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The role of the Mt. Merapi eruption in the 2011 Arctic ozone depletion

V.V. Zuev [a, b, c], N.E. Zueva [a], E.S. Savelieva [a, *]

[a] Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences, 10/3, Academichesky Ave., 634055 Tomsk, Russia
[b] National Research Tomsk State University, 36, Lenina Ave., 634050 Tomsk, Russia
[c] National Research Tomsk Polytechnic University, 30, Lenina Ave., 634050 Tomsk, Russia

HIGHLIGHTS

- Arctic ozone loss in 2011 was due to the spring strengthening of the polar vortex.
- Tropical heating after the Mt. Merapi eruption intensified the Arctic polar vortex.
- Tropical volcanic eruptions in autumn–winter period can lead to Arctic ozone loss.

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ABSTRACT

One of the strongest ozone depletion events in the Arctic stratosphere was observed in March 2011 due to the strengthening of the polar vortex in February 2011. Earlier, in November 2010, the eruption of Mt. Merapi volcano (Java, Indonesia) with a maximum plume altitude of 18.3 km was recorded. The effect of aerosol heating in the tropical lower stratosphere after the Mt. Merapi eruption on the Arctic polar vortex strengthening in winter–spring 2011 is examined. Based on the ERA-Interim reanalysis temperature data, we show that significant aerosol heating in the lower tropical stratosphere was observed in February–March 2011 and could lead to an increase in the stratospheric equator-to-pole temperature gradient resulting in an enhanced Arctic polar vortex. We also analyze the correlation between large tropical volcanic eruptions occurring in autumn–winter periods and Arctic ozone depletion events observed in the following winter–spring periods.

1. Introduction

The Arctic ozone loss in spring 2011 was one of the strongest events in the Northern Hemisphere for the last 39 years (Manney et al., 2011; Hurwitz et al., 2011; Kuttippurath et al., 2012a; Varotsos et al., 2012; Petkov et al., 2014). In winter–spring 2011 the total ozone over the polar cap (for latitudes north of 63° N) decreased by 14.0% and 23.9% in February and March, respectively, in comparison with the values in 1997, i.e. 15.3% and 24.6%, respectively, from corresponding values of these months averaged over 1979–2016.

The polar vortex strengthening in spring plays a crucial role in springtime ozone destruction in the polar regions (Newman et al., 2001; Solomon, 1999). The Arctic polar vortex reaches its peak intensity in midwinter and decays in later winter to spring. The springtime breakdown of the polar vortex causes the inflowing of warm and ozone-rich air into a polar region, resulting in polar stratospheric clouds (PSC) melting and ozone accumulation in a polar lower stratosphere, whereas the springtime intensification of the polar vortex leads to keeping and developing PSCs at extremely low temperatures. The PSCs are necessary for the occurring of catalytic cycles describing ozone depletion in the presence of weak solar radiation during the Boreal spring (Solomon et al., 1986; Solomon, 1999; Newman, 2010). Similarly, the severe Arctic ozone loss during March 2011 was observed as a result of the Arctic polar vortex strengthening in February 2011 (Zhang et al., 2012; Olascoaga et al., 2012).

Abbreviations: EP flux, Eliassen–Palm flux; EPG, stratospheric equator–to–pole temperature gradient; PSCs, polar stratospheric clouds; VEI, volcanic explosivity index; SST, sea surface temperature; QBO, Quasi Biennial Oscillation; DU, Dobson units.

* Corresponding author.

E-mail addresses: vvzuev@imces.ru (V.V. Zuev), vzuev@list.ru (N.E. Zueva), ekat.savelieva@gmail.com (E.S. Savelieva).

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Hurwitz et al. (2011) revealed that positive sea surface temperature (SST) anomalies in the North Pacific (the 40–50° N, 160–200° E region) in January and February 2011 are anti-correlated with Arctic lower stratospheric temperature anomalies in March which are developed under strong vortex conditions. Positive SST anomalies in the North Pacific tend to weaken the Aleutian low, which results in reducing vertical wave activity flux, characterized by the Eliassen–Palm (EP) flux, entering the stratosphere (Garfinkel et al., 2010). The breaking and dissipation of westward propagating planetary waves weaken or reverse the eastward zonal flow (i.e. the stratospheric polar vortex) and induce heat by adiabatic processes, which often results in a major sudden stratospheric warming (Kuttippurath and Nikulin, 2012b; Newman et al., 2001; Varotsos, 2002). The EP flux weakening may be caused by large tropical volcanic eruptions (Stenchikov et al., 2002). A volcanic aerosol layer in the tropical stratosphere induces cooling the tropical and subtropical lower troposphere, resulting in the descent of meridional temperature gradient near the surface between 30° N and 60° N in winter. A decrease of mean zonal energy and planetary wave amplitudes in the troposphere results in a descent of a vertical wave activity flux in the lower stratosphere (Stenchikov et al., 2002). The EP flux was defined in very small values from mid-February to early April 2011 (Kuttippurath et al., 2012a), which contributed to keeping the Arctic polar vortex strengthening in the springtime.

The increase in a stratospheric equator–to–pole temperature gradient (EPG) as a result of aerosol heating in the tropical lower stratosphere after major volcanic eruptions, in turn, tends to cause the additional strengthening of the Arctic polar vortex (Stenchikov et al., 2002; Driscoll et al., 2012). The winter–spring increase in the EPG plays a key role in the spring strengthening of the polar vortex.

One of the strongest eruptions of Mt. Merapi volcano (Indonesia) was observed in November 2010 with volcanic explosivity index (VEI) of 4 (Surono et al., 2012). The aerosol heating in the tropical lower stratosphere after the Mt. Merapi eruption was observed up to early April 2011. The effect of the stratospheric aerosol heating on the Arctic polar vortex strengthening and the resulting severe Arctic ozone depletion in spring 2011 are considered in this study. We also analyzed the correlation between large tropical volcanic eruptions and Arctic ozone depletion events. A number of studies (Kodera, 1994; Perlwitz and Graf, 1995; Kirchner et al., 1999; Stenchikov et al., 2002, 2006; Driscoll et al., 2012) showed only the effect of very large tropical volcanic eruptions (such as the Pinatubo eruption in June 1991 and the El Chichon eruption in April 1982) on the springtime polar ozone depletion.

2. Data and methods

The information on ozone profiles over Summit station (Greenland; 72.3° N, 38.3° W) is contained in the NOAA's National Weather Service Network for the Detection of Atmospheric Composition Change (NDACC, http://www.ndsc.ncep.noaa.gov) online database. The data on wind speed for 60° N and minimum temperature for 50°–90° N on the 70 and 50 mb pressure surfaces, PSC volume for 60°–90° N, total ozone for 63°–90° N and maximum potential vorticity inside the polar vortex on the 850, 600 and 460 K isentropic surfaces used in this study were taken from the NASA's Goddard Space Flight Center (GSFC, http://ozonewatch.gsfc.nasa.gov/SH.html) online database. The temperature data for 45°N–45°S on the 70 and 50 mb pressure surfaces were retrieved from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data (Dee et al., 2011; http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/). The data on volcanic eruptions were taken from the Smithsonian Institution Global Volcanism Program (GVP, http://volcano.si.edu).

To expose ozone losses in the ozone profiles over Summit station (Greenland; 72.3° N, 38.3° W) in March 2011, we obtained the 12-year climatological mean vertical profile for March over the period 2005–2016 with standard deviation (σ). The climatological mean and standard deviation were smoothed by a 10 point Fast Fourier Transform (FFT) Filter. To explore variations of meteorological data from August 2010 to July 2011, we obtained the 38-year climatological mean seasonal cycles of wind speed, minimum temperature, PSC volume, total ozone and maximum potential vorticity in the Arctic stratosphere over the period 1979–2016 and the 22-year climatological mean seasonal cycle of tropical lower stratospheric temperature over the period 1995–2016 with standard deviations. The climatological means and standard deviations were smoothed by a 30 point FFT Filter. The temperature climatology was obtained for the period 1995–2016 because of significant tropical temperature variability after very large volcanic eruptions occurred before 1995. Besides, the seasonal cycle of tropical lower stratospheric temperature was determined separately for the easterly and westerly phase of the Quasi Biennial Oscillation (QBO). The phase of the QBO is characterized by zonal winds in the equatorial region at 30 mb (Baldwin et al., 2001; http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html).

3. Results

3.1. Arctic ozone depletion after the polar vortex strengthening in spring 2011

Hommel et al. (2014) examined in detail the chemical compound transformations occurring in the Arctic polar vortex in winter–spring 2010/2011. More than 70% of ozone was depleted in the altitude range of 16–20 km, and the ozone minimum was at a record low (close to 220 Dobson Units (DU)) in March 2011 and remained unusually low up to early April. Fig. 1 shows the vertical ozone profiles over Summit station (Greenland) compared to the

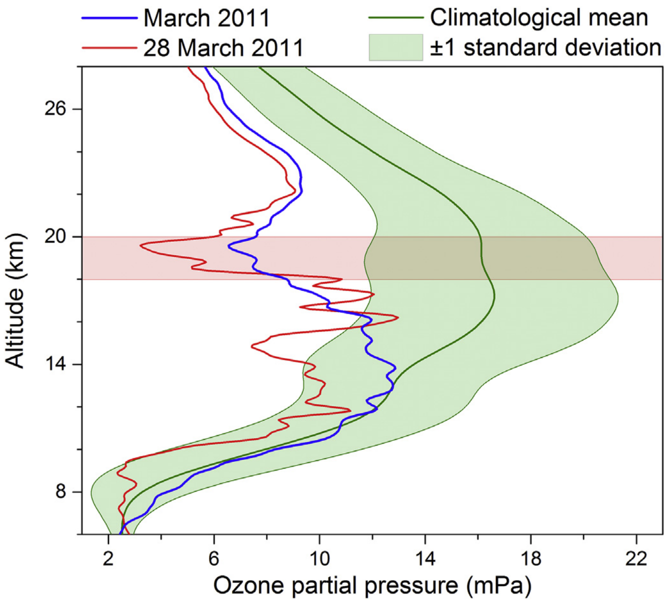

Fig. 1. Vertical ozone profiles for 28 March 2011 (red), averaged over March 2011 (blue), and the 2005–2016 climatological mean for March (green) with ±1 standard deviation (green area) over Summit station (Greenland; 72.3° N, 38.3° W).