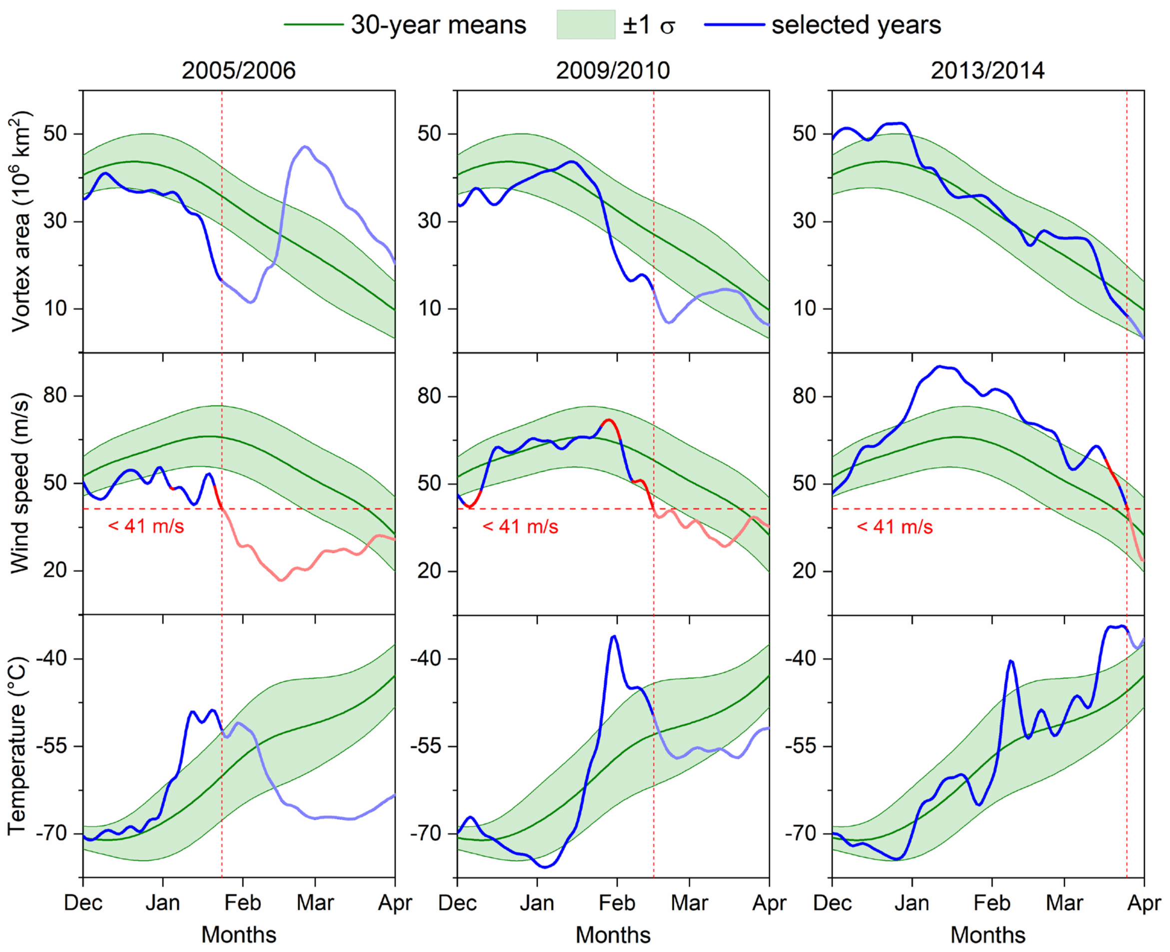

Figure 1. Time series of the Arctic polar vortex area, mean wind speed along the vortex edge and mean temperature inside the vortex at the 10 hPa level from December to March of 2005/2006, 2009/2010 and 2013/2014 in comparison with the 30-year means with ±1 σ.

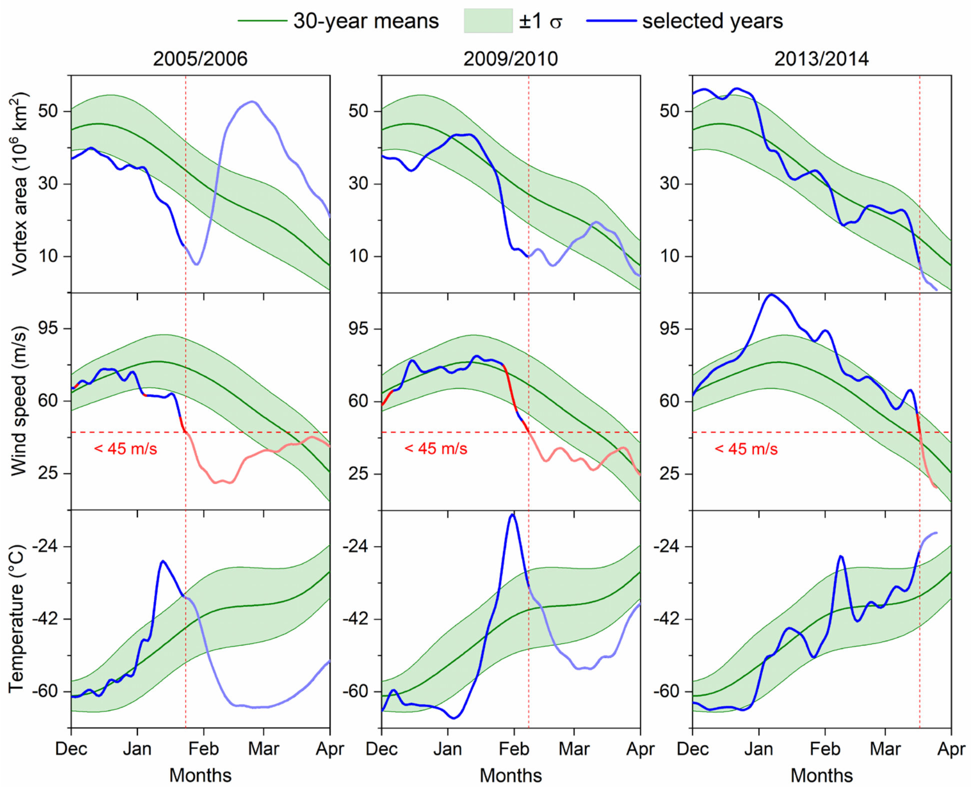

Figure 2. Time series of the Arctic polar vortex area, mean wind speed along the vortex edge and mean temperature inside the vortex at the 5 hPa level from December to March of 2005/2006, 2009/2010 and 2013/2014 in comparison with the 30-year means with ±1 σ.

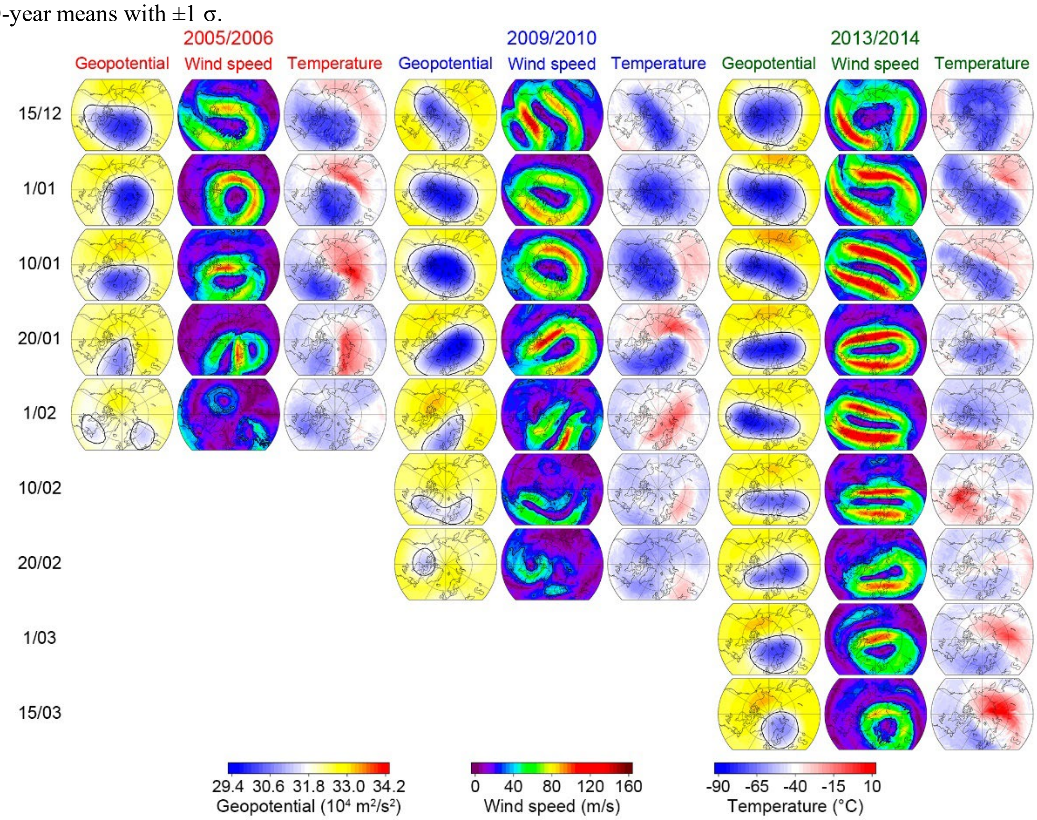

Figure 3. Geopotential, wind speed and temperature distributions at the 7 hPa level over the Arctic from 15 December to 15 March of 2005/2006, 2009/2010 and 2013/2014.

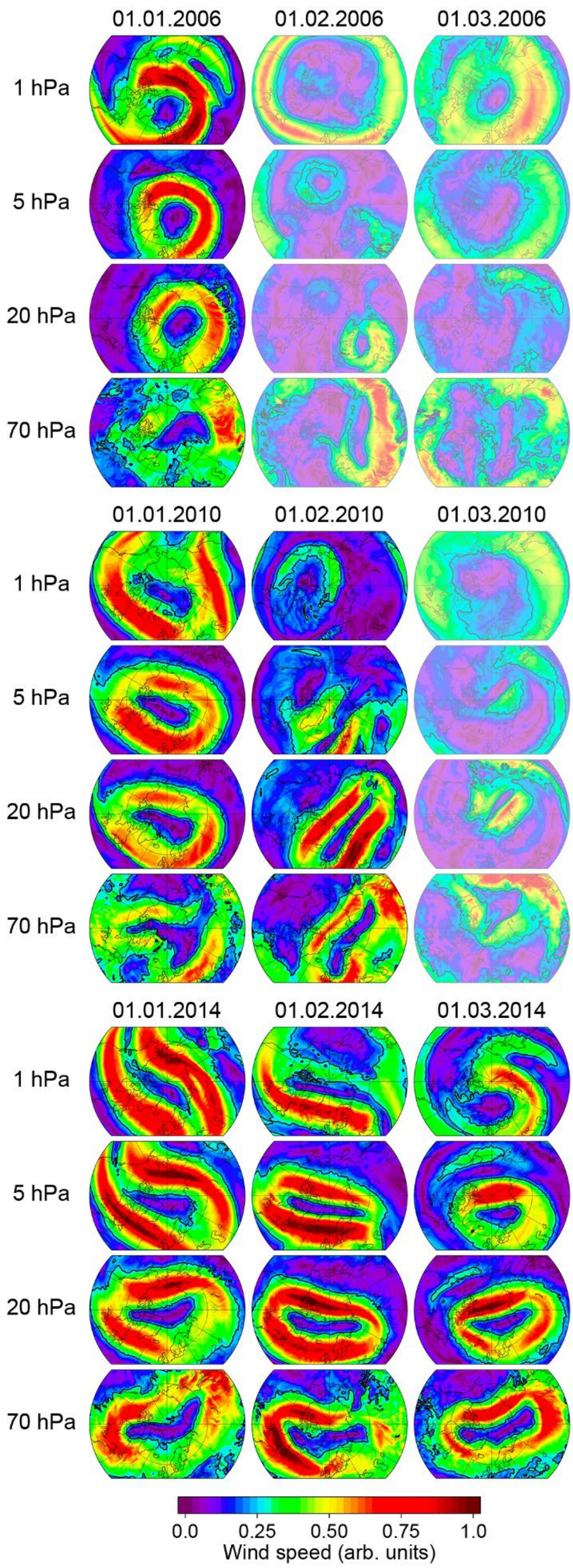

Figure 4. Wind speed distributions (in arbitrary units) at the 70, 20, 5 and 1 hPa levels over the Arctic for 1 January, 1 February and 1 March of 2006, 2010 and 2014.

4 Conclusion

In this work, using the vortex delineation method by geopotential, based on the ERA5 reanalysis data, we examined the criteria for the weakening of the Arctic polar vortex dynamic barrier in the middle and upper stratosphere using the 2005/2006, 2009/2010 and 2013/2014 cases. In the studied years, the breakdown of the Arctic polar vortex occurred in January 2006, February 2010 and March 2014, respectively. Despite the different time periods of polar vortex breakdown, in each case it was observed after the weakening of the dynamic barrier, or the weakening of the dynamic barrier preceded the vortex breakdown. In all cases, a weakening of the dynamic barrier (accompanied by a change in temperature inside the vortex) was observed with a *local* decrease in wind speed along the vortex edge below 27, 28 and 29 m/s at levels of 10, 7 and 5 hPa, respectively. At the same time, the breakdown of the polar vortex occurred simultaneously with or shortly after a decrease in *mean* wind speed along the vortex edge below 41, 43 and 45 m/s at levels of 10, 7 and 5 hPa, respectively. We also showed that the weakening of the dynamic barrier does not necessarily occur throughout the entire vertical extent of the polar vortex, but can be observed only in some part of it, covering several pressure levels. Furthermore, in all cases, the weakening and subsequent collapse of the Arctic polar vortex was first observed in the upper stratosphere and then gradually spread into the middle and lower stratosphere.

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