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Diurnal cycle of liquid water path over the subtropical and tropical oceans

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Abstract. The diurnal cycle of liquid water path (LWP) over the subtropical and tropical oceans is examined using two complete years of TMI (Tropical Rainfall Measuring Mission Microwave Imager) satellite microwave radiometer data. Diurnal amplitudes are a considerable fraction of the mean, especially in low cloud regions to the west of continents, where values of 15-35% are typical. Early morning maxima occur throughout most of the subtropics, consistent with a diurnal cycle driven largely by cloud solar absorption. In deep convective regions of the west Pacific the diurnal cycle is also strong and peaks slightly later. Interestingly, the diurnal amplitude in the SE Pacific and Atlantic stratus regions is considerably larger than in their northern hemisphere counterparts, suggesting differences in the dynamics and structure of low clouds may exist from region to region. The data provide important constraints for models simulating the diurnal cycle of clouds.

1. Introduction

The diurnal cycle of cloud cover and liquid water has important consequences for the earth's radiative budget (e.g. *Bergman and Salby* [1997]) and provides an important test of the effectiveness of numerical models. Considerable diurnal modulation of low cloud amounts (*Minnis and Harrison* [1984], *Rozendaal et al.* [1995]), and liquid water path (*Fairall et al.* [1990], *Weng and Grody* [1994], *Zuidema and Hartmann* [1995], *Greenwald and Christopher* [1999]) has been observed. *Fairall et al.* [1990], using a 17 day period of near-continuous ground based microwave radiometer data around the time of the First ISCCP Regional Experiment (FIRE), found a large diurnal cycle in cloud LWP, with an amplitude that was 60-70% of the mean. However, the proximity of the observations to the continental coast casts some doubt onto the generalization of the result to cloud fields farther from land. *Zuidema and Hartmann* [1995] examined a two-point sampling of the LWP diurnal cycle of using the special sensor microwave imager (SSM/I) and found morning (7-9 hr local) mean LWP to be 22-42 g m^{-2} higher than in the late afternoon in three stratiform regions. The morning-afternoon differences were notably larger in the SE Pacific and SE Atlantic than in the NE Pacific. *Weng and Grody* [1994] present global maps of cloud LWP from SSM/I, showing that an appreciable diurnal cycle exists over much of the global ocean. These diurnal variations, however, were not examined in quantitatively. *Ciesielski et al.* [2001] has examined the diurnal cycle of a number of cloud and other parameters during ASTEX. The results suggest that there may be significant diurnal modulation of subsidence rates (see also *Dai and Deser* [1999]) in quite remote ocean locations (1000 km from continental landmasses) that could also impact the diurnal cycle of cloud LWP over the oceans. *Rozendaal et al.* [1995] examined the diurnal cycle of ISCCP (International Satellite Clouds and Climatology Project) low cloud amounts over the global ocean. A strong diurnal cycle in low cloud amount was found over much of the subtropical ocean. In the boreal summer season, the diurnal cycles in the NE and SE Pacific were approximately the same. However, in the boreal winter, southern hemisphere clouds showed considerably larger diurnal amplitudes than those in the north.

Most of the findings in marine boundary layer clouds are consistent with a diurnal cycle driven primarily by cloud solar absorption, but with considerable local variations. Such variations that might impact the diurnal cycle of LWP include subsidence rates and the presence of thin high cloud. Cloud diurnal variations, especially in regions of persistent low cloud over the ocean, have a considerable effect upon the earth's radiation budget (e.g. *Rozendaal et al.* [1995]; *Bergman and Salby* [1997]). It is therefore important that large scale numerical models, especially climate models, are able to simulate accurately the diurnal cycle of clouds. This requires that accurate and extensive observations exist of the diurnal cycles of both the cloud liquid water content and the cloud coverage. Here we present an analysis of the liquid water path diurnal cycle using two entire years (1999-2000) of data from the TMI passive microwave radiometer. We break the analysis down by region and season.

2. Analysis methods

The TMI instrument is flown on the Tropical Rainfall Measuring Mission (TRMM) satellite. Details of the imager are given in *Kummerow et al.* [1998]. The LWP retrieval algorithm uses the brightness temperatures observed at three frequencies (19.35, 22.235, 37 GHz). Of these, the 37 GHz channel is most sensitive to liquid water content and this has a 16×9 km footprint. The LWP retrieval algorithm is described in *Wentz* [1997]. Random retrieval errors in LWP are estimated to be 25 g m^{-2} with a small systematic error of 5 g m^{-2}. Satellite microwave and visible/near infrared estimates of LWP compare favourably where there is a completely overcast field of view (*Greenwald et al.* [1997]) with underbias in the microwave retrieval for broken clouds that is in near linear proportion to the sub-field of view cloud fraction. This suggests that the microwave retrieved LWP is more appropriately described as the area-mean value over both clear and cloudy regions of the footprint. To clarify this we refer to LWP_{cld} as being the mean LWP of just the

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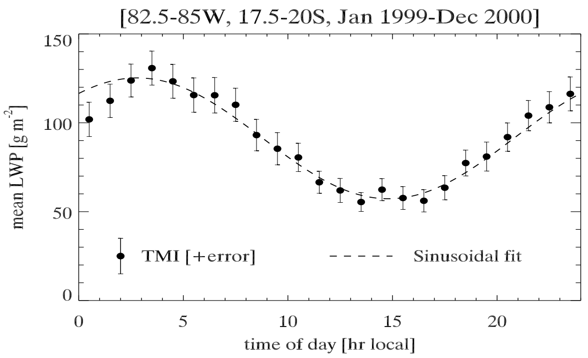

Figure 1. Example of two year mean diurnal cycle from the TMI for a single 2.5×2.5° region in the SE Pacific, showing sinusoidal fit to data.

cloudy fraction of a region of broken clouds. In regions of low cloudiness, the uncertainties in the observed LWP are likely to exceed the mean values and are less trustworthy. The retrievals are unusable over land, and these measurements are excluded from the analyzed dataset. Retrievals are unusable during periods of heavy rain and these are flagged and excluded from the analysis.

The TRMM satellite samples the complete range of local times. Data are provided by Remote Sensing Systems Inc. as swath data interpolated onto a 0.25×0.25° grid at latitudes 40S-40N. We combine the dataset onto a 2.5×2.5° spatial grid for analysis purposes. We bin the data into hourly local time bins (00-01 hr, 01-02 hr etc.) to obtain for each region and time period a series of the mean LWP as a function of local time. The data are then fitted using the sinusoid:

$$\overline{LWP}_{lat,lon}(T) = A_{LWP}\sin[\pi(T+\phi)/12] + \overline{LWP}_{lat,lon,T} \quad (1)$$

where $\overline{LWP}_{lat,lon}(T)$ is the mean liquid water path in spatial bin (lat, lon) at local time T, A_{LWP} is the amplitude of the diurnal cycle of LWP, ϕ is the phase, and $\overline{LWP}_{lat,lon,T}$ is the all-time mean LWP in bin (lat, lon). The least-squares weightings for each local time bin are $w = N_{lat,lon,T}/\sigma^2_{lat,lon,T}$ where $N_{lat,lon,T}$ is the number of observations in each latitude-longitude-local time bin and $\sigma_{lat,lon,T}$ is the standard deviation of the LWP measurements in each bin. The weight w is the inverse of the square of the estimated error in $\overline{LWP}_{lat,lon}(T)$.

An example of the diurnal cycle of LWP is shown for a region in the SE Pacific dominated by low cloud (82.5-85W, 17.5-20S) in Fig. 1. The error bars are the estimated errors in the mean value obtained using the variance of the hourly means (for the days in which these are available) in each 2.5×2.5° box and the number of available days. Over two years, each box is sampled on approximately 60-70 days in each local time bin. This also allows us to perform a seasonal analysis, but a monthly analysis would require a longer time record. Also shown in Fig. 1 is the fitted sinusoid, which provides an adequate model of the diurnal signal, although we note that there are periods with significant deviations (e.g. around 0 UTC, Fig. 1). These deviations do not impair the utility of the sinusoidal model, but highlight that there may exist a somewhat more complicated diurnal cycle possibly linked to local variations. For example, this local variability could include differences in the phase of the diurnal cycle in subsidence rate (*Dai and Deser* [1999]).

2.1. Data reliability

We compared the TMI data with retrievals of LWP from the MODIS instrument on the NASA Terra satellite. MODIS uses an independent method of retrieving the cloud liquid water path, based upon optical thickness and effective radius derived from daytime visible/near infrared radiometry (King et al. 1997). We locate all 1×1° regions for which

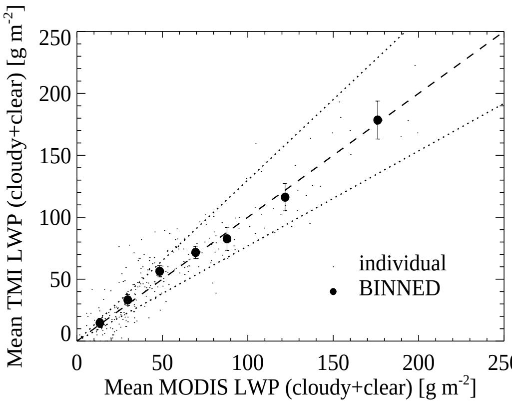

Figure 2. Comparison of LWP (cloud+clr mean) for 251 cases where MODIS and TMI viewed identical 1x1 degree regions simultaneously (± 1 hour) in the NE Pacific (dots). Circles show binned mean values with 2-σ error in mean. The dashed and dotted lines indicates perfect agreement and 25% difference respectively.

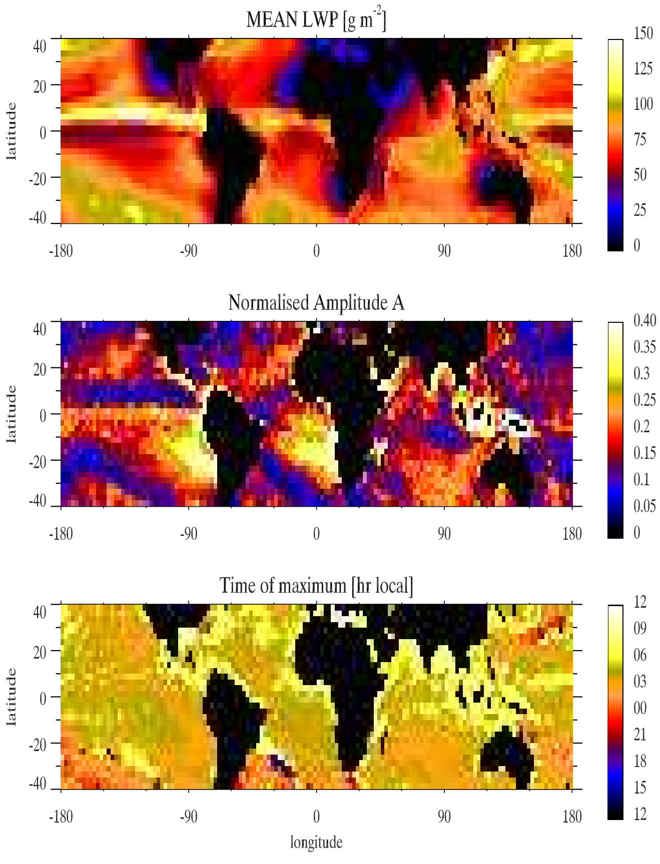

Figure 3. Mean LWP, normalized amplitude $A = A_{LWP}/\overline{LWP}$, and time of maximum LWP between 40S and 40N for the two complete years of TMI data.

the two instruments have coincident (±1 hour) overpasses in the NE Pacific (Sept/Oct 2000). Only clouds with tops warmer than 270K (determined using MODIS) are included in the comparison. The comparison of the two LWP measurements are shown in Fig. 2. Encouragingly, the binned means agree to within 10 g m^{-2} with an RMS difference of 17 g m^{-2} for the individual overpasses.

3. Results

Figure 3 shows maps of the mean LWP, the normalized diurnal amplitude $A = A_{LWP}/\overline{LWP}$ and the local time of the peak LWP for the 2.5×2.5° TMI data for 1999-2000. Mean LWP is highest (> 100 g m^{-2}) in the ITCZ regions of the Pacific and Atlantic Oceans, with additional high values associated with midlatitude systems found towards the north and south of the domain. The extensive regions of low cloud to the west of continents typically have somewhat lower yearly mean LWP in the range 50-80 g m^{-2}. The normalized amplitudes of the diurnal cycle are greatest ($0.15 < A < 0.35$) in these low cloud regions with additional high values in the tropical West Pacific. Here, the largest amplitudes tend to be found close to the island landmasses and may be accentuated by the effect of sea/land breeze triggering of deep convection. Liquid water path during heavy rainfall cannot be retrieved and this may contaminate the diurnal cycle in these regions as LWP and rainrate are likely to be correlated. We expect this to have only a modest impact because only 0.33% of all the 2.5×2.5° analysis regions examined contained more than 5% rain-flagged data.

Only small ($A < 0.1$) diurnal cycles are found in the remote oceanic tropical deep convective regions and in the regions of midlatitude cyclonic activity. A significantly larger diurnal cycle exists in the southern hemisphere subtropical cloud regions of the Pacific and Atlantic when compared with their corresponding northern hemisphere counterparts. The time of the peak LWP is quite uniform in the low cloud regions, peaking typically at 02-05 hr local time. However, there are exceptions to this, with the NE Atlantic subtropical high pressure region having slightly delayed peak times. The time of peak LWP in the tropical West Pacific and the Northern Indian Ocean also tends to occur later, around 09 hr local time. The reasons for this are not clear.

We select five regions of extensive subtropical low cloud, all between 15-30N or 15-30S, defined in Table 1 and compare the 1999-2000 mean values, amplitudes (both in absolute terms and relative to the mean) and peak times. Differences between the northern and southern Atlantic and Pacific regions are found in both the absolute [g m^{-2}] and relative (A) sense. Mean values of the normalized amplitudes for a subdivision of the data into seasonal periods (DJF, MAM, JJA, SON) are shown in Fig. 4. Peak values of A are found during local summer and are reduced in the winters. During the boreal summer, the NE and SE Pacific regions have approximately the same mean value of A.

The seasonal variation of the mean diurnal amplitude is close to 20% of the mean (half of the maximum-minimum mean diurnal amplitude over the year), similar to that in the daytime peak TOA solar flux change over the year (≈17% at the 22.5° north and south latitudes). It is difficult to explain the large geographical differences. Analysis of MODIS data (not shown) reveals that LWP_{cld} distributions in the SE Pacific tend to be narrower for a given area-mean LWP. Because solar absorption increases only slowly with LWP at the range of LWP found in boundary layer clouds, it is possible that a more uniformly distributed cloud layer will be more susceptible to daytime thinning and breakup. Our results however, cannot confirm this hypothesis. It might also be expected that clouds atop shallower boundary layers may be more susceptible to diurnal breakup because the shortwave heating rates are mixed through a shallower layer. Testing these hypotheses requires improvements in both measurements (e.g. by developing climatologies of boundary layer depth) and cloud modeling.

Salby and Callaghan [1997] show that the effects of undersampling the diurnal cycle can introduce biases into estimations of time-mean quantities. Our concern is the inverse of this: are the seasonal variations that are known to exist in cloud properties contaminating our estimates of the diurnal amplitude? The TRMM satellite is in a precessing orbit with a 36-72 day return period depending upon latitude. We

Table 1. Diurnal cycle of LWP for the five subtropical regions dominated by low cloud. Figures in square brackets are standard deviations of all the 2.5×2.5° values in each region.

Region	$\overline{LWP}$ [g m^{-2}]	$\overline{A_{LWP}}$ [g m^{-2}]	$\overline{A}$	T_{max} [hr]
NE Atlantic (40-10W; 15-30N)	44 [16]	9.3 [4.3]	0.21	5.3 [1.6]
NE Pacific (150-110W; 15-30N)	66 [19]	13.4 [5.9]	0.20	3.5 [2.0]
SE Atlantic (20W-20E; 15-30S)	63 [14]	16.9 [6.5]	0.27	3.6 [2.0]
SE Pacific (120-70W; 15-30S)	74 [10]	20.7 [8.0]	0.28	3.4 [1.2]
S Indian (60-110E; 15-30S)	77 [9]	16.8 [4.9]	0.22	3.1 [1.2]

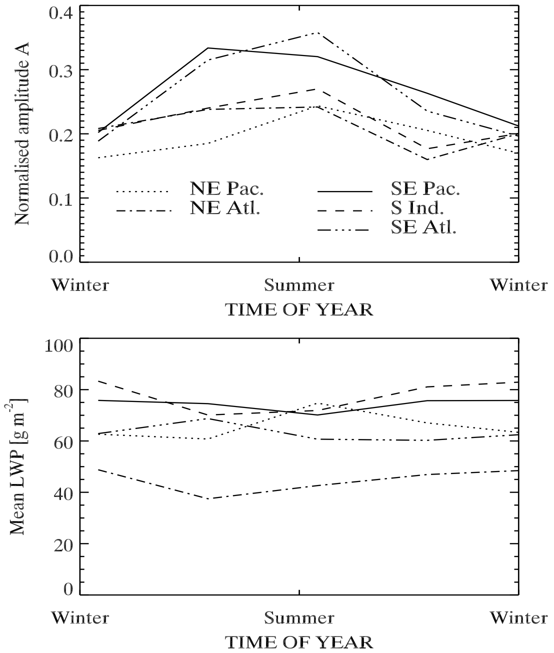

Figure 4. Seasonal variation of LWP diurnal cycle for the five regions dominated by subtropical low cloud shown in Table 1. Southern hemisphere regions are phase shifted relative to those in the north because of the seasonal reversal between hemispheres.

used the known sampling times together with a model containing yearly and diurnal cycles of LWP forced using observations. Hypothetically-sampled diurnal amplitudes match the model ones at all latitudes (40S-40N) to within 4% for yearly averages. Contamination by the seasonal cycle of the mean LWP onto the diurnal cycle is most severe at the higher latitudes and in seasons with the strongest gradients in the mean LWP, but the model diurnal amplitude is matched to within 8% at all latitudes by the hypothetical sampling. We therefore conclude that our diurnal amplitude estimates are not severely biased by sampling issues.

We also examined the ISCCP diurnal cycle of low cloud (*Rossow and Schiffer* [1991]) and found that the geographical variations of the diurnal cycle of LWP are closely related to those in low cloud (see also *Rozendaal et al.* [1995]). Low cloud amount and LWP diurnal cycles are in phase in subtropical regions, indicating that a sizeable fraction of the LWP diurnal cycle is the result of changes in cloud coverage. The normalized amplitude of the low cloud amount diurnal cycle is, on average, 50% of that in LWP, with sizeable variations between seasons and regions. This suggests that diurnal modulation of cloud amount and LWP of the cloudy fraction LWP_{cld} contribute in roughly equal proportion to the diurnal cycle of area-mean LWP. Shortwave radiative transfer calculations based upon these results suggest that the cloud amount diurnal cycle has a greater (factor 2-3) impact than changes in LWP_{cld} upon the morning-afternoon differences in TOA shortwave radiative forcing.

4. Conclusions

We have presented the first quantitative and extensive (two full years of data over the entire subtropical and tropical oceans) study of the diurnal cycle of LWP. We find a strong diurnal cycle especially in regions of extensive low cloud to the west of continents, with an early morning peak in LWP. This peak is in phase with diurnal peak in low cloud amount (*Rozendaal et al.* [1995]) which have diurnal amplitudes of 5-10% in these regions. We find that the LWP cycle has an even greater amplitude of 15-35%, suggesting that a considerable fraction of the diurnal cycle in area-mean LWP is associated with a modulation of the LWP of the cloudy fraction LWP_{cld} in addition to cloud breakup. The results also suggest that the large diurnal cycle observed in FIRE (*Fairall et al.* [1990]) may not be representative of the vast areas of stratiform cloud over the subtropical oceans.

Most compelling in our findings is the larger diurnal cycle in the SE Atlantic and Pacific subtropical low cloud regions relative to those in the northern hemisphere Pacific and Atlantic. It is unclear what physical explanation lies behind the asymmetry, although we hypothesize that a more uniform horizontal distribution of LWP may result in a more pronounced diurnal cycle. Diurnal cycles of subsidence rate that differ from region to region would also have an impact upon the low cloud diurnal cycle. Another possibility is that mid and high cloud cover may differ between the regions studied and may impact upon the diurnal cycle of the low clouds. We expect the mid/high cloud impact upon the low cloud diurnal cycle to be minimal during the summer season in each hemisphere but the N-S hemisphere differences are appreciable. Relatively low droplet concentrations in S hemisphere clouds (*Boers et al.* [1996]) may result in enhanced drizzle depletion of liquid water (*Albrecht* [1989]), which could accentuate the rate of daytime decoupling from their oceanic water source. However, improved understanding of the effect of drizzle upon low cloud is necessary before this effect can be tested. The observations should be useful for comparison with both large scale and more detailed numerical cloud models.

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References

Albrecht, B. A., Aerosols, cloud microphysics, and fractional cloudiness. *Science*, *245*, 1227-1230, 1989.

Bergman, J. W., and M. L. Salby, The role of cloud diurnal variations in the time-mean energy budget. *J. Clim.*, *10*, 1114–1124, 1997.

Boers, R., J. B. Jensen, P. B. Krummel, and H. Gerber, Microphysical and short-wave radiative structure of wintertime stratocumulus clouds over the Southern Ocean. *Quart. J. Roy. Meteor. Soc.*, *122*, 1307-1339, 1996.

Ciesielski P. E, W. H. Schubert and R. H. Johnson. Diurnal variabiity of the marine boundary layer during ASTEX. *J. Atmos. Sci.*, *58*, 2355–2376, 2001.

Dai, A., and C. Deser, Diurnal and semidiurnal variations in global surface wind and divergence fields. *J. Geophys. Res.*, *104*, 31109–31125, 1999.

Fairall, C. W., J. E. Hare, and J. B. Snider, An eight-month sample of marine stratocumulus cloud fraction, albedo, and integrated liquid water. *J. Clim.*, *3*, 847–863, 1990.

Greenwald, T.J., S.A. Christopher, and J. Chou, Cloud liquid water path comparisons from passive microwave and solar reflectance satellite measurements: Assessment of sub-field of view cloud effects in microwave retrievals. *J. Geophys. Res.*, *102* D16, 19585–19596, 1997.

Greenwald, T. J., and S. A. Christopher, Daytime variation of marine stratocumulus microphysical properties as observed from geostationary satellite. *Geophys. Res. Lett.*, *26*, 1723–1726, 1999.

King, M. D., S-C. Tsay, S. E. Platnick, M. Wang, K-N. Liou, Cloud retriveal algorithms for MODIS. Optical thickness, effective particle radius, and thermodynamic phase. *MODIS Algorithm Theoretical Basis document No. ATBD-MOD-05*, NASA, 1997.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.*, *15*, 809–817, 1998.

Minnis, P. and E. Harrison, Diurnal Variability of Regional Cloud and Clear-Sky Radiative Parameters Derived from GOES Data. Part II: November 1978 Cloud Distributions. *J. Appl. Meteor.*, *23*, 1012–1031, 1984.

Rossow, W. B., and R. A. Schiffer, ISCCP Cloud Data Products. *Bull. Am. Meteorol. Soc.*, *72*, 2–20, 1991.

Rozendaal, M. A., C. B. Leovy, S. A. Klein, An Observational Study of the Diurnal Cycle of Marine Stratiform Cloud. *J. Clim.*, *8*, 1795–1809, 1995.

Salby, M. L. and P. Callaghan, Sampling error in climate properties derived from satellite measurements: consequences of undersampled diurnal variability. *J. Clim.*, *10*, 18–36, 1997.

Weng, F., and N. C. Grody, Retrieval of cloud liquid water using the special sensor microwave imager (SSM/I). *J. Geophys. Res.*, *99*, 25535–25551, 1994.

Wentz, F. J., A well calibrated ocean algorithm for special sensor microwave/imager. *J. Geophys. Res.*, *102*, 8703–8718, 1997.

Zuidema, P., and D. L. Hartmann, Satellite determination of stratus cloud microphysical properties. *J. Clim.*, *8*, 1638–1656, 1995.

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