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Effects of aerosol and SST gradients on marine stratocumulus albedo

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[1] Airborne data are reported on the effect of sea surface temperature and aerosol gradients on the albedo of marine stratocumulus clouds off the coast of central California. Both types of gradients, at the magnitudes and spatial scales observed, produce significant and comparable trends in the cloud albedo (∼15% changes over 40 km). *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Hegg, D. A., P. A. Durkee, H. H. Jonsson, K. Nielsen, and D. S. Covert (2004), Effects of aerosol and SST gradients on marine stratocumulus albedo, *Geophys. Res. Lett.*, *31*, L06113, doi:10.1029/2003GL018909.

1. Introduction

[2] The potential modulation of cloud albedo by anthropogenic aerosols has been a topic of substantial interest for many years now [cf., *Twomey*, 1977, 1991; *Albrecht*, 1989]. The nature of the dependence, i.e., its functional form, has suggested that the aerosols will have the greatest effect in marine air [*Twomey*, 1991] and, indeed, the most convincing evidence for aerosol modulation of cloud properties has been derived from the marine atmosphere, specifically, from the marine stratocumulus scenario [e.g., *Taylor et al.*, 2000; *Brenguier et al.*, 2000]. This is most prevalent in the eastern regions of the subtropical oceans and is thought to be an important component of the global radiation budget [*Stevens et al.*, 2003]. However, it is important to remember that many variables other than aerosol properties markedly influence both the albedo and geographic extent (cloud fraction) of marine stratocumulus.

[3] One of the most important variables influencing the marine stratocumulus albedo and cloud fraction is the sea surface temperature (SST). Since the higher material fluxes of heat and water vapor caused by higher SSTs moisten the marine boundary layer (MBL) and produce higher temperatures and water vapor mixing ratios at cloud base, thicker and moister clouds result. Numerous studies, both theoretical and observational, support this [e.g., *Wyant and Bretherton*, 1992; *Wyant et al.*, 1997; *Pincus et al.*, 1997]. While much of this work has centered on the evolution of the stratocumulus topped MBL as it advects over SST gradients in a Lagrangian sense, it is clear that one would also expect to see Eulerian correlations of cloud albedo and SST arising from the same linkage. Similarly, one would expect to see gradients in cloud albedo associated with MBL aerosol gradients based on the work reported by *Taylor et al.* [2000] and *Brenguier et al.* [2000]. Nevertheless, little quantitative data are available. The question naturally arises as to the relative importance of SST and aerosol variability for otherwise identical meteorological conditions. Some of the work cited above suggests that the SST effect would be more pronounced [cf., *Pincus et al.*, 1997] but nothing definitive is yet in hand. Furthermore, the absolute magnitudes of the gradient changes in SST and aerosol concentrations are quite different. A key issue is therefore simply how to compare the variability in SST and aerosol concentration. Our approach is to compare the effects of observed variability, irrespective of absolute magnitude, in either parameter in the same venue, assessing the influence of each parameter when the other is essentially constant. In this study, data gathered during a field program offshore of the mid-California coast is utilized to study the effectt of both SST and aerosol variability on the albedo of marine stratocumulus.

2. Design of Study

2.1. Venue

[4] The well-known area of frequent and extensive marine stratocumulus off the central to southern California coast is one of the three most intensive marine stratocumulus areas in the world [*Norris*, 1998]. Clouds in this area have been shown to be sensitive to albedo modification both by remote sensing studies [*Platnick and Twomey*, 1994] and by a number of in-situ observational studies conducted during the MAST experiment [cf., *Durkee et al.*, 2000]. It is also an area where both SST and aerosol gradients are common, the latter being associated with anthropogenic emissions from California and the former with upwelling of cold water along the California coast. It is thus an excellent location for assessing the effect of both SST and aerosol gradients on stratocumulus albedo. It is also favorable from a logistics standpoint since the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter research aircraft, the main instrument platform for this study, is based at Marina, CA (on Monterey Bay just north of Monterey) and thus within easy flight range of the stratocumulus decks. Hence, this was the locale selected for the first field deployment of the Cloud-Aerosol Research in the Marine Atmosphere (CARMA) study. The overarching objective of this project is to quantify both the influence of aerosols on clouds in the marine boundary layer and the effect these clouds have on aerosols that are processed by them.

2.2. Instrumentation

[5] All in-situ instrumentation utilized in this study was onboard the CIRPAS Twin Otter research aircraft. The

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Table 1. Summary of the Twin Otter Flights With Sufficient Data to Evaluate the Effect of Gradients on Albedo

Flight date	Measurement Time (UTC)	Location (Latitude and Longitude)	Mean Aerosol Conc. (cm^{-3})	Mean SST (° C)	Δ Albedo (%) (Observed)	Δ Albedo (%) (Modeled)
August 29th	1914–1934	37.0°N, 125.0°–124.3°W	256	14.0	17	12
August 30th	2046–2124	38.0°N, 124.0°–123.3°W	153	12.4	14	14
August 31st	1951–2130	36.6°–36.4°N, 124.2°–124.8°W	353	15.7	6	1

Note that local noon is 2000 UTC.

instrumentation on the aircraft, while variable according to mission, can be parsed from a number of publications [e.g., *Hegg et al.*, 2002; *Wang et al.*, 2004]. For this study, the key instruments are summarized as follows. For measurement of aerosols in the size range most relevant to cloud drop nucleation, and thus cloud microphysics, the PMS/DMT PCASP-100 (size range from 0.12 to 3.2 μm diameter; 0.12 to 1.0 μm utilized) was employed [cf., *Hegg and Jonsson*, 2000]. The cloud drop size distribution was measured by two instruments, the PMS/DMT Fssp-100 and the DMT CAPS probe (which measure from 2 to 40 and from 0.5 to 50 μm diameter, respectively) but only the FSSP data is reported here. The cloud liquid water content can also be determined by integration of the FSSP size distribution. The SST was measured by means of an IR thermometer made by Heitonics (model KT19.85).

[6] In addition to the in-situ instrumentation, satellite remote sensors were utilized to retrieve the cloud albedo along the flight tracks where the Twin Otter sampled either in cloud or near cloud (cloud base or cloud top). The sensors used were the AVHRR radiometer aboard the NOAA 15, 16 and 17 satellites, and the standard spectral radiometer employed on GOES (channel 1, visible). Both radiometers have been described in previous studies [cf., *Rao et al.*, 1999].

2.3. Sampling Plans

[7] The primary purpose of the investigation was to determine both SST and aerosol gradients, by which we mean a systematic variability or trend in each parameter over the flight transects flown by the Twin Otter aircraft, and to correlate these with observed spatial trends in the albedo of the stratocumulus cloud decks. To this end, flight legs were conducted along paths where either sort of gradient might be expected. When found, the flight legs were extended to yield traverses of about 20 minutes duration, corresponding to spatial scales of ~60 km. It is important to note that the flight legs were conducted at constant altitude essentially perpendicular to the mean wind, even if this meant some attenuation in the variability of either parameter. This flight plan ensured that the cloud properties reflected the local values in the SST or aerosol concentration since transport transverse to the mean wind is much slower than the mean MBL mixing timescale of ~15 minutes (the time necessary for even surface fluxes to reach the top of the MBL; [cf., *Stull*, 1988]. Fortunately, the cases examined had MBL winds which were quite close to perpendicular to the examined gradients. The initial traverses were usually conducted at cloud base to permit both measurement of any aerosol gradient and the SST trend by the IR thermometer. A traverse was then conducted along the same path but in-cloud to determine any co-varying cloud microphysical properties. Usually, a sounding was conducted at each end of the traverse to elucidate the thermodynamic structure of the MBL along the traverse. After each flight in which a gradient was explored, the cloud albedo along the flight paths was retrieved from satellite data.

2.4. Numerical Modeling

[8] To aid in the analysis of the measurements, a simple mixed layer model (MLM) of the cloud-topped MBL was employed as a diagnostic tool. The model utilized is similar in structure to that of *Bretherton and Wyant* [1997], which permits cloud-base and cloud-top heights to vary with, and feed back upon, cloud drop number concentrations and dynamics. However, a somewhat more elaborate radiative transfer formulation was employed, based on that of *Moeng* [1986] for the long wave and *Gierasch and Goody* [1970] for the short wave. We emphasize from the outset that the model is used only as an analytical tool and not as a prognostic device.

3. Results and Discussion

[9] Suitable flight legs both in and below cloud for gradient analysis were obtained on 4 of the 13 flights. Of these, two showed no significant gradient in either aerosol concentration or SST, one showed a significant gradient in aerosols but not in SST, and one showed the converse. Of the two non-gradient flights, the cloud deck covered only a portion of the transect in one of these (September 3rd) and it is discussed no further. The remaining three flights are listed in Table 1. It can be seen that the observed changes in albedo are much higher for the cases where gradients were observed (flights on August 29th and 30th) as compared to the non-gradient flight. Nevertheless it is important to note that even here the albedo is not constant over each traverse and that some background "noise" must be taken into account. Additionally, the aerosol concentrations suggest that the venue is mildly polluted albeit definitely marine air. This would tend to somewhat attenuate the susceptibility of the clouds to albedo modification through aerosol as compared to more pristine marine conditions [cf., *Platnick and Twomey*, 1994].

[10] The first flight on which a gradient was observed was August 29th. The SST changed very little over the course of the transect (Figure 1a), with a standard deviation of the mean of only 0.3 °C. In contrast, substantial variability in the aerosol concentration was observed (Figure 1b). There is a general downward trend in concentration from east to west though a local maximum occurs between 124.5 and 124.6 degrees longitude. Looking at the flight paths in cloud for the same traverse, the cloud drop number concentration shows overall agreement with the below-cloud aerosol gradient (Figure 1c), both decreasing by approximately a factor of two from the east to west ends of the transect. However, the local maximum

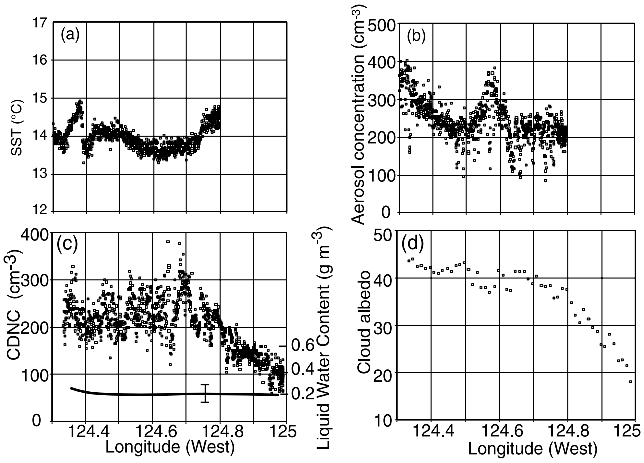

Figure 1. Observed gradients for August 29th. Data points are taken at 1 Hz. The trend line for liquid water content in panel (c) is a smoothed trace of 1 Hz data with an error bar to indicate the variability.

in below-cloud aerosol concentration between 124.5 and 124.6 longitude is only faintly echoed in the cloud drop number concentration (CDNC) and appears to be slightly displaced to the west (~10 km). We attribute this to mixing and advection during the 30 minutes between measurements in-cloud and below-cloud. The ~3 ms−1 wind parallel to the traverse could account for much of this displacement. Additionally, it is difficult to assess correspondence between the strong CDNC decrease after 124.7 longitude and the below cloud aerosol concentration since the below-cloud transect was terminated at 124.8 due to air traffic. Nevertheless, the trend shown for CDNC is difficult to rationalize without a corresponding decrease in aerosol concentration, particularly since the cloud liquid water content along the traverse shows no significant trend (Figure 1c). The cloud albedo retrieved from satellite for this transect is shown in Figure 1d. There is a clear correspondence between the variability in the albedo and in the CDNC. Both parameters decrease by a factor of two from east to west and, additionally, reflect one another in the marked change of slope in the trend at 124.7° longitude. This behavior is consistent with an aerosol effect but not with the observed or theoretical effect of SST variations.

[11] The next flight shown in Table 1, that of the 30th, forms a strong counterpoint to the trends seen during the flight on the 29th. In this case, the aerosol concentration varied little along the flight path, a constancy reflected in the cloud drop number concentration profile shown in Figure 2a. On the other hand, the SST gradient for this flight was substantial, as can be seen in Figure 2b. Interestingly, this gradient in SST appears to produce, or at least be co-incident with, a gradient in the cloud liquid water content as shown in Figure 2c. Such a correspondence would be expected due to an enhanced moisture flux from the warmer sea surface and, indeed, the water vapor mixing ratio close to cloud base does show an increase from east to west of about 6% (see discussion below relating this to cloud properties), in agreement with the sense of the SST gradient. The retrieved albedo (Figure 2d), shows a trend consistent with that shown in the SST.

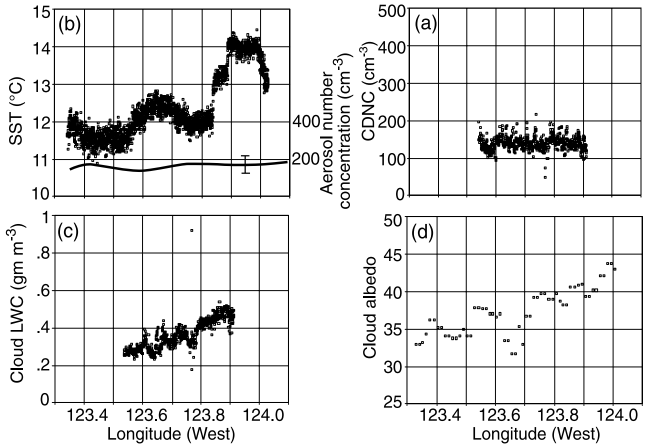

Figure 2. Observed gradients for the 30th. The trend line for submicron aerosol is shown in panel (a).

[12] In order to form a baseline with which the albedo, aerosol, and SST gradients can be compared, we next examine the case of August 31st, in which minimal gradients in either aerosol or SST were observed. The measured values of SST and submicron aerosol concentration along the flight transect are shown in Figures 3a and 3b, respectively. The variation in SST along the transect is less than 3% and for the aerosol concentration it is less than 9%(in contrast to the SST gradient of 15% observed on the 30th and the 59% aerosol gradient observed on the 29th). The corresponding albedo gradient, shown in Figure 3d, reflects this, showing the small, ~6% variation previously cited in Table 1. Because other meteorological parameters such as humidity above the inversion, inversion height and strength, etc. were essentially the same for each of the four cases examined, it seems clear that the albedo gradients observed can be associated with the gradients in either SST or submicron aerosol concentration.

[13] An interesting aspect of the above analysis is the apparent differing linkage between cloud albedo and the type of gradient that caused it. In the case of the aerosol number concentration gradient, the albedo was mediated through the change in CDNC, as expected from the analyses

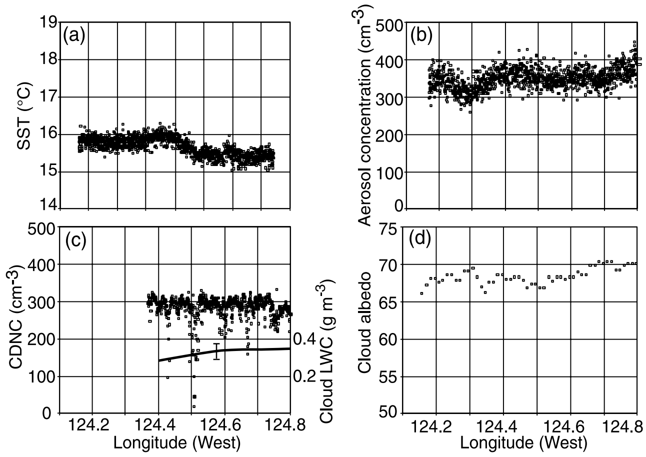

Figure 3. Observed gradients for the 31st. The trend line for cloud LWC is in panel (c).

of cf., *Twomey* [1991]. For the SST gradient, however, the mediation of the cloud optical depth and thus albedo was rather through the change in cloud liquid water content. This is reasonable a priori because the higher SSTs, which correspond with the higher albedo's, would be expected to yield higher vapor and heat fluxes from the surface and thus raise the water vapor mixing ratio and temperature at the lifting condensation level. For similar (or higher due to higher sensible heat fluxes) vertical velocities, this would yield higher liquid water contents and a larger liquid water path (the integral of the liquid water content over the cloud thickness). Hence, optically thicker clouds would be expected [*Twomey*, 1991; *Pincus and Baker*, 1994]. Our MLM modeling work is in agreement with this. For example, in the case of August 30th, the ~6% change in water vapor mixing ratio from east to west at cloud base cited above produced a change in the cloud liquid water content of ~40%, in reasonable agreement with the observed change of ~60% in the same sense shown in Figure 2c. The depth of the cloud layer also increased in agreement with observation. Nevertheless, this is not precisely in accord with all previous thinking on this issue. For example, the modeling work of *Krueger et al.* [1995] and *Wyant et al.* [1997] suggests that the higher sensible and latent heat fluxes associated with higher SSTs could initiate the stratocumulus to cumulus transition and thus break-up the cloud deck. On the other hand, *Pincus et al.* [1997] concluded, on the basis of observations of stratocumulus quite close to the CARMA-I operations area, that higher SSTs acted on clouds with two time scales. On the longer time scale the higher SSTs would indeed lead to the breakup of the stratocumulus decks but on shorter time scales, more in accord with our observations, the effect would in fact be to thicken the cloud decks. To explore this issue further within our data set, and to support the causality of the correlations we see, we next turn to some simple modeling of the influence of SST and aerosol variability on stratocumulus albedo.

[14] The MLM model was initialized and run with data for each end of the traverses discussed above. While the traverse ends do not precisely correspond with the minima and maxima for the albedo for each of the respective traverses, they are close, and are locations for which soundings of the entire MBL are generally available to more closely constrain the model. The model predictions of albedo change are shown in Table 1. It can be seen that the percentage changes in cloud albedo predicted by the model are in reasonable accord with the observed changes, showing agreement within 30% for the gradient cases and similarly relatively low values for the no-gradient case. Since the model is being forced only by either the SST or aerosol gradients, the agreement between the magnitudes of the predicted and observed changes in albedo provide support for the causal relationship between the gradients and the albedo changes.

4. Conclusions

[15] The analysis presented here suggests that gradients in either SST or aerosol concentration on the meso β scale (20 to 200 km) can modulate the albedo of marine stratocumulus clouds on the same scale. Furthermore, the observed gradients on these scales produce similar changes in the cloud albedo. Though this does not imply similar sensitivities to the two variables in absolute terms, it does imply that neither variable overwhelms the other in influence and that both must be taken into account in any assessment of albedo modulation on this scale.

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