

An analysis of statistical characteristics of stratus and stratocumulus over eastern Pacific

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[1] Observational measurements of cloud base, top, thickness, fraction, and liquid water path (LWP) are analyzed to study the macro- and micro-physical properties of stratus and stratocumulus over the eastern Pacific. It is found that the increase in liquid water content with height in cloud is significantly less than the adiabatic rate. The variations of cloud base and top both contribute to the variation of cloud thickness that approximately fits a normal distribution better than either cloud base or top. Because the distribution of LWP depends on the intervals of cloud fraction (or other environmental variables, for example, relative humidity), the determination of cloud fraction from the mean LWP alone would introduce large uncertainties particularly when LWP is large. **Citation:** Zhou, M., X. Zeng, M. Brunke, Z. Zhang, and C. Fairall (2006), An analysis of statistical characteristics of stratus and stratocumulus over eastern Pacific, *Geophys. Res. Lett.*, 33, L02807, doi:10.1029/2005GL024796.

1. Introduction

[2] Clouds strongly affect the earth's climate due to their influence on radiation. The treatment of cloud properties, for example, cloud fraction (CF), condensate and its horizontal distribution, is still poor in weather and climate models. For instance, most models estimate CF based on the mean relative humidity or the relative humidity combined with cloud liquid water content (LWC) in a grid box. In the NCAR Community Atmosphere Model (CAM3), while LWC is computed prognostically, marine stratocumulus CF is empirically diagnosed using the static stability between the surface and 700 mbar derived by *Klein and Hartmann* [1993], and CFs for other types of clouds are diagnosed using relative humidity as the predictor. There are several earlier studies evaluating the performance of the cloud fraction parameterizations using observations or model outputs [e.g., *Xu and Randall*, 1996a].

[3] Calculation of the radiative properties of inhomogeneous clouds remains a central problem in cloud physical properties. *Stephens* [1986] showed that a cloud with an inhomogeneous horizontal distribution of LWC has a lower albedo than a cloud with the same mean (but uniform LWC). Despite its importance, the horizontal distribution of LWC is not considered in most models.

[4] The purpose of this paper is to provide the statistical relationships among macro- and micro-physical properties of stratus and stratocumulus over ocean using observational data over the eastern Pacific and other regions. These results are expected to improve the treatment of stratus and stratocumulus clouds in weather and climate models.

2. Data

[5] The data used in this paper are taken from the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC) experiment in the stratocumulus region over the eastern Pacific (20°S–10° N, 80°W–95° W) during September and October of 2001. From the Galapagos Islands, the R/V Ronald H. Brown steamed west on 9 October to 95°W, then south along 95°W into the southeast Pacific stratocumulus-capped boundary layer. On 25 October, the R/V reached the port of Arica in northern Chile. The observational program of EPIC 2001 was described in detail by *Bretherton et al.* [2004] and *Raymond et al.* [2004].

[6] The observation of stratocumulus cloud optical properties was carried out continuously on the R/V during the experimental period. Used in this study were CF, LWP, and the heights of cloud base and top derived from the observations of cloud optical properties. The CF and cloud base height were derived from ceilometer measurements, and cloud top height was derived from cloud radar. LWP was derived from the microwave radiometer which was a passive remote sensing system aboard the ship. The CF is taken as an average for a period of 5 min of measurements and the cloud base height is the median value in the same period. The cloud top height is taken as the median value in a period of 10 min of measurements. The retrieval of cloud LWP is calculated over a 5-min period [e.g., *Liljegren et al.*, 2001]. To avoid the possible influence of continental contamination, only data from 10–14 October 2001 with entire measurements of CF, LWP, and the heights of cloud base and top were used for this study, since the R/V in this period was in the southeast Pacific region far away from coast.

3. Results

3.1. Cloud LWC Versus Height

[7] Variations of cloud LWC with height have been mostly determined using aircraft observations. Some studies indicated that stratocumulus cloud exhibits adiabatic or near-adiabatic profiles of LWC, while others showed sub-adiabatic change of LWC with height [e.g., *Pawłowska et al.*, 2000]. This is an important issue for cloud microphysical parameterizations and for radiation calculations in global models.

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[8] LWP is defined as the integral of LWC over a cloud thickness h , and can be easily derived as

$$\text{LWP} = \alpha(A/2)h^2, \quad (1)$$

where A is the adiabatic change of LWC with height, usually $2.0\text{--}2.8 \times 10^{-3} \text{ gm}^{-4}$ [e.g., *Albrecht et al.*, 1990; *Austin et al.*, 1995; *Wood and Taylor*, 2001], and α is a constant describing the deviation from adiabatic LWC. For the EPIC data used here, the value of A varies from $2.1\text{--}2.6 \times 10^{-3} \text{ gm}^{-4}$ with a median value of $2.24 \times 10^{-3} \text{ gm}^{-4}$. One hour (rather than 10-min) median values of cloud thickness and LWP based on the EPIC data were used to be consistent with previous studies. The relevant hourly data from TIWE and ASTEX surface-based remote sensing measurements [*White et al.*, 1995, Table 2] and aircraft data from FIRE [*Austin et al.*, 1995, Table 2], RACE [*Raisanen et al.*, 2003, Table 1] and ASTEX [*Wood and Field*, 2000, Figures 1 and 2] were also used for comparison. Figure 1a shows that LWP is proportional to h^2 , consistent with (1). The value of αA estimated from all data used in Figure 1a is $1.76 \times 10^{-3} \text{ gm}^{-4}$. The value of α is then 0.79 using the median A value and varies from 0.68 to 0.84 depending on the actual value of A , implying that the mean increase in LWC with height is around 21% less than the adiabatic value. The entrainment of upper dry air into the cloud top could reduce the LWC within the cloud, especially in the upper part of the cloud [*Gerber et al.*, 2005]. Only a small amount of entrained dry air can cause a considerable reduction of LWC near the top of the cloud. This is likely the main reason for the sub-adiabatic rate of LWC within the cloud. In addition, drizzle may also influence the α value by causing the ceilometer to underestimate cloud base height. However there is less drizzle in the data period we used compared with other days in Figure 8 of *Bretherton et al.* [2004]. Furthermore, using data of 10 October 2001 with almost no drizzle, the calculated α would be similar to the above value.

[9] This issue can be further addressed from a different perspective. The standard deviation of LWP normalized with that of cloud thickness $\sigma_{\text{LWP}}/\sigma_h$ can be derived from (1) as a function of LWP:

$$\sigma_{\text{LWP}}/\sigma_h = \alpha^{1/2}(2A)^{1/2}(\text{LWP})^{1/2}. \quad (2)$$

This relation is shown in Figure 1b based on the EPIC data. In order to obtain reasonable statistics for the calculation of these standard deviations, 2-h time series with statistical stationarity were chosen. Because of the limited amount of data, the 2-h time periods (for which the standard deviations were calculated) were shifted every 10 min instead of every 2-h. The value of α estimated from the data shown in Figure 1b is 0.46 using the median value of A and could vary from 0.41 to 0.50. This means that the increase of $\sigma_{\text{LWP}}/\sigma_h$ with increasing LWP is less than the adiabatic value, consistent with the results in Figure 1a, though the value of α from Figure 1b is less than that in Figure 1a.

[10] *Wood and Taylor* [2001] calculated the standard deviation of LWP normalized with that of the cloud base $\sigma_{\text{LWP}}/\sigma_{\text{base}}$ instead of $\sigma_{\text{LWP}}/\sigma_h$, assuming that the fluctuation in cloud top height is small in comparison with cloud base fluctuations. They found that the increase of $\sigma_{\text{LWP}}/\sigma_{\text{base}}$ with

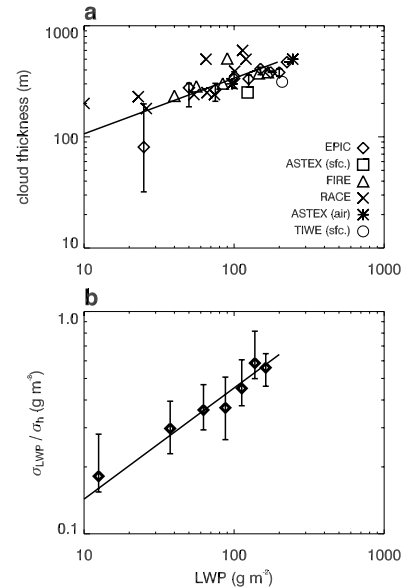


Figure 1. (a) The log-log relationship between cloud thickness and LWP in 25 gm^{-2} bins using surface and aircraft measurements over different oceanic regions. The vertical thin lines for the EPIC data represent the interquartile range (IQR), that is, the difference between the 25th and 75th percentiles, and the other solid line represents the best fit using the EPIC data. The surface and aircraft data were obtained during the Atlantic Stratocumulus Transition Experiment (ASTEX) over the north Atlantic ($27^{\circ}\text{--}37^{\circ}\text{N}$, $22^{\circ}\text{--}27^{\circ}\text{W}$), the aircraft data from the First ISCCP (International Satellite Cloud Climatology Program) Regional Experiment (FIRE) over the Pacific along the California coast ($30^{\circ}\text{--}34^{\circ}\text{N}$, $119^{\circ}\text{--}125^{\circ}\text{W}$), the aircraft data from the Radiation, Aerosol and Cloud Experiment (RACE) in the Bay of Fundy and central Ontario, Canada, and the surface data from the Tropical Instability Wave Experiment (TIWE) over the equatorial central Pacific (0°N , 140°W). (b) The log-log relationship between $\sigma_{\text{LWP}}/\sigma_h$ and LWP in 25 gm^{-2} bins. The vertical thin lines represent the IQRs, while the other solid line represents the best fit to the EPIC data.

LWP is greater than the adiabatic rate by around 30% which is opposite to the results in Figure 1. In an attempt to reconcile these different results, we repeated the computation of *Wood and Taylor* [2001] using the EPIC data, and found that, indeed, $\sigma_{\text{LWP}}/\sigma_{\text{base}}$ increases with LWP higher than adiabatic by about 20–50% depending on the chosen value of A . Therefore, the assumption that the fluctuations of cloud thickness are mainly induced by those of cloud base is not supported by the EPIC data.

3.2. Distributions of Cloud Base Height, Top Height and Thickness

[11] Distributions of cloud base height (z_b), cloud top height (z_t) and h are useful parameters in macro- and microphysics of stratus and stratocumulus. So far these distributions and the relationships among them have not been established. In the statistical model describing the CF and LWP in work by *Considine et al.* [1997], a normal distribution of cloud thickness was assumed. *Wood and Taylor*

[2001] also assumed a normal distribution of cloud thickness and but their assumption that σ_h could be replaced by σ_{base} seems unwarranted.

[12] The EPIC time series show that the cloud top, base and thickness vary significantly with time. Their distributions are shown in Figures 2a–2c. To obtain a reasonable degree of statistical stationarity, five time series of cloud thickness from the EPIC data, each 10–20 hours in length, rather than the whole time series, were used. Figures 2a–2c shows that cloud thickness and cloud base fit the normal distribution better than z_t , but the distribution of z_b becomes narrower and sharper compared with that of h . The probability distribution of z_t is negatively skewed. These three probability distributions are statistically indistinguishable from normal distributions according to Kolmogorov-Smirnov significance testing [Gille, 2004], but the distribution of z_t is the least likely to be the same as a normal distribution.

[13] Theoretically there are relations between the probability distribution function of cloud thickness, $p(h)$, and those of cloud top height, $p(z_t)$, and cloud base height, $p(z_b)$, according to the definition of h ($h = z_t - z_b$). The EPIC 2001 data indicate that the relationship between z_b and z_t is non-linear though the data are somewhat scattered (Figure 2d). If $p(h)$ follows a normal distribution, $p(z_t)$ or $p(z_b)$ would be different from normal distributions due to the non-linear relationship between z_b and z_t .

[14] Physically the negatively skewed distribution of z_t (Figure 2b) might be caused by a complicated process at cloud top. The presence of a cloud top inversion serves to inhibit upward motions and can lead to a smooth cloud top. However, recent studies showed that there frequently exist narrow regions with less liquid water content and cooler temperature than average background values, so-called holes, downdraughts or entrainment events, at the top of stratocumulus [e.g., Gerber *et al.*, 2005; Wang and Albrecht, 1994]. These regions are assumed to be the result of water evaporated by the entrainment of dryer air from above the cloud. This process could induce a fast decrease of cloud top in narrow regions, leading to the formation of strong negative skewness in $p(z_t)$.

3.3. CF and Distribution of LWP Versus Mean LWP

[15] As mentioned in Section 1, weather and climate models usually diagnose CF as a function of the mean relative humidity, the relative humidity combined with cloud water mixing ratio [Xu and Randall, 1996b], or other model variables (e.g., the static stability between the surface and 700 mbar derived by Klein and Hartmann [1993]). *Considine et al.* [1997] developed a simple statistical model to parameterize CF based on the probability distribution of LWP. Here we further address the relationships of CF and LWP distributions versus the mean LWP based on the EPIC data.

[16] The CF can be defined as

$$\text{CF} = \int_{\delta}^{\infty} p(\text{LWP})d(\text{LWP}), \quad (3)$$

where $p(\text{LWP})$ is the probability distribution of LWP. The δ value denotes the transition from clear to cloudy, that is, a threshold of liquid water at which air is defined as cloud

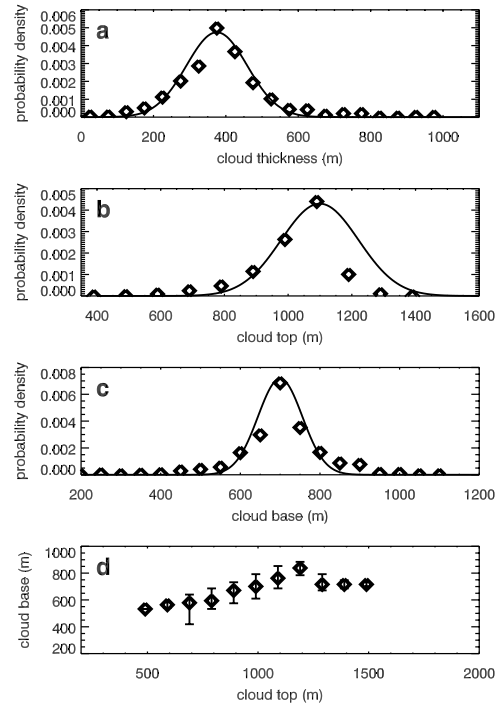


Figure 2. Mean probability distribution functions of (a) cloud thickness, (b) cloud top and (c) base. The solid lines are fitted normal distributions. (d) The median z_b versus z_t in 100 m bins; the vertical thin lines represent the IQRs.

(taken as 3 gm^{-2} by *Considine et al.* [1997]). $p(\text{LWP})$ can be related to $p(h)$ by

$$p(\text{LWP})d(\text{LWP}) = p(h)dh. \quad (4)$$

As discussed above, it is reasonable to assume $p(h)$ to be normally distributed, then

$$p(h) = \frac{1}{\sigma_h \sqrt{2\pi}} \exp \left[-\frac{(h - \bar{h})^2}{2\sigma_h^2} \right], \quad (5)$$

where \bar{h} and σ_h are the mean value and the standard deviation of cloud thickness respectively. Equations (1), (4) and (5) then yield

$$p(\text{LWP}) = \frac{(\sqrt{(2\alpha A)(\text{LWP})})^{-1}}{\sqrt{2\pi\sigma_h^2}} \cdot \exp \left[-\frac{(\sqrt{\text{LWP}} - \sqrt{\text{LWP} - (1/2)\alpha A\sigma_h^2})^2}{\alpha A\sigma_h^2} \right]. \quad (6)$$

[17] Furthermore, σ_h and σ_{LWP} are analytically related through (2). Therefore if σ_h or σ_{LWP} is known, CF can be obtained directly by the integration of (3). The analysis of the EPIC data in Figure 3a indicates that σ_{LWP} increases nearly linearly with LWP for LWP less than 100 gm^{-2} and becomes nearly constant when LWP is greater than 100 gm^{-2} .

[18] Theoretically CF could be estimated using the mean LWP through equations (2), (3), and (6) and the relationship

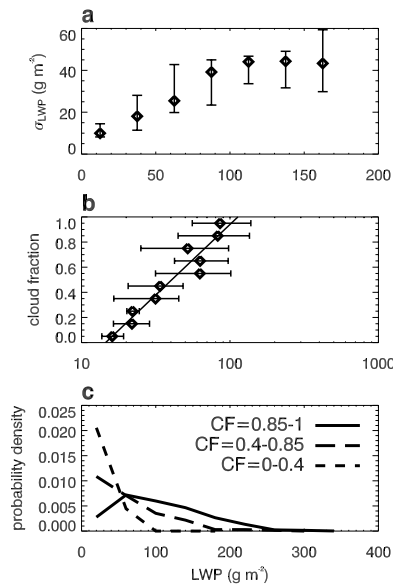


Figure 3. (a) Relationship of σ_{LWP} with LWP in 25 g m^{-2} bins; (b) relationship between LWP (in logarithmic scale) and CF in 0.1 bins with horizontal lines representing the IQRs and the other line denoting the fit to the data; and (c) $p(LWP)$ for different CF intervals.

between σ_{LWP} and LWP in Figure 3a. On the other hand, the relationship of cloud fraction with LWP can also be directly evaluated using the EPIC data. Figure 3b shows that the CF increases logarithmically with the increase of LWP, but scattering becomes large when CF is larger than 0.5. To further understand the results in Figure 3b, Figure 3c shows the $p(LWP)$ in different CF intervals based on the EPIC data. The distribution of LWP is lognormal for $CF = 0.85-1.0$, but close to exponential for $CF = 0-0.4$. The $p(LWP)$ for $CF = 0.4-0.85$ is in between. These three intervals were chosen so that each interval has enough data to create the distribution of LWP. We have also computed $p(LWP)$ for different CF intervals (0.1–0.4, 0.4–0.99, and 0.99–1.0) for comparison with *Xu et al.* [2005], and found that $p(LWP)$ is nearly exponential for $CF = 0.1-0.4$, but lognormal for $CF = 0.4-0.99$ or $0.99-1.0$, consistent with their results based on satellite data analysis.

[19] The observational $p(LWP)$ in Figure 3c can be directly compared with those estimated from (6) along with (2) and σ_{LWP} in Figure 3a. When LWP is less than 50 g m^{-2} (or roughly CF less than 0.6 based on Figure 3b), $p(LWP)$ from (6) is closer to exponential than lognormal (figure not shown), consistent with observational $p(LWP)$. When LWP is larger than 50 g m^{-2} , the $p(LWP)$ is close to normal, with a tail in the direction of high LWP values. This is different from the lognormal distribution from data (e.g., Figure 3c), and this might be the reason for the larger IQR (the difference between the 25th and 75th percentiles) when LWP is large (Figure 3b).

[20] In summary, while it is tempting to use the simple relationship between CF and LWP (e.g., through Figure 3b or through (2), (3), (6) and Figure 3a) in numerical models, it is more appropriate to use different CF versus LWP

relations for different regimes, for example, different CF intervals in Figure 3c, or, more relevant to model applications, carrying out a similar analysis using different relative humidity intervals.

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