P2.14 DIURNAL CYCLE OF LIQUID WATER PATH OVER THE SUBTROPICAL AND TROPICAL OCEANS

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1. INTRODUCTION

For numerical models to be reliable predictors of future climate change, it is imperative that they accurately simulate the response of clouds to changes in large scale forcings. 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. Other parameters relating to the properties of low clouds such as turbulence intensity (Hignett 1991), temperature and humidity profiles (Betts 1990) are also shown to exhibit diurnal modulation.

Fairall et al. (1990) analysed a 17 day period of near-continuous ground based microwave radiometer data around the time of the First ISCCP Regional Experiment (FIRE) and found a large diurnal cycle in cloud liquid water path, with an amplitude of 60-70% of the mean LWP. However, the proximity of the observations to the continental coast cast some doubt onto the generalization of the results to the cloud fields farther from land. Zuidema and Hartmann (1995) examined a two-point sampling of the diurnal cycle (7-9 hr and 15-16 hr local time) of LWP using the special sensor microwave imager (SSM/I) and found morning 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. Hignett (1991) found a considerable diurnal modulation of boundary layer turbulence and cloud properties from FIRE balloon measurements. Weng and Grody (1994) present global maps of cloud liquid water path from a microwave imager (SSM/I), showing that an appreciable and measurable diurnal cycle exists over much of the global ocean. However, the diurnal variations were not examined in detail. 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 liquid water path 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. The datasets used were derived from thermal infra-red measurements. A strong diurnal cycle in low cloud amount was found over much of the subtropical ocean. In the boreal summer season (JJA), the diurnal cycles in the NE and SE Pacific were approximately the same. However, in the boreal winter (DJF), the southern hemisphere clouds showed considerably larger diurnal amplitudes than those in the north.

Most of the findings in shallow boundary layer clouds are consistent with a diurnal cycle driven primarily, but not necessarily exclusively, by cloud solar absorption. A better understanding of the processes controlling the diurnal cycle, and therefore the shortwave radiative properties of clouds, requires improved observations of the cycle over large spatial and temporal scales.

2. ANALYSIS METHODS

In this study we analyse two years (1999-2000) of TMI passive microwave radiometer retrievals of cloud liquid water path. This instrument is flown on the Tropical Rainfall Measuring Mission (TRMM) satellite, a project funded jointly by the United States and Japan. Details of the imager are given in Kummerow et al. (1998). The retrieval algorithm uses the brightness temperatures observed at four frequencies (19.35, 22.235, 37 and 85.5 GHz) and allows for simultaneous retrievals of cloud liquid water path, near-surface wind speed and column water vapour path, as described in Wentz (1997). Random retrieval errors in liquid water path 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 cloud liquid water path compare favourably where there is a completely overcast sub-pixel field of view (Greenwald et al. 1997), with results suggesting that in broken clouds the LWP algorithm is retrieving the area-mean liquid water path including clear and cloudy regions. The diurnal cycle in this liquid water path can, in principle, be entirely dominated by diurnal change in cloud fraction. The retrievals are unusable in regions of strong rainfall or over land, and these measurements are excluded from the analysed dataset following the criteria described in Wentz (1997).

The TRMM satellite offers the opportunity, unique among low earth orbit platforms, to sample the complete range of local times. The data were obtained from Remote Sensing Systems Inc. (URL *www.remss.com*), 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 liquid

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water path as a function of local time. The data are then fitted using a non-linear least squares fit to 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 at in latitude, longitude 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 $\overline{LWP}_{lat,lon}(T)$. This weighting method is standard practice for least-squares fitting. The fitting technique also provides standard errors for the fit parameters. In addition to the fitting, we also compute the standard deviation of all the liquid water path measurements in each spatial bin for comparison.

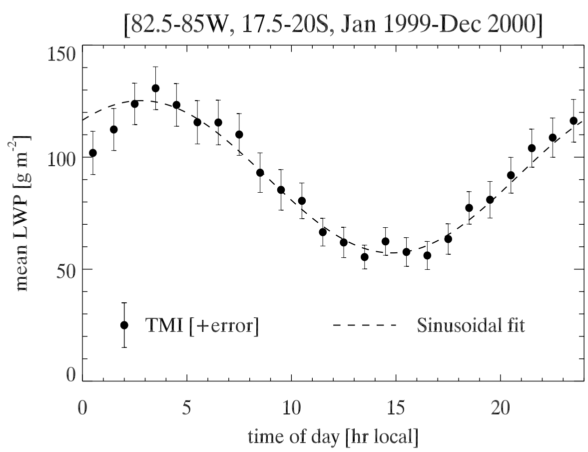

Figure 1: Example of two year mean diurnal cycle from the TMI for a single 2.5×2.5° region in the SE Pacific, showing sinusoidal fit to data.

An example of the diurnal cycle of LWP is shown for a region in the SE Pacific dominated by low stratiform cloud (82.5-85W, 17.5-20S) in Fig. 1. The LWP in each local time bin is the mean value for the entire two year period of this study. A strong diurnal cycle is evident. 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 sinusoidal fit, which provides an adequate fit to the diurnal signal, although we note that there are periods with significant deviations (e.g. around 0 UTC in 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 linked to local variability. For example, this local variability could include differences in the phase of the diurnal cycle in subsidence rate (Dai and Deser 1999).

a. Data reliability

The TMI data can also be compared against retrievals of liquid water path from the MODIS instrument on the NASA Terra satellite, which use an entirely 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 the two instruments have coincident (within 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. The binned means agree to within 10 g m^{-2} with an RMS difference of 17 g m^{-2} for the individual overpasses which is encouraging.

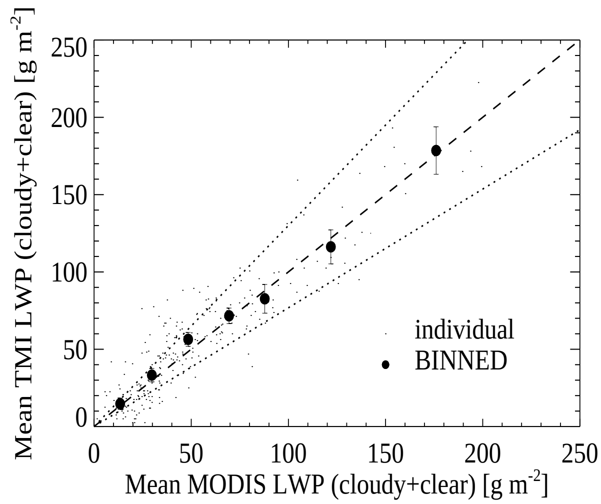

Figure 2: Comparison of LWP (cloud+clr mean) for 251 cases where MODIS and TMI viewed identical 1x1 degree regions simultaneously (± 1 hour) in the NE Pacific (dots). Circles show binned mean values with 2-σ error in mean. The dashed and dotted lines indicates perfect agreement and 25% difference respectively.

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, often exceeding 0.4, found 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 circulations which can trigger deep convection.

Only small ($A < 0.1$) diurnal cycles are found in the purely oceanic tropical deep convective regions and in the regions of midlatitude cyclonic activity. Most interesting is the significantly larger diurnal cycle 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.

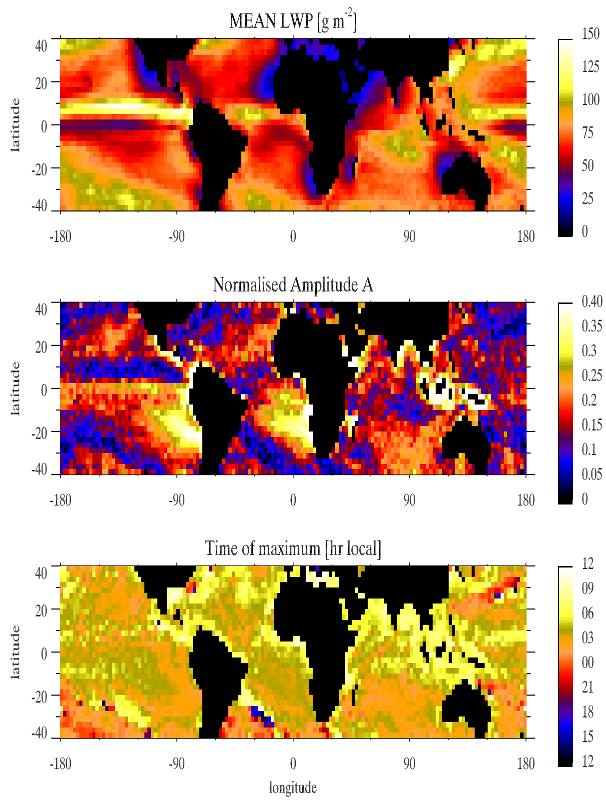

Figure 3: Mean LWP, normalized amplitude $A = A_{LWP}/\overline{LWP}$, and time of maximum LWP between 40S and 40N for the two complete years of TMI data.

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. The 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

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 areas are NE Atlantic(40-10W; 15-30N), NE Pacific (150-110W; 15-30N), SE Atlantic (20W-20E; 15-30S), SE Pacific (120-70W; 15-30S), S Indian (60-110E; 15-30S)

Region	$\overline{LWP}$ [g m^{-2}]	$\overline{A_{LWP}}$ [g m^{-2}]	$\overline{A}$	T_{max} [hr]
NE Atlantic	44 [16]	9.3 [4.3]	0.21	5.3 [1.6]
NE Pacific	66 [19]	13.4 [5.9]	0.20	3.5 [2.0]
SE Atlantic	63 [14]	16.9 [6.5]	0.27	3.6 [2.0]
SE Pacific	74 [10]	20.7 [8.0]	0.28	3.4 [1.2]
S Indian	77 [9]	16.8 [4.9]	0.22	3.1 [1.2]

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. This is close to the findings of Rozendaal et al. (1995) for cloud amount.

The seasonal variation of the mean diurnal cycle is close to 20% of the mean (half of the maximum-minimum mean diurnal amplitude over the year), consistent with daytime peak top-of-atmosphere solar flux change over the year (≈17% at the $22.5°$ north and south latitudes). It is more difficult to explain the large geographical differences. High resolution MODIS data suggest that the low clouds in the SE Pacific are somewhat more uniform than their NE Pacific equivalents. The LWP distributions in the SE Pacific distributions tend to be narrower for a given 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 through shortwave absorption. 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. Adequately testing these hypotheses requires improvements in both measurements (i.e. by developing climatologies of boundary layer depth) and cloud modeling.

4. CONCLUSIONS

The diurnal cycle of cloud liquid water path over the global oceans has been examined using data from the TMI microwave radiometer. We find a strong diurnal cycle especially in the regions of extensive boundary layer cloud off the west coasts of continents. Here, the liquid water path peaks in the early hours of the morning. This peak is in phase with diurnal peaks in low cloud amount (Rozendaal et al., 1995) which have diurnal amplitudes of 5-15% in these regions. We find that the liquid water path cycle has an even greater amplitude of 15-35%,

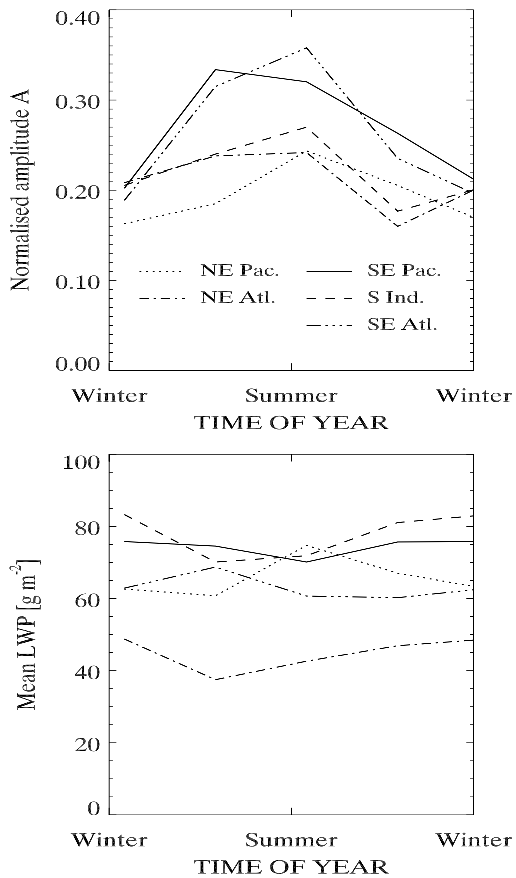

Figure 4: Seasonal variation of LWP diurnal cycle for the five regions dominated by subtropical low cloud shown in Table 1. Southern hemisphere regions are phase shifted relative to those in the north because of the seasonal reversal between hemispheres.

suggesting that a considerable fraction of the diurnal cycle in liquid water path is associated with a thinning of the clouds 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 of all 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. In addition, southern hemisphere stratiform boundary layer clouds, through their relatively low droplet concentrations (Boers et al. 1996) are likely to be prone to more extensive drizzle depletion of liquid water (Albrecht 1989). This enhanced drizzle production, through subcloud evaporative cooling, could accentuate the rate of daytime decoupling from their oceanic water source (e.g. Turton and Nicholls 1987). However, improved understanding of the effect of drizzle upon low cloud is necessary before this effect can be tested. The data presented in this study provide important constraints for models simulating the diurnal cycle of clouds.

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REFERENCES

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

Betts, A. K., 1990: Diurnal variation of California coastal stratocumulus from two days of boundary layer soundings. *Tellus*, **41A**, 302-304.

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

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

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

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

Greenwald, T.J., S.A. Christopher, and J. Chou, 1997: 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.

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

Hignett, P., 1991: Observations of diurnal variation in a cloud-capped marine boundary layer. *J. Atmos. Sci.*, **48**, 1474–1482.

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

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

Minnis, P. and E. Harrison, 1984: 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.

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

Turton, J. D. and S. Nicholls, 1987: A study of the diurnal variation of stratocumulus using a multiple mixed layer model. *Quart. J. Roy. Meteorol. Soc.*, **113**, 969-1009.

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

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

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