Relative influence of meteorological conditions and aerosols on the lifetime of mesoscale convective systems

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Using collocated measurements from geostationary and polar-orbital satellites over tropical continents, we provide a large-scale statistical assessment of the relative influence of aerosols and meteorological conditions on the lifetime of mesoscale convective systems (MCSs). Our results show that MCSs' lifetime increases by 3–24 h when vertical wind shear (VWS) and convective available potential energy (CAPE) are moderate to high and ambient aerosol optical depth (AOD) increases by 1 SD (1σ). However, this influence is not as strong as that of CAPE, relative humidity, and VWS, which increase MCSs' lifetime by 3–30 h, 3–27 h, and 3–30 h per 1σ of these variables and explain up to 36%, 45%, and 34%, respectively, of the variance of the MCSs' lifetime. AOD explains up to 24% of the total variance of MCSs' lifetime during the decay phase. This result is physically consistent with that of the variation of the MCSs' ice water content (IWC) with aerosols, which accounts for 35% and 27% of the total variance of the IWC in convective cores and anvil, respectively, during the decay phase. The effect of aerosols on MCSs' lifetime varies between different continents. AOD appears to explain up to 20–22% of the total variance of MCSs' lifetime over equatorial South America compared with 8% over equatorial Africa. Aerosols over the Indian Ocean can explain 20% of total variance of MCSs' lifetime over South Asia because such MCSs form and develop over the ocean. These regional differences of aerosol impacts may be linked to different meteorological conditions.

mesoscale convective systems | aerosols | meteorological parameters

The hypothesis that aerosols may delay precipitation and increase cloud lifetime of shallow marine clouds (1) has motivated many researchers to study the aerosol indirect effect on convective clouds; however, the influence of aerosols on enhancing cloud lifetime has remained under debate. Mesoscale convective systems (MCSs) are deep convective clouds that cover several hundred kilometers. Previous studies have shown that aerosols affect deep convection, in particular that aerosols increase the number of smaller size cloud condensation nuclei (CCN) (2), which weaken coagulation and coalescence that form rain droplets, and consequently delay warm rainfall (3, 4). These processes allow more cloud droplets to rise above the freezing level and increase latent heat released due to glaciation (5), resulting in stronger updraft speed, enhanced cloud ice content (6), larger anvil size (5), and higher cloud top height (7). The top of the troposphere warms owing to the aerosol-induced changes in convective anvils (8). Although these aerosol effects have been seen in observations from field campaigns (9, 10), they have been undetectable on large spatial and multiyear scales. Rosenfeld et al. (11) have attributed this lack of detectability on the large scale of aerosol invigoration of convection to its variation with meteorological conditions and to the lack of knowledge of the relative humidity (RH) outside the clouds.

The variation of aerosol effects on convection with meteorological parameters has been studied previously (11). For example, model simulation has shown that an increase in aerosol concentrations up to an optimal level can invigorate the MCSs under weak vertical wind shear (VWS) and higher RH but suppress the MCSs

under strong VWS in a dry environment (12, 13). They found that, due to a significant enhancement in the convective available potential energy (CAPE), corresponding to an increase in RH from 50% to 70%, aerosol impact on ice crystal mass becomes pronounced, with a dramatic increase in the size of the anvils and the mass of ice crystals of the deep convection. However, such impacts are negligible when RH increases from 40% to 50%, due to little increase in CAPE (13). Moreover, consumption of CAPE for a given amount of rainfall is converted to an equal amount of kinetic energy that invigorates the convection (5, 14). These studies indicate that VWS, RH, and CAPE are important factors that can influence aerosol impacts on the MCSs. However, no quantitative assessment of the relative influence of aerosols versus these meteorological parameters on convective lifetime using satellite measurements has been established (11).

The influence of aerosols on the MCSs is expected to vary in different phases of the convective life cycle. For example, Rosenfeld et al. (5) hypothesized that the impact of aerosol on deep convection is stronger and more prominent during the dissipating phase. Using cloud-resolving simulations, Fan et al. (15) found out that aerosol microphysical effects intensify the deep convection during the mature and decaying phases by forming a larger number of smaller and long-lasting particles, whereas additional latent heat released due to aerosols' thermodynamic effect is responsible for invigorating the deep convections during the growing phase. Hence, the detection of aerosol impacts might not be visible until the mature phase, as no satellite can directly measure the thermodynamic properties.

Significance

Mesoscale convective systems (MCSs) are the primary source of precipitation over the tropics and midlatitudes, and their lifetime can have a large influence on the variability of rainfall, especially extreme rainfall that causes flooding. The hypothesis that aerosols can increase the lifetime of the MCSs by weakening or delaying precipitation has long been proposed, but we have not known whether that increase is significant on global and regional scales, and, if so, how it compares with the influence of meteorological conditions. We use multiyear collocated geostationary and polar-orbital satellite datasets to provide, to our knowledge, the first observational assessment of such an aerosol effect and its relative importance compared with other meteorological conditions in determining the variability of MCSs' lifetime.

Most of the studies discussed above were based on either model simulations or limited case studies from field campaigns. Observational assessments of how the influence of aerosols depends on meteorological conditions and the convective life cycle, and whether aerosols could have a significant influence on the lifetime of the MCSs at climate and large spatial scales, have not been available (11). Stevens and Feingold (16) suggested that climate models with parameterized cloud and turbulence schemes tend to overestimate the effect of aerosols on clouds compared with the models that resolve cloud processes and large eddies. The extrapolation of the results obtained from a limited number of field campaigns to global and climate scales is questionable. Hence, whether aerosols could increase the lifetime of the MCSs on large spatial and climate scales, and, if so, how such an effect would vary with meteorological conditions and the convective life cycle, has not been clear. Detection, measurement, and retrieval of the aerosols' properties from the satellite data in the vicinity of deep convective clouds at various stages of a cloud's lifecycle are challenging (17).

Isolating the impact of aerosols from other meteorological conditions observationally requires large samples of the MCSs under similar meteorological conditions and at different phases of their life cycle (11). For this purpose, we use a suite of collocated geostationary and polar-orbital satellite measurements, along with reanalysis products, constrained by both physical principles in the atmospheric model and observations, to determine the phases of MCSs' lifecycle, MCSs' lifetime, and ice water content of the MCSs and associated ambient meteorological and aerosol conditions (see Methods). We examine 2,430 cases of the MCSs with collocated International Satellite Cloud Climatology Project (ISCCP) convective clouds and Moderate Resolution Imaging Spectroradiometer aerosol optical depth (MODIS AOD) measurements to estimate changes of MCSs' lifetime with aerosol as a function of changing meteorological conditions. We estimate changes in MCSs' lifetime with various meteorological parameters as a function of aerosol and other meteorological parameters. We can also estimate the relative influences of aerosols and various meteorological parameters on MCSs' lifetime using multiple linear regression at different stages of the convective lifecycle and over different regions.

Results and Discussion

The lifetime of the MCSs is influenced by CAPE (18–20), a useful measure for cloud buoyancy and vertical velocity (21, 22), moisture entrained from the warm atmospheric boundary layer

(19, 20, 22), and lateral entrainment of free tropospheric moisture, which can dilute the buoyancy of the rising air and account for up to 33–50% of the rainfall (23). VWS contributes to organizing the storms, determining whether updraft and downdraft regions overlap, slantwise accent of the moist air, and precipitation (19, 24–27). We evaluate the influence of both the low-level VWS (26, 28) and the deep tropospheric VWS (see Methods). The former influences rainfall and total condensation (26), whereas the latter influences vertical velocity (26) and also MCS anvil formation (8, 26, 28–30).

Past studies have shown that the response of deep convective clouds to aerosols is nonlinear. Over land, aerosol microphysical effects on deep convective clouds saturate and reverse at AOD > 0.3 (31). Moderate concentrations of aerosols (or CCNs) maximize the invigoration effect of aerosols, whereas higher aerosol concentrations can reduce the vigor of the convection (5). However, over humid land and oceans, more aerosol is required to suppress rainfall. Thus, a threshold of AOD ≈ 0.3 is likely to be optimal as a threshold of pollution to determine the influence of aerosols on the MCSs (32, 33). We use AOD > 0.15 over land and AOD > 0.3 over the ocean as the threshold for a polluted environment.

To isolate the effect of aerosols on MCSs' lifetime and compare it to the effect of these primary meteorological conditions, we evaluate how the lifetime of the MCSs changes with 1 SD (1σ) of CAPE, RH at 850 hPa (~1.5 km above the sea level, RH_{850}), RH at 500 hPa (~5.5 km above the sea level, RH_{500}), deep tropospheric VWS, and the fraction of the number of aerosol pixels with AOD (f_{AOD}) greater than 0.15 (0.3) over land (the ocean) to the total number of AOD pixels within a range of 2° latitude/longitude from the boundary of the MCSs over all three regions (Methods and Supporting Information). Our analysis shows that using AOD > 0.3 as a threshold for polluted environment over both land and ocean does not significantly change the influence of aerosols on MCSs' lifetime (Fig. S1). Also, the MCSs' lifetime is not significantly correlated with the lower tropospheric VWS (Fig. S2). Moreover, response of MCSs' lifetime to a 1σ increase in CAPE is weaker when we consider lower tropospheric VWS (Fig. S2 C and D), compared with that under the influence of deep VWS (Fig. 1A). Thus, we show our results in the main body of this work using AOD > 0.15 as the threshold for a polluted environment over land, and AOD > 0.3 as the threshold for a polluted environment over ocean, and also show results for deep tropospheric VWS.
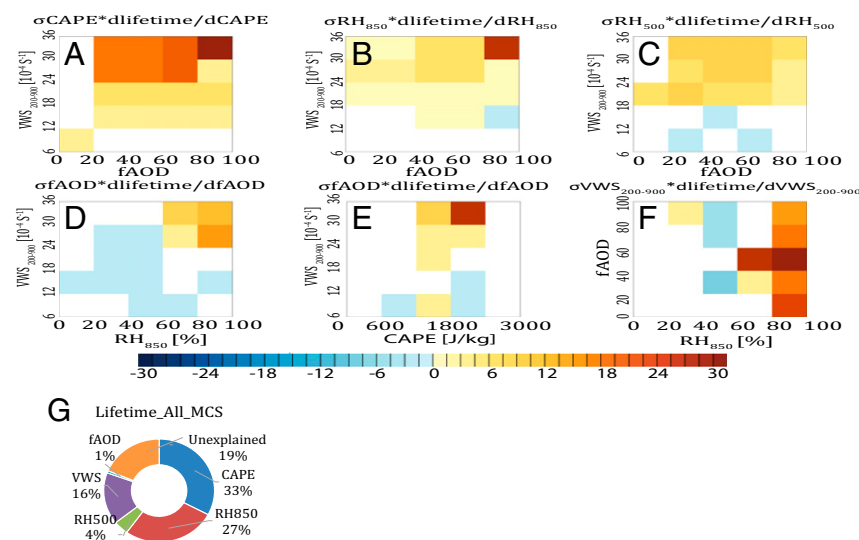

Fig. 1. The rate of change of MCSs' lifetime (hours, color shades) with (A) CAPE, (B) RH_{850}, and (C) RH_{500} as a function of f_{AOD} using AOD > 0.15 over land and AOD > 0.3 over the ocean as the threshold for a polluted environment and the deep tropospheric VWS, (D) f_{AOD} as a function of RH_{850} and the deep tropospheric VWS, (E) f_{AOD} as a function of CAPE and the deep tropospheric VWS, and (F) VWS as a function of the RH_{850} and f_{AOD}. The rates represent a change of MCSs' lifetime in hours associated with the variation of 1σ of that parameter. The bins with the number of samples less than 20 and insignificant rate of change at 95% confidence level are not shown. Note that $f_{AOD} = NP_{AOD > 0.15}/(NP_{AOD > 0.15} + NP_{AOD < 0.15})$ over land and $f_{AOD} = NP_{AOD > 0.30}/(NP_{AOD > 0.30} + NP_{AOD < 0.30})$ over ocean. NP is the number of pixels. The pie chart in G shows the fraction of variance of MCSs' lifetime explained by the environmental variables using multiple linear regression for all of the MCSs.
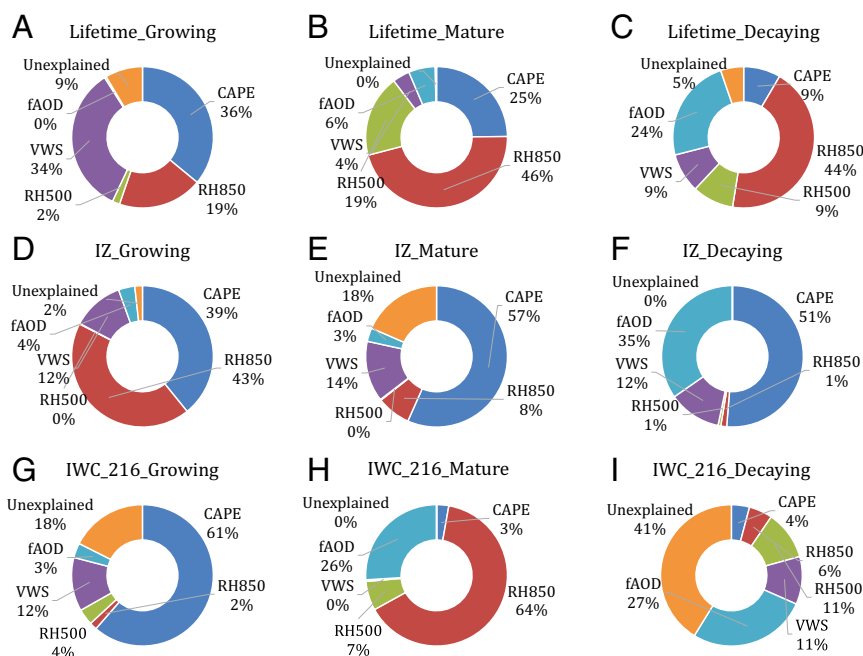
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Fig. 2. Fraction of the total variance of the MCS's lifetime (*A–C*), IZ (*D–F*), and IWC_216 (*G–I*) explained by the environmental variables based on the multiple linear regression during the growing (*A, D,* and *G*), mature (*B, E,* and *H*), and decaying (*C, F,* and *I*) phases of the MCSs.

These above-mentioned conditions are determined by the ISCCP convective tracking, MODIS, and the Modern-Era Retrospective analysis for Research and Applications (MERRA) datasets. Our calculations on the global tropical continental scale indicate that MCSs' lifetime increases at the highest rates with an increase of CAPE under intermediate to high VWS values and polluted conditions. MCSs' lifetime increases about 3–30 h for an increase of CAPE by 1σ (Fig. 1*B*). The multiple linear regression (Fig. 1*F*) also shows that CAPE explains 33% of the total variance of MCSs' lifetime, larger than any other meteorological and aerosol conditions. RH_{850} is the second most influential parameter on MCSs' lifetime, explaining 27% of its total variance (Fig. 1*B*). MCSs' lifetime increases by 3–27 h per 1σ increase of RH_{850} under intermediate to high VWS values and polluted conditions. The lifetime of the MCSs also increases with RH_{500} by 3–9 h for 1σ increase of RH_{500} under polluted conditions (Fig. 1*C*), explaining only 4% of the total variance of MCSs' lifetime. MCSs' lifetime decreases by 6–9 h for a 1σ increase of VWS in dry environments with low f_{AOD} values but increases by 3–30 h for a 1σ increase of VWS in the high RH_{850} environment. Overall, VWS explains 16% of the total variance of the lifetime of MCSs. It is the third most influential meteorological condition on MCCs' lifetime. In addition, increases in MCSs' lifetime with other meteorological and aerosol conditions (CAPE, RH_{850}, RH_{500}, and f_{AOD}) are stronger at moderate to high levels of VWS (Fig. 1 *A–E*), possibly because precipitation efficiency decreases below 50% when VWS is above 20×10^{-4} s^{-1} (27), whereas weak to moderate VWS is associated with heavy convective rainfall (22, 34).

The lifetime of MCSs appears to increase with aerosols by 3–15 h with 1σ increase of f_{AOD}, but only under high RH_{850} and moderate to high VWS (Fig. 1*D*). MCSs' lifetime decreases with f_{AOD} under lower RH_{850} by 3–6 h per 1σ increase of f_{AOD}. MCSs' lifetime increases with f_{AOD} by 3–24 h under high values of CAPE and moderate to high values of VWS (Fig. 1*E*), and also decreases at low values of CAPE and VWS at the rate of 3–6 h due to 1σ increase of f_{AOD}. Overall, f_{AOD} explains less than 1% of the total variance of MCSs' lifetime. Thus, on the scale of global tropical continents, the lifetime of the MCSs is mainly linked to meteorological conditions and dominated by the CAPE

and lower tropospheric humidity, which is consistent with previous studies (18, 19, 22, 23, 35). These results do not vary significantly for f_{AOD} using AOD > 0.3 instead of AOD > 0.15 as the threshold for polluted environment over land (Fig. 1 and Fig. S1).

However, the aerosol influence on MCSs' lifetime, cloud ice water content, and convective anvils may not become detectable by satellites until the mature or decay phases, as the available satellite sensors cannot effectively detect changes of cloud particle size in the lower and middle troposphere inside of convection and cloud thermodynamic effects. Thus, we separately analyze the variations of MCSs' lifetime with ambient conditions during the growing, mature, and decay phases. Fig. 2 *A–C* shows that CAPE dominates the variance of MCSs' lifetime during the growing phase, explains 36% of its total variance, but becomes less influential during the mature and decay phases, explaining 25% and 9%, respectively, of the total variance. RH_{850} dominates the variance of MCSs' lifetime during the mature and decay phases, explaining 46% and 44%, respectively, of the total variance. VWS explains about 4–34% of the total variance of the durations of these phases. The dominant influence of RH and CAPE over VWS reflects mainly the large geographic variations of MCSs' lifetime with the ambient atmospheric humidity that is needed to sustain the MCSs. In comparison, aerosols explain 6% and 24% of the total variances of the mature and decay phase longevity, respectively, and do not appear to have detectable influence on the duration of the growing phase of the MCSs.

Are the empirical relationships between MCSs' lifetime and ambient meteorological and aerosol conditions shown above physically reasonable? Based on the hypothesized underlying mechanism of aerosol influence on convective lifetime, an increase in MCSs' lifetime is due to increase of cloud ice, especially in the form of smaller cloud particles above the freezing level within convective cores and anvils. Such effects may be more apparent and detectable by satellite sensors, as slower sedimentation of a larger amount of smaller ice particles can sustain convective anvils for a longer time. Thus, we analyze the vertically integrated cloud ice content of the MCSs (IZ; see *Methods,* *Supporting Information,* and Fig. S4) derived from CloudSat (Fig. 2 *D–F*)

and ice water content at 216 hPa (~12 km above the sea level, IWC_216) of convective anvils from the Aura Microwave Limb Sounder (MLS) datasets based on 966 cases of the MCSs (over the limited period of June 2006 for CloudSat to June 2008 for ISCCP-convective tracking data sets) with collocated ISCCP, CloudSat, and MLS measurements in Fig. 2 *D–I*. Notice that IZ represents the mass of larger ice particles above the freezing level (above 5 km) mainly within the convective cores and lower portion of the anvils, whereas IWC_216 represents the mass of smaller particles near the top of the convective anvil. Hence, their relationships with meteorological and aerosol conditions can be different.

Fig. 2*D* shows that IZ's variance is primarily explained by RH_{850} (43%) and CAPE (39%) during the growing phase. VWS explains 12% of the total variance of the IZ (Fig. 2*D*). The result is broadly expected based on the controlling factors of convection reported in the literature (18–20, 22). The variance of the cloud ice in the convective anvil (IWC_216, Fig. 2*G*) during the growing phase is explained mostly by CAPE, presumably because convective detrainment in the upper troposphere or anvils generally increases with buoyancy. During the mature phase, CAPE and VWS explain 57% and 14%, respectively, of the total variance of the IZ (Fig. 2*E*), presumably because of their influence on convective mass flux above the freezing level. In contrast, RH_{850} and f_{AOD} appear to be most influential on the ice water content of the anvils, explaining 64% and 26%, respectively, of its total variance, presumably because of their strong influence on the amount and effective size of smaller ice particles (15). During the decay phase, CAPE and f_{AOD} dominate the variance of IZ, explaining 51% and 35%, respectively, of its total variance. The f_{AOD} dominates the IWC_216 variation, explaining 27% of its total variance. VWS and RH_{500} also have significant influence on IWC_216, each explaining 11% of the total variance in the decay phase. Such increasing influences of aerosols, middle tropospheric humidity, and deep tropospheric VWS are also physically plausible, as the MCSs at decay phase become increasingly detached from the lower troposphere.

The analysis of these independently measured variables in Fig. 2 suggests a stronger influence of aerosols on the duration of the MCSs' decay phase, probably due to the stronger influence of aerosols on cloud ice water content in both convective cores and anvils during this phase. CAPE, RH_{850}, and VWS dominate the explanation of variance of MCSs' lifetime and ice water content of the convective cores and anvils during the growing and mature phases. Generally, aerosols have a stronger influence on convective anvils than on ice water content of convective cores and MCSs' lifetime, presumably because of the formation of a larger number of smaller ice particles (15), which are sensitive to aerosol loading. The smaller ice particles are more likely suspended in convective anvils, and thus can influence the anvil ice water content and lifetime.

Fig. 3 shows the relative influences of ambient aerosols versus meteorological conditions on MCSs' lifetime within each continent. Fig. 3*A* shows that meteorological parameters explain ~92% and f_{AOD} explains up to 8% of the total variance of the lifetime of the MCSs over equatorial Africa. Over South Asia, only 39% of the total variance of the MCSs' lifetime can be explained by meteorological and aerosol conditions when we consider all of the MCSs (Fig. S3). However, we found that 45% of the MCSs formed and matured over the Indian Ocean, Bay of Bengal, and Arabian Sea (Fig. 4*C*). Evaluating the relationship between these MCSs when they were over the ocean and the associated ambient meteorological conditions and f_{AOD} (using AOD > 0.3 as the threshold), we find that RH_{850} dominates the lifetime of these MCSs, explaining about 45% of the total variance; f_{AOD} also has an important impact, explaining ~20% of the total variance (Fig. 3*B*). RH_{500} and VWS explain 15% and 12%, respectively, of the total variance. What causes the large fraction
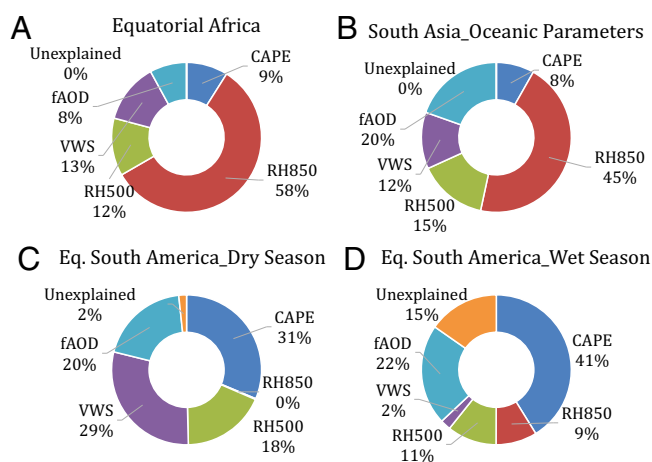

Fig. 3. Fraction of the total variance of MCS's lifetime over different geographic regions: (*A*) equatorial Africa, (*B*) South Asia, (*C*) equatorial South America during dry season, and (*D*) equatorial South America during wet season. For the Asian domain, we use the environmental parameters associated with the MCSs over the ocean and the AOD threshold of 0.3 for polluted conditions in the vicinity of the MCSs.

of the unexplainable variance of the MCSs over the Indian continent remains unclear.

The dominant MCSs' type and aerosol conditions over equatorial South America are sharply different between the wet (December to April) and dry (June to September) seasons. Thus, we separately evaluate the influences of meteorological and aerosol conditions on the MCSs for the dry or wet season. CAPE, VWS, and f_{AOD} explain ~31%, ~29%, and ~20%, respectively, of the total variance of MCSs' lifetime during the dry season (Fig. 3*C*), suggesting a comparable role between these three variables. Ambient RH_{500} also explains a significant fraction of lifetime variance, likely because the drier middle troposphere is a stronger limiting factor for the occurrence of MCSs during the dry season than in the wet season over equatorial South America (36). During the wet season, CAPE and f_{AOD} explain ~41% and ~22%, respectively, of the total variance. The link between RH and MCSs' lifetime in South America is weaker compared with other tropical continents, presumably because humidity is not as strong a limiting factor as in the drier continents (Fig. 4*B*).

Could different meteorological conditions explain variations of the relative environmental influences on the MCSs between different phases of the convective lifecycle and the three tropical regions? Fig. 4*A* shows that aerosol concentrations and meteorological conditions do not change significantly between the three phases of the MCSs' lifecycle. Thus, the decrease of the total variance explained by meteorological conditions is unlikely to be caused by their changes during the MCSs' lifetime. The increased fraction of the total variance of MCSs' lifetime explained by aerosols during the decay phase is consistent with numerical model simulations (15, 37) and supports the cloud lifetime enhancement by the aerosols during that phase. This can be explained by the significant fraction of the variance of ice content inside the convective core and smaller cloud particles in convective anvils explained by f_{AOD}. These effects could reduce sedimentation of ice particles and dissipation of convective anvils. We cannot rule out an influence of the reduced background aerosol loading on lifetime (5, 38).

Fig. 4*B* shows that equatorial Africa is the driest region and has highly variable RH in the low and middle troposphere, as shown by the means and SDs of the RH_{850} and RH_{500}. The region also has relatively low VWS, but is rich in aerosols (f_{AOD}). Thus, moisture
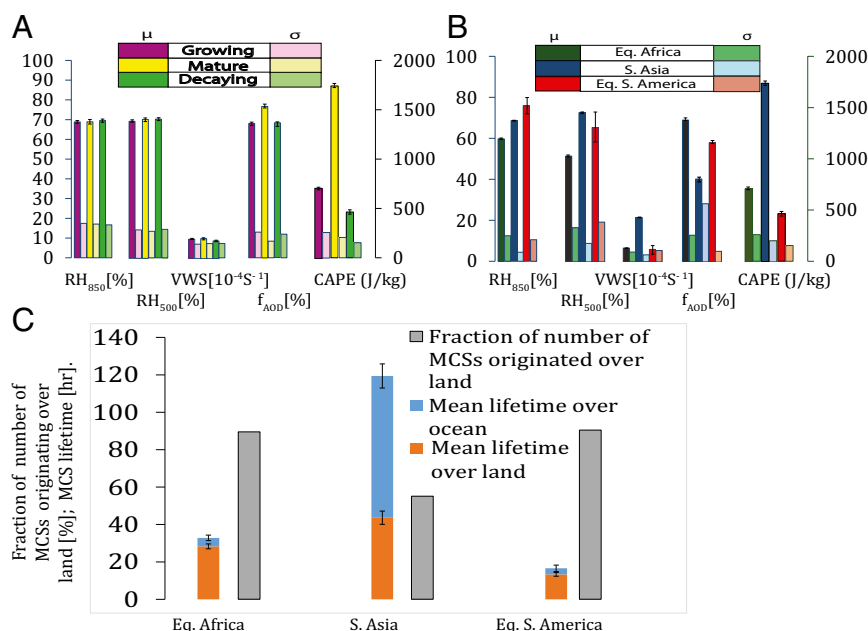
Fig. 4. (A) Variations in mean values (μ, dark colors) and SDs (σ, light colors) of RH$_{850}$, RH$_{500}$, VWS, f$_{AOD}$ (left y axis), and CAPE (right y axis) at different phases of the convective life cycle. The error bars associated with the mean values represent intervals of 2 SEs around the mean. (B) Same as in A but over different regions. (C) Mean and 2 SEs of MCSs' lifetime spent over the land (orange bars) and ocean (blue bars) for equatorial Africa, South Asia, and equatorial South America in 2007. For South Asia, only monsoonal MCSs during June–September have been considered. The gray bars in each plot represent the fraction of MCSs that originated over the land for each region. For the Asian domain, the parameters in A and B are estimated over the ocean and f$_{AOD}$ is computed using AOD > 0.3 as the threshold for a polluted environment.

availability could be the primary limiting factor for lifetime of the MCSs (19), and the RH$_{850}$ and RH$_{500}$ together explain about 70% of their total variance. The MCSs over equatorial South America are surrounded by the lowest f$_{AOD}$ (when we consider f$_{AOD}$ over the land sectors of all three regions) and VWS (Fig. 4B) and the highest amount of RH$_{850}$. Such favorable meteorological (Fig. 1B) and aerosol conditions may explain the stronger connection between f$_{AOD}$ and MCSs' lifetime over South America (Fig. 3 C and D) than those over equatorial Africa and South Asia. In addition, MCSs over equatorial South America are smaller in size (mean radius ~168 km) and have lesser numbers of convective cores [mean number of convective cores (NCC) ~3] and shorter lifetime (<20 h) compared with those of equatorial Africa (mean radius ~440 km, 37 h, and mean NCC ~10) and South Asia (mean radius ~490 km, 120 h, and mean NCC ~9). The combination of these meteorological conditions, aerosol conditions, and MCSs' structures may contribute to a stronger influence of aerosols on those MCSs over equatorial South America.

Over the Indian Ocean, Bay of Bengal, and Arabian Sea, f$_{AOD}$ that surrounds the MCSs over the ocean is 35% less than that over the land. The mean CAPE, RH$_{500}$, and deep-level VWS associated with the MCSs over the ocean are the strongest among all of the regions. Mean CAPE over land (~860 J/kg) is lower than that over the ocean, consistent with previous findings based on reanalysis (39) and meteorological stations' datasets (40). RH$_{850}$ associated with the MCSs over the oceanic surface is also high. Based on Fig. 1, such meteorological conditions favor a stronger increase of MCSs' lifetime with f$_{AOD}$. Fig. 4C shows the mean and variability (SD) of the MCSs' lifetime over the three regions of our analysis and the adjacent oceans. The MCSs over South Asia have the longest lifetime, on average 120 h, which is 3 times the average lifetime of the MCSs over equatorial Africa (37 h) and 6 times that over equatorial South America (19 h). Only 55% of the MCSs over South Asia originally form over the land, whereas about 80–90% of the MCSs originated from land over equatorial South America and equatorial Africa. Moreover, when we consider all of the MCSs, we find that the mean lifetime of convection (irrespective of whether it originates over land or ocean) over the land (orange bar) is approximately half of the time convection spends over the ocean (blue bar). In

other words, 45% of the systems that end up decaying over the land spend much of their lifetime over the ocean.

Throughout our analysis, f$_{AOD}$ explains high fractions of total variance of the MCSs' lifetime when f$_{AOD}$ values are low, for example, over equatorial South America (with the lowest continental f$_{AOD}$ over all of the regions), over the Indian Ocean, Bay of Bengal, and Arabian Sea, and during the decaying stage.

Many environmental parameters, such as the CAPE (18–21), RH (13, 20, 22, 23), and VWS (12, 22, 26, 28, 34), have been known to influence MCSs' lifetime. However, to our knowledge, this is the first satellite-based global tropical continental-scale assessment of the relative roles of meteorological conditions versus aerosols in determining the variations of cloud ice and lifetime of the MCSs using collocated geostationary satellites, closely synchronized A-train polar orbital satellite, and MERRA reanalysis datasets on MCSs' lifetime. These results show that aerosol can either increase MCSs' lifetime under higher relative humidity and CAPE and moderate-to-high deep tropospheric VWS or decrease MCSs' lifetime under lower relative humidity and CAPE and low VWS. On the global tropical continental scale, an increase in MCSs' lifetime with aerosol is most apparent during the decay phase, presumably by increasing the ice water content of convective anvils and convective cores. Such a dependence of the aerosol effect on specific meteorological conditions and phases of the MCSs' lifecycle presumably explains the difficulty of establishing aerosol effects on a global scale with variations in meteorological conditions. It also appears to broadly explain a stronger influence of aerosols on MCSs' lifetime in humid equatorial South America during the wet season and over the Indian Ocean/Bay Bengal with lower aerosol loading, versus the relatively dry conditions with higher aerosol loading over equatorial Africa and dry season South America. Thus, the approach developed in this study can potentially provide a key to reconcile the differences of the aerosol effects on the MCSs reported in various literature.

MCSs produce heavy rainfall, and thus their lifetime should be important for determining rainfall/flood and diabatic heating for atmospheric circulations. However, our understanding of aerosol impacts on MCSs' lifetime has been very limited, in large part, due to lack of adequate long-term observations on large scales. The large samples of the MCSs observed by a suite of satellite

sensors over global tropical continents have enabled us to evaluate aerosol effects during different phases of MCSs' lifecycle under similar meteorological conditions. In doing so, this work has advanced our capability to evaluate whether or not aerosols can increase convective lifetimes on the climate scale and to identify the favorable meteorological conditions for aerosols to affect the lifetime of the MCSs. These are fundamental questions that have motivated many studies for decades. However, we did not address the influence of different types of aerosols (such as absorbing or scattering) on MCSs' lifetime, nor directly observe the effect of aerosols on cloud microphysics. Use of aerosol type data from in situ measurements, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation as well as aerosol index data from the Ozone Monitoring Instrument along with ground-based measurements could be the next step to address these limitations.

Methods

We collocate MODIS and ISCCP datasets to identify the convections that are observed by different satellites between January 2003 and June 2008, to have sufficient numbers of the MCSs needed for the statistical analysis used in this study. For South Asia, only monsoon months (June−September) of every year are considered. Domains of analysis, details of the collocation technique, and related error estimation processes are given in Chakraborty et al. (41). Once a collocated MCS is observed, we compute f_{AOD} using the MODIS AOD pixels (5, 31–33) within an area of 2° latitude/longitude in the vicinity of an MCS. We determine MCSs' lifetime, phase of convective life cycle, and different convective properties from the ISCCP DX dataset (42), and calculate the CAPE, RH_{850}, RH_{500}, and VWS (28) from the MERRA data (41). We integrate the mean vertical reflectivity profile (Z) above the freezing level to represent the columnar IWC (43) or IZ. For details of the calculations and equations, please see *Supporting Information*. We have used multiple linear regression statistics (41) based on the linear combination of the predictors (CAPE, RH_{850}, RH_{500}, VWS, and f_{AOD}) to form a set of predictive equations to estimate the variance of MCS explained lifetime (see *Supporting Information*).

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