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Short Communication

Balloon-borne cryogenic frost-point hygrometer observations of water vapour in the tropical upper troposphere and lower stratosphere over India: First results

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ABSTRACT

Balloon-borne cryogenic frost-point hygrometer (CFH) observations of water vapour in the upper troposphere and lower stratosphere (UTLS) region carried out over India, from Trivandrum [8.5°N, 76.9°E] and Hyderabad [17.5°N, 78.6°E], were compared with that obtained from quasi-collocated Aura-Microwave Limb Sounder (MLS) satellite observations. Comparisons show a small dry bias for MLS in the stratosphere. Saturated or super-saturation layers observed near the base of tropical tropopause layer (TTL) are consistent with the quasi-collocated space-based observations of tropical cirrus from KALPANA-1 and CALIPSO. Disturbance of large scale waves in the upper troposphere appears to modulate the water vapour and cirrus distribution.

1. Introduction

Water vapour is the most dominant greenhouse gas and is the main source for hydroxyl radicals in Earth's atmosphere (e.g., Rohrer and Berresheim, 2006). Variability of water vapour in the upper troposphere and lower stratosphere (UTLS) region can exert significant impact on the climate system (e.g., Forster et al., 2002) as it interacts strongly with the infra-red radiation. Water vapour in the UTLS region plays an important role in the weather and climate of the Earth-atmosphere system through their potential contribution in heterogeneous chemistry at this low temperature regime and also in the formation of liquid and ice clouds in this region (Oltmans et al., 2000; Rosenlof et al., 2001). Water vapour determines the ozone layer chemistry in the stratosphere and plays a pivotal role in formation of ice clouds by hydrating and/or dehydrating the upper troposphere (Jensen et al., 1996a). Water vapour in the UTLS region originates mostly from deep convection that penetrates the cold tropopause region, forming ice clouds by freeze-drying and cold trap mechanisms (Jensen and Pfister, 2004; Read et al., 2008; Schiller et al., 2009), the so called Tropical Tropopause Layer (TTL). However, the air-mass may get dehydrated as it passes through the region characterized by widespread cirrus near the cold point tropopause. Over the tropics, the cross-tropopause transport of water vapour in to the lower stratosphere is mainly regulated by cold-point tropopause temperature, convective overshooting, horizontal circulation in the UTLS levels, dehydration processes in the TTL (Park et al., 2008; Fueglistaler et al., 2009), and the transport associated with the Brewer-Dobson Circulation (Holton et al., 1995). Large-scale equatorial waves close to the tropopause region plays a significant role in modulating the water vapour and cirrus distribution in the tropical UTLS region (e.g., Fujiwara et al., 2001, 2009; Suzuki et al., 2013). Fujiwara et al. (2001) demonstrated the role of equatorial waves around the tropopause region in maintaining the dryness of tropical lower stratosphere.

Indian region is of particular interest due to large annual migration of Inter Tropical Convergence Zone (ITCZ), persistence of anticyclonic circulation and divergence in the upper troposphere and exceptionally deep convection over Bay-of-Bengal during Asian summer monsoon period (June-September) (Gettelman et al., 2002b; Devasthale, Fueglistaler, 2010) and the influence of extra tropical wave forcing, particularly during northern hemisphere winter (Fukutomi and Yasunari, 2014). During pre-monsoon and post monsoon period, relatively high thunderstorm activity prevails over this region (Manohar et al., 1999). All the above processes plays a crucial role in the distribution of mass and moisture in the upper troposphere as well as in the lower stratosphere. Over the Indian subcontinent, the distribution of water vapour and cirrus in the UTLS region shows large variability (e.g.,

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Devastale and Grassl, 2009; Meenu et al., 2010; Sunilkumar et al., 2010; Jain et al., 2013, 2015; Uma et al., 2013, 2014) in response to the prevailing dynamics in the troposphere. Satellite based measurements showed large amount of water vapour in upper troposphere (e.g., HALOE on-board UARS, MLS on-board Aura, AIRS on-board Aqua) over the Indian region during monsoon season compared to other tropical locations (Gettelman et al., 2002a, 2004; Randel and Park, 2006; Jain et al., 2013, 2015; Uma et al., 2013, 2014). However, the microphysics of cirrus formation and dehydration in the TTL, the mechanism/process controlling the entry/amount of water vapour in the stratosphere, and how it is freeze-dried, are not well understood (Newell and Gould-Stewart, 1981; Kley et al., 1982; Dessler, 1998; Winker and Trepte, 1998, Selkirk et al., 2010). This necessitates the need for continuous and accurate monitoring of water vapour in the UTLS region over the tropics. Accurate *in situ* measurements of water vapour in the UTLS region are rather limited due to the technical difficulty in measuring very low amount of water vapour at low temperatures and also due to high cost of sophisticated instruments. Cryogenic Frost-point Hygrometer (CFH) is one of the most proven instrument used for accurately measuring water vapour in the altitude region from surface to about 28 km. This has been used as a reference instrument for validating the water vapour profiles obtained from other sensors (Vömel et al., 2007b). Several campaigns focusing on the water vapour distribution in the UTLS region were carried out at different locations in the tropics using cryogenic frost point hygrometers (e.g., Fujiwara et al., 2001, 2010; Vömel et al., 2002, 2007a, 2007b, Selkirk et al., 2010) and snow white chilled-mirror hygrometers (e.g., Suzuki et al., 2010).

Over India, though frost point hygrometers soundings were carried out at Hyderabad in April 1961 during its development stage (Mastenbrook, 1962), the first flight of the improved version of cryogenic frost point hygrometer (CFH) was carried out over Thumba, Trivandrum on 17 April 2014 at 17:30 IST as part of tropical tropopause dynamics (TTD) experiment under the GARNETS (GPS Aided Radiosonde Network Experiment for Troposphere-stratosphere Studies) programme. CFH soundings were also carried out on 13 May 2014 at Trivandrum and on 28 May 2014 at Hyderabad. This paper report the first results of water vapour distribution in the UTLS region over India obtained from these three CFH soundings and discuss the variability of water vapour in the UTLS region with the dynamical field variables and collocated space-based observations of tropical cirrus.

2. Balloon-borne cryogenic frost-point hygrometer experiment

The Cryogenic Frost-point Hygrometer (CFH) is a small lightweight microprocessor controlled instrument and operates on the chilled-mirror principle using a cryogenic liquid as cooling agent. This is an upgraded version of NOAA/CMDL instrument (Vömel et al., 2002) capable of measuring accurate water vapour continuously from surface to about 28 km altitude. A small mirror attached at the end of the cold finger piece is electrically heated or cryogenically cooled to maintain a constant thin layer of frost or dew that is optically detected. Under this condition the condensate layer on the mirror is in thermal equilibrium with the vapour phase of the air passing over the mirror. The mirror temperature is then equal to the ambient dew point or frost point temperature and is measured by a tiny thermistor embedded in the surface of the mirror. This frost-point temperature is used to calculate the partial pressure of water vapour in air (Goff and Gratch, 1946) and determine the water vapour mixing ratio (WVMR) (Vömel et al., 2002, 2007a). Accuracy of the thermistor calibration is less than 0.04 °C over the range of mirror temperatures from 25 °C to −94 °C. The largest source of uncertainty in the frost-point temperature measurement comes from the stability of the feedback controller (0.5 °C). The total uncertainty in the frost-point measurement is better than 0.51 °C (Vömel et al., 2007a), which translates to a mixing ratio uncertainty of about 4% in the lower tropical troposphere to about 10% in the middle stratosphere and tropical tropopause. Details of instrument design and measurement characteristics are described by Vömel et al. (2007a). In our experiment, CFH is interfaced with ECC Ozonesonde and the data is transmitted through iMet-1 Radiosonde. These combined payloads were attached to a 2000 g meteorological balloon to reach an altitude of ∼30 km with an ascent rate of ∼5 m s^{-1}. Accuracy of iMet air temperature measurement is 0.3°C and that of pressure is 0.5 hPa (Hurst et al., 2011). Mutual consistency of the temperature measurements from different types of radiosondes (iMet-1, Graw, Meisei) has been tested by launching them together over Trivandrum. It is found that the data from these sondes agrees well within the accuracy limits of the respective sondes. Hurst et al. (2011) reported good agreement between the iMet-1 and Vaisala RS92 measured temperatures. The relative humidity with respect to ice (RHi) is calculated from frost-point temperature (T_{FP}) and ambient air temperature (T). The uncertainty of RHi thus estimated is 5–7% and better than 10% of the RHi values in the upper troposphere and lower stratosphere respectively. Altitude profiles of T, T_{FP}, WVMR, RHi obtained during the CFH flight were regridded with an altitude resolution of 100 m.

Regional characteristics of tropospheric clouds over the Indian subcontinent and the surrounding oceanic regions during the period of CFH observations were derived from the brightness temperature (BT) observed in the water vapour (WV) and thermal infra-red (TIR) bands of KALPANA-1 VHRR (Rajeev et al., 2008) employing the bi-spectral method (Roca et al., 2002). Quasi-collocated CALIPSO data on the day of CFH flight were used to infer the vertical properties of cirrus. Quasi-collocated observations of water vapour mixing ratio obtained from EOS-Aura Microwave Limb Sounder (MLS) data available at different pressure levels in the UTLS region were used to compare with CFH observations.

3. Results

Fig. 1 shows the altitude profiles of ambient temperature (T), frost-point temperature (T_{FP}), relative humidity with respect to ice (RHi), and water vapour mixing ratio (WVMR) in the upper troposphere and lower stratosphere obtained from CFH flight carried out on 17 April 2014 at 17:30 IST over Trivandrum.. In the troposphere while the frost-point temperature decreases rapidly with height, the decrease of T_{FP} with height is very slow above the cold point tropopause (CPT). Altitude structure of T_{FP} showed structured features with their values close to ambient temperature (indicating saturation) in the altitude region of 11–13 km. These features are reflected in the altitude structure of RHi which indicates the possibility of cloud occurrence in this altitude region. The altitude region 13–14 km is dry, while RHi between 14.5 and 18.2 km is rather moderate (50–65%). The altitude at which the vertical gradient of potential temperature reaches its lowest value below CPT is taken as convective tropopause (COT). The region between COT and CPT is referred as the tropical tropopause layer (TTL) (Gettelman and Forster, 2002; Mehta et al., 2008; Sunilkumar et al., 2013). The TTL-base and -top altitude obtained from temperature profile are marked in Fig. 1, which shows the occurrence of moderately humid TTL on this day.

In general, WVMR decreases with increase in altitude in the troposphere and varies by four orders of magnitude from ∼30,000 ppm by volume (ppmv) near the surface to less than 10 ppmv above 15 km. The WVMR decreases drastically from ∼20 ppmv at 13.5 km