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Satellite observed aerosol-induced variability in warm cloud properties under different meteorological conditions over eastern China

Fu Wang [a,b], Jianping Guo [b,*], Yerong Wu [c], Xiaoye Zhang [b], Minjun Deng [b], Xiaowen Li [d], Jiahua Zhang [e], Jing Zhao [d]

[a] School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] Institute of Atmosphere Composition, Chinese Academy of Meteorological Sciences, 46, Zhong-Guan-Cun South Avenue, Haidian District, Beijing 100081, China
[c] Geoscience and Remote Sensing Faculty of Civil Engineering and Geoscience, Delft University of Technology, 2628 CN Delft, The Netherlands
[d] School of Geography, Beijing Normal University, Beijing 100875, China
[e] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China

HIGHLIGHTS

- We examine warm cloud in response to aerosol from MODIS over land vs. ocean of China.
- Cloud droplet radius decreases as aerosol increases over land only in stable condition.
- Cloud droplet radius decreases as aerosol increases over ocean.
- Cloud fraction is positively associated with aerosol, regardless of Earth surface types.
- Cloud top pressure and relative humidity has little impact on aerosol indirect effect.

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ABSTRACT

By taking meteorological conditions into account, this paper studies aerosol indirect effect on summertime warm clouds over the Yangtze River Delta (YRD) and East China Sea (ECS). The observed aerosol and cloud data are from MODIS/Aqua Level 2 datasets, and meteorological variables are from NCEP Final Analyses Operational Global Analysis datasets. To minimize meteorological effect on statistical analyses of aerosol–warm cloud interaction, several meteorological variables such as cloud top pressure (CTP), relative humidity (RH), pressure vertical velocity (PVV) and lower tropospheric stability (LTS) are considered in this study.

Results show that cloud droplet radius (CDR) decreases with increasing aerosol optical depth (AOD) over ECS, while increases with increasing aerosol abundance over YRD. By taking CTP and RH into account, aerosol effects on cloud fraction (CF) are investigated. When aerosol loading is relatively small, CF is found to increase more sharply over YRD than over ECS in response to aerosol enhancement regardless of RH conditions. Therefore, we argue that the horizontal extension of cloud is prone to be driven by aerosol rather than meteorological conditions. Meanwhile, joint correlative analysis of AOD–CF and AOD–CTP reveals that CTP effect on AOD–CF is not significant, indicating CTP makes little contribution to observed AOD–CF relationship. Constrained by lower tropospheric stability (LTS) and pressure vertical velocity (750 hPa), CDR variation in response to AOD is analyzed. In general, CDR tends to decrease as aerosol increases over both ECS and YRD under stable conditions (higher LTS value). In contrast, CDR positively responds to aerosol over land under unstable conditions. Dynamically, CDR has stronger effects on than the ascending motion than on the sinking motion with the same aerosol loading over both land and ocean. The reason can be partially explained by the phenomena that updrafts favor the growth of cloud droplets. Overall, the observed cloud variations can be extremely difficult to be attributed to aerosol particles alone due to dynamical and thermodynamical processes in cloud systems.

* Corresponding author. Tel.: +86 10 58993189; fax: +86 10 62176414.
E-mail addresses: jpguocams@gmail.com, jpguo@cams.cma.gov.cn (J. Guo).

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1. Introduction

Aerosol has twofold effect on climate. The first effect is called direct radiative effect, where aerosol scatters or absorbs downward solar radiation. The second effect is more of microphysics related process, by which aerosol can alter the cloud microphysical processes and even change the precipitation mechanism by serving as Cloud Condensation Nuclei (CCN) (Rosenfeld, 2000; Twomey, 1974) or Ice Nucleus (IN) (Lohmann, 2002), as is collectively known as indirect effect.

Assuming constant liquid water path, an increases in atmospheric aerosol abundance usually lead to smaller Cloud Droplet effective Radius (CDR), higher CCN and cloud droplet concentrations, thus increases in cloud albedo (Twomey, 1977). The reduced CDR, therefore, can somehow prolong the cloud lifetime due to the longer existence period in the air (Albrecht, 1989), and thus maintaining larger liquid water path (Feingold et al., 2001; Peng et al., 2002).

Both case studies and statistical analyses have been widely performed to study aerosol cloud interaction. For example, assuming two cloud systems have the same macro-physical properties such as cloud texture, shape and cloud base temperature through visual interpretation, it is claimed that meteorological influence has been removed, thus the variation of cloud microphysical properties can be attributed to dust aerosol in polluted cloud (Rosenfeld et al., 2001). However, the inner cloud profiles are still not clear, so the atmospheric dynamic influence may be not similar for the two cloud systems.

Recently, resorting to a large amount of aerosol–cloud interaction data is the best bet for us to figure out the aerosol indirect effect in a statistical sense. Previous researchers have demonstrated that aerosol can alter dramatically cloud microphysical properties using multiple satellite measurements (Costantino and Bréon, 2010; Menon et al., 2008; Quaas et al., 2004). Satellite observations showed that CDR tends to become smaller under influences of marine aerosol (Meskhidze and Nenes, 2010), smoke (Kaufman et al., 2005a), dust (Klüser and Holzer-Popp, 2010) and industrial air pollution (Matheson et al., 2005). Also, field campaign over specified regions of interest suggests that CDR is negatively associated with aerosol abundance (Byung-Gon et al., 2003; Rosenfeld, 2000), which is consistent with the Twomey effect. However, the opposite (positive) relationship between aerosol optical depth (AOD) and CDR from space is also revealed in some other studies, especially over land (Bulgin et al., 2008; Grandey and Stier, 2010; Yuan et al., 2008). The anti-Twomey effect occasionally observed over land could be due to the incapability of satellite in distinguishing complex aerosol composition and chemical properties (McFiggans et al., 2006) and further complicated by the high variations of meteorological conditions (Matheson et al., 2005; Reutter et al., 2009).

The pervasive convolution between aerosols and meteorological conditions, key to the aerosol indirect effect, is required to be resolved to disentangle meteorological impact from aerosol effects on clouds (Teller and Levin, 2006). Efforts have been made to minimize large-scale meteorological effects to figure out the true aerosol effect on cloud properties (Koren et al., 2005; Loeb and Schuster, 2008; Su et al., 2010). In particular, various meteorological parameters dictating dynamical and thermodynamic conditions are often required to be singled out and made constant prior to the correlative analysis between aerosol and cloud microphysical properties (Koren et al., 2010). To make sure meteorological conditions are similar between polluted and clean cases, aerosol cloud interaction studies were restricted to specified temporal and spatial domain with fixed size (5 km), and proved to be able to resolve the convolution between aerosol and meteorology (Loeb and Schuster, 2008). Besides, vertical velocity (Su et al., 2010) and wind shear (Fan et al., 2009) are found to be important factors affecting aerosol–(convective) cloud interaction.

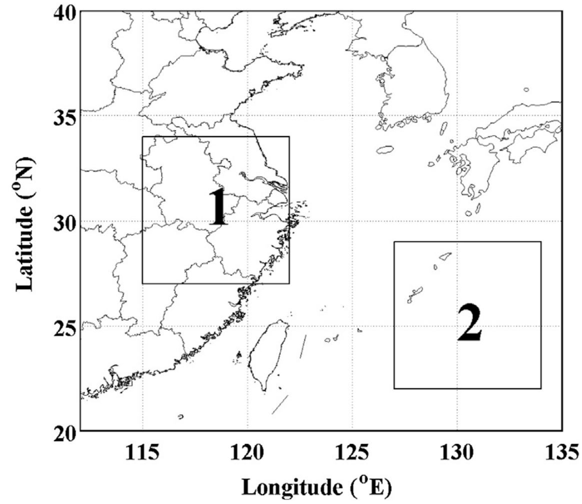

Fig. 1. Location map of the two domains for summertime aerosol–warm cloud interaction over the Yangtze River Delta (YRD), indicated by black hollow rectangle 1 (27°N–34°N and 115°E–122°E), and the Eastern China Sea (ECS), indicated by black hollow rectangle 2 (24°N–31°N and 127°E–134°E).

It is well known that aerosol–cloud interaction from observations are likely to be either "real" (increased hygroscopic aerosol particles lead to smaller CCN that affects cloud formation), or artifacts of the retrievals (contamination of adjacent cloud as aerosol lies in the vicinity of clouds) (Ignatov et al., 2005). In particular, partly cloud-covered area is occasionally mistaken for high aerosol burden, resulting in false aerosol cloud correlation (Zhang et al., 2005). Interestingly, clouds affected by aerosols are found to be able to enhance (Matheson et al., 2005) or reduce cloud fraction (Koren et al., 2004). In this case, the impact of aerosols on clouds is far from understood (Lohmann et al., 2010), which depends on factors such as location (Yuan et al., 2008), season and the spatio-temporal scale of the analysis (Khain, 2009).

Considering the complex aerosol composition and increasing aerosol trend in recent decade across China (Guo et al., 2011), systematic satellite assessment of aerosol indirect effects is desperately needed, in particular contrast over land versus ocean. In this paper, we attempt to figure out aerosol-induced variability in summertime warm cloud properties under different meteorological conditions in eastern China using seven consecutive years (2002–2008) of MODIS/Aqua derived aerosol and cloud data. The paper is organized as follows: Section 2 describes the dataset used in the analyses of aerosol–cloud interaction, and introduces the statistical analyzing methods to investigate aerosol indirect effect. Aerosol effect on cloud properties such as CDR and cloud fraction (CF) is described in Section 3, with various meteorological factors are taken into account to better understand the possible mechanisms. Major conclusions and potential future improvements to the current work are summarized in Section 4.

2. Data and methodology

2.1. Study area

Efforts to combine land with neighboring oceanic regions, characterized by different aerosol emission levels, have been