Relationships between Tropical Cyclone Intensity and Satellite-Based Indicators of Inner Core Convection: 85-GHz Ice-Scattering Signature and Lightning

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ABSTRACT

A key component in the maintenance and intensification of tropical cyclones is the transverse circulation, which transports mass and momentum and provides latent heat release via inner core convective updrafts. This study examines these updrafts indirectly, using satellite-borne observations of the scattering of upwelling microwave radiation by precipitation-sized ice particles and satellite-borne observations of lightning. The observations are then compared to tropical cyclone intensity (defined here as maximum sustained wind speed) and the resulting relationships are assessed. Substantial updrafts produce large ice particles aloft, which in turn produce microwave ice-scattering signatures. The large ice, together with supercooled liquid water also generated by substantial updrafts, is a necessary ingredient in charge separation, which leads to lightning. Various parameters derived from the inner core ice-scattering signature are computed for regions encircling hurricanes and typhoons, and observations of lightning activity or inactivity are analyzed.

High correlations with future tropical cyclone intensity result from the ice-scattering signature parameters most closely associated with the areal extent of at least moderate precipitation rates. As expected, the relationship reveals increasing intensity with increasing ice-scattering signature. Indicators of more intense convection yield less information concerning tropical cyclone intensity. Correlations tend to be of the same sign for both present cyclone intensity at the time of the satellite overpass and subsequent intensity change. Correlations are higher for future cyclone intensity than for either of these. The lightning observations are much more limited than the microwave observations, because the short amount of time in which lightning can be detected may not adequately represent a particular storm’s electrical activity. The inner core lightning observations show no clear relationship to tropical cyclone intensification. However, the lightning observations do suggest an increased likelihood of inner core lightning in weak tropical storms and strong hurricanes/typhoons. In the examination of case studies, the paradoxical situation of much greater lightning frequency in rainbands than in eyewalls is noted.

1. Introduction

Observations of tropical cyclones are limited by their remote locations over the oceans. Satellites (and in some cases reconnaissance aircraft) provide the most common means for monitoring these storms before they make landfall, where they rapidly weaken. The tropical cyclone responds to latent heat fluxes from the underlying ocean surface. The secondary (transverse) circulation of a well-organized hurricane features low-level inflow to the eyewall, where latent heat is released in outward sloping convective updrafts. In response to the upward branch of this circulation, subsidence warming in the eye is hydrostatically responsible for the low central pressure, which, in turn, sustains the primary circulation. The central pressure is sometimes referred to as the tropical cyclone’s intensity; in this paper, the maximum sustained wind speed is used to define intensity.

Research aircraft can provide direct measurements of the vertical drafts in tropical cyclones. Studies of hurricanes using flight-level measurements (horizontal resolution ~100 m) (Jorgensen et al. 1985) and vertically pointing Doppler radar (horizontal resolution ~750 m) (Marks and Houze 1987; Black et al. 1996) found typical maximum updraft velocities in eyewalls to be less than about 8 m s$^{-1}$. More extreme updrafts occasionally are found, but in general hurricane updrafts are a factor of two weaker than continental updrafts (Jorgensen et al. 1985). Hurricane rainbands were found to have slightly weaker updraft magnitudes than eyewalls (Jorgensen et al. 1985). All of these studies (and others) point to the conclusion that tropical cyclones (and tropical oceanic convection in general) contain rather modest vertical velocities. Typical values for mean vertical velocities in eyewall updrafts are ~4 m s$^{-1}$, with maximum vertical velocities typically 7–8 m s$^{-1}$. Black et al. (1996) provides a more thorough review of literature on this subject.

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Of course, practical constraints limit the availability of such data from research aircraft. Although aircraft data and ground-based radar data can provide detailed information on the storms they do sample, satellite data facilitate the observation of tropical cyclones in remote locations. Visible and infrared (IR) imagery from geostationary satellites provide the most continuous data for these storms. Data at microwave frequencies from polar-orbiting satellites, however, are more directly related to precipitation than those from visible and IR channels. The upwelling radiation at these microwave frequencies can therefore be used to assess the latent heat release in the tropical cyclone's precipitation regions. Previous studies (Glass and Felde 1992; Rao and MacArthur 1994; Rodgers et al. 1994; Rodgers and Pierce 1995; Rao and McCoy 1997) have related information from microwave data to tropical cyclone intensity, future intensity, and intensity change with varying degrees of success.

The 85-GHz microwave channel is sensitive to precipitation-sized ice particles, which scatter the upwelling radiation and reduce the brightness temperature (Spencer et al. 1989). This result is termed an “ice-scattering signature,” as the depressed brightness temperature indicates the presence of precipitation-sized ice aloft. A low 85-GHz brightness temperature can therefore imply increased updraft strength. Stronger updrafts produce more supercooled liquid water, and hence larger graupel through riming. The large graupel scatter the upwelling microwave radiation. In conjunction with the strong updrafts and large ice, increased latent heat release and precipitation can be inferred. We rarely detect the extreme ice-scattering signatures associated with strong updrafts and large graupel in tropical cyclones, and explore whether or not such an occurrence is related to intensity or intensity change. Normally less extreme ice scattering is observed.

Glass and Felde (1992) examined the 85-GHz horizontally polarized brightness temperature for a set of western North Pacific tropical storms and typhoons. The sample included 19 storms from 1987 and 1988, with 15 Defense Meteorological Satellite Program Special Sensor Microwave Imager (SSM/I) overpasses of intensifying storms and 10 overpasses of decaying storms. Boxes having “radii” (half the length of the side) ranging from 0.25° to 3.0° lat were constructed about each storm, and the percentage of pixels having brightness temperatures below threshold values was computed for each box. The 0.5° radius box generally produced the highest correlations with tropical cyclone intensity. The optimal brightness temperature thresholds were 220 K and 230 K, with each producing correlations exceeding 0.9 for intensifying storms and 0.7 for decaying storms.

Rao and MacArthur (1994) examined western North Pacific typhoons, primarily from 1987, and the associated precipitation fields as derived from SSM/I brightness temperatures. All four SSM/I frequencies (19.35 GHz, 22.2 GHz, 37.0 GHz, 85.5 GHz1) were utilized in the precipitation algorithm. Rainfall rates were more highly correlated with 24-h future typhoon intensity than with either current intensity or 24-h change of intensity. Among boxes with radii ranging from 0.25° to 4.0°, rainfall rates in the 2.0° radius box produced the highest correlation (0.68) with future intensity. This correlation improved to 0.81 when the sample was limited to northward-moving typhoons, but this reduced the sample size from 27 overpasses to 16. Rao and McCoy (1997) found similar correlations between 85-GHz brightness temperatures on the left side of the typhoon (relative to the direction of motion) and 24-h future intensity for nearly the same set of typhoons.

With a dramatically larger sample size, Rodgers and Pierce (1995) examined precipitation characteristics derived from the SSM/I 85-GHz channel for western North Pacific tropical depressions, tropical storms, and typhoons occurring during the period from 1987 through 1992. In this study, the 12-h increase in inner core (1.0° radius) rain rate was compared to the 12-h and 24-h change in maximum wind speed of the tropical cyclone. Cases in which the rain rate decreased over 12 h were ignored. A total of 123 SSM/I observations of tropical depressions, 61 observations of tropical storms, and 73 observations of typhoons comprised the sample. Results for both 12- and 24-h change in maximum wind were similar, with tropical depressions yielding a correlation of 0.25 and tropical storms yielding a correlation of 0.51. Surprisingly, the typhoon sample yielded a negligible correlation (0.04).

Rodgers et al. (1994) performed a similar study using Western North Atlantic tropical cyclones, but with a much smaller sample size. Twenty-two observations of tropical depressions, 17 observations of tropical storms, and 11 observations of hurricanes were used. Correlations were much smaller than those from the western North Pacific for both tropical depressions and tropical storms (0.06 and 0.27, respectively), but the hurricane sample produced a correlation of 0.78. Rodgers and Pierce (1995) suggest that differences in sample size or a greater number of steady state/weakening typhoons in the western North Pacific sample may be responsible for this inconsistency. Adverse effects of vertical wind shear and decreasing sea surface temperatures (SST) are also proposed as possibly influencing more storms in the typhoon sample than in the hurricane sample.

A less commonly used (and less commonly available) approach for judging the convection in a tropical cyclone is to analyze lightning activity. Most theories for charge separation (leading to lightning) involve collisions between large and small ice particles in the presence of supercooled liquid water (Illingworth 1985).

1 For simplicity, the 85.5-GHz channels are referred to as “85 GHz” in this paper.
However, supercooled liquid water is somewhat rare in tropical cyclones (Jorgensen et al. 1985; Willoughby et al. 1985; Black and Hallett 1986). This is consistent with the previously cited studies that reveal rather modest updraft strength. The presence of lightning in a tropical cyclone may therefore reveal that the convection is particularly vigorous. Many of the studies of lightning in tropical cyclones have utilized the National Lightning Detection Network or similar land-based networks, which only observe lightning within a few hundred kilometers of land. Nonetheless, individual reports (e.g., Black et al. 1986; Lascody 1992; Black et al. 1994; Lyons and Keen 1994; Molinari et al. 1994, 1999; Henning 1997; Samsury et al. 1997) link lightning in the inner regions of tropical cyclones with intensification of the cyclones. In some of these reports, lightning is suggested as a precursor to subsequent tropical cyclone intensification (Lyons and Keen 1994) or an indicator of ongoing intensification (Molinari et al. 1999; Henning 1997), whereas others point out the occurrence of lightning before, during, and after intensification (Samsury et al. 1997).

The manner in which tropical cyclone inner core updrafts are related to the intensity of the parent tropical cyclone is an open question. The 85-GHz brightness temperature is physically linked to these updrafts, in that a depressed brightness temperature requires large ice aloft, which in turn requires a significant amount of vertical mass flux and latent heat release in the production of the ice. Similarly, lightning appears to require a combination of large and small ice particles together with supercooled liquid water. Significant vertical mass flux and latent heat release would also be required to meet these conditions. It is plausible that both of these observables should be related to the intensity of a tropical cyclone in some way. Previous research has indeed suggested relationships. Wide varieties of approaches have been attempted using 85-GHz brightness temperatures, and generally have found low brightness temperatures to be related to tropical cyclone intensity, as expected. Studies of lightning in tropical cyclones have been severely hampered by the difficulty in detecting lightning at remote locations. These studies tend to focus on storms in which both lightning and cyclone intensification are observed, but most do not systematically consider storms in which one occurs without the other.

In the present study, several aspects of observed 85-GHz brightness temperature fields are examined for their relationships with tropical cyclone intensity. Observations of lightning from the optical transient detector (OTD) (Goodman et al. 1996) are also compared with tropical cyclone intensity. For both observables, indicators of convective activity are considered statistically for a large number of storms and are also considered in selected case studies. The key questions to be addressed are the following: 1) Which indicators of convective activity provide the most information about tropical cyclone intensity? 2) How much information do these indicators provide? 3) Are these indicators more related to tropical cyclone intensity at the time of the observation, future intensity, or intensity change?

2. Data and methods

a. SSM/I

The DMSP F11 and F13 satellites carry SSM/I in sun synchronous orbits with overpasses near local sunrise and local sunset. The SSM/I swath width is approximately 1400 km and the 85-GHz footprint is approximately 13 km × 15 km (Hollinger 1991). The orbits provide at most two “independent” observations of a tropical cyclone per day, about 12 h apart. Additional overpasses may occur within 1 h of each other, but would provide somewhat redundant information. Such overpasses are not included in the statistical portion of the study, but are instead considered in case studies, as they provide some insight into how rapidly the features being studied evolve, and how representative a single snapshot at 12-h intervals might be. Because the 1400 km swath width is less than the distance between orbits in the Tropics, not every location is viewed twice on a given day. Due to the swath width, the movement of tropical cyclones, and occasional losses of data, gaps of up to ~60 h exist in the database.

As mentioned before, upwelling 85-GHz radiation is scattered by precipitation-sized ice, reducing the brightness temperature. To differentiate between low brightness temperatures due to ice scattering and those due to the low surface emissivity of the ocean (especially evident in the horizontally polarized channel), Spencer et al. (1989) define a polarization corrected temperature PCT as

\[ \text{PCT} = 1.818 \text{TB}_V - 0.818 \text{TB}_H, \]

where \( \text{TB}_V \) is the brightness temperature for the vertically polarized channel and \( \text{TB}_H \) is that of the horizontally polarized channel at 85 GHz. Spencer et al. (1989) found that the PCT range of 250–260 K is generally a threshold below which precipitating systems are found, with 250 K roughly corresponding to a moderate rain rate (~3 mm h\(^{-1}\)). Spencer et al. and the Goddard scattering algorithm (GSCAT, described by Adler et al. 1994) basically utilize a linear relationship between 85-GHz brightness temperature depression and rain rate. Based on rain rate estimates from GSCAT, Mohr and Zipser (1996a,b) used the existence of a 225 K PCT (~10 mm h\(^{-1}\)) to indicate the presence of cumulonimbus convection. Independently, McGaughey et al. (1996), using high-resolution data from the Advanced Microwave Precipitation Radiometer, derived 225 K as

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2 Because the 85-GHz signatures respond to scattering instead of emission, the PCT is not a thermal signal. It should not be confused with thermodynamic temperature.
a threshold for tropical oceanic convection. Indeed, 225 K pixels at the satellite scale invariably feature inhomogeneities with lower brightness temperatures in the high resolution data, indicative of deep convection. Mohr et al. (1996) noted a dramatic increase in lightning flash rates in continental convection having PCT below 200 K.

In the present study, parameters based on the 85-GHz PCT field are computed for a combination of annular and circular regions centered on the tropical cyclones. These parameters are the areal mean (or average) PCT, the minimum PCT, and the percentage area having PCT at or below threshold values of 250 K, 225 K, and 200 K. These are referred to as 250 area, 225 area, and 200 area in later discussions. Lower thresholds were originally considered but rarely met, providing little information. Following Mohr and Zipser (1996a,b) and Mohr et al. (1996), the 250 K PCT is considered an indicator of moderate rain, 225 K PCT is considered an indicator of deep convection, and lower PCTs are considered indicators of more intense convection. For convenience, the term “convection” is used rather loosely in this paper to refer to regions meeting the specified PCT thresholds. The PCT parameters are computed for 0.5°-lat wide annuli covering the inner 2° radius of a tropical cyclone, 1° and 2° radius circles obtained by combining the annuli, and the 1°–2° radius annulus. Figure 1 demonstrates this geometry, with 0.5°-wide annuli covering the inner 4° radius of Typhoon Oscar (1995). The range rings are centered on the interpolated best-track position, which does not exactly match the eye in the PCT field. This discrepancy is addressed in section 2c.

b. OTD

The OTD is in low earth orbit at 740 km with a 1300 km × 1300 km field of view (Goodman et al. 1996). The OTD monitors an oxygen emission line at 777.4 nm to detect intracloud and cloud-to-ground lightning both night and day. The orbital and field of view characteristics place a particular region in the OTD’s field of view at most twice per day, for less than 5 min at a time. As with SSM/I, a tropical cyclone may go unsampled (or poorly sampled) by OTD for multiple days. The OTD detects optical pulses (events) associated with the dissociation and excitation of oxygen due to lightning (Christian et al. 1989) and groups them into flashes. Instrumental spatial resolution is on the order of 15 km, but satellite navigation errors typically reduce the location accuracy to 30 km (D. Boccippio 1997, personal communication). The flash detection efficiency at the nominal instrumental threshold is estimated to be roughly 55% during both day and night. Overall, less than 10% of the flashes reported in the OTD dataset are false alarms, which are produced by radiation, electronic noise, or solar glint (K. Driscoll 1997, personal communication).

The detection efficiency and short view time limit the OTD’s ability to monitor low flash-rate storms. This should be particularly troublesome for oceanic convection, where lightning frequency is an order of magnitude less than over continents (Orville and Henderson 1986; Goodman and Christian 1993; Zipser 1994). These factors, combined with the location uncertainty in the lightning data, limit the conclusions to be drawn concerning lightning in this study. However, given the extremely low flash rates found in the inner regions of tropical cyclones, any observation of lightning during such a short sampling time may be significant (Molinari et al. 1999). OTD provides an opportunity to systematically examine some aspects of the electrical activity over re-
mote tropical oceans. Lightning (or the lack of lightning) in the innermost 100 km radius of tropical cyclones is examined in this study. Molinari et al. (1998) found a local minimum in flash rates extending 100 km beyond an inner maximum in hurricanes. This result suggests that the OTD location uncertainties should not significantly limit the ability to distinguish between inner and outer core flashes. Because view times vary across the OTD swath, some criteria must be established to determine whether a particular orbit adequately samples a storm. In this study, an orbit is used if (a) any flashes are detected in the innermost 1° radius circle or (b) at least 80% of this region is viewed for at least 180 s.

c. Tropical cyclone track and intensity information

Tropical cyclone post-analysis best tracks for 1995 and 1996 were provided by the National Hurricane Center (now known as the Tropical Prediction Center) for Atlantic (ATL) and eastern North Pacific (NEPAC) tropical cyclones and by the Joint Typhoon Warning Center (JTWC) for western North Pacific (NWPC) tropical cyclones. The postanalysis merges available data to produce a (sometimes smoothed) time history of the cyclone’s center position, maximum sustained winds, and minimum sea level pressure. The available data sometimes include ship reports and land- or island-based observations, or aircraft reconnaissance data in accessible regions of the ATL. Otherwise, satellite estimates of location and intensity, relying heavily on the Dvorak technique (Dvorak 1984), are used. Important questions regarding the reliability of these estimates for research have been raised (JTWC 1995). In general, all of the best-track intensities can be questioned, but some estimate ultimately must be made.

The current project uses maximum sustained wind speed as the definition of “intensity.” Minimum sea level pressure is also commonly referred to as intensity. Without direct measurements of either of these, the NEPAC and NWPC best tracks essentially assume a direct relationship between wind and pressure. The ATL best tracks contain separate information for wind and pressure. Pressure was experimented with as the definition of intensity change. The number of satellite overpasses in the region of interest decreases with increasing size of the region considered (e.g., the inner 1° radius of a storm may lie within an SSM/I data swath whereas the inner 2° radius is only partially sampled). It also decreases with increasing time for the future intensity or intensity change computation (e.g., a storm may move poleward of 35° 15 h after the overpass, in which case only 0-, 6-, and 12-h intensities remain in the dataset). The number of overpasses used for each computation is given in Table 1.

d. Statistical analysis

For the overpasses that remain in the dataset after these restrictions are imposed, linear correlations are computed between each of the PCT parameters described in section 2a (for each annular or circular region) and the tropical cyclone intensity at the time of the overpass, the future intensity at 6-h intervals after the overpass, and the intensity change between the time of the overpass and the 6-h intervals. Correlations are not computed using the lightning data because so many OTD overpasses reveal no lightning associated with tropical cyclones. Instead, the percentage of OTD overpasses that do indicate lightning is examined as a function of tropical cyclone intensity, future intensity, or intensity change. The number of satellite overpasses in the computations decreases with increasing size of the region considered (e.g., the inner 1° radius of a storm may lie within an SSM/I data swath whereas the inner 2° radius is only partially sampled). It also decreases with increasing time for the future intensity or intensity change computation (e.g., a storm may move poleward of 35° 15 h after the overpass, in which case only 0-, 6-, and 12-h intensities remain in the dataset). The number of overpasses used for each computation is given in Table 1.

e. Case studies

Case studies displaying the evolution of the PCT fields and the observations (or lack thereof) of lightning demonstrate some of the reasons for the relationships that emerge from the statistical analyses. They also demonstrate some of the usefulness and some of the drawbacks of the data that do not show up in the simple parameters used for the statistical analyses. ATL Hur-
Table 1. Number of SSM/I observations in sample by annular region and lag time between satellite overpass and tropical cyclone intensity measure.

<table>
<thead>
<tr>
<th></th>
<th>0–56 km</th>
<th>56–111 km</th>
<th>111–166 km</th>
<th>166–222 km</th>
</tr>
</thead>
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<tr>
<td><strong>Atlantic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 h</td>
<td>107</td>
<td>101</td>
<td>89</td>
<td>82</td>
</tr>
<tr>
<td>6 h</td>
<td>98</td>
<td>92</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>12 h</td>
<td>91</td>
<td>86</td>
<td>76</td>
<td>71</td>
</tr>
<tr>
<td>18 h</td>
<td>86</td>
<td>81</td>
<td>71</td>
<td>66</td>
</tr>
<tr>
<td>24 h</td>
<td>83</td>
<td>78</td>
<td>67</td>
<td>63</td>
</tr>
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<td>30 h</td>
<td>77</td>
<td>72</td>
<td>63</td>
<td>59</td>
</tr>
<tr>
<td>36 h</td>
<td>72</td>
<td>68</td>
<td>59</td>
<td>56</td>
</tr>
<tr>
<td><strong>Eastern North Pacific</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 h</td>
<td>31</td>
<td>28</td>
<td>27</td>
<td>24</td>
</tr>
<tr>
<td>6 h</td>
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<td>18 h</td>
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<td>21</td>
</tr>
<tr>
<td>36 h</td>
<td>25</td>
<td>24</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td><strong>Western North Pacific</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 h</td>
<td>139</td>
<td>134</td>
<td>130</td>
<td>117</td>
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<td>6 h</td>
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<td>30 h</td>
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<td>36 h</td>
<td>91</td>
<td>87</td>
<td>86</td>
<td>77</td>
</tr>
</tbody>
</table>

3. Results

The main questions in this paper ask which of the indicators of convective intensity show the strongest relationships with tropical cyclone intensity, how strong those relationships are, and whether the relationships are stronger for current intensity, future intensity, or intensity change. For clarity, results involving ice-scattering signatures and those involving lightning are presented separately. To aid in interpretation of the results, ice-scattering signatures and lightning are then considered together in case studies of three individual tropical cyclones.

a. Relationships between ice-scattering signature and hurricane/typhoon intensity

The ice-scattering signatures tend to have higher correlations with future storm intensity than with either current intensity or intensity change. Figure 2 demonstrates the correlations between the PCT parameters for the 1° radius circle and hurricane or typhoon intensity or future intensity. Table 2 lists these correlations for 24-h future intensity. Figure 3 demonstrates similar correlations, but with respect to intensity change. In each of these figures (and also Figs. 4–5 to follow), the negative of the correlations for average PCT and minimum PCT are plotted for clarity, so they will have the same sense as the correlations for area below the threshold PCT values. When PCT parameters for separate annular regions are considered (Figs. 4–5, Table 3), the correlations with future intensity increase inward, as expected. The correlations with intensity change do not

Table 2. Linear correlation coefficient between 0° and 1° radius PCT parameters and 24-h future hurricane/typhoon intensity.

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>ATL</th>
<th>NEPAC</th>
<th>NWPAC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean PCT</strong></td>
<td>-0.65</td>
<td>-0.73</td>
<td>-0.84</td>
<td>-0.62</td>
</tr>
<tr>
<td><strong>250 area</strong></td>
<td>0.61</td>
<td>0.73</td>
<td>0.74</td>
<td>0.54</td>
</tr>
<tr>
<td><strong>225 area</strong></td>
<td>0.45</td>
<td>0.54</td>
<td>0.79</td>
<td>0.39</td>
</tr>
<tr>
<td><strong>200 area</strong></td>
<td>0.20</td>
<td>0.07</td>
<td>0.46</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Min. PCT</strong></td>
<td>-0.35</td>
<td>-0.21</td>
<td>-0.69</td>
<td>-0.42</td>
</tr>
</tbody>
</table>
contain a clear trend, but are generally so low that they will not be discussed. Figure 2 clearly implies that average PCT and 250 area are highly (negatively) correlated with each other, and they tend to produce the highest correlations with intensity and future intensity. Indicators of more intense convection (such as the minimum PCT or 200 area) produce consistently lower correlations with tropical cyclone intensity and future intensity. Comparing Figs. 2b–d, it is apparent that the highest of these correlations emerge from the NEPAC sample, followed fairly closely by the ATL sample and next by the NWPAC sample.

Figure 4 and Table 3 demonstrate that although the parameters associated with the intensity of convection produce their highest correlations in the innermost 0.5° radius circle, the parameters associated with moderate rainfall produce substantial correlations in both of the two innermost 0.5° radius annuli. Combining these annuli into a 1° radius circle provides a better depiction of the tropical cyclone, and most of the correlations involving this circle (as in Fig. 2) exceed those involving either of the constituent annuli.

In Fig. 2, the highest correlations between 1° radius areal mean PCT and future intensity occur with 18-h intensity for ATL storms (~0.74), 18-h intensity for NEPAC storms (~0.86), and 12-h intensity for NWPAC storms (~0.65). The total sample (all three basins combined) produces a ~0.67 correlation with 12-h intensity. More insight into the relationships between mean PCT and intensity can be found by examining scatterplots of the data.

As a starting point, Fig. 6 displays the hurricane or typhoon intensity at the time of the overpass as a function of 1° radius areal mean PCT for all of the SSM/I overpasses in the sample. In general, more intense tropical cyclones are associated with lower average PCT, but the overall correlation is only ~0.54 and there is a large amount of scatter in the relationship. All but two of the hurricanes and typhoons that exceed 130 kt (67 m s⁻¹) at the time of the overpass represent the NWPAC. These account for many (but not all) of the greatest outliers in the plot. Otherwise the greatest outliers have extremely low mean PCT (below 250 K) but have sustained winds of less than 80 kt (41 m s⁻¹). Only one of the NEPAC observations has such a low mean PCT. Whether this is a matter of sampling (the 1995 and 1996 NEPAC hurricane seasons were not typical, as will be mentioned later, and the NEPAC sample size is much smaller than the ATL and NWPAC sample sizes) or is a consistent feature of the NEPAC has not been determined.

Figure 7a is similar to Fig. 6, but it shows the 24-h future intensity instead of the intensity at the time of the overpass. Not surprisingly, the largest outliers to the best-fit line belong to the NWPAC sample. Several other features can be noted from Fig. 7a. All of the most intense storms again belong to the NWPAC sample, and the least intense storms belong to the NEPAC. Several overpasses (some from each basin) find storms with 24-h intensities between 110 and 120 kt (~57–62 m s⁻¹), but with a wide range of mean PCT. In fact, once the future intensity exceeds 90 kt (46 m s⁻¹), hardly any

**Fig. 4.** (a) Correlations between 24-h future hurricane/typhoon intensity and PCT parameters for 0.5° wide annular regions. The outer radius (° lat) of the annulus is plotted on the abscissa: (b) ATL only, (c) NEPAC only, and (d) NWPAC only.
relationship with mean PCT can be found. On the other hand, 90% of the storms with 24-h intensities exceeding 90 kt (46 m s$^{-1}$) are associated with mean PCT of 260 K or less.

Considering the basins separately, most of the ATL observations (Fig. 7b) fall close to the best-fit line, which is similar to the best-fit line for the three basins combined. The correlation coefficient here is $-0.73$. The correlation improves to $-0.84$ in the NEPAC, but the slope of the best-fit line changes markedly (Fig. 7c). Comparing Fig. 7c with Fig. 7a, the NEPAC storms do fall along either best-fit line, within the range of scatter observed for other basins. If the observations having mean PCT below 250 K were removed from the other basins, the slopes of the corresponding best-fit lines would similarly steepen. In contrast to the ATL and NEPAC, a tremendous amount of scatter is found for the NWPAC (Fig. 7d). The correlation is only $-0.62$. The best-fit line is similar to that for the total dataset, but large outliers from either line abound. Many of the greatest outliers are not the result of poorly positioning the storm center (as might be suspected), but instead represent very intense typhoons whose mean PCT is not correspondingly extreme.

If the average PCT is better correlated with future intensity than current intensity, there should also be a correlation with intensity change. Figure 8 reveals a weak relationship between this parameter and 24-h intensity change. The most rapidly intensifying storms produce mean PCT between 250 and 260 K, but other storms in the same PCT range weaken dramatically. Just as Fig. 7a indicated that 90% of the storms having 24-h intensities greater than 90 kt (46 m s$^{-1}$) also had mean PCT below 260 K, Fig. 8 indicates that 90% of the storms in the sample that strengthened by at least 20 kt (10 m s$^{-1}$) in 24 h also had mean PCT below 260 K. Although this threshold certainly does not indicate that intensification will occur, it does seem to indicate that a hurricane or typhoon has the potential to either reach or maintain (if it has already reached) an extreme intensity.

Generally speaking, most of the correlations between PCT and intensity change are very low, with a large amount of scatter, as in Fig. 8. This is the case regardless of which PCT parameter or annular/circular region is considered. An exception is that the intensity change correlations are consistently higher in the NEPAC than in other basins. The highest correlations involving intensity change are found between the 1–1.5° radius annulus minimum PCT and 24-h intensity change for the NEPAC. This parameter shows no relationship with intensity change in the other two basins, but in the NEPAC the correlation reaches $-0.69$. The NEPAC sample size is much smaller than the other two, but a clear rela-

| Table 3. Linear correlation coefficients between PCT parameters for 0.5° wide annular regions and 24-h future hurricane/typhoon intensity for ATL, NEPAC, and NWPAC combined. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0–0.5°          | 0.5–1°          | 1–1.5°          | 1.5–2°          |
| Mean PCT        | -0.48           | -0.62           | -0.40           | -0.30           |
| 250 area        | 0.48            | 0.54            | 0.24            | 0.17            |
| 225 area        | 0.41            | 0.34            | -0.01           | 0.04            |
| 200 area        | 0.22            | 0.07            | -0.07           | 0.11            |
| Min. PCT        | -0.41           | -0.24           | -0.17           | -0.27           |

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Fig. 6. Intensity (kt) (1 kt $= 0.5$ m s$^{-1}$) at the time of the SSM/I overpass as a function of $0°–1°$ radius areal mean PCT. Letters indicate the basin producing each data point: A = ATL, E = NEPAC, and W = NWPAC.
tionship does appear, with weakening storms producing high minimum PCT in this region.

b. Relationships between lightning and tropical cyclone intensity

Due to limitations in the OTD dataset, a large number of storms is needed to conduct a thorough investigation of possible relationships between lightning and tropical cyclone intensity. The requirement that a region be viewed for 180 s if no flashes occur can severely restrict the sample size. However, 1 flash in 180 s would produce a 20 flash per hour flash rate, which many tropical oceanic mesoscale convective systems fail to produce (Restivo 1995). Reduction of the view-time threshold does increase the sample size, but also increases the likelihood that electrically active storms are assigned zero flash rates simply because they are not viewed for enough time.

Lightning in the inner regions of tropical cyclones occurs most often in the weak tropical storms [34–45 kt (17–23 m s\(^{-1}\)) maximum sustained wind] and strong hurricanes or typhoons [>95 kt (49 m s\(^{-1}\)) maximum sustained wind] in this sample (Fig. 9a). Forty-four percent and 37% of the OTD observations of these respective categories of storms reveal lightning in the inner regions. The percentages decrease to 15% for tropical depressions [<34 kt (17 m s\(^{-1}\)) maximum sustained wind], 32% for strong tropical storms [45–63 kt (23–32 m s\(^{-1}\)) maximum sustained wind], and 17% for weak hurricanes or typhoons [64–94 kt (33–48 m s\(^{-1}\)) maximum sustained wind].

Possible relationships between lightning and tropical cyclone intensity change appear somewhat ambiguous in this dataset. Because a large majority of tropical depression observations contain no lightning and no change in intensity, only cyclones of at least tropical storm magnitude [34 kt (17 m s\(^{-1}\))] are considered for intensity change. An examination of the short-term intensity trend at the time of an OTD observation reveals that lightning occurs more often in storms undergoing small changes in intensity [<±5 kt (2.5 m s\(^{-1}\))] during the 6-h period spanning the observation than in those undergoing more dramatic intensity changes, whether positive or negative. On the longer term, lightning appears to be slightly more likely in storms that intensify moderately [5–15 kt (2.5–7.5 m s\(^{-1}\))] during the 24 h following an observation than in those that weaken moderately during this time period (Fig. 9b). Fifty-seven percent of the observations in the former category and 44% of those in the latter include lightning. Thirty percent of the observations of storms changing intensity by <5 kt (2.5 m s\(^{-1}\)) or less include lightning. Only 25% of the observations of the most rapidly intensifying systems and 8% of the observations of the most rapidly weakening systems include lightning. These percentages vary depending on the intensity change intervals used in a computation and on the period of time for which an intensity change is considered. The most consistent result is that lightning is found least often in the rapidly weakening systems and most often in systems that undergo small to moderate changes of intensity, whether strengthening or weakening. These results focus only on whether or not lightning is found by OTD, without regard to the number of flashes found. For the vast majority of the observations, five or fewer flashes are noted.
c. Case studies

The statistics just presented were designed to quantify aspects of the ice-scattering signature or electrical activity in order to study a large number of observations. By examining individual cases, we can go beyond the objective formulas used to compute ice-scattering signature parameters; the details of storm structure that result in a given mean PCT, for example, can be analyzed. The cases were selected to display a variety of storm life cycles, to demonstrate how the computed parameters relate to cyclone intensity, and to demonstrate how these parameters sometimes fail to represent cyclone intensity.

1) ATL HURRICANE LUIS (1995)

Hurricane Luis evolved from a very compact storm (in terms of the spatial extent of its ice-scattering signature) in the eastern Atlantic into a very broad system as it crossed the northeastern Leeward Islands. After maintaining maximum sustained winds of 110–120 kt (57–62 m s\(^{-1}\)) for seven days, Luis turned northward and weakened (Fig. 10). Its long lifetime as a major hurricane provides ample opportunity for study.

During its formative stages, Luis experienced very intense convection. As a tropical depression on 28 August and a tropical storm (Fig. 11a) the following day, several areas with PCT below 175 K were found. Lightning was also observed during this time by OTD (Fig. 12a). The intense convection fluctuated, as evidenced by the lack of lightning near Luis’s center and the reduced area of extreme ice scattering in subsequent observations. Luis remained only a minimal tropical storm until 30 August, when a 60-h intensification from 40 kt (21 m s\(^{-1}\)) to 115 kt (59 m s\(^{-1}\)) began. The development of a closed eyewall drastically reduced the mean PCT for the inner regions of Luis. Whereas the 0°–1° areal mean PCT had generally been around 270 K during the tropical storm stage, it was near 250 K after the eyewall formed.

Figures 11b,c demonstrate fluctuations in PCT on a rather short temporal scale. At 0841 UTC 2 September (Fig. 11b), the \(F13\) satellite found PCT below 175 K in the rainband about 1.5° east of the center of Luis. Much of this rainband had PCT below 225 K with a relatively large area below 200 K. When the \(F11\) satellite observed Luis less than 90 min later (Fig. 11c), only a small portion of the rainband had PCT below 225 K, although the minimum PCT was again below 175 K. It should be noted that data from such “near coincident” overpasses by the \(F11\) and \(F13\) satellites...
displayed no systematic tendency for one satellite to observe lower PCT than the other. At 1244 UTC, OTD viewed Luis for 2.5–4 min, observing three lightning flashes in the rainband but none in the eyewall.

The 0°–1° areal-mean PCT continued to lower as Luis maintained 115–120 kt (59–62 m s⁻¹) intensity. At 0952 UTC 3 September (Fig. 11d) Luis produced the lowest such mean PCT (232 K) of any storm in this study. A large outer eyewall nearly enclosed the eye with PCT below 225 K, whereas remnants of an inner eyewall contributed further to the low mean PCT. Luis had just reached peak intensity [120 kt (62 m s⁻¹)] and would remain at this intensity for two days. Subsequent SSM/I observations featured less intense eyewall ice-scattering signatures, but the large area with low (if not extreme) PCT continued to produce quite low areal-mean PCT values (mostly below 250 K). Multiple eyewalls were often evident, which may have been a limiting

Fig. 11. As in Fig. 1 except for Hurricane Luis at (a) 0748 UTC 29 August 1995, (b) 0841 UTC 2 September 1995, (c) 1004 UTC 2 September 1995, and (d) 0952 UTC 3 September 1995.
factor on Luis’s intensity. Previous studies (e.g., Willoughby 1990) have established that an outer eyewall often causes the dissipation of an inner eyewall and wind maximum, thus modifying the storm’s intensity.

Most of the OTD observations of hurricanes in this study suggest that lightning is rather limited in these storms, at least for the short sampling duration of the OTD. That may be the case, but Fig. 12b demonstrates that highly electrically active rainbands do exist and can be detected by the OTD. Three consecutive OTD overpasses on 6 September reveal such rainbands in Luis’s southeast quadrant. Many flashes were detected even in regions that spent less than 60 s in the field of view.

To describe Hurricane Luis in terms of the parameters that were analyzed statistically, time series of some of these parameters are presented in Fig. 13. For the large sample of storms, $0^\circ - 1^\circ$ radius mean PCT produces the highest correlations with intensity. It roughly corresponds to the total latent heat release in that region, under the assumption of a linear relationship between brightness temperature and rain rate (e.g., Spencer et al. 1989; Adler et al. 1994). This parameter, along with Luis’s intensity, is plotted in Fig. 13a. At the other extreme is the minimum PCT, which represents the intensity of the most highly convective pixel. Lightning is also related to the most highly convective areas. These parameters are plotted in Fig. 13b. Unlike in the statistical analysis, any $F11$ or $F13$ SSM/I overpass available is plotted here. That is, if both satellites sample Luis at sunrise on the same day, both observations are plotted. Lightning data are plotted only for overpasses in which either lightning is observed in the $0^\circ - 1^\circ$ radius region or that region is sampled for at least 180 s without lightning.

As indicated by minimum PCT, Luis’s most intense convection occurred early during the tropical storm stage, then the convection weakened as the larger-scale storm developed (Fig. 13b). The lone OTD observation of inner core lightning also occurred early in Luis’s life (Fig. 13b). On the other hand, the large, radiometrically cold eyewall resulted in very low areal mean PCT for the inner regions of Hurricane Luis as the storm approached and then maintained 110–120 kt (62 m s$^{-1}$) intensity for several days. A wide range of areal-mean PCT were encountered while Luis basically maintained peak intensity (Fig. 13a), with no apparent response to changes in the already low mean PCT. The hurricane’s intensity appears to have been modulated by eyewall replacement cycles during this time.

2) NEPAC HURRICANE BARBARA (1995)

Hurricane Barbara produced at least 100 kt (51 m s$^{-1}$) maximum sustained winds for five days in July 1995 in the eastern North Pacific before dissipating in the Central Pacific (Fig. 14). Barbara quickly developed from a weak tropical storm to a hurricane, with a rapid intensification episode [at least 42 hPa of deepening in 24 h, as defined by Holliday and Thompson (1979)] following. The hurricane weakened slightly from 115 kt (59 m s$^{-1}$) to 100 kt (51 m s$^{-1}$), then reached a peak intensity of 120 kt (62 m s$^{-1}$). Sustained weakening followed as the storm moved over cooler waters. Both SSM/I and OTD data are available at the onset of rapid
intensification, and also during the period in which Hurricane Barbara fluctuated between 100 and 120 kt (51–62 m s\(^{-1}\)).

PCT as low as 137 K were observed near the center of Barbara early in its tropical storm stage. Four lightning flashes were observed, also near the center, in 200 s. In contrast, PCT remained generally in the 225–250 K range as precipitation wrapped around Barbara’s center at the onset of rapid intensification (Fig. 15a). Ice-scattering signatures were less intense but much more organized at this point compared to the tropical storm stage. An OTD overpass near the onset of rapid intensification revealed no lightning associated with Hurricane Barbara.

After an initial peak intensity of 115 kt (59 m s\(^{-1}\)) on 10 July, Hurricane Barbara weakened to 100 kt (51 m s\(^{-1}\)) as the eye disappeared from IR imagery. Figure 15b demonstrates a distinct eye in the SSM/I data at 0216 UTC 12 July, which is obscured in the IR data. The eye reappeared in IR imagery later on 12 July, with a subsequent reintensification of the storm to 120 kt (62 m s\(^{-1}\)). During this reintensification, Barbara’s spatial extent decreased dramatically (Fig. 15c), with the eyewall nearly contained by the 0.5° radius circle and the entire region with an ice-scattering signature nearly contained by the 1° radius circle at 0204 UTC 13 July. Strong eyewall convection persisted, however, with PCT again reaching below 200 K at 1440 UTC. As Barbara eventually weakened, the tiny area of reduced PCT (Fig. 15d) bore little resemblance to what one normally thinks of as a hurricane’s precipitation field, despite best-track winds near 100 kt (51 m s\(^{-1}\)).

The 0°–1° radius mean PCT was identified earlier as being highly correlated with future intensity. This parameter remained somewhat low (250–260 K) for most of Hurricane Barbara’s life, until rising above 270 K as the storm weakened (Fig. 16a). Although no correlation is seen with intensity change, a low mean PCT suggested that the minimal hurricane on 9 July had the potential to become a major hurricane, as it did the following day. The continued low mean PCT (resulting from an active, well-developed eyewall) after Barbara’s initial weakening on 11 July confirmed that the storm could not yet be discounted. The OTD sampled Barbara during many stages of the storm’s life cycle, including the rapid intensification period, but detected lightning only at the beginning of the tropical storm stage (Fig. 16b).

3) NWPAC Super Typhoon Ryan (1995)

While meandering in the South China Sea, Ryan gradually strengthened to typhoon intensity (Fig. 17). Intensification continued as Ryan accelerated northeastward, passing near Taiwan with 130 kt (67 m s\(^{-1}\)) intensity. Weakening followed as the storm approached and made landfall on Japan. Ryan was well sampled by
SSM/I throughout the intensification from tropical storm to super typhoon. Nearly coincident overpasses of the SSM/I and OTD on 21 September provide a direct comparison of 85-GHz PCT and short view time lightning observations for a super typhoon reaching its peak intensity.

The intensity of convection in the inner regions of Ryan fluctuated but the degree of spatial organization in the PCT field increased as Ryan developed through its tropical storm and typhoon stages. Extreme ice scattering (with PCT near 140 K) was encountered in the eyewall at times, such as 2213 UTC 19 September (Fig. 18a) and 0915 UTC 21 September (Fig. 18c). Although the total area experiencing rather low PCT (below 225 K) remained impressive, the minimum eyewall PCT at 2201 UTC 20 September (Fig. 18b) and 2148 UTC 21 September (Fig. 18d) only reached near 200 K.

The fluctuations in intensity of eyewall convection on 21 September are also suggested by OTD. Five lightning flashes were detected at 0908 UTC (Fig. 19a) when
the eyewall was in view for approximately 40–100 s. Geolocation appears to be questionable for these flashes (the platform carrying OTD may have been temporarily unstable), but they are clearly associated with the intense eyewall convection depicted by the SSM/I. The eyewall was in view for a slightly longer time (60–120 s) at 2148 UTC (Fig. 19b), but this time no flashes were detected in the eyewall region. Minimum PCT at this time was near 200 K. That no flashes were detected by OTD in less than 2 min certainly does not mean that the eyewall had become electrically inactive, but at least suggests a reduced flash rate compared with earlier in the day. This is consistent with the much higher minimum PCT found at 2148 UTC compared with 0915 UTC. Even though view time decreased to the east of the center, 19 flashes associated with the rainband 2° east of the center were detected by OTD in a 70-s span. PCTs as low as 128 K were detected with this band. The correspondence seen here between PCT and electrical activity is not surprising, given the importance of large ice to the scattering of 85-GHz radiation and to the charge separation process. In other cases, however, the correspondence has not always been as straightforward.

Another OTD overpass at 0822 UTC 22 September indicated lightning in both the eyewall and the rainband located east of Ryan’s center. View times were again less than 120 s and decreased to the east of the center, but the rainband produced more lightning (11 flashes) than the eye (2 flashes). Within hours of this OTD observation, Ryan began to weaken. SSM/I observations later that day continued to identify intense convective cells in the rainband, but also revealed a greatly diminished eyewall with the weakening storm.

Of the cases presented individually, Super Typhoon Ryan provides the clearest example of a relationship between 0° and 1° areal mean PCT and future tropical cyclone intensity (Fig. 20a). The best-track intensity increases as the mean PCT decreases, then peaks after the mean PCT shows a slight increase. Further increases in mean PCT accompany the decrease in Ryan’s intensity as the storm approaches Japan. The 243 K mean PCT at 2213 UTC 19 September is an exception to the trend of best-track intensity smoothly following the mean PCT. The intense convection at this time was also depicted in IR imagery, and leads to a question concerning the accuracy of the best-track intensities, which will be addressed in section 4. Inner core lightning was observed twice while Ryan was at or near its peak intensity, including one OTD overpass just before weakening began (Fig. 20b).

4. Discussion

High correlations (~0.7) are found between inner core areal-mean PCT (and 250 area) and future hurricane/typhoon intensity. OTD lightning observations reveal an increased likelihood of lightning in weak tropical storms and strong hurricanes, but no clear trends are found connecting lightning to intensity change. Given the inherent limitations of OTD in such a study, the
lightning results are inconclusive. Individual case studies reveal both advantages and drawbacks in using SSM/I imagery to analyze tropical cyclones, while also providing new information with the lightning observations.

The first aspect of these results to address is the higher correlations between inner core ice-scattering signatures and future intensity than between ice-scattering signatures and either present intensity or intensity change. Why are the correlations highest for future intensity? A respectable correlation with present intensity was expected (and found); after all, satellite-derived intensity estimates of tropical cyclones basically attempt to measure the organization and vigor of the cyclone’s convection (Dvorak 1984). If the latent heating implied by the ice-scattering signature provides more energy than would be necessary to sustain the system, an intensification of the cyclone’s circulations should result. These statements mean that the ice-scattering signature is related to both current intensity and intensity change, with the combined effect being an increased correlation with
future intensity. That is, there may be a temporal lag between the production of the ice-scattering signature and the response of the primary circulation.

The next results to address are the high correlations between indicators of moderate rainfall (250 area and average PCT, which are highly correlated with each other) and tropical cyclone intensity, compared to those between indicators of intense convection (minimum PCT and 200 area) and tropical cyclone intensity. Glass and Felde (1992) reported that the area having horizontally polarized brightness temperatures below 220–230 K produced high correlations with intensity. This range of brightness temperatures typically corresponds to 230–250 K PCT. Considering the various reports of convective bursts associated with deepening tropical cyclones (e.g., Lyons and Keen 1994; Molinari et al. 1994; Black et al. 1994), why do the indicators of intense convection produce such low correlations? The parameters that produce the highest correlations with intensity respond primarily to the mesoscale nature of the precipitation, as opposed to the convective scale. The minimum PCT parameter depends on a single 13 km × 15 km pixel. Although intense convection is sometimes associated with significant intensification of the large-scale vortex, such a small region of intense convection may have little impact on the cyclone’s intensity when other organized precipitation (e.g., a well-formed eyewall) is lacking.

In contrast to each of the results discussed thus far is the relatively high correlation mentioned for NEPAC 1°–1.5° radius minimum PCT and tropical cyclone intensity change. The ATL and NWPAC produce low correlations with intensity change for this parameter, and the 1°–1.5° region generally produces lower correlations with intensity than do regions inward of 1° radius. What is peculiar about the NEPAC sample, and why does the 1°–1.5° region stand out? The NEPAC sample includes a higher percentage of decaying storms than the ATL and NWPAC samples, due to the equatorward extent of
cool waters in this basin. The NEPAC storms that weakened rapidly had very high minimum PCT beyond 1° radius, with the spatial extent of the ice-scattering signature decreasing dramatically with time. This helped produce relatively high correlations for all of the PCT parameters with intensity change (Fig. 5c) and similarly with future intensity (Fig. 4c).

The lowest correlations between ice-scattering signature and intensity involve NWPAC typhoons. These correlations are much lower when the 1995 sample is considered separately (Cecil 1997), but the combined 1995–96 sample also produces lower correlations for the NWPAC than for the other basins. Much of the scatter involves very intense or rapidly intensifying tropical cyclones, which are more often observed in the NWPAC than in the ATL or NEPAC. In the more intense systems, processes such as eyewall cycles become more common (Willoughby 1990); these cycles can significantly affect a cyclone’s intensity. Even in the absence of an eyewall cycle, the eyewall location and degree of symmetry cannot be determined from PCT parameters computed for a 1° radius circle, but such details are closely linked to the cyclone’s intensity. This result is similar to the finding by Marks (1985) that the intensity of Hurricane Allen (1980) was related to its eyewall evolution, but the rain rate (thus latent heat release) inside a 1° radius circle showed little response to changes in the eyewall. As demonstrated in numerical studies (Shapiro and Willoughby 1982; Schubert and Hack 1982), not only the magnitude of the heating but also the location of the heating must be taken into consideration. A wide variety of eyewall structures may yield similar values for the PCT parameters used here. These simple parameters ultimately cannot make up for pattern recognition.

Another potential cause for lower NWPAC correlations is possible inaccuracy in the best-track intensity data. In the absence of aircraft reconnaissance, tropical cyclone intensities in the Pacific Ocean are primarily derived from satellite data, using the Dvorak (1984) technique. These intensity estimates sometimes include adjustments based on the expected rates of intensification for tropical cyclones. Super Typhoon Ryan provides a disturbing example of the constraints these expected intensification rates can impose on the best-track intensity. Without these adjustments, objective application of Dvorak’s technique yields intensity estimates of 140 kt (72 m s⁻¹) on 19 September and early on 20 September (Lander and Angove 1998) (Fig. 21). The final best-track intensity during this time is 80–90 kt (41–46 m s⁻¹). Ryan is a rather exceptional case, because the objective application of Dvorak’s technique more often falls roughly in line with the final best-track data. However, as pointed out by Lander in JTWC (1995), these rapid changes in intensity, if they are real, would seriously compromise the usefulness of the best-track data in studies involving intensity. With more rapid intensifiers in the NWPAC than the other basins, the potential problem is greater in the NWPAC.

The OTD lightning data used in this study reveal that weak tropical storms and strong hurricanes or typhoons are most likely to feature inner core lightning. The greatest likelihood of lightning occurs with weak tropical storms, which is consistent with the frequent observations of extremely low minimum PCT during this stage in the case studies presented. As in the published literature, examples of inner core lightning either preceding or coinciding with cyclone intensification are observed, but inner core lightning is also observed preceding or coinciding with cyclone weakening and is most often observed during periods in which the cyclone’s intensity remains fairly steady. Although this does not necessarily contradict reports that link inner core lightning to intensification, it does indicate that any such relationship is far from being clear cut. Usually only a few flashes are observed in a particular area, but examples of high flash rates occur almost exclusively with rainbands, as opposed to eyewalls. This is somewhat paradoxical, although not a new result (Samsury and Orville 1994; Molinari et al. 1994, 1999), given that neither Jorgensen et al. (1985) nor Black et al. (1996) find evidence for rainbands having stronger updrafts than eyewalls. The OTD was not designed for individual case study, and given its limited view times, any attempts at quantification of the lightning observations should be deemed inconclusive.

That the observations of lightning show little (if any) relationship with tropical cyclone intensity change is consistent with the result that SSM/I indicators of intense convection are only mildly correlated with hurricane/typhoon intensity and intensity change. A single intense convective cell may produce a very strong ice-scattering signature and a great deal of lightning. The spatial coverage and organization, more so than the inten-
tensity, of the precipitation shows the greater relationship with overall hurricane/typhoon intensity.

Both of the key components of this study (SSM/I and OTD) involve observations from satellites that encounter the targeted storms at most twice per day. These observations concern convective and mesoscale entities operating on much shorter temporal scales. As the number of observations increases (i.e., observations from more storms are combined), some trends become clearer. When individual observations are examined, the possibility of fluctuations in convective intensity must be considered. Such fluctuations were demonstrated in the SSM/I observations of Hurricane Luis; short timescale fluctuations in lightning flash rates have also been reported by Molinari et al. (1999). This makes direct comparison of individual observations potentially extremely misleading, as one observation may correspond to a short timescale maximum in convective vigor, whereas the other corresponds to a short timescale minimum in convective vigor.

A note should be made concerning the representativeness of the sample in this study. All the storms considered occurred during 1995 and 1996, which were unusual years for tropical cyclones. In fact, 1995 and 1996 were among the most active ATL seasons on record. On the other hand, NEPAC experienced a far below normal hurricane season each year. The peculiarities of the 1995 and 1996 seasons may have affected the results presented here in unseen ways.

Many factors seem to influence tropical cyclone intensity [e.g., SST (Merrill 1988), vertical wind shear (DeMaria et al. 1993), relative eddy angular momentum flux convergence (DeMaria et al. 1993), potential vorticity advection (Molnar et al. 1995), and internal dynamics (Shapiro and Willoughby 1982)]. Through its relationship with rainfall, the ice-scattering signature can be expected to respond to each of the factors mentioned above. Considering the complexities of tropical cyclones, the correlations between ice-scattering signature and hurricane/typhoon intensity are remarkably high. Particularly noteworthy is that such simple measures as areal-mean PCT contain so much information.

Correlations between mean PCT and 24-h intensity are highest for NEPAC \((-0.84)\) and ATL \((-0.75)\) storms, with lower correlations \((-0.62)\) for NW Pac storms. The greatest scatter in plots of future intensity versus mean PCT tend to be associated with very intense or rapidly intensifying systems. Such systems occur more frequently in the NW Pac than in the other basins. It is proposed that such large scatter results from the intense/rapidly intensifying typhoons because details of the eyewall(s) are more important in these storms, and are poorly resolved by the simple PCT parameters used here. Without in situ observations in these typhoons, the input intensity estimates are also questioned. The questions particularly address the legitimacy of intensity estimates for rapidly intensifying systems, again leaving the NW Pac more susceptible to error.

OTD observations of inner core lightning indicate a greater likelihood of lightning in weak tropical storms and in strong hurricanes or typhoons than in other tropical cyclones. These lightning observations do not appear to be a useful indicator of intensity change. Lightning is observed in a spectrum of tropical cyclone situations; for example, tropical storms showing no signs of intensification, typhoons undergoing rapid intensification, and super typhoons that soon decrease in intensity. The most common scenario for inner core lightning in this sample involves storms whose intensity changes slowly, if at all. Storms are sampled by OTD for less than 5 min at a time, making large flash counts rare. These are encountered, however, most often in rainbands instead of eyewalls. The lack of any apparent relationship between lightning occurrence and subsequent cyclone intensity change is consistent with the relatively low correlations between tropical cyclone intensity change and PCT-based indicators of intense convection. The lack of a relationship may also be related to the limitations of OTD in such a study.

These results raise several issues for further study. Would other oceanic basins mimic the high correlations found in the NE Pac, the lower correlations found in the NW Pac, or would they fall somewhere in between, as does the ATL? The highest correlations basically involve 0°–1° radius latent heat release. Would other microwave channels that are more intimately tied to latent heat release, but have lower resolution than the 85 GHz 13 km \(\times\) 15 km footprint, likewise produce such high correlations? The lack of a relationship between indicators of intense convection (such as lightning) and tropical cyclone deepening seems to be in conflict with previous reports. Would a more detailed dataset (such as lightning observations from a geostationary satellite) resolve this conflict, and if so, with what result? Finally, could a tropical cyclone intensity forecasting tool be developed based on improvements to the parameters studied here? At what point would increasing the complexity of the parameters cease to improve the resulting forecasts?

5. Conclusions

This paper uses 85-GHz PCT as a proxy for updraft strength, convective vigor, and precipitation intensity. With this proxy, relationships are sought between PCT parameters and tropical cyclone intensity, future intensity, and intensity change. Of the relationships sought, the strongest involve the spatial coverage of at least moderate inner core rainfall. Correlations are of the same sense for both present intensity (at the time of the satellite overpass) and subsequent intensity change, but these effects combine to produce even higher correlations for future intensity—that is, a temporal lag exists between the production of an ice-scattering signature and the response of the hurricane/typhoon intensity.
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