Response of Aerosol Direct Radiative Effect to the East Asian Summer Monsoon

Bingqi Yi, Ping Yang, Andrew Dessler, and Arlindo M. da Silva

Abstract—Asian summer monsoon and atmospheric aerosol simultaneously influence the climate in the East Asian region. However, substantial uncertainties exist in the current understanding of the interactions between monsoon and aerosol and their combined effects. Previous studies have shown that aerosols influence the strength of monsoon and monsoon-related water cycles; however, monsoon strongly regulates the aerosol spatial distribution. This letter investigates the radiative flux response at the top of the atmosphere to the Asian summer monsoon by using observations made by the Clouds and Earth’s Radiant Energy System and the Moderate Resolution Imaging Spectroradiometer. In comparison with the ten-year (2002–2011) mean climatology, the aerosol radiative effect is estimated over two eastern Asia regions for the months of July in 2002 and 2003, corresponding to a weak and a strong summer monsoon event, respectively. The dramatically different influences show the aerosol radiative forcing over land to be strongly responsive to Asian summer monsoon. Furthermore, the reanalysis-based estimate of the aerosol radiative effect is consistent with its observation-only counterpart.

Index Terms—Aerosol direct radiative forcing, Clouds and Earth’s Radiant Energy System (CERES) observations, East Asian summer monsoon, MERRaero reanalysis.

I. INTRODUCTION

In the densely populated East Asian region, monsoon and atmospheric aerosol are among the most important factors present with the ability to modulate the regional climate. Monsoon has long been an active research area because of its known role in regulating the wind, temperature, cloud, and precipitation in East Asia. With the rapid economic development in recent decades, East Asia has become a heavily polluted area due to increased human industrial activities. Previous findings [1], [2] have demonstrated the important radiative influence of aerosol due to both aerosol direct and indirect effects. Analyses of the relationship and interactions between monsoon and aerosol have been reported in the literature. For example, Lau and Kim [3] have shown that absorbing aerosols can change the atmospheric heating in different spatial regions and thus further influence the monsoon strength. Lau and Kim [4] have further shown the possible impact of absorbing aerosols on monsoon-related rainfall. From a modeling perspective, previous studies [5]–[7] have suggested that aerosols cause significant anomalies in the Asian summer monsoon. Monsoon-related wind and precipitation transport disperse the aerosol loading and change the aerosol distribution and corresponding aerosol radiative effect both spatially and temporally. However, little effort has been focused on the reverse modification of aerosol radiative effect by monsoon circulation. Given the fact that monsoon transports and redistributes aerosols, no quantification has been made as to how large the effect can be in terms of aerosol direct radiative forcing.

By using observations and simulations related to a weak summer monsoon year (WSMY, 2002) and a strong summer monsoon year (SSMY, 2003), Liu et al. [8] and Yan et al. [9] have shown that the aerosol distribution over East Asia is substantially influenced by the Indian summer monsoon. This letter is intended to quantify the response of aerosol direct radiative forcing to Asian summer monsoon. To the best of the authors’ knowledge, this is the first study based on satellite observations of aerosols and radiative fluxes about the changes in aerosol radiative effects due to monsoon influence in the most prominent East Asian monsoon region. The remainder of this letter is as follows. Section II describes the data and method. Section III presents the results and the relevant discussion, and Section IV summarizes the study.

II. DATA AND METHOD

In this letter, the areas of interest are two subregions in a northern region (NR; 35°–44° N, 115°–130° E) and a southern region (SR; 23°–32° N, 105°–120° E) of East Asia, defined by the coordinates specified in [8] and [9]. The satellite retrieval products derived from observations made by the Clouds and Earth’s Radiant Energy System (CERES) and the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the Terra satellite are employed to provide aerosol, cloud, and radiative flux information for the summer month of July in 2002–2011 [10]. Only the CERES level 2 Edition 3A Single Scanner Footprint (SSF) in cross-track flight mode (FM1) on Terra is used to provide short wave (SW) fluxes at the top of the atmosphere (TOA). The CERES–MODIS spread function weighted aerosol optical depth (AOD) at 0.55 μm, aerosol type, and cloud fraction in the corresponding CERES footprint [11] are used to identify the aerosol-laden regions, aerosol types, and clear-sky areas over land.

We define the aerosol direct radiative effect (ADRE) as the difference in the TOA net (downward minus upward) SW
radiative flux under clear-clean-sky (no aerosol and cloud) and aerosol-sky conditions, i.e.,
\[
\Delta F_{\text{TOA}}^{\text{AER}} = F_{\text{FAER}}^{\text{net TOA}} - F_{\text{FOLLOW}}^{\text{net TOA}} = F_{\text{CLEAN}}^{\text{TOA}} - F_{\text{FAER}}^{\text{TOA}}
\]

where \(\Delta F_{\text{TOA}}^{\text{AER}}\) is the ADRE, \(F_{\text{FAER}}^{\text{net TOA}}\) is the net SW flux at the TOA under aerosol-sky condition, \(F_{\text{FOLLOW}}^{\text{net TOA}}\) is the net SW flux at the TOA under clear-sky (without aerosol) condition, \(F_{\text{CLEAN}}^{\text{TOA}}\) is the upward SW flux at the TOA under clear-sky condition, and \(F_{\text{FAER}}^{\text{TOA}}\) is the upward SW flux at the TOA under aerosol-sky condition.

The selected clear-sky scenes criteria are that the MODIS cloud fraction is lower than 0.01 and the MODIS subpixel clear area percentage is larger than 99.9%. Following Zhang et al. [12] and Patadia et al. [13], we derive the clear-sky SW fluxes by using the linear regression relationship between the CERES SW TOA fluxes and the MODIS AOD over land for July 2002 and July 2003. The MODIS aerosol type products classify aerosols into four types: mixed, dust, sulfate, and smoke. Furthermore, only the CERES footprints that have 100% of one type of aerosol are selected. The instantaneous ADRE, which is the SW flux induced by aerosol, is converted to the 24-h averaged ADRE with the method developed by Remer and Kaufman [14]. The diurnally averaged ADRE for every latitude–longitude bin is derived accordingly.

The NASA Global Modeling and Assimilation Office has extended the Modern-Era Retrospective Analysis for Research and Application (MERRA) with five atmospheric aerosol species (sulfates, organic carbon, black carbon, mineral dust, and sea salt) based on the GOCART module [15]. This inclusion of aerosol reanalysis data is now known as MERRAer and includes AOD observations derived from the MODIS sensor on both Aqua and Terra satellites. MERRAer provides gridded aerosol data in fine resolution covering 2002 to the present time, which is especially suited for studies of aerosol–atmosphere interactions.

III. Results and Discussion

According to the previous study [8, Fig. 5], the AOD distribution over East Asia significantly changed from a WSMY (2002) to a SSMY (2003). A positive AOD anomaly is found in the NR in a SSMY (2003), and a negative AOD anomaly is found in the SR. Evidently, monsoon related wind transport plays a crucial role in the redistribution of aerosols. Moreover, a modeling perspective study [9] illustrates that the monsoon circulation is a key factor dominating the emission or deposition processes in the determination of aerosol redistribution. Fig. 1 shows the vertically integrated black carbon mass flux anomaly in July 2002 and July 2003 relative to the mean state during a ten-year (2002–2011) period using the MERRAer reanalysis data. The figure well compares the contrasting monsoon wind related black carbon aerosol mass flux within the NR and SR subregions in 2002 and 2003.

The redistribution of aerosols would have had an impact on both radiation budget and regional climate. Fig. 2 shows the scatterplot of instantaneous smoke aerosol SW direct radiative effect versus the AOD in July 2002 and July 2003 for the NR and SR subregions. We find that smoke aerosol is the only type of aerosol that has ample valid pixels to form a linear regression relationship between AOD and ADRE. As evident in Fig. 2, smoke ADREs observed in the WSMY (2002) and the SSMY (2003) are pronounced and distinct between the two subregions. Because the aerosol emission sources remain mostly unchanged [9], the differences shown between the two contrasting Julys can be mostly regarded as monsoon-induced consequences. Although all the cases show increasing SW ADRE with increasing AOD, the aerosol radiative effect efficiencies are dramatically different in both the two subregions and periods.

Table I shows the smoke aerosol radiative effect efficiencies for the NR and SR subregions in July 2002 and July 2003. The aerosol radiative effect efficiency for the SR (32.15 Wm\(^{-2}\)r\(^{-1}\)) is found to be almost twice that for the NR (17.53 Wm\(^{-2}\)r\(^{-1}\)) in July 2002. However, in the July 2003 case, the entire spatial pattern reverses, showing much greater ADRE efficiency for the NR than for the SR. We also notice that the minimum and maximum values of aerosol radiative effect efficiencies for the SR are always higher than their counterparts for the NR subregion. For the SR subregion (see lower panel in Fig. 2), the AOD values for July 2003 are generally lower than 0.5, while a broader
TABLE I
SMOKE AEROSOL SW RADIATIVE EFFECT EFFICIENCY (W m\(^{-2}\) \(\tau\)^{-1})
OVER THE TWO SUBREGIONS IN JULY 2002 AND JULY 2003

<table>
<thead>
<tr>
<th></th>
<th>NR</th>
<th>SR</th>
</tr>
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<tbody>
<tr>
<td>Weak summer monsoon year (2002)</td>
<td>17.53</td>
<td>32.15</td>
</tr>
<tr>
<td>Strong summer monsoon year (2003)</td>
<td>31.38</td>
<td>19.85</td>
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The range of AOD variations is observed for July 2002. The variation is mainly due to the northward wind transport of aerosols in the SSMY. The corresponding SW aerosol radiative effect is weaker in the SSMY in the SR subregion than in the WSMY. The center of high ADRE, with the value up to \(-35\) Wm\(^{-2}\), has been found to shift from the SR in July 2002 to the NR in July 2003. Similar to former studies, we find that the averaged AOD in the NR and SR subregions changes in accordance with the strength of the Asian summer monsoon (see Table II). The ADRE generally follows the AOD variation pattern, except that the NR–SR contrast of ADRE is not apparent in the SSMY (2003), which indicates that factors other than summer monsoon circulation could also be important in the process.

Table II shows the regional averaged AOD and aerosol SW direct radiative effect (W m\(^{-2}\)) for all aerosols over the NR and SR subregions in July 2002 and July 2003 as well as the ten-year (2002–2011) mean. The numbers in parentheses show the anomalies relative to the ten-year mean.

IV. SUMMARY

We utilized the observations made by the MODIS and CERES instruments aboard the Terra satellite to estimate the changes in TOA SW ADRE induced by monsoon circulation. Two contrasting months, one in a WSMY (July 2002) and the other in a SSMY (July 2003), were chosen for comparison.

Based on former observational and modeling studies, the Asian summer monsoon wind intensity is believed to be the most critical reason for the anomalous spatial AOD distribution in East Asia. Previous modeling results further show that the local
aerosol emission and deposition processes play minor roles compared with the aerosol transport effect. We used the MODIS aerosol type product over land and looked at the smoke type aerosol. The smoke aerosol radiative effect efficiencies in the WSMY (2002) and the SSMY (2003) in the two subregions are found to be quite different. Overall, we found the NR–SR aerosol radiative effect efficiency contrast to be reversed between the WSMY and the SSMY. The NR has higher AOD and stronger ADRE mainly due to the monsoon transport process of aerosol in the SSMY. In the WSMY, aerosol transport from the SR to the NR is much weaker, giving rise to lower ADRE in the NR. Analysis of the ten-year (2002–2011) satellite-observed AOD and ADRE further illustrates that the aerosols and related radiative effects in the SR subregion are influenced the most in the SSMYs. Similar results are found based on the estimation made with the MERRAero reanalysis data. In conclusion, the Asian summer monsoon not only is important for the transport and redistribution of aerosols but also greatly influences the aerosol radiative effect. To further accurately estimate the effect of Asian summer monsoon on aerosol radiative effect, more sophisticated methods and new observational and modeling capabilities need to be combined to study the problem.

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REFERENCES