The Diurnal Cycle of the Boundary Layer, Convection, Clouds, and Surface Radiation in a Coastal Monsoon Environment (Darwin, Australia)

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ABSTRACT

The diurnal variation of convection and associated cloud and radiative properties remains a significant issue in global NWP and climate models. This study analyzes observed diurnal variability of convection in a coastal monsoonal environment examining the interaction of convective rain clouds, their associated cloud properties, and the impact on the surface radiation and corresponding boundary layer structure during periods where convection is suppressed or active on the large scale. The analysis uses data from the Tropical Warm Pool International Cloud Experiment (TWP-ICE) as well as routine measurements from the Australian Bureau of Meteorology and the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program. Both active monsoonal and large-scale suppressed (buildup and break) conditions are examined and demonstrate that the diurnal variation of rainfall is much larger during the break periods and the spatial distribution of rainfall is very different between the monsoon and break regimes. During the active monsoon the total net radiative input to the surface is decreased by more than 3 times the amount than during the break regime—this total radiative cloud forcing is found to be dominated by the shortwave (SW) cloud effects because of the much larger optical thicknesses and persistence of long-lasting anvils and cirrus cloud decks associated with the monsoon regime. These differences in monsoon versus break surface radiative energy contribute to low-level air temperature differences in the boundary layer over the land surfaces.

1. Introduction

The processes governing rainfall in coastal areas affected by monsoon rains are of great importance as such regions include major population areas around the globe. One of the best tropical rainfall observing systems in the world is located around Darwin, Northern Australia, which experiences just such a regime. While the population of Darwin is modest, the rainfall distribution and the seasonal and diurnal cycle of precipitation have direct relevance to many other parts of the world. Sites affected by coastal monsoon commonly experience very different convective intensity and diurnal cycles depending whether monsoon or buildup and break conditions prevail (Keenan et al. 1989; Keenan and Carbone 1992; Mapes and Houze 1992).

The “wet” season across Northern Australia begins with a buildup period with locally forced convection leading to the monsoon onset with high rainfall and a reversal of low-level wind direction (Drosdowsky 1996). The monsoon is then characterized by a high degree of variability with “break” periods where conditions are similar to the buildup phase. Monsoons and break periods each extend for periods of a week to several weeks [see May (2011) for a review]. It has been well documented that during the buildup and break periods convection in the Australian monsoon exhibits...
a strongly continental character with intense updrafts, prodigious lightning, and a strong afternoon maximum in convection (e.g., Keenan and Carbone 1992; May and Ballinger 2007; Protat et al. 2010). On the other hand, monsoon rainfall tends to be more widespread, with little lightning, and exhibits a comparatively small diurnal cycle. Such behavior is typical of monsoonal regimes (e.g., Keenan and Carbone 1992). Note the instability is similar in the two regimes (McBride and Frank 1999).

As background, it is useful to note that there are substantial spatial variations of the diurnal cycle of convective activity across the tropics (e.g., Ohsawa et al. 2001; Yang and Slingo 2001). With the diurnal fluctuations in rain, the cloud cover, radiative impact, and cloud feedbacks have a corresponding cycle. Models struggle to reproduce these patterns, and the diurnal change in convection is a key to understanding this and likely impacts climate simulations. Observations covering all these components of the cloud system in the tropics are rare. The aim of this paper is to characterize the diurnal cycle of several key parameters of the tropospheric system: boundary layer, convection, clouds, and resulting shortwave and longwave radiation at the earth’s surface. An underlying motivation of this work is also to provide an observational basis for the evaluation of the diurnal cycle of these same quantities in large-scale models.

2. Datasets

Darwin and the surrounding area have been the focus of both intensive experiments as well as long-term research quality observations (e.g., Keenan et al. 2000; May et al. 2008; Mather et al. 1998). This manuscript uses data from the international Tropical Warm Pool International Cloud Experiment (TWP-ICE) experiment. The timing of the experiment was fortunate in that it sampled both classic monsoonal weather and break conditions (May et al. 2008). The data, combined with regular Bureau polarimetric weather radar and Darwin Atmospheric Radiation Measurement (ARM) Cloud Research Facility (ACRF) observations, provide a unique opportunity to document and study this diurnal behavior. This TWP-ICE experiment included 3-hourly soundings from five sites in an approximate circle around Darwin (Fig. 1), with sondes also launched at the Darwin site. These sites included a ship for open ocean observations, coastal observations on the Tiwi Islands (Pirlangimpi at Garden Point) and on a long narrow peninsula (Cape Don), and sites that were well inland. This campaign continued for 23 days and used Vaisala RS92 radiosondes. The soundings reached the freezing level on approximately 97% of launches and the tropopause on 89% of the launches. The data quality is generally high, although there is a dry bias during the daytime induced by solar heating of the sensor (Miloshevich et al. 2006). This was most marked in the mid- to upper troposphere, but also affected data in the low levels with biases of about 9% during the day near the surface (Hume 2007). The sounding data have been corrected using the procedures described by Hume (2007).

In addition to the specific TWP-ICE data, the Darwin area boasts one of the most comprehensive observing systems for cloud and rain characteristics anywhere in the tropics. Of particular interest for this paper are the research 5-cm wavelength polarimetric weather radar (C-POL; Keenan et al. 1998), a millimeter wave cloud radar (Moran et al. 1998), a micropulse lidar, and radiometers. The C-POL radar is located at Gunn Point (see Fig. 1), while the vertically pointing radar and lidar are located near Darwin International Airport.
The rainfall estimates used in this paper are made with the polarimetric radar using a multiparameter rainfall algorithm described by Bringi et al. (2001, 2002). These are substantially more accurate than conventional reflectivity-based estimates (e.g., May et al. 1999). The polarimetric radar data from the 2005/06 wet season is used in the rainfall analysis here and other seasons are very similar. We use the standard hourly rainfall accumulation product produced with the radar (and available as an “external” dataset at www.arm.gov).

The C-POL radar sampling with 10-min time resolution extends out to a maximum range of 150 km. There are long-range surveillance scans but these are not used here. The minimum detectable reflectivity at 150 km for the C-POL radar is about 0 dBZ.

The Darwin ARM site radiation systems use Eppley normal incidence pyrheliometers (NIP), precision spectral pyranometers (PSP), and shaded Model 8-48 “Black and White” pyranometers (B&W) for the shortwave (SW) measurements and Eppley precision infrared radiometers (PIR) for the longwave (LW) measurements to produce 1-min averages from 1-s samples. (Details about these radiation systems and the instruments used are available at www.arm.gov.) The smaller radiometer systems deployed at the Cape Don and Pirlangimpi sites also use Eppley PSP and PIR radiometers, and also include Delta-T Devices model SPN1 total and diffuse radiometers. Estimates of the 2-σ uncertainties of the measurements are 3% or 4 W m\(^{-2}\), 6% or 20 W m\(^{-2}\), 6% or 10 W m\(^{-2}\), and 2.5% or 4 W m\(^{-2}\) (whichever value, the given W m\(^{-2}\) or percent of signal, is largest for each) for the downwelling diffuse SW, direct normal SW, total (global) SW, and LW, respectively (Stoffel 2005). Manufacturer estimates of 95% level of accuracy for the SPN1 are given as 8% for individual readings and 5% for hourly averages. Similar to ARM, these radiometer systems also log 1-min averages of 1-s individual readings.

The surface radiometer measurements are used, in conjunction with estimations of corresponding clear (i.e., cloudless) sky data, to infer the cloud radiative impacts and estimations of fractional sky cover. Clear-sky downwelling SW estimates are produced using the Long and Ackerman (2000) methodology and clear-sky downwelling LW estimates are produced using the methodology of Long and Turner (2008). The clear-sky upwelling SW and LW estimation techniques are described in Long (2005), and the estimation of daylight fractional sky cover is described in Long et al. (2006). All of these clear-sky estimation techniques first analyze the time series of the relevant data, detect clear-sky periods, use the detected clear-sky data to empirically fit clear-sky functions, and then use the fitted functions to produce continuous estimates of clear-sky radiation. For the Darwin site, upwelling SW and LW data are available. The radiometer systems deployed at the Cape Don and Pirlangimpi sites did not include upwelling measurements. However, the land surfaces where the radiometers were located at these two sites are quite similar to that at Darwin. A methodology was developed as part of the TWP-ICE effort, described in Long (2008), to provide estimations of upwelling all-sky SW and LW for the Cape Don and Pirlangimpi sites. The effective transmissivity is calculated as the ratio of measured downwelling SW over the corresponding clear-sky downwelling SW. The cloud radiative forcing is calculated as the difference between the measured net irradiance minus the corresponding clear-sky net irradiance. For example, the net SW is the downwelling SW minus the upwelling SW, with a positive value denoting a net energy gain by the surface. The SW cloud radiative forcing is then the net measured (or all sky) SW minus the net clear-sky SW, again where a positive value denotes an energy gain (over clear-sky amounts) to the surface due to the presence of clouds.

The methodology for examining the diurnal cycle has focused on the use of compositing techniques rather than harmonic analysis—that is, all observations at a particular time of day are averaged together and mean days are built up by a series of such averages. This methodology has the advantage that it does not arbitrarily assume sinusoidal variations and allows for sudden onsets. Sharp changes in a signal have the impact of generating higher harmonic frequencies in a Fourier type analysis, which is not always a good model of the dominant physics. The disadvantage is that this method is sensitive to the occasional large excursion and ideally requires long datasets. The thermodynamic data are very limited in duration, but nevertheless some general conclusions are able to be drawn. For the remaining part of the analysis dealing with rainfall and cloud patterns, data from a single wet season (the summer of 2005/06) are used, but the basic results are repeatable for other years. Analyzing over a season allows the highly spatially variable rainfall to be averaged so that accumulation patterns are robust. The relevant thermodynamic features can be drawn out with surprisingly little data.

The analysis breaks the sampled periods into a monsoon category and a “buildup or break” period (which will also be referred to as “regimes” in the following) according to the sign of the zonal 850-hPa wind in the Darwin soundings (westerlies = monsoon; easterlies = buildup or break). Before being used to divide the dataset, the winds were smoothed using a seven-point (42 h) running mean to minimize the impacts of short period variations, such as may be associated with squall
lines. Various definitions for the Australian monsoon are in the literature (Drosdowsky 1996; Holland 1986) but these only give small variations in the dates of active monsoon periods. The periods of monsoon circulation from the current analysis are given in Table 1. Data collected from November 2005 to March 2007 are analyzed.

### Table 1. Monsoon dates.

<table>
<thead>
<tr>
<th>Date of monsoon onset</th>
<th>Date of end of monsoon burst</th>
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<tr>
<td>10 Jan 2006</td>
<td>2 Feb 2006</td>
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<tr>
<td>10 Jan 2007</td>
<td>21 Jan 2007</td>
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<tr>
<td>2 Feb 2007</td>
<td>27 Feb 2007</td>
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3. **Spatial distribution and diurnal cycle of rainfall**

The aim of this section is to examine the rainfall distribution in the area around Darwin and its diurnal cycle in the two regimes previously identified. The rainfall patterns in the “buildup and break” periods are strongly modulated by convective initiation on local sea breeze circulations and subsequent storm outflows (e.g., Keenan and Carbone 1992; Wilson et al. 2001; May et al. 2002; Schafer et al. 2002). Sea surface temperature (SST) in the region is consistently about 29°C during the summer. During the break periods, surface air temperature frequently is in the range of 33°–35°C and sea breezes are generated as seen in surface, radar, and satellite data. In contrast, during the monsoon, the land–sea temperature contrast is small throughout the day and no clear sea or land breeze signatures are seen. The monsoonal westerlies also act to inhibit sea breeze development. Figure 2 shows the total rainfall estimated using the polarimetric radar for the monsoon (upper-left panel) and buildup or break periods (upper-right panel). It is plain to see that the break rainfall is concentrated over the land areas, particularly near the west coasts, with some smaller maxima just offshore, whereas the monsoon rainfall is more evenly distributed, although with distinct spatial structures. There is a distinct east–west gradient across the domain during monsoon conditions with significantly more rain falling over the oceans than the land. The systematic decrease in rain at the edges of the domain is an artifact of the radar quality and interactions between them and the sea breeze (e.g., Keenan and Carbone 1992; Wilson et al. 2001; May et al. 2002) even if the gust front strong density variations are known to be relatively weak (e.g., May 1999; May et al. 2002). There is a strong tendency for the rainfall to increase as the afternoon progresses in the break periods when outflows from early storms interact with each other and the sea breeze. This effect is clearly manifested over the Tiwi Islands [Fig. 2 (1000–1800 LT)], where the typical cycle is for early storms over the eastern part of the island and some peninsulas. As these storms move westward and interact with the sea breeze, larger, more intense storm systems may occur (e.g., Wilson et al. 2001) and with cell mergers a multiplicative effect in storm size and intensity (Simpson et al. 1993). The evening storms, in contrast, show an eastern maximum (Fig. 2). This is primarily associated with squall lines propagating in from the east (e.g., Drosdowsky and Holland 1987). These may be associated with long-lived disturbances such as gulf lines where a propagating disturbance is generated over Cape York in northern Queensland and propagates across the Gulf of Carpentaria and across the “top end” of the Northern Territory toward Darwin (Drosdowsky and Holland 1987). The timing of these is that they tend to reach the Darwin area in the early to midevening. However, the squalls tend to dissipate as they approach, probably because the surface layer has had significant radiative cooling in the early evening and the boundary layer has often been highly modified by previous storm activity. On some occasions, however, the most vigorous convection in the area may be associated with intense squall lines in the evening. Note the relatively flat topography (Fig. 1) results in it playing little role. The last panel shows the weak offshore maximum in the early morning during the break. This is presumably associated with convection initiated on the land breezes. These cells are relatively shallow and weak, but are a common feature. Note that alternative explanations for an offshore nocturnal maximum do exist with wave propagation away from mountains being cited (Mapes et al. 2003). However, the land breeze seems a more likely explanation here because of the lack of significant topography and the warm ocean temperatures with skin SST temperatures of about 29°C. We will see that the land temperature during active phases of the monsoon is comparable to this temperature and thus sea breeze circulations are less important during the monsoon.

Rainfall accumulation during the monsoon (Fig. 2, upper-left panel) also shows a very clear spatial pattern, but it is very different to the break distribution. During the monsoon periods, the western oceanic areas show high rainfall and a strong gradient along the coastal regions. The monsoon rainfall often includes a substantial stratiform component (e.g., Keenan and Rutledge 1993). The diurnal cycle on the oceanic side is relatively...
Fig. 2. Polarimetric rainfall accumulations measured with the C-POL radar during monsoon and break conditions. The total 2005/06 accumulation is shown along with the accumulations during the early morning (0200–1000 LT), afternoon (1000–1800 LT), and evening (1800–0200 LT). Note other years have been examined and show very similar patterns.
small compared to the break, while there is significant rain over the land in the afternoon. This shows a similar pattern to the break period rainfall with decreasing rainfall away from the coast but for different reasons. In the break, storms initiate inland and propagate to the west toward the coast and develop. Then they tend to decay after they move offshore (e.g., Wilson et al. 2001). However, in the monsoon the storms propagate to the east but on average decrease in rainfall intensity. This decrease is not readily seen in individual storms, but the signal on average is clear in Fig. 2. Interestingly, the ocean area to the north does not show the heavy rainfall decay.

**Fig. 3.** Average snow and high reflectivity fraction measured over the radar domain as a function of local time and height.

**Fig. 4.** Cloud occurrence measured by the cloud radar and the difference between the monsoon and break periods. (top) Total ice cloud and (bottom) the convective fraction. The difference is not displayed when one of the two frequencies of occurrence is lower than 0.5% for clarity.
that occurs in the western region. This may be associated with it being downstream of the islands and the potential strong modification of the boundary layer, but this will require detailed modeling combined with observations to further investigate.

There are significant thermodynamic and dynamical differences associated with the “monsoon” and “break or buildup” regimes leading to and associated with the corresponding cloud characteristics and attendant radiative characteristics. In principle there tends to be mean tropospheric descent in the breaks and thus less cloudy skies and more solar radiation to the surface. In contrast, there is mean ascent in the monsoon (e.g., May and Ballinger 2007) leading to very different cloud system characteristics, radiation budgets, and boundary layer structure. These effects, combined with the distribution of the land and ocean, produce markedly different rainfall distributions and diurnal variability with the break dominated by locally forced circulations. It is the purpose of the next sections to better characterize these diurnal cycles further with available observations in the Darwin area.

4. Diurnal cycle of convective and cloud ice

The substantial differences in the diurnal cycle of convection and differences in storm intensity in the two
regimes (e.g., Keenan and Carbone 1992; May and Ballinger 2007) imply that substantial differences may be expected in the associated anvil and cirrus cloud cover. This is explored using two methods. First, weather radar data statistics are examined. The second method makes use of vertically pointing cloud radar and lidar measurements at the Darwin ACRF site sampling conditions at just one site. The advantage of the first approach is that it includes a large horizontal domain around Darwin to build up statistics. However, it does not include all clouds, owing to the limited sensitivity of the C-band weather radar to smaller cloud droplets when compared to that of the ACRF Millimeter Cloud Radar (MMCR). The advantage of the second approach is that virtually all clouds except optically thin cirrus are detected (e.g., Comstock et al. 2002), but statistics are built from vertically pointing observations. It is shown in Protat et al. 2009 that cloud statistics derived from these local observations averaged over a sufficient length of time are fairly representative of the cloud statistics at regional scale, although we will see that there are some differences in the diurnal signals associated with local circulations.

Figure 3 shows the fraction of the C-POL radar domain covered by reflectivity greater than 40 dBZ and
polarimetric classifications of snow (the primary form of precipitation above the freezing level) as a function of local time and height for the 2005/06 wet season from C-POL radar data. Note that “snow” in this instance includes nonprecipitating ice crystals, but the reflectivity threshold is approximately 0 dBZ as this is the limit of sensitivity at maximum range (150 km). The 40-dBZ area is broadly consistent with the rain accumulations shown in Fig. 2 with a clear peak in the afternoon during the break, although the nocturnal maximum between 0100 and 0500 LT is surprisingly of similar area. Note that squall lines propagating into the region will have significant convective areas and often large stratiform area (Keenan and Carbone 1992). The monsoon 40-dBZ distributions show a clear nocturnal maximum and a minimum in the late afternoon. The snow area, indicating thick anvil cloud and all precipitation above the freezing level, shows similar patterns with a clear lag of the maximum snow area after the maximum in convection. The break also shows much greater snow area after the afternoon maximum consistent with deeper and more intense afternoon convection compared with the evening storms over the water. It is also well known that in the monsoon there are extensive areas of stratiform rain with high snow area (Mapes and Houze 1992) almost continuously through the diurnal period extending to the freezing level, while in the break periods the snow area is dominated by anvil cloud at higher altitudes.

Fig. 6. (b) Similar to Fig. 6a, but for net SW.
The second approach is to examine several years of cloud profile data collected at the Darwin ARCS site with a 35-GHz cloud radar and micropulse lidar. The radar–lidar observations include “ice cloud” profiles (defined as not having a liquid layer below the ice, such as non-precipitating ice anvils, altocumulus/altostatus clouds, and cirrus clouds) and “convective ice” profiles (the ice part of precipitating systems). Care has been taken to split the datasets into ice clouds and convective ice using the “target categorization” approach [see http://www.met.rdg.ac.uk/~swrhgnrj/publications/categorization.pdf and Delanoë and Hogan (2008)], which consists of classifying each observed scene as a meteorological or nonmeteorological target from the cloud radar, lidar, and microwave radiometer measurements and assigning a water phase (liquid, ice, or mixed phase) and a data quality flag to each cloud scene (Protat et al. 2010). Attenuation of the cloud radar in heavy precipitation will affect the convective ice statistics, and will primarily have an impact on cloud microphysical retrievals as well as cloud-top height for the heaviest rain.

The diurnal composites of the frequency of occurrence for these two categories of ice clouds are shown for four wet seasons (2005–2006/09) in Fig. 4. The cloud cover in the break lags the corresponding local convective maximum as may be expected as later convection produces larger areas of cirrus building on cloud generated in earlier storms (Figs. 3 and 4). The profile observations in Fig. 4 for the break period also do not show the separate morning maximum that is seen in the areal data, as the cirrus being generated by the evening and morning offshore storms are initiated away from Darwin and are usually advected away to the west by the upper-level easterly winds. This cloud does not persist and by sunrise the average cirrus coverage is small. This manifests itself in both the downwelling shortwave and longwave radiation, which both exhibit large diurnal variations as seen from data collected at multiple sites during TWP-ICE (Figs. 5 and 6). The radiation measurements at the different sites show the site dependence of the earliest effect of diurnal convection. The significantly less cloud cover exhibited during the break allows significant daylight heating of the surface and boundary layer and this is manifested as an afternoon peak in the downwelling longwave radiation. Note that there are almost always some clouds present, even during suppressed conditions.

As expected from the weaker diurnal cycle of convection in the active monsoon, there are high amounts of cloud cover throughout the day that correlate with but lag the peaks in convection. The corresponding longwave radiation observations exhibit significantly less variation across the diurnal cycle as a result of the persistent cloud amounts. The extensive cloud cover decreases the direct shortwave but increases the diffuse shortwave radiation during the day to being comparable in magnitude to the total SW. The active monsoon diffuse is significantly larger than the diffuse shortwave radiation during the break periods. The greater cloud cover and decreased shortwave input into the surface also limit the amplitude of the diurnal cycle of temperature (section 5 and Fig. 7), which also manifests itself as almost uniform downwelling longwave radiation in time.

The differences in cloud occurrence show a significantly greater amount of cloudiness in the monsoon (Fig. 4) and thicker clouds, while there is a little more late afternoon very high cloud in the break periods consistent with a greater depth of detrainment. Figure 8a shows the daylight sky cover is persistently greater than 85% for the three reference sites during the monsoon phase, compared to the 10%–70% ranges across the three sites for the break phase. Both the Cape Don and Pirlangimpi sites exhibit substantially less cloudiness during the morning than afternoon for break conditions, while the Darwin site shows the opposite. For the wet phase, it is persistently overcast across the daylight hours. These differences in cloud amounts manifest themselves as significantly different transmissivity of the shortwave radiation as shown in Fig. 8b. During the monsoon phase only 30%–50% of the clear-sky equivalent shortwave reaches the surface for all three sites, compared to 70%–90% for Darwin and Cape Don during the break phase. For Pirlangimpi during the break phase, the influence of thunderstorms over the islands is evident, with effective SW transmissivity equivalent to Darwin and Cape Don in the morning, but then decreasing significantly in the afternoon as Hector develops.

5. Diurnal cycle of the boundary layer and its regional variability

The diurnal cycles of clouds, rainfall, and radiation are expected to have a significant impact on boundary layer development. There were five radiosonde sites launching 3-hourly flights during TWP-ICE, as discussed in section 2. They range from the open ocean (ship), a peninsula where the boundary layer was mostly oceanic (Cape Don), a coastal site (Pirlangimpi), a site ~10 km inland (Point Stuart), and a site well inland approximately 120 km from the nearest coast (Adelaide River). During the active monsoon period it was almost continuously overcast, and there was frequent convection. During TWP-ICE, there was a relatively unusual suppressed monsoon period where there was high-level cirrus, but limited local convection that was generally relatively shallow with radar echo tops lower than 8–10 km (May et al. 2008). This suppressed period will
not be discussed further except to note that the very strong low-level winds associated with this event produced a deeper mixed layer over the ocean.

There are clear spatial differences in the diurnal composites of potential temperature for each site and regime and distinct differences in these patterns associated with the different rainfall regimes (Fig. 7). The strongest spatial differences are seen in the break period, with distinct growth in the mixed layer depth at sites that are farther inland. The inland site was associated with mixed layer depths of about 1.5 km (Fig. 9), while the coastal sites were about 1 km and the ocean and peninsula sites showed the typical oceanic mixed-layer depths of about 500 m and a much smaller amplitude in the diurnal cycle than inland.
In contrast, the monsoon period when there were nearly always extensively overcast conditions was characterized by very weak diurnal cycles and only shallow boundary layer development with not easily discernible mixed layers, although there are variations of a few degrees kelvin near the surface. This even distribution with temperatures close to the skin SST offshore means that sea breeze circulations are not important during active periods of the monsoon.

Another way to quantify this is the fraction of time and the height range that well-mixed layers are detectable (Fig. 9). The relatively weak diurnal cycle of the ocean mixed layer is clear and always showed little diurnal variation. These general features can be seen by the relative depths and occurrence rates of profiles with thermally well-mixed layers (defined here as $d\theta/dz < 1.5^\circ \text{ km}^{-1}$). These highlight the small diurnal variations in the monsoon everywhere, although over land there is an afternoon maximum, and over the ocean always. The growth of deeper mixed layers inland is also obvious, as the impact of sea breezes occurs later in the daily heating cycle. The daily cycle in the breaks is reinforced with the limited cloud cover in the morning, allowing more heating and corresponding sea breezes that initiate deep convection (Figs. 5 and 7). However, the lifetime of the convectively generated cirrus is

![Fig. 8](image-url)
sufficiently short in that break regime that the subsequent days are not greatly affected by convection on the previous days. Exceptions to this are when the occasional squall line propagates in from far to the east in the morning.

6. Radiative impacts of clouds

Given the differences in cloud cover and solar transmissivity discussed above, it is obvious that the effect of clouds on the surface radiative energy budget also differs between the monsoon regimes. The surface exhibits a greater skin temperature than the sky and thus the upwelling LW amount is greater than the downwelling amount. The relatively large column water vapor amounts present in the tropical atmosphere, and the relatively warm air temperatures, produce comparatively large clear-sky downwelling LW irradiance. Thus, any increase due to the presence of clouds can only contribute a limited amount to the downwelling LW. However, solar heating of the dry surface can significantly increase the surface temperature and in turn significantly increase the upwelling LW, dependent on the particular surface properties such as soil moisture content, etc. When the direct sun is blocked by cloud, the large loss of downwelling solar energy then does not heat the dry surface nearly as much, and can have a more significant impact on the surface net LW. Figure 5

Fig. 8. (b) Similar to Fig. 8a, but for all-sky transmissivity.
illustrates these effects, showing the all-sky downwelling (solid) and upwelling (dashed) LW diurnal average for the active monsoon (top) and break (bottom) regimes. For the active monsoon regime, the downwelling all-sky LW exhibits no significant diurnal signature, while the upwelling LW shows an increase during daylight hours peaking at about 490–500 W m$^{-2}$ near local noon. For the break periods, both the downwelling and upwelling LW diurnal cycle show increases for daylight hours, but the change in the upwelling LW is the much larger of the two. Here, the aggregate downwelling LW peaks between 430 and 440 W m$^{-2}$ between the three sites, where the upwelling LW peaks between 530 and 535 W m$^{-2}$ for Cape Don and Pirlangimpi and peaks at 555 W m$^{-2}$ for Darwin.

Defining the net radiation as the downwelling (input to the surface) minus the upwelling (output from the surface) then produces values where positive values denote net energy input to the surface and negative values denote a net energy loss. The net LW is always a negative value for the tropical regime, denoting a net LW energy loss at the surface. Figure 6a shows the all-sky (solid) and corresponding clear-sky (dashed) net LW for the monsoon (upper) and break (lower) periods. The difference between the all-sky net LW and clear-sky net LW is noticeably greater for the monsoon than for the break regime for all three sites because the break period had significantly more solar heating of the surface, whereas the persistent cloudiness of the monsoon period greatly decreased the solar surface heating. The results for the suppressed monsoon period (not shown) lie again between the monsoon and break results.

For the SW, the net energy input at the surface consists of the downwelling SW minus that amount that is reflected from the surface, which is again dependent on surface characteristics. For the three sites, the average surface albedo ranged from 14% to 16% (Long 2008), and thus the net energy input amounted to 84%–86% of
the downwelling amount. Naturally, there is no solar energy input at night. Figure 6b shows the all-sky (solid) and corresponding clear-sky (dashed) net SW amounts for the monsoon (upper) and break (lower) periods. The break period received about 80% of the clear-sky amount during daylight periods because of the modest amounts of cloud cover (Figs. 4 and 8). It can also be seen that during the monsoon phase, the persistent cloudiness caused a significant decrease in the SW energy deposited at the surface, which received on average only about 40% of the clear-sky amount.

The net SW and LW cloud radiative forcing is shown in Fig. 10. The net SW effects occur only during daylight but are much larger in magnitude that the corresponding LW effects, which occur over the entire 24 h. For the monsoon period (Fig. 10, top), the net SW effect reaches magnitudes of 400 W m\(^{-2}\) or greater during the midday hours, compared to the much smaller magnitude 50–100 W m\(^{-2}\) of the LW cloud effects. For the break period (Fig. 10, bottom), the magnitudes of the SW and LW cloud effects are smaller, only reaching 100–300 W m\(^{-2}\) and 20–40 W m\(^{-2}\) for the SW and LW, respectively. Again, the magnitudes for the suppressed period (not shown) fall in between. Combining the SW and LW cloud effects yields the total net surface radiative cloud forcing shown in Fig. 11. The presence of clouds considerably affects the surface net
radiation budget for the monsoon season (Fig. 11, top), especially during the daytime. At night, the cloud radiative forcing is positive at about 30–50 W m$^{-2}$. But during daytime the SW cloud effects dominate the forcing, producing large negative values as large in magnitude as 500 W m$^{-2}$. Overall, the 24-h diurnal average net cloud radiative forcing is $-113$ W m$^{-2}$ for Darwin, $-146$ W m$^{-2}$ for Cape Don, and $-121$ W m$^{-2}$ for Pirlangimpi for the monsoon period. These contrast with the 24-h diurnal average of $-19$ W m$^{-2}$ for Darwin, $-25$ W m$^{-2}$ for Cape Don, and $-59$ W m$^{-2}$ for Pirlangimpi for the break period, where the nighttime cloud forcing at Cape Don and Pirlangimpi is only about 5–10 W m$^{-2}$ and only about 20 W m$^{-2}$ for Darwin. The daylight SW dominated forcing only reaches $-200$ W m$^{-2}$ usually near midday.

Thus, the prevalent and often optically thick cloudiness of the monsoon period has a large impact on the surface radiation budget, decreasing the radiative energy input into the surface by on average $-127$ W m$^{-2}$. For the break period, on the other hand, the modest cloud amounts typically comprising comparatively optically thinner clouds decrease the surface radiation budget much less—on average only about $-35$ W m$^{-2}$. For the

![Fig. 11. The aggregate diurnal total net surface radiative cloud forcing for the (top) monsoon and (bottom) break periods of TWP-ICE at the Darwin (dark gray), Cape Don (light gray), and Pirlangimpi (black) sites.](image-url)
suppressed period (not shown), the daily average net surface radiative cloud forcing lies in between at \(-63\) W m\(^{-2}\).

7. Summary

The diurnal cycle of cloud properties and associated radiative impacts in the tropics remains a significant problem for global-scale numerical models and climate simulations (e.g., Slingo et al. 2004). To provide an observational reference for the improvement of models, the analysis conducted in the present study has characterized with state-of-the-art observations the diurnal cycle of convection, cloud, radiation, and boundary layer structure in the two dominant monsoonal regimes—namely, the “monsoon” and “buildup or break” regimes. It clearly demonstrates the consistency and interdependence of the convective activity, resulting rainfall, cloud cover, and radiative properties feeding back onto the boundary layer structure in both convectively active and unstable monsoon conditions and in (break) conditions that are convectively suppressed on the large-scale where convective initiation is dominated by local forcing. In turn, the amount of convective activity and resulting cloud cover and heating profiles (Schumacher et al. 2007) feeds back onto large-scale circulation (Mapes and Houze 1992). The break period situation is important in both the large-scale context of convection in the Maritime Continent [Keenan et al. (2000), and more recent studies showing the diurnal variation over islands] on daily and seasonal time scales. The results shown herein also very clearly highlight the large variability of the diurnal cycle properties as a function of the two regimes. It will be very important to evaluate if current large-scale models are able to reproduce these crucial features of the diurnal cycles in the tropics.

The spatial distribution of rainfall showed distinct structure in both monsoon and break periods. In the monsoon there is a pronounced east-west asymmetry with more rainfall over the ocean. The break period showed distinct peaks on the western coasts associated with the advection and intensification of storms as they propagate toward the coast and there are mergers of cells (e.g., Simpson et al. 1993). The break also exhibited a much stronger diurnal signal in rainfall and resulting cloud cover, but there remained significant diurnal variation in the monsoon also.

The active monsoon decreases the total net radiative input to the surface more than 3 times the amount that the suppressed break regime does. This total radiative cloud forcing is dominated by the SW cloud effects because of the much larger optical thicknesses and persistence of ice clouds associated with the monsoon regime. While the total net cloud radiative forcing is modestly positive at night, the daylight loss of radiative input to the surface is many times larger in magnitude. These differences in monsoon versus break surface radiative energy contribute to low-level air temperature differences in the boundary layer over the land surfaces, which in turn influence the strength of the sea breezes, although quantification is difficult as we cannot measure the advective terms nor do we have spatially resolved surface flux measurements.

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