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Equatorial stratospheric thermal structure and ozone variations during the sudden stratospheric warming of 2013

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ABSTRACT

Ozone mass mixing ratio (OMMR) obtained from both European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis (ERA)-Interim and Sounding of Atmosphere by Broadband Emission Radiometry (SABER) instrument onboard Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite shows large values in the equatorial upper stratosphere during the occurrence of a major stratospheric sudden warming (SSW) in January 2013 preceded by a large reduction of planetary wave activity. However, surprisingly equatorial stratospheric temperature is found to decrease at pressure levels where the ozone mixing ratio is larger. The computed radiative heating rate using Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model also shows positive heating rate indicating that the temperature should increase in response to the ozone accumulation over equator. In addition to radiative heating due to ozone, heating rate due to other dominant factors, namely, ascending motion and convergence of meridional heat flux, which could influence the thermal structure of the equatorial stratosphere, are estimated. It is found that the observed low temperature during SSW is mainly due to large upward motions. The estimated heating rates agree reasonably well with the observed heating rates at 10-8 hPa indicating the dominance of transport at lower stratosphere. The large discrepancy between the estimated and observed heating rates in the upper stratosphere may be due to the dominance of photochemistry.

1. Introduction

Sudden stratospheric warming (SSW) is a dramatic phenomenon. It was first observed by Scherhag (1952) as an abrupt increase in temperature in the cold polar stratosphere and deceleration and sometimes of reversal of zonal winds within a short span of time. The SSW occurs due to the interaction between zonally averaged circulation and planetary waves (Matsuno, 1971; Schoeberl, 1978). Large amplitude planetary waves (PW) dominate the winter middle atmosphere and their interaction with zonal mean flow is a major driver of winter stratospheric dynamics (Alexander et al., 2010; Charney and Drazin, 1961; Limpasuvan et al., 2011; Mukhtarov et al., 2009). PW activity is stronger and more frequent in the northern hemisphere than in the southern hemisphere due to larger thermal and orographic forcing (Andrew et al., 1987; Pancheva et al., 2007) and hence SSW is more prevalent in the Arctic region than in the Antarctic region (Manney et al., 2005; Pancheva et al., 2008). An increase in planetary wave activity is observed prior to the onset of an SSW which preconditions the atmosphere (Teweles and Finger, 1958; Chshyolkova et al., 2007; Hoffmann et al., 2007), leading to an upward and poleward heat flux resulting in the poleward heat transport (Eliassen and Palm, 1961; Andrews et al. 1987). There is a heating tendency at polar latitudes (Lowenthal, 1957; Murray, 1960) and cooling at tropical latitudes as a result of heat flux divergence leading to zonal mean upward (downward) motion at polar (tropical) latitudes (Sathishkumar et al., 2009). Although vertical motions play a major role in evolution of stratospheric temperature during a polar warming event (Craig and Hering, 1959), the event is believed to originate from the dominance of eddy heating over the effect of the mean upward motions (Matsuno, 1971). This mechanism predicts a polar warming and lower latitude cooling in agreement with observations (Fritz and Soules, 1970; Labitzke, 1972).

The large planetary wave activity prior to the onset of SSW strengthens the Brewer–Dobson circulation (BDC), which plays a major role in transporting ozone from equatorial region, where its production is maximum, to higher latitudes. It has major implication in the generation of semi-diurnal tides and hence on low-latitude ionospheric current system. Sridharan et al. (2012b) noted decrease of semi-diurnal tide just prior to the occurrence of SSW, when planetary wave amplitudes are larger. During the SSW, planetary wave activity decreases considerably at high latitudes

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and even at low-latitudes (Sathishkumar and Sridharan, 2009). It has been proposed that the enhancement of semi-diurnal tide at low-latitude mesosphere is due to the accumulation of ozone at low-latitudes due to weakening of the BDC and hence weakening of upward and poleward circulations, as semi-diurnal tides are largely generated due to the absorption of solar insolation by ozone molecules (Sridharan et al., 2012a; Goncharenko et al., 2012). Due to the enhancement of semi-diurnal tidal amplitudes, occurrence of counter-electrojet events for several days consecutively has been reported by Sridharan et al. (2009b). Pancheva et al. (2009) observed that the zonally symmetric planetary waves play an important role in coupling the dynamical regimes of the high- and low-latitude stratosphere particularly during the major strat warm event.

If the ozone concentration is larger in the equatorial region, stratospheric temperature is expected to increase, as ozone absorbs the incoming solar ultra-violet radiation directly. In this study, though accumulation of ozone molecules is observed during the SSW of January 2013, temperature shows an abrupt decrease. The variations of ozone concentration with temperature and planetary wave activity and also the factors responsible for the anomalous decrease in temperature despite the increase in ozone concentration during a sudden stratospheric warming event are investigated.

2. Data analysis

2.1. ECMWF ERA-interim data

ERA-Interim is the latest European Centre for Medium-Range Weather Forecasts (ECMWF) global atmospheric reanalysis of the period 1979 to present (Berrisford et al., 2009). This follows on from the ERA-15 and ERA-40 re-analysis projects. The dataset includes data on surface, PV, potential temperature and pressure surfaces. Before ERA-interim, ECMWF has produced three major reanalyses namely, FGGE, ERA-15 and ERA-40 in the past. The last of these consisted of a set of global analyses describing the state of the atmosphere and land and ocean-wave conditions from mid-1957 to mid-2002. ERA-Interim is an ‘interim’ reanalysis of the period 1989-present in preparation for the next-generation extended reanalysis to replace ERA-40.

The key strengths of ERA-Interim data sets are spatially and temporally complete data set of multiple variables at high spatial and temporal resolution, improved low-frequency variability and stratospheric circulation when compared to ERA-40. There is no key limitation in the ERA-Interim temperature and ozone data sets. The ERA-Interim analysis provides data for the pressure levels (hPa) 1, 2, 3, 5, 7, 10, 20, 30, 50, 70, 100 to 250 by (in steps of) 25, 300 to 750 by 50, 775 to 1000 by 25.

In this study, ERA-Interim data has been used for the observation of ozone as well as temperature (grid $1.5^\circ \times 1.5^\circ$) variations for the above pressure levels during the sudden stratospheric warming event occurred in January 2013. The ERA-Interim temperature at 60°N and at 10 hPa available for different longitudes are subjected spatial Fourier transform (along longitude) and the amplitudes of the first two harmonics representing planetary wave amplitudes of zonal wave numbers 1 and 2 respectively are computed for each day to obtain the time variation of the planetary wave activity.

2.2. SABER data

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument is one of the four instruments on NASA's Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) satellite, the first mission of the NASA Solar Connections program. The primary goal of the SABER experiment is to provide the data needed to advance the understanding of the fundamental processes governing the energetics, chemistry, dynamics, and transport in the mesosphere and lower thermosphere. SABER accomplishes this with global measurements of the atmosphere using a 10-channel broadband limb-scanning infrared radiometer covering the spectral range from 1.27 μm to 17 μm. The data uncertainty is 5% for ozone volume mixing ratio for the height range 15–65 km and above 65 km it is 20%. The temperature uncertainty is 1.5 K in the stratosphere.

In this study, SABER data is used for showing latitudinal variation of ozone volume mixing ratio (ppmv) and temperature during the polar stratospheric warming event.

2.3. SBDART model

Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) is a software tool that computes plane-parallel radiative transfer in clear and cloudy conditions within the Earth's atmosphere and at the surface (Ricchiazzi et al., 1998). This program is based on a collection of highly developed and reliable physical models namely Cloud model, Gas Absorption Model, Extraterrestrial Source spectral model, Standard Atmospheric Models, Standard Aerosol Models, radiative Transfer Equation Solver and Surface Models. In the present study, SBDART model is used to obtain the radiative heating rate due to ozone concentration over equator during the time period 01 December 2012–28 February 2013. The input parameters used for this model are given in Table 1.

In this model, the ozone density and altitude (obtained from pressure levels given as input data) have been provided as user specified atmospheric profile. By running this model, the radiative heat transfer rate (K/day) due to the high ozone concentration over equator has been obtained during the polar stratospheric warming event.

3. Results

ERA-Interim temperature data for November 2012–March 2013 are used to infer the state of high latitude winter at 10 hPa. The time variation of the strength of the planetary wave activity of waves with zonal number $k=1$ and $k=2$ is shown in Fig. 1a. The amplitude of PW of $k=1$ is in general larger than that of PW of $k=2$. Most of the times, it is below 20 K, Occasionally, it exceeds 20 K during the day numbers 29–39 and 86–99. It increases to 39 K on day number 34 and 24 K on day numbers 90 and 99. The PW of $k=2$ shows normally less than around 5 K and it shows variability with large values of 16 K, 13 K and 16 K on day numbers 31, 39 and 42. Corresponding to the increase of PW of $k=1$, the zonal mean temperature difference between the latitudes 90°N and 60°N (Fig. 1b) increases and becomes positive reaching 20 K on day number 35. Immediately, it decreases and shows variability resembling the variability of the PW of $k=2$. The positive temperature difference, indicating the occurrence of warming persists mainly on day numbers 34–53. Large deceleration of zonal mean zonal wind (Fig. 1c) occurs in association with the decrease of PW activity from 30 m/s on day number 29 to -9 m/s on day number 37. Westward wind persists during day numbers 35–57. Maximum westward wind of 13 m/s is observed on day number 49. The PW activity around day number 89 does not lead to any change in temperature difference and winds. The focus is on the large PW activity followed by the occurrence of the major warming event during the day numbers 29–59. The longitude-time cross section of PW of $k=1$ in temperature at 60°N (Fig. 2) suggests that the wave is a westward propagating one with maximum (minimum) temperature values in the longitude region 90–160°E (250–360°E) during the day numbers 20–50.