Potential aerosol indirect effects on atmospheric circulation and radiative forcing through deep convection

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[1] Aerosol indirect effects, i.e., the interactions of aerosols with clouds by serving as cloud condensation nuclei or ice nuclei constitute the largest uncertainty in climate forcing and projection. Previous IPCC reported negative aerosol indirect forcing, which does not account for aerosol-convective cloud interactions because the complex processes involved are poorly understood and represented in climate models. Here we elucidated how aerosols change convective intensity, diabatic heating, and regional circulation under different environmental conditions. We found that aerosol indirect effect on deep convective cloud systems could lead to enhanced regional convergence and a strong top-of-atmosphere warming. Aerosol invigoration effect occurs mainly in warmed-based convection with weak shear. This could result in a strong radiative warming in the atmosphere (up to +5.6 W m^{-2}), a lofted latent heating, and a reduced diurnal temperature difference, all of which could potentially impact regional circulation and modify weather systems. The positive aerosol radiative forcing on deep clouds could offset the negative aerosol radiative forcing on low clouds to an unknown extent. **Citation:** Fan, J., D. Rosenfeld, Y. Ding, L. R. Leung, and Z. Li (2012), Potential aerosol indirect effects on atmospheric circulation and radiative forcing through deep convection, *Geophys. Res. Lett.*, *39*, L09806, doi:10.1029/2012GL051851.

1. Introduction

[2] Aerosol-cloud interactions are recognized as one of the key factors influencing cloud properties and precipitation regimes, but it constitutes the largest uncertainty in climate forcing and projection [*Intergovernmental Panel on Climate Change*, 2007]. Aerosol direct and indirect effects can potentially change the vertical distribution and magnitude of diabatic heating [*Ramanathan et al.*, 2005; *Lau and Kim*, 2006; *Rosenfeld et al.*, 2008], with important implications to atmospheric circulation and regional/global climate change. As for aerosol effect on circulation, past studies have focused mainly on aerosol direct effect [e.g., *Ramanathan and Carmichael*, 2008; *Lau and Kim*, 2006]. Current climate models can only represent aerosol indirect effect (AIE) for stratiform/cirrus clouds, but not convective clouds. This is because convective parameterizations used in climate models do not include cloud microphysics that can be directly connected with cloud condensation nuclei (CCN). Only very recently attempts have been made towards accounting for aerosol effects on convection in climate models by incorporating cloud microphysics representations in cumulus parameterization [*Song and Zhang*, 2011] or embedding a two-dimensional cloud-resolving model (CRM) in each grid column of global climate models (GCM) [*Wang et al.*, 2011] to simulate both cloud microphysics and convection explicitly. Aerosol indirect forcing estimated by all previous climate modeling studies is negative, even when aerosol-deep convective cloud (DCC) interactions were included in a simple manner [*Lohmann et al.*, 2010; *Quaas et al.*, 2009]. However, a conceptual model [*Rosenfeld et al.*, 2008] and an observational analysis [*Koren et al.*, 2010] suggest that aerosol-DCC interactions can lead to warming at top-of-atmosphere (TOA) because aerosols can invigorate convection, leading to an expanded anvil area. Aerosol invigoration effect (AIV) has not yet been reported in any climate modeling studies.

[3] The interactions between aerosol and deep convective clouds (DCCs) are exceptionally complicated because of the strong feedbacks between dynamics and microphysics. Past observational and cloud-resolving modeling studies indicated that precipitation of DCCs could be suppressed [e.g., *Rosenfeld*, 2000; *Khain and Pokrovsky*, 2004; *van den Heever et al.*, 2006; *Tao et al.*, 2007] or enhanced by aerosols [e.g., *Khain et al.*, 2005; *Wang*, 2005; *Lin et al.*, 2006; *Fan et al.*, 2007; *Zhang et al.*, 2007]. Weak wind shear and relatively humid conditions favor invigoration and enhance precipitation by aerosols for isolated DCCs based on model simulations [*Khain et al.*, 2008; *Fan et al.*, 2009]. Although weak wind shear was explicitly shown to be important for AIV in isolated storms [*Fan et al.*, 2009], does it work in the same way in deep convection cloud systems? Can AIV enhance latent heat release aloft enough to produce a positive feedback on diabatic heating that can significantly affect regional or even large-scale circulation? Observational studies showed that smoke aerosols caused intense thunderstorms over the Amazon and suggested a substantial effect on positive radiative forcing and on the regional and global circulation systems [*Andreae et al.*, 2004]. The observed enhanced precipitation rate, low-level convergence, lightning, hail and tornado activities over the Eastern U.S. at mid-week was presumably due to high aerosols [*Bell et al.*, 2008, 2009; *Rosenfeld and Bell*, 2011]. A recent study over the U.S. Southern Great Plain (SGP) revealed a long-term net aerosol invigoration effect for warm-based deep mixed-phase clouds especially in the summer seasons [*Li et al.*,

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2011a]. It was also shown to affect the circulation of tropical cyclones [*Rosenfeld et al.*, 2012]. The observed intensification of rain rate under the polluted conditions from the tropics to mid-latitudes globally [*Koren et al.*, 2012] suggests a possible impact of aerosols on Hadley/Walker circulation.

[4] However, real-case modeling investigation of aerosol indirect effect on circulation and radiative forcing through deep convection is lacking. Taking advantage of advances in computing power, we conducted high-resolution model simulations of deep convective cloud systems at a cloud-resolving scale (~2 km) but over regional domains covering the size of ~650 km (inner domain), to explore how aerosols could affect circulation and radiative forcing through interaction with deep convection systems and test the hypothesis of AIV suggested in many observational studies. Moreover, we employed a spectral-bin microphysics (SBM) [*Khain et al.*, 2004] where aerosol-cloud interactions and cloud microphysical processes are explicitly represented, since bulk microphysical scheme may not be able to simulate AIV [*Fan et al.*, 2012]. We showed significant invigoration of convection by CCN on a large spatial scale for the summer convection and the important role of wind shear in aerosol effects on convection.

[5] Using the NCAR Weather Research & Forecasting (WRF) model [*Skamarock et al.*, 2005] coupled with the SBM [*Fan et al.*, 2012], we conducted two-way nested simulations for two study regions with the finest resolutions of about 2 km (Figure S1 in Text S1 in the auxiliary material) for two convective systems with warm (T > 15°C) and cool cloud bases (T < 15°C), respectively.[1] Convective clouds in the tropics and mid-latitudes typically fall into these two categories. The warm-based DCCs occurred in southeastern China on July 17, 2008 when field measurement data are available from the Atmospheric Radiation Measurement (ARM) Mobile Facility field campaign in China (AMF-China) [*Li et al.*, 2011b]. Wind shears are weak and cloud bases are quite warm (22°C) in this case (referred to as "ChinaWWS"). The cool-based DCC case is from the U.S. SGP 2006 Intensive Operation Period (IOP) on April 2, 2006. It features a frontal system with strong wind shear and cool cloud base temperature of about 11°C (referred to as "SGPSWS"). Simulations were performed to examine aerosol indirect effect on mass fluxes and atmospheric circulation by perturbing aerosols in the inner domain from clean to polluted conditions, with CCN concentrations of 280 and 6 × 280 cm^{-3}, respectively (corresponding to the observed range of aerosol condensation number (CN) of 1,000–6,300 cm^{-3} at SGP). The direct radiative effects of aerosols were not considered in this study since we assumed the composition of sulphate, which is no-absorbing particle and aerosol direct effect is not important. To examine AIE under different controlled wind shear environments, we conducted model experiments by changing wind speeds in the outer domain only. For ChinaWWS, we increased U and V components of wind speed by 2.5 times over the vertical profile at the initial time step and the lateral boundaries to create a stronger wind shear case (referred to as "ChinaSWS"). For SGPSWS, we reduced U and V by a factor of 0.3 in the same way to create a weaker wind shear case (referred to as "SGPWWS"). See Figure S2 in Text S1 for the vertical wind shears of all four cases. AIE was examined in the same way as the original cases. Stretched vertical coordinate is used with a range of resolution of 40–1200 m (51 vertical layers in total). The two-way nesting approach in this study allows for the feedback of meteorological and microphysical properties from the smaller domain to the larger domain and those properties in the larger domain are also fed to the smaller domain, which is a more realistic approach compared with one-way nesting or a single domain run to appropriately examine aerosol impact on circulation and radiative forcing.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL051851.

2. Significance of Aerosol-DCC Interactions to Convergence/Circulation

[6] Figure 1 shows that CCN could drastically change horizontal and vertical mass fluxes in weak wind shear. For the warm-base summer convection, the vertical mass fluxes are increased by 10–20% at 1–14 km by the increase of CCN (black lines in Figure 1a). The averaged horizontal mass flux between 2–10 km is increased by 25% (solid line in Figure 1c). However, as the wind shear is increased by 2.5 times (i.e., ChinaSWS), the increase in the vertical mass flux is <5% and about 10% in averaged horizontal mass flux (red color in Figure 1a and dotted line in Figure 1c), both of which are much less significant relative to the original weak wind shear case. For the cool-based frontal system, under its original strong wind shear condition, we see a 50% decrease in horizontal mass flux by the increase of CCN (dotted line in Figure 1d) and correspondingly the vertical mass flux is also decreased. When wind shear is reduced by a factor of 0.3 (SGPWWS), the opposite trend is seen: the significant decrease trend in horizontal mass flux is reversed to be an increase trend (solid line in Figure 1d) and vertical mass flux also has an increase trend at 3.5–8 km (peak at 4–5 km; black lines in Figure 1b). To find out if the changes in vertical mass fluxes are mainly due to changes in updraft area or in convective intensity, Figure S3 in Text S1 clearly shows that both updraft area and convective intensity are remarkably enhanced by the increase of CCN in ChinaWWS, indicating more vigorous DCCs in the polluted environment. For SGPWWS, which is cool-based, the updraft area in the domain is slightly reduced (~4–5%) by CCN (Figure S4b in Text S1) but the vertical velocity (w) increases remarkably, with the average vertical velocity for grid points with $w > 2$ m s^{-1} increased from 3.5 to 5 m s^{-1} (Figure S4c in Text S1). This large increase in vertical velocity but a slight reduction in the updraft area is related to a change in cloud regime: some shallow clouds of larger area in the clean environment transform to smaller number of deeper clouds as CCN increase. Clearly, as wind shear increases, the changes of vertical mass fluxes by CCN become much smaller (compare Figure S3b with and Figure S3a in Text S1) and the sign could even be reversed (compare Figure S4d with Figure S4a in Text S1). Therefore, AIV on DCCs and the associated changes in convergence/circulation (shown as mass fluxes here) are the most significant for warm-based DCCs with weak wind shear. As wind shear increases, the enhancement in convective intensity and horizontal and vertical mass fluxes by CCN becomes much smaller or even reversed. The role of vertical wind shear in the aerosol effects on the DCC systems is similar to our previous study for isolated DCCs using a different CRM [*Fan et al.*, 2009]. While it is

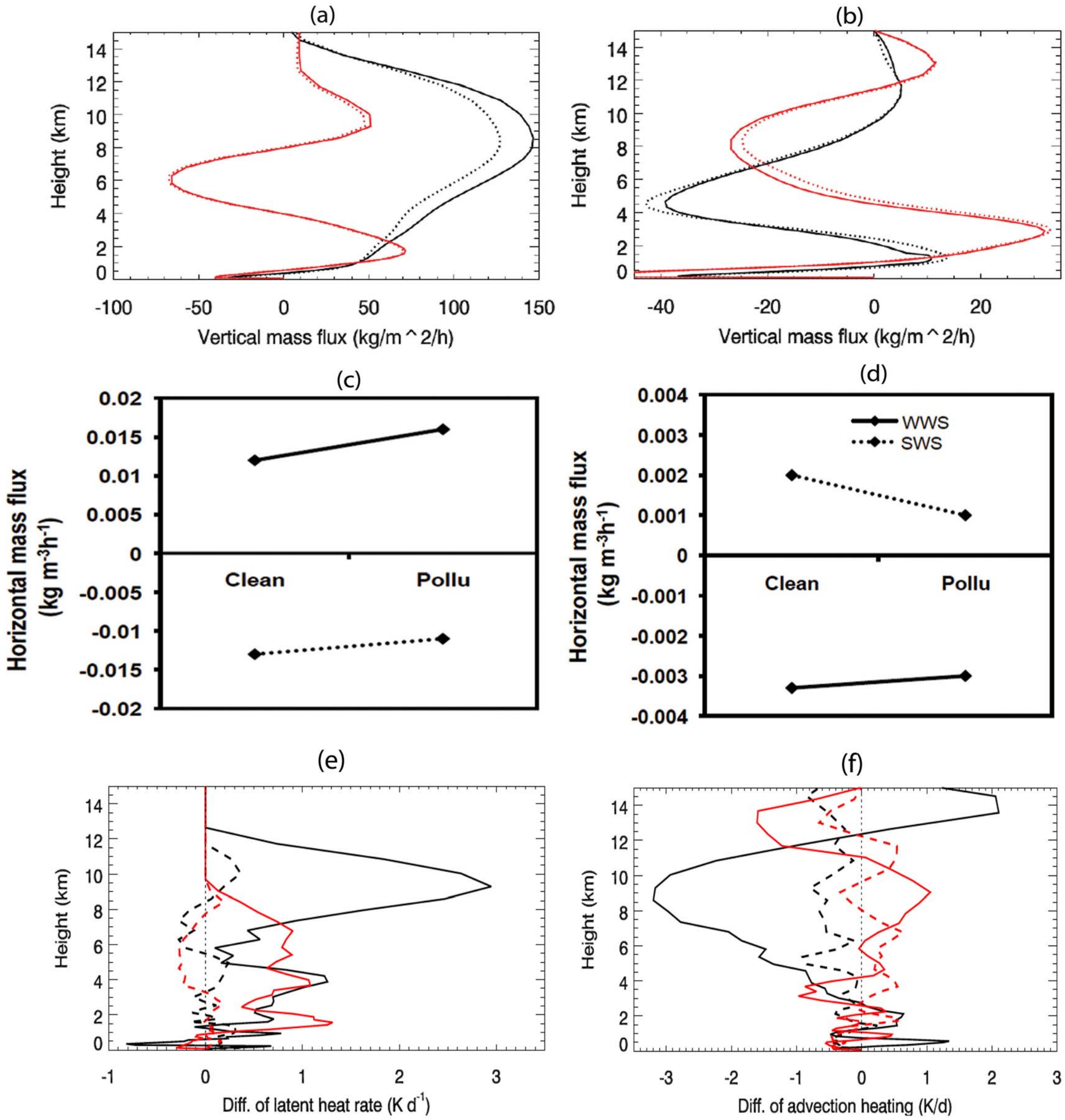

Figure 1. Profiles of vertical mass fluxes for the (a) China and (b) SGP cases and the averaged horizontal mass fluxes over 2–10 km under clean and polluted conditions for the (c) China and (d) SGP cases from the nested domain (Domain 2 in Figure S1 in Text S1). (e and f) Differences of vertical profiles of latent heating rate and advection heating rate between the polluted and clean conditions for ChinaWWS (solid black), ChinaSWS (dotted black), SGPWWS (solid red), SGPSWS (dotted red) over Domain 2 in Figure S1 in Text S1. Black color in Figures 1a and 1b denotes weak wind shear condition under the polluted (solid) and clean (dotted) conditions and red color is for stronger wind shear. Vertical mass flux is calculated by (air density × vertical velocity). Horizontal mass flux is calculated by (air density × convergence) and the negative values indicate divergence. The last 2 hours of simulation data are used in the figures for model simulations except the radiative forcing, because the impact on the regional circulation builds up gradually during the run time.

hard to quantify "weak" versus "strong" since the effects of wind shear may be affected by other atmospheric parameters such as relative humidity (RH) and stability, we clearly demonstrated that AIV depends strongly on wind shear condition and cloud base temperature. Sensitivity tests in which only wind shear within 0–5 km was increased based on ChinaWWS showed qualitatively similar results in aerosol effects on convection with ChinaSWS where wind shear is increased over the vertical profile, indicating the important role of lower-level wind shear in regulating aerosol impact on convection.

[7] The invigoration/suppression of DCCs by CCN under weak/strong wind shear conditions can be clearly explained by the profiles of latent heat release (Figure 1e). Latent heat release is generally increased by 0.5 to 1 K d^{-1} (about 10–20%) above 2 km from the clean to polluted conditions in both ChinaWWS and SGPWWS (Figure 1e). For the summer MCS (ChinaWWS), the largest increase of latent heat is at the upper levels where freezing of supper-cooled water occurs and ice deposition growth peaks, while the peak at the lower-levels is associated with droplet nucleation and the condensational growth. Much greater

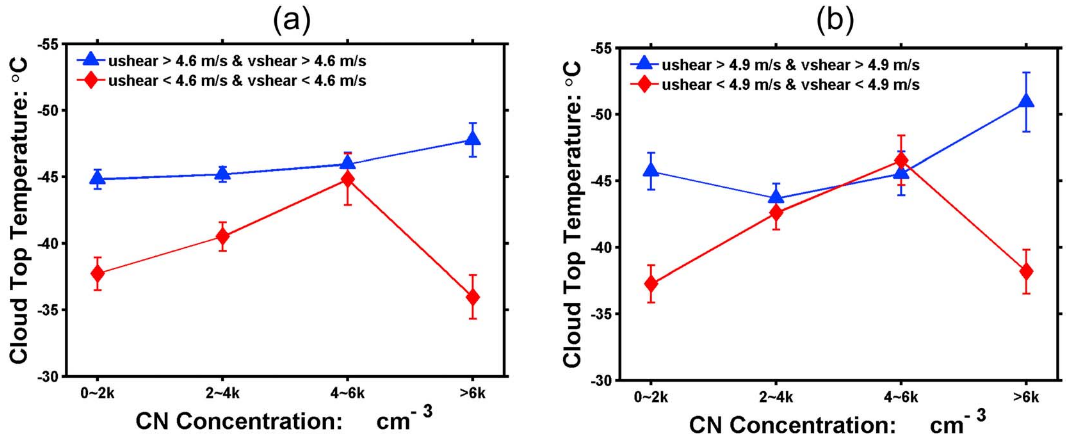

Figure 2. Cloud top temperature vs. CN concentrations for warmed-based mixed-phase clouds in (a) all seasons and (b) summer only. The red color denotes the group with weak wind shear and the blue color represents the group with stronger wind shear. The lower tercile of 4.6 m s^{-1} in Figure 2a and median values in Figure 2b of the U and V wind shear are used to distinguish the effects of wind shear on cloud top temperature. Data are from 1999–2009 over SGP.

heating rates in ChinaWWS than SGPWWS is found at the upper troposphere, associated with stronger convection for the moist and warm-based DCCs. It is expected that aerosol effects on the cold-based clouds are less significant because droplets have shorter distance between cloud base and freezing level for coalescence into raindrops. Therefore, aerosols have less potential to prevent rainout, leading to respectively less added latent heat from freezing and deposition growth. As wind shear increases, the change of net latent heat is only within ± 0.3 K d^{-1} in ChinaSWS and is reduced in SGPSWS. Based on the analysis reported in our previous study [*Fan et al.*, 2009], the net change in latent heat release is controlled by the balance between the changes in latent heating and latent cooling as CCN increase. Weak wind shear conditions favor a larger increase in latent heating than latent cooling, leading to a net increase in latent heating and an invigoration effect. As wind shear gets stronger, the tilted or even layered updrafts and downdraft can make cloud microphysical response to changes in CCN very different from the weak shear case. In addition, the increase in evaporative cooling becomes larger and compensates or overpowers the increase in latent heating in strong wind shear [*Fan et al.*, 2009], which would result in smaller invigoration or even suppression of convection.

[8] The magnitude of the change in latent heat induced by CCN of up to 3 K d^{-1} (Figure 1e) is remarkable, compared to the observed latent heating of $\sim$4 K d^{-1} for tropical convective clouds [*Schumacher et al.*, 2004]. This aerosol indirect effect on diabatic heating through latent heat release associated with deep convection is also much more significant compared to the estimated heating (about 0.5 K d^{-1}) induced by aerosol radiative effects for stratocumulus clouds during INDOEX [*Ramanathan et al.*, 2001]. Furthermore, since the heating is lofted in the atmosphere, it may alter the atmospheric circulation more significantly compared to heating at the boundary layer induced by black carbon [*Ramanathan and Carmichael*, 2008; *Tripathi et al.*, 2007]. From the comparable magnitudes of advection heating and latent heating for the case where AIV is significant (Figure 1f), we can easily infer that the change of latent heating by aerosol invigoration effect is the main factor contributing to the change of advection (i.e., circulation).

[9] Despite the significant changes in convection, mass fluxes, and radiative forcing, the precipitation response to CCN is not as significant, as consistently shown by many past studies. CCN increases the accumulated precipitation by about 7% in ChinaWWS and 3% when wind shear is stronger (ChinaSWS). For the frontal system over SGP, the accumulated precipitation is reduced by CCN in SGPWWS but increased in SGPSWS by about 4% each. Note that the CCN effect on precipitation is opposite to that on convective intensity in the frontal system, which could be related to the stronger advection in the polluted air under weak wind shear that causes more water vapor/hydrometeors to flow out of the domain compared to the reduced advection under strong wind shear. In addition, the increased rain frequency for the heavy rain and the decreased rain frequency for the light rain in the polluted environment studied in the past studies [*Qian et al.*, 2009; *Li et al.*, 2011a] are also seen here when aerosols significantly invigorate convection.

[10] Cloud top height (CTH) or cloud top temperature (CTT), although not always a good indicator of AIV, is a quantity with extensive measurements that can be analyzed and compared with model simulations. From the simulations, CTH of the convective core area generally increases from clean to polluted conditions for weak wind shear, while the increase is either reduced or reversed as wind shear increases (Figures S5a and S5b in Text S1). These changes correspond to the changes in convective intensity by CCN as shown in Figures S5c and S5d in Text S1. Therefore, CTH or CTT can be used as a proxy for convective intensity in observational analysis since vertical velocity measurements are seldom available [*Li et al.*, 2011a].

3. Observational Support

[11] Many observational studies have indicated AIV and suggested substantial impact on regional circulation systems [*Andreae et al.*, 2004; *Bell et al.*, 2008; *Koren et al.*, 2012], consistent with our simulated results. Also consistent with our results, the long-term ground-based observational

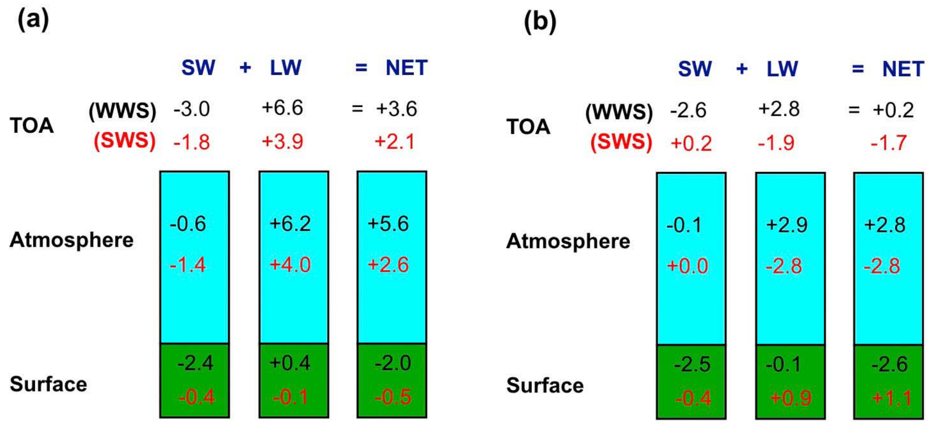

Figure 3. SW, LW, and net radiative forcing of aerosol indirect effect at the TOA, atmosphere, and SFC for the (a) China and SGP (b) cases. Values in red are for the stronger wind shear condition. Values are averaged over the last 24-hr simulation over Domain 2.

analysis at SGP showed that AIV was most significant in the summer when wind shears are weaker and cloud bases are warmer compared to other seasons [*Li et al.*, 2011a]. Following *Li et al.* [2011a], we further analyzed the data by binning the values of the U wind shear and V wind shear (see auxiliary material) for warm-based deep mixed-phase clouds in all seasons of 10 years into two groups (Figure 2). A significant decrease of CTT is observed for the group with relatively weak wind shear (i.e., U and V shears less than the lower tercile of 4.6 m s^{-1}) when CN is below 6000 cm^{-3} (Figure 2a). However, the decrease in CTT is negligible for the group with larger wind shear values. Under very polluted conditions with CN > 6000 cm^{-3}, CTT increases significantly for the weaker wind shear group but not the stronger wind shear group. Besides exceeding the optimum CCN indicated by *Rosenfeld et al.* [2008] and *Fan et al.* [2009], the smaller sample size also makes it less reliable. Similar to *Li et al.* [2011a], we also examined other observed dynamic and thermodynamic parameters such as the lower tropospheric static stability (LTSS), surface temperature, column water vapor, sensible and latent heat, among others, and we did not find any other factors that can consistently explain the different aerosol effect on CTT for the two groups of cases (Figures S6 and S7 in Text S1). By further separating the summer warm-based mixed-phase clouds into two groups based on the median values of U and V shears (Figure 2b), we see even a larger increase of CTT vs. CCN for the weaker wind shear group for CN < 6000 cm^{-3}. These observational results qualitatively support one of our findings that weak wind shear favors aerosol invigoration effects on DCCs, especially for warm-based clouds, while stronger wind shear condition impairs it.

4. Radiative Forcing

[12] The radiative forcing due to aerosol indirect effects is fairly significant when AIV is significant (Figure 3). The TOA shortwave (SW) forcing for the weak wind shear cases is negative while the longwave (LW) forcing is strongly positive as convection is invigorated. As a result, the net TOA radiative forcing is about +3.6 W m^{-2} (Figure 3a) for ChinaWWS, a strong warming effect on the atmosphere (+5.6 W m^{-2}), although this warming effect could be modulated when cloud cover is reduced by cloud regime change (from larger area coverage of shallow clouds to smaller area coverage of deeper clouds) in SGPWWS. Besides warming in the atmosphere, a strong cooling at the surface (SFC), i.e., -2 to -3 W m^{-2} is simulated when AIV occurs due to the increase of liquid water path (LWP) and cloud albedo (increased cloud cover also contributes to surface cooling in ChinaWWS). On the contrary, the warming effect on both TOA and atmosphere is reduced when AIV is impaired in ChinaSWS and even becomes a cooling effect when convection is suppressed in SGPSWS (Figure 3b). Note that the radiative calculation includes clouds and water vapor, so the warming effect could be partially attributed to the transported water vapor from the lower atmosphere by deep convection. By examining the diurnal cycle, we found that the increased LW at night contributes significantly to the warming (Figure S8 in Text S1) due to increased cloudiness from the expanded anvils due to AIV (Figure S9 in Text S1). Therefore, AIV results in stronger cooling at SFC during daytime but stronger warming at night. This reduced diurnal temperature range and lofted diabatic heating can significantly alter local to regional atmospheric circulation from sea breezes to monsoons that depend on the diurnal temperature and atmospheric heating differences between land and ocean. The TOA warming associated with AIV reported here is consistent with the satellite observational study of *Koren et al.* [2010]. We want to emphasize that the radiative forcing of aerosol indirect effects reported here is only averaged over a short time (24-hr). We expect that the magnitudes of warming or cooling would be smaller over long-time period such as a month and a season, depending on how often DCCs occur.

5. Conclusions and Discussion

[13] Using high-resolution model simulations with an explicit bin cloud microphysics over regional domains, we elucidated how aerosols can change convective intensity and convergence/circulation under different environmental conditions. Combining with our previous study of isolated DCCs [*Fan et al.*, 2009], we concluded that vertical wind shear plays a key role in determining the significance of aerosol invigoration effect: increased aerosols can invigorate

convection and enhance diabatic heating under weak wind shear conditions, smaller invigoration or even suppression of convection is seen because of enhanced evaporative cooling and different responses of tilted or even layered updrafts and downdrafts to changes of CCN. These results are supported by the observation analysis presented in this study and a very recent observational study [*Li et al.*, 2011a].

[14] We also showed that aerosols can enhance local convergence and circulation by altering latent heat release and radiative forcing through aerosol-DCC interactions when aerosol invigoration of convection is significant. We demonstrated that aerosol invigoration effects can result in a strong radiative warming on the atmosphere, a lofted latent heating, and a reduced diurnal temperature difference, all of which could impact regional circulation such as sea breezes and even large-scale circulation such as monsoons and Hadley/Walker circulation. For example, the reduced diurnal temperature difference could contribute to the observed weakening of East Asia monsoon [e.g., *Yu et al.*, 2004], which was suggested as a main reason for the "South Flooding and North Drought" decadal trend in China. Past studies showed lofted heating by a dust layer through absorption of solar radiation could increase the occurrence of deep convection, strengthen monsoon circulation and increase local precipitation [*Stephens et al.*, 2004; *Miller et al.*, 2004]. Latent heating has also been shown to result in a deep meridional circulation and enhanced local monsoon precipitation over West Africa [*Hagos and Zhang*, 2010]. In a similar way, the strong lofted latent heating induced by aerosol invigoration effects for the relatively polluted regions where summer convection often occurs such as Southeast of US and Southeast of China could produce similar impacts. This was observed to lead to a monsoon-like modulation of the land-ocean circulation over the southeast U.S [*Bell et al.*, 2008].

[15] Therefore, we improved the fundamental understanding of how aerosols invigorate convection and under what conditions significant aerosol invigoration effect should be expected, which would help better parameterize aerosol-DCC interactions in regional and global climate models. For the first time, we estimated the radiative and thermodynamic forcing of aerosol-DCC interactions and showed the significance of aerosol indirect effect in modifying convergence/circulation and radiative forcing, emphasizing the potential impact on climate and providing modeling support for past conceptual and observational studies [*Andreae et al.*, 2004; *Bell et al.*, 2008; *Rosenfeld and Bell*, 2011; *Koren et al.*, 2010, 2012]. To fully understand the impact on circulations and the feedback, we need a much larger domain or even a global domain and a much longer time scale, which cannot be realized presently with CRM simulations using bin microphysics. Therefore, it is an imperative task to properly parameterize aerosol-deep convection interactions in regional and global climate models, to more accurately predict severe weather and reduce the large uncertainties associated with aerosol effects on climate forcing and climate projection. Given the significance of aerosol invigoration effect on warmed-based DCCs, it could be used as an important metric to diagnose and evaluate performances of climate model.

[16] Although our findings are limited to short-term case studies because of the large computational requirement associated with the bin microphysics, the cases we selected are, nevertheless, representative of sub-tropical convection. It is our intention to carry out longer-term simulations at the CRM scales, but such simulations would require significant computing resources so they will be reported as our follow-on work.

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