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Meteorological bias in satellite estimates of aerosol-cloud relationships

Guillaume S. Mauger[1] and Joel R. Norris[1]

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[1] Several recent studies have reported a substantial correlation between satellite retrievals of aerosol optical depth (AOD) and cloud fraction, which is ascribed to an aerosol microphysical mechanism. Another possible explanation, however, is that the history of meteorological forcing controls both AOD and cloud fraction. The present study examines the latter hypothesis by comparing meteorological conditions along parcel back-trajectories for cases of large and small AOD and cloud fraction. Cloud and aerosol observations are obtained from the MODIS instrument aboard Terra, and meteorological information is obtained from ECMWF analyses. For continuity with previous investigations, the analysis focuses on the stratocumulus cloud region of the Northeast Atlantic during June through August 2002, the season of maximum cloud cover. Results show that scenes with large AOD and large cloud fraction had origins closer to Europe and experienced greater lower tropospheric static stability (LTS) during the past 2–3 days than did scenes with small AOD and small cloud fraction. Controlling for variations in LTS reduces the dependence of cloud fraction on AOD by at least 54%. We conclude that meteorological forcing must be accounted for in assessing aerosol impacts on cloud forcing, and that doing so requires a Lagrangian analysis of parcel histories. **Citation:** Mauger, G. S., and J. R. Norris (2007), Meteorological bias in satellite estimates of aerosol-cloud relationships, *Geophys. Res. Lett.*, *34*, L16824, doi:10.1029/2007GL029952.

1. Introduction

[2] It is well established that stratocumulus clouds found over eastern ocean basins exert a strong cooling effect on the Earth's climate, primarily due to their weak greenhouse effect, extensive coverage, and high albedo relative to the ocean. Anthropogenic aerosols can impact cloud properties by increasing the number of nuclei on which cloud drops form. If cloud water remains constant, an increase in the cloud drop population will result in smaller droplets and consequently, a higher albedo [*Twomey*, 1977]. Smaller droplets are also less likely to collide and coalesce, which may inhibit precipitation formation and thus increase cloud water and cloud fraction [*Albrecht*, 1989]. However, in some situations increased entrainment drying, a consequence of decreased precipitation, can be sufficient to offset the increase in cloud water [*Ackerman et al.*, 2004]. The effects on albedo and cloud water are known as the first and second aerosol indirect effects, respectively. Due to the high albedo of stratocumulus clouds, small changes due to aerosols have the potential to strongly perturb the earth's energy balance. It is therefore important to quantify the response of stratocumulus clouds to changes in aerosol burden.

[3] Numerous researchers have used remote sensing data to investigate aerosol-cloud relationships on regional and global scales [e.g., *Sekiguchi et al.*, 2003; *Matheson et al.*, 2005; *Kaufman et al.*, 2005a; *Matsui et al.*, 2006]. A priority of these studies is to exploit the large sample size available to derive statistical relationships between quantities, particularly the presumed influence of aerosols on shortwave forcing by clouds. In general, these investigations are consistent in showing correlations between aerosol optical depth (AOD) and properties related to cloud radiative forcing. Nevertheless, since correlation does not imply causation, such results cannot simply be used to attribute cloud variations to aerosol microphysical impacts. Alternative explanations include measurement biases, sampling biases, and systematic variations in meteorological state.

[4] A major challenge in aerosol-cloud studies is to quantify the variations in cloud properties *independent of large-scale meteorological forcing*. For example, large-scale convergence could increase cloudiness as well as concentrate aerosols, thus producing an apparent correlation between aerosol and cloud with no direct physical connection. Aerosol indirect effects can generally only be accurately estimated when meteorological variations are held constant. This amounts to estimating the partial derivative of each cloud property with respect to changes in aerosol by controlling for variations in dynamic and thermodynamic state. Different cloud types must be considered separately, variations in climatology must be minimized, and the relevant meteorological parameters must be monitored.

[5] An important consideration is that concurrent meteorological conditions are not sufficient to fully account for cloud state. *Klein et al.* [1995] demonstrated that low-level cloud amount correlates better with sea surface temperature (SST) and 750 hPa temperature 24 to 30 hours upwind than with the local SST and 750 hPa temperature. These results imply that stratocumulus clouds have "memory," or that the history of meteorological forcing is an important determinant of cloud state. This can be interpreted in terms of the time-scale for boundary layer adjustment, as governed by surface fluxes, entrainment and subsidence rates, and temperature and humidity profiles of the free troposphere. Accounting for previous meteorological impacts necessitates a Lagrangian perspective on cloud evolution. Parcel trajectories permit a retrieval of the history of cloud forcings, as well as a simple diagnosis of meteorological differences between cloud states.

[6] The present study introduces new techniques to assess cloud sensitivities to aerosols and to examine the impact of meteorology on the observed relationship between AOD

[1]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

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Table 1. Correlation of Aerosol Optical Depth With Variables[a]

Variable	Correlation With AOD
CF	0.40 (0.36, 0.44)
RE	−0.13 (−0.18, −0.09)
LWP	−0.005 (−0.05, 0.04)
LTS	0.26 (0.22, 0.30)
CTP	−0.29 (−0.33, −0.25)

[a]AOD, aerosol optical depth, showing 95% confidence limits in parentheses; CF, cloud fraction; R_E, droplet effective radius; LWP, liquid water path; LTS, lower tropospheric static stability; and CTP, cloud top pressure.

and cloud fraction. Parcel back-trajectories are used to identify the previous locations and movement of air within and above the boundary layer at the time of the cloud and aerosol measurements. The combination of reanalysis parameters and back-trajectory information is then used to determine the previous large-scale meteorological conditions experienced by the boundary layer. Comparison of cloudiness for trajectories with differing AOD but similar meteorology enables an accurate estimation of the sensitivities of cloud properties with respect to aerosols.

2. Methods

[7] The analysis is focused on the subtropical Northeast Atlantic (25–34N, 35–20W, shown in Figure 1) during June through August 2002, chosen to correspond with the location and season of maximum cloud coverage by stratocumulus. The domain is chosen to be farther north than the domain of *Kaufman et al.* [2005a] in order to avoid the heavy dust region west of Africa, and farther west than the domain of *Matheson et al.* [2005] in order to focus on remote marine clouds. The conclusions of this study are not sensitive to the exact location of the region considered. Reasons for the specific choice of study region are discussed in detail below.

[8] Satellite observations of cloud and aerosol were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Terra as daily gridded averages (MOD08_D3, Collection 005) at a resolution of $1^\circ \times 1^\circ$. Meteorological parameters were obtained from the European Centre for Medium-Range Weather Forecasting (ECMWF) operational analyses and regridded from T106 spectral resolution, with 21 vertical levels. Parcel back-trajectories were computed from the ECMWF analyses using the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HySPLIT). Trajectory calculations were started at two altitudes, one within and one above the boundary layer (500 and 2000 m), and extend 72 hours prior to the time of observation.

[9] One shortcoming of MODIS AOD is that retrievals cannot be made in the presence of clouds. Consequently, cloud observations and aerosol observations come from different locations within a $1^\circ \times 1^\circ$ grid box. Nevertheless, since *Anderson et al.* [2003] show that aerosol variations have length scales between 40 and 400 km, we believe that MODIS AOD from clear areas is largely representative of aerosol conditions in neighboring cloudy areas. Another limitation of MODIS AOD is that it does not provide information on the vertical distribution of aerosol. However, an examination of preliminary Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data for June through August of 2006 indicates that aerosol plumes are most common below 2 km in altitude (not shown). Thus, the aerosol particles revealed by MODIS are likely to be relevant to stratocumulus clouds.

[10] Scene selection was designed to maximize the number of aerosol and low-level cloud observations while excluding high-level clouds, dust, and overly polluted scenes. Mid- and high-level cloud observations were screened out by rejecting all cases with a grid box mean cloud top pressure less than 640 hPa, or where ice particles were detected in any of the nine adjacent grid boxes. Since dust has the potential to contaminate measurements due to ambiguities in distinguishing dust from clouds [*Gao et al.*, 2002] and to complicate aerosol-cloud interactions through infrared absorption, our study region was chosen to avoid regions of heavy dust influence (A. Zhu, personal communication, 2006). Solar absorption by dust and pollution plumes (semi-direct effect) can also impact cloud dynamics. In order to minimize this effect, we limited the analysis to observations of AOD less than 0.3. Further motivation for this choice stems from the potential for comparison with the results of *Kaufman et al.* [2005a], who reported that clouds are most sensitive to aerosol when AOD is less than 0.3. Finally, it is possible that ambiguities in distinguishing clouds from clear sky in the presence of aerosols may lead to an artificial positive correlation between retrieved AOD and retrieved cloud fraction [*Matheson et al.*, 2005; *Charlson et al.*, 2007]. Although this issue is mitigated by the sample selection outlined above, as well as the rigid cloud screening of MODIS measurements of AOD [*Kaufman et al.* 2005b], it is possible that some bias remains.

[11] It is important to avoid sampling biases associated with geographic and seasonal variations in aerosols and cloudiness that could artificially increase the apparent correlation between the two. In order to eliminate this possibility, the analysis region was divided into $3^\circ \times 3^\circ$ grid boxes. The same number of cases were selected from each grid box for each month, thus ensuring unbiased sampling throughout the domain.

3. Results

[12] Table 1 shows linear correlations between AOD and several cloud properties over the region considered in this study. Correlations were computed from daily anomalies obtained by subtracting the mean for each $1^\circ \times 1^\circ$ grid box for each month, in order to remove geographic and seasonal biases. AOD and cloud fraction are substantially correlated, consistent with the results of *Kaufman et al.* [2005a]. However, only a very weak relationship exists between AOD and cloud droplet effective radius, an indication that variations in dynamical factors are impacting cloud response. Similarly, there is no aerosol microphysical mechanism by which AOD could strongly influence lower tropospheric static stability (LTS, defined as θ_{700}-θ_{SFC}), a parameter that is symptomatic of variations in the large-scale meteorological state. The strong correlation with LTS is of particular interest because it is closely connected to variations in low-level cloud fraction [*Klein and Hartmann*, 1993]. While by no means precluding an aerosol micro-

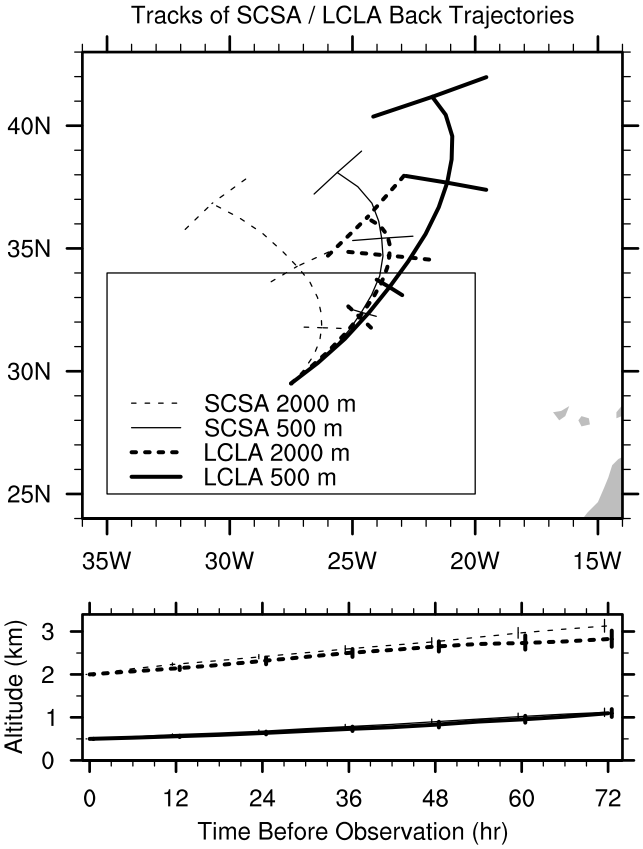

Figure 1. Geographic position and altitude of the mean large cloud fraction, large AOD (LCLA, thick lines) and small cloud fraction, small AOD (SCSA, thin lines) trajectories. The solid lines represent trajectories that were initiated within the boundary layer, at 500 m, and the dashed lines represent trajectories that begin at 2000 m. Error bars indicate 95% confidence intervals for parcel positions. The plot also shows an outline of the study region as well as the Canary Islands and the Northwest tip of the African continent.

physical effect on cloudiness, these results suggest that the observed correlations are due in part to other factors.

[13] In order to explore the possibility that meteorological variations are contributing to the aerosol-cloud correlations in Table 1, we analyzed the subset of cases that contribute most to the observed AOD-cloud fraction relationship. Specifically, we selected the daily 1° × 1° observations that fall within the upper terciles of both AOD and cloud fraction, again selecting data uniformly from each 3° × 3° grid box and month. For convenience, these are called LCLA cases: "Large Cloud fraction, Large Aerosol optical depth". Similarly, we selected the observations that corresponded to the opposite extreme, SCSA: "Small Cloud fraction, Small Aerosol optical depth". Although our results do not depend on selecting only the more extreme values in cloud fraction and AOD, doing so increases the signal to noise ratio, thus simplifying the diagnosis of dominant parameters. Given the selected observations, back-trajectories were then calculated for the date and location of each contributing daily 1° × 1° observation. Figure 1 shows the altitude and position of the mean trajectories, averaged over all LCLA and all SCSA cases. The mean trajectories are plotted relative to the center of the study region, each representing the average of approximately 45 trajectories. The boundary of the study region is also plotted, and visible in the southeast corner are the Canary Islands and a small portion of the continent of Africa. In Figure 1 and all subsequent plots, error bars indicate the 95% confidence interval, determined using a bootstrap method that estimates the probability distribution of outcomes and accounts for autocorrelation between observations. Two important conclusions can be drawn from Figure 1. First, LCLA cases tend to have origins closer to Europe and thus closer to pollution sources. Second, consideration of parcel histories provides new information for differentiating between observations.

[14] Comparison of atmospheric properties at locations along the LCLA and SCSA trajectories permits an analysis of the meteorological differences between the two. Figure 2 shows the mean values of AOD, cloud fraction, droplet effective radius (R_E), and LTS averaged over the LCLA and SCSA trajectories for the three days prior to the time of observation. By construction we see that large cloud fraction is associated with large AOD and small cloud fraction is associated with small AOD. Moreover, R_E is generally smaller for larger AOD, as would be expected if aerosol particles act as cloud condensation nuclei. There is also a large difference in LTS between the LCLA and SCSA cases that becomes more significant as we look back into the

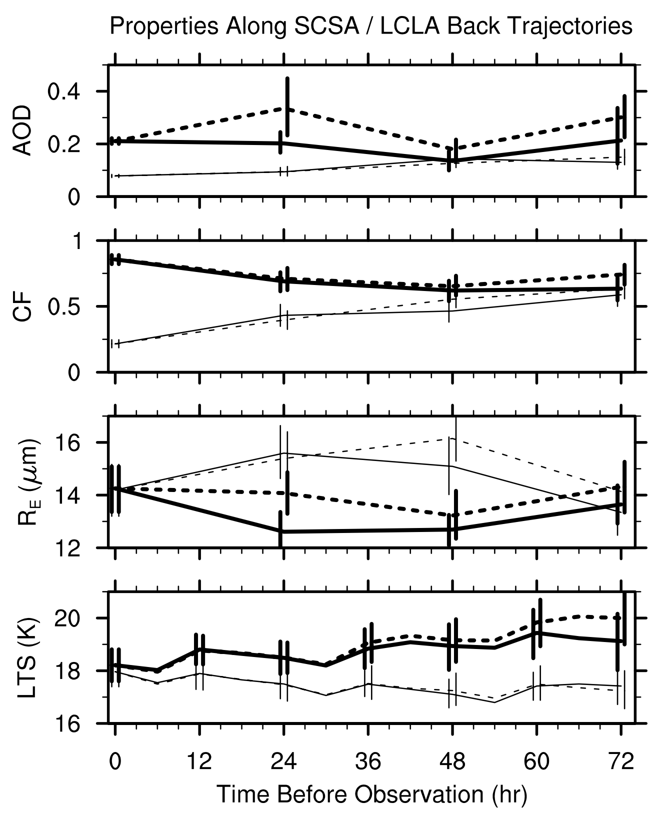

Figure 2. Average AOD, cloud fraction, R_E, and LTS along the LCLA (thick lines) and SCSA (thin lines) back trajectories displayed in Figure 1. Error bars indicate 95% confidence intervals.

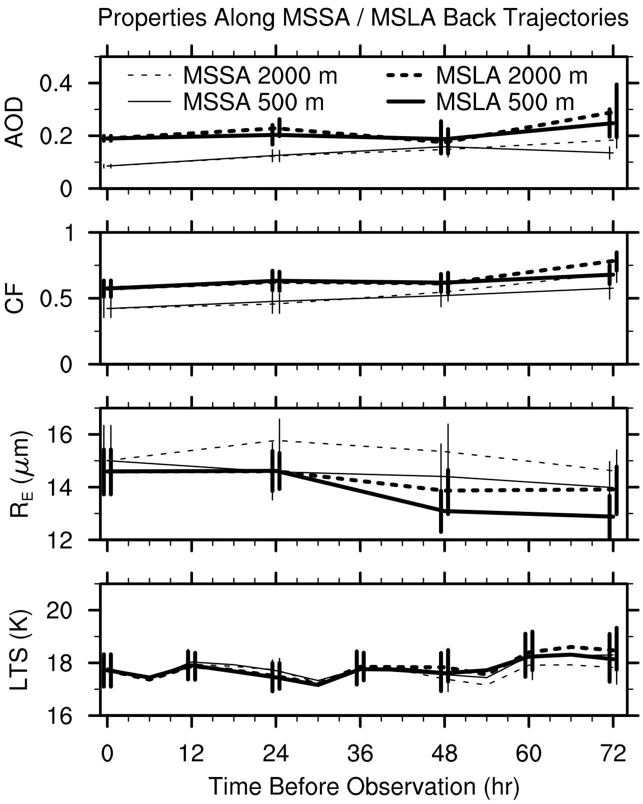

Figure 3. Same as Figure 2, except for median LTS, large AOD (MSLA, thick lines) and median LTS, small AOD (MSSA, thin lines) back trajectories.

history of each parcel. The greater distinction in LTS for prior days indicates that an examination of atmospheric conditions only at the time of the cloud and aerosol observations is not sufficient to fully characterize the meteorological forcing experienced by the clouds and aerosols. In fact, the correlation between cloud fraction and LTS averaged over the previous 48 hours is 0.26 whereas the correlation between cloud fraction and LTS at the observation time is only 0.07.

[15] The evidence in Figure 2 implies that covariation of LTS and AOD is artificially increasing the correlation between cloud fraction and AOD. To test this assumption, we resampled from the data, taking high and low aerosol observations while keeping LTS constant. This allows us to make an LTS-independent estimate of aerosol impacts on cloud properties. For each daily $1^\circ \times 1^\circ$ observation, the average along-trajectory LTS was computed over the 48 hours prior to the observation time. Large and small AOD cases were selected from the subset of samples for which the 48-hour mean LTS was closest to its median value. Figure 3 displays the mean trajectories for cases of MSLA (median stability, large AOD) and MSSA (median stability, small AOD). As before, each average represents the mean of approximately 45 individual trajectories. An examination of mean LTS along the MSLA and MSSA trajectories demonstrates that the sample selection has successfully constrained LTS to be nearly identical across cases of large and small AOD. Although the difference in AOD between MSLA and MSSA is nearly as large as that in Figure 2, the differences in cloud fraction and R_E are significantly smaller. Since this change in outcome is solely the result of a constraint on LTS, we conclude that the majority of the observed aerosol-cloud correlation is caused by systematic variations in lower tropospheric stability rather than aerosol microphysical effects. Similar results are obtained if estimated inversion strength (EIS) [*Wood and Bretherton*, 2006] is used instead of LTS.

[16] Since the preceding results are based only on the upper and lower terciles in cloud fraction and AOD, we recomputed an estimate of the sensitivity of cloud fraction to changes in AOD, this time using all of the data. The cloud sensitivity without correction for LTS was obtained by computing the linear regression of cloud fraction with respect to AOD, using the original daily $1^\circ \times 1^\circ$ values. In this case, a 0.1 increase in AOD is associated with a 0.34 increase in cloud fraction over the summertime subtropical Northeast Atlantic. The confounding influence of LTS within AOD variability was then removed by calculating residuals from the linear trend of AOD with respect to LTS. As for the MSLA/MSSA cases, the LTS was averaged over the 48 hours prior to the observation time, in order to control for the history of meteorological conditions. Finally, we computed a new linear regression of cloud fraction with respect to the AOD residuals. The resulting coefficient represents the sensitivity of cloud fraction to changes in AOD that are linearly independent of changes in LTS. Now, a 0.1 increase in AOD is associated with only a 0.16 increase in cloud fraction, a value that is 54% smaller than the coefficient when LTS is not taken into account.

[17] The true sensitivity is likely to be even weaker than 0.16 cloud fraction per 0.1 AOD for two reasons. The first is that LTS is probably not the only meteorological parameter correlated with both cloud fraction and AOD. Were these additional meteorological effects to be removed, we expect that AOD would explain even less independent variance in cloud fraction. The second reason is that the ECMWF analysis is an imperfect measure of the true atmospheric state. While we have no reason to believe that errors in the analysis are systematically related to variations in AOD, random errors will reduce the apparent correlation between meteorological parameters and AOD. This will lead to an underestimate of the variance removed from AOD by the regression on parameters like LTS and consequently lead to an overestimate of the variance in cloud fraction explained by the AOD residual.

4. Conclusion

[18] This study presents a new technique for distinguishing the impacts of past meteorological forcing from the influence of aerosol on the development of boundary layer clouds. Computed parcel back-trajectories are used to evaluate the origin and atmospheric conditions previously experienced by observed low-level clouds. The method was applied to the stratocumulus region of the subtropical northeast Atlantic, where recently published studies have presented evidence for a substantial correlation between satellite-retrieved aerosol and cloud fraction. We found aerosol-cloud relationships similar to those reported by prior studies but additionally discovered that both aerosol amount and cloud fraction covaried with the static stability of the

lower troposphere during the previous several days along the parcel back trajectories. Controlling for variations in static stability reduced the estimated sensitivity of cloud fraction to aerosol by at least 54%, which represents a significant correction to the indirect forcing estimates of previous studies. Our results do not preclude the existence of a measurable aerosol impact on cloud properties, but they do indicate that sensitivity estimates based solely on satellite observations of aerosol burden and cloudiness grossly overestimate the magnitude of the indirect effect. It is essential to take into account the meteorological history experienced by clouds and aerosols.

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G. S. Mauger and J. R. Norris, Scripps Institution of Oceanography, University of California, San Diego, MC 0221, 9500 Gilman Dr., La Jolla, CA 92093-0221, USA. (gmauger@ucsd.edu)