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DIURNAL CYCLE OF RAIN RATE AND RAIN COVERAGE AT TRMM GROUND VALIDATION SITES

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1. INTRODUCTION

The Tropical Rainfall Measuring Mission (TRMM) Satellite Validation Office (TSVO) has four primary ground validation (GV) radar sites: Melbourne, Florida (MELB); Houston, Texas (HSTN); Darwin, Australia (DARW); and Kwajalein, Republic of the Marshal Islands (KWAJ). The TSVO performs quality control procedures on radar data from each site and creates rainfall products in an effort to provide validation for developers of space-based precipitation retrievals. Examination of the diurnal cycle of rainfall using most passive microwave platforms, such as AMSR-E, SSM/I and AMSU-B are inadequate due to inherent sampling issues resulting from their sun-synchronous orbits. While the TRMM satellite orbit was designed specifically to aid in sampling the diurnal cycle, it does so only with a period of about 40 days, while robust sampling, such as is done at GV sites, would require significantly more time. Provided is a quantitative analysis of diurnal precipitation cycles, intensity, and areal coverage.

In this study we analyze the diurnal cycle of rain rate and the percentage of areal coverage for five different precipitation intensity thresholds. The TSVO 2A-53 (rain rate) product from 2000-2007 were used to calculate the conditional mean rain rate and the percentage of area with rain rates greater than 0, 1, 2, 5, and 10 mm hr^{-1}. TSVO uses NASA's Radar Software Library (RSL) and the TRMM Ground Validation System (GVS) to process radar data. For detailed information on RSL see Wolff and Kelley (2009). Rain rates in the 2A-53 product were determined by comparison of radar reflectivity and rain gauge data via the Probability Matching Method (PMM - Rosenfeld et al 1994). The 2A-53 product has a 151 x 151 km^2 coverage area with 2 km horizontal resolution. Wolff et al. (2005) provides a detailed description of TSVO products. Additional calculations were performed to find percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} during diurnal minimums and maximums.

2. MELBOURE, FLORIDA

The MELB rainfall coverage area is centered on the KMLB WSR-88D radar located at 28.1°N, 80.6°W (Figure 1). Seventy percent of MELB's annual rainfall occurs between June and September. A large majority of the rainfall is due to sea-breeze-induced isolated convective systems and large organized tropical storms. MELB also receives a contribution from mid latitude synoptic systems during Northern Hemispheric winter months when frontal boundaries occasionally affect MELB weather (Wolff et al. 2005).

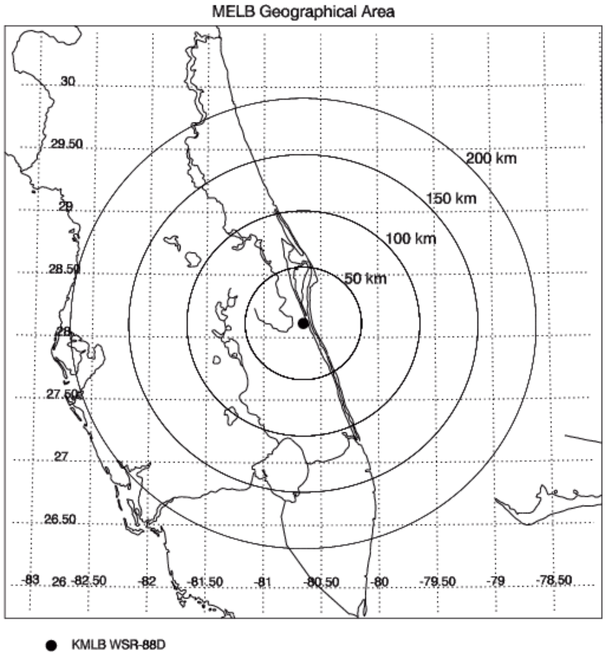

Figure 1. *Map of the MELB Geographical region.*

2.1 Conditional Mean Rain Rate

The diurnal cycle of conditional mean rain rate contains data when the rain rate is greater than zero. As shown in Figure 2, a large amplitude diurnal cycle is present at MELB, a maximum

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occurs near 1500 local time (LT) with a conditional mean rain rate of 5.5 mm hr^{-1} and a minimum near 0100 LT with a conditional mean rain rate of 3.1 mm hr^{-1}. Sea breeze induced convection is the major contributor to the afternoon maximum.

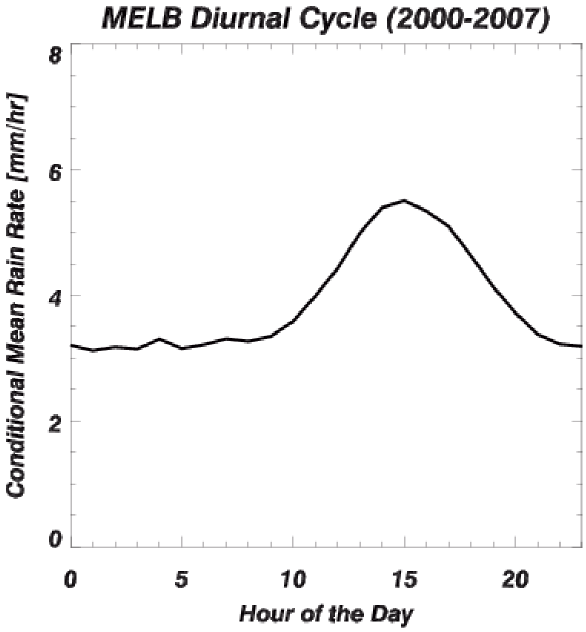

__Figure 2.__ Diurnal cycle of conditional mean rain rate for MELB. These statistics were derived from the 2A-53 rain rate product over an eight year period from 2000-2007.

2.2 Areal Coverage of Precipitation

MELB's areal coverage of precipitation yields a similar diurnal cycle to the conditional mean rain rate. The afternoon has the largest area covered by rainfall, with 4.2% of the area receiving rain compared to 1.8% of the area receiving rain during the nocturnal minimum. Figure 3 shows the diurnal cycle of rain area for all five rain intensities. Rainfall rates greater than 10 mm hr^{-1} occur over 17.3% of the rain area during the diurnal maximum and 12.4% during the diurnal minimum. Table 1 shows percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} during the diurnal minimum and maximum. There is a 232% increase in heavy rain (greater than 10 mm hr^{-1}) between the diurnal maximum and the diurnal minimum. The large increase between the minimum and maximum can be attributed to afternoon sea breeze induced convection which greatly increases the rain rates within the rain area.

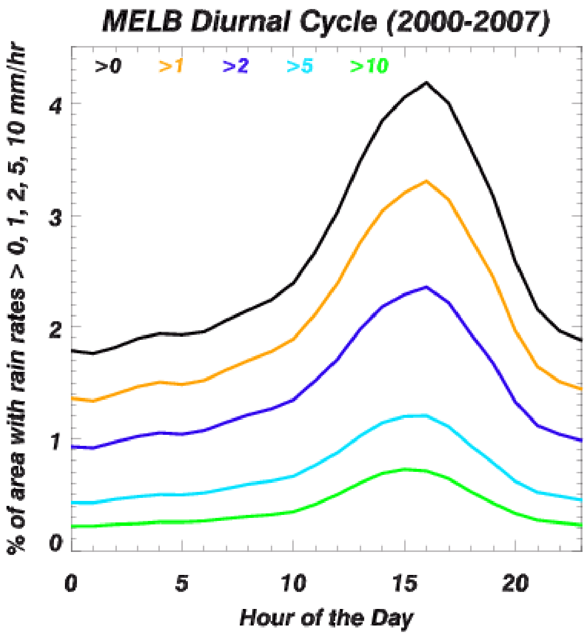

__Figure 3.__ Diurnal cycle of rain area at MELB for rain rates greater than 0, 1, 2, 5, and 10 mm hr^{-1}. These statistics were derived from the 2A-53 rain rate product over an eight year period from 2000-2007.

event	rain area	> 1 mm hr^{-1}	> 2 mm hr^{-1}	> 5 mm hr^{-1}	> 10 mm hr^{-1}
max	4.2%	79.0%	56.3%	28.8%	17.3%
min	1.8%	76.0%	52.1%	24.2%	12.4%

__Table 1:__ Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} for MELB during the diurnal minimum and maximum. Max occurs near 1600 LT and min near 0100 LT.

3. HOUSTON, TEXAS

The HSTN rainfall coverage area is centered on KHGX WSR-88D radar located at 29.5°N, 95.1°W (Figure 4). Rainfall in HSTN is dominated by air mass and sea breeze induced convection. Easterly waves, synoptic systems, and tropical storms contribute to HSTN rainfall along with Mesoscale Convective Systems (MCS) that occur during the spring and fall.

3.1 Conditional Mean Rain Rate

As shown in Figure 5, HSTN's diurnal cycle of conditional mean rain rate is bimodal with one mode near 0600 LT with a mean rain rate of 5.6 mm hr^{-1}, a dominant mode near 1400 LT with a mean rain rate of 6.9 mm hr^{-1}, and a minimum near 2200 LT with a mean rain rate of 3.5 mm hr^{-1}.

The dominant mode can be attributed to sea breeze induced convection. The early morning mode is due to MCS's that develop overnight in central/eastern Texas during the spring and fall and dissipate over the HSTN area during the early morning (Yang et al. 2006).

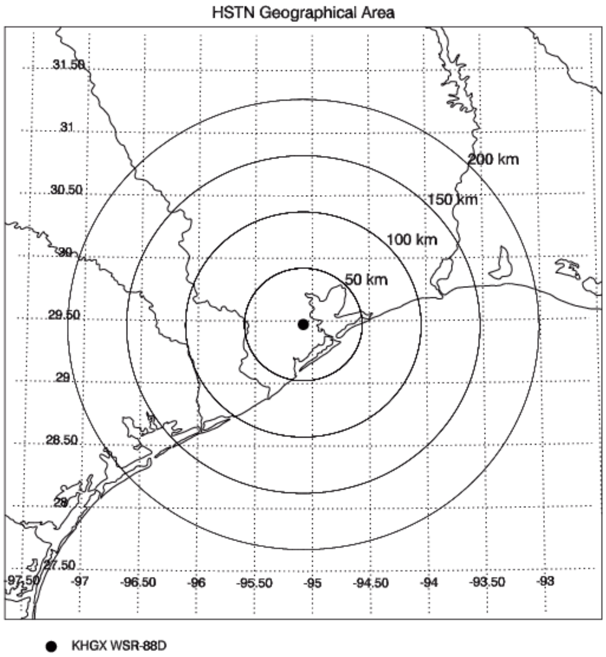

Figure 4. *Map of the HSTN Geographical region.*

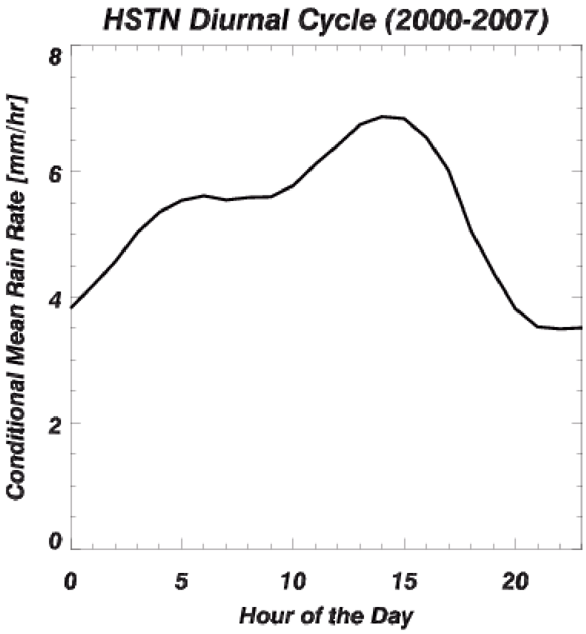

Figure 5. *Diurnal cycle of conditional mean rain rate for HSTN. These statistics were derived from the 2A-53 rain rate product over an eight year period from 2000-2007.*

3.2 Areal Coverage of Precipitation

The bimodal cycle seen in conditional mean rain rate is not evident in the diurnal cycle of rain area. During the period from 0300 LT to 1500 LT the intensity of the rain has a moderate change while the amount of area with rain has a minimal change; therefore a bimodal cycle is not evident in the diurnal cycle of rain area (Figure 6). The long period of nearly consistent areal coverage can be attributed to dissipating morning MCS's and the afternoon development of sea breeze induced convection. During HSTN's diurnal maximum only 2.3% of the area is receiving rainfall, though within that area 32.6% has a rain rate of 10 mm hr^{-1} or greater. Within HSTN's diurnal minimum, heavy rain is a large influence with 1.2% of the area receiving rain and 30.1% of that rain being 10 mm hr^{-1} or greater (Table 2).

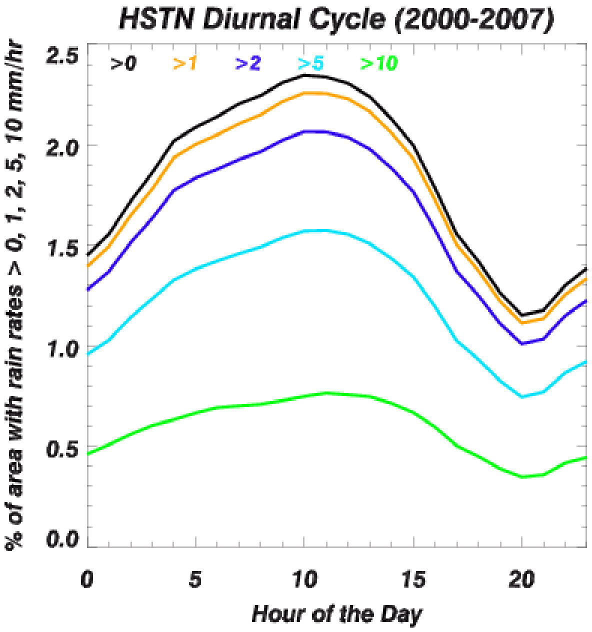

Figure 6. *Diurnal cycle of rain area at HSTN for rain rates greater than 0, 1, 2, 5, and 10 mm hr^{-1}. These statistics were derived from the 2A-53 rain rate product over an eight year period from 2000-2007.*

event	rain area	> 1 mm hr^{-1}	> 2 mm hr^{-1}	> 5 mm hr^{-1}	> 10 mm hr^{-1}
max	2.3%	96.2%	88.0%	67.1%	32.6%
min	1.2%	96.6%	87.6%	64.6%	30.1%

Table 2: *Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} for HSTN during the diurnal minimum and maximum. Max occurs near 1000 LT and min near 2000 LT.*

4. DARWIN, AUSTRALIA

The DARW rainfall coverage area is centered on the Bureau of Meteorology Research Centre (BMRC) C-band dual-polarimetric radar (CPOL – Keenan et al, 1998) in Darwin located at 12.2°S, 131.0°E (Figure 7). The annual rainfall cycle at DARW consists of a dry and wet season. Our data covers the wet season which runs from November to April over a four year period from 2000-2003. DARW has two primary rain regimes during the wet season: monsoon and break periods. Monsoonal periods are associated with a westerly maritime flow characterized by weak convection but widespread regional coverage (Holland 1986). Break periods are identified with an easterly continental flow regime characterized by deep convection; some of the deepest in the world, in association with large organized propagating squall lines and smaller isolated convective systems (Carey and Rutledge 2000; Wolff et al. 2005). Madden-Julian Oscillation (MJO) induced convection also contributes to DARW's rainfall (Pope et al. 2009).

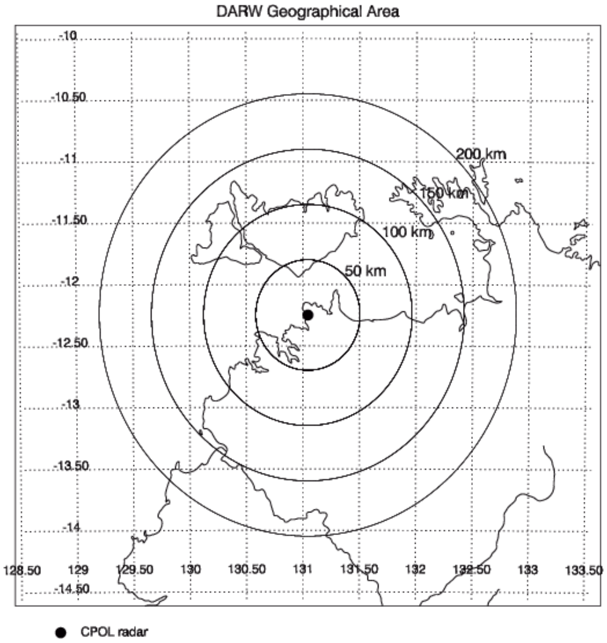

Figure 7. *Map of the DARW Geographical region.*

4.1 Conditional Mean Rain Rate

As shown in Figure 8, DARW's diurnal cycle of conditional mean rain rate is bimodal. One mode occurs near 1000 LT with a mean rain rate of 6.8 mm hr^{-1}, and a dominant mode near 2000 LT with a mean rain rate of 11.6 mm hr^{-1}. Maritime convection during the late morning contributes to the morning mode (Pope et al. 2008). DARW has two diurnal minimums, one occurs near 0400 LT with a mean rain rate of 4.9 mm hr^{-1} the second occurs near 1600 LT with a mean rain rate of 5.5 mm hr^{-1}.

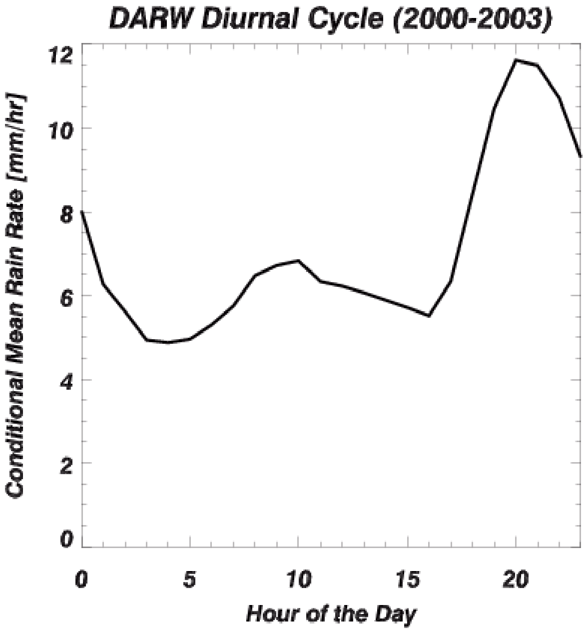

Figure 8. *Diurnal cycle of conditional mean rain rate for DARW. These statistics were derived from the 2A-53 rain rate product over a four year period from 2000-2003 during the wet season November* to April.

4.2 Areal Coverage of Precipitation

As shown in the diurnal cycle of rain area graphs (Figure 9), there is a third mode that occurs at 0200 LT for the greater than 0, 1, 2, and 5 mm hr^{-1} rain intensities. This mode is caused by nocturnal convection over the ocean (Pope et al. 2008). This convection is weak but widespread, producing only light to moderate rain, thus the mode does not appear in the diurnal cycle of rain area greater than 10 mm hr^{-1} and the diurnal cycle of conditional mean rain rate. Diurnal minimums occur at different times with the conditional mean rain rate minimum occurring near 0400 LT and the rain area minimum occurring near 1600 LT. The light nature of the nocturnal oceanic convection leads to the conditional mean rain rate minimum near 0400LT and the widespread nature of the convection allows this time period not to be the minimum for rain area. DARW has the largest areal coverage of the four sites, with 5.8% of its area receiving rain during its diurnal maximum and 22.0% of that rain being 10 mm hr^{-1} or greater.

During the diurnal minimum 3.1% of the area is receiving rain and 17.0% of that rain is greater than 10 mm hr^{-1}. Table 3 shows the percentage of the rain area for the four intensities during all diurnal maximums and minimums. Min 1 in Table 3 has a larger overall rain area than min 2 though heavy rain is more of a factor in min 2. The onset of intense convection contributes to the heavier precipitation seen in min 2.

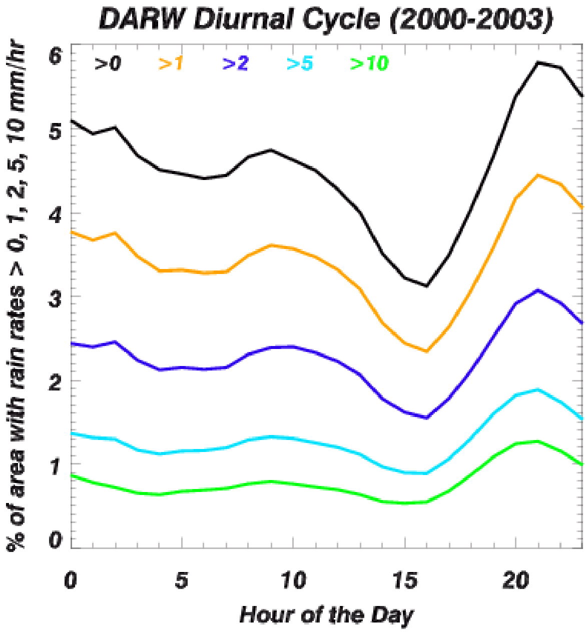

Figure 9. *Diurnal cycle of rain area at DARW for rain rates greater than 0, 1, 2, 5, and 10 mm hr^{-1}. These statistics were derived from the 2A-53 rain rate product over a four year period from 2000-2003 during the DARW wet season November to April.*

event	**rain area**	**> 1 mm hr^{-1}**	**> 2 mm hr^{-1}**	**> 5 mm hr^{-1}**	**> 10 mm hr^{-1}**
max 1	5.0%	74.9%	49.0%	25.8%	14.3%
max 2	4.7%	76.0%	50.5%	27.9%	16.7%
max 3	5.8%	76.8%	53.1%	32.6%	22.0%
min 1	4.5%	73.2%	47.0%	24.7%	14.0%
min 2	3.1%	75.0%	49.6%	28.4%	17.0%

Table 3: *Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} for DARW during diurnal minimums and maximums. Max 1 occurs near 0200 LT, max 2 near 1000 LT, max 3 near 2100 LT, min 1 near 0500 LT, and min 2 near 1600 LT.*

5. KWAJALEIN

The KWAJ rainfall coverage area is centered on the S-band dual-polarimetric radar (KPOL) located at 8.7°N, 167.7°E (Figure 10). KWAJ is located on the northern edge of the Pacific intertropical convergence zone (ITCZ) and on the eastern boundary of the western Pacific warm pool. Most of the rainfall occurs in association with the northward migration of the ITCZ between April and October (Schumacher and Houze 2000; Wolff et al. 2005). MCS's, MJO, and easterly waves contribute to the annual rainfall at KWAJ.

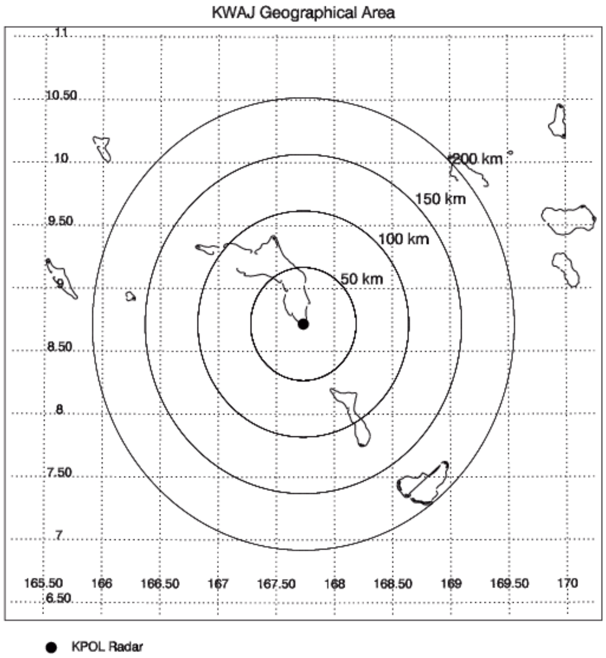

Figure 10. *Map of the KWAJ Geographical region.*

5.1 Conditional Mean Rain Rate

The KWAJ diurnal cycle of conditional mean rain rate has a nocturnal maximum near 0200 LT with a mean rain rate of 4.8 mm hr^{-1} and a daytime minimum near 1000 LT with a mean rain rate of 4.3 mm hr^{-1} (Figure 11). The KWAJ diurnal cycle of conditional mean rain rate is rather weak, with the difference between maximum and minimum hourly rain rates of only 0.5 mm hr^{-1}. The weak diurnal cycle is normal for oceanic sites; KWAJ has a near equal chance of precipitation throughout the day.

5.2 Areal Coverage of Precipitation

The diurnal cycle of rain area shows a somewhat stronger cycle with a peak of about 5% areal coverage near 0500 LT, a second peak of

4.3% near 1400 LT, and a distinct minimum of 3.7% near 2100 LT (Figure 12). The second peak is due to an initial increase in convective cells due to day time heating. Solar radiation incident on cloud tops provides a warming and stabilizing influence thereby leading to the late day minimum. During the rain area diurnal maximum 17.2% of the rain area has a rain rate greater than 10 mm hr^{-1} with 16.4% during the diurnal minimum (Table 4). Rain rates within the rain area change minimally throughout the day. The diurnal cycle of rain area shows a distinct daily cycle of rainfall with an early morning peak near 0500 LT and an evening minimum near 2100 LT.

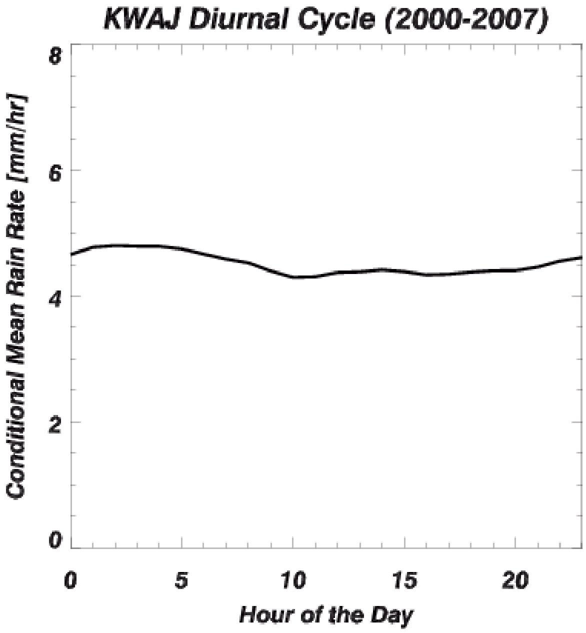

Figure 11. *Diurnal cycle of conditional mean rain rate for KWAJ. These statistics were derived from the 2A-53 rain rate product over an eight year period from 2000-2007.*

event	rain area	> 1 mm hr^{-1}	> 2 mm hr^{-1}	> 5 mm hr^{-1}	> 10 mm hr^{-1}
max 1	4.8%	83.0%	60.8%	31.1%	17.2%
max 2	4.4%	82.1%	59.5%	30.4%	16.8%
min 1	4.3%	81.6%	58.6%	29.6%	16.4%

Table 4: *Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} for KWAJ during diurnal minimums and maximums. Max 1 occurs near 0500 LT, max 2 near 1400 LT, and min 1 near 2100 LT.*

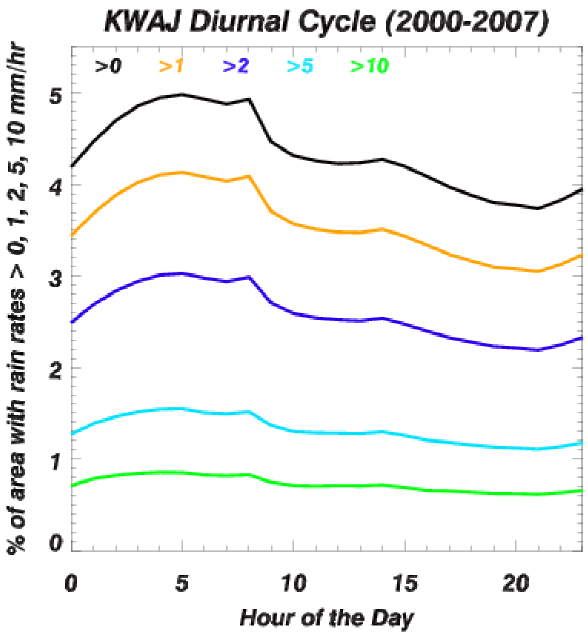

Figure 12. *Diurnal cycle of rain area at KWAJ for rain rates greater than 0, 1, 2, 5, and 10 mm hr^{-1}. These statistics were derived from the 2A-53 rain rate product over an eight year period from 2000-2007.*

6. SUMMARY

MELB has a large amplitude diurnal cycle, evident in both the diurnal cycle of conditional mean rain rate and the diurnal cycle of rain area. Intense afternoon sea breeze induced convection is the major contributor to the large diurnal difference. Rain rate increases 77% between the conditional mean rain rate diurnal minimum and maximum. The diurnal cycle of rain area increases 138% between the diurnal minimum and maximum. Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} show increases of 4%, 8%, 19%, and 40% between the diurnal minimum and maximum.

HSTN's diurnal cycle of conditional mean rain rate is bimodal where as the diurnal cycle of rain area is unimodal. From 0300 LT to 1500 LT rain area remains nearly consistent, whereas rain intensity changes resulting in a bimodal cycle for conditional mean rain rate and a single mode for rain area. The long period of nearly consistent areal coverage can be attributed to dissipating morning MCS's and the afternoon development of sea breeze induced convection. The conditional mean rain rate associated with the diurnal maximum is 97% higher than the diurnal minimum. The diurnal cycle of rain area increases of 104%

between the diurnal minimum and maximum. Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} show minimal increases of 0%, 0.5%, 4%, and 8% between the diurnal minimum and maximum. HSTN may have a large difference in rain rate and rain area though the intensities within the rain area are consistent. Of the four sites analyzed in this study, HSTN has the largest relative percentage areal coverage of rain intensity 10 mm hr^{-1} or greater. Throughout the day on average over 30% of HSTN's rain area is receiving rain of 10 mm hr^{-1} or greater.

DARW's diurnal cycle of conditional mean rain rate is bimodal whereas the diurnal cycle of rain area is trimodal, the third mode occurs near 0200 LT for the greater than 0, 1, 2, and 5 mm hr^{-1} rain intensities. The third mode is caused by nocturnal convection over the ocean which is weak but widespread, producing only light to moderate rain, therefore it is not a factor in the diurnal cycle of rain area greater than 10 mm hr^{-1} and the diurnal cycle of conditional mean rain rate. The diurnal minimums occur at different times with the conditional mean rain rate minimum occurring near 0400 LT and the rain area minimum occurring near 1600 LT. The light nature of the nocturnal oceanic convection leads to the conditional mean rain rate minimum near 0400LT and the widespread nature of the convective allows this time period not to be the minimum for rain area. Rain rate increases 138% between the conditional mean rain rate diurnal minimum and maximum. The diurnal cycle of rain area shows an increase of 85% between the diurnal minimum and maximum. Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} show increases of 2%, 7%, 15%, and 29% between the diurnal minimum and maximum. Rain rate and rain area have large increases between the diurnal minimum and maximum though the intensities within the rain area remain similar for greater than 1 and 2 mm hr^{-1} with larger differences between the greater than 5 and 10 mm hr^{-1} intensities. Overall DARW has the largest amount of rain area and the highest mean rain rate of our four sites.

Typical of tropical oceanic locations, the diurnal cycle at KWAJ is small, but nonetheless displays a distinct nocturnal maximum and a daytime minimum. The nocturnal maximum is 12% higher than the rain rate during the diurnal minimum. The diurnal cycle of rain area reveals a more pronounced diurnal cycle with the most areal coverage occurring during the early morning and the least areal coverage occurring during the evening. A second mode occurs in the diurnal cycle of rain area and is due to an initial increase in convective cells due to day time heating. Solar radiation incident on cloud tops provides a warming and stabilizing influence thereby leading to the evening minimum. Rain area increases 33% between the diurnal minimum and maximum. Percentage of the rain area with rain rates greater than 1, 2, 5, and 10 mm hr^{-1} show minimal increases of 2%, 4%, 5%, and 5% between the diurnal minimum and maximum. Overall KWAJ rain rates are consistent throughout the day while rain area has a more pronounced diurnal cycle.

The continued study of diurnal cycles in tropical climates, with expansion to mid-latitude and northern regimes will be beneficial for ground validation of Global Precipitation Measurement (GPM) satellite precipitation retrieval algorithms.

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