Atmospheric Environment 122 (2015) 148–153

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Enhancement in the upper tropospheric humidity associated with aerosol loading over tropical Pacific

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HIGHLIGHTS

- Using observations we show that aerosols increase the upper tropospheric humidity.
- Quantifies atmospheric warming as a result of upper tropospheric humidity increase.
- Study is significant in understanding the enhanced greenhouse effect of water vapor.

ARTICLE INFO

Article history:
Received 7 April 2015
Received in revised form
12 September 2015
Accepted 15 September 2015
Available online 16 September 2015

Keywords:
Upper tropospheric humidity
Aerosols
Longwave cloud radiative forcing
Water vapor feedback

ABSTRACT

Many modeling studies have indicated that aerosol interactions with clouds increase the upper tropospheric humidity (UTH), but observational evidences are sparse. Using satellite datasets of upper tropospheric humidity and aerosols, this study shows that aerosols increase the upper tropospheric humidity over the tropical North West Pacific (NWP) and North East Pacific (NEP). The observations show an increase in the UTH by 2.8%RH over NEP for an increment of 0.12 in aerosol optical depth (AOD) and 2%RH increase in UTH over NWP for an increment of 0.19 in AOD. The study also quantifies the change in longwave cloud radiative forcing (LWCRF) as a consequence of the increase in UTH due to aerosols. The LWCRF increases by 3.38 W m^{-2} over NEP and by 4.46 W m^{-2} over NWP. The result that aerosols increase the upper tropospheric humidity is significant since the latter plays a crucial role in regulating the Earth's radiation budget and water vapor feedback.

1. Introduction

The global warming is now a phenomenon existing beyond any doubt and there are many indications that the Earth's temperature has been increasing over the past several decades (Hansen and Lebedeff, 1987). The monitoring of atmospheric water vapor under a changing climate plays a central role in the prediction of future climate and this is largely due to its positive feedback effect. It has been shown from model studies that water vapor feedback doubles the surface temperature change caused as a result of the doubled CO_2 concentration. Of the total water vapor in the troposphere, about two thirds of the feedback is attributed to the water vapor in the free troposphere (Held and Soden, 2000). Therefore, relatively small variations in the amount of water vapor in the upper troposphere will have a large influence on the radiation budget. Hence, monitoring the long-term fluctuations of water vapor especially in the upper troposphere, and the various factors governing these fluctuations is inevitable for progressing with studies on climate change.

Deep convection transports energy and moisture vertically and is the main source of upper tropospheric humidity and clouds. It is well known that cloud formation is aided by the presence of aerosols which act as cloud condensation nuclei (CCN), around which cloud droplets form. Clouds forming under aerosol contaminated environments are more prone to convection due to suppression of warm rain as well as suppression of freezing, eventually resulting in the release of latent heat at higher altitudes (Koren et al., 2005, 2010).

In global aerosol-climate model, increase in the upper tropospheric clouds and water vapor due to rise of anthropogenic sulfate and soot concentrations has been shown by Liu et al. (2009). Using spectral microphysics cloud model, Khain and Pokrovsky (2004) have shown the presence of more ice particles in the upper

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http://dx.doi.org/10.1016/j.atmosenv.2015.09.043
1352-2310/

troposphere under an aerosol contaminated air than under a pristine condition. It is also suggested that larger the concentration of ice crystals in the upper troposphere, the larger is the potential for sublimation, which in fact implies an increase in the amount of upper tropospheric humidity. Ramanathan et al. (2001) have also argued that the suppression of precipitation associated with increase in the amount of aerosol will in turn increase the amount of water vapor in the upper troposphere. These studies indicate that there could be an intrinsic link between UTH and aerosol concentration. It is also possible that the anthropogenic aerosol concentration could have increased the humidity as well as the cloudiness in the upper troposphere.

Su et al. (2011) using observations of microwave limb sounder on Aura satellite and the MODIS aerosol optical depth, have studied the correlations among aerosols, temperature and water vapor of the tropical tropopause layer. They have speculated that the increase in water vapor could be related to the increase in temperature, as a result of increased aerosols. The aerosol effect on upper tropospheric humidity has come into focus only very recently and there have not been many dedicated studies so far, especially regarding an understanding of interactions between aerosol and upper tropospheric humidity using observations. Bister and Kulmala (2011) have argued that the aerosol concentration might increase the relative humidity in the upper troposphere. A recent study by Riuttanen et al. (2014) reports that anthropogenic aerosols increase the UTH over the China outflow region in the Pacific.

The geographical regions where the impact of aerosols on UTH is large, need to be identified. The present study looks into the aerosol-UTH interactions over the regions in tropical Pacific during Northern hemisphere summer. We investigate whether aerosols increase the UTH and further analyze how any enhancement in UTH affects the top-of-the atmosphere longwave cloud radiative forcing. The following section describes satellite data used in the study. Section 3 provides the methodology and section 4 presents the results. The paper concludes with section 5.

2. Satellite data

2.1. Radiative forcing

The longwave cloud radiative forcing data used in this study is from Clouds and the Earth's Radiant Energy System (CERES) onboard the Aqua and Terra satellites (Loeb et al., 2009). We have used the monthly mean values available at a resolution of 1.0° × 1.0° latitude–longitude grids from June to August for the years 2007–2009. This data can be downloaded from http://ceres.larc.nasa.gov/. The difference between the top-of-the-atmosphere radiative fluxes of clear-sky and all-sky condition quantifies the cloud radiative forcing. The top-of-the-atmosphere longwave cloud radiative forcing (LWCRF) is defined as:

$$\mathrm{LWCRF} = \mathrm{LWFLUX_{clear}} - \mathrm{LWFLUX} \tag{1}$$

where $\mathrm{LWFLUX_{clear}}$ and LWFLUX are the top-of-the-atmosphere clear-sky and all-sky longwave fluxes respectively. The LWCRF is generally positive, because when clouds are present, lesser longwave energy escapes to space than under clear-sky conditions.

2.2. Upper tropospheric humidity

The upper tropospheric humidity derived from 183 ± 1 GHz channel of the microwave humidity sounder (MHS) onboard NOAA (National Oceanic and Atmospheric Administration)-18 satellite, has been used in this study. Buehler and John (2005) have shown a linear relationship between the logarithm of UTH and the 183 ± 1 GHz channel brightness temperature and have described an algorithm for UTH retrieval. UTH from 183 ± 1 GHz can be retrieved under almost all–sky conditions except when very thick ice clouds are persistent (John et al., 2011). Prior to UTH retrieval, the cloud contaminated measurements were excluded following a cloud filtering method described in Buehler et al. (2007). The UTH data were binned onto 1.0° × 1.0° latitude–longitude grids and monthly mean values for the months June to August were constructed for the period 2007–2009. The upper tropospheric humidity derived from microwave measurements on NOAA satellites is useful for atmospheric studies (Kottayil et al., 2013, 2012).

2.3. Cloud and aerosol

Monthly mean values of aerosol optical depth (AOD), ice cloud particle effective radii and the cloud top pressure available from MODIS (Moderate Resolution Imaging Spectroradiometer) onboard the Terra satellite has been used in the present study. The AOD over ocean used in this study is retrieved from 0.5 μm channel and the algorithm for retrieval is described in Tanré et al. (1997). The solar reflected radiation at 0.664 and 1.621 μm (2.142 μm) have been used for ice cloud optical depth and particle effective radius retrieval and the details can found in King et al. (1997). The cloud top pressure (CTP) is retrieved using CO_2 slicing method which uses the spectral radiances measured around 15 μm CO_2 absorption band (Menzel et al., 2008). Three months (June to August) of data have been used for the years 2007–2009 and are available at 1.0° × 1.0° latitude–longitude grids. The data can be procured from http://modis-atmos.gsfc.nasa.gov/MOD08_M3/.

3. Methodology

This study has been undertaken over two regions over the tropical Pacific. The first region is in North East Pacific (0°–10° N; 110° W–130° W) and will be denoted as NEP and the second one lies in North West Pacific (0°–10° N; 110° E–150° E) and will be denoted as NWP. The study region is shown in Fig. 1. The 183 ± 1 GHz channel is sensitive to humidity fluctuations approximately between 200 and 500 hPa and thus the retrieved UTH from this channel is the layer average relative humidity. Therefore all the variables (UTH, AOD, LWCRF and ice cloud particle effective radius) used in this study have been filtered based on the cloud top pressure. The variables are retained only if the numerical values of cloud top pressure is below 600 hPa. The linear least square regression relationship has been used for inferring the relationship between the various variables considered in this study. The uncertainty of the regression parameters have been deduced using the bootstrap method (Lahiri, 2006).

4. Results and discussion

In general, the aerosol optical depth and its variability over the Pacific is lower than for those regions affected by continental influence such as the regions around China and the Indian subcontinent. The June to August mean AOD for three years for NEP and NWP are 0.101 ± 0.026 and 0.099 ± 0.074, respectively. The aerosols found over the tropical Pacific are mostly of natural origin and are dominantly maritime aerosols (Smirnov et al., 2002). The aerosol impact on upper tropospheric humidity for the two study regions (NEP and NWP) over the tropical Pacific is shown in Fig. 2.

The increase in the upper tropospheric humidity with high aerosol loading is clearly seen over the regions NEP and NWP. The linear least square regression slope for the region NEP is found to be $17.07 \pm 6.825\ \frac{\%\mathrm{RH}}{\mathrm{AOD}}$. For NEP, a change in AOD from 0.07 to 0.19 is found to increase the upper tropospheric humidity approximately