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Tropical upper tropospheric ozone enhancements due to potential vorticity intrusions over Indian sector

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ABSTRACT

Influence of potential vorticity (PV) intrusions at 13.5°N over and near Indian sector (50°E–90°E) on tropical upper tropospheric ozone mixing ratio (OMR) variations is demonstrated based on two case studies. Increase of ECMWF (European Centre for Medium-range Weather Forecasting) reanalysis (ERA)-interim OMR in the upper troposphere (200–500 hPa) is observed during the intrusion events consistently in both cases. The OMR also shows similar tongue like structure as PV and it even follows the spatial shift of the PV tongue. In addition, the enhancements in the upper tropospheric OMR during the intrusion events are confirmed using microwave limb sounder (MLS) ozone data at 216 hPa. It is suggested that the existence of strong downdrafts, associated with the ageostrophic circulation due to jet stream, which is inferred from longitude-height cross-section of ERA-interim vertical velocity could bring the ozone further down, though high PV tongue remains only at higher level (above 400 hPa). The importance of these results lies in demonstrating the role of PV intrusion events on the enhancement of tropical upper tropospheric ozone over Indian sector, where the impact of the PV intrusions is not well understood when compared to that over Pacific and Atlantic sectors.

1. Introduction

Stratospheric ozone protects us from ultra-violet radiation, whereas upper tropospheric ozone is a greenhouse gas and it contributes positively towards the radiation budget by trapping global outgoing longwave radiation (OLR) and thereby increases the surface temperature (Worden et al., 2008). The photochemical reaction and downward transport from the stratosphere are the major sources for the upper tropospheric ozone (Danielsen, 1968; Logan, 1985), though the latter dominates the former (Roelofs and Lelieveld, 1997). The upper tropospheric ozone is mainly controlled by stratosphere–troposphere exchange (STE) processes at mid- and high latitudes (Barre et al., 2012), though the influence of these processes on low-latitudes is yet to be understood (Levy et al., 1985; Hsu and Prather, 2009). Besides, ozone variabilities show close connection with quasi-biennial oscillation and El-Nino Southern Oscillation (Zerefos et al., 1992). Seasonal cycle of ozone concentration at tropopause and the substantial mass flux across tropopause determines the downward flux of ozone to the upper and middle troposphere (Škerlak et al., 2014). The tropopause folds are favourable for the cross-tropopause exchange (Danielsen, 1968) and they can be identified from large potential vorticity (PV) value in the upper troposphere (Elbern et al., 1998; Tyrlis et al., 2014; Škerlak et al., 2015). These PV intrusions, transport trace gases like ozone from the stratosphere to the upper troposphere and further to lower levels (Sprenger et al., 2007), though major contribution to tropospheric ozone comes from photochemical production (Staehelin et al., 1994; Yenger et al., 1999). Fadnavis et al. (2010) studied seasonal variation of ozone over India and they observed that the upper tropospheric ozone is more during winter and pre-monsoon months. Consistent with this, Sandhya and Sridharan (2014) noted more PV intrusions over Indian sector during pre-monsoon and winter. Rossby wave breaking at mid-latitude stratosphere leads to intrusion of high potential vorticity air from mid-latitude stratosphere to tropical troposphere in the presence of upper tropospheric westerlies, which are favourable conditions for the intrusions (Waugh and Polvani, 2000). These PV intrusions play a vital role on promotion of convection (Kiladis, 1998, Sandhya and Sridharan, 2014), inhibition of convection (Russell et al., 2008), intensification of cyclone (Browning, 1997) etc. Most of the studies on the influence of PV intrusions on surface or lower tropospheric ozone variabilities are from Northern Hemispheric mid-latitudes (Wakamatsu et al., 1967; Chung and Dann, 1967; Davies and Schuepbach, 1994; Bithell et al., 2000 ; Langford et al., 2012; Lin et al., 2012 to state a few). Not much work has been done from low-latitudes and in particular over Indian sector due probably to the less number of occurrence of PV

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intrusion events. The present study shows an evidence for the increase in ozone mixing ratio (OMR) in the tropical upper troposphere associated with a few PV intrusion events over Indian sector.

2. Data analysis

2.1. ERA-interim data sets

European Centre for Medium Range Weather Forecasting (ECMWF) data are produced on model levels (hybrid pressure-sigma coordinates) and at the surface. ECMWF data are also interpolated to pressure levels and some datasets include data on isentropic levels. The ECMWF reanalysis (ERA) interim uses 60 levels with the model top at 0.1 hPa. The ERA-interim data sets are results from the analysis conducted at 6-h intervals available for latitude–longitude grids $3^\circ \times 3^\circ - 0.125^\circ \times 0.125^\circ$ and are prepared by ECMWF using their variational data assimilation system (Berrisford et al., 2009). The data sets are currently available in the website http://apps.ecmwf.int/datasets/data/interim-full-daily// for 15 isentropic levels and 37 pressure levels.

In the present study, potential vorticity, ozone mixing ratio and vertical velocity (Omega) at different pressure levels and potential vorticity and zonal wind at 350 K isentropic level and zonal wind, meridional wind, geopotential at 200 hPa pressure level are used. The ERA-Interim data is divided mainly in to three periods namely Pre GOME assimilation period (till 1995), GOME assimilation period (1996–2002) and the post GOME assimilation period (2003 onwards). Dragani (2010) studied the quality of ERA-Interim ozone data by comparing with in situ measurements. They reported that in the pre GOME assimilation period, the residuals between ozonesondes and the corresponding ERA-Interim ozone profiles were within $\pm 10\%$ in the tropics and mid-latitudes at most levels and within $\pm 20\%$ at high-latitudes. However in GOME assimilation and post assimilation periods, the level of disagreement was within $\pm 5\%$ in the tropics.

2.2. MLS-Ozone data

The Aura Microwave Limb Sounder (MLS) onboard Earth Observing System (EOS) launched on 15 July 2004. It is sun synchronous with altitude 705 km and with 98° inclination. ML2O3 version 3 data is used for the present study. This is a standard product for ozone derived from radiances measured by the 240 GHz radiometer. The spatial coverage is near-global (-82° to $+82^\circ$ latitude), with each profile spaced 1.5° or ~165 km along the orbit track (roughly 15 orbits per day). The recommended useful vertical range is from 261 to 0.0215 hPa and the vertical resolution is between 2.5 and 6 km (Cheung et al., 2014).

3. Results

The intrusion of high PV tongues, from high to low latitudes can be identified from latitude to longitude cross-section of PV at 350 K isentropic level, for the days 15 May, 2011 and 7 May, 2009 respectively in Fig. 1a and b. On 15 May 2011, the tongue of high PV greater than 1.4 PVU (potential vorticity unit; $1\ \text{PVU} = 10^{-6}\ \text{km}^2\ \text{kg}^{-1}\ \text{s}^{-1}$) reaches up to 12°N over 65°E–70°E and on 7 May 2009, it crosses 13.5°N over 60°E–65°E. The latitude–longitude cross-section of magnitude of the resultant wind obtained from the zonal and meridional wind components and geopotential at 200 hPa (~ 350 K) for the same days are shown in Fig. 2c and d. The subtropical jet flow can be inferred from the wind speed greater than 50 m/s over 20°N – 40°N on 15 May 2011 with the trough of subtropical jet over 65°E–70°E. The existence of trough can also be identified from the folded geopotential contour. Fig. 2d also shows the subtropical jet flow over 30°N–40°N on 7 May 2009, when the trough of the jet stream is over 60°N–65°N at latitude 13.5°N. Extratropical air with high PV can enter to the tropical troposphere through the tropopause fold at the western side of the upper level trough associated with jet streams (Kentarchos et al., 1999, Ding and Wang, 2006).

In order to show the time evolution of PV intrusion shown in Fig. 1, the time-longitude cross-sections of PV and zonal wind at

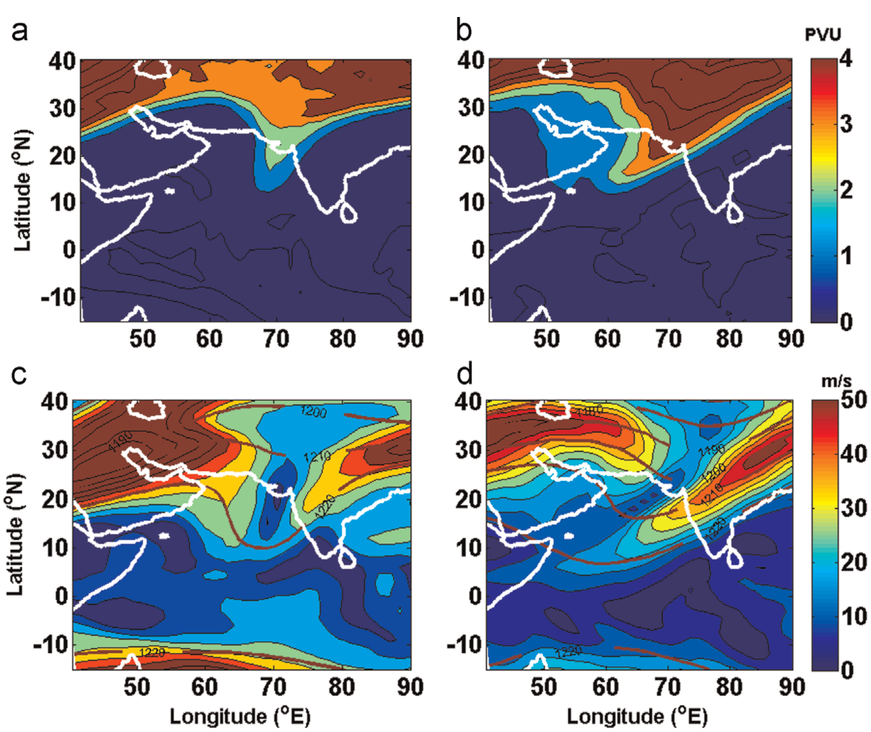

Fig. 1. Latitude–longitude cross-sections of (a, b) PV at 350 K isentropic level and (c, d) resultant wind speed and geopotential at 200 hPa for the days 15 May 2011 and 7 May 2009.