A STUDY OF THE IMPACT OF SYNOPTIC WEATHER CONDITIONS AND WATER VAPOUR ON AEROSOL-CLOUD RELATIONSHIPS

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ABSTRACT

We study three areas, one in mid-latitudes, one in the sub-tropics and one in the tropics, using a decade of MODIS observations. The observations include aerosol optical depth (AOD), cloud cover (CC) and water vapour. We also use NCAR/NCEP sea level pressure (SLP) data. Over all studied areas, for all SLP regimes, cloud cover is found to increase with AOD, thus pointing out that the cloud cover dependence on aerosols is not solely due to meteorological co-variability. More importantly, water vapour is found to have a stronger impact on cloud cover than aerosols. This impact is more pronounced at high aerosol load than at low aerosol load. Hence, studies of AOD-CC relationships based on satellite data, might greatly overestimate or underestimate the aerosol impact on cloud cover in regions where aerosols and water vapor have similar or opposite seasonal variations, respectively. Further, this impact shows that the hydrological cycle interferes with the aerosol climatic impact and we need to improve our understanding of this interference.

Keywords: aerosols, cloud cover, aerosol-cloud interactions, water vapor.

1. Introduction

Aerosols are known to impact the formation, optical properties, and life cycle of clouds (Boucher *et al.*, 2013), either by increasing the cloud droplet number concentration and simultaneously decreasing the droplet size with a fixed water content, known as the first indirect effect (Twomey, 1974), or by suppressing precipitation formation, enhancing at the same time the cloud cover and cloud lifetime, known as the second indirect effect (Albrect, 1989). In addition, by scattering or absorbing solar and terrestrial radiation (direct effect), aerosols affect temperature on the Earth's surface also perturbing the vertical temperature structure (Haywood and Boucher, 2000). So, it is important to understand and quantify the microphysical impact of both natural and anthropogenic aerosols on clouds, in order to understand and predict climate change (Anderson *et al.*, 2003).

The areas studied here, are a mid-latitude one, the Beijing-Tianjin-Hebei area (BTH), a sub-tropical one, the Yangtze River Delta (YRD), and a tropical one the Pearl River Delta (PRD), in China, which exhibit high aerosol load and are characterized by a spectacular population growth the last 20 years. These regions, with aerosol loads some times higher than the global average, constitute extensive spatial sources of large quantities of aerosols as a result of human activities (industry, construction, traffic, etc.) and biomass burning, while occasionally transport of mineral dust from China’s deserts adds to the aerosol burden of these regions (Jin and Shepherd, 2008). Moreover, the three regions exhibit significant climatic differences, driven also by the Asian monsoon, and hence they are suitable for the investigation of aerosol-cloud relations under different meteorological conditions. The aim of this study is to study the influence of synoptic weather conditions and atmospheric water vapour amounts on AOD-CC relationships. Towards this aim, we use 10 consecutive years (2003 - 2013) of AOD, CC, and clear sky water vapor (WV) satellite data from MODIS AQUA in conjunction with sea level pressure (SLP) from NCEP/NCAR reanalysis data.

2. Data and methods

The BTH domain (35.5^o-40.5^{o}N, 113.5^{o}E-120.5^{o}E) is an area with rapid industrial and economic development, reflected also at the high AOD levels (more than 4 times the global average) over the region. The YRD domain (28.5^o-33.5^{o}N, 117.5^o-123.5^{o}E), is an area with significant black carbon (Bond *et al*., 2004) and sulfate (Lu *et al.*, 2010) emissions. Finally, the PRD domain (21.5^o-24.5^{o}N, 111.5^o-115.5^{o}E) is an area within the Inter-Tropical Convergence Zone (ITCZ) migration belt, with high anthropogenic aerosol emissions (Lei *et al.*, 2011). Over the 3 regions of interest and within the study period, only weak overall aerosol upward trends have been reported (Guo *et al.*, 2011). Aerosol and cloud parameters from the MODIS instrument aboard the AQUA satellite (collection 5.1, level-3, 1^{o}x1^o daily data) for the period 2003-2013 are used in this study. In particular, to investigate aerosol-cloud interactions, we use aerosol optical depth at 550 nm (AOD550 or just AOD), CC, and WV for clear conditions from both satellites. Additionally, to examine the aerosol-cloud interactions under different meteorological conditions, such as low and high pressure systems, we used daily Sea Level Pressure (SLP) data from the NCEP/NCAR Reanalysis for the same period. The original 2.5^{o}x2.5^o NCEP/NCAR SLP data were spatially interpolated in order to match the MODIS 1^o×1^o level-3 dataset. Considering that meteorological conditions may have an impact on satellite derived aerosol-cloud relationships, the AOD and CC observations were classified into three different SLP condition classes (less than 1008 hPa for low pressure systems, between 1008 and 1017 hPa, and finally greater than 1017 hPa for high pressure systems) and also according to atmospheric WV quantities.

3. Calculations performed

To gain an insight into the levels, trends, interannual variability and seasonal variation of AOD and CC over the study regions, we first examined the timeseries of AOD, CC, and WV from the MODIS AQUA satellite over grid points located in the areas under study, for the period 2003-2013 (Figs. not shown). The results from both satellites are similar, with the highest values of AOD, CC and WV occurring during the summer months, over all grid points. The BTH area, with an average AOD550 of 0.65±0.15 during the study period experiences somewhat heavier aerosol loading than the other 2 regions with average AODs of 0.64±0.18 (YRD) and 0.59±0.16 (PRD). Further, as we move from north to south, CC and WV increases. Additionally, in the variables we will use in this study, no large trends are apparent during the study period. To investigate the influence of synoptic meteorological conditions on the AOD-CC relationship, and to exclude artefacts on the AOD-CC relationship resulting from synoptically induced co-variance (Quaas *et al.*, 2010; Gryspeerdt *et al.*, 2014), the MODIS data were classified into 3 SLP classes (from NCAR/NCEP data, see above) and we examined the AOD-CC-WV relationship at the low and high SLP classes. The SLP<1008 hPa class is representative of the core of low pressure systems and hence of atmospheric circulation typical of these systems (e.g. ascending motions of air). The SLP>1017 hPa class is representative of the core of high pressure systems and hence of atmospheric circulation typical of these systems (e.g. descending motions of air). Furthermore, the low and high SLP systems are completely different in terms of horizontal transport patterns. The 1008 hPa<SLP<1017 hPa class is less clearly defined in terms of atmospheric conditions, since it might contain meteorological conditions typical of the periphery of low pressure systems or typical of the periphery of high pressure systems (e.g. troughs, ridges etc.), and hence it is omitted from the discussion.

4. Results

Fig. 1 shows the AOD - CC - WV relationship over the 3 studied regions for low SLP and high SLP. With increasing SLP the amount of WV in the atmosphere decreases. This is due to the fact that the majority of available AOD-CC retrieval pairs for the low SLP class occurs during summer, when also the majority of available AOD-CC retrieval pairs for WV>3cm occurs (Fig. not shown). Additionally, as low SLP synoptic systems are associated with updrafts, the occurrence of these systems in summer, when land and sea temperatures and hence also evaporation are higher, more WV can be transported up in the atmosphere. Other authors have also noted the correlation of AOD with WV. For example, Alam *et al*. (2010), report positive

AOD-WV correlation over Pakistan due to their common seasonal patterns while Balakrishnaiah *et al*. (2012) report positive AOD-WV correlation over India but negative over some Indian Ocean regions. It is evident that WV has a strong impact on CC, perhaps even stronger that the AOD impact on CC (Fig. 1). In fact, over the tropics the impact of AOD on CC for constant WV seems negligible (Fig. 1). In the other two regions, the subtropics and the mid-latitudes CC might increase by up to 0.1 at most as AOD increases from 0.2 to 1 under constant WV, while CC might increase by up to 0.4 for WV increases from 1 to 8 cm under constant AOD.

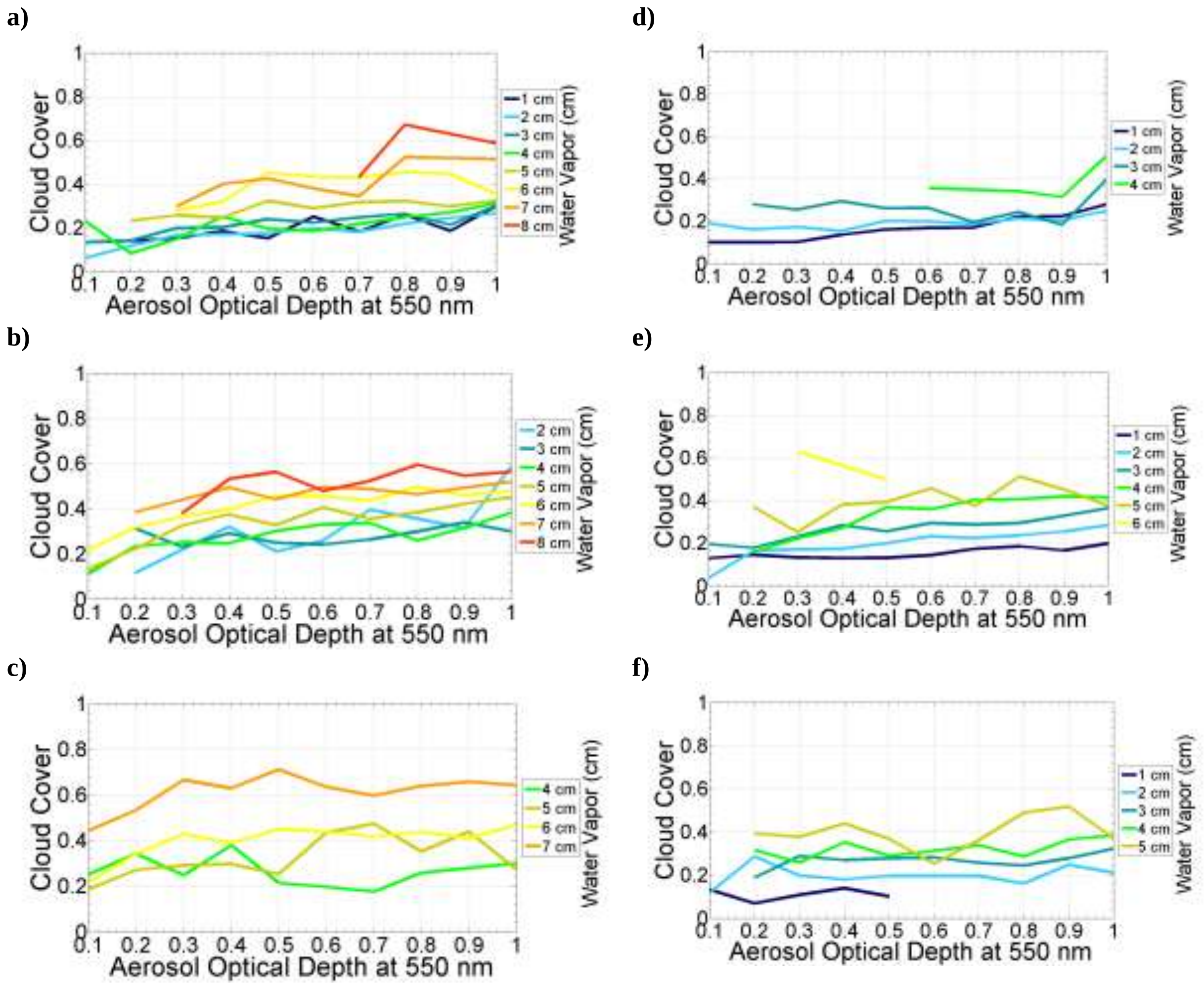

Figure 1: MODIS AQUA 2003-2013 AOD-WV-CC relationships. Top: mid-latitude area. Middle: subtropical area. Bottom: tropical area. Figures on the left present data for low pressure systems while figures on the right present data for high pressure systems.

Hence, studies of AOD-CC relationships based on satellite data that do not take into account WV, might greatly overestimate the AOD impact on CC in regions where AOD and WV have similar seasonal variations, while they might greatly underestimate the AOD impact on CC in regions where AOD and WV have opposite seasonal variations. This result is in agreement with recent results from other authors that noted the large possible impact of different meteorological variables on the AOD-CC relationships (e.g. Chand *et al.*, 2012; Grandey *et al.*, 2013). Most importantly, it is in agreement with recent reports that gave qualitative indications that water vapor (Ten Hoeve *et al.*, 2011) or relative humidity (Koren *et al.*, 2010; Grandey *et al.*, 2013) might have a strong influence on AOD-CC relationships. We also note, that despite the remarks made above, AOD does have an impact on CC even if synoptic and WV variability are accounted for (Fig. 1), although this impact in our study regions is much smaller than the one that would have been estimated ignoring synoptic and WV variability. In fact, in the three areas of study, where AOD and WV have similar seasonal variations, if the water vapor effect is taken into account the slopes of the CC/AOD relationship for AOD>0.2 might be reduced up to 80%. Further, it is apparent that the largest part of the differences in the AOD-CC slope between low and high SLP synoptic conditions is due to the differences in WV between these conditions.

5. Conclusions

We find that WV has a stronger impact on CC than aerosols and thus, studies of aerosol-cloud interactions based on satellite data that do not account for this parameter, may result in erroneous quantitative and qualitative results. Namely, studies of AOD-CC relationships based on satellite data, might greatly overestimate the AOD impact on CC in regions where AOD and WV have similar seasonal variations, while they might greatly underestimate the AOD impact on CC in regions where AOD and WV have opposite seasonal variations. In the three areas of study, where AOD and WV have similar seasonal variations, if the water vapor effect is taken into account the slopes of the CC/AOD relationship for AOD>0.2 might be reduced up to 90%. Further, this WV impact on AOD-CC relationships shows that the hydrological cycle interferes with the aerosol climatic impact and we need to improve our understanding of this interference and the feedbacks between the hydrological cycle, aerosols, clouds and climate.

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