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Tropopause height characteristics associated with ozone and stratospheric moistening during intense convective activity over Indian sub-continent

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ABSTRACT

In this present investigation, a threefold analysis has been portrayed to comprehend the atmospheric dynamics at the Tropopause height on both short and long term basis over the Indian sub-continent. The Tropopause height as determined from the gridded temperature profiles from ERA Interim reanalysis is using a concept of "threshold lapse-rate". It has also been noticed that an exchange between water vapour and ozone occurs along the Tropopause (100 hPa) region during occurrences of deep moist convection. The eastern Indian coastal region experiences enormous convective strength during summer (March–May), hence an increase in specific humidity (as proxy of water vapour) with subsequent decrease in ozone levels in the east-coastal stations are found comparable with the inland stations. Again, the vertical convective transport during deep convection has been found to be supported by stronger vertical wind in the coastal regions compared to inland locations. Finally, it has been comprehended that vertical transport of water vapour gradually decreases in the eastern Indian coastal regions while not much change has been noticed in inland regions.

1. Introduction

The upper troposphere and lower stratosphere (UTLS) has an important significance on the climate system due to exchange processes of minor constituents through this region. The troposphere and stratosphere differ from each other in terms of a lot of physical and chemical properties such as air density, static stability and chemical composition, and, thus, air mass exchange between these two regions of the atmosphere has gained primary importance. However, both these regions are separated by the Tropopause; the thermal definition of which has been utilized based on the standard WMO lapse-rate criterion (WMO, 1957). Hence, a study of Tropopause is necessary to investigate the stratosphere-troposphere exchange (STE) processes (Holton et al., 1995) to precisely calculate radiative forcing (Stuber et al., 2001) and to inspect the Tropopause height variability over a region (Randel and Wu, 2000; Santer et al., 2003a, 2003b; Sausen and Santer, 2003; Seidel and Randel, 2006). This paper provides an insight of STE with a focus on the climatic processes in the partly tropical and sub-tropical Indian sub-continent. It also addresses the relevance of STE for tropospheric chemistry, particularly its influence on the ozone capacity of the stratosphere. Ozone (O_3) plays a significant role in modulating the global weather and climate even though the total atmospheric composition of ozone is less than that of other trace gases. Long ago, Reed (1950) had pointed out that vertical motions in the stratosphere are associated with considerable horizontal divergence and convergence. The concentrations of many important chemically and radiatively-active gases, including ozone and water vapour, depend on the transport between troposphere and stratosphere (Midya and Saha, 2011a; Saha and Maitra, 2014). All these factors lead to a measurable amount of ozone being carried down to the troposphere and hence to the surface of the earth by diffusion, subsidence and eddy mixing (Randel et al., 2006; Midya and Saha, 2011b; Midya et al., 2011a; Midya and Saha, 2011c; Fadnavis et al., 2014). Indeed, many of the important interactions involve processes around the Tropopause; composition changes around the Tropopause can be particularly important for radiative transfer, and hence climate. Stratospheric Moistening (SM) is the process of intrusion of water vapour from upper troposphere to lower stratosphere and is controlled by air mass transport through the Tropopause region (Liu et al., 2010; Jain et al., 2013; Saha and Maitra, 2014). Increased stratospheric water vapour may be a principal cause of global warming as it warms the troposphere beneath, thereby cooling the stratosphere above. Upper tropospheric water vapour is a crucial factor for maintaining the current climate primarily through its greenhouse absorption (Dethof et al., 1999; Sherwood et al., 2003; Chakraborty et al., 2017a; Saha et al., 2017b). SM provides the most direct evidence of air parcel entering the stratosphere with large scale ascent in the tropics through

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STE with a shallow exchange of water vapour at the extra tropics. In addition, a significant dryness in the stratosphere along with the yearly stratospheric water vapour variation as revealed by Mote et al. (1996) manifests that air passes through cold tropical Tropopause to stratosphere (Randel et al., 2006). However, in other regions of the atmosphere, such as, the lower and middle stratosphere, the Brewer-Dobson circulation (Brewer, 1949) driven by the Rossby and gravity waves cause intrusion of water vapour into the extra tropical lower stratosphere (Holton et al., 1995; Pan et al., 2009). Breaking of these waves may contribute to exchange of ozone and water vapour through upper troposphere lower stratosphere (UTLS) region with the help of turbulent vertical mixing (Pan et al., 2009). In this process, SM can affect the ozone concentration, surface climate and stratospheric temperatures in various spatial and temporal scales. Sources of lower stratospheric water vapour are considered to be areas of intense convection in the tropical region, where overshooting cumulonimbus clouds can mix the air residing at troposphere and stratosphere region (Dethof et al., 1999). According to IPCC Fourth Assessment Report on Climate Change (2007) represented by Trenberth and Dai (2007), it can be inferred that although methane oxidation is one of the major sources of water vapour in stratosphere and has been increasing over the industrial period, yet the total change in stratospheric water vapour is too large and hence cannot be attributed to methane oxidation alone (Oltmans et al., 2000). In spite of this, the detailed mechanism of how tropospheric air enters the stratosphere in the tropics is still heavily debated. Stratosphere, in extremely dry conditions, having water vapour mixing ratios lesser than that obtained from the mean tropical Tropopause temperature, must require a mechanism which would enable moisture ingress through the coldest regions of the tropical Tropopause (Highwood and Hoskins, 1998; Jain et al., 2010). Thus, Newell and Stewart (1982) suggested that the air ascends slowly into stratosphere only through limited regions called stratospheric fountains, where Tropopause temperatures are minimal, during specific seasons of the year. The context of SM was questioned some years later by Dessler (1998), who made it clear that air can enter the stratosphere throughout the year (Mote et al., 1996). Entrainment of moisture in the lower stratosphere from the lower/mid/upper troposphere following the formation of shallow cumulus is the primary ingredient for the formation of deep convection (Liu et al., 2010; Midya et al., 2011b; Jain et al., 2013; Saha and Maitra, 2014; Saha et al., 2012, 2014; Chakraborty et al., 2015; Chakraborty et al., 2017b). Nevertheless, the rate of decrease of total ozone column (TOC) is at maximum during the pre-monsoon (March–May) season as the rate of increase of surface RH is also at its maximum level at the same time (Midya and Saha, 2011a). Decrease in ozone concentration caused by the OH radical is predominant in the troposphere but this process also extends to the lower stratosphere (Saha and Maitra, 2014).

Tropopause height has a great influence in the intrusion of moisture and depletion of ozone along the UTLS region during intense convective activities (Bethan et al., 1996; Fadnavis et al., 2014). Hence, this phenomenon is highly variable with respect to seasonal air buoyancy and location. Thus, a study of Tropopause, wind profiles, moisture and ozone based on long and short term approach has been investigated over the Indian sub-continent during pre-monsoon season. In the first section, a determination of Tropopause height from the vertical profiles of atmospheric temperature has been completed using the temperature lapse rate criterion (2 °C km^{-1}) from the ERA Interim reanalysis data for twenty two different locations over India. The aforesaid method will be utilized to analyze the seasonal variation of the Tropopause level over the Indian region. The result has been validated with Tropopause height data from Aqua - AIRS satellite. In the second segment, the role of tropical Tropopause layer (TTL) on the intrusion of upper tropospheric water vapour to the lower stratosphere through STE process has been studied during deep moist convective occurrences. Also, the chemical and dynamical coupling of water vapour in the UTLS region with that of ozone derivatives in the Tropopause has been studied. Finally, in the last section, investigation has been progressed with the long term variation of intrusion of water vapour and subsequent depletion (formation) of ozone in the stratosphere (troposphere) at some stations of eastern and western coastal regions, some inland stations and southern Indian peninsular region as a whole.

2. Site description, data used and methodology

2.1. Site description

India (7°N–38°N, 66°E–98°E, Fig. S1) experiences a subtropical climate in north and a tropical climate in south. This region is bounded by the Himalayan range in the north, Thar Desert in the west and the southern side is bounded by seas (Bay of Bengal in the South-East, Arabian Sea in the South-West and Indian Ocean at the South). The coastal regions of India are also bounded by hilly terrain (Eastern Ghats facing the Bay of Bengal and the Western Ghats adjacent to the Arabian Sea). Other geographical features include the Vindhyas and Satpuras hills in the central region and Aravallis hills in the north-west.

As this study is mainly focused on various regions of the Indian sub-continent, hence, a series of stations have been taken in various parts of the study. First, for depicting the average temperature profiles, Radiosonde data of four metropolitan regions have been recorded, the location of which are shown in Table 1. Next, to depict the seasonal variation of lapse rates at Tropopause, four separate groups of stations are selected on the basis of their geographical location and topographic agreement. The list of stations is given in Table 2. In the later sections, the profiles of ozone and specific humidity and their correlation coefficients are depicted for the two coastal regions of India, namely: Kolkata in the eastern coast and Goa at western coasts. Additionally, to study the altitudinal variability of vertical wind an exhaustive study has been incorporated for 42 stations covering 21 stations each for the coastal and inland region. After that, a time series simulation of atmospheric parameters has been depicted for Kolkata, West Bengal (22.57°N, 88.36°E) and Barguna, Bangladesh (22.15°N, 90.12°E) regions respectively, during two cyclonic storms namely, AILA on May 25, 2009 and SIDR on 15 November 2007. These regions are chosen after examining the storm tracks generated by UNISYS weather (website: http://weather.unisys.com/hurricane/n_indian/2009H/index.php (last accessed on January 28, 2017) which reveals that in both the cases the eye of the cyclone covered these locations. Finally, to have a concluding perspective on long term variation of stratospheric intrusion, two stations namely: Rameswaram in the eastern coasts and Delhi at the deep inland regions are depicted.

2.2. Data used

According to India Meteorological Department (IMD), the span of 12 months in the year can be divided into four seasons namely: Winter or the fall (December–February), Pre-monsoon or the summer (March–May), Monsoon or the wet (June–September) and Post-Monsoon or the retreating monsoon (October–November). As, pre-monsoon season experiences the most number of intense convective occurrences, hence the analysis has been mainly done on the pre monsoon season. Radiosonde observations have been obtained from University of Wyoming (website: http://www.uwyo.edu) to study the

Table 1
Metropolitan stations chosen over the Indian sub-continent to study using Radiosonde data.

Region	Stations	Latitude (°N)	Longitude (°E)	Elevation (m)
Eastern	Kolkata	22.57	88.36	9
Southern	Chennai	13.08	80.27	6.7
Western	Mumbai	19.08	72.88	14
Northern	Delhi	28.61	77.21	216