Dynamics of the Arctic polar vortex during the 1984/1985 sudden stratospheric warming

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Abstract. The Arctic stratospheric polar vortex usually forms in October, reaches its peak intensity in December, and decays from February to April. In most cases, the breakdown of the Arctic polar vortex occurs under the influence of vertically propagating planetary Rossby waves. The influence of planetary wave activity on the polar vortex leads to a displacement or breakdown accompanied by a sudden stratospheric warming (SSW). One of the earliest SSWs was observed on December 29, 1984, after which the polar vortex in the lower stratosphere had not fully recovered and existed for less than 3 months since October. In this study, we analyze the dynamics of the stratospheric polar vortex under the influence of planetary wave activity in the winter of 1984-1985.

1. Introduction
The Arctic stratospheric polar vortex usually exists for 5–7 months, from autumn to spring, whereas the Antarctic polar vortex usually exists more than 8 months. The earlier breakdown of the Arctic polar vortex occurs due to the influence of vertically propagating planetary Rossby waves [1]. Vertical fluxes of Rossby wave activity (Eliassen–Palm (EP) fluxes), moving from the troposphere, are destroyed in the polar stratosphere as a result of interaction with the eastward zonal flow (i.e. the stratospheric polar vortex) [2–4]. The sudden stratospheric warmings (SSWs), which occur due to adiabatic heating of the middle stratosphere during the planetary wave breaking, are accompanied by a displacement or splitting of the polar vortex [5, 6]. SSWs are characterized by a sudden increase in the latitudinal mean temperature poleward from 60° latitude at the 10 hPa level (~ 30 km) or below [2]. SSWs are divided into major and minor ones. A strong displacement of the polar vortex occurs during minor SSWs, whereas major SSWs are accompanied, as a rule, by the polar vortex splitting into two smaller vortices.

The dynamics of the polar vortex plays an important role in the stratospheric ozone distribution, the movement of air masses in the polar stratosphere and the change in the stratospheric temperature over the polar region [7, 8]. The winter and spring stratospheric circulation is determined by the activity of the polar vortex, and its changes are associated with variations in the shape and location of the vortex. The area and extent of the stratospheric ozone depletion over the polar region depend on the polar vortex strength and persistence in spring [9]. The polar vortices act as containment vessels and prevent the inflow of warm and ozone-rich air masses from the midlatitude stratosphere into the polar region [10, 11]. At the same time, polar stratospheric clouds (PSCs) form at extremely low temperatures (lower than ~78 °C) inside the polar vortex. Heterogeneous reactions, releasing photochemically active molecular chlorine, occur on and in PSC particles [12]. The stratospheric ozone depletion over the
polar region occurs as a result of catalytic cycles involving chlorine species in the presence of weak solar radiation from late winter to spring [13].

The influence of planetary wave activity on the polar vortex does not always lead to its breakdown. Short-term splitting of the polar vortex is sometimes observed for several days, after which the polar vortex strengthens again and PSCs form inside the vortex. Such a recovery of the polar vortex is most probable in winter. Major SSWs appearing due to the polar vortex splitting usually occur in February or in late January [2]. However, there are 2 cases when major SSWs which appeared in the lower stratosphere were observed in late December: the 1984/1985 SSW and the 1998/1999 SSW. Some studies [14, 15] investigated the dynamics of the stratospheric circulation in the winter of 1984-1985 before and after the SSW. The preSSW state was characterized by the strong polar vortex and deep penetration of planetary waves in the upper stratosphere [14]. In contrast, the postSSW state showed the weak polar vortex and higher wave activity in the lower stratosphere [14]. The aim of this study is to investigate the dynamics of the Arctic polar vortex under the influence of planetary wave activity in the winter of 1984–1985 using the ERA-Interim reanalysis data and the NASA GSFC satellite data.

2. Data and methods
The EP fluxes data were taken from the NOAA Earth System Research Laboratory's Physical Sciences Division (ESRL PSD) [16]. The potential vorticity and temperature data for 30°–90° N on the 50, 10, and 1 hPa pressure surfaces were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data [17; http://apps.ecmwf.int/datasets]. The data on zonal mean zonal wind for 60° N and zonal mean temperature for 60°–90° N on the 50, 10, and 1 hPa pressure surfaces, zonal mean eddy heat flux for 45°–75° N on the 10 hPa pressure surface, the area of the polar vortex on the 460 K isentropic surface and PSC volume for 60°–90° N were retrieved from the NASA Goddard Space Flight Center (GSFC) online database [18; http://ozonewatch.gsfc.nasa.gov].

To explore variations of meteorological data from November 1984 to March 1985, we obtained 38-year climatological mean seasonal cycles of zonal wind and temperature in the Arctic stratosphere over the 1979–2016 period and 40-year climatological mean seasonal cycles of eddy heat flux, vortex area and PSC volume in the Arctic stratosphere over 1979–2018 with standard deviations (σ). The climatological means and standard deviations were smoothed by a 15-point fast Fourier transform (FFT) filter.

3. Results

3.1. 1984/1985 sudden stratospheric warming
SSWs appear due to the breaking and dissipation of planetary waves (in particular, the EP fluxes) as a result of interaction with the stratospheric polar vortex [2]. Figure 1 shows 1-day averaged EP flux vectors from 5 December 1984 to 30 March 1985 with a time step of 2–8 days, taken from the NOAA ESRL PSD. An increase in the EP flux during the winter-spring 1984/1985 was observed from 1 to 7 December, from 25 December to 4 January, from 9 to 11 January, and from 9 to 10 March. The maximum activity of the EP flux was observed on 28 December (Figure 1), after which the SSW was recorded on 29 December. Thus, as seen from Figure 1, in the 1984/1985 winter-spring period an increase in the EP flux was observed in December, and an unusual decrease in February and March.

Potential vorticity and temperature are usually used to describe SSWs. Enhanced values of potential vorticity in the winter-spring period usually determine the location of the polar vortex, whereas lower and higher temperatures are observed inside and outside the polar vortex, respectively. Figure 2 shows potential vorticity and temperature distributions at the 50, 10, and 1 hPa pressure levels (~ 20, 30, and 46 km) over the Arctic from December 1984 to March 1985 retrieved from the ERA-Interim reanalysis. As seen from Figure 2, the polar vortex had a slightly elongated shape and was displaced relative to the pole on 20 December. Then the polar vortex elongated, and its splitting in the lower, middle, and upper stratosphere was observed on 29 December. Two regions of high values
of potential vorticity on 29 December 1984 indicate the polar vortex splitting and the occurrence of the SSW.

**Figure 1.** EP fluxes from December 1984 to March 1985.
Figure 2. Potential vorticity and temperature distributions at the 50, 10 and 1 hPa pressure levels over the Arctic from December 1984 to March 1985.

The SSW that began on December 29 was most clearly pronounced in the middle stratosphere on January 1, 1985 [15] (Figure 2). After such an early SSW the process of polar vortex recovery started, and then it was interrupted on January 10 as a result of intensification of the EP fluxes (Figures 1 and 2). A constant change in the recovery and elongation (preceding the splitting) of the polar vortex was observed during January. The second splitting was observed in the lower stratosphere on January 20,
after which at the 50 hPa pressure level the polar vortex no longer appeared in the winter-spring 1984/1985. While there is still an area of high potential vorticity values over the Arctic, the polar vortex is not well defined [15] (Figure 2). The potential vorticity values are lower than those in early winter and are spread more thinly over the Arctic [15]. In the middle and upper stratosphere, a weak polar vortex appeared in the temperature distributions (Figure 2) in February and in early March. Then, after a small increase in the EP fluxes on March 10, the eastward zonal flow was replaced by the westward one in mid-March about 20 days earlier than usual.

3.2. Arctic polar vortex dynamics during the winter 1984/1985

Figure 3 shows the time series of the zonal wind for 60° N and the temperature for 60°–90° N in the lower, middle, and upper stratosphere (at the 50, 10 and 1 hPa pressure levels) from November 1984 to March 1985 compared to its 38-year climatological mean seasonal cycles over 1979–2016 with ±1 standard deviations. All time series and seasonal cycles are retrieved from the ERA-Interim reanalysis. As seen in Figure 3, after the impact of planetary waves in late December 1984 the polar vortex recovered in the middle and upper stratosphere in February and was destroyed in mid-March. The zonal wind in the upper stratosphere even exceeded the climatological mean in February. It is important to note that in the upper stratosphere high temperatures are observed within the strong polar vortex, while the weakening of the vortex leads to their decrease. For this reason, during the polar vortex splitting in late December 1984, in contrast to the temperature increase in the lower and middle polar stratosphere, in the upper stratosphere an abrupt temperature decrease was observed (Figure 3).

![Figure 3](image_url)

**Figure 3.** Time series of zonal mean zonal wind for 60° N and zonal mean temperature for 60°–90° N at the 50, 10 and 1 hPa pressure levels from November 1984 to March 1985 (red lines) and 1979–2016 climatological means (green lines) with ±1 standard deviations (green areas).

Figure 4 shows the time series of an eddy heat flux for 45°–75° N at the 10 hPa pressure level, the polar vortex area at the 460 K isentropic level (~ 20 km), and the PSC volume for 60°–90° N from November 1984 to March 1985 compared to its 40-year climatological mean seasonal cycles over 1979–2018 with ±1 standard deviations. All time series and seasonal cycles are retrieved from the NASA GSFC database. In the time series of the heat flux, extremes are observed on 5 and 28 December 1984 and 10 March 1985 (Figure 4), which is in good agreement with the NOAA ESRL PSD data (Figure 1). At the same time, the polar vortex splitting in the lower stratosphere was
observed on January 20 under the conditions of low activity of planetary waves in January. It is assumed that the high influence of the planetary wave activity played a key role in the development of the Arctic polar vortex in the winter-spring of 1984-1985. After the impact of planetary waves on December 28, 1984, even a relatively small increase in the wave activity in January led to the second splitting of the polar vortex in the lower stratosphere. The dynamics of the polar vortex described above can be traced in the time series of the vortex area in the lower stratosphere (Figure 4). Finally, the absence of PSCs from January to March 1985, which are formed in the lower stratosphere, confirms that after the splitting on December 29, 1984 the polar vortex did not fully recover during the winter-spring of 1984-1985.

![Figure 4](image)

**Figure 4.** Time series of zonal mean eddy heat flux for 45°–75° N at the 10 hPa pressure level, polar vortex area at the 460 K isentropic level, and PSC volume for 60°–90° N from November 1984 to March 1985 (red lines) and 1979–2018 climatological means (green lines) with ±1 standard deviations (green areas).

4. **Conclusions**

In most cases, the effect of planetary waves on the polar vortex from December to early January is limited to a displacement or short-term splitting observed for several days, after which the polar vortex recovers. An increased activity of EP fluxes was recorded on December 28, 1984. The polar vortex splitting which occurred on December 29 was so strong that the relatively small subsequent activity of the EP fluxes did not allow the vortex to fully recover. The newly formed vortex was characterized by temperatures that were insufficiently low for the formation of PSCs, and after the polar vortex splitting in December no PSCs appeared until late spring. It is assumed that the high-intensity impact of planetary waves on the polar vortex on December 28, 1984 determined the further dynamics of the vortex. As a result, even the short-term small intensification of the EP fluxes, which, as a rule, does
not have a significant effect on the polar vortex, prevented its recovery this time. Thus, the case of the 1984/1985 SSW is one of the exceptional ones because, as a result of the impact of planetary waves on December 28, the polar vortex in the lower stratosphere had not fully recovered and existed for less than 3 months since October.

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