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Revisiting the maximum intensity of recurving tropical cyclones

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ABSTRACT: Previous studies have indicated that recurving western North Pacific tropical cyclones, initially westward moving tropical cyclones that turn toward the east, often reach their maximum intensity close to the time of recurvature. Those results have often been cited in the literature and sometimes inferred to be valid in other tropical cyclone basins. This study revisits this topic in the western North Pacific, North Atlantic and Southern Hemisphere tropical cyclone basins. The timing of lifetime maximum intensity associated with recurving tropical cyclones is examined using best track datasets from the United States' Joint Typhoon Warning Center and the National Hurricane Center, Miami during the period 1980–2006. Results reveal that tropical cyclones are less likely to experience peak intensity within ±12 h and ±24 h of recurvature than has been previously reported in the western North Pacific. Furthermore, it is shown that tropical cyclones that become most intense (i.e. intensities greater than 52 m s^{-1}) have a greater tendency to reach peak intensity before recurvature than weaker storms save for in the South Pacific where the most intense storms have a slightly greater probability of reaching their maximum intensity following recurvature. It also appears that weak tropical cyclones (i.e. lifetime peak intensities less than 33 m s^{-1}) often reach peak intensity prior to or close to recurvature in all tropical cyclone basins as others have reported. However, findings suggest that the cumulative distributions of maximum intensity with respect to the time of recurvature can be quite different for other intensity ranges suggesting that a universal relationship between peak intensity and time of recurvature does not exist.

KEY WORDS tropical cyclone; hurricane; typhoon; recurvature; intensity; Atlantic; western North Pacific; Southern Hemisphere

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1. Introduction

Tropical cyclone (TC) maximum intensity (V_{max}) has been reported to often be coincident with the recurvature of TCs [Riehl (1972), hereinafter R72; Evans and McKinley (1998), hereinafter EM98]. Recurving TCs initially move westward and as they head poleward they turn eastward. The point of recurvature is defined by the point along the track at which the meridional motion is poleward and the zonal component of motion changes from westward to eastward. Both R72 and EM98 found that roughly two-thirds of TCs that reach typhoon/hurricane intensity ($V_{max} \geq 33$ m s^{-1}) reached their maximum lifetime intensity within 12 h of recurvature in the western North Pacific (There are regional names for TCs that reach 33 m s^{-1} (64 kt) or greater. In the western North Pacific such storms are referred to as typhoons and in the North Atlantic such storms are called hurricanes. In the Southern Hemisphere the generic name 'cyclone' is used to refer to all TCs.). EM98 also found that the maximum intensity of tropical storm strength ($V_{max} \geq 17$ m s^{-1}) TCs occurred 45% (70%) of the time in the Northwest Pacific and 25% (46%) of the time in the Atlantic within 12 h (24 h) of recurvature. The results were based on western North Pacific and North Atlantic basin TCs during 1980–1996. EM98 concluded that weaker TCs are clearly affected by recurvature: (1) weaker TCs are most likely to reach their V_{max} within 24 h of recurvature, (2) the vast majority of TCs reach their V_{max} prior to recurvature (>80%) or by the 12 h following recurvature (>94%). Because of the limited number of recurvature cases in their North Atlantic sample, EM98 did not comment on relationships between V_{max} and recurvature in that basin.

The R72 and EM98 results from the western North Pacific – particularly the statement that the majority of the typhoons (i.e. TCs with intensities greater than 33 m s^{-1}) reach their peak intensity at or near recurvature, has led to confusion and misapplication of these ideas to other TC basins. From an observational standpoint, the maximum intensity of a TC should occur prior to the point of recurvature in most circumstances because recurvature often indicates that the steering flow and thus the environmental vertical wind shear are changing with respect to time. Also as a TC moves further poleward it generally encounters decreasing sea surface temperatures (SSTs), oceanic heat content, and mid-level moisture, and

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increasing westerly vertical wind shear – all conditions associated with TC weakening (e.g. Emanuel *et al*., 2004; DeMaria *et al*., 2005; Knaff *et al*., 2005). Furthermore, storms that eventually recurve are most often located poleward of an equatorial trough, and equatorward and under the influence of a deep sub-tropical ridge in the westward moving portion of their existence, which is often a favourable environment for TC development and intensification (e.g. Gray, 1968).

Since the EM98 study, the Atlantic TC record has dramatically increased and the TC records in the Southern Hemisphere have become available. The historical record of TC intensity change has increased in length and temporal resolution with the advent of and regular use of geostationary satellites to estimate TC intensity using the Dvorak method (see Velden *et al*., 2006 for a historical perspective). With these new and more expansive datasets, this article will examine the records of recurving TCs in the North Atlantic, West Pacific and Southern Hemisphere in the years 1980–2006 to try to confirm past studies and determine if the results of EM98 and R72 can be generalized to other basins. (The North Indian Ocean and eastern North Pacific have too few recurving TC cases to examine such relationships.)

2. Datasets and methodology

TC track and intensity information comes from the best track archives. The Joint Typhoon Warning Center (JTWC) maintains best track datasets for TCs occurring in the western North Pacific and Southern Hemisphere. The National Hurricane Center (NHC), which is the World Meteorological Organization's Regional Specialized Meteorological Centre, maintains best tracks for the North Atlantic TC basin. Both datasets are stored in the Automated Tropical Cyclone Forecast system (ATCF; Sampson and Schrader, 2000) with six-hourly time resolution. These datasets represent the best post-season analysis available at the end of each TC season, but like any subjectively generated record, they have systematic and random errors due to the manner in which they were constructed, as noted by Landsea *et al*. (2006). The JTWC best tracks were re-analysed to remove discrepancies in the historical records as described in Chu *et al*. (2002), where the authors also note that data prior to 1985 should be used with caution. In addition, the historical records of TC intensities from both JTWC and NHC would likely benefit from re-analysis based on a common set of rules. However, to be consistent with EM98, this study will utilize best track data from 1980 through 2006 and simply acknowledge the possibility of these data quality issues.

To define the point of recurvature objectively a mathematical definition is used. Recurvature is simply defined for westward moving TCs as the first point where the first derivative of longitude with respect to time is equal to zero and the curvature or second derivative of the longitude is positive (i.e. a minimum). Derivatives are taken using a central difference with errors of the order of Δt^2, where Δt is 6 h. Using this definition, recurvature is simply the first point when a westward moving TC is no longer moving toward the west and eventually turns toward the east. Once the point of recurvature is defined, only storms with certain characteristics are retained for this study. These characteristics are: (1) the storm must exist for at least 72 h in the best track, (2) the recurvature point is also the minimum longitude in the best track (i.e. the absolute minimum), (3) the recurving storm has to experience eastward movement within 18 h of the point of recurvature, (4) the intensity of the storm must be at least 35 kt (17 m s^{-1}) at the point of recurvature, (5) the storm cannot come within 50 km of land prior to or within 48 h of the point of recurvature, and (6) the latitude of any future point cannot be less than the latitude of the recurvature point (i.e. no looping storm tracks or equatorward recurving storms). This methodology results in 71, 194, and 142 recurving TC cases in the North Atlantic, western North Pacific, and Southern Hemisphere, respectively, during 1980–2006. During this same time period there were a total of 190, 399, and 321 tropical storm strength cases in those same basins, respectively. To simply give the reader an idea of what tracks were captured by this objective method, the tracks of the resulting recurving TCs are shown in Figure 1(a)–(d) Since the individual tracks are difficult to follow in Figure 1, Figure 2(a)–(d) shows the recurving TCs for just the 2005 season in each basin used in this study; keeping in mind that the 2005 Southern Hemisphere season runs from 1 July 2004 to 30 June 2005.

Of the recurving TC cases, 59 (83.1%), 153 (78.9%), and 116 (81.6%) storms achieved at least typhoon/hurricane intensity (i.e. 65 kt or 33 m s^{-1}) and 27 (38.0%), 100 (51.8%), and 59 (41.5%) had intensities that exceed 52 m s^{-1} or Category 3 of the Saffir-Simpson Hurricane Scale (Simpson and Riehl, 1981) in the North Atlantic, western North Pacific and Southern Hemisphere, respectively. For this study, the time of the lifetime maximum intensity is associated with its first occurrence, which is also the methodology used by EM98. Using these datasets, several aspects related to the timing of maximum intensity with respect to the point of recurvature in these three separate TC basins are examined.

A potential source of bias in this study is the use of the first occurrence of maximum intensity to represent the time of maximum intensity since storms can remain at their maximum intensity for several six-hourly time periods. To examine this potential source of bias, the number of hours that the storm maintains its maximum intensity is also computed. While the use of this definition of when maximum intensity occurs does not impact the comparative results, which were compiled in the same manner as EM98, it will help the reader better interpret the impact on those results associated with how the timing of maximum intensity is defined.

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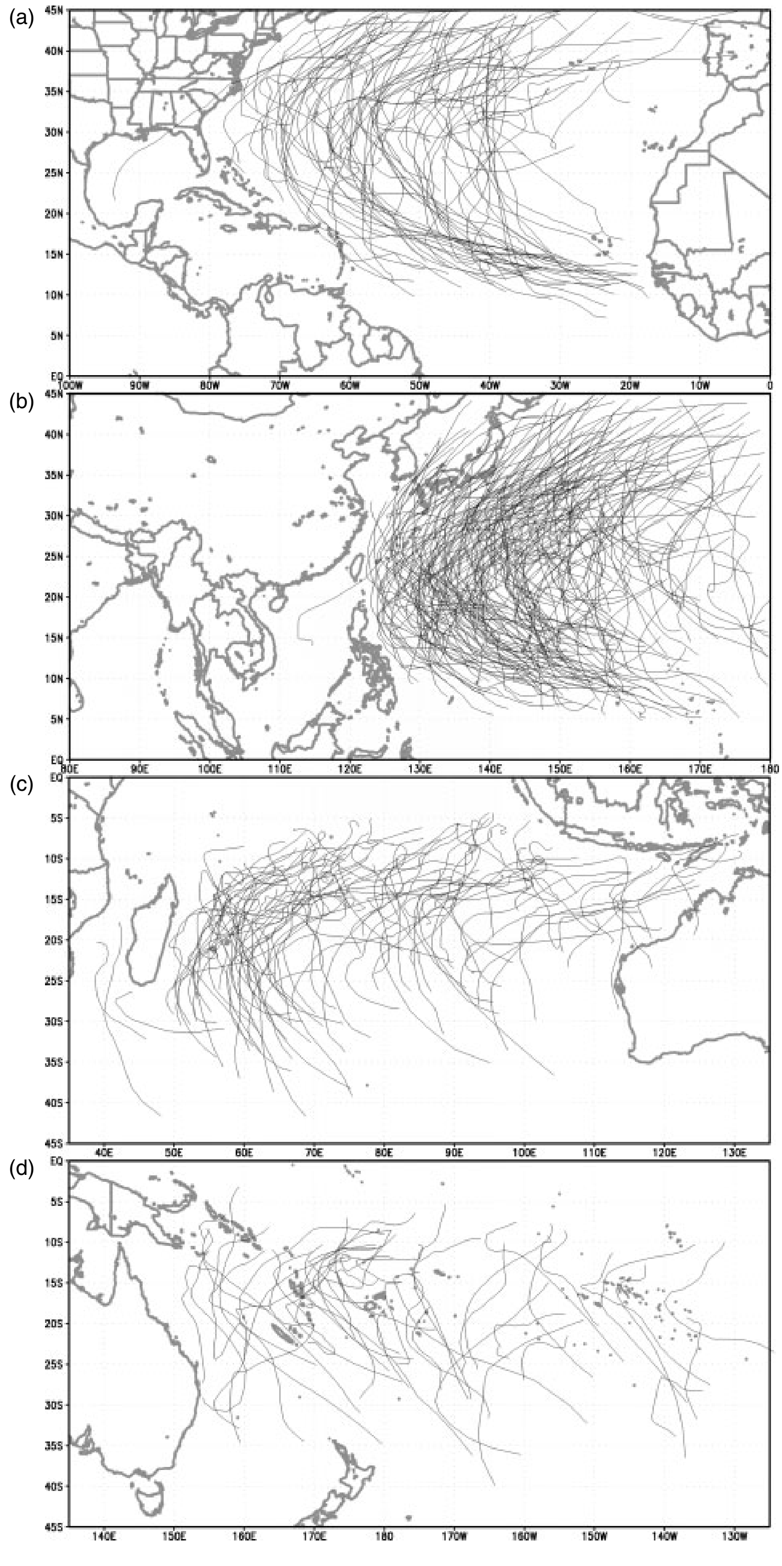

Figure 1. The tracks of recurving tropical cyclones 1980–2006 used in this study. Storm tracks are shown in the North Atlantic (a), western North Pacific (b), South Indian Ocean (c), and South Pacific Ocean (d) regions.

3. Results

The timing of V_{max} with respect to the point of recurvature has been compiled using histograms based on the time with respect to the point of recurvature. Histograms have been compiled for different V_{max} stratifications including all tropical storms, all hurricanes, all major hurricanes, only tropical storms and only minor hurricanes. Stratifications by TC basin and intensity are presented in this section in terms of cumulative percentages and are summarized for the reader along with latitude of recurvature and V_{max} statistics in Table I.

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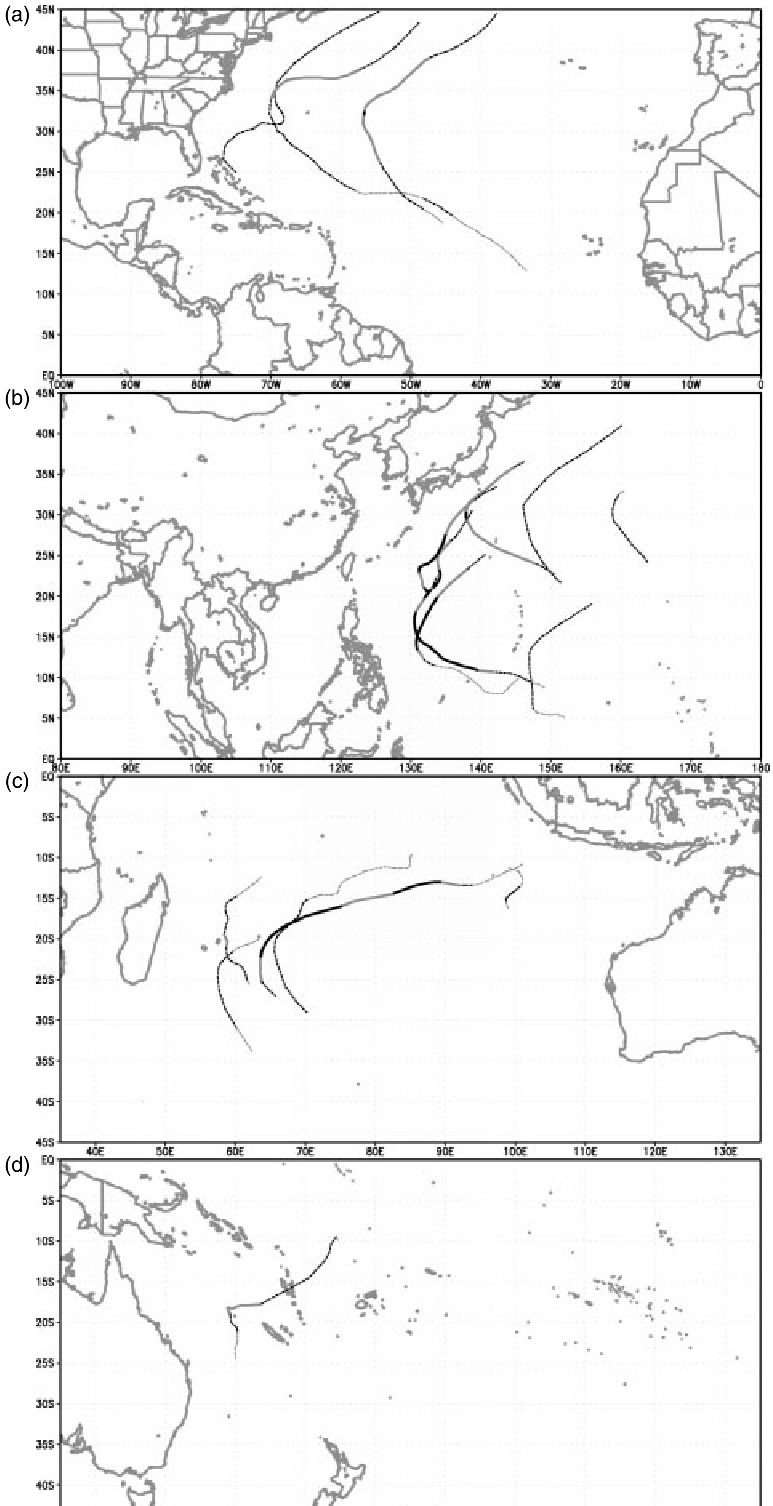

Figure 2. The tracks of recurving tropical cyclones that occurred during the 2005 seasons are shown. Storm tracks are shown for the North Atlantic (a), western North Pacific (b), South Indian Ocean (c), and South Pacific Ocean (d) regions. The line shading indicates the intensity where dashed grey lines indicate tropical depression intensities (i.e. less than 17 m s^{-1}), the dashed black lines indicate tropical storm intensities, the solid grey lines indicate hurricane/typhoon intensity, and the solid black lines indicate major hurricane/typhoon intensity.

The results from the western North Pacific are only somewhat similar to the results reported in EM98 and R72. For all recurving TCs of tropical storm strength (>17 m s^{-1}) or greater, 28.8% reached maximum intensity within ± 12 h and 50.0% reached their maximum intensity within ± 24 h of recurvature. The mean latitude of recurvature was 22.9 °N with a standard deviation of 6.1°. When only storms of typhoon strength

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Table I. Summary statistics associated with recurving tropical cyclones of differing intensities for the western North Pacific, North Atlantic, Southern Hemisphere 35°E–135°W, the South Indian Ocean 35°E–135°E, and the South Pacific Ocean (135°E–135°W).

Western North Pacific	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$V_{max} \geq 17$ m s^{-1}	28.9	50.0	36.6	69.1	13.4	22.9	6.1	41.7	15.8
$V_{max} \geq 33$ m s^{-1}	28.1	47.7	38.6	70.6	13.7	22.8	5.8	46.7	13.8
$V_{max} \geq 52$ m s^{-1}	26.0	43.0	46.0	80.0	11.0	22.0	5.2	52.4	13.0
17 m s^{-1} $\leq V_{max} <$ 33 m s^{-1}	31.7	58.5	29.3	63.4	12.2	23.1	7.2	22.9	4.0
33 m s^{-1} $\leq V_{max} <$ 52 m s^{-1}	32.1	56.6	24.5	52.8	18.2	24.6	5.8	36.0	13.8

North Atlantic	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$V_{max} \geq 17$ m s^{-1}	16.9	36.6	36.6	56.3	26.8	29.4	6.5	34.6	11.6
$V_{max} \geq 33$ m s^{-1}	13.6	32.2	37.3	54.2	30.5	29.8	6.7	37.2	10.7
$V_{max} \geq 52$ m s^{-1}	18.5	44.4	44.4	66.7	11.1	29.7	8.6	44.2	9.5
17 m s^{-1} $\leq V_{max} <$ 33 m s^{-1}	33.3	58.3	33.3	66.7	8.3	27.7	5.1	21.3	4.1
33 m s^{-1} $\leq V_{max} <$ 52 m s^{-1}	9.4	21.9	31.2	43.8	46.9	29.9	4.6	31.5	7.9

Southern Hemisphere (whole)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$V_{max} \geq 17$ m s^{-1}	29.6	48.6	34.5	64.1	16.9	−19.0	5.9	33.8	13.9
$V_{max} \geq 33$ m s^{-1}	24.1	42.2	38.8	63.8	19.0	−19.0	5.8	36.5	14.0
$V_{max} \geq 52$ m s^{-1}	20.3	39.0	39.0	67.8	22.0	−18.5	5.6	42.3	15.0
17 m s^{-1} $\leq V_{max} <$ 33 m s^{-1}	53.9	76.9	15.4	65.4	7.7	−19.0	6.3	21.8	3.9
33 m s^{-1} $\leq V_{max} <$ 52 m s^{-1}	28.1	45.6	38.6	59.7	15.8	−19.5	6.1	30.5	9.7

South Indian Ocean	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$V_{max} \geq 17$ m s^{-1}	26.3	44.2	44.2	68.4	11.6	−19.6	5.8	34.2	13.0
$V_{max} \geq 33$ m s^{-1}	22.5	40.0	48.8	70.0	11.3	−19.8	5.8	36.4	12.8
$V_{max} \geq 52$ m s^{-1}	19.1	35.7	52.4	76.2	11.9	−19.8	5.8	41.7	12.9
17 m s^{-1} $\leq V_{max} <$ 33 m s^{-1}	46.7	66.7	20.0	60.0	13.3	−19.1	6.0	21.8	3.8
33 m s^{-1} $\leq V_{max} <$ 52 m s^{-1}	26.3	44.7	44.7	63.2	10.5	−19.5	5.9	30.7	10.0

South Pacific	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$V_{max} \geq 17$ m s^{-1}	36.2	57.5	14.9	55.3	27.7	−17.7	6.0	33.1	15.7
$V_{max} \geq 33$ m s^{-1}	27.8	47.2	16.7	50.0	36.1	−17.4	5.7	36.5	16.4
$V_{max} \geq 52$ m s^{-1}	23.5	47.1	5.9	47.1	47.1	−15.1	3.4	43.6	19.7
17 m s^{-1} $\leq V_{max} <$ 33 m s^{-1}	63.6	90.9	27.3	72.7	0.0	−18.7	7.0	21.8	4.1
33 m s^{-1} $\leq V_{max} <$ 52 m s^{-1}	31.6	47.3	26.3	52.6	26.3	−19.6	6.6	30.3	9.4

The columns for each basin indicate:

(1) Percentage of tropical cyclones whose maximum intensity occurs ±12 h of recurvature
(2) Percentage of tropical cyclones whose maximum intensity occurs ±24 h of recurvature
(3) Percentage of tropical cyclones whose maximum intensity occurs <24 h prior to recurvature
(4) Percentage of tropical cyclones reaching maximum intensity prior to or at recurvature
(5) Percentage of tropical cyclones reaching maximum intensity >24 h after recurvature
(6) Mean latitude of recurvature
(7) Standard deviation of the latitude of recurvature
(8) Mean intensity at recurvature (m s^{-1})
(9) Standard deviation of intensity at recurvature (m s^{-1})

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are considered, 28.1 and 47.7% of the cases reach their maximum intensity within 12 and 24 h, respectively. These percentages are notably lower than previously reported. As may be expected due to environmental conditions, a majority of TCs, 69.1% of the tropical storm strength or greater, and 70.6% of the typhoons reach their maximum strength prior to or at the point of recurvature. This result is similar to those of EM98. An interesting result is that 80.0% of storms that have lifetime maximum intensities greater than 95 kt (52 m s^{-1}) reach this intensity at or prior to recurvature, while 26.0% (43.0%) reach their maximum within ±12 h (±24 h) of recurvature. Figure 3 shows the cumulative distributions of the timing maximum intensity with respect to the point of recurvature for recurving tropical storms (17 m $s^{-1} \leq V_{max} < 33$ m s^{-1}), all minor typhoons (33 m $s^{-1} \leq V_{max} < 52$ m s^{-1}), and all major typhoons ($V_{max} \geq 52$ m s^{-1}). Figure 3 suggests that major typhoons tend to reach their maximum intensity earlier than weaker storms. In fact, for tropical storms, minor typhoons, and major typhoons, the maximum intensity occurs 24 h or more prior to recurvature 29.3, 24.5, and 46.0% of the time, respectively.

Using our dataset during the 1980–1996 period it was found that the number of recurving cases is similar to those found in EM98. However, the 1980–1996 maximum intensity timing results are similar to the results found during the 1980–2006 period. During that time period, 136 recurving TCs, 107 recurving typhoons, and 68 typhoons that reach an intensity of at least 52 m s^{-1} are identified using the objective identification method (*cf*, Section 2). This is only slightly different than the 154 TC and 109 typhoon cases found subjectively in EM98, suggesting along with tracks shown in Figure 1 that the objective methodology is capturing similar events. It was found that 30.8 and 52.2% of all TCs reached (first) maximum intensity within ±12 and ±24 h, respectively, and 29.9 and 51.4% of typhoons reach maximum intensity within ±12 and ±24 h, respectively. This can be compared with 45 and 70% of all recurving TCs reaching maximum intensity within ±12 and ±24 h, respectively, that was reported in EM98. It is acknowledged that our removal of storms that come within 50 km of land and a 3-day minimum storm record may be a source of the differences in the number of cases. It is also acknowledged that the tracks, not intensities, of a few of the TCs during this period were changed by the Chu *et al*. (2002) study. These track changes and small differences in methodology would be expected to change the results only slightly. It is also unclear from EM98 if the temporal resolution of the best tracks was 6-hourly. It is possible that the temporal resolution may have been 12-hourly, which would certainly bias their results. However, the large differences between their results and those shown here are unexplainable without the details of the individual cases and temporal resolution used in EM98.

The results of R72 were also re-examined. The process seems repeatable using the criteria listed in R72 insofar as 66 recurving typhoons were found in the 1957–1968 period. (Note that the cases between 0 and 50 km of land had to be included to observe the 66 cases.) However, the percentage of these storms reaching their maximum within ±12 and ±24 h of recurvature are 43.9 and 59.1%, respectively. As was the case with EM98, the results were not repeatable. R72's results may

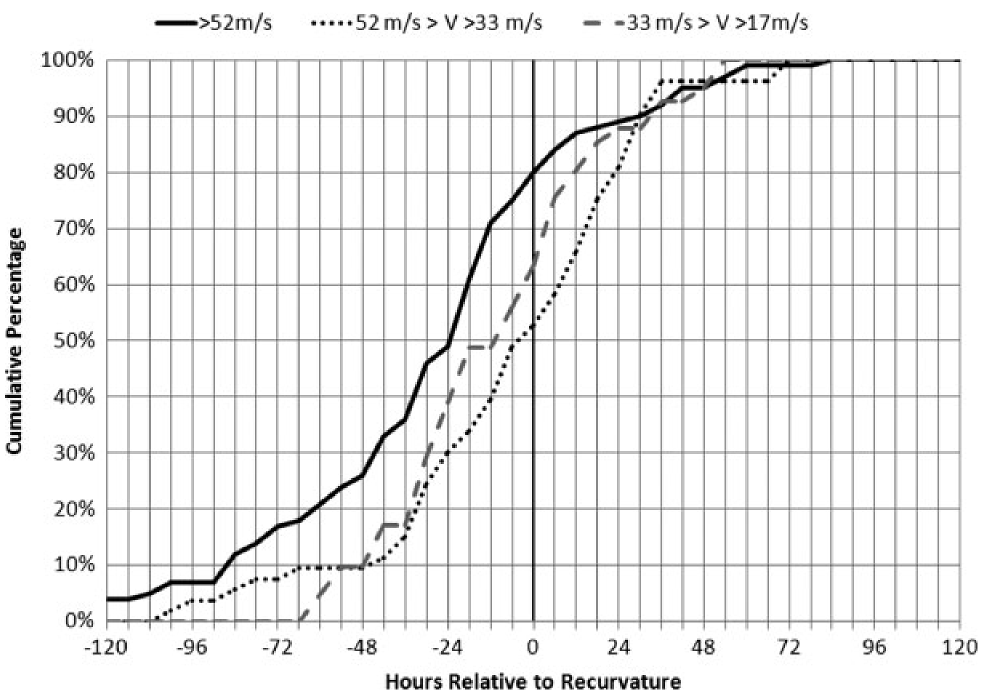

Figure 3. The cumulative distribution of timing of maximum intensity with respect to the point of recurvatrue for all TCs whose maximum intensities reach tropical storm (17 m $s^{-1} < V_{max} < 33$ m s^{-1}) typhoon (33 m $s^{-1} < V_{max} < 52$ m s^{-1}) and major typhoon ($V_{max} > 52$ m s^{-1}) strength in the western North Pacific.

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not be repeatable because they were based on aircraft reconnaissance wind observations, which are noted to sometimes have irregularities from one observation to the next (Riehl, 1972), and likely required a subjective analysis to determine the timing of maximum intensity. The study also required a subjective determination of the point of recurvature. This uncertainty was documented by the author's statement 'It must, however, be noted that the exact place of recurvature is probably not known closer than to the nearest 12 h; different sources of storm-track data disagree to this extent' (Riehl, 1972). Temporal resolution of the R72 data is also likely less than the 6-hourly resolution used in this study.

Similar analyses were carried out in the North Atlantic basin during 1980–2006. The cumulative distribution of the timing of maximum intensity with respect to the point of recurvature and as a function of maximum intensity is show in Figure 4. The maximum lifetime intensity of Atlantic TCs appears more variable with respect to recurvature, but results for major hurricanes are similar. For all recurving TCs of tropical storm strength (>17 m s^{-1}) or greater, 16.9% reached maximum intensity within ±12 h, and 36.6% reached their maximum intensity within ±24 h. The mean latitude of recurvature for all cases was 29.4° with a standard deviation of 6.5°. When only storms of hurricane strength are considered, 13.6 and 32.2% of the cases reach their maximum intensity within 12 and 24 h, respectively. These results are much different than those found in the western North Pacific. In the Atlantic, only 56.3% of all tropical strength – or greater – storms, and 54.2% of hurricanes reach their maximum prior to or at recurvature. This is contrasted by 66.7% of major hurricanes that reach their maximum at or prior to recurvature. If the results are stratified as before, 33.3% of tropical storms, 31.3% of minor hurricanes and 51.9% of major hurricanes reached their maximum intensity at least 24 h prior to recurvature. These results also show that the TCs of the North Atlantic are more likely to reach their maximum intensity following recurvature than those of the western North Pacific TCs. In fact, while the majority of major hurricanes have peak intensity occurring prior to the point of recurvature, there is almost an equal chance of the peak intensity of a hurricane occurring 24 h or more prior to recurvature, ±24 h of recurvature, and 24 h or more following recurvature in the North Atlantic.

In the Southern Hemisphere, the cumulative distributions of the timing of maximum intensity are different than the other two basins, with an almost equal probability of maximum intensity occurring before or after recurvature (Figure 5). In the Southern Hemisphere nearly equal percentages of tropical storms, hurricane strength and major hurricane strength cyclones reach their maximum prior to, or at recurvature, or 64.1, 63.8, and 67.8%, respectively. For all recurving TCs of tropical storm strength (>17 m s^{-1}) or greater, 29.6% reached maximum intensity within ±12 h, and 49.6% reached their maximum intensity within ±24 h. When only storms of typhoon/hurricane strength are considered, 24.1 and 42.2% of the cases reach their maximum intensity within 12 and 24 h, respectively. Similarly, if results are stratified into tropical storms, minor hurricanes, and major hurricanes, the maximum intensity was reached 23.8, 42.1, and 47.5% of the time at 24 h or more prior to recurvature. In the Southern Hemisphere, it also appears

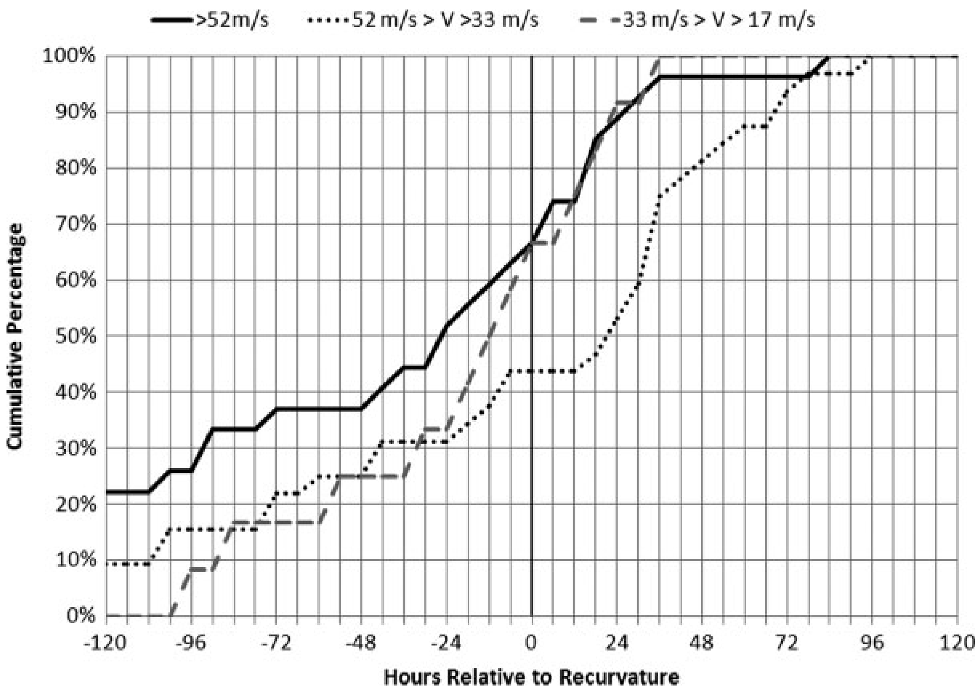

Figure 4. The cumulative distribution of timing of maximum intensity with respect to the point of recurvatrue for all TCs whose maximum intensities reach tropical storm (17 m s^{-1} < V_{max} < 33 m s^{-1}) hurricane (33 m s^{-1} < V_{max} < 52 m s^{-1}) and major hurricane (V_{max} > 52 m s^{-1}) strength in the North Atlantic.

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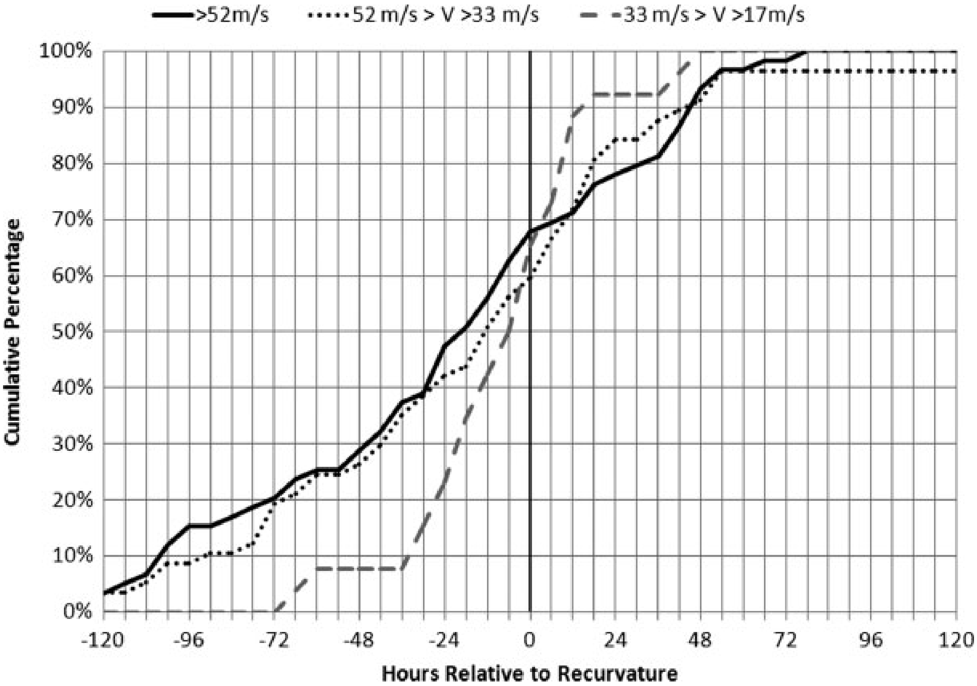

Figure 5. The cumulative distribution of timing of maximum intensity with respect to the point of recurvatrue for all TCs whose maximum intensities reach tropical storm (17 m s^{-1} < V_{max} < 33 m s^{-1}) hurricane (33 m s^{-1} < V_{max} < 52 m s^{-1}) and major hurricane (V_{max} > 52 m s^{-1}) strength in the whole Southern Hemisphere.

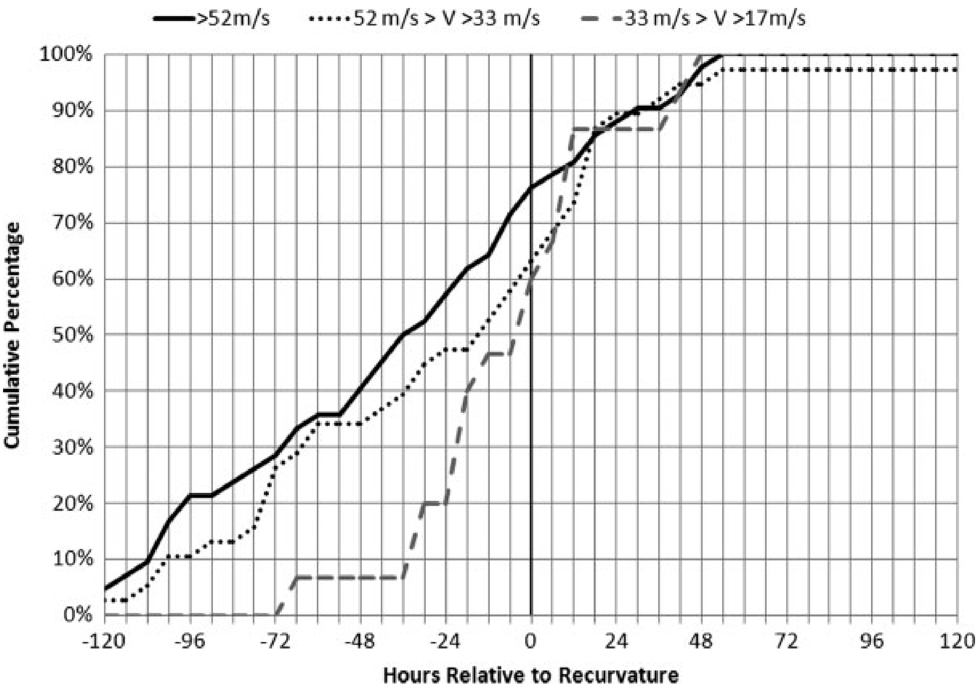

Figure 6. The cumulative distribution of timing of maximum intensity with respect to the point of recurvatrue for all TCs whose maximum intensities reach tropical storm (17 m s^{-1} < V_{max} < 33 m s^{-1}) hurricane (33 m s^{-1} < V_{max} < 52 m s^{-1}) and major hurricane (V_{max} > 52 m s^{-1}) strength in the South Indian Ocean (35 °E–135 °E).

that a larger percentage of major hurricanes peak 24 h or more after recurvature than was the case in the other basins examined. However, it is observed that Southern Hemisphere tropical storm strength TCs often reach their maximum very close or prior to recurvature. It is also noteworthy that storms recurve at low latitude. The mean latitude of recurvature is −19.0° with a standard deviation of 5.9°.

The results discussed above were based upon combining all of the Southern Hemisphere TC data, but it has been shown that the South Indian Ocean has quite different TC tracks than the South Pacific with the mean motions that are toward the west and toward the east, respectively (Neumann, 1993). Could the different climatological tracks result in different maximum intensity timing with respect to recurvature? Figure 6 shows the cumulative distributions of the timing of maximum intensity with respect to recurvature for the South Indian Ocean (35 °E–135 °E) and Figure 7 shows the same distributions for the South Pacific (135 °E–90 °W). The results of this stratification show that South Pacific TCs have a greater probability of reaching their maximum intensity after recurvature as well as the indication of a shorter lifecycle than in other basins. In the South Pacific, 27.7, 36.1 and 47.6% of the tropical storm, hurricane, and major hurricane strength TCs reach their maximum intensity 24 h or more after recurvature compared to 11.6, 11.3, and 11.9% of the time, respectively in the South Indian Ocean. Recurvature in the South Pacific also takes place at lower latitudes suggesting a stronger low-latitude deep-layer westerly in this region. These results suggest that on average major hurricanes are slightly more likely to form following recurvature in the South Pacific region.

Using the summaries provided in Table I, results show that the timing of maximum intensity associated with recurving TCs varies substantially from basin to basin. The timing of the maximum intensity of western North Pacific TCs appears best related to the point of recurvature. Other basins show weaker relationships. There is an indication that tropical storm strength TCs are most likely to reach their peak intensity relatively close or prior to the point of recurvature, which is likely due to the shorter life cycles associated with these weaker storms. Most interesting are the TCs that form in the South Pacific and which show a greater tendency to intensify after recurvature than in other basins. Unlike all the other basins, South Pacific TCs, including major hurricane strength TCs, are just as likely to experience peak intensity following recurvature as before recurvature.

To better interpret these results, statistics of the period of maximum intensity were also compiled for the individual basins and by intensity categories. For TCs that reach only tropical storm strength, the mean times to remain at maximum intensity are 24.6, 26.0, and 22.0 h in the Atlantic, western North Pacific, and Southern Hemisphere with standard deviations of 17.1, 20.8 and 14.6 h, respectively. If just storms of hurricane/typhoon strength are examined the average times are 21.4, 20.1, and 18.1 h with standard deviations of 14.9, 22.0, and 12.3 h, again, respectively. The time associated with the maximum intensity of those storms with maximum intensities greater than 52 m s^{-1} is even shorter with average times of 15.9, 16.4, and 16.3 h in the Atlantic, western North Pacific, and Southern Hemisphere, with relatively small standard deviations of 11.5, 13.1 and 10.7 h, respectively. So it appears that if a mean time of maximum intensity, or the last time at maximum intensity were used to create the distributions shown in Figures 3–7, the cumulative probabilities would be shifted to the right with slightly larger percentages of the weaker system occurring latter.

4. Discussion

The primary motivations for re-examining the timing of maximum intensity with respect to the point of

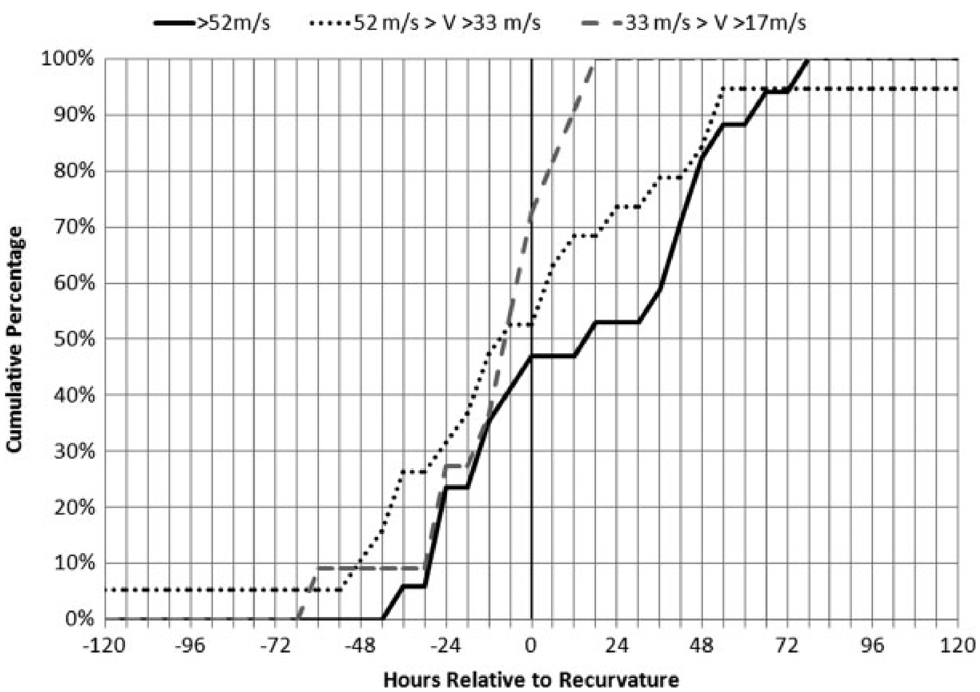

Figure 7. The cumulative distribution of timing of maximum intensity with respect to the point of recurvatrue for all TCs whose maximum intensities reach tropical storm (17 m s^{-1} < V_{max} < 33 m s^{-1}) hurricane (33 m s^{-1} < V_{max} < 52 m s^{-1}) and major hurricane (V_{max} > 52 m s^{-1}) strength in the South Pacific Ocean (135 °E–135 °W).

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recurvature were twofold. First, the results of both R72 and EM98 did not seem to match the likely physical controls on TC intensity or more recent observations of maximum intensity with respect to recurvature. For instance, there are no predictors in the Statistical Hurricane Intensity Prediction Scheme (DeMaria *et al.*, 2005) or the Statistical Typhoon Intensity Prediction Scheme (Knaff *et al.*, 2005) that suggested that TCs should peak in intensity at or near recurvature into the westerly flow. On the contrary, these simple statistical models show that TCs are favoured to intensify and maintain current intensity in specific environmental conditions that are characterized by relatively warm SSTs, low and easterly vertical wind shear, relatively moist atmospheric condition, and cool upper level temperatures. These conditions most often occur well equatorward of the mean latitude of recurvature in the Atlantic and western North Pacific regions (i.e. in regions that are equatorward of the mid-tropospheric sub-tropical ridge). Furthermore, the observations suggested that the most intense storms were generally moving westward at latitudes equatorward of the mean recurvature latitudes when the maximum intensity was realized.

Given this first motivating factor, the second motivation for this study was to examine if the above line of thinking leads to a universal relationship (i.e. that TCs, especially the most intense TCs, reach their maximum intensity prior to recurvature). The results presented in Section 3 suggest that generalizations about maximum intensity timing and the point of recurvature cannot be made. This information is significant not only from a forecasting point of view but also for anticipated future climate change scenarios.

This study shows that recurving TCs are well distributed about the point of recurvature, but that the more intense storms have a higher probability of reaching their maximum intensity prior to recurvature than weaker TCs. Results also show that more than approximately 45% of major hurricane strength TCs reach their peak intensity at least a day prior to recurvature. This is true in the western North Pacific, North Atlantic and South Indian TC basins. This result is likely simply related to more favourable conditions (warmer SSTs, moister atmospheres and less baroclinicity) for both intensification and maintenance of intensity closer to the equator in these basins (climatologies taken from Sadler, 1975; Sadler *et al.*, 1987a,b).

The results found in the South Pacific TC basin, namely that both hurricane and major hurricane strength systems are more likely to reach maximum intensity following recurvature, were somewhat unexpected. This observation likely indicating that the South Pacific TC environment following recurvature is generally more conducive for further intensification than other basins. There are two factors that may account for this result. First, the mean latitude of recurvature is only 17.7 °S, and the climatological SSTs for November–March suggest that SSTs are generally greater than 27 °C equatorward of 21 °S (Sadler *et al.*, 1987a), which is warm enough to empirically support a major hurricane (*cf*, Knaff and Sampson, 2008). Secondly, the mean flow (200–850 hPa) becomes west to east, south of ∼15 °S during the hurricane season as evidence by the mean easterly TC tracks documented in Neumann (1993). The result is that storms in this basin often remain in favourable environmental conditions for further intensification following low-latitude recurvature – this is generally not true in the western North Pacific, South Indian Ocean and the North Atlantic TC basins.

5. Summary and conclusions

It is often instructional to re-evaluate previous research findings when improved observational data becomes available. In this article, the often-referenced result that most recurving TCs reach their peak intensity close to the time of recurvature is revisited. This result has been cited in the literature and broadly applied to recurving TCs in other basins. However, during the 1980–2006 time period, the historical record has increased in size, and the temporal sampling of TC has improved with the availability of geostationary satellites. The primary purposes of this study were (1) to confirm previous work on the timing of maximum intensity and recurvature in the western North Pacific and (2) to determine if those findings could be generalized to other TC basins.

Findings suggest that a substantially lower percentage of western North Pacific TCs experience their first lifetime maximum intensity within ±12 h and ±24 h of recurvature than has been previously reported. Instead of 45 and 70% of all western North Pacific TCs peaking within ±12 h and ±24 h of recurvature as reported in EM98 for the period 1980–1996, the datasets from 1980–2006 suggest these percentages are closer to 28.9 and 50.0% respectively. Results presented here also challenge the R72 finding that two-thirds of typhoons reach their maximum intensity within ±12 h of recurvature. Findings suggest that less than one-third of typhoons reach their peak in that time frame. EM98 also found that weaker storms were likely to peak in intensity close to recurvature. This result is confirmed. Also, 48% of western North Pacific tropical storms reach their maximum intensity within ±24 h of recurvature.

Results found in the western North Pacific are difficult to generalize to other TC basins. It does appear that one could generalize that weaker storms (i.e. tropical storms) peak nearer the point of recurvature. However, the percentage of all TCs with intensities greater than 17 m s^{-1} that peak near recurvature in the western North Pacific were 28.9%, and 50% peak within ±12 h and ±24 h respectively, much lower than previously reported. These percentages are even lower in the Southern Hemisphere and much lower in the North Atlantic. In fact, chances are 30% that the peak intensity associated with a hurricane could occur 24 h or more after recurvature in the North Atlantic. It also appears, as may be suspected from our knowledge of environmental influences on TC, that more intense storms with intensities greater

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than 52 m s^{-1} have a greater probability of reaching maximum intensity before recurvature in the Atlantic, western North Pacific and the South Indian Ocean. Most curious is the tendency for hurricanes and major hurricanes in the South Pacific to have slightly greater chances of reaching peak intensity after recurvature.

In summary, the percentage of recurving TCs that experience peak intensity near recurvature is lower than previous studies have indicated in the western North Pacific. Statistics also indicate that the more intense TC, particularly those with intensities greater than 52 m s^{-1} tend to peak prior to recurving toward the east save for South Pacific major hurricanes whose peak intensity most often occurs following recurvature and 47% of these storms reach their maximum 24 h or more after recurvature. Modifying how the timing of maximum intensity is determined also was found to simplify results in a nearly uniform shift in these timing distributions. It therefore appears that the only possible generalization about the intensity of recurving TCs is that weaker storms (i.e. tropical storms) peak near to, or prior to, recurvature.

The first implication of this study is simply that the long-held belief that the maximum intensity of most hurricanes/typhoons occur near the time of recurvature is not supported by the observations. In contrast, the observations suggest that the most intense TCs experience peak intensities in regions that are generalized by generally warmer SST, moisture atmospheres, and lower vertical wind shears that most often occur well before recurvature. This is true in all the TC basins examined except for the South Pacific where recurvature occurs at low latitudes and the climatological deep-layer mean flow (i.e. the steering flow) is from west to east even in the tropical latitudes and over relatively warm SST. The second implication of this study is that the cumulative distributions of maximum intensity with respect to the point of recurvature are quite different for other intensity ranges suggesting that a universal relationship between peak intensity and time of recurvature does not exist. Such information, therefore, is likely to be useful to both TC forecasters and to the climate change community.

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