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Daytime Variation of Marine Stratocumulus Microphysical Properties as Observed from Geostationary Satellite

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Abstract. Daytime changes in the droplet effective radius (r_e) and cloud liquid water path (LWP) were examined over a large area of marine stratocumulus off the coast of California over a six-day period using Geostationary Operational Environmental Satellite (GOES) 9 imager measurements. Amplitude and phase of the first harmonic of the Fourier series were used to represent the daytime cycle. Complex spatial variation in the amplitude was found. Mean amplitudes were 0.65 μm (r_e) and 13.8 g m^{-2} (cloud LWP). For cloud LWP the cycle peaked predominantly in the morning while r_e maxima occurred in both morning and afternoon. While attention has focused on the r_e afternoon maximum, these observations show that in fact the morning maximum is more common and has a stronger cycle, underscoring the poorly understood nature of the diurnal cycle of marine stratocumulus microphysical properties.

1. Introduction

Because of their large impact on the Earth's net radiation budget making them potentially important in global climate change, boundary layer clouds, particularly stratocumulus, have been actively studied over the last decade or more. Intensive field studies, such as the First ISCCP Regional Experiment (FIRE) in 1987 [*Cox*, 1987] and the 1992 Atlantic Stratocumulus Transition Experiment (ASTEX) [*Albrecht et al.* 1995] have been devoted specifically to further understanding various aspects of marine stratocumulus.

Observational studies have demonstrated that marine stratocumulus often exhibit diurnal signatures in cloud amount and physical properties [e.g., *Minnis et al.*, 1992; *Rozendaal et al.*, 1995]. Other studies using polar orbiting satellite data have shown that marine stratiform clouds have morning/afternoon differences in droplet effective radius and cloud liquid water path (LWP) [*Han et al.*, 1994; *Zuidema and Hartmann*, 1995].

Numerous modeling studies support the idea that a decoupling of the cloud layer dynamics from the subcloud layer plays a crucial role in producing the diurnal cycle observed in stratocumulus properties [e.g., *Bougeault*, 1985]. This decoupling process, which occurs during the day, strongly influences the vertical motion profile. Using a steady-state model, *Considine* [1997] proposed that these vertical motion changes, accompanied by a decrease in the cloud top entrainment and the activation of fewer droplets in the updrafts, give rise to larger droplet sizes near cloud-top in contrast to the coupled cloud situation.

The goal of this study is to quantify the magnitude and phase of the daytime cycle of effective radius and cloud LWP of marine stratocumulus using the Geostationary Operational Environmental Satellite (GOES) 9 imager and, for the first time, examine the detailed nature of this cycle over an extensive region. An exceptional case of a persistent marine stratocumulus system was selected off the coast of California during July 25-30, 1997.

2. Data and Analysis Methods

Half-hourly data from the GOES 9 imager were used. The imager has channels with half-power response bandwidths of 0.52-0.74 μm (channel 1), 3.79-4.04 μm (channel 2), 6.47-7.06 μm (channel 3), 10.2-11.2 μm (channel 4), and 11.6-12.5 μm (channel 5). To simplify the retrievals and reduce the computational burden, the channel 1 data (effective spatial resolution of 0.57 x 1 km) were sampled every fourth pixel to match the lower resolution channels (resolution of 2.3 x 4.0 km).

Channel 1 of the GOES imager was not designed for long-term accurate radiometry and thus has no onboard calibration. The other channels, however, have onboard calibration. Limited evidence suggests that channel 1 of the GOES 9 imager has degraded far less than GOES 8, about 4.9% per year [*Ellrod et al.*, 1998]. Because of the ongoing work on quantifying the changes in the channel 1 calibration, no adjustment was made here to the GOES 9 data.

Cloud optical depth (τ) and drop size can be derived simultaneously from above-cloud solar reflectance measurements at nonabsorbing shortwave visible (0.5-0.7 μm) and water absorbing near-infrared (e.g., 3.7-3.9 μm) wavelengths. *Greenwald et al.* [1997] and *Greenwald et al.* [1999] give specific details regarding the GOES retrievals used in this study. Retrievals were limited to solar zenith angles less than roughly 65° (local time of 0730-1700).

Cloud droplet size is represented by the effective radius (r_e), defined as the third moment of the size distribution divided by the second moment [e.g., *Han et al.*, 1994]. *Nakajima and King* [1990] show that the retrieved r_e typically represents 90% of the value of r_e at cloud top, but varies somewhat depending on the magnitude of r_e, the cloud optical depth, and the vertical variation of r_e. With the optical depth and effective radius known, the cloud LWP follows as LWP = $4\tau\, r_e \rho_w / 3Q_{ext}$ [e.g., *Han et al.*, 1994], where ρ_w is the density

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of liquid water and Q_{ext} is the average extinction efficiency over the droplet size distribution ($Q_{ext} \approx 2$ at visible wavelengths). A comparison of the GOES 9 retrievals of cloud LWP with surface microwave radiometer observations has yielded root-mean-square differences of 17 g m^{-2} with only small systematic errors [*Greenwald et al.*, 1999].

Fourier analysis was used to quantify the daytime variation of the r_e and cloud LWP observations. The first step was to average the data to approximately 25 x 25 km bins. Then composites were computed for bins containing at least four days of data at all half-hourly time periods. From these composites, the amplitude and phase of the first harmonic of the Fourier series were computed. To establish the statistical significance of the derived harmonic amplitudes we used a χ^2 test with two degrees of freedom [*Randall et al.*, 1991]. Following *Randall et al.* [1991], the necessary criterion for rejecting the null hypothesis is

$$\frac{2N[\overline{A}^2+\overline{B}^2]}{\sigma_A^2+\sigma_B^2} > M$$

where N is the number of independent samples (i.e., the number of days), $\overline{A}$ and $\overline{B}$ are the mean cosine and sine components of the first harmonic amplitude for N samples, and σ_A and σ_B are the respective standard deviations of these components. At the 95% confidence level, M = 6. The means and standard deviations of the harmonic amplitude components were estimated by computing the harmonics separately for each day and only for bins where $N \geq 3$.

3. Results

The derived spatial fields of amplitude and phase for r_e and cloud LWP are given in Figure 1. Distinct spatial patterns are evident in both amplitude fields. Some parts of these fields are also well correlated, particularly the major maxima, where a morning maximum in the phase predominates. *Greenwald et al.* [1997] also found a strong relationship between cloud LWP and r_e for South American stratocumulus using datasets of these properties that were completely independent. Overall, the cloud LWP field contains more areas with statistically significant amplitudes than the r_e field.

Figure 2 illustrates a summary of the amplitude fields in the form of histograms. The mean and standard deviation of the r_e and cloud LWP amplitudes were found to be 0.65±0.32 μm and 13.8±7.1 g m^{-2}, respectively. Using twice the mean amplitude to represent a morning/afternoon difference, our cloud LWP results are consistent with *Zuidema and Hartmann* [1995] who found a morning/afternoon difference of 22 g m^{-2} for California marine stratiform clouds.

In contrast to the amplitude fields, the overall behavior of the phase for r_e versus cloud LWP over this region is very different (Figure 3). The peak of the cloud LWP cycle nearly always occurs in the morning (8-10 AM) and rarely in the afternoon. This is in agreement with other studies for observed morning/afternoon differences using satellite data [e.g., *Zuidema and Hartmann*, 1995] and time series of ground-based data [*Minnis et al.*, 1992]. It is thought that the cloud LWP tends to be larger in the morning because the cloud depth is usually greater than during the afternoon, where entrainment and solar heating combine to produce a thinning of the cloud [*Considine*, 1997].

The phase of r_e has a maximum in both the morning and afternoon (Figure 3). In the morning, the maximum occurs slightly earlier than the cloud LWP maximum. The morning maximum is consistent with the results of *Minnis et al.* [1992]. Evidence of an afternoon maximum in the effective radius lends support to the idea proposed by *Considine* [1997] that dynamical changes in coupled (morning) clouds versus decoupled (afternoon) clouds can lead to significant changes in the droplet effective radius near cloud top. *Considine* [1997] found a morning/afternoon difference in effective radius of −1.5 μm. We find an average difference of about −1.1 μm, although many of these amplitudes were indistinguishable from the background variation (i.e., statistically insignificant).

An example of the daytime cycle in r_e and cloud LWP shows that these properties often, but not always, change in unison (Figure 4). *Minnis et al.* [1992] speculated that r_e and cloud LWP reach a peak in the morning due to drizzle, which

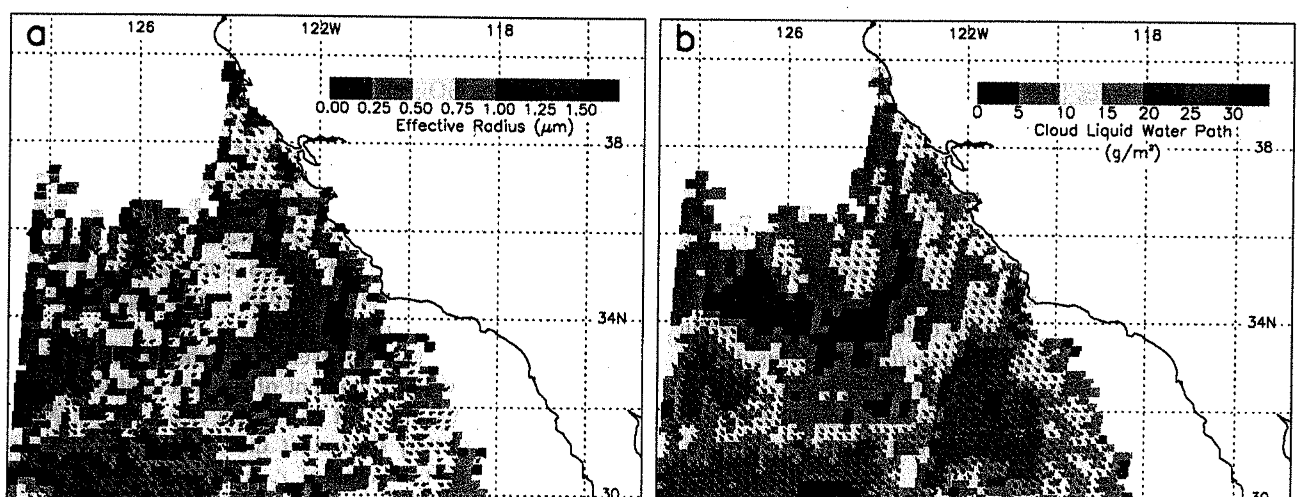

Figure 1. Spatial distributions of the first harmonic amplitude for (a) droplet effective radius and (b) cloud liquid water path. Vectors indicate harmonic amplitude and phase, where an east-pointing vector is 6 AM local time, a south-pointing vector is noon, and so forth. Data with vectors had statistically significant amplitudes at the 95% confidence level.

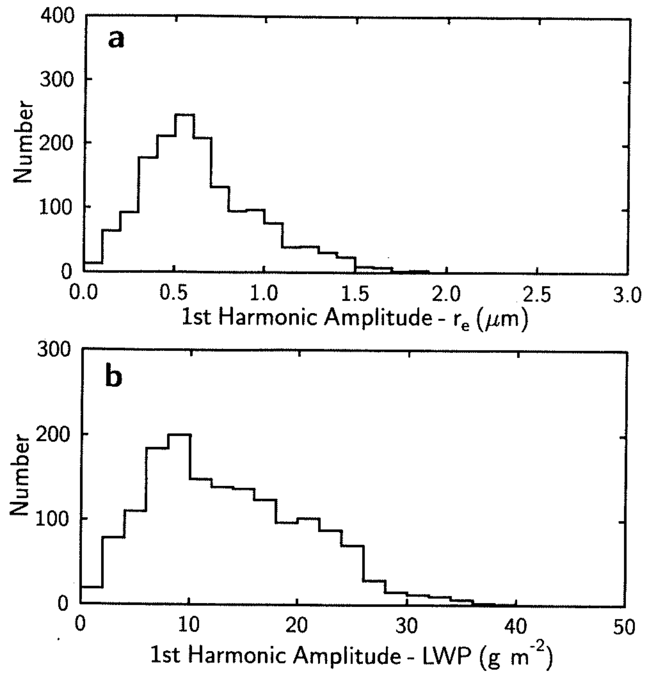

Figure 2. Number distributions of amplitude of first harmonic for (a) effective radius (r_e) and (b) cloud liquid water path (LWP) as a function of local hour.

was found to be more prevalent in the evening and early morning over San Nicolas Island. Drizzle formation, along with shortwave cloud absorption, leads to a depletion of the liquid water content and a reduction in r_e later in the day.

Another interesting feature in Figure 1 is the tongue of small r_e amplitudes stretching away from the southern coast of California. These results suggest a possible influence of land-based aerosols on the daytime cycle. In situ measurements have shown that marine air, when polluted by continental cloud condensation nuclei, generally produces greater numbers of smaller drops with a narrower size distribution that diminishes the collision-coalescence process, thus significantly reducing drizzle production [*Hudson and Li*, 1995]. The effects of these continental aerosols can reach several thousands of kilometers over the ocean [*Hudson and Li*, 1995; *Garrett and Hobbs*, 1995]. We find that the mean r_e is 2-3 μm

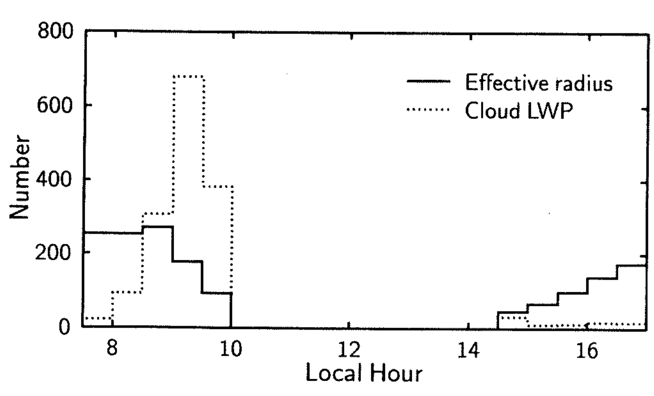

Figure 3. Number distributions of phase of first harmonic for droplet effective radius and cloud liquid water path as a function of local hour.

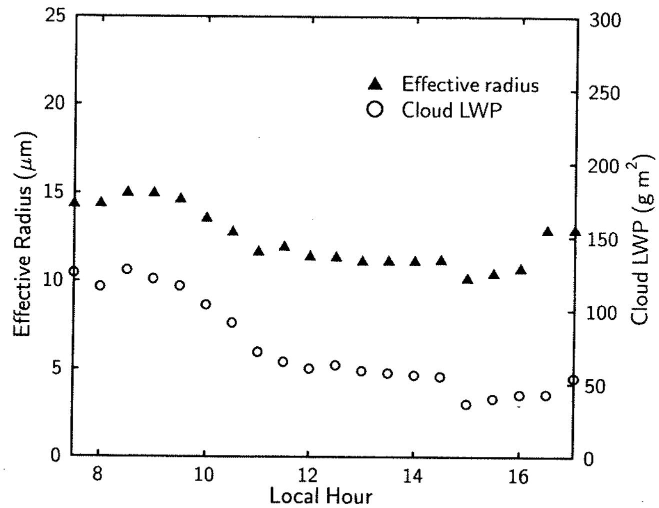

Figure 4. Daytime cycle of droplet effective radius and cloud LWP at 30.90°N and 124.93°W.

smaller in this region than in nearby areas where the daytime r_e cycle is larger, a result quantitatively consistent with in situ measurements [*Garrett and Hobbs*, 1995]. Further investigation of this phenomenon is, unfortunately, beyond the scope of this study.

4. Conclusions

A new application of the imager on the advanced GOES I-M series of satellites has provided an unprecedented look at the daytime cycle of the bulk microphysical properties of Californian marine stratocumulus. One new key feature of the GOES I-M imagers is the inclusion of a near-IR (3.9 μm) channel with reduced instrument noise and far higher spatial resolution, which, coupled with the high temporal sampling, allows for detailed diurnal studies of cloud properties.

The amplitude of the cycles of near-cloudtop effective radius and cloud LWP both exhibited complex spatial variation. Cloud LWP reached a peak primarily in the morning, which is consistent with previous observational and modeling studies. The maximum of the effective radius cycle was found to occur in both morning and afternoon, with the largest amplitudes generally appearing in the morning. While a mechanism for the afternoon maximum in r_e has been proposed, our results showed that in fact a morning maximum is a somewhat more acute and common trait of these clouds, at least over this limited region and time period. Clearly, a full understanding of the physical mechanisms responsible for the daytime cycle of marine stratocumulus microphysical properties remains elusive. These results should pose a significant challenge for the modeling community to realistically simulate the diurnal cycle of stratocumulus and its spatial variation.

Further efforts will explore the daytime cycle of these cloud properties across other larger oceanic regions and over longer time periods to better understand their climatic characteristics and assess possible continental aerosol effects. With the increasing use of GOES data for quantitative aerosol and cloud studies, work should also continue to monitor and evaluate the possible degradation of the visible channel on the imagers.

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