Observational evidence for aerosols increasing upper tropospheric humidity

Reply to Anonymous Referee #1

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Comments by Referee #1:

General Comments:
This is a very interesting study to investigate the impacts of aerosol on the increase in upper tropospheric humidity by using remote sensing datasets over the ocean east of China. The study shows that increased aerosol loads are associated with higher upper tropospheric humidity via changes in the microphysics of deep convection. Based on long-wave radiation transfer calculation, the authors concluded that an increase in upper tropospheric humidity leads to a positive regional radiative effect. The results are well presented and structured, and the topic is suitable for publication in Atmos. Chem. Phys. after addressing some specific comments listed below.

Authors' response:

We thank the Anonymous Referee #1 for his / her comments. Please find our response to the specific comments below.

Specific Comments:
An increase in the number of atmospheric aerosols acting as cloud condensation nuclei (CCN) would slow down the diffusion growth of droplets, and thus smaller cloud droplets. To better support this mechanism using observational evidences, cloud particle effective radii (or cloud albedo) and cloud fraction, which can be retrieved by remote sensing observations, are suggested to be included in the analysis.

The referee suggests adding cloud properties by satellite instruments to the study. Cloud processes are an essential step in the proposed AOD-UTH causality chain. However, as deep convective clouds develop quite rapidly, data with a very fine time resolution would be needed. We definitely think such a study would be worthwhile, but would not be within the scope of this paper as a different source of data would be needed (e.g. from a measurement campaign).

Several studies have already shown that in polluted environments cloud droplets and ice crystals associated with deep convective clouds are smaller and more numerous than in clean environments. Both observational studies (e.g. Koren et al. 2005; Sherwood 2002; Jiang et al. 2009) and modelling studies (e.g. Fan et al. 2013; Khain et al. 2005; Morrison and Grabowski 2011; Storer and van den Heever 2013) show it (see also IPCC AR5, Boucher et al. 2013). We have added these references to the revised manuscript on Section 1.

Identification of deep convective clouds might further improve the results. MODISdetected cloud top pressure and CloudSat data would be helpful to select the cases with deep convective clouds.

Also identification of deep convective clouds separately would be useful in a cloud-scale study with a lagrangean approach. Such an approach, however, would be different than in our study. We have used a precipitation limit to separate cases with deep convection to cases without precipitation or precipitation from shallow clouds. We have added the following explanation to the revised manuscript Section 2.4:

"We use the limit of 1 mm to exclude cases without any deep convection from the study."

It should be noted and be mentioned in the article that using AOD as a measure of CCN concentration may introduce substantial uncertainties which is dependent on the aerosol type, vertical profile and hygroscopic growth.

We agree with the Referee #1 that using AOD as a measure of CCN concentration may introduce uncertainties which depend on the aerosol type, vertical profile and hygroscopic growth. We have added the following sentence to section 2.1:

"However, it should be noted that AOD does not provide information on aerosol type, vertical profile of the aerosols or hygroscopic growth of the aerosol particles." Causality questions related to the hygroscopic growth of the particles are further discussed in section 3.2.

The discussion on long-wave radiative effect is somewhat incomplete and unclear. For instance, the time period of the calculated the top-of-the-atmosphere radiative effect should be clarified, monthly mean or instantons values, in Section 2.5. Moreover, discussions on radiative effect are too short in Section 3.3. It would be better to discuss the radiative effect in detail, such as the difference between tropical moist (TM) and mid-latitude dry (MLD) conditions.

We have added text about the radiative effect and modified chapter 3.3 as following:

"Outgoing long-wave radiation is sensitive to the upper tropospheric water vapour concentration (Held and Soden, 2000). Water vapour is a greenhouse gas that mainly affects climate by absorbing outgoing longwave radiation. To balance the decrease in outgoing long-wave radiation that results from increased UTH, an increase in surface and lower atmospheric temperatures is required that acts to increase the outgoing long-wave radiation.

To quantify these effects, radiative transfer calculations (see Section 2.5) were conducted for two reference soundings of tropical moist (TM) and mid-latitude dry (MLD) air. The results show that a 1 %RH increase in the UTH of moist tropical air causes a local positive radiative effect of 0.25 W m^{-2} (0.39 W m^{-2} for dry air, see Table 3). In dry air the impact is larger as the fractional increase in water vapour concentration for a fixed increase in RH is larger in dry air (Held and Soden, 2000).

The observed summertime increase of 2.2 ± 1.5 %RH in UTH (5.8 ± 1.4 %RH without removal of AOD dependence on cirrus fraction) due to aerosols corresponds to the radiative effect of +0.5 ± 0.4 W m^{-2} (+1.4 ± 0.3 W m^{-2}, interpolated from Table 3) in tropical moist air. The real radiative effect by this phenomenon may be even larger than these values, since the effect of wet scavenging may partially obscure the microphysical effects of aerosols on UTH in our study region."

Technical Corrections:
Caption of Figure 11: please check the labels of panels in the caption.

Labels of panels in Figure 11 have been corrected.

Page 6, Line 8: MSL should be defined here.
We have replaced MSL with "mean sea level" on page 6, line 8.

Figure 10: the abbreviations like omega and dir in this figure need to be specified in the caption.

Specifications of the abbreviations “omega” and “dir” has been added to the caption of Figure 10.

References:

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Jiang *et al.:* Aerosol-CO relationship and aerosol effect on ice cloud particle size: Analyses from Aura Microwave Limb Sounder and Aqua Moderate Resolution Imaging Spectroradiometer observations. *J Geophys. Res.*, 114, D20, 2009.

Khain *et al.:* Aerosol impact on the dynamics and microphysics of deep convective clouds. *Q. J. R. Meteorol. Soc.,* 131, 611, 2639-2663, 2005.

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Sherwood, S.: Aerosols and Ice Particle Size in Tropical Cumulonimbus. *J. Clim.*, 15, 9, 1051-1063, 2002.

Storer and van den Heever: Microphysical processes evident in aerosol forcing of tropical deep convective clouds. *J. Atmos. Sci.,* 2013, 70, 2, 430-446, 2013.