Cloud and Radiative Characteristics of Tropical Deep Convective Systems in Extended Cloud Objects from CERES Observations

ZACHARY A. EITZEN
Science Systems and Applications, Inc., Hampton, Virginia
KUAN-MAN XU AND TAKMENG WONG
NASA Langley Research Center, Hampton, Virginia

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ABSTRACT

The physical and radiative properties of tropical deep convective systems for the period from January to August 1998 are examined with the use of Clouds and the Earth’s Radiant Energy System Single-Scanner Footprint (SSF) data from the Tropical Rainfall Measuring Mission satellite. Deep convective (DC) cloud objects are contiguous regions of satellite footprints that fulfill the DC criteria (i.e., overcast footprints with cloud optical depths $>10$ and cloud-top heights $>10$ km). Extended cloud objects (ECOs) start with the original cloud object but include all other cloudy footprints within a rectangular box that completely covers the original cloud object. Most of the non-DC footprints are overcast but have optical depths and/or cloud-top heights that are too low to fit the DC criteria. The histograms of cloud physical and radiative properties are analyzed according to the size of the ECO and the SST of the underlying ocean.

Larger ECOs are associated with greater magnitudes of large-scale upward motion, which supports stronger convection for larger sizes of ECOs. This leads to shifts toward higher values in the DC distributions of cloud-top height, albedo, condensate water path, and cloud optical depth. However, non-DC footprints become less reflective with increasing ECO size, as the longer-lived large convective systems have more time to develop thin cirrus anvils. The proportion of DC footprints remains fairly constant with size. The proportion of DC footprints also remains nearly constant with SST within a given size class, although the number of footprints per object increases with SST for large objects. As SSTs increase, there is a decrease in the proportion of updraft water that goes into detrainment, causing the non-DC distributions of albedo, condensate water path, and cloud optical depth to shift toward lower values. The all-cloud distributions of cloud-top temperature and outgoing longwave radiation (OLR) shift toward lower values as SST increases owing to the increase in convective instability with SST. Both the DC and non-DC distributions of cloud-top temperature do not change much with satellite precession cycle, supporting the fixed anvil temperature hypothesis of Hartmann and Larson. When a joint histogram is formed from the cloud-top pressures and cloud optical depths of the ECOs, it is very similar to the corresponding histogram of the deep convective weather state obtained by cluster analysis of International Satellite Cloud Climatology Project data.

1. Introduction

Tropical deep convection is an important part of the global radiative and hydrological budgets. It produces a significant percentage of the earth’s precipitation, and the area covered by convective anvils is a significant portion of the tropics. These clouds are both highly reflective and are opaque to upwelling longwave fluxes from the surface. Thus, the differences in radiative fluxes at the top of the atmosphere between cloudy and clear regions are large for both longwave and shortwave radiation (e.g., Cess et al. 2001). If the areal coverage of deep convective (DC) clouds is significantly altered as the climate changes, there could be large effects on the amplification of the changes in the global climate system. Current general circulation models (GCMs) with parameterized convection still have difficulty simulating the observed spatial and temporal variability of tropical convection (J.-L. Lin et al. 2006), which can make an accurate projection of future climate changes difficult.
(Solomon et al. 2007). Rigorous validation of model
simulations, particularly the models’ physical parame-
terizations, requires observational datasets that describe
finescale variability.

Recently, Xu et al. (2005) proposed an innovative
satellite data classification approach called “cloud ob-
jects” using observations from the Clouds and the Earth’s
Radiant Energy System (CERES) project (Wielicki et al.
1996). The deep convective cloud objects are defined as
contiguous regions of overcast CERES footprints with
cloud-top heights greater than 10 km and cloud optical
depths (τ) greater than 10. Xu et al. (2005) studied dif-
fences in cloud object properties between March 1998
(when a strong El Niño was taking place) and March
2000 (when a weak La Niña was taking place). The study
of Xu et al. (2007) examined the behavior of tropical
deep convective cloud objects throughout January–
August 1998, and they found that the distributions of
cloud-top temperature did not change much with satel-
lite precession cycle (despite significant changes in the
distribution of SST with precession cycle), supporting
the fixed anvil temperature hypothesis of Hartmann and
Larson (2002). Other studies by Xu et al. (2008) and
Eitzen et al. (2008) have addressed boundary layer cloud
objects. In these observational studies, histograms of
cloud physical and radiative properties were examined,
instead of traditional gridbox means averaged over
monthly time scales. Most histograms were found to
vary strongly with cloud object size, with larger cloud
objects having higher cloud tops and more reflective
clouds. The cloud-top heights of deep convective cloud
objects also tended to increase with SST, but the re-
fectivity of clouds did not change much with SST (Xu
et al. 2007). These observations were used by Eitzens
and Luo et al. (2007) to evaluate and help improve cloud-resolving model (CRM) simulations of
tropical deep convection. The above studies examined
the properties of only those satellite footprints and
CRM columns that fit the selection criteria.

By contrast, in the CRM study of Eitzen and Xu (2008,
hereafter EX08) the properties of all cloudy (τ > 1)
columns were analyzed in sets of simulations that ex-
amined the sensitivity of deep convective cloud objects
to changes in the SST and large-scale forcing. In EX08,
it was found that, as the strength of advective tempera-
ture and moisture forcings was increased, the proportion
of cloudy columns that fit the DC criteria increased. Since
DC columns tend to be higher and more reflective than
non-DC columns, the increase in the proportion of DC
columns with forcing caused the all-cloud distributions
of cloud-top height and albedo to be skewed toward
higher values. In EX08, it was also found that the
proportion of cloudy columns that were DC remained
roughly constant with SST, but the cloud-top heights
tended to increase with SST and the albedos tended to
decrease with SST.

Another widely used satellite dataset for model evalu-
ation is the International Satellite Cloud Climatology
Project (ISCCP) (Rossow and Schiffer 1999), which
classifies clouds based on their cloud-top pressure (p_c)
and τ. Recently, Jakob and Tselioudis (2003), Jakob
et al. (2005), and Rossow et al. (2005) have performed
cluster analyses on 2D histograms of p_c and τ in the
tropics. Each of the histograms represent the joint dis-
tribution of ~5 km satellite pixel values of p_c and τ
within a 2.5° × 2.5° grid cell. Note that although the
ISCCP pixels are approximately 5 km in size, they are
approximately 30 km apart. Thus, each 2.5° × 2.5° grid
cell has approximately 80 samples. In these analyses,
cluster centroids are called cloud regimes or “weather
states” and are given names such as deep convection,
thin cirrus, and marine stratus. These weather states do
not generally correspond to a single cloud type; for
example, there are some midlevel clouds in the deep
convective weather state, thin cirrus in the stratocumu-
lus weather state, etc. Williams and Tselioudis (2007)
and Chen and Del Genio (2009) have used the ISCCP
cloud regimes to evaluate general circulation models.

This paper introduces the concept of extended cloud
objects (ECOs). To avoid confusion, the cloud objects as
originally defined in Xu et al. (2005) are hereafter re-
ferred to as contiguous cloud objects. As will be ex-
plained in section 2, an ECO covers the maximum zonal
and meridional extents of the contiguous cloud object
without using a fixed Eulerian grid box. An ECO in-
cludes all cloudy satellite footprints bounded by the
most easterly, westerly, northerly, and southerly foot-
prints of the contiguous cloud object. Thus, areas of
optically thin and/or low clouds adjacent to the contig-
uous cloud object are included in the ECO. For the
smallest ECOs (associated with contiguous cloud ob-
jects with equivalent diameters of 100 km) there are at
least 100 footprints, which is a greater tally than the
amount of satellite pixels in a 2.5° × 2.5° ISCCP grid
cell. These ECOs may be superior to contiguous cloud ob-
jects for comparing model results to satellite observa-
tions, as all cloud types within the ECOs are included in
the same area of meteorological data analyses from
which initial soundings and heat and moisture forcings
are calculated and used in the CRM simulations of Luo
et al. (2007) and EX08. Thus, the simulated DC cloud
properties and non-DC cloud properties and their rela-
tive proportions can be simultaneously compared with
the ECO observations to explore the origins of model
deficiencies (see Xu 2009 for further discussion). There
are some similarities between the ECOs in this study
and the tropical deep convective systems studied by B. Lin et al. (2006). One major difference is that the ECOs in this study are larger in area (focusing on scales comparable to the size of mesoscale convective systems) than many of the systems classified by precipitating cores in B. Lin et al. (2006). Also, when looking at how cloud properties changed with SST, B. Lin et al. (2006) looked at the mean value of the properties for each SST bin, rather than examining how the distributions of those properties changed with SST. Subtle changes in cloud properties can be difficult to interpret or missed entirely when only the mean values are examined. Examples of this will be given later.

The purpose of this paper is to introduce, present, and understand properties of deep convective ECOs. Section 2 will describe the satellite data used as well as the procedure for identifying the ECOs. The proportions of DC and non-DC footprints and the DC and non-DC distributions of selected cloud properties and how the distributions change with size will be addressed in section 3. The way in which DC and non-DC cloud property distributions change with SST will be presented in section 4. The behavior of cloud-top temperature with satellite precession cycle is examined in section 5. A comparison between the $p_{c-t}$ joint histograms of the deep convective ECOs and the deep convective weather state (WS1) from Rossow et al. (2005) is shown in section 6. A summary and conclusions will be given in section 7.

2. Data

The dataset from which contiguous cloud objects are generated and the method of their generation are described in detail in Xu et al. (2005). In summary, the contiguous cloud objects are generated using the CERES Single-Scanner Footprint (SSF) data product (Wielicki et al. 1996). The broadband radiative fluxes in the CERES SSF are calculated on the ~100 km$^2$ satellite footprints using angular distribution models derived from the CERES Tropical Rainfall Measuring Mission (TRMM) broadband radiance measurements (Loeb et al. 2003). Cloud microphysical (liquid water path, ice water path, water droplet radius, and ice particle diameter), macrophysical (cloud fraction, effective cloud height, effective cloud-top pressure, and effective cloud-top temperature), and optical (visible cloud optical depth and cloud infrared emissivity) properties are obtained using the high-resolution (~2 km × 2 km) Visible/Infrared Scanner (VIRS) on the TRMM satellite. Hereafter, the word “effective” is omitted from cloud height, cloud-top temperature, and cloud-top pressure. For details about the VIRS retrievals, see CERES algorithm theoretical basis documents (Baum et al. 1997; Minnis et al. 1997) and Minnis et al. (1998). The properties obtained from the VIRS imager are averaged over the CERES footprints using an energy point-spread function (Smith 1994). If the VIRS retrievals indicate that there are two separate cloud layers within an SSF footprint, then the properties are averaged for each of the layers (Baum et al. 1997). Uncertainties in the retrieved properties can be found in the aforementioned documents. Estimates of the systematic biases and random errors for histograms of cloud object properties from CERES SSF data are given in Xu et al. (2007).

To find the deep convective contiguous cloud objects, those CERES footprints that meet the DC selection criteria (cloud-top height greater than 10 km, cloud optical depth greater than 10, and cloud fraction of at least 0.999) are identified. As with Xu et al. (2005, 2007), this study is limited to deep convective cloud objects that occur over the tropical (25°S–25°N) Pacific Ocean between January and August 1998. These footprints are then used as “seed points” in the region-growing algorithm of Wielicki and Welch (1986). As noted in Xu et al. (2005), the shape of the contiguous cloud object can be irregular, with “holes” within the object, and it can sometimes be cut off by the edge of the satellite swath. The code used to find the cloud objects in Xu et al. (2005, 2007) has been slightly altered. The viewing zenith angles used to identify the cloud objects analyzed in Xu et al. only extended to approximately 40° from nadir; this has been extended to approximately 48° from nadir in order to use the full swath of CERES SSF data. Also, there was a small error in matching up the central sample numbers within individual scans; this has been corrected. The net effect of these alterations to the code has been to increase the number of cloud objects in each size category by 36%, 31%, and 24% for the small, medium, and large categories (defined below), respectively. The properties of the DC footprints are very similar to those found in Xu et al. (2007), as will be shown later.

To form an extended cloud object, the maximum and minimum latitude and longitude of the object are used. These four points define a rectangle, as shown in Fig. 1. Then, all of the cloudy satellite footprints that fall within this rectangle from the same orbit as the contiguous cloud object are considered to be the ECO. As will be discussed in section 3, footprints that are partly cloudy and/or have multilayer clouds are included in the ECO. The contiguous cloud object only includes footprints corresponding to the cumulonimbus and thick anvils formed directly from the detrainment of condensate from convective cores. The ECO also includes footprints farther away from convective cores with $\tau < 10$ (thin or dissipative anvils) and all clouds with tops lower than 10 km, so the properties are expected to be distinctly
different between the DC and non-DC portions of the ECOs. Note that, if the contiguous cloud object is close to the edge of the satellite swath, the box that defines the ECO may have a corner that is not covered by satellite footprints, an example of which is shown in Fig. 1. The size category of each ECO is classified by the equivalent diameter of the contiguous cloud object, defined by 100–150 km (small), 150–300 km (medium), and greater than 300 km (large). The equivalent diameter is obtained from the cloud object area, which is the product of the number of footprints in the object and the average footprint size ($100 \text{ km}^2$). The three size categories (100–150 km, 150–300 km, and >300 km) are defined in order to have a large number of cloud objects in each category. The distribution of cloud objects is shown in Fig. 2, which shows that the cloud object locations are spread throughout much of the study area with the exception of the northern central Pacific and the southeast Pacific. The locations of cloud objects are similar between the small, medium, and large categories, although the number of large cloud objects per $5^\circ \times 5^\circ$ grid cell is smaller because the overall number of large objects is smaller, as will be shown shortly. Each cloud object is a statistically independent event, which is why the number of cloud objects is the focus. Although the smaller cloud objects occur more frequently, the total number of footprints in the large category is larger than the small and medium categories combined, owing to the high number of footprints per object in the large category (Xu et al. 2005, 2007). This is further illustrated in Fig. 3a, where the smallest contiguous cloud objects are shown to occur the most frequently, and in Fig. 3b, where the cumulative frequency distribution of overall ECO footprints is plotted versus equivalent diameter.

3. Variations in extended cloud object characteristics with size

The total number of objects and footprints observed for large, medium, and small extended cloud objects are shown in Table 1. As noted in section 2, the number of cloud objects has increased for each size category versus the study of Xu et al. (2007). There are two main categories of footprints: DC (comprised of DC object and DC nonobject footprints) and non-DC (comprised of overcast non-DC, partly cloudy, and multilayer footprints). DC object footprints are footprints within the original cloud object. DC nonobject footprints are footprints that meet the DC selection criteria but are not attached to the main cloud object. Overcast non-DC footprints are diagnosed by the SSF data product as being at least 99.9% cloudy and having a single layer. Partly cloudy footprints are also composed of a single layer but have less than 99.9% cloud cover. Finally, multilayer footprints are diagnosed as having two distinct layers within the footprint, regardless of the amount of cloud cover. Very few (<1%) footprints within the extended cloud objects are clear for all size categories. This is consistent with the very high fractions of cloud cover seen in the deep convective regime identified from ISCCP data by Jakob et al. (2005) and Rossow et al. (2005). This lack of clear footprints may be due to the fairly high thresholds of optical depth and cloud-top height ($t > 10$ and 10 km) for the footprints of the contiguous cloud object. Since footprints with these characteristics generally represent areas of active convection or thick anvil, it is not surprising that most nearby areas are at least partially cloudy. Because there are so few clear footprints in the data for most extended cloud objects, the analyses in this paper will be restricted to cloudy footprints.

As mentioned in the introduction, one of the applications of cloud object data is to explore the origin of model deficiencies, as in Xu (2009). Xu found that the European Centre for Medium-Range Weather Forecasts (ECMWF) model did not reproduce the dependence of cloud object properties with cloud object size, although its effective resolution (Pielke 1991) was in the size range of medium and large cloud objects. As the resolution of models increases, it is expected that all of the three size categories of cloud objects will be adequately resolved. This provides an added motivation for presenting the following analyses.
The fraction of footprints that fit the DC criteria is roughly constant with cloud object size. Note that the terms “cloud object size” and “ECO size” are used interchangeably later, with the categorization following the definition given in section 2. The fraction of overcast non-DC and multilayer footprints also do not change much with size. The fraction of partly cloudy footprints is small for all three size categories, but is somewhat smaller for the small category. As was the case in EX08, the all-cloud probability density function (PDF) of a given quantity is related to the DC and non-DC PDFs by

$$\text{PDF}_{\text{all}} = \left( \frac{A_{\text{DC}}}{A_{\text{all}}} \right) \text{PDF}_{\text{DC}} + \left( \frac{A_{\text{NDC}}}{A_{\text{all}}} \right) \text{PDF}_{\text{NDC}},$$

where $A$ is the number of footprints for all cloud objects in a size category and the subscripts all, DC, and NDC denote the all-cloud, DC, and non-DC populations. As the distributions are compared to one another, the statistical significance of the differences between them can be ascertained using the bootstrap method (Efron and Tibshirani 1993). Details of the method used here are given in Xu (2006).

In Xu et al. (2007), it was shown that large contiguous cloud objects tend to be associated with stronger upward large-scale vertical motions than contiguous cloud objects in the small and medium categories. ECMWF operational analysis data (model cycle dated 1998) was used in Xu et al. (2007); here, we use the ECMWF Re-Analysis (ERA)-Interim data, which represent the
current state of the art in ECMWF reanalysis, with improvements in data assimilation, moist processes, and bias corrections (Uppala et al. 2008). Frequency diagrams of the ECO-matched pressure velocity, $\omega$, as a function of pressure are shown in Figs. 4a–c for small, medium, and large cloud objects. The upward motion tends to be stronger for larger objects, particularly in the upper troposphere, which supports higher cloud tops. The distribution of ERA-Interim vertical velocity at 500 hPa for the three size categories is shown in Fig. 4d, and these distributions are qualitatively consistent with those shown in Xu et al. (2007), with strong ($\omega_{500} < -200 \text{ hPa day}^{-1}$) vertical motions occurring more frequently among large cloud objects than among small or medium cloud objects. However, the magnitudes of the vertical motions in Fig. 4 are smaller than those shown in Xu et al., probably because the grid size of the ERA-Interim coarse-resolution data ($1.5^\circ \times 1.5^\circ$) used here is larger than that of the ECMWF operational analysis ($0.5625^\circ \times 0.5625^\circ$) used in Xu et al. (2007), and vertical motions tend to be weaker when averaged over a larger area.

The all-cloud, DC, and non-DC distributions of albedo are shown for the three size categories in Figs. 5a,c,e. Note that comparisons between the DC distributions of albedo and other cloud properties for the small, medium, and large size categories are similar to those shown in Xu et al. (2007). However, the footprints included in the construction of the DC distributions here are slightly different in that there are more cloud objects included in this study. Also, satellite footprints that fit the DC criteria but lie outside the original cloud object (i.e., the “DC nonobject” category in Table 1) are included in the DC distributions here. The effect of the additional cloud objects and the inclusion of the DC nonobject footprints on the shape of the DC distributions is small for albedo and the other cloud properties examined in this study. The all-cloud distributions of albedo show that all three size categories have a fairly broad distribution of albedo from approximately 0.05 to 0.80, but there are larger amounts of both higher (>0.60) and lower (<0.35) albedos for large ECOs than small ECOs. The changes in the shape of the all-cloud distributions of albedo are fairly obvious, but the arithmetic mean value of albedo is nearly constant with size (0.494 for small objects, 0.484 for medium objects, and 0.517 for large objects).

Table 1. Number of footprints in different categories (see text for a detailed description) for small, medium, and large ECOs. Numbers in parentheses represent the fraction of total cloudy footprints in that category.

<table>
<thead>
<tr>
<th>Category</th>
<th>Large</th>
<th>Medium</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of objects</td>
<td>618</td>
<td>1172</td>
<td>1166</td>
</tr>
<tr>
<td>DC object</td>
<td>1 066 969 (0.514)</td>
<td>400 125 (0.481)</td>
<td>132 426 (0.517)</td>
</tr>
<tr>
<td>DC nonobject</td>
<td>55 656 (0.027)</td>
<td>21 506 (0.026)</td>
<td>4846 (0.019)</td>
</tr>
<tr>
<td>Total DC</td>
<td>1 122 625 (0.541)</td>
<td>421 631 (0.507)</td>
<td>137 272 (0.536)</td>
</tr>
<tr>
<td>Overcast non-DC</td>
<td>626 349 (0.302)</td>
<td>258 723 (0.311)</td>
<td>75 327 (0.294)</td>
</tr>
<tr>
<td>Partly cloudy</td>
<td>53 485 (0.026)</td>
<td>23 601 (0.028)</td>
<td>4986 (0.019)</td>
</tr>
<tr>
<td>Multilayer</td>
<td>274 410 (0.132)</td>
<td>127 067 (0.153)</td>
<td>38 597 (0.151)</td>
</tr>
<tr>
<td>Total non-DC</td>
<td>954 244 (0.459)</td>
<td>409 391 (0.493)</td>
<td>118 910 (0.464)</td>
</tr>
<tr>
<td>Total cloudy</td>
<td>2 076 869</td>
<td>831 022</td>
<td>256 182</td>
</tr>
</tbody>
</table>
and 0.489 for large objects), showing that using an average value of a property can neglect important changes in the distribution of that property. The increase in the frequency of albedos greater than 0.60 with cloud object size is partially due to the presence of higher albedos among DC footprints (Fig. 5c). This increase in albedo among DC footprints was also seen in the results of Xu et al. (2007). Conversely, there is also an increase in the frequency of low albedos in the all-cloud distribution because the albedos of the non-DC footprints decrease with cloud object size (Fig. 5e). This increase in the frequency of low albedos with size for non-DC footprints may be partially due to the longer lifetime of large mesoscale convective systems and subsequent production of thin anvils, as explained further below.

When a bootstrap test (Xu 2006) is applied, the differences between the all-cloud distributions of albedo between pairs of size categories (small and medium, medium and large, small and large) are all found to be strongly significant, with \( p \) (probability) values less than 0.01. The DC and non-DC distributions of albedo are also significantly different from one another with \( p < 0.01 \). In fact, for every cloud physical property examined here, the distributions of small-, medium-, and large-sized ECOs were found to be strongly significantly different from one another according to the bootstrap test. For the DC distributions, this result is consistent with the results of Xu et al. (2007). Note that the differences between a pair of distributions need not be large to be significant if each of the distributions has a large number of independent samples, as is the case here.

The all-cloud distributions of \( \tau \) are peaked at low values of \( \tau \) for large- and medium-sized objects (Fig. 5b), indicating that the non-DC footprints with \( \tau < 10 \) make up a significant portion of the overall distribution. Note that these distributions of \( \tau \) actually extend to 120, but only the portion up to 50 is plotted here. The small-sized cloud objects have a peak at approximately \( \tau = 10 \). In Xu et al. (2007), a comparison of the distributions of cloud optical depth for different size classes of contiguous cloud objects showed that the proportion of footprints with relatively small optical depths \( (10 < \tau < 25) \) decreased with size category. This is true among the DC distributions (Fig. 5d). The stronger large-scale upward motion associated with larger systems (Fig. 4) support more vigorous convection that has higher values of \( \tau \). However, the fraction of non-DC clouds with low optical depths \( (\tau < 5) \) increases with size for non-DC footprints (Fig. 5f). Note that the discontinuity at \( \tau = 10 \) in
Fig. 5f is due to the definition of DC footprints. Xu et al. concluded that cumulonimbi and thick anvil clouds are more abundant for the larger size categories of contiguous cloud objects. This is supported in the DC distributions of $t$, but the non-DC distributions of $t$ indicate that the anvils outside the convective core tend to have lower optical depths for larger cloud systems.

The distributions of condensate water path (Fig. 6), which are closely related to those of $t$ (Fig. 5), are log-normal in shape. Here, condensate water path is the sum of cloud liquid water path and cloud ice water path. Because the majority of cloud-top temperatures (Fig. 7a) are well below 273 K, most of the condensate in these distributions is ice. The all-cloud distributions of condensate water path have maxima at low values (<600 g m$^{-2}$), but the magnitude of this narrow peak decreases with size, as the larger ECOs have more footprints with relatively large condensate water paths.
The DC distributions of condensate water path have a single peak as well, but it is at slightly higher values due to the cloud optical depth cutoff. There tend to be more DC footprints with large values of condensate water path as the cloud object size increases. By contrast, the non-DC condensate water paths tend to decrease with ECO size. This indicates that although there is a large amount of cloud condensate within the DC portions of large ECOs, the non-DC portions of large ECOs have relatively little cloud condensate in comparison to medium and small ECOs.

Machado et al. (1998) and Horváth and Soden (2008) have examined the evolution of MCSs using geostationary satellite data. In these studies, it was found that larger MCSs tend to have longer lifetimes, and the larger MCSs spend a long period of time expanding their anvil areas compared to small MCSs. In a study of Lagrangian trajectories by Luo and Rossow (2004), it is shown that thick anvil clouds go through cirrostratus (3.6 ≤ τ ≤ 23 in the ISCCP classification) and then cirrus (τ < 3.6) stages. For large, long-lived MCSs, it is more likely that some of the non-DC area has decayed to the cirrus stage.

The distributions of cloud-top temperature shown in Figs. 7a,c show that there is a notable shift of probability density toward lower cloud-top temperatures as the size of the ECOs increase for both the all-cloud and DC distributions. The stronger upward large-scale vertical motion for large cloud objects (Fig. 4) is supportive of higher cloud tops; this was also seen in Xu et al. (2007). Machado et al. (1998) saw an increase in the frequency of low infrared brightness temperatures with the size of MCSs, which is consistent with these results, although the study by Machado et al. focused on areas close to the Americas rather than the Pacific. The non-DC distributions of cloud-top temperature (Fig. 7e), which are wider with peaks at higher temperatures than the DC counterparts, change very little with ECO size between the small and medium categories in comparison to the DC and all-cloud distributions. It is interesting to note that the cloud-top temperature distributions shown here have only one peak, in contrast to other studies which have also identified peaks in cloud-top height or cloud-top temperature associated with shallow and congestus clouds (Kubar et al. 2007; Haynes and Stephens 2007; Kubar and Hartmann 2008). Since ECOs are associated with large, contiguous areas of deep convection, there tend to be relatively few boundary layer or congestus clouds in their vicinity.

In Figs. 7b,d,f, the distributions of OLR are shown. The DC distributions of OLR are restricted from 80 to 180 W m⁻², whereas the all-cloud distributions of OLR stretch from approximately 80 to 280 W m⁻², with primary maxima that shift from approximately 160 W m⁻² for small cloud objects to 125 W m⁻² for large cloud objects (Fig. 7b). The shift to lower values of OLR (closely related to the shift to lower values of cloud-top temperature, Figs. 7a,c) with increasing cloud object size is due to an increase in the strength and vertical extent of convective systems with large-scale upward motion (Fig. 4). The large ECOs tend to have slightly lower values of OLR among non-DC footprints than the small and medium cloud objects, but these differences are minor in comparison to those among the all-cloud and DC distributions (Figs. 7b,d,f).
4. Variations in extended cloud object characteristics with SST

The behavior of deep convective systems with SST has been reexamined with advanced satellite data by several researchers, including Del Genio et al. (2005) and B. Lin et al. (2006). These studies have tended to look at average behavior within a given SST range rather than changes in distributions, as in this study. The number of footprints associated with large ECOs in different SST ranges is shown in Table 2. The SST of a given ECO is determined by averaging over the SSTs of all satellite footprints within it. The number of objects and the overall number of footprints is strongly peaked in the 302.0–303.0-K range, indicating that most large ECOs occurred in a fairly narrow range of SST. For small and medium ECOs, the distribution of SSTs is slightly wider (not shown, see Xu et al. 2007), but most of these objects occur at SSTs between 301.0 and 303.0 K. The number of footprints per object also increases with SST, particularly between the SST = 302.0–303 K (3517 footprints per object) categories. This is largely consistent with the results of Del Genio and Kovari (2002), who found that...
storms over the tropical oceans tend to increase in size with SST, and B. Lin et al. (2006), who found that there was a small positive trend in the size of deep convective systems with SST for SSTs between 300 and 304 K but a decrease with SST for SSTs between 294 and 300 K. Note that the definitions of convective systems used in these three studies are significantly different.

Thus, some of the changes in cloud physical and radiative properties with cloud object size that were seen in section 3 may also be present with increasing SST. Since there is a significant increase in the size of cloud objects with SST between the two lowest SST categories, the larger cloud objects are likely associated with wider areas of thin cirrus, as discussed in section 3. Although relatively few large ECOs occur at SSTs below 301.0 or above 303.0 K, the proportion of DC footprints remains nearly constant for all SSTs, at 0.53–0.55. The value of $A_{DC}/A_{all}$ also did not change much with SST in the modeling study of EX08, although the value itself was considerably lower than the observations shown here.

The proportion of DC footprints also remains nearly constant with SST for small (0.52–0.54) and medium (0.49–0.51) ECOs (not shown). This indicates that within a cloud object size category the SST has little impact on the proportion of DC footprints.

The distributions of albedo for large ECOs of four SST ranges are shown in Figs. 8a,b. The all-cloud distributions of albedo show that albedo tends to decrease with SST (Fig. 8a), particularly between the two lowest SST ranges. The arithmetic mean all-cloud albedo is 0.522, 0.493, 0.483, and 0.487 for <301 K, 301–302 K, 302–303 K, and >303 K, respectively. The DC distributions of albedo are fairly similar for different SSTs (not shown). The non-DC distributions of albedo are much more different from one another, with a systematic decrease of albedo with increasing SST (Fig. 8b). There was also a decrease in albedo among the non-DC columns with SST in the modeling study of EX08, although it was shown in terms of shortwave cloud radiative forcing. Because the size of cloud objects increases with SST, these larger cloud objects have a greater opportunity to form thin cirrus, as noted in section 3. Also, Del Genio and Kovari (2002) have shown that the fraction of updraft water that goes into detrained cloud condensate peaks at approximately 301 K. As will be shown, there is a greater proportion of non-DC footprints with low condensate water paths for high SSTs. The low condensate water paths are associated with low albedos. Because $A_{DC}/A_{all}$ does not change much with SST for large ECOs, these differences in the non-DC distributions of albedo are the primary source of the variations in the all-cloud distribution of albedo with SST [see Eq. (1)].

As might be expected from the results for albedo, the all-cloud distributions of cloud optical depth show that $\tau$ tends to decrease with SST (Fig. 8c) with shifts in the position of the peak. The DC distributions of $\tau$ do not change much with SST (not shown). However, the peaks in the non-DC distributions of $\tau$ become much sharper and occur at lower values of $\tau$ as SST increases (Fig. 8d). As discussed earlier, the proportion of clouds within tropical deep convective systems that fit the DC criteria remains fairly constant with SST (Table 2), and these DC clouds have similar distributions of $\tau$. As the amount of condensate detrained into anvils and low clouds outside the DC portion of these systems tends to decrease with SST, these clouds tend to be optically thinner as SST increases. This explanation is supported by Figs. 8e,f.

There are notable shifts toward lower cloud-top temperatures as SST increases, as shown in Fig. 9a. This is associated with shifts toward lower cloud-top temperatures in both DC and non-DC distributions of cloud-top temperatures (Figs. 9c,e). These results and the behavior of corresponding distributions of cloud-top height (not shown) indicate that, as the SST increases, the convection reaches higher altitudes and detrains at these altitudes, primarily because convective instability increases with SST. The amount of non-DC cloud-top temperatures lower than 240 K increases with SST, indicating that convection at high SSTs has more high, optically thin anvils surrounding the area of strongest convection. This is illustrated by the joint distributions of $\tau$ and cloud-top height for ECOs with SST <301 K and ECOs with SST >303 K (Fig. 10). The increase in cloud-top height with cloud optical depth for both of these joint

<table>
<thead>
<tr>
<th>SST Range</th>
<th>Number of objects</th>
<th>Number of footprints</th>
<th>Average number of footprints per object</th>
<th>DC</th>
<th>Non-DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;301 K</td>
<td>62</td>
<td>152 542</td>
<td>2360</td>
<td>84 031 (0.551)</td>
<td>68 511 (0.449)</td>
</tr>
<tr>
<td>301–302 K</td>
<td>168</td>
<td>553 237</td>
<td>3293</td>
<td>295 186 (0.534)</td>
<td>258 051 (0.466)</td>
</tr>
<tr>
<td>302–303 K</td>
<td>316</td>
<td>1 111 269</td>
<td>3517</td>
<td>600 062 (0.540)</td>
<td>511 207 (0.460)</td>
</tr>
<tr>
<td>&gt;303 K</td>
<td>72</td>
<td>259 821</td>
<td>3609</td>
<td>143 346 (0.552)</td>
<td>116 475 (0.448)</td>
</tr>
</tbody>
</table>
distributions differs somewhat from the results of Kubar et al. (2007), who found that cloud-top temperature was nearly invariant with $t$, except for very high $t$. Part of the reason for these differences may be that the observations of Kubar et al. were not confined to instantaneous observations in the vicinity of deep convection, as is the case in this study.

As noted in Xu et al. (2007), there are two peaks in the distribution of OLR for contiguous cloud objects at approximately 124 and 140 W m$^{-2}$, associated with deep convective cores and thick anvil clouds, respectively. This is also the case for the all-cloud and DC distributions of OLR for deep convective ECOs, as shown in Figs. 9b,d. As the SST increases, the amplitude of the convective core peak increases relative to the thick anvil peak. The distributions of OLR for non-DC footprints have only one peak, located at approximately 170 W m$^{-2}$ for all SST ranges (Fig. 9f). These distributions are less dependent on SST, but there are slightly higher values of probability density for lower values of OLR as SST increases. The implied cloud feedback from the decreases in OLR and albedo with SST (Fig. 8a) is likely positive for ECOs, but the length and timing of the dataset shown here (8 months in a strong El Niño year) warrant

Fig. 8. (left) All-cloud and (right) non-DC distributions of (a),(b) albedo, (c),(d) cloud optical depth, and (e),(f) condensate water path for large ECOs in different SST ranges.
caution in terms of this interpretation. As shown in Xu et al. (2007), the large-scale dynamics associated with each SST range are not fixed, creating another possible source of differences. As Del Genio and Kovari (2002) note, the changes in the thermodynamic and dynamic structure of the atmosphere associated with SST in the current climate are likely to be stronger than those associated with a global-scale increase in temperature.

The above changes in the properties of tropical deep convective ECOs with SST can be summed up as follows. As SST increases, the fraction of high, optically thick clouds (DC footprints) remains approximately constant. Both DC and non-DC portions of the ECOs reach higher in altitude, and this is also associated with decreases in OLR and cloud-top temperature. The reflectivity of the ECOs decrease with SST, primarily because of changes in the non-DC clouds. This is partially due to an increase in optically thin anvils, which may result from the larger-sized, longer-lasting ECOs at high SST (see Machado et al. 1998, section 3). Also, there is observational evidence that the fraction of updraft water that goes into detrained cloud condensate
rather than precipitation peaks at approximately 301 K (Del Genio and Kovari 2002). The increase in the altitude at which thick anvil clouds form with higher SST is primarily due to the increase of convective instability with higher SST, which favors high convective cores at higher SSTs. Therefore, at high SSTs, the convection detrains at higher altitudes and produces anvils of approximately the same size relative to the DC portion of the ECO, but the amount of ice in the anvils decreases.

5. Variation of cloud-top temperature with satellite precession cycle

The fixed anvil temperature hypothesis of Hartmann and Larson (2002) states that owing to the strong dependence of saturation water vapor (and thus, radiative emission related to water vapor) on temperature, the temperature at which tropical convective anvil clouds occur will remain constant during climate change. Xu et al. (2007) noted that there was a lack of change in the distributions of cloud-top temperature with satellite precession cycle during January–August 1998, despite significant changes in the distribution of SST with precession cycle due to the 1998 ENSO event. However, as previously noted, the study of Xu et al. only examined DC footprints. The all-cloud, DC, and high non-DC distributions of cloud-top temperature for different satellite precession cycles are shown in Fig. 11. Here, “high non-DC” footprints are those that are at least 10 km in cloud-top height, but do not fit the other DC criteria, and “all high” footprints include those from the high non-DC and DC categories. The lower-altitude footprints are ignored because they are not relevant to the fixed anvil temperature hypothesis. The precession cycle of the TRMM satellite is 46 days, and the first cycle (January–February) was selected to begin near the peak of the El Niño phase on 14 January 1998, and the final cycle (July–August) ended on 31 August, as in Xu et al. (2007). In addition to having a sample of the full (daytime) diurnal range of observations for each location, the large-scale dynamics between precession cycles tend to be closer to one another than between SST ranges, as noted in Xu et al. Figure 11 shows that the distribution of cloud-top temperature for high non-DC footprints also does not change much with satellite precession cycle.

A bootstrap test between the all-cloud distributions of cloud-top temperature verifies that for the most part, the differences between the all high cloud distributions of cloud-top temperature are not significant between adjacent precession cycles, which was also the case for the DC distributions examined in Xu et al. (2007). An exception is between the April–May and June–July cycles, which are different with a p value of 0.04. The differences between nonadjacent precession cycles (March–April versus June–July, January–February versus July–August) are significant with p values less than 0.01. This appears to be largely due to differences in the distributions of cloud-top temperatures at temperatures greater than approximately 225 K among high non-DC clouds (Fig. 11c). The distributions of cloud-top temperature below this value are more similar to one another, despite considerable variations in the SST (Fig. 11d). This is a further confirmation of the fixed anvil temperature hypothesis of Hartmann and Larson (2002).

6. Joint distributions of cloud-top pressure and cloud optical depth

As noted in section 1, Rossow et al. (2005) have used ISCCP data to define weather states in terms of joint histograms of \( p_c \) and \( \tau \) in the tropics [defined as from 15°S to 15°N by Rossow et al., (2005)]. Figure 12a shows the joint distribution of \( p_c \) and \( \tau \) for the “WS1” centroid in Rossow et al., identified as the most convectively active weather state in the ISCCP data. The corresponding distribution among large deep convective ECOs (Fig. 12b) is quite similar to WS1. As noted in section 1, the CERES SSF data used here has more samples for a given cloud system than the ISCCP data. The correlation between the joint histogram in Fig. 12b and the most convectively active ISCCP weather state from the six-cluster analysis (obtained online at http://isccp.giss.nasa.gov/tclus ter.html) is very high, at 0.94. The correlation between the medium-sized deep convective ECOs and the deep convective ISCCP weather state is also quite high (0.93), and the correlation between small-sized deep convective ECOs and the deep convective ISCCP weather state
has a similar value (0.91). The joint distribution of \( p_c \) and \( \tau \) for the DC footprints of large ECOs (not shown) is solely limited to the highest and optically thickest bins in the ISCCP categorization.

These results indicate that although the distributions of different cloud physical properties change with ECO size, the joint distributions of \( p_c \) and \( \tau \) for all three deep convective ECO size classes have fundamental similarities to the deep convective ISCCP weather state. The differences between the deep convective weather state portrayed by current GCMs and that of the deep convective ISCCP weather state are far greater than those between the CERES and ISCCP deep convective weather states (see Williams and Tselioudis 2007). Therefore, comparing 1D histograms of cloud physical properties for the deep convective weather states simulated by these models to those presented here should serve as a useful diagnostic tool to help isolate the problems that these models have in the simulation of deep convection [see Xu (2009) for further discussion].

7. Summary and conclusions

In this study, tropical deep convective extended cloud objects (ECOs) have been introduced and their properties have been examined. Like the contiguous cloud objects introduced by Xu et al. (2005), these ECOs are focused on individual instances of convection, but the ECOs also capture surrounding areas of low clouds and thin anvils that are likely to be associated with the convective system. In addition to examining the all-cloud distributions of cloud and radiative properties, the distributions of only those footprints that fulfill the DC criteria are examined, as well as the distributions of those footprints that do not fit the DC criteria. This allows for the effects of changes in the highest, thickest clouds on the overall distributions of cloud properties to be separated from the effects of changes in the non-DC clouds. As summarized below, the changes in the non-DC cloud physical properties are often different in magnitude and/or opposite in sign to the changes in DC cloud physical properties, making this an important supplement to the results of Xu et al. (2007), who only studied DC properties.

As ECOs increase in size, the reflectivity of the DC clouds increases with higher albedos, condensate water paths, and cloud optical depths. However, the non-DC values of albedo, condensate water path, and cloud optical depth decrease with cloud object size. This dichotomy may be due to the longer lifetimes of large
MCSs (Machado et al. 1998), which allows for more thin anvils to form while there is still an area of strong convection. The cloud-top heights of ECOs also tend to increase with size, and larger ECOs are also associated with lower values of OLR and cloud-top temperature. This increase in convective strength is likely due to the increased magnitude of large-scale upward motion associated with large ECOs. The changes in the DC portion of ECOs contribute to the shift toward lower values of cloud-top temperature and OLR in the all-cloud distributions, as well as higher cloud tops. The changes in the non-DC distributions of cloud macrophysical properties are relatively minor.

Within each size category of ECOs, the proportion of cloudy footprints that fulfill the DC criteria $A_{DC}/A_{all}$ remains fairly constant with SST, although the number of footprints per object increases with SST for large objects. This was also the case in the modeling study of EX08, although the simulated values of $A_{DC}/A_{all}$ were considerably lower than those observed. The reflectivity of large ECOs tended to decrease with SST, primarily because the albedo, optical depth, and condensate water path of non-DC footprints tended to decrease with SST. This is consistent with the results of Del Genio and Kovari (2002), who found that the fraction of updraft water that goes toward detrainment peaks at approximately 301 K. As SST increases, the cloud-top heights tend to increase and cloud-top temperature and values of OLR tend to decrease for ECOs. An increase in convective instability helps the vigor of convection to increase with SST (as indicated by the decrease in cloud-top temperatures, particularly among DC footprints). These changes in cloud physical and radiative properties with SST are qualitatively consistent with those seen in the modeling study by EX08. The positive cloud feedback for ECOs implied by the decreases in albedo and OLR with SST shown here deserves further research over longer time periods. At a minimum, the changes in cloud forcing solely due to SST changes must be isolated from those associated with variability in the large-scale environment.

The DC, high non-DC, and all high-cloud histograms of cloud-top temperature did not change much with satellite precession cycle. This is despite the fact that the SSTs changed significantly between January 1998 (near the peak of the 1997–98 El Niño) and August 1998 (the dissipative phase of the 1997–98 El Niño). This supports the fixed anvil temperature hypothesis of Hartmann and Larson (2002).

The joint histogram of $p_c$ and $t$ for large ECOs is very similar to the WS1 (or deep convective) weather state studied by Rossow et al. (2005). The density of satellite footprints for a given cloud object is higher for the ECO data presented here than for the ISCCP data, owing to the sampling method used by ISCCP. When a GCM is tested against the observed WS1 $p_c$–$t$ categorization, the summary histograms from ECOs can also be used to test that GCM’s ability to simulate other cloud physical and radiative properties. These summary histograms can detect systematic differences in cloud property distributions that may correspond to minor differences in arithmetic means of those properties.

In the future, data from the CERES instruments on the Terra and Aqua spacecraft will be used to study deep convective ECOs and boundary layer clouds over the full annual cycle and interannual variability. The deep convective ECOs will be used to evaluate the performance of ECMWF cloud parameterizations in a manner similar to that shown in Xu (2009).

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REFERENCES


Uppala, S., D. Dee, S. Kobayashi, P. Berrisford, and A. Simmons, 2008: Towards a climate data assimilation system: Status update of ERA-Interim. ECMWF Newsletter, No. 115, ECMWF, Reading, United Kingdom, 12–18.


