Optimizing the Probability of Flying in High Ice Water Content Conditions in the Tropics Using a Regional-Scale Climatology of Convective Cell Properties

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ABSTRACT

In this paper, statistical properties of rainfall are derived from 14 years of Tropical Rainfall Measuring Mission data to optimize the use of flight hours for the upcoming High Altitude Ice Crystals (HAIC)/High Ice Water Content (HIWC) program. This program aims to investigate the convective processes responsible for the generation of the high ice water content that has been recognized as a threat to civil aviation. The probability that convective cells are conducive to HIWC is also further investigated using three years of C-band polarimetric radar data. Further insights into the variability of convective rainfall and favorable conditions for HIWC are also gained using two different methods to characterize the large-scale atmospheric conditions around Darwin, Australia (the Madden–Julian oscillation and the Darwin atmospheric regimes), and the underlying surface type (oceanic vs continental). The main results from the climatology relevant to flight-plan decision making are (i) convective cells conducive to HIWC should be found close to Darwin, (ii) at least 90% of convective cells are conducive to HIWC at 10- and 12-km flight levels, (iii) multiple flights per day in favorable large-scale conditions will be needed so as to utilize the 150 project flight hours, (iv) the largest numbers of HIWC radar pixels are found around 0300 and 1500 local time, and (v) to fulfill the requirement to fly 90 h in oceanic convection and 60 h in or around continental convection, a minimum “acceptable” size of the convective area has been derived and should serve as a guideline for flight-decision purposes.

1. Introduction

Since the mid-1990s it has been recognized that jet engines are susceptible to engine power loss and damage events when flying in some clouds, with many events occurring in the vicinity of deep convection in the tropics and subtropics. The first description of the meteorological conditions suspected in these jet engine power loss events was reported by Lawson et al. (1998) after a series of events on a commuter-class aircraft. Mason et al. (2006) reported that these events were observed on essentially all airframes and jet engine types and provided further detailed information on the common observations from commercial aircraft flight data recorder and pilot’s reports associated with engine power loss events. These common observations are the following:

- The aircraft flies near deep convective cores (usually avoiding them);
- the aircraft lies in a warm tropical environment;
- the pilots report a light to moderate turbulence and an effect of “rain on the windshield”;
- there is a lack of significant airframe icing (i.e., supercooled liquid water is not required for that type of icing);
- there is an anomaly in measured aircraft total air temperature (TAT) by the TAT probe; and

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• the pilot radar echoes are below 30 dBZ (and sometimes below 20 dBZ) at aircraft altitude, implying the absence of graupel and hail.

Grzych and Mason (2010) and Mason and Grzych (2011) then developed statistics based on approximately 100 engine events on the relative frequency of distinct cloud-system types associated with engine events. They found that most cases occurred within mesoscale convective systems (72%) of oceanic origin, with approximately equal numbers over land and over ocean. The remaining cases occurred in other types of convective systems. Further analysis by Mason and Grzych (2011) also suggested that engine events may be more likely when the aircraft has passed through a relatively long distance of deep convective cloud, implying that exposure time might be an important factor to trigger an engine event.

Lawson et al. (1998) and Mason et al. (2006) concluded that engine power loss events were likely due to ingestion of large concentrations of small ice particles, a previously not well-recognized form of engine icing. Mason et al. (2006) further established that supercooled liquid water content (LWC) was not required, and that aircraft were always in radar reflectivity < 30 dBZ (and sometimes < 20 dBZ), and not necessarily in the vicinity of a flight-level high-reflectivity core. The simultaneous occurrence of high ice water content (HIWC) and relatively low radar reflectivity implied that the ice particles are smaller than usual (to produce relatively small radar reflectivity) but in very high concentration (to produce significant ice water content). This will be referred to as HIWC conditions throughout this paper. Gayet et al. (2012) have also recently described in situ and airborne cloud radar observations of such environmental conditions.

The power loss events take on several forms, including combustor flameout, engine surge, and stall, all of which are short-duration events from which recovery is automatic or manual depending on the engine. Rollback may occur in smaller engines when ice buildup partially blocks the airflow to the compressor. Engine power can only be restored by warming the ice through descent to a warmer altitude. Engine compressor blade damage can be the result of the ice shedding impacting downstream rotor blades. Although the details of the physics of ice accretion in an initially warm engine are not yet fully understood (Mason et al. 2010), studies have shown that high concentrations of ice are required to lower the temperature of engine surfaces sufficiently to initiate accretion. A link between smaller ice crystals and the physics of ice accretion has not been established, but their ability to melt faster than larger ice crystals in the engine may provide liquid for accretion despite short residence times associated with the high-velocity airflow through an engine. Areas of cloud with smaller ice crystals are also more likely to be penetrated during flights because of their lower radar reflectivity.

Ice crystal icing in HIWC conditions have also been implicated in the failure of air data systems such as those that measure air temperature, airspeed, and angle of attack. Such failures can also cascade into disengagement of the autopilot and require pilot situation awareness. Safety concerns related to these engines and air data system events, and high costs associated with engine repairs led the international regulation authorities and scientific communities to define actions to fully investigate this specific threat. The Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) have published intentions to institute new aircraft certification standards for ice crystal icing (Federal Aviation Administration 2010; European Aviation Safety Agency 2011). High Ice Water Content Study (HIWCS) science and technical plans have then been issued for an investigation of the characterization of in situ properties of HIWC regions of deep convection (Strapp et al. 2014). This effort includes an international airborne field campaign based in Darwin, Australia, called the HAIC/HIWC project (Dezitter et al. 2013), which is a collaboration of

• the North American–based HIWC Study consortium led by FAA and the National Aeronautics and Space Administration (NASA), with partners including Environment Canada, Transport Canada, Boeing, Airbus, and the Australian Bureau of Meteorology; and
• the European-based High Altitude Ice Crystal (HAIC) Project consortium (38 members from research and industry; see http://www.haic.eu/ for further details).

The data will be used for the development of new engine certification standards, techniques for detecting and provision of warnings from satellite and nowcasting systems, and improved scientific understanding of the microphysical and dynamical mechanisms responsible for the formation of HIWC regions. A Falcon 20 research aircraft from France, funded by HAIC, FAA, and EASA, will collect up to 150 research flight hours of in situ particle size distribution, in situ bulk HIWC measurements, and vertical cross sections of cloud radar observations during this experiment. Flight objectives and methodologies noted below are extracted from the HIWC Study science and technical plan and HAIC/HIWC operations plan. The objective of the field

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1 Radar reflectivity in the Rayleigh regime is proportional to the diameter of the ice crystals at the sixth power. Large particles therefore usually dominate the radar-reflectivity signal.
campaign will be to fly 85% of the time in convection in oceanic air masses (60% over ocean and 25% over land), and 15% in the vicinity of more traditional vigorous continental convection, reflecting the proportion of engine events in each cloud type (Mason and Grzych 2011). As observed by Mason et al. (2006) and Grzych and Mason (2010), engine events in assumed HIWC conditions were most often associated with low reflectivity at flight altitude but heavy rain (high reflectivity) below the aircraft. During the HAIC/HIWC project, to identify potential suitable conditions at flight altitude, the aircraft operational radar will first be tilted downward to find precipitation areas below the aircraft that are a product of active convective cells, and then scanned horizontally to ensure that the associated flight-level reflectivity does not exceed 30 dBZ.

The following have been chosen as the three priority temperature levels for the aircraft in situ microphysical sampling:

1) Level −50° ± 3°C is a typical cruise altitude for commercial jet aircraft, the temperature at which any remaining liquid water in updrafts will have frozen because of homogenous nucleation, and the level perhaps at which the smallest ice particles will be measured. The −50°C level is approximately 12.4 km above ground.

2) Level −30° ± 3°C is a midaltitude with possibly intermediate particle size and is also potentially the approximate region of maximum total water content based on adiabatic calculations of deep lift. The −30°C level is approximately 10.2 km above ground.

3) Level −10° ± 3°C is a low flight level where study of mixed-phase processes and ice initiation in updrafts may be critical to understanding evolution of the microphysics and where particles in precipitation regions may be approaching their maximum size before melting. The −10°C level is approximately 7 km above ground.

The current hypothesis of this experiment is that HIWC conditions consistent with engine events should be found in convective cells for which the 30-dBZ conditions consistent with engine events should be present. This hypothesis is based on previous studies that have characterized this frequency of occurrence of 30-dBZ echo-top height in convective cells around Darwin. May and Ballinger (2007) characterized the maximum height reached by convective cells containing 35 or 45 dBZ, but there is no information on the reflectivity altitude profile, which is needed in our case. Kumar et al. (2013b) recently characterized the frequency of occurrence of the 5-dBZ echo-top height but not the 30-dBZ echo-top height. Zipser and Lutz (1994) described median reflectivity values in convective cells at different tropical locations as a function of height. Although they do not characterize the 30-dBZ echo-top height statistics needed, it shows that the median reflectivity value in convective cells around Darwin drops below 30 dBZ at heights greater than 6 and 11 km in tropical oceanic and tropical continental cells, respectively. This result implies at least that oceanic convective cells are potentially more conducive to favorable HIWC–low reflectivity conditions than continental cells.

In this paper, we derive a regional-scale climatology of selected properties of convective rainfall for the 15 January–15 March (JFM) period from the Tropical Rainfall Measuring Mission (TRMM; Huffman et al. 2007) to optimize the use of the 150 HAIC/HIWC campaign flight hours, and to assist in precampaign flight planning strategies. We first produce a regional climatology of mean rainfall rate and rainfall frequency to assess the suitability of Darwin as the primary airport for the experiment and the need for additional secondary airports. We then investigate the probability that convective cells exhibit characteristics compatible with the presence of HIWC given the height of their 30-dBZ level, using three JFM seasons (2004–07) of observations from the ground-based research dual-polarization C-band polarimetric (CPOL) radar (Keenan et al. 1998). Further insights into the variability of convective rainfall and favorable conditions for HIWC within the JFM period are also obtained using two different methods to characterize the large-scale atmospheric regimes around Darwin and the underlying surface type (oceanic vs continental). The first method for large-scale regimes is based on the commonly used phases of the Madden–Julian oscillation (MJO). The second method is a clustering technique of long-term local radiosounding information.

2. Observations

a. TRMM 3B-42 rainfall

The regional rainfall climatology and its variability as a function of the different large-scale circulation conditions were prepared using the 14 JFM (1998–2012) seasons of the TRMM 3B42, version 7, rainfall product (Huffman et al. 2007). The data contain estimated rain rate (mm h−1) created by calibrating the IR brightness temperatures to the high-quality microwave estimates. The product is available as 3-h temporal and 0.25° × 0.25° spatial resolution globally, extending from 50°S to 50°N latitude from 1998 to present. Although the TRMM 3B42 rainfall product has been widely used in the analysis of rainfall characteristics at several locations around the globe, there exists a known bias between the TRMM
rainfall-rate estimates and the ground-based station rainfall-rate estimates (Cheema and Bastiaanssen 2012; Chen et al. 2013). In general, the TRMM 3B42 product underestimates the rainfall rate from deep convection over the tropical mountains (Rasmussen et al. 2013) with some exceptions under certain conditions when overestimation is observed (Montero-Martínez et al. 2012). In addition, the TRMM 3B42 product is found to be more accurate over ocean than over land (Chen et al. 2013). It is therefore important to estimate how accurate this product is over our region of interest, which will be done in section 2c.

b. **CPOL radar and surface type definition**

CPOL (Keenan et al. 1998) is a research-grade C-band (5.5 GHz) dual-polarization Doppler radar located near Darwin. CPOL performs volumetric scans every 10 min within a radius of 150 km of Darwin from November through April each year (wet season). The scans include 15 elevation angles (from 0.5° to 43.1°) with azimuth and radial resolutions of 1° and 300 m, respectively. These radar data are then gridded at 2.5- and 0.5-km resolution horizontally and vertically, respectively (these individual radar volumes will be hereinafter referred to as the “radar pixels”). This multiyear CPOL dataset has recently been used to statistically characterize several properties of convective rainfall and their variability as a function of the large-scale forcing (Penide et al. 2013; May et al. 2012; Kumar et al. 2013a,b; Dolan et al. 2013). In our study these observations will be primarily used to characterize the statistical properties of the 30-dBZ echo-top height in convective cells (ETH30) as a proxy for a favorable condition for HIWC if this ETH30 is anywhere below the flight level.

Four different surface-type areas of the CPOL radar domain, shown in Fig. 1, will also be considered to characterize the variability of the convective cloud properties: oceanic I northwest of Darwin, oceanic II northeast of Darwin, continental, and the Tiwi Island. The location of the geographical regions further discussed below is also given in Fig. 1.

c. **TRMM 3B-42 rainfall product evaluation**

Given the global-scale variability of the accuracy of the TRMM 3B42 product discussed in section 2a, it is important to build confidence in TRMM 3B42 rainfall-rate estimates in our region of interest, because these are used semi-quantitatively in section 4. A comparison is thus performed for eight wet seasons over land first in the Darwin area between the daily rainfall rates from the average of rain gauge stations located in the dashed box in Fig. 1, the TRMM 3B42 product in that box, and the CPOL radar estimate for that box (Fig. 2a). Owing to the very different sampling volumes of the instruments and resolution of the products such comparisons are obviously not a truly quantitative estimate of the product accuracy, but nevertheless give a good qualitative indication of the agreement between the different rainfall-rate estimates. The CPOL rainfall rates have been derived from the polarimetric radar variables using the technique outlined in Bringi et al. (2009) and Penide et al. (2013). Figure 2a shows that the comparison points generally scatter around the 1:1 curve, that the spread increases for smaller rainfall rates, and that the correlation between TRMM 3B42 and the rain gauges (0.64) is slightly lower than the correlation between CPOL and the rain gauges (0.74). The second set of rainfall-rate comparisons is carried out between TRMM 3B42 and CPOL using all common pixels over land (Fig. 2b) and over ocean (Fig. 2c) for the same eight wet seasons. Over ocean, the agreement between TRMM 3B42 and CPOL is slightly better than over land (0.76 versus 0.73), in agreement with the analysis of Chen et al. (2013). In both cases the level of correlation between CPOL and TRMM 3B42 is similar to that between CPOL and the rain gauges (0.74, Fig. 2a) in the dashed domain of Fig. 1, which indicates that the TRMM 3B42 product is roughly at the same level of accuracy as the ground-based radar in our region at the daily time scale. This is sufficient for the purpose of this study, which is focused on the variability of mean daily rainfall rate rather than absolute rainfall-rate values.

3. **The large-scale atmospheric regimes**

Convection produced in the Darwin area is heavily modulated by the prevailing large-scale conditions, which will be hereinafter referred to as “the large-scale regimes.” The first-order modulation of these large-scale conditions is the wet versus dry regimes in that tropical region. It is therefore important to characterize what large-scale conditions will be more or less favorable for the development of HIWC and trigger flights in those favorable conditions. In this paper, we characterize the modulation of rainfall rate and frequency using two well-established methods to characterize the large-scale regimes in our region of interest: the so-called MJO phases and Darwin atmospheric regimes.

a. **The MJO phases**

The MJO (Madden and Julian 1972) is characterized by eastward migrating strong positive convection anomalies in the Indian and western Pacific Oceans. The intraseasonal variability associated with the MJO is known to significantly modulate the deep convective activity over the tropics, both near the MJO source region (e.g., Hendon and Liebmann 1990; Wheeler and
McBride 2005) and remotely through complex teleconnections (e.g., Jones 2000; Pohl et al. 2007). In particular, it has been shown that it has a large impact on northern Australian rainfall and circulation (Wheeler et al. 2009), which is the region of interest of our study. In this study, we use the eight phases of the MJO as defined by the daily index developed by Wheeler and Hendon (2004). This daily index is based on a pair of empirical orthogonal functions of the combined fields of near-equatorially averaged 850-hPa zonal wind, 200-hPa

![Figure 1](https://example.com/fig1.png)
of the time over the whole JFM period (not shown). From Fig. 3, however, some systematic variability can be identified during JFM for some of the MJO phases. The frequency of occurrence of phases 1, 2, and 3 tends to drop from weeks 5 to 9 (February), while for these same weeks the frequency of occurrence of MJO phases 4 and 5 is increasing. The opposite is true after week 10. There is no clear variability for the other MJO phases.

b. The Darwin atmospheric regimes

Cluster analysis on the wind and thermodynamic information from radiosonde data at Darwin for 49 yr from 1957 to 2006 has been recently carried out (Pope et al. 2009) to define objective large-scale regimes over northern Australia, which will hereinafter be referred to as the “Darwin atmospheric regimes.” Five objectively derived regimes are obtained, which are found to differ significantly in their synoptic environment, cloud patterns
and rainfall distributions (Pope et al. 2009). The frequency of occurrence of these regimes during the wet season is shown in Fig. 4 for an extended period of 55 yr (1957–2012). During JFM, three regimes dominate, corresponding to typical wet-season conditions. In what follows we will only consider those three regimes. See Pope et al. (2009) and Kumar et al. (2013b) for more details about these regimes. We will here only briefly summarize their most salient features. The average duration of each Darwin regime and the mean number of times a Darwin regime occurs in a JFM period are also estimated and discussed below.

The first regime is characterized by an easterly lower-tropospheric zonal flow, extending throughout the entire troposphere. The meridional winds for this regime are also very light. This regime also has a smaller dewpoint depression than the other easterly regimes. This regime will be referred to as the “moist easterly” (ME) regime and corresponds to the so-called break periods in the monsoon literature (e.g., May et al. 2008 and references therein). From Fig. 4 (red line) it is observed that the frequency of occurrence of this regime is 40% in early January and linearly increases up to about 50% at the end of the wet season. The mean duration of each ME regime burst is 3.4 days, and there are on average 11 ME periods in JFM.

The second regime identified in Pope et al. (2009) is characterized by a westerly zonal wind profile up to about 7-km height and easterly zonal winds above this level. The meridional wind profile is northerly, changing to southerly above 8-km height (Kumar et al. 2013b). This regime has the strongest upper-tropospheric zonal winds of all the regimes. The temperature profile exhibits a small dewpoint depression, indicative of a very moist atmosphere. This regime is therefore referred to as the “deep westerly regime” (DW) and corresponds to the “active monsoon periods” in the monsoon literature. It is found to be present 20%–25% of the time up to week 10 (Fig. 4, green profile), which corresponds to early March, and then drops quickly from week 10 to week 13. The mean duration of each DW regime burst is 3.6 days, and there are on average 5.7 DW periods in JFM.

The third regime exhibits a shallow westerly wind below about 2-km height, with weak easterly winds above that level (e.g., Kumar et al. 2013b). The meridional winds are southerly throughout the depth of the troposphere. The moisture profile shows a larger dewpoint depression than the deep westerly regime. It will be referred to as the “shallow westerly” (SW) regime. The frequency of occurrence of this regime follows closely that of the DW regime, which is due to the fact that it generally happens prior to the DW regime. The mean duration of each SW regime burst is 2.6 days, which is shorter than for the ME and DW regimes, and there are on average 8.5 SW periods in JFM.

4. Satellite regional-scale climatology

In this section we develop a regional climatology of seasonal mean rainfall rate and daily rainfall frequency
of occurrence using the TRMM 3B42 product to identify the best potential areas for HIWC conditions in JFM. The other objectives of this climatology are to characterize the interannual variability of rainfall properties and to document the variability of rainfall properties as a function of MJO phase or Darwin atmospheric regime. These results are then used to inform flight-decision planning for the HIWC experiment.

a. Interannual variability of mean rainfall rate

Figure 5 shows the climatology of seasonal mean rainfall rate in millimeters per day as derived from 14 JFM seasons of the TRMM 3B-42 product. As clearly seen from this figure, the Darwin area is one of the four major rainy areas of the northern part of Australia, with values up to 14 mm day\(^{-1}\) within the area of operation of the Falcon 20 aircraft when taking off from Darwin. Convective cells should therefore be found without flying too far from Darwin. Whether these convective cells are potentially conducive to HIWC will be evaluated in section 5. The variability of seasonal mean rainfall rate is reasonably small in that region, with largest values of less than 4 mm day\(^{-1}\). To further explore this variability Fig. 6 shows the least and most rainy JFM seasons of our 14 JFM periods. Year 2002 was characterized by much lower rainfall rates than the climatology (Fig. 6a), with seasonal mean rainfall rates less than 10 mm day\(^{-1}\) in the Darwin area. In contrast, year 2011 was characterized by much larger rainfall rate than the climatology in the Darwin area (Fig. 6b), with peak seasonal mean rainfall rate of up to 18–20 mm day\(^{-1}\). Other years exhibited extreme rainfall rates in excess of 20 mm day\(^{-1}\) in the Darwin area (not shown) but comparatively smaller seasonal mean rainfall rates in other areas of the region (years 2000, 2007, and 2008).

![Figure 5](image1.png)

**Fig. 5.** Climatology of (a) seasonal mean rainfall rate (mm day\(^{-1}\)) and (b) standard deviation of the seasonal mean rainfall rate (mm day\(^{-1}\)) derived from 14 JFM seasons of the TRMM 3B-42 product.

![Figure 6](image2.png)

**Fig. 6.** Illustration of the variability of the seasonal mean rainfall rate: (a) least rainy season in 2002 and (b) most rainy season in 2011.
The west coast of Cape York (the elongated part of Australia at 142°–144° longitude in Fig. 5) on the east side of the Gulf of Carpentaria and the coastal area extending north-northeast of Broome (which will be hereinafter referred to as the “Broome area”) are the two other favorable regions, characterized by a similar amount of seasonal mean rainfall as the Darwin area. Note that we exclude the maximum in Queensland (on the east coast of Australia) because it is out of reach of the aircraft for the experiment. Therefore we suggest that these areas should be used as backup areas of operation for the HIWC aircraft in case suppressed conditions are encountered in the Darwin area. This would mean temporarily relocating the aircraft closer to Cape York or Broome. However, only in years 1998, 2003, and 2010 was the seasonal mean rainfall rate over Cape York and the Gulf of Carpentaria much larger than in the Darwin area. So the probability that the aircraft would need to be relocated most of the time in the JFM period is low.

In sections 4c and 4d, we investigate which large-scale environments, if any, are associated with enhanced rainfall production over the Cape York or Broome areas and reduced Darwin-area rainfall to characterize when within a JFM season aircraft relocation might be needed. Note also that the coast off Broome is characterized by a much larger variability of mean seasonal rainfall rate than the other two regions. It is therefore not as likely to be a favorable region as the other two.

b. Interannual variability of rainfall frequency

The analysis of seasonal mean rainfall rate suggests whether an area of our domain of interest may be favorable for flight operations overall, but it does not tell anything about the frequency of occurrence of daily rainfall in that region (hereinafter “rainfall frequency”). Some convective storms and tropical cyclones produce a lot of rain in this area, but they do not happen very often. Flying a large number of hours in convective cells requires an area of interest with a high frequency of occurrence of high rainfall rates. Therefore, in this section we investigate the frequency of occurrence of days with more than 1 mm day$^{-1}$ per 25-km pixel from the TRMM 3B-42 product (Fig. 7). This threshold ensures that only convective storms producing large rainfall rates are captured. From this figure it is clearly observed that areas of high frequency of occurrence of rainfall are the same as the areas of high seasonal mean rainfall rates. In most of the Darwin area, the rainfall frequency exceeds 60%. This implies that convective cells could be found more than 60% of the time. Whether those cells potentially carry HIWC will be studied further at the radar scale in the next section. A 60-day experiment corresponds to 36 flight days, or 126 flight hours (for a Falcon 20 flight of 3.5 h). This is slightly less than the 150 h allocated to the project. An important implication for flight planning of the HAIC/HIWC flight program is that multiple flights per day should be encouraged during favorable conditions so as to maximize the efficient use of 150 flight hours. To identify when in the JFM period multiple flights per day should be recommended, the variability of rainfall frequency as a function of different large-scale environments, as defined by the MJO phase and the Darwin atmospheric regimes, is characterized in sections 4c and 4d. Figure 7 also shows that the rain frequency is slightly larger over the Cape York area and slightly smaller in the Broome area than in the Darwin area. This suggests that if suppressed conditions occur at Darwin, favorable flight conditions might be found in one
or both of those two backup regions under specific large-scale conditions, with Cape York being statistically favored. This is studied further in the next two sections.

c. Intraseasonal scale: MJO variability

As concluded in sections 4a and 4b, there are three areas that are particularly favorable for HAIC/HIWC flight sampling: the Darwin, Cape York, and Broome areas. The preferred area of operations is Darwin. However, the interannual variability suggests that it may be necessary to temporarily relocate the aircraft nearer to the two backup areas in case of suppressed conditions around Darwin. Furthermore, the rain frequency climatology suggests maximizing the frequency of flights during favorable conditions, including flying more than once a day to effectively use the 150 flight hours allocated to the field experiment.

In this section our aim is to characterize how these climatologies of seasonal mean rainfall rate and rainfall frequency vary as a function of the MJO phases. Given that the MJO phase can be monitored in near–real time (http://www.bom.gov.au/climate/mjo/), this information will be available during the field experiment to guide flight-planning decisions. Figures 8 and 9 show the MJO variability of seasonal mean rainfall rate and rain frequency, respectively. First, it is observed that in a weak MJO situation, the climatology of rainfall rate and frequency are very similar to the total climatology (Fig. 5a). This is expected as this situation occurs on the average about 40% of the time. During MJO phases 1, 2, and 3, the large-scale conditions favorable for MJO convection are located over the Indian Ocean in the 60°–100°E longitude band (west of our domain) and progressively move toward northern Australia. During MJO phase 8,
favorable conditions are located far east of Darwin, near the date line. The associated spatial distributions of mean rainfall rate (Fig. 8) and rain frequency (Fig. 9) are quite similar for MJO phases 1, 2, 3, and 8. Convective activity is also much reduced over the ocean relative to the climatology (as shown by the much reduced mean rainfall rate in Fig. 5a). However, the coastal and continental zones in the Darwin, Cape York, and Broome areas are still characterized by mean rainfall rates in excess of 10 mm day$^{-1}$ and rain frequencies in excess of 60%. Some convective activity is also observed over the ocean north of the Broome area during MJO phase 1.

The implication of this result from a flight-planning point of view is that it may be necessary to target moderate continental convective cells and coastal convective cells west of Darwin during MJO phases 1, 2, 3, and 8, given the reduced convective activity over the ocean in those phases. During MJO phases 4, 5, and 6, large-scale conditions favorable for MJO convection are present over the northern part of Australia. As a result, both rainfall amount and frequency are enhanced during those three phases in the Darwin area, with maximum convective activity reached during phase 5, where seasonal mean rainfall rate is in excess of 20 mm day$^{-1}$ (Fig. 8) and rainfall frequency exceeds 80% (Fig. 9). Those are the three phases during which oceanic convection in the Darwin area should be targeted, with as many flights as practically possible, including multiple flights per day if conditions are favorable. During MJO phase 7, the large-scale conditions favorable for MJO convection are located east of Australia. As a result, mean rainfall rate and frequency revert back to values close to the total climatology in the Darwin area. It is also interesting to note that enhanced convective activity is observed in the Cape York area. Relocation of the aircraft to this area should therefore be considered during
MJO phase 7 (and perhaps during MJO phase 6) if conditions are suppressed in the Darwin area. Convective rainfall amount, but not frequency, is also enhanced in the Broome area in MJO phase 6, so possible relocation of the aircraft to that area should also be considered.

The overall conclusion of this analysis is that there is a large statistical variability of rainfall properties between MJO phases, which can be used to optimize the aircraft operations over the JFM period, to target either oceanic or continental convection, and possibly to relocate the aircraft near Cape York or Broome under some specific large-scale conditions. Specifically, one might consider targeting oceanic and coastal convection near Broome during MJO phases 1 and 6, moderate continental convection near Darwin area during MJO phases 1, 2, 3, and 8, and oceanic convection near the Cape York area during MJO phases 7 and 6.

d. Intraseasonal scale: Darwin atmospheric regime variability

As discussed in section 3, another way to capture a change in large-scale conditions in our area of interest is to use Darwin radiosoundings (Pope et al. 2009). Three wet regimes were identified earlier in section 3b. The mean seasonal rainfall rate and rain frequency for these three regimes are shown in Figs. 10 and 11, respectively. The general impression from these figures is that there is less variability between these regimes than between MJO phases (Figs. 8 and 9). The most favorable flight conditions are found during the DW regime, which corresponds to the well-known active monsoon regime. Both mean rainfall rate and rain frequency are higher under this DW regime in the three identified areas and over the surrounding ocean. Coastal convective activity is clearly enhanced near Broome during the DW regime. However, the rain frequency is slightly smaller near Broome than near Darwin and Cape York. In terms of flight planning, the recommendation here is clearly to target oceanic convection near Darwin and northeast of Broome, and attempt to fly twice a day during this DW regime. During the SW regime, large-scale conditions are close to the rainfall climatology, with, however, a slight reduction in rain frequency near Darwin, especially over the ocean west of Darwin. In contrast, mean

![Diagram](image-url)
rainfall rate and rain frequency are slightly enhanced near Cape York and reduced near Broome. It might therefore be worth considering temporarily relocating the aircraft to the Cape York area during a SW regime. During the ME regime, the well-known break period in the Darwin area, there is enhanced convective activity over ocean over the northeast quadrant of the domain but reduced activity in the south part of the Gulf of Carpentaria. The rainfall properties are generally similar to the total climatology, and the Darwin area clearly seems to be the most favorable region to fly.

5. Radar-scale climatology of convective cell properties

In section 4, the general regional patterns of rainfall properties and their variability were discussed. General recommendations were also made regarding flight planning and optimal use of flight hours. The Darwin area has been identified as the appropriate primary area for aircraft operations, with the areas near Cape York and Broome as main backup options if specific large-scale conditions prevail in our region of interest and if relocating to these areas is practical or even possible. Focusing on the Darwin area, the analysis of favorable conditions for HIWC can be refined using radar observations from the CPOL radar. The main hypothesis for this work and strategy for flight sampling has been developed and discussed in the HIWC technical and science plan (Strapp et al. 2014), based mostly on the analysis of engine events conducted by Mason et al. (2006), Grzych and Mason (2010), and Mason and Grzych (2011). The assumption is that these favorable conditions for HIWC are produced by convective cells or ensemble of convective cells, usually within large mesoscale convective systems, with radar reflectivity not exceeding 30 dBZ (and sometimes even 20 dBZ) at flight level, but usually with high radar reflectivity below the aircraft. As a result the main parameter we will characterize in this section is the ETH30 associated with convective clouds over 3 JFM seasons (2004–07). If the ETH30 is below flight altitude at the aircraft location then the convective cell is deemed favorable for HIWC conditions.

As discussed in section 1, there are priority temperature levels for the flight measurements, corresponding to about 7-, 10-, and 12-km altitude above sea level (which will be hereinafter referred to as “altitude” or “height”). The HIWC conditions will be measured with flight tracks at 10- and 12-km altitude level, while microphysical processes leading up to the formation of HIWC will be investigated through the flight tracks at about 7-km altitude. Within the radar domain, convective radar pixels are identified using the Steiner et al. (1995) convective/stratiform classification technique and only convective pixels are retained for the analysis. Convective rainfall accumulation contributes to about 50% of the total rainfall accumulation in the CPOL radar domain but convective rainfall is also characterized by a much smaller spatial fraction (approximately 8%) than the fractional coverage of stratiform clouds (Penide et al. 2013). The incidence of ETH30 convective pixels over the 3 JFM seasons is found to be 321,000, which corresponds to about 150 convective pixels per hour. This is equivalent to a $30 \times 30 \text{ km}^2$ convective area that can be flown in an hour. Note that the actual 10-min resolution radar-derived convective area will generally be smaller than this equivalent convective area because some radar pixels could be counted up to six times in the number of convective pixels per hour. However, this equivalent convective area is a better estimate of the actual convective area that the aircraft will really encounter during one flight hour because it will be able to go through the same convective pixel multiple times. The ETH30 is then derived for each convective profile to produce the statistics shown below. Since only three JFM seasons are available in our radar analysis, the number of days included in each MJO phase is too small (typically 10) to perform a statistical analysis. Also the Darwin atmospheric regimes are by construction most representative of the large-scale context in our Darwin area. As a result, we only discuss in this section the variability of ETH30 as a function of the Darwin atmospheric regimes and underlying surface type. ETH30 is also binned as a function of local time (in 1-h bins) to characterize the diurnal variability of potentially favorable HIWC conditions.

a. Cumulative probability of 30-dBZ echo-top height

Figure 12 shows the cumulative probability of convective profiles having an ETH30 at any given height or lower in the troposphere during the JFM period. It also shows how this cumulative probability changes under the different Darwin atmospheric regimes and surface types (as defined in Fig. 1). The probability of ETH30 being lower than 12-, 10-, and 7-km height (which corresponds to favorable conditions for HAIC/HIWC flights) is 96.9%, 93.7%, and 55.9%, respectively. This indicates that most convective profiles identified should actually be favorable for HAIC/HIWC flights at 10- and 12-km height. This result is important, as it shows that the HIWC conditions should actually be quite common in the Darwin area and not a transient or rare event. Practically it means that the probability of flying in the sought after conditions is high. As seen in Fig. 12, this probability of favorable conditions is highest during the
DW regime (the probability of ETH30 lower than 10 km exceeds 96.5%), and higher than average for convective cells over the oceanic I area and the Tiwi Islands (over 94.2%). Conversely, the conditions are least favorable for HAIC/HIWC flights during the SW regime (probability of ETH30 lower than 10 km is 90.0%), and over continental surfaces and the oceanic II area (90.0% and 90.9%, respectively). However, even in these least favorable large-scale atmospheric conditions, there are still at least over 90% of convective cells that are favorable for HIWC conditions at or above 10-km flight level.

b. Diurnal variability of 30-dBZ echo-top height

The diurnal variability of convective cloud properties is large in the Darwin area (e.g., May et al. 2012; Kumar et al. 2013b). It is therefore important to characterize the diurnal variability of ETH30 as well to investigate for which local times and under which large-scale conditions it would be optimal to fly. In Fig. 13, the diurnal cycle of the hourly number of convective 2.5 × 2.5 km² radar pixels within the radar domain that are favorable for HIWC conditions is given, which will be denoted as “the number of HIWC radar pixels” in the following. From Fig. 13, it is observed that the largest incidences of HIWC radar pixels are found around 1500 LT (main peak), and around 0300 LT (second peak). In terms of flight planning, the two periods 0200–0500 LT and 1400–1700 LT, or as close to those periods as practical, should therefore be targeted in priority. As discussed in section 4, multiple flights per day should be envisaged so as to make sure that all flight hours are utilized. These two periods should allow for a sufficient number of opportunities.

We now turn to an investigation of how these favorable periods change under the different Darwin atmospheric
regimes and for the different underlying surface types. During the DW regime (active monsoon; Fig. 13), the most favorable periods are centered on 0500 LT (later than the average) and 1400 LT (earlier than average). During the ME (break) regime, the early morning peak occurs earlier than average, at about 0300 LT. During the SW regime, the overall structure of the diurnal cycle of the number of HIWC radar pixels is similar to the average but the incidence of HIWC radar pixels is larger than average. The variability of the diurnal cycle as a function of surface type (Fig. 14) is found to be larger than for the Darwin atmospheric regimes, which has important implications for the HIWC flight planning. The best time of day to fly over the oceanic I region in HIWC is primarily around 0300 LT. There is also a secondary peak around 2100–2200 LT, which is much later than the average afternoon peak (see black line in Fig. 13). In contrast the diurnal cycle of favorable conditions in the oceanic II region is very flat with, however, some slight peaks at around 0500 and 2300 LT. Over the continental area the best time to fly is clearly in the late afternoon (1700–2000 LT).

Over the Tiwi Islands, the largest incidence of HIWC radar pixels is clearly found around 1500 LT, associated with the development of the so-called Hector storm in that area.

c. Number of flight hours versus convective area size in the Darwin area

As discussed in Strapp et al. (2014), there are two major operational objectives for the HAIC/HIWC experiment: (i) to fly 60% of the time in oceanic convection (90 h; 34 flights), and 40% within moderate continental convection or around intense continental HIWC regions (60 h; 9 flights), reflecting the proportion of engine events in each cloud type (Mason and Grzych 2011), and (ii) to target as much as possible large mesoscale convective systems to investigate if the engine events happen in response to an instantaneous high value of IWC or to a cumulative effect over a long path within convective systems. Although it has been shown in sections 5a and 5b that most convective cells should be conducive to HIWC and that there are times during which these favorable conditions are enhanced for each Darwin atmospheric regime and surface type, we are still yet to determine whether the Darwin area offers a sufficient number of incidences to fulfill these operational targets.

To investigate this, we first define an “HIWC radar pixel” as a convective radar pixel that has (i) an ETH30 at 10-km altitude or lower and (ii) a radar estimate of the true cloud-top height at height equal or greater than 12-km altitude. These two requirements imply that there is strong convection below the aircraft but no reflectivity above 30 dBZ at 12-km flight altitude and also that the aircraft is still in cloud. That is currently our best estimate of what an HIWC radar pixel should look like. Figure 15 shows the number of hours in a JFM period as a function of the number of HIWC radar pixels for the different surface types indicated in Fig. 1.
a function of the number of HIWC radar pixels for the different surface types indicated in Fig. 1. As an example Fig. 15 shows that for the continental area, there are 150 h in a JFM period on average which are characterized by 100 HIWC radar pixels or more. As each radar pixel is $2.5 \times 2.5 = 6.25 \text{ km}^2$ in size, this number of HIWC radar pixels can also be translated into an equivalent convective area. For the example given previously (150 h in the convective area) this corresponds to a convective area of 625 km$^2$ (a 25 km $\times$ 25 km square). In other words, if the requirement of the field experiment was to fly 150 h in the continental area, Fig. 15 implies that all situations where the convective area is equal or greater than 25 $\times$ 25 km$^2$ should be considered; otherwise, statistically not all of the 150 flight hours of the field experiment will be used.

As discussed previously, an operational target of the experiment is to fly 90 h in oceanic convective systems as large as possible. From Fig. 15, it is obtained that this operational target of 90 h (60 h in the oceanic I region + 30 h in the oceanic II region) can be achieved with a minimum acceptable number of HIWC radar pixels of about 190, corresponding to a $34 \times 34 \text{ km}^2$ convective area. However, presumably not all opportunities will be taken in the field, given that the number of flight hours per day is limited. It is therefore probably more realistic to lower this acceptable minimum convective size. Assuming that only half of the opportunities will be taken, then for 180 h the minimum convective area that should be considered as acceptable becomes about $22 \times 22 \text{ km}^2$ (80 HIWC radar pixels), corresponding to 110 h in the oceanic I region and 70 h in the oceanic II region. Figure 16a shows how these hours spread out along the diurnal cycle over the oceanic regions. Note that the main difference between the diurnal cycles of Fig. 14 and Fig. 16 is that times containing less than 80 HIWC radar pixels are screened out. As a result the diurnal cycles could potentially be different. From Fig. 16a, it is clearly seen that the most favorable times in oceanic region I are between 0300 and 0600 UTC. However, there are only 38 favorable hours between 0300 and 0600 over the oceanic I region in JFM, which is not sufficient to fulfill the 90-h requirement. This implies that other local times and other oceanic areas need to be explored during the field experiment. There are two other periods of the diurnal cycle with about 4–7 favorable hours, between 0700 and 1200 LT (32 favorable hours) and between 2000 and 0000 LT (26 favorable hours), which will need to be considered. This diurnal cycle is broadly consistent with that shown in Fig. 14, indicating that the diurnal cycle of the larger convective areas dominate the overall diurnal cycle. In contrast the diurnal amplitude of the number of favorable times is lower over the oceanic II region, where more than four times per JFM period can be found between 2300 and 0800 LT (50 favorable hours in that time interval). Again the diurnal cycle is consistent with that of Fig. 14.

The operation target of 60 flight hours within moderate or around very intense continental convective cells seems easier to reach than the oceanic target, given the much larger number of favorable hours as a function of minimum convective area (Fig. 15). From Fig. 15, it is obtained that this operational target of 60 h (30 h in the Tiwi region + 30 h in the continental region) can be achieved with a minimum acceptable number of HIWC pixels equal to 400, corresponding to a $50 \times 50 \text{ km}^2$ convective area. However, again, assuming that only half of the opportunities will be taken in the field, then for 120 h the minimum convective area that should be considered as acceptable becomes about $41 \times 41 \text{ km}^2$ (270 HIWC radar pixels) corresponding to 55 h in the continental region and 65 h in the Tiwi region. Figure 16b shows how these hours spread out along the diurnal cycle over the continental and Tiwi regions. The largest diurnal amplitude is found over the Tiwi region, with a well-defined peak between 1400 and 1700 UTC. In that period there are about 27 favorable hours. The advantage of such a well-defined peak is that it will be easy to target operationally and will provide about half of the requested hours. Over the continental area, the afternoon and evening periods are clearly the most favorable, as also found in Fig. 14. However, it is found that the largest number of favorable hours is found two hours later than in Fig. 14 (between 1900 and 2100 LT). This implies that larger convective areas are produced later in the diurnal cycle. Between 1700 and 2400 LT, there are about 32 favorable hours, which should provide the second half of the flight opportunities around continental convection.

6. Summary and conclusions

In this paper, we have derived a regional-scale climatology of seasonal mean rainfall rate and rainfall frequency of occurrence from 14 JFM seasons of the TRMM 3B42 product and a radar-scale climatology of ETH30 from three JFM seasons around the Darwin area. The fundamental aim of this analysis is to optimize the use of flight hours devoted to a field experiment in the Darwin area named the High Altitude Ice Crystals/High Ice Water Content project.

Our results indicate that convective cells conducive to HAIC/HIWC sampling should be found easily near Darwin. The Darwin area is one of the three major rainy areas of the northern part of Australia. Also, the interannual variability of seasonal mean rainfall rate is
reasonably small in that region. In most of the Darwin area, convective cells should be present approximately 60% of the time. This would allow a flight-hour total of about 125 flight hours if no opportunity is missed. Therefore, to make full and effective use of the 150 project flight hours, multiple flights per day should be encouraged during the most favorable conditions.

We summarize our main findings in Table 1, where the three most likely favorable regions for each large-scale condition are described. The most favorable large-scale conditions in the Darwin area are during MJO phases 4 and 5 and during the DW (active monsoon) regime. It is also found that during MJO phase 6 and 7 and during the SW regime, when conditions are least favorable in the Darwin area, the west coast of Cape York should be considered as the main backup area. A second area northeast of Broome may also be favorable under some conditions.
Table 1. List of the three most likely favorable flight conditions for each large-scale condition, as derived from this study. When available, the most favorable time of day and a recommendation for multiple flights per day are also given.

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<th></th>
<th>MJO phase</th>
<th>Darwin atmospheric regime</th>
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<tbody>
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<td></td>
<td>1, 2, 3, 8</td>
<td>DW</td>
</tr>
<tr>
<td>Darwin oceanic</td>
<td>Darwin coastal</td>
<td>Darwin oceanic</td>
</tr>
<tr>
<td>0500 LT</td>
<td>2 flights per day at 0300 and 2100 LT</td>
<td>oceanic</td>
</tr>
<tr>
<td>Darwin continental</td>
<td>Broome (phase 1) coastal</td>
<td>Broome oceanic/coastal</td>
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<tr>
<td>1800 LT</td>
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<td>1800 LT</td>
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<tr>
<td>Darwin Tiwi Island</td>
<td>0300 or 2100 LT</td>
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<td>1500 LT</td>
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Among all convective cells, we find that more than 92% of convective cells are favorable for HAIC/HIWC flight sampling objectives at the 10-km flight level. Even in the least favorable large-scale atmospheric conditions (SW, over the continental and oceanic II surfaces), at least 90% of convective cells are still favorable for HAIC/HIWC sampling at 10- and 12-km flight levels. The largest incidences of HIWC radar pixels are found around 1500 LT, and also around 0300 LT.

To fulfill the requirement to fly 90 h in oceanic convection and 60 h in or around continental convection, all convective areas equal or greater than 22 × 22 km² and 41 × 41 km², respectively, should be considered. These numbers should serve as a guideline for flight-decision purposes.

In practice, it is acknowledged that other factors will also need to be considered in flight-decision making. For example, is lightning or heavy turbulence more likely in clouds that can be associated with a particular time of day, land type, and so on independent of the reflectivity characteristics analyzed in this study? Engine events occur in relatively benign clouds with only light to moderate turbulence and with little lightning (Mason et al. 2006). Other practical issues such as the availability of suitable airports for relocating and/or refueling, the acceptable daily hours of flight operations, and crew duty cycle, to name a few, will undoubtedly have a major influence on flight decisions.

The results obtained in this study will be first used in real time for flight-decision making during the HAIC/HIWC experiment in Darwin. However, as the Darwin area hosts the most comprehensive meteorological observing capability anywhere in the tropics, bringing together the Australian Bureau of Meteorology and U.S. Department of Energy Atmospheric Radiation Measurement facilities, it is expected that many more field experiments will be organized there in the future following the Tropical Warm Pool International Cloud Experiment (TWP-ICE; May et al. 2008) and HAIC/HIWC (Strapp et al. 2014; Dezitter et al. 2013) field experiments and will benefit from the signatures identified in the present study.

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