6.10 STRATOCUMULUS SENSITIVITY TO AEROSOLS AND DYNAMICS

Guillaume S. Mauger*, and Joel R. Norris
Scripps Institution of Oceanography, La Jolla, CA

1. ABSTRACT

A new technique is presented for quantifying the impacts of aerosols on clouds while controlling for variations in meteorology. The recent work of Kaufman et al (2005a) has shown observational evidence for large aerosol effects on clouds. We present work that builds on these results by separating aerosol from meteorological effects on cloud forcing. The new technique uses parcel back-trajectories to account for differences in cloud history. Observations are obtained from the MODIS instrument aboard Terra, and are supplemented with ECMWF reanalyses. Geographic and seasonal biases are removed so that climatological variations cannot contribute to false correlations between aerosols and cloud properties. The present work is focused specifically on the stratocumulus cloud region of the Northeast Atlantic for June through August 2002, the season of maximum cloud cover. Trajectories are grouped into high and low terciles of aerosol optical depth (AOD) and cloud fraction (CF), and evaluated for systematic aerosol-meteorology correlations. Results show statistically significant differences in the meteorology of polluted versus pristine aerosol cases, indicating that variations in the dynamics are contributing to the observed correlation between aerosols and cloud forcing. Specifically, lower tropospheric stability (LTS) is shown to correlate significantly with both aerosol optical depth and cloud fraction. Resampling while holding LTS constant removes almost the entire aerosol-cloud correlation. We conclude that meteorological variations must be accounted for in assessing aerosol microphysical impacts on cloud forcing.

2. INTRODUCTION

Numerous studies have used remote sensing data to investigate aerosol-cloud effects on regional and global scales (eg, Sekiguchi et al, 2003; Matheson et al., 2005; Kaufman et al., 2005a). A priority of these studies is to exploit the large sample size to derive statistical relationships between quantities, particularly the influence of aerosols on the shortwave forcing of clouds. In general, the results of these studies are consistent in showing a correlation between aerosols and cloud forcing. However, since correlation does not imply causation, such results cannot simply be used to attribute cloud variations to aerosol impacts. Possible causes that must be investigated include measurement and sampling biases as well as meteorological processes which impact both aerosols and clouds. These biases must be removed before inferring a true causal relationship between aerosol burden and cloud properties.

A major challenge in aerosol-cloud studies is to quantify the variations in cloud properties *independent of meteorological variations*. This amounts to estimating the partial derivative of each cloud property with respect to variations in aerosol. Since, for example, stratocumulus clouds respond differently to dynamics than trade cumuli, a proper analysis of aerosol-cloud impacts necessitates differentiation by cloud type (Xu et al. 2005). In addition, geographic variations in climatology, if unaccounted for, can contribute to erroneously large correlations between aerosols and clouds. This can be seen, for example, in the subtropical North Atlantic, where high concentrations of dust emitted from North Africa coincide with a stratocumulus regime. In the central Atlantic, where cloud cover is climatologically low, dust concentrations are significantly less compared to the eastern Atlantic. As a result, a correlation that includes both of these regions will reflect climatological variations instead of aerosol impacts. Similarly, seasonal differences must be accounted for before an aerosol effect can be estimated. Finally, aerosols and clouds can be correlated when both are driven by a similar change in dynamics. For example, in certain regimes, large-scale convergence would be expected to

* *Corresponding author address:* Guillaume S. Mauger, SIO-UCSD, MC 0221, 9500 Gilman Dr., La Jolla, CA 92093-0221. gmauger@ucsd.edu

increase cloudiness as well as concentrate aerosols. To summarize, aerosol indirect effects can only be estimated when all other variables are held constant. This requires separate consideration of different cloud types, accounting for differences in climatology, and the monitoring of relevant meteorological quantities.

A convenient way to assess meteorological impacts on clouds is from a Lagrangian perspective on cloud evolution. A study by Klein et al. (1995) showed that low cloud amount correlates better with sea surface temperature (SST) and upper air temperature 24 to 30 hours upwind than with the local SST and upper air temperature. These results imply that stratocumulus clouds have "memory," or that the history of forcings is an important determinant of cloud state. This is likely to be a symptom of boundary layer development, which is determined by surface fluxes, subsidence rate, and temperature and humidity profiles of the free troposphere. Lagrangian parcel trajectories permit not only retrieval of the history of cloud forcings, but a simple diagnosis of meteorological differences between cloud states.

This study introduces a new technique developed to assess cloud sensitivities to aerosols, and to test the observed correlation between aerosol optical depth and cloud fraction. The work described in this manuscript represents a preliminary analysis of cloud sensitivity to aerosols through the use of this new technique.

3. METHODS

Satellite observations are combined with meteorological reanalyses for scene selection. The analysis is focused on the subtropical Northeast Atlantic (22-34N, 35-20W) for June through August of 2002. The region and time period are chosen to correspond with stratocumulus-dominated climatologies, and with the period of maximum cloud coverage. The area considered is shifted to the north relative to Kaufman et al. (2005a), in order to avoid the dust region west of Africa, which is subject to both measurement and attribution uncertainties in aerosol optical depth (AOD).

Satellite observations are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard Terra. MODIS data is obtained as daily gridded averages (MOD08_D3), at a resolution of 1°x1°, from the NASA Langley Research Center Atmospheric Science Data Center. European Centre for Medium-Range Weather Forecasting (ECMWF) operational analyses were obtained from the National Center for Atmospheric Research (NCAR) data archive, regridded from T106 spectral resolution, with 21 vertical levels. All data is regridded to a 1°x1° regular grid for analysis. Parcel back trajectories are computed using the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT). Trajectory calculations are started at two altitudes, both within and above the boundary layer (750 and 1500m), and extend 72 hours prior to the time of observation.

Scene selection is designed to maximize the number of aerosol-cloud observations while adequately screening for high clouds. The aerosol optical depth (AOD) retrievals available in the MODIS product have already undergone the rigid cloud screening procedures described by Kaufman et al. (2005b). The present analysis additionally screens aerosol observations by rejecting all cases with a gridbox mean cloud top pressure less than 640 hPa, or where ice clouds are detected in any of the nine adjacent gridboxes. This also serves to limit the analysis to low-level clouds. Finally, the results of Kaufman et al. (2005a) indicate that clouds are most sensitive for AOD less than 0.3. The analysis is therefore limited to aerosol optical depths within this more sensitive regime.

4. RESULTS

The goal of the present work is to identify the cause of the strong correlations observed between aerosol optical depth (AOD) and cloud fraction (CF). Table 1 shows correlations obtained over the region considered in this study. The data in the first column show a significant correlation between aerosol and cloud fraction, consistent with the results of Kaufman et al. (2005a). However, there is only a very weak relationship with effective radius, which is a necessary precondition for an aerosol microphysical enhancement of cloud fraction. Si-

	Correlation to AOD	Correlation to AOD (geographic & monthly anomalies)
CF	**0.412** (.369-.453)	**0.379** (.336-.422)
R_E	**-0.0796** (-.129--.0295)	**-0.0128** (-.0629-.0374)
CTT	**-0.093** (-.142--.043)	**-0.119** (-.168--.0694)
LTS	**0.364** (.271-.341)	**0.306** (.260-.351)

Table 1 – Correlation of aerosol optical depth (AOD) with cloud fraction (CF), droplet effective radius (R_E), cloud top temperature (CTT), and lower tropospheric stability (LTS), showing 99% confidence limits in parentheses. The 1st column shows correlations for anomalies are calculated relative to the entire region and time span, whereas the 2nd column shows the results for anomalies calculated separately for each 3°x3° gridbox as well as for each month. Note the strong correlation between AOD and LTS, which matches closely with the correlation between AOD and CF.

milarly, it is not clear why such a robust relationship should exist with lower tropospheric stability (ϑ_{700}-ϑ_{1000}) or cloud top temperature, both of which are symptomatic of meteorological variations. While by no means precluding an aerosol effect, these results suggest that the observed correlations are due in part to other factors.

As described in the introduction, sampling biases associated with geographic and seasonal variations in aerosols and cloud cover could artificially increase the observed correlations. We remove these biases by sampling uniformly from each month and each gridbox. This is implemented by splitting the region into 3°x3° gridboxes and selecting a fixed number of samples from each month and each 3°x3° box. New correlations, recomputed using this technique, are shown in column two of Table 1. In general, the correlations remain the same, indicating that for the region considered, systematic climatological variations are not contributing significantly to the observed relationship between aerosols and clouds.

In order to explore the possibility that meteorological variations are contributing to the correlation, we analyze the cases that contribute most to the observed correlation. Specifically, we select observations that fall within the upper terciles of both AOD and CF. For convenience, these are called LCLA cases: "Large Cloud fraction, Large Aerosol optical depth". Similarly, cases are selected that correspond to the opposite extreme, SCSA: "Small Cloud fraction, Small Aerosol optical depth". As described above, cases are selected from each gridbox and each month. These are then combined and averaged to provide an ensemble mean trajectory for each extreme. Figure 1 shows the altitude and position of the mean trajectories obtained for the LCLA and SCSA cases. Each trajectory represents the average of approximately 120 trajectories. Error bars are estimated using a bootstrap method, which accounts for autocorrelation between observations. Note that the LCLA cases tend to come from closer to Europe and thus closer to pollution sources. In addition, the cases with large cloud cover tend to have stronger subsidence.

Comparison of LCLA and SCSA cases permits an analysis of the meteorological differences between the two. It is important to point out that it is not necessary to select only the extrema in

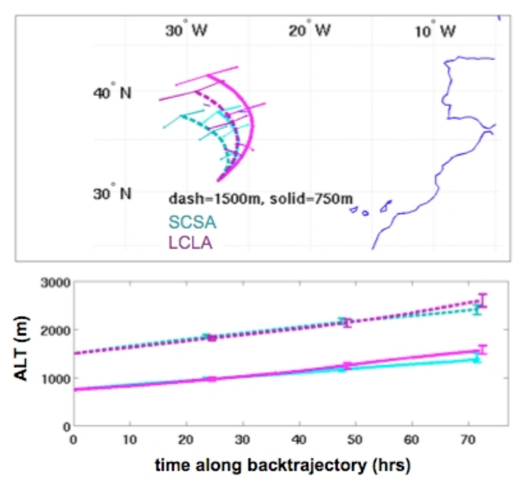

Figure 1 – Geographic position and altitude of the mean LCLA and SCSA trajectories. The solid lines represent trajectories that were initiated within the boundary layer, at 750m, while the dashed lines represent trajectories that begin at 1500m. Note that the more polluted cases tend to come from closer to the continent. In addition, although the vertical resolution makes it difficult to distinguish, the large cloud cases tend to have stronger subsidence.

CF and AOD. However, doing so is an effective means of increasing the signal to noise ratio, thus simplifying the diagnosis of dominant parameters. Figure 2 shows the mean trajectories for AOD, CF, droplet effective radius (R_E), and lower tropospheric stability (LTS, defined as ϑ_{700}-ϑ_{1000}). Due to the sample selection, we see a large cloud fraction associated with a large aerosol optical depth. In addition, we see the expected decrease in effective radius associated with the more polluted cases. Strangely, however, these observations are joined by a large difference in lower tropospheric stability, which becomes particularly strong approximately 12 hours before the cloud fractions are observed to diverge.

The above evidence indicates that lower tropospheric stability plays a significant role in determining cloud fraction. To test this assumption, high and low aerosol cases are selected from the subset of samples for which the mean LTS over the 48 hours prior to observation is close to its median value. Again, it is important to emphasize that the only reason to subsample for aerosol extrema is to accentuate the cloud signal, simplifying the diagnosis of sensitivities. Figure 3 shows the mean trajectories for these cases, where MSSA indicates "medium stability, small AOD," and MSLA indicates "medium stability, large AOD." As before, each average represents the mean of approximately 120 individual trajectories. From the mean LTS trajectories it is clear that the sample selection has successfully filtered the LTS data to consider only those with comparable values over the 48 hours prior to the time of observation. As in Figure 2, we see an equivalent difference in AOD. However, in contrast with Figure 2, both the cloud fraction and effective radius show very little response to the change in aerosol burden, indicating that the majority of the observed aerosol-cloud correlation can be attributed to systematic variations in lower tropospheric stability.

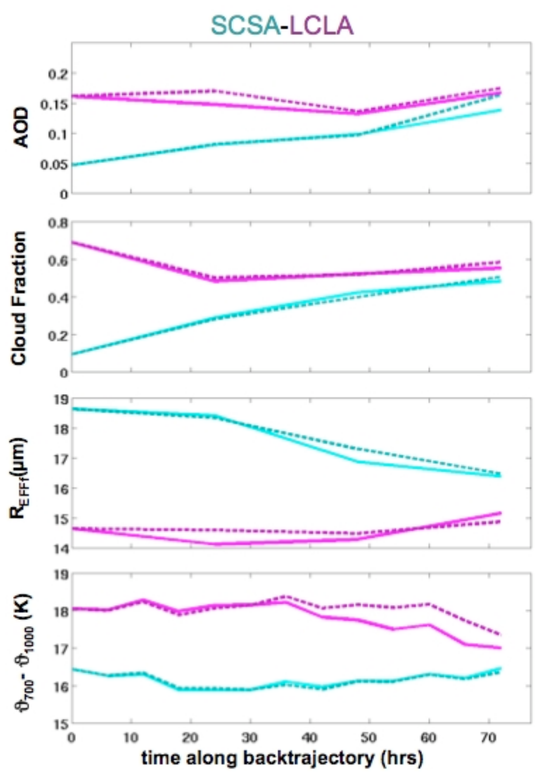

Figure 2 – Aerosol, cloud and meteorological properties along mean LCLA and SCSA back trajectories. Note the large difference in LTS between the high and low aerosol cases.

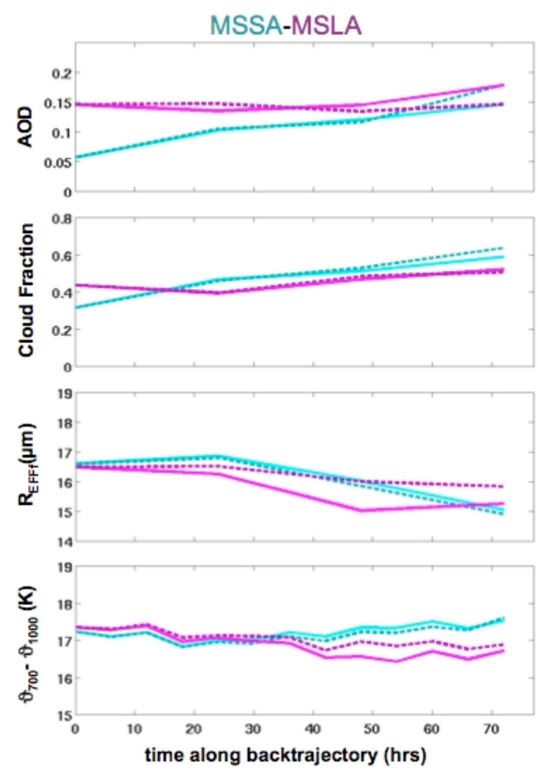

Figure 3 - Aerosol, cloud and meteorological properties along averaged MSLA and MSSA back trajectories. Cloud variations are significantly diminished when LTS is held constant.

5. CONCLUSION & FUTURE WORK

The goal of this work is to quantify the impacts of aerosols on the top-of-atmosphere forcing by clouds. Prior work has established the potential importance of the aerosol indirect effect. Global-scale studies have recently presented evidence for a strong correlation between aerosol optical depth and cloud cover. The work presented above builds on these results by evaluating the cause behind this correlation. We find that lower tropospheric stability correlates significantly with both aerosol optical depth and cloud fraction, with statistically similar correlation coefficients. Significantly, we find that controlling for variations in LTS removes nearly all of the aerosol-cloud correlation.

These results do not preclude the existence of a measurable aerosol impact on cloud albedo. However, they do indicate that sensitivity estimates based solely on the correlation between aerosol burden and cloud cover grossly overestimate the magnitude of the indirect effect. As a result, future work will be directed towards obtaining a corrected estimate of the sensitivity of cloud shortwave forcing to aerosols. This amounts to estimating the partial derivative, which will require further analysis to determine if additional systematic meteorological variations contribute to the aerosol-cloud correlation. Finally, these results are likely to be different in other regions. We intend to expand our analysis to consider other regions, which are under the influence of different aerosol types and different climatologies.

6. ACKNOWLEDGEMENTS

We would like to thank Roland Draxler for his help with preparing ECMWF meteorological files for HYSPLIT, as well as Lorraine Remer and Charles Ichoku for valuable help and information about MODIS. This work was made possible by the NSF Career Award ATM02-38527, as well as a summer student fellowship from the California Space Institute.

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