



Long-term (2004–2015) tendencies and variabilities of tropical UTLS water vapor mixing ratio and temperature observed by AURA/MLS using multivariate regression analysis

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ABSTRACT

Long-term variabilities and tendencies in the tropical (30°N–30°S) monthly averaged zonal mean water vapor mixing ratio (WVMR) and temperature in the upper troposphere and lower stratosphere (UTLS), obtained from the Microwave Limb Sounder (MLS) instrument onboard Earth Observing System (EOS) satellite for the period October 2004–September 2015, are studied using multivariate regression analysis. It is found that the WVMR shows a decreasing trend of 0.02–0.1 ppmv/year in WVMR below 100 hPa while the trend is positive (0.02–0.035 ppmv/year) above 100 hPa. There is no significant trend at 121 hPa. The WVMR response to solar cycle (SC) is negative below 21 hPa. However, the magnitude decreases with height from 0.13 ppmv/100 sfu (solar flux unit) at 178 hPa to 0.07 ppmv/100sfu at 26 hPa. The response of WVMR to multivariate El Niño index (MEI), which is a proxy for El Niño Southern Oscillation (ENSO), is positive at and below 100 hPa and negative above 100 hPa. It is negative at 56–46 hPa with maximum value of 0.1 ppmv/MEI at 56 hPa. Large positive (negative) quasi-biennial oscillation (QBO) in WVMR at 56–68 hPa reconstructed from the regression analysis coincide with eastward (westward) to westward (eastward) transition of QBO winds at that level. The trend in zonal mean tropical temperature is negative above 56 hPa with magnitude increasing with height. The maximum negative trend of 0.05 K/year is observed at 21–17 hPa and the trend insignificant around tropopause. The response of temperature to SC is negative in the UTLS region and to ENSO is positive below 100 hPa and mostly negative above 100 hPa. The negative response of WVMR to MEI in the stratosphere is suggested to be due to the extended cold trap of tropopause temperature during El Niño years that might have controlled the water vapor entry into the stratosphere. The WVMR response to residual vertical velocity at 70 hPa is positive in the stratosphere, whereas the temperature response is positive in the UTLS region and negative above 56 hPa. Besides, the interannual variability and the response of the WVMR to the different parameters are explained based on the response of temperature at 100 hPa (proxy for tropopause) to those parameters.

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1. Introduction

Though the water vapor content in stratosphere is small, it plays a major role in determining the radiative energy balance (Forster and Shine, 1999, 2002), in acting as a source of hydroxyl radicals and in the destruction of polar ozone by involving in the activation of chlorine on polar stratospheric clouds (Solomon, 1999). Water vapor is important in heterogeneous ozone loss in the polar regions because it lowers the threshold for formation of polar stratospheric clouds. More important perhaps, it also increases the heterogeneous reactivity of key reactions in polar

ozone loss (Drdla and Muller, 2012). Brewer (1949) suggested that the water vapor in the lower stratosphere must have passed through the cold tropopause region over the tropics, slowly ascending within the circulation that later became known as Brewer–Dobson circulation (BDC). Methane oxidation is an important source of water vapor in the middle stratosphere (Jones and Pyle, 1984; Rohs et al., 2006). The tropical tropopause temperature controls the water vapor entering into the stratosphere (Fueglistaler et al., 2009). The annual variation in stratospheric water vapor is a response to the annual cycle in tropopause temperatures (Mote et al., 1996; Holton et al., 1995). Increase of tropospheric temperature leads to high stratospheric water vapor and through feedback process to further warming of troposphere (Dessler et al., 2013). The large positive anomaly of stratospheric WVMR during 1997–98 was attributed to the El-Niño event, which

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warmed the tropical tropospheric temperature by 2 K (Randel et al., 2004). The interannual variability of stratospheric water vapor is less, when compared to its annual changes and is mainly governed by quasi-biennial oscillation (QBO) (e.g. Giorgetta and Bengtsson, 1999), El-Niño Southern Oscillation (ENSO), and Brewer–Dobson circulation (BDC) (Randel et al., 2006; Dhomse et al., 2008). Thermal-wind relationship of QBO suggests warmer tropopause temperature during the eastward shear of QBO winds leading to more stratospheric water vapor, when compared to the westward shear of QBO (Baldwin et al., 2001). During winter, water vapor along with other chemical constituents get transported from the upper troposphere to extra-tropical stratosphere by BDC, which is forced mainly by the breaking of planetary-scale Rossby waves mostly at mid-latitudes. Besides seasonal and interannual variabilities, it is important to investigate the long-term tendencies in water vapor quantitatively. All climate models predict that there is an increase the stratospheric water vapor trends (Gettelman, 2010). Multi-year observations over mid-latitudes show that there is a positive trend in water vapor data considered for the years 1954–2000 (Rosenlof et al., 2001) and 1980–2010 (Hurst et al., 2011). However, there are only a few studies, which showed altitude dependence with positive trends in upper stratosphere and negative trends in lower stratosphere for the water vapor data extending back to 1986 (Scherer et al., 2008; Hegglin et al., 2014). Over the tropics, stratospheric water vapor for the years shows no significant long-term trend just above the tropopause (82 hPa) (Dessler et al., 2014).

In this paper, long-term trends and variabilities of upper tropospheric and lower stratospheric (UTLS) water vapor mixing ratio (WVMR) over the tropics (30°S–30°N) obtained by the Microwave Limb Sounder (MLS) instrument on board Aura Earth Observing System satellite (EOS) for the period October 2004–September 2015 are studied using multivariate regression analysis.

2. Observational datasets and data analysis

2.1. Water vapor mixing ratio (WVMR) data

The MLS instrument on board Aura EOS satellite was launched on 15 July 2004. It uses a sun-synchronous orbit at an altitude of 705 km and with 98° inclination. The standard water vapor product of v4.2 is taken from the 190 GHz channel. The horizontal grid is every 1.5° or ~165 km along the orbit track. The version 4.2 (v4.2) stratospheric water vapor data used in this study are the update to the v3.3 and v2.2 versions, which are validated and described by Hurst et al. (2014) and Lambert et al., (2007) respectively. The MLS v4.2 and v3.3 data have significant improvements for a number of species (Livesey et al., 2011), including the H₂O product. Correlative measurement comparisons show a fine-scale oscillation in the v2.2 H₂O retrievals, and this retrieval artifact has been eliminated in the v4.2 and v3.3 retrievals. The single profile precision is expected to be better than 0.2–0.3 ppmv (4–9%) in the stratosphere. This precision is not obtained in the UTLS region with values of 10–20% at 121–82.5 hPa (Read et al., 2007). The accuracy is estimated to be 0.2–0.5 ppmv (4–11%) at 68–0.01 hPa. MLS v3 and v4 profiles of water vapor volume mixing ratio generally compare well with collocated measurements, with a slight dry bias (v4: $-8 \pm 4\%$) near 22–26 hPa, a slight wet bias (v4: $+12 \pm 5\%$) near 68–83 hPa, and a more substantial 15 dry bias (v4: $-32 \pm 11\%$) in the upper troposphere (121–261 hPa), whereas the temperature profiles contain significant cold biases relative to collocated temperature measurements in several layers of the lower–middle stratosphere and in the upper troposphere (Yan et al., 2016). The recommended useful vertical range is from 316 to 0.002 hPa (Hurst et al., 2014). The vertical resolution for H₂O is

about 2.5 km at 316–215 hPa, and 3 km at 100–1.0 hPa. The MLS measures in the microwave region and hence it is less sensitive to stratospheric aerosol variations and clouds so as to obtain reliable measurements in the tropopause region, whereas earlier space-borne WVMR measurements made by HALOE and SAGE are solar occultation measurements made in infrared domain and hence are susceptible to interference from aerosols (Dessler et al., 2014). Besides, the solar occultation measurements have sparse sampling over the tropics, whereas MLS's coverage over tropics is more with nearly 30,000 observations per month. In this paper, the WVMR and temperature measurements for the period October 2004–September 2015 are considered. In order to detect trends on the order of a few percentages per decade, stability of long-term measurements is essential. This is particularly important for long-term ground based and satellite sensors, which may be subject to some degradation during their lifetime. However, there is no detectable instrumental drift in the MLS for stratospheric water vapor measurements (Hurst et al., 2014).

Fig. 1a and b shows height-time cross section of zonal mean tropical (30°N–30°S) WVMR for the years October 2004–September 2015 and for the pressure levels 178–100 hPa and 100–1 hPa respectively. There is a drastic reduction in WVMR from greater than 20 ppmv at 178 hPa to 3–4 ppmv at 100 hPa. The WVMR is less than 3 ppmv in the height region 100–68 hPa and is in the range 3–3.5 ppmv at 68–56 hPa. However, it shows an increase above 10 hPa. The WVMR also exhibits a strong seasonal variation. It is greater than 3.5 ppmv in the height region 56–21 hPa during December–April. However, it begins to increase (> 3.5 ppmv) from May reaching maximum (> 5 ppmv) in August–September. The seasonal variation of the lower stratospheric water vapor is defined by tape recorder, which is the imprint of the tropopause temperatures on stratospheric water vapor (Mote et al., 1996) and it follows the seasonal northward movement of inter tropical convergence zone (Panwar et al., 2012). Fueglistaler et al., (2005) showed that the observed seasonal cycle can be accurately simulated using Lagrangian trajectory calculations suggesting the dehydration at tropopause as a simple explanation of the large seasonal variation (Randel, 2010), though the model exhibits a dry bias. Besides the seasonal variation (Fig. 1), the WVMR shows a large interannual variability in the upper troposphere. It is larger during the years 2006 and 2010 and is less during 2008, 2011 and 2012 in the lower stratosphere. Above 21 hPa also, the WVMR shows large interannual variability. Low WVMR values are noticed in January–March of 2006, 2008, 2011 around 3 hPa and large WVMR values are observed in December 2006, 2008, 2009, 2011, 2013 and 2014 at 1 hPa, when compared to other periods.

2.2. Factors influencing the long-term variabilities of WVMR

The stratospheric WVMR variations are influenced by QBO, ENSO and BDC as discussed earlier and also by other parameters, namely, solar cycle (SC) and tropospheric temperature etc. (Dessler et al., 2013; Dhomse et al., 2008). Their time variations of proxies of SC, QBO, BDC and ENSO are shown in Fig. 2a–d. In the present study, the F10.7 (2800 MHz) flux is used as a proxy for the SC variation. The F10.7 radio emissions are more from chromosphere and less from the corona of the solar atmosphere. The F10.7 variations agree well with those of sunspot number as well as a number of ultraviolet (UV) and visible solar irradiance records. The F10.7 has been measured consistently since 1947, first at Ottawa, and then at the Penticton Radio Observatory in British Columbia. Unlike many solar indices, the F10.7 radio flux is the most reliable measurement from the Earth's surface, in all types of weather. The F10.7 can vary from ~50 solar flux units (sfu) to ~300 sfu, over the course of a SC. From the Fig. 2a, we can infer that the extended solar minimum from 2006 to 2010. From 2010, the solar flux

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