Statistical Analyses of Satellite Cloud Object Data from CERES. Part V: Relationships between Physical Properties of Marine Boundary Layer Clouds

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ABSTRACT

Relationships between physical properties are studied for three types of marine boundary layer cloud objects identified with the Clouds and the Earth’s Radiant Energy System (CERES) footprint data from the Tropical Rainfall Measuring Mission satellite between 30°S and 30°N. Each cloud object is a contiguous region of CERES footprints that have cloud-top heights below 3 km, and cloud fractions of 99%–100% (overcast type), 40%–99% (stratocumulus type), or 10%–40% (shallow cumulus type). These cloud fractions represent the fraction of ~2 km × 2 km Visible/Infrared Scanner pixels that are cloudy within each ~10 km × 10 km footprint. The cloud objects have effective diameters that are greater than 300 km for the overcast and stratocumulus types, and greater than 150 km for the shallow cumulus type. The Spearman rank correlation coefficient is calculated between many microphysical/optical [effective radius (re), cloud optical depth (τ), albedo, liquid water path, and shortwave cloud radiative forcing (SW CRF)] and macrophysical [outgoing longwave radiation (OLR), cloud fraction, cloud-top temperature, longwave cloud radiative forcing (LW CRF), and sea surface temperature (SST)] properties for each of the three cloud object types. When both physical properties are of the same category (microphysical/optical or macrophysical), the magnitude of the correlation tends to be higher than when they are from different categories. The magnitudes of the correlations also change with cloud object type, with the correlations for overcast and stratocumulus cloud objects tending to be higher than those for shallow cumulus cloud objects.

Three pairs of physical properties are studied in detail, using a k-means cluster analysis: re and τ, OLR and SST, and LW CRF and SW CRF. The cluster analysis of re and τ reveals that for each of the cloud types, there is a cluster of cloud objects with negative slopes, a cluster with slopes near zero, and two clusters with positive slopes. The joint OLR and SST probability plots show that the OLR tends to decrease with SST in regions with boundary layer clouds for SSTs above approximately 298 K. When the cloud objects are split into “dry” and “moist” clusters based on the amount of precipitable water above 700 hPa, the associated OLRs increase with SST throughout the SST range for the dry clusters, but the OLRs are roughly constant with SST for the moist cluster. An analysis of the joint PDFs of LW CRF and SW CRF reveals that while the magnitudes of both LW and SW CRFs generally increase with cloud fraction, there is a cluster of overcast cloud objects that has low values of LW and SW CRF. These objects are generally located near the Sahara Desert, and may be contaminated with dust. Many of these overcast objects also appear in the re and τ cluster with negative slopes.

1. Introduction

Marine boundary layer clouds are very important to the Earth’s radiative energy budget because they reflect sunlight that would otherwise be absorbed by the much darker underlying ocean (Randall et al. 1984). However, considerable variability still exists among different general circulation models (GCMs) in their depiction of boundary layer clouds in the current climate (Bony and Dufresne 2005), because current parameterizations cannot represent the subtle interactive processes that operate in the boundary layer. Therefore, it is important to understand the observed interdependent relationships among physical processes associated
with boundary layer clouds in order to test improved parameterizations of boundary layer clouds for simulations of current and future climate.

One way in which boundary layer clouds have been studied is with short-term field experiments that take place over a limited area (e.g., Albrecht et al. 1988; Stevens et al. 2003; Bretherton et al. 2004). These field experiments provide high-resolution, detailed data that have contributed greatly to our understanding of physical processes that take place in the boundary layer. However, they are insufficient for understanding the full range of spatial and temporal variability associated with all boundary layer cloud types. Fortunately, satellite data can be used to observe boundary layer clouds on broader spatial and temporal scales than are possible with field experiments.

There are many approaches in which satellite data can be used to understand the interdependent relationships associated with boundary layer clouds. The conventional approach is to use gridded data that represent averages over an area that is comparable to the grid size used in GCMs (e.g., Kiehl and Ramanathan 1990; Cess et al. 2001). These gridded data are often temporally averaged over the period of a month. A disadvantage to this approach is that different types of clouds can be present in such gridded data, especially when it is also temporally averaged. There have also been satellite studies that adopt an approach that is somewhat similar to that of the field experiments described above, that is, the data are high resolution but the number of cases studied is relatively small (e.g., Nakajima and Nakajima 1995; Barker et al. 1996). Both of these approaches have been used to study relationships between pairs of cloud physical properties, a few of which are discussed below.

One relationship between cloud physical properties that has been extensively studied is that between cloud-top pressure ($p_c$) and cloud optical depth ($\tau$), through the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999). Although this categorization of clouds has proved to be very useful to the modeling community, the categorization of low cloud types by optical depth is somewhat suspect. This is because, although cloud optical depth tends to increase with cloud fraction, the probability density functions (PDFs) of $\tau$ have considerable overlap among different categories of boundary layer clouds (Hahn et al. 2001; Xu et al. 2008, hereafter Part IV). The ISCCP $p_c$--$\tau$ data have recently been used to define cloud regimes of the tropical Pacific using cluster analysis (Jakob and Tselioudis 2003; Jakob et al. 2005; Rossow et al. 2005). This is a promising approach for identifying different relationships between cloud properties that exist in large data volumes. It has been adopted, albeit with modifications, by this study for the examination of other cloud physical property pairs.

In Szczodrak et al. (2001), the relationship between effective droplet radius ($r_e$) and $\tau$ is examined using individual Advanced Very High Resolution Radiometer (AVHRR) scene data, focusing on 25 stratocumulus cases off the coast of California and six cases over the Southern Ocean. In Szczodrak et al. (2001), it was found that for many marine boundary layer clouds, $r_e$ was proportional to $\tau^{1.5}$. This fit with theoretical results by researchers such as Brenguier et al. (2000). However, Nakajima and Nakajima (1995), in a study that looked at two cases [from the first ISCCP Regional Experiment (FIRE) off the coast of California and the Atlantic Stratocumulus Transition Experiment near the Azores], showed that there is a wide variety of relationships between $r_e$ and $\tau$ within individual AVHRR scenes in areas of boundary layer clouds.

Another relationship between atmospheric properties that has been studied is that between outgoing longwave radiation (OLR) and sea surface temperature (SST). The relationship between OLR and SST for clear atmospheres has been studied by several researchers, including Hallberg and Inamdar (1993), Raval et al. (1994), Wong et al. (2000), Su et al. (2006), and Huang et al. (2007). In Hallberg and Inamdar (1993), it was noted that for clear skies, OLR tended to decrease with SST for SSTs above 298 K (i.e., the atmospheric greenhouse trapping increases more rapidly than the surface emission of longwave radiation). This result was largely attributed to an increase in moisture with SST.

The relationship between longwave (LW) and shortwave (SW) cloud radiative forcing (CRF) has also been examined by a number of researchers, including Kiehl and Ramanathan (1990), Kiehl (1994), Chen et al. (2000), and Cess et al. (2001). These studies have generally used data that are averaged over relatively large ($\sim$280 km $\times$ 280 km) spatial areas, often using monthly mean data. This averaging over large spatial and temporal time scales causes a mixture of cloud types within the data. On the other hand, the CRFs examined in this study are calculated using instantaneous data at the scale of individual footprints ($\sim$10 km $\times$ 10 km) for distinct cloud types.

Another way in which satellite data can be used to understand the interdependent relationships associated with boundary layer clouds is by determining contiguous regions of clouds with similar properties (cloud objects) from the satellite data. Xu et al. (2005, hereafter Part I), Xu et al. (2007), and Part IV have used Clouds and the Earth’s Radiant Energy System (CERES; Wielicki et al. 1996) cloud object data and matched
atmospheric state data to examine the statistical properties of boundary layer clouds and tropical deep convection. This method is designed to combine the best features of the monthly mean gridded satellite data products (global coverage) with the best features of the limited-area satellite studies (the ability to isolate individual cloud types). Luo et al. (2007, hereafter Part III) compared observed tropical deep convective cloud objects with those simulated by a cloud-resolving model. Portions of Part I and all of Part IV of this series have focused on the 1D PDFs of cloud physical properties for the following three types of boundary layer cloud objects: shallow cumulus, stratocumulus, and overcast. Part I and Part IV found that there are significant differences between the 1D PDFs of each cloud type for most cloud characteristics. In this article, the relationships between pairs of cloud physical properties will be examined for each of these boundary layer cloud types through the use of 2D (joint) PDFs as well as Spearman rank correlations. The Spearman rank correlation is used rather than the standard Pearson linear correlation. One advantage of the Spearman rank correlation is that it is robust (Wilks 2006); that is, the correlation is not sensitive to the form of the correlation between two variables, as long as it is monotonic. Another advantage of the Spearman rank correlation is that it is resistant; that is, the correlation is not sensitive to a small number of outliers in the data (Wilks 2006). The relationships presented here are expected to be robust because of the use of large data volumes and distinct cloud types. Because of this, they should be valuable for testing and improving parameterizations of boundary layer clouds in mesoscale and climate models.

The cloud physical properties analyzed here fall into two broadly defined categories. The first category, microphysical and optical properties, is composed of \( r_e \), \( \tau \), albedo, liquid water path (LWP), and SW CRF. Even though albedo and SW CRF are radiative properties of clouds, they are primarily determined by cloud microphysical and optical properties, as will be shown in section 3. Obviously, both LWP and \( \tau \) partially depend on cloud physical thickness, which is a cloud macrophysical property. LWP itself is often considered a macrophysical property, but it is grouped with \( \tau \) and albedo because of its close association with these quantities, as shown in Part IV. The second category, macrophysical properties, is comprised of OLR, cloud fraction, cloud-top temperature (CTT), and LW CRF. OLR and LW CRF are included in this category because they are closely related to the emitting temperature of the cloud. An additional environmental property, SST, is also included within the analyses of macrophysical cloud properties although it is not a property of the clouds themselves. Cloud-top height, though available, is not examined in this study in order to limit the total number of physical property pairs.

The purpose of this paper is to examine relationships between pairs of physical properties for marine boundary layer clouds between 30°S and 30°N in a way that isolates particular cloud types, but is more representative of the overall boundary layer cloud population than studies that are limited to a small number of cases. Two particular emphases of this study are to examine whether these relationships change with boundary layer cloud type and whether the correlations within a given cloud object type are stronger between pairs of microphysical/optical properties, macrophysical properties, or “mixed” properties (i.e., one of the pairs is a microphysical property, and the other is macrophysical). Although it is beyond the scope of this study to thoroughly examine each of the cloud property pairs, more detailed analyses will be carried out for \( r_e \) and \( \tau \), OLR and SST, and LW CRF and SW CRF. These break down as one pair of microphysical/optical properties (\( r_e \) and \( \tau \)), one pair of macrophysical properties (OLR and SST), and one mixed pair (LW CRF and SW CRF). These three pairs were also chosen because, although their relationships have been studied previously as noted earlier, most of these studies have not isolated specific cloud types over a broad range of cases.

2. Data

As defined in Part I, a cloud object is a contiguous region of satellite footprints that fulfill a set of selection criteria. For boundary layer cloud objects, the cloud tops must be less than 3 km. The footprints of the shallow cumulus, stratocumulus, and overcast types must also have 10%−40%, 40%−99%, and 99%−100% cloud cover, respectively. These cloud fraction categories are similar to the “scattered cumulus,” “broken stratocumulus,” and “overcast stratocumulus” categories in Barker et al. (1996). Note that all of the footprints in a given cloud object must fulfill both the cloud height and cloud fraction criteria of that cloud object type. With the 3-km cloud-top height criterion, it is possible for some of the clouds to be above the boundary layer. However, the cloud objects are referred to here as “boundary layer cloud objects” for simplicity and in order to be consistent with previous papers in this series (Part I; Part IV). The cloud objects analyzed in this paper were identified over the ocean between 30°S and 30°N using the CERES single scanner footprint (SSF) data product derived from the CERES broadband scanning radiometer and the Visible/Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission.
(TRMM) satellite. Cloud objects with centers that are poleward of 30°N or 30°S are excluded as in Part IV in order to avoid multiple samples of the same cloud object resulting from the TRMM orbital path. These observations took place during daylight hours (from approximately 0800 to 1600 LST) in the period from January to August 1998. Details of the CERES–TRMM data product will be described shortly. The cloud objects examined here are those that have effective diameters larger than 300 km for overcast and stratocumulus objects, and diameters greater than 150 km for shallow cumulus objects. A lower size threshold is used for shallow cumulus objects because very few shallow cumulus objects with effective diameters over 300 km were observed (Part IV). In total, there are 1272 overcast, 1209 stratocumulus, and 1448 shallow cumulus cloud objects selected for this study.

The OLR and top-of-the-atmosphere (TOA) broadband albedo come from radiative flux measurements over the entire CERES footprint, which are produced from broadband radiance data using angular distribution models described in Loeb et al. (2003). The SST for each footprint is obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses with a grid spacing of 0.5625° × 0.5625°.

Cloud properties that are retrieved using VIRS (cloud optical depth, liquid water path, effective radius, cloud-top temperature) are energy weight averaged over only the cloudy 2 km × 2 km VIRS pixels within each CERES footprint. VIRS measures radiance at the following five channels: 0.63, 1.6, 3.75, 10.8, and 12.0 μm. The visible cloud optical depth is derived from the reflectance measured by the 0.63-μm VIRS channel. The effective radius is retrieved using measurements from multiple VIRS channels, and the liquid water path is obtained using the retrieved radius and τ. The cloud-top temperature is derived with the use of the 10.8-μm VIRS channel radiance and emittance. Additional details of the retrieval methods used for the VIRS instrument are described in CERES algorithm theoretical basis documents (Baum et al. 1997; Minnis et al. 1997) and in Minnis et al. (1998). VIRS cloud property retrievals have been validated by Dong et al. (1999) for low overcast clouds. Because the 2-km size of the VIRS pixels is larger than many shallow cumuli, the results for this type should be treated with caution. The use of a higher-resolution imager would be an improvement in this regard, but there are uncertainties in assigning cloud fraction even at very high resolutions (Wielicki and Parker 1992).

The shortwave and longwave cloud radiative forcings were calculated in the following manner for this work. First, a rectangular region was defined, with the southwest (northeast) corner of the region defined by the most southerly (northerly) latitude and most westerly (easterly) longitude of the cloud object. Then, clear footprints were identified within this rectangular region, and the average OLR and reflected shortwave radiation fluxes for these clear footprints were calculated. Finally, the cloud radiative forcing was calculated for each individual footprint within the cloud object by subtracting the observed OLR and reflected shortwave radiation fluxes of that footprint from the averaged clear-sky value. For a small percentage of cloud objects, there were no clear footprints in the rectangular region. In these cases, the SW and LW CRFs were estimated using estimates of the clear-sky values for each footprint from the CERES Clouds and Radiative Swath (Rutan et al. 2005) data product, which uses the radiative transfer model of Fu and Liou (1993) to estimate the clear-sky shortwave and longwave radiative fluxes.

The PDFs of SW CRF and LW CRF are shown for all three boundary layer cloud object types in Fig. 1. As one might expect, the footprints associated with overcast cloud objects tend to have larger magnitudes of both shortwave and longwave CRF than footprints with smaller cloud fractions. The values of SW CRF tend to be larger in magnitude than those of LW CRF for all three cloud types, which is due to the relatively low cloud-top heights associated with boundary layer
clouds and the fact that the cloud objects were all observed during daylight hours. There are portions of the PDFs, particularly for the shallow cumuli, that appear to have an unusual sign for the respective CRF (positive for SW CRF, negative for LW CRF). These CRFs can be caused by instantaneous random errors of 2%–3% and 1%–2% associated with the measurement of reflected SW flux and OLR, respectively (Part IV). Strong inversions near the tops of boundary layer clouds and the misidentification of dust or aerosols as clouds (see section 4) can also have effects on the LW CRF and SW CRF, respectively. There are also random and systematic errors associated with other quantities in the CERES data product. These include random errors of 1.8 mm for \( r_c \), 41 g m\(^{-2} \) for LWP, and 2.1 K for cloud-top temperature. For a more complete discussion of these errors, see Part IV. Systematic errors do not have an impact on the strength of correlations, but random errors tend to decrease the magnitude of correlations.

3. Correlations between physical properties

The easiest way to visualize the joint relationship between a pair of variables is either with a scatter diagram between the two variables if the number of data points is limited, or with a plot of the joint PDF between the two variables if the number of data points is large, as is the case in this study. However, because there are dozens of combinations of cloud physical properties for each of the three cloud object types, it is impossible to fit all of the associated plots into a single paper. A compact summary of the relationship between two variables is a correlation coefficient.

In this section, we will examine tables of Spearman rank correlation coefficients for CERES cloud object data. These tables are supplemented with selected joint PDFs shown in this section as well as in section 4. The tables are organized in terms of both cloud object type and the category of cloud physical properties that are being compared. These categories are microphysical/optical, macrophysical, and mixed (i.e., one of the physical properties is microphysical and the other is macrophysical). The sampling uncertainty for the correlation coefficients is approximately 0.05–0.06 for all three cloud types when calculated following Press et al. (1992) using the number of cloud objects (e.g., 1272 for the overcast cloud objects), rather than footprints, as the number of degrees of freedom.

a. Microphysical and optical properties

Before discussing the correlations between cloud microphysical/optical properties, the joint PDFs of cloud optical depth and albedo are shown in Fig. 2 for all three cloud object types. The maximum frequency for each panel is noted in the caption and represents the maximum fraction of cloud object footprints that fall into a single \( \tau \)-albedo bin interval. This definition of maximum frequency applies to other pairs of physical properties that are shown later. The relationship between these two properties is clearly not linear for overcast objects (Fig. 2a), although each value of \( \tau \) corresponds to a fairly narrow range of albedo. The close association between \( \tau \) and albedo is reflected in the high Spearman rank correlation between the two prop-

![Fig. 2. Contour plots of the joint PDFs of \( \tau \) and albedo for (a) overcast, (b) stratuscumulus, and (c) shallow cumulus cloud objects. Contour intervals are 10% of the maximum frequency in each plot, which is (a) 0.015, (b) 0.063, and (c) 0.153. Bin sizes are 1.0 and 0.02 for \( \tau \) and albedo, respectively.](image-url)
properties ($R = 0.919$). The Pearson linear correlation coefficient, while still high (0.860), is significantly lower. Because the optical depths of the stratocumulus objects are confined over a narrower range (Fig. 2b) than those of the overcast objects, the relationship between $\tau$ and albedo is more linear, and the Spearman rank coefficient (0.771) is very close to the Pearson linear coefficient (0.779). As noted shortly below, the presence of clear skies within stratocumulus footprints reduces the correlation between $\tau$ and albedo. This is even more apparent for shallow cumulus cloud objects (Fig. 2c), with a Spearman rank coefficient of only 0.328.

The correlations between microphysical/optical properties for all three cloud object types are shown in Table 1. For overcast cloud objects, the magnitude of many of these correlations is quite high, with higher optical depths being associated with higher albedos ($R = 0.919$) and LWPs ($R = 0.921$), and higher values of negative SW CRF ($R = -0.869$). Similarly, higher LWPs are associated with increased albedos and more negative SW CRFs, and higher albedos are also associated with more negative SW CRFs. There is a weaker (but significant at 0.245) positive correlation between $r_e$ and $\tau$. This positive correlation is consistent with the findings of Szczodrak et al. (2001), although as Nakajima and Nakajima (1995) have shown, the shape of the joint distribution of $r_e$ and $\tau$ among marine stratocumulus clouds can vary widely. The relationship between these two variables will be studied in much further detail in section 4. Larger effective radii are associated with higher values of albedo and higher values of negative SW CRF, but these correlations are fairly weak at 0.153 and $-0.082$, respectively.

Unlike overcast cloud objects, there is a significant amount (up to 60%, although 10%–40% is more typical) of clear sky in the footprints of stratocumulus cloud objects. This means that albedo, which is based on CERES broadband observations, is partially determined by the properties of clear sky and the surface within each footprint. This may explain why the correlations between $\tau$ and albedo (0.771) and between LWP and albedo (0.677) are smaller for stratocumulus cloud objects than for overcast cloud objects, as shown in Table 1. The SW CRF of each footprint can be approximately expressed as the product of the cloud fraction and the SW CRF of the cloudy portion of that footprint. Because the footprint cloud fraction is constrained for the stratocumulus type, the latter factor is likely to dominate the variability of SW CRF. Three other properties—LWP, $r_e$, and $\tau$—are averaged over only the cloudy portion of the footprint. The correlations between these four properties that depend largely on the cloudy portion of the footprints are relatively similar for stratocumulus cloud objects to those for overcast cloud objects.

For shallow cumulus cloud objects, the majority of the area of each footprint is clear. This causes the clear-sky albedo of the sea surface to play a substantial role in the albedo of footprints in the shallow cumulus category. The albedo of the sea surface itself is largely determined by the solar zenith angle and surface wind speed, which are not cloud properties. This causes the correlation between albedo and $\tau$ (0.328) and between albedo and LWP (0.270) to be smaller than for the stratocumulus and overcast cloud objects. In fact, most correlations between microphysical variables are substantially smaller for shallow cumulus objects than for overcast and stratocumulus objects. The exceptions to this are correlations between the three variables that are averaged over only the cloudy portions of the footprints: $\tau$, LWP, and $r_e$. The small magnitudes of the correlations of SW CRF with other microphysical variables may be due to the larger uncertainty in the calculation of SW CRF for shallow cumulus cloud objects discussed in section 2 and the larger uncertainties that exist in the retrievals of $\tau$, LWP, and $r_e$ with this type.

b. Macrophysical properties

The correlations between macrophysical properties for all three cloud object types are shown in Table 2. For overcast cloud objects, the strong positive correlation (0.616) between CTT and OLR makes sense, because warmer cloud tops generally correspond to higher values of OLR, particularly for overcast clouds,
because of their high emissivity. The strong negative correlations between OLR and LW CRF (−0.651) and between CTT and LW CRF (−0.658) are also as expected, because for a given atmospheric column, we expect higher clouds to result in lower values of CTT and OLR and higher values of LW CRF. The strong positive correlation between SST and CTT (0.597) is surprising and probably comes from the fact that the cloud-top heights and lapse rates of boundary layer clouds lie in a somewhat limited range, causing the CTT to have a relatively predictable relationship with SST.

Although the SST is correlated strongly with the CTT, as is CTT with OLR, the correlation between SST and OLR (0.300) is much weaker, although still significant. In general, the correlations among OLR, SST, CTT, and LW CRF in Table 2 are not as strong as those among τ, LWP, albedo, and SW CRF shown in Table 1 for overcast objects. This may partially be due to the fact that the SST is based on ECMWF operational analyses and is temporally and spatially smoothed. Conversely, the quantities in Table 1 are based only on actual satellite retrievals of data from the CERES and VIRS instruments, some of which are inherently related to one another through the retrieval algorithms used (see section 2).

For stratocumulus cloud objects, the correlations between macrophysical properties are slightly smaller than those seen for overcast objects, except for those involving SST. As the cloud fraction gets larger for stratocumulus objects, there is a decrease in the amount of sea surface scene within each footprint that radiates directly to space, and this causes the OLR and LW CRF to decrease and increase, with R = −0.243 and R = 0.345, respectively. The increase in clear area may also be partially responsible for an increase in the strength of the correlations between SST and OLR (0.422) and between SST and LW CRF versus those seen for overcast cloud objects. The correlations between cloud fraction and SST (−0.044) and between cloud fraction and CTT (−0.119) are relatively weak by comparison.

The correlations between LW CRF and other variables for shallow cumulus objects are smaller than the corresponding correlations for stratocumulus and overcast objects. This is probably because LW CRF tends to be quite small for shallow cumulus (Fig. 1b), with an absolute value that is comparable to the uncertainty associated with the instantaneous longwave flux measurement. It seems surprising that the correlation between SST and OLR (0.088) is smaller among shallow cumulus than for stratocumulus or overcast objects, in spite of the increased clear fraction for shallow cumulus footprints. The relationship between these two variables will be explored further in section 4.

c. Mixed properties

The correlations between microphysical/optical and macrophysical properties are shown for all three cloud object types in Table 3. They are much smaller in general than when both physical properties are of the same
category, as shown in Tables 1 and 2. To show an example of these small correlations, the joint PDFs of CTT and albedo are shown in Figs. 3a–c for overcast, stratocumulus, and shallow cumulus cloud objects. Each of the cloud object types has a negative, albeit somewhat weak, relationship between the two properties. There is an interesting secondary maximum in the joint PDF of overcast objects (Fig. 3a) associated with high CTTs and low albedos (i.e., relatively warm, and weakly reflecting clouds). A somewhat similar feature in the joint PDF of LW CRF and SW CRF will be discussed in much further detail in the following section.

Most of the correlations among mixed properties are relatively small in magnitude, but above the significance threshold for the overcast cloud objects, suggesting that there are physical relationships between most of these properties. For example, CTT has a negative correlation with LWP, which was also seen in the results of Zuidema and Hartmann (1995). Because τ has a strong positive correlation with albedo for overcast cloud objects (Table 1), it makes sense that albedo is also negatively correlated with CTT and OLR \( R = -0.339 \) (see Fig. 3a) and \( R = -0.199 \), respectively, and positively correlated with LW CRF \( R = 0.253 \). The strong negative correlation between \( \tau \) and SW CRF similarly explains why SW CRF is positively correlated with CTT and OLR \( R = 0.275 \) and \( R = 0.096 \), respectively, and negatively correlated with LW CRF \( R = -0.189 \). Warmer SSTs appear to be associated with less reflective (lower \( \tau \) and albedo) boundary layer clouds. This appears to be related to the weak inversion strength over the warm oceans (Part IV), which can lead to optically thin boundary layer clouds, which have lower values of \( \tau \) and albedo.

The correlations between many of the cloud physical properties are somewhat similar for stratocumulus cloud objects as those seen for overcast objects. However, the negative correlation between LW CRF and SW CRF \( (R = -0.403) \) is significantly stronger for stratocumulus cloud objects than for overcast cloud objects (Table 3). This may be because as the LWP of a cloud at a given altitude increases from 0 to approximately 30 g m\(^{-2}\), both the emissivity (and, hence, LW CRF) and albedo (and, hence, magnitude of SW CRF) increase (Stephens 1978). For values of LWP above 30 g m\(^{-2}\), the albedo continues to increase, but the emissivity is saturated at 1. Because stratocumulus cloud objects have a much higher proportion of footprints with LWP < 30 g m\(^{-2}\) than do overcast objects (Part IV), the increased magnitude of the correlation between LW CRF and SW CRF for stratocumulus objects is expected. The relationship between these quantities will be discussed further in section 4. The cloud fraction is positively correlated with cloud optical depth \( R = 0.408 \), which is consistent with the results of Barker et al. (1996), although the sample size used in that study was relatively small.

As we saw with the microphysical/optical properties in section 3a and the macrophysical properties in section 3b, the correlations between mixed properties tend to be smaller for shallow cumulus cloud objects than for overcast or stratocumulus objects. Detailed discussions of the correlations are omitted for brevity. It is noted.

Fig. 3. Contour plots of the joint PDFs of cloud-top temperature and albedo for (a) overcast, (b) stratocumulus, and (c) shallow cumulus cloud objects. Contour intervals are 10% of the maximum frequency in each plot, which is (a) 0.014, (b) 0.024, and (c) 0.085. Bin sizes are 2 K and 0.02 for cloud-top temperature and albedo, respectively.
that the optical depth of shallow cumulus objects tends to increase with cloud fraction \( R = 0.162 \), but the correlation is much weaker than for stratocumulus objects. The albedo and SW CRF increase and decrease with cloud fraction \( R = 0.347 \) and \( R = -0.488 \), respectively, for the same reason given above for the stratocumulus type.

4. Detailed analysis of selected physical property pairs

In this section, detailed analyses of three physical property pairs are performed using the \( k \)-means cluster analysis method (Anderberg 1973) in order to isolate the inherent subsets within the overall relationship between physical properties. Simply speaking, \( k \)-means clustering is an algorithm used to group the cloud objects based on their attributes into \( k \) clusters, where \( k \) is an integer greater than 1. The grouping is done by finding the data points that are closest (in terms of Euclidean distance) to each cluster centroid, and then recalculating the centroids iteratively. In deciding the number of clusters to be chosen for each physical property pair, the general approach of Jakob et al. (2005) is followed. Two clusters are initially calculated for each pair, and the analysis is repeated with higher numbers of clusters. For both the LW CRF–SW CRF and \( \tau-r_e \) pairs, the use of four clusters produces four noticeably different joint distributions, but when more clusters are used, some of them are difficult to distinguish from one another. The LW CRF–SW CRF and \( \tau-r_e \) clusters described below are distinct. This means that for each cluster, the Euclidean distance to the centroid of the closest neighboring cluster is more than twice the standard deviation of the Euclidean distance of its members to its centroid. For OLR and SST, two clusters were sufficient for the partitioning into “dry” and “moist” regimes described below. As will be shown later, the chosen attributes for forming the cluster centroids can be different for different pairs of physical properties. The results of the cluster analysis include the relative frequency of occurrence (RFO), the 2D joint PDF of the physical properties, and the geographic locations of the cloud objects for each cluster.

a. LW CRF and SW CRF

The joint PDFs between LW CRF and SW CRF are shown in Fig. 4 for all three boundary layer cloud object types. Each of the joint PDFs has a negative slope, which is consistent with the correlations shown in Tables 1–3. The range of LW CRF and (particularly) SW CRF decreases with decreasing cloud cover, which is consistent with the 1D PDFs shown in Fig. 1.

The radiative effect of shortwave cooling versus longwave warming by clouds can be measured by the ratio \( N = -(\text{SW CRF})/\text{LW CRF} \), as shown by Cess et al. (2001). The dominance of SW CRF for boundary layer clouds is consistent with the temporally averaged results of Cess et al. (2001, see their Fig. 1), where regions that often have overcast and stratocumulus clouds were observed to have values of \( N \) greater than 2.8. Because the cloud object observations are taken from instantaneous observations between 0800 and 1600 LST, the magnitudes of SW CRF are larger than those that
would result from data averaged over the full diurnal cycle.

The attribute used for analyzing the relationship between LW CRF and SW CRF is the cloud object mean values of LW CRF and SW CRF (denoted by $\bar{L}$ and $\bar{S}$, respectively) because we are interested in isolating the large variability in these fields, which is dominated by SW CRF. As shown in Figs. 5b–d, clusters 2, 3, and 4 are generally determined by the amount of SW CRF in the overcast cloud objects, and they each have similar ranges of LW CRF. The magnitude of $\bar{S}$ and its variability increase in the following order: cluster 1, 3, 4, and then 2. The RFO of clusters 2, 3, and 4 is 0.17, 0.36, and 0.40, respectively. Cluster 1 has an RFO of only 0.06, and will be discussed in detail shortly. The geographic locations of clusters 2, 3, and 4 (Figs. 6b–d) are generally in the typical overcast stratocumulus regions, that is, close to the western coasts of North America, South America, southern Africa, and Australia, particularly for cluster 2.

The joint PDF of LW CRF and SW CRF for overcast clouds has a small maximum associated with low magnitudes of both LW CRF and (surprisingly) SW CRF (Fig. 4a). Figure 5a shows that there is a cluster of overcast cloud objects that tend to have low magnitudes of LW and SW CRF. These cloud objects tend to be located near the west coast of Africa (Fig. 6a). Loeb and Manalo-Smith (2005, see their Fig. 8) compared the cloud masks produced by two algorithms: the National Oceanic and Atmospheric Administration (NOAA) SSF algorithm, which is used for inferring aerosol properties for the CERES SSF product on the Terra satellite (Ignatov and Stowe 2002), and an alternative algorithm (MOD04; Remer et al. 2005), which is used to produce the MODIS aerosol product. The NOAA SSF algorithm used for the Terra satellite is similar to that used for the TRMM satellite, described in Ignatov and Stowe (2000). In Loeb and Manalo-Smith (2005), it was shown that satellite footprints classified as being overcast by CERES are frequently classified as dust aerosol.

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**Fig. 5.** Contour plots of the joint PDFs of LW CRF and SW CRF for clusters of overcast cloud objects. Clusters are arranged in order of increasing RFO. Contour intervals are 10% of the maximum frequency in each plot, which is (a) 0.0149, (b) 0.0031, (c) 0.0055, and (d) 0.0046. Bin sizes are 2 and 10 W m$^{-2}$ for LW CRF and SW CRF, respectively.
by the MOD04 algorithm in this same area. There are also eight cloud objects associated with cluster 1 that are located over the Pacific Ocean, far from any sources of dust or aerosol (Fig. 6a). These cloud objects tend to have values of SW CRF and optical depth that are higher in magnitude than the other members of cluster 1 (not shown), indicating that the Pacific members of cluster 1 are likely to simply be optically thin overcast clouds.

There were 31 cloud objects from cluster 1 that were observed in June–August (JJA) of 1998 near the west coast of northern Africa; their locations are shown in Fig. 7. The wind vectors shown in Fig. 7 correspond to the JJA 1998 average 925-mb winds from ECMWF operational analyses subtracted from the ECMWF 925-mb winds averaged over the 25 separate times in JJA 1998 that 31 members of cluster 1 were observed near the west coast of northern Africa (some members of the cluster occurred within the same 6-h period of an ECMWF analysis). We can see that the winds from these 25 times tend to have a stronger easterly component than the JJA 1998 climatology. Similar analyses using winds at 10 m yield similar results. There were also two members of cluster 1 observed at 1644 and 1646 UTC 17 February 1998 that were observed near (within several hundred kilometers) the Aerosol Robotic Network (AERONET) site at Cape Verde (16.73°N, 22.94°W). On the same day, the Cape Verde
site measured aerosol optical depths of approximately 0.9. Unfortunately, AERONET data at this site were only available for January and February 1998.

When a similar cluster analysis is applied to stratocumulus and shallow cumulus clouds (not shown), the shapes of the joint PDFs associated with each cluster are similar to one another within the two types (i.e., none of the clusters are associated with very small magnitudes of both LW CRF and SW CRF relative to the other clusters). Also, each of the stratocumulus and shallow cumulus clusters has many cloud objects that are in typical locations for marine stratocumulus and shallow cumulus clouds, which are further from the western coasts of continents than the overcast cloud objects (e.g., Part IV, their Figs. 1 and 2).

b. Cloud optical depth and effective radius

Joint PDFs of cloud optical depth and effective droplet radius are shown for each of the three boundary layer cloud types in Fig. 8. In these figures, it is evident that there is a positive relationship between the two variables, with considerable spread, as would be expected from the correlations between 0.245 and 0.316 in Table 1. As noted in section 3, $\tau$ tends to be larger for overcast cloud objects than for stratocumulus objects, which in turn have larger optical depths than shallow cumuli objects.

The slope $b$ from a least squares fit between $\ln \tau$ and $\ln r_e$ was calculated for each individual cloud object. The results of a cluster analysis for overcast cloud objects with $b$ as the centroid are shown in Fig. 9, and the locations associated with each of the cloud objects belonging to the four clusters are shown in Fig. 10. The clusters in Fig. 9 are arranged in order of increasing slope, with the RFO indicated on each panel. Cluster 1 has a decidedly negative slope and an RFO of 6%, while cluster 2 has a slope that is near zero, and an RFO of 24%. The two clusters with distinctly positive slope centroids, clusters 3 and 4, occur more frequently than clusters 1 and 2. A more detailed depiction of the distribution of $b$ is shown in Fig. 11. The PDF of $b$ for overcast cloud objects is somewhat consistent with the results of Szczodrak et al. (2001), although their results indicated that a large number of marine stratocumulus clouds had values of $b$ very close to 0.2.

It is interesting to note that many of the overcast cloud objects associated with cluster 1 are located (Fig. 9).
be associated with dust (Fig. 9a). These members of the cluster may have large droplets near the base of the cloud layer, similar to the 10 and 16 July 1987 cases from FIRE studied in Nakajima et al. (1991); these cases also had negative correlations between $\tau$ and $r_e$. The stratocumulus and shallow cumulus objects that have negative correlations between $\tau$ and $r_e$ may also have large droplets near the base of the cloud layer. Most of the overcast cloud objects associated with clusters 2–4 are located near the west coasts of North America, South America, southern Africa, and Australia (Figs. 10b–d), which are well-known locations of overcast stratocumulus clouds. There does not seem to be a particular trend in the spatial locations of the overcast cloud objects with increasing slope for clusters 2–4.

Apart from occurring at smaller optical depths, the four clusters associated with stratocumulus clouds are relatively similar in shape and RFO to those of overcast clouds (Fig. 12). However, note that the centroid slopes of stratocumulus clusters 1 and 4 ($-0.119$ and $0.192$, respectively) cover a narrower range than the slopes of overcast clusters 1 and 4 ($-0.231$ and $0.251$, respectively). This is consistent with Fig. 11, which shows that the range of slopes among stratocumulus objects is narrower than that of the overcast objects. When plotted on linear scales (not shown), the clusters take on triangular shapes that have some resemblance to some of the scatterplots shown in Figs. 17 and 18 of Nakajima and Nakajima (1995). Many of the locations of the cloud objects associated with stratocumulus cluster 1 (not shown) are near the Sahara desert, but this cluster also contains a significant number of objects located in the northeast Pacific, where there are no major nearby sources of dust. The locations of stratocumulus clusters 2–4 are relatively similar to one another (not shown), and are similar to the locations of the overcast objects (Fig. 10), though somewhat farther offshore from the west coasts of continents.

As was the case with the stratocumulus clusters, the four clusters associated with shallow cumulus cloud objects are qualitatively similar in shape and RFO to those of overcast clouds (not shown), although the optical depths of the shallow cumulus objects are much lower. The values of the centroids of the shallow cumulus clusters ($-0.206$, $0.009$, $0.126$, and $0.237$) are also similar to those of the overcast clusters, which is consistent with the similar distributions of $b$ that the two cloud types have (Fig. 11). The locations of shallow cumulus cluster 1 are similar to those of shallow cumulus clusters 2–4 (not shown), with no particular concentration of locations close to the Sahara. This is in contrast to the results associated with the overcast cloud objects.

**Fig. 8.** Log–log contour plots of the joint PDFs of $r_e$ and $\tau$ for (a) overcast, (b) stratocumulus, and (c) shallow cumulus cloud objects. Contour intervals are 10% of the maximum frequency in each plot, which is (a) 0.101, (b) 0.079, and (c) 0.094. Bin intervals of $r_e$ and $\tau$ are visible on the right and top axes respectively in each panel.
c. OLR and SST

The joint PDFs of OLR and SST are shown in Fig. 13. The OLR of the overcast cloud objects (Fig. 13a) appears to slowly increase with SST for SSTs below approximately 297 K, and is flat above this point. For the stratocumulus cloud objects (Fig. 13b), the OLR behaves somewhat similarly with SST, with a decrease in OLR as SST increases above 298 K. For shallow cumulus cloud objects (Fig. 13c), the joint PDF of OLR and SST is roughly triangular in shape, with the highest OLRs associated with each SST increasing with SST up to about 301 K, while the lowest OLRs associated with each SST are flat or decrease with SST throughout the range of SST.

Although their study was confined to clear atmospheres, Huang et al. (2007) have noted that for cloudy atmospheres, the amount of greenhouse trapping is sensitive to changes in the vertical profiles of water vapor and temperature above the cloud top. Thus, we will explore how changes in the precipitable water of the middle and upper troposphere alter the relationship between SST and OLR. To accomplish this, the integrated precipitable water from 700 hPa to the top of the atmosphere (hereafter denoted by $W_{700}$) was interpolated to the location of each footprint for all three cloud object types. ECMWF operational analyses were available every 6 h, and the value of $W_{700}$ was chosen from the closest available analysis time to the time at which the cloud object was observed, that is, within 3 h. Two clusters were formed in terms of the cloud object mean values of $W_{700}$ for each cloud type; the cluster with relatively low values of $W_{700}$ is referred to as the “dry” cluster, and the cluster with relatively high values of $W_{700}$ is referred to as the “moist” cluster.

In Figs. 14a,b, joint PDFs of OLR and SST are shown for overcast cloud objects that are associated with the dry and moist clusters of $W_{700}$. The relationship between OLR and SST has a distinctly positive slope for the dry cluster, even at high SSTs (Fig. 14a). For the moist cluster of $W_{700}$ (Fig. 14b), the relationship be-
The relationship between OLR and SST changes with $W_{700}$ in a similar manner for stratocumulus footprints (Figs. 14c,d). The joint PDFs of OLR and SST have positive slopes for the dry cluster of $W_{700}$ (Fig. 14c), while OLR is fairly constant with SST for the moist cluster of $W_{700}$ (Fig. 14d). The RFO of the dry and moist clusters (0.67 and 0.33, respectively) are similar to the corresponding values of RFO for the overcast clusters. However, the centroid values of $W_{700}$ for the

When PDFs of vertical velocity at 700 hPa for the moist and dry clusters are compared to one another, the subsidence associated with the dry clusters tends to be stronger than the subsidence associated with the moist clusters (not shown).

The locations of the overcast cloud objects that comprise the dry cluster (Fig. 15a) are generally farther from the equator than those in the moist cluster (Fig. 15b). This trend is also evident for the stratocumulus and shallow cumulus cloud object types (not shown).
FIG. 11. PDF of the optical depth exponent $b$ for each of the three boundary layer cloud object types.

FIG. 12. Log–log contour plots of the joint PDFs of $r_e$ and $\tau$ for clusters of stratocumulus cloud objects. Clusters are arranged in order of increasing slope (see text for details). Contour intervals are 10% of the maximum frequency in each plot, which is 0.083, 0.070, 0.079, and 0.094 for clusters 1, 2, 3, and 4, respectively. Bin intervals of $r_e$ and $\tau$ are visible on the right and top axes respectively in each panel.
dry and moist clusters (2.44 and 9.41 mm, respectively) are somewhat lower than the corresponding values for the overcast clusters. The centroid values of the dry and moist clusters (2.95 and 9.79 mm, respectively) are fairly close to the corresponding values for the overcast clusters. The above results are broadly consistent with those of Raval et al. (1994), who used monthly mean Earth Radiation Budget Experiment (ERBE) data, and showed that there are negative correlations between the all-sky OLR and precipitable water for latitudes between 30°N and 30°S, although the results of Raval et al. were obtained from monthly gridded data that had mixed cloud types. Furthermore, the changes in the joint PDFs of OLR and SST with cloud object type are substantial for both the dry and moist clusters, resulting from the change in OLR with cloud fraction. Without the separation into cloud object types, the distinct relationships between OLR and SST for individual types would be mixed into a far different one, covering large ranges of OLR and SST. This also applies to other pairs of physical properties examined in this study.

5. Summary and conclusions

This study has investigated the relationships between physical properties for distinct boundary layer cloud object types identified with the CERES footprint data product over the ocean between 30°S and 30°N. Spearman rank correlation coefficients were calculated between cloud physical properties. The k-means clustering algorithm was used for a more detailed examination of the relationships between three pairs of cloud physical properties (LW and SW CRF, τ and r, and OLR and SST). The major findings are as follows:

- Correlations between physical properties change with boundary layer cloud type. This is particularly the case for shallow cumulus clouds, which have smaller correlations than stratocumulus and overcast clouds. Because less than 40% of the pixels of each shallow cumulus footprint are cloudy this means that the albedo and OLR of each footprint are heavily weighted by the clear atmosphere of that footprint rather than the cloudy atmosphere. The 2 km pixel size of the VIRS instrument also may play a role, because shallow cumuli often have horizontal dimensions smaller than 2 km.
- When both physical properties are of the same category (microphysical/optical or macrophysical), the correlations tend to be higher than when they are of different categories. However, a few physical property pairs in the same category have fairly low corre-
FIG. 14. Contour plots of the joint PDFs of OLR and SST for clusters of (a), (b) overcast cloud objects; (c), (d) stratocumulus cloud objects; and (e), (f) shallow cumulus cloud objects. Clusters are arranged in increasing order of \( W_{700} \) for each type; the left column represents the dry clusters, and the right column represents the moist clusters. Contour intervals are 10\% of the maximum frequency in each plot, which is (a) 0.0067, (b) 0.0081, (c) 0.0071, (d) 0.0125, (e) 0.0105, and (f) 0.0236. Bin sizes are 2 W m\(^{-2}\) and 0.5 K for OLR and SST, respectively.
lations (e.g., \( r_c \) and SW CRF, and cloud-top temperature and cloud fraction).

- The shortwave cooling associated with boundary layer clouds is more important than their longwave warming during the daytime, consistent with other studies. Overcast clouds tend to have greater magnitudes of both LW CRF and SW CRF than stratocumulus and shallow cumulus clouds, but the change in SW CRF with cloud type is more rapid, so the ratio \( N = -\text{SW CRF}/\text{LW CRF} \) tends to be higher for overcast clouds than for stratocumulus clouds, which in turn have higher values of \( N \) than shallow cumulus clouds. A cluster analysis of the LW and SW CRFs of the overcast clouds indicates that about 6% of the overcast cloud objects belong to a cluster that has fairly low magnitudes of both LW CRF and SW CRF. Many of these objects are located near the Sahara desert, indicating that they may be contaminated with dust, or that some overcast cloud objects may actually be dust (see Loeb and Manalo-Smith 2005).

- A slope-based cluster analysis of the relationship between \( \tau \) and \( r_c \) revealed that for each boundary layer cloud type, there was a cluster of cloud objects with negative slopes, a cluster with slopes near zero, and two clusters with positive slopes. The relative frequencies of occurrence of these four clusters were similar for each cloud type. Analysis of the locations of the cloud objects in each cluster indicates that many members of the cluster with negative slopes for overcast clouds may be associated with dust, while this is probably not the case with stratocumulus or cumulus objects. These cloud objects may have large droplets near the base of the cloud layer rather than the top (see Nakajima et al. 1991).

- The overall relationship between OLR and SST for boundary layer clouds is that OLR tends to increase with SST for SSTs below about 298 K, and then remains roughly constant with SST for SSTs above this value. This result is somewhat similar to the clear-sky results of Hallberg and Inamdar (1993) and Huang et al. (2007). A cluster analysis of the relationship between OLR and SST based upon the amount of precipitable water above 700 hPa, \( W_{700} \), indicates that there are two regimes for each boundary layer cloud type. For the dry clusters, which make up about 70% of the total cloud object population for each boundary layer cloud type and are associated with stronger subsidence at 700 hPa in predominantly subtropical regions, OLR tends to increase with SST, even for high SSTs. For the moist clusters, which are associated with weaker subsidence at 700 hPa and tend to be located nearer to the equator, the greenhouse trapping of the atmosphere increases with \( W_{700} \), causing the OLR to stay roughly constant with SST, and typically at lower values of OLR than are seen in the dry clusters. The change of the OLR–SST relationships with cloud object type is substantial for both the dry and moist clusters resulting from the change of OLR with cloud fraction.

In the future, these results should be extended to include CERES Terra data, which have been collected starting in 2000. The cluster analyses between cloud physical properties shown in this work can also be extended to other pairs of cloud physical properties as well as different cloud types. It will also be interesting to test cloud-resolving models using the boundary layer cloud objects and matched meteorological data, which
has been done for deep convective cloud objects by Eitzen and Xu (2005) and Part III. Furthermore, the strong and robust interdependent relationships found in this study can also be used to evaluate and improve the performance of numerical models of boundary layer clouds, particularly regional climate models with grid spacings that are comparable to the size of a CERES footprint (Wang et al. 2004).

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