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Unusual enhancement in tropospheric and surface ozone due to orography induced gravity waves

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ABSTRACT

In this study, we investigate the causative processes responsible for the observed enhancement in the tropospheric and surface ozone during December 09–11, 2008 orography induced gravity wave event over Himalayan region. The analysis is done using surface ozone measurements and satellite datasets from Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit-A (AIRS/AMSU-A), COSMIC, TES and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). Observations depict a two fold increase in surface and tropospheric ozone during the event as compared to normal days in both AIRS and TES ozone measurements. COSMIC temperature perturbations show generation of shorter vertical wavelengths efficient for the sub-tropical tropopause folding due to orography induced gravity waves. Moreover, the intense tropopause folding as evidenced by upward-downward vertical velocities couplet could trigger the intrusion of stratospheric ozone rich air into upper tropospheric ozone poor air as also confirmed by high values of potential vorticity during the observational period. Hence, present study reemphasizes the importance of wave induced atmospheric dynamics on atmospheric constituents' especially tropospheric ozone over Himalayan region.

1. Introduction

Ozone is one of the most important atmospheric trace gas in both stratosphere and troposphere affecting the Earth-atmosphere radiative balance and hence the climate (Cracknell and Varotsos, 2011). The stratospheric ozone constituting about 90% of total ozone concentration in the atmosphere, although very small amounts as compared to other gases, protects life on earth by blocking harmful UV radiation reaching surface (Cracknell and Varotsos, 1994, 1995; Varotsos and Cracknell, 1994). On the other hand, tropospheric ozone, constituting to only ~10% of total ozone in the atmosphere, found to be having adverse effects on vegetation as well as on human health (Zeng et al., 2008; Kumar et al., 2010; Lelieveld et al., 2015). Although, very less in concentration but tropospheric ozone happens to be third most powerful greenhouse gas (after carbon-dioxide and methane) with radiative forcing of $0.40 \pm 0.20\ W\ m^{-2}$ (IPCC, 2013). Thus, increase (decrease) in tropospheric (stratospheric) ozone is of recent interest to the scientific community because of enormous impact on the society, especially, on human health related issues like irritation in respiratory system, reduction in the efficiency of the lung function, aggravations in asthma etc. Tropospheric and surface ozone showed increasing trend over most of the locations in Indian region (Naja and Lal, 1996; David and Nair, 2013). Moreover, a recent report showed tropospheric ozone causes roughly 22,000 premature deaths per year in 25 countries in European Union (WHO, 2012). It is imperative that if the percentage of contribution of tropospheric ozone increase could result in fourfold increment in the death figures in Indo Gangetic plain region because of heavy population density (Lelieveld et al., 2015). Ghude et al. (2016) has also estimated the mortality rate by chronic obstructive pulmonary disease (COPD) due to O_3 exposure is about 12,000 people on a national scale. Hence, it is crucial to understand different processes responsible for the enhancement of tropospheric ozone over local, region and global scales.

The photochemistry involving different trace gases largely emitted from various anthropogenic sources (e.g. motor vehicle exhaust, industrial emissions, etc.), controls the ozone budget (e.g. Kumar et al., 2013). It has been shown that the transport of ozone rich air from polluted regions to pristine high altitude or marine regions (Chand et al., 2001; Naja et al., 2004; Lal et al., 2013; Girach et al., 2017) could influence ozone budget in those regions. Further, greater uncertainties exits in the downward transport of ozone and dry deposition process

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(Stevenson et al., 2006). Downward transport of ozone has been suggested to have contribution in higher levels of ozone during winter/spring at a number of sites across the globe and about 0.1% of total stratospheric ozone (about 5×10^{13} molecules cm^{-2} s^{-1}) is suggested to transported to the troposphere (e.g. Logan, 1985; Crutzen, 1995; Ojha et al., 2014, Sarangi et al., 2014). Stratospheric-ozone intrusions into the troposphere during events of cyclones also been observed over Indian regions (Das et al., 2016a, 2016b).

Past studies showed that ozone enters into troposphere from stratosphere by means of large scale phenomena as a part of Brewer Dobson Circulation triggered by a variety of processes (Levy et al., 1985; Holton et al., 1995; Hocking et al., 2007; Chen et al., 2011; Nath et al., 2016). Moreover, this large-scale circulation is one of the most important contributors for the enhancement in the tropospheric ozone in extra-tropical latitudes (Holton et al., 1995; Nath et al., 2016). Recent study showed that an increasing trend and westward shift of number of intrusions contributing to the increased tropospheric ozone over the central pacific (Nath et al., 2016). The episodes of downward intrusion of stratospheric air (dry air causing low humidity) are, in general, associated with the behaviour of subtropical jet stream and these are strongest in winter over the Himalayan region and hence the intrusion of air masses from the stratosphere may contribute to higher upper tropospheric ozone in winter than in summer leading to an additional radiative impact over Tibetan Plateau (Chen et al., 2011; Naja et al., 2016; Niranjan Kumar et al., 2016). It is also worth mentioning here that previous reports showed that the frequent laminated vertical ozone structures over sub-tropical latitudes are related to atmospheric circulation phenomena (Varotsos et al., 1994). Additionally, Tobo et al. (2008) showed that high ozone stratospheric intrusion into troposphere is closely associated with the tropopause folds and the frequencies of these folds directly linked with stratospheric intrusions and vertical distribution of ozone over Himalayan region. In this context, it has become mandatory to quantify various factors contributing to the tropospheric ozone and once such dynamical episodic event outlined in the present report.

Furthermore, satellite observations showed that "ozone mini-hole" events are transporting ozone from troposphere (ozone poor) into stratosphere (ozone rich) through tropopause during summer season over the Himalayan region (Zhou and Zhang, 2005; Tobo et al., 2008; Bian, 2009). However, during winter and early spring, stratospheric (ozone rich) intrusions into troposphere (ozone poor) are more frequent thereby injecting the ozone into upper and lower troposphere. In this perspective, it is essential to understand and quantify the plausible reasons for intrusion of stratospheric ozone into troposphere which has immense impact on atmospheric radiation budget over Himalayan region.

Very few studies in the recent past highlighted the importance of vertically propagating disturbances/gravity waves propagating to tropopause especially during tropical cyclone events could result in stratosphere-troposphere exchange (STE) process. These studies emphasized the potential of wind profiler radars by providing observational evidence of stratospheric ozone intrusions into troposphere as a part of campaign mode and also during tropical cyclone events (Hocking et al., 2007; Das, 2009; Niranjan Kumar and Ramkumar, 2008; Niranjan Kumar et al., 2011; Das et al., 2016a, 2016b; Pathakoti et al., 2016). On the other hand, mountain waves are not so frequent but will have high amplitudes when these waves are triggered over the Himalayan region where some of the highest mountains on earth are located causing hindrance to the horizontal wind flow thereby setting up of oscillations. These waves have the potential to show signatures not only to upper troposphere but also to stratosphere and mesosphere. However, it is based on the strength of the initial disturbance, and under suitable meteorological conditions, these waves are capable for vertical propagation (Niranjan Kumar et al., 2012, Lyapustin et al., 2014; Kim et al., 2016; Kaifler et al., 2015). Hence, recent studies around the globe have opened up a new window not only illustrating the importance of vertical forcing in quantifying the tropospheric ozone but also gave a strong message that vertically propagating disturbances/gravity waves cannot be neglected keeping in mind the importance of STE processes on day-to-day basis.

In view of the above scenario, present study for the first time attempts to understand the enhancement of tropospheric and surface ozone by means of STE process triggered by orography induced atmospheric gravity waves over Himalayan region. This study utilizes different satellite datasets such as Microwave Limb Sounder (MLS), Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit-A (AIRS/AMSU-A), COSMIC temperature perturbations, Tropospheric Emission Spectrometer (TES) on board Aqua satellite, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) to understand the impact of mountain waves on the unusual enhancement in the tropospheric ozone during December 2008 over the Himalayan region. In the following sections, we have identified the mountain waves through AIRS observations and established the link between mountain waves and ozone transport. Finally, we have discussed the plausible mechanism responsible for the stratospheric ozone intrusion into upper troposphere causing unusual enhancement in tropospheric and surface ozone over the Himalayan region.

2. Data used

The present study utilizes the data from AMSU-A and AIRS sounders on board the National Aeronautics and Space Administration (NASA) Aqua satellite. Tropospheric and stratospheric temperature sounding is done using twelve channels covering 50 to 60 GHz oxygen band. In this study, we have used the raw radiance measurements, from 53.6 GHz channel with weighting function peaks at ~600 hPa, to identify the gravity wave perturbations in the troposphere (Aumann et al., 2003). The methodology used for the retrieving the radiance perturbations are closely followed from Niranjan Kumar et al. (2012). In this study, we make use of the AIRS (level-2 and level-3) version-6 ozone, temperature, and humidity information at different pressure levels. More technical details and retrieval of surface and atmospheric parameters of the AIRS/AMSU system can be found elsewhere (Aumann et al., 2003; Susskind et al., 2003). As a supplement to the utilization of AIRS/AMSU measurements, the along track tropopause height from CALIPSO data provided by the Global Modeling and Assimilation Office (GMAO) data assimilation system is also utilized.

The dynamical analysis, in support of AIRS/AMSU observations, is done using the European Centre for Medium Range Weather Forecasts (ECMWF) interim Re-Analysis (ERA) data (Dee et al., 2011). ERA-interim products are available on the ECMWF data server at various spatial (latitude, longitude) resolutions at 37 pressure levels from 1000 to 1 hPa. In the present analysis, we have used the vertical (pressure) velocities and potential vorticity fields at 1.5×1.5 degree spatial intervals.

We have utilized Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) temperature profiles during December 07–11, 2008 to estimate the vertical wavelengths generated due to orographic generated gravity waves over Himalayan region. COSMIC is a Taiwan-US joint mission with a constellation of six microsatellites equipped with GPS receivers and provides ~2500 occultations per day over the globe. COSMIC satellites were launched in early 2006 and providing continuous data from April 2006, however, coverage is low over equatorial region. Further details about COSMIC mission can be found in earlier papers (Kursinski et al., 1997; Anthes et al., 2008). In the present study, COSMIC level 2 temperature profiles are chosen nearest to the latitude (longitude) belt of 35–45°N (65–75°E) which is the region of intense mountain wave activity. Data points flagged with bad quality are not considered for the analysis.

Tropospheric Emission Spectrometer (TES) ozone is on the Aura satellite which has a ~705 km sun-synchronous polar orbit with an equator crossing time of ~13:45 and a 16-day repeat cycle was designed to measure the global vertical distribution of tropospheric ozone, as well as