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A quantitative re-examination of lightning as a predictor of peak winds in tropical cyclones.

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We use the World Wide Lightning Location Network (WWLLN) to investigate lightning strike variations in eight years of category 4 and 5 tropical cyclones. A cross correlation analysis is performed between the lightning and maximum sustained wind variations, giving lag and lead times related to the peak linear correlation for each tropical cyclone. There is a moderate to strong correlation between lightning and wind variations. Using a lightning collection window of < 500 km, we confirm the general results of previous studies that lightning can be used on a $\sim$1 day timescale to predict the evolution of the winds in tropical cyclones. Investigation of different lightning collection window sizes indicates the lightning lead times are highly dependent upon the window size. Smaller collection windows have modal lightning lead times of $\sim$2.75 and 0 days, indicating that the lightning location inside the cyclone is as important as the total lightning variation.

1. Introduction

1.1. Overview

Accurate forecasting of tropical cyclones is of great importance for communities where landfall might occur. The most likely future path of a tropical cyclone can be modeled [e.g., *McAdie and Lawrence*, 2000] with low error (160 nautical miles for the North Atlantic in 2000-2005, *DeMaria, Knaff and Sampson* [2007]). Improvements to these forecasts has meant that the lead-time for hurricane warnings issued by the National Hurricane Center increased from 3 days to 5 days in 2003, with the incorrectly modeled cyclones being monitored and tested [e.g., *Brennan and Majumdar*, 2011]. However, while the global forecasting models are successful at predicting the track of the cyclone, they are not as good at predicting the wind intensities [*Rappaport et al.*, 2009; *DeMaria, Knaff and Sampson*, 2007].

Early studies on tropical cyclones gave no detail of their electrical activity [e.g., *Simpson and Riehl*, 1981], while later studies observe lightning activity mainly in the rainbands with occasional eyewall activity linked to supercell development [*Lyons and Keen*, 1994]. Lightning in the eyewall was later characterized as rare, requiring updrafts stronger than 10 ms^{-1} [*Black and Hallett*, 1999]. *Willis et al.* [1994] showed that a rapid electric field gradient is formed when the tropical cyclone exhibits strong vertical velocities with charge separation forming from the interaction of graupel and small ice particles. Recently researchers have been investigating the lightning within tropical cyclones in an attempt to better understand storm structure and the changes in wind intensity [e.g., *Thomas et al.*, 2010; *Fierro and Reisner*, 2011; *Reinhart et al.*, 2014]. *Price, Mustafa and Yair*

[2009] performed an analysis of 56 category 4 and 5 tropical cyclones, and concluded that lightning flash rates have a typical 30 hour lead on the maximum winds in a tropical cyclone. In a similar style, *Pan, Qie and Wang* [2014] performed a study of super and weak typhoons which resulted in lightning lead times of 30 and 60 hours respectively. *Abarca and Corbosiero* [2011] showed that lightning flash density is higher when tropical cyclone wind speeds are increasing, leading to a study of rapid intensification changes by *DeMaria et al.* [2012], who concluded that lightning can be used to improve short term (24 hour) predictions of wind intensification.

Our paper re-examines the study of *Price, Mustafa and Yair* [2009] and we aim to test the validity of their conclusions and extend their method to a much larger storm dataset. In this study we will henchforth refer to all high category tropical storms as tropical cyclones, regardless of their basin of origin and thus include hurricanes and typhoons.

1.2. Data sources

We are using data from the International Best Track Archive for Climate Stewardship (IBTrACS v03r05), a World Meteorological Organization Tropical Cyclone Programme endorsed database for the wind, pressure and location of the tropical cyclones [*Knapp et al.*, 2010]. We restrict our observations to those recorded by WMO endorsed stations. We use lightning data (version Reloc-B) from the ground based World Wide Lightning Location Network (WWLLN). WWLLN is a global network consisting of over 65 detection stations using Very Low Frequency (3-30 kHz) receivers to detect lightning flashes using a time-of-group-arrival technique. A recent description of the WWLLN network operation and characteristics can be found in *Hutchins et al.* [2012] and at *http://wwlln.net.*

2. Recreating the results of Price et al., 2009.

2.1. Overview of results and conclusions

Price, Mustafa and Yair [2009] (hereafter referred to as Price), investigated a dataset of 58 tropical cyclones for 2005 to 2007 said to be classified as category 4 and 5 (>114 kts) on the Saffir-Simpson scale [*Saffir*, 1973; *Simpson*, 1974]. Their tropical cyclone subset was mainly focused in the West Pacific (40%) but also included cyclones in the West Atlantic, East Pacific and Indian Oceans. Price used WWLLN to determine the total lightning within the tropical cyclone using a 10° x 10° square window centered on the eye. The maximum sustained wind and pressure data for each cyclone was taken from the National Hurricane Center and the Joint Typhoon Warning Center with 6 hour resolution and then smoothed using a 24 hour running average. The same averaging method was used on the lightning data by collating the sub microsecond resolution lightning strike data into 6 hour totals and then applying a 24 hour running average. A comparison between average wind speeds and lightning strike rate was then performed.

Price reported a positive correlation ($r = 0.82$) of strong significance (>90%) between the variation in winds and lightning for 56 of the 58 cyclones. The peak correlation had a variable time offset, with the lightning leading the winds by as much as 6 days in some cases, and in others the lightning lagged the winds by up to 3 days. The mean and median lead time of the lightning variability was reported as 30 hours. When each tropical cyclone was compared using this 30 hour lead time, 31 events showed a positive correlation with 19 of these showing a statistical significance > 90%. We begin by comparing the IBTrACS database to the WWLLN lightning data for the Price storm set.

2.2. Reanalysis of the data

Using IBTrACS, 38 of the 58 cyclones used by Price have a maximum sustained wind speed below the 114 kt category 4 limit defined by the Saffir-Simpson scale. Using tropical cyclone 'Sonca' as an example, Price's supplementary material showed that the smoothed peak winds reach ∼115 kts whereas the un-smoothed IBTrACS maximum wind speed for this cyclone is only 100 kts (the smoothed peak is 90 kts). The 'Sonca' winds in Price develop the same way over time as the IBTrACS data, showing a single wind peak just before 25 April 2005, although there is a constant offset in wind speeds at all times. It should be noted that these 38 cyclones with a maximum sustained wind <114 kts still fall under the Hong Kong Observatory classification of a 'severe Typhoon' (equivalent to a category 4 classification with a lower limit of 81 kts). However, we note that the magnitude differences between Price and IBTrACS are not important in this study as the cross correlation procedure to determine peak lag and lead times involves subtracting the mean from each data set, centering the data around 0 regardless of its original magnitude.

We begin, in a similar style to Price, with Hurricane Dennis. This tropical cyclone was tracked between 5-15 July 2005. To perform the running average we initially attempted using the average of 4 time bins (a 24 hour period), however an even number of bins requires an interpolated time value to be used. This interpolation was tested and did not reproduce the Price wind and pressure results. The number of bins was increased to 5 (a 30 hour period), allowing use of whole time bins and correctly reproducing the wind and pressure variation. The wind and pressure variation in Hurricane Dennis is shown in panel a) of Figure 1. However, the lightning strike variation using the same 30 hour average approach produces different results from Price as shown in panel b) of Figure 2. We see a similar shape in the smoothed lightning activity with the second peak at approximately the same activity rate as Price. However, the initial lightning activity peak is lower than Figure 2c in Price and the third peak is much higher. We have attempted multiple methods to reproduce Price's values including: median averaging, larger and smaller time windows to average over, different total lightning flash bin sizes, introducing bias to the averaging and using older WWLLN products with no improvement. The reproduction of hurricane Dennis has been independently performed by three of the authors and all have reproduced the variability shown in Figure 1b. We perform a cross correlation of the wind and lightning strike data seen in our Figure 1, taking the time difference associated with the peak value, then shift the two data sets and perform a linear correlation. For hurricane Dennis, we find the lightning leads the winds by 30 hours with a correlation of 0.96 and a statistical significance over 99.9%. This is very close to the Price values for this storm of 24 hours and a correlation of 0.95. The small differences are most likely to arise from our inability to perfectly reproduce the Price lightning curve. The direct wind to pressure correlation was also calculated giving a linear correlation value of -0.98.

We repeated this process for all 58 tropical cyclones in the Price dataset, but included two extra conditions. The first condition is that the first and last two time bins of the wind and lightning data are removed after the running average is performed. This removal ensures that the data points which do not have sufficient neighboring values to average over are not included. The second condition is that the cross correlation time difference between the lightning and wind values are limited to +6 days and -3 days as Price reports no differences outside these limits. Our analysis of the direct wind and pressure relation is highly negatively correlated as expected, with a mean correlation of -0.988 and median correlation of -0.993. The varying lightning to wind correlations for the Price cyclones are given in panel c) of Figure 1. Each tropical cyclone is given a symbol similar to Price's Figure 4, based on the statistical significance of the result as shown in the legend. The average correlation of the 58 cyclones has a mean of 0.72 and median of 0.73, in comparison to the mean correlation value of 0.82 given by Price. Three cyclones ('Khanun', 'Sidr' and 'Wipha') have a statistical significance $< 90\%$ ($\sim 85\%$ for all three).

Panel d) of Figure 1 shows the distribution of the tropical cyclone lag data for comparison to Price's Figure 3. Here a positive lag indicates that the lightning variation leads the wind variation. The time resolution of the lag distribution is set to 6 hours (grey bars). Again, the distribution does not match the specific values seen in Price. A summation of the distribution in Figure 3 in Price exceeds 200%, suggesting some errors in this figure. Despite the difference, we still find mean and median lag times close to the 30 hour values reported by Price. The mean lag time for our analysis is +24 hours with a median value of +27 hours. These average lag times are indicated on panel d) by the solid (mean) and dashed (median) lines. As a final test the three cyclones with statistical significance less than 90% are removed and the averages recalculated, giving little change to the mean lag (+24 hours) and providing a median lag of +24 hours. Smoothing the lag distribution data across 5 bins (30 hours, solid blue line) produces a distribution which looks closer to Price's Figure 3.

We conclude that while there appear to be issues in the results presented by Price, their approach does indicate that there is a moderate to strong correlation between lightning and wind variations, with the lightning leading the wind by approximately 1 day.

3. Repeating the method for a larger subset of storms

3.1. Identifying tropical cyclones

The Price analysis approach is now extended to a larger and longer tropical cyclone dataset. Classification of cyclones by wind intensity depends upon its basin of origin. NOAA's Hurricane Research Division identifies 7 basins of origin for tropical cyclones which can be split into 5 regions. These regions are Hurricanes (West Atlantic and East Pacific north of the equator to the International Dateline), Typhoons (International Dateline to 110o longitude north of the equator), Australian TC (100° eastwards to -120° longitude, south of the equator), Indian TC (30° to 100° longitude both sides of the equator), and any other location (including the Mediterranean). The intensity classifications for each area are included in Table 1 with the maximum sustained wind speeds converted to knots. The hurricane classification is from the latest update of the Saffir-Simpson wind scale at the National Hurricane Center, the typhoon classification is taken from the Hong Kong Observatory and the Australian classification is taken from the Australian Bureau of Meteorology. The classifications for the Indian Ocean basins are taken from the Indian Regional Specialized Meteorological Center, who use 7 categories (1 to 4, 5(i), 5(ii) and 6) for tropical storms. These have been matched up to be consistent with those of other agencies in Table 1. For our larger cyclone dataset only category 4 and 5 tropical cyclones (equivalent to 5(ii) and 6 in the case of those with Indian Ocean basin of origin) will be included.

The basin of origin is determined by the latitude and longitude of the first maximum sustained wind speed data point in the IBTrACS database for each cyclone. We find 144 tropical cyclones which can be classified as category 4 or 5 between January 2005 and February 2013 ($\sim$20% of the tropical cyclone list for these dates). The initial position of the 144 tropical cyclones are shown in panel a) of Figure 2. The color of each start position represents the peak maximum sustained wind speed of the cyclone ranging from 85 to 160 kts. All 58 cyclones in the Price dataset passed the minimum sustained wind speeds to be classed as a category 4 or 5 tropical cyclone using the classifications in Table 1 and are included in this 8 year dataset.

3.2. Analysis of the 8 year tropical cyclone dataset

Panel b) of Figure 2 shows the 8 year dataset in a similar style to panel c) of Figure 1. The x-axis indicates the start date of the tropical cyclone instead of the name of the storm. Each data point symbol relates to the category of the tropical cyclone. The maximum sustained wind speed, basin of origin and the mean/median/total lightning strikes in the cyclone were examined and no relation to the linear correlation or optimal lag value was found. There are two tropical cyclones not plotted which have a negative correlation value ('Carina' in 2006, r = -0.15 and 'Roke' in 2011, r = -0.35). The mean (0.74) and median (0.78) linear correlations are very close to the 3 year dataset of Price shown in panel c) of Figure 1, indicating that the Price tropical cyclones are a fair sample of the larger population. Panel c) of Figure 2 shows the distribution of lag times in a similar style to panel d) of Figure 1. Once again the mean (29 hours) and median (30 hours) lags are very similar to the ∼1 day timescale discussed in both Price and *DeMaria et al.* [2012].

3.3. Lightning strike collection window

To collect the 6 hour lightning strike totals, Price used a 10° x 10° square window. Up to now we also used the same window size and shape but now investigate a window more suited to the shape of a tropical cyclone. The 10° x 10° square is changed to a circular window with a radius set in km rather than degrees. At the equator 10° is ∼1100 km so we rerun the analysis on the 8 year dataset for radii ranging from 500 km down to 100 km in 100 km increments as well as a 50 km radius. A range of toroidal rings were also calculated.

A comparison of the circular to square window is performed by investigating the 500 km radius circular window centered on the cyclone. As expected there are only small changes in the results between the 500 km radial and 10° square window. The circular window giving both mean and median lags of 30 hours (in comparison to 29 and 30 hours from the square window) and the median linear correlation was 0.76. In Section 2.2 we described an initial condition limiting the cross correlation to +6 and -3 days to match the Price approach. We now remove this limitation for analysis of the individual circular lightning collection windows, the lag distribution smoothing (e.g., panel c of Figure 2) is also reduced to a more conservative 3 bin distance (18 hours). The cross correlation and linear correlation was performed for each cyclone and lightning radial distance window described above. The 300 km radius window resulted in the highest linear correlation of lightning to wind variability with $r = 0.80$, shown in panel a) of Figure 3. A full table including each radial distance collection window with the average correlations and lags are included in the supplementary material.

4. Discussion

We find broadly similar results to Price when we extend their approach to a longer 8 year dataset of tropical cyclones. However, while the typical linear correlations give values in the range of 0.7 to 0.8, this does not necessarily indicate a true ability to match the evolving wind and lightning variation. Visual inspection of each of the 144 cyclones was performed to investigate the accuracy of the cross correlation procedure. We plotted: the lightning against winds in a similar style to panel b) of Figure 1, the lag times against cross correlation value, and the time shifted lightning data with wind data to determine the accuracy of the variation matching process. This inspection found 3 cyclones where the wind and lightning variation show no similarities and a further 8 instances of the cross correlation performing poorly, giving a failure rate of $\sim$8%. The two sources of cross correlation failure were; double peaked winds with the lightning peak(s) linked to the wrong wind peak, and lightning data which had a sharp lightning strike gradient at the beginning or end of the data (an example is shown in the supplementary material). This large gradient in the 6 hour lightning strike total forced the cross correlation procedure to match poorly and resulted in lags > 84 hours and < -84 hours (3.5 days).

In Section 3.3 we noted that a 300 km radius resulted in the best median linear correlation, shown in panel a) of Figure 3. While the mean and median lags show a value similar to that quoted by Price, the lags show a double peak distribution at +66 hours (2.75 days) and 0 hours, with these average values sitting between them. Taking the average provides little to no information in this specific case. We further investigate these peaks by looking at radial distances smaller than 300 km. Panel b) of Figure 3 shows the < 50 km radial distance which has only a single clear peak between 0 and +6 hours. *Molinari et al.* [1994], used a distance less than 40 km as corresponding to eyewall lightning in hurricane Andrew, while *Zhang et al.* [2012] determined lightning at < 60 km was eyewall lightning. We can therefore assume that our < 50 km radial window is providing correlations predominately for eyewall lightning. *Molinari, Moore and Idone* [1999] showed that lightning density in tropical cyclones is bi-modal as a function of radial distance, with one distribution in the eyewall and the other in the rainband region (150-300 km). Investigation of other radial distances, including the 150-300 km region, provides no other single peaks in the lag distribution. When looking at the < 300 km circular window in panel a) of Figure 3, it is interesting to note that *Pan, Qie and Wang* [2014] found a modal lightning lag of +60 hours (2.5 days) when looking at weak tropical cyclones in the Northwest Pacific (using a < 600 km radius window). *DeMaria et al.* [2012] also determined that inner core lightning outbreaks are "a signal that an intensification is coming to an end", (i.e., the peak winds have been reached).

5. Conclusions

We have recreated the Price approach for a set of 58 tropical cyclones but were unable to duplicate the exact results that were found in this study. However, we confirmed their broad conclusions that lightning variability seems to be correlated to wind variability and that on average, the lightning variation leads the wind variation by ∼1 day. The Price approach has been extended from the original 3 years of data to an 8 year dataset which returns broadly similar lag and correlation results when using a lightning collection window of 10° square or of 500 km radius. The cross correlation matching between wind and lightning only has an ∼8% failure rate. We have calculated both the 10° x 10° square lightning detection window, a radial distance in kilometers, and performed the lightning to wind cross correlation for a range of circular distances including toroidal rings. The highest correlations were found for the < 300 km radial window with a median linear correlation of 0.8. The calculated lag time for each tropical cyclone using this < 300 km collection window, shows a double peak distribution at 0 and +66 hours, at this smaller radius a median or mean lag is not appropriate. The eyewall lightning at distances < 50 km from the center of the storm provides only a single peak around a zero time lag.

These results suggest that the predictive timescale of lightning is highly dependent upon which region of the cyclone is investigated. When using a spatially large lightning collection window our results agree with other studies of high category tropical cyclones [e.g., *Price, Mustafa and Yair*, 2009; *DeMaria et al.*, 2012; *Pan, Qie and Wang*, 2014] of a ∼1 day value. When we look at the region containing the eyewall we find a 0 day value, indicating that eyewall lightning cannot be used to predict the wind evolution. When we consider the < 300 km region (rainband and eyewall) we find a double peaked structure at ∼3 days (agreeing with *Pan, Qie and Wang* [2014] for weak tropical cyclones) and 0 days. This 0 day lag is independent of the eyewall correlation peak, confirmed by the 150-300 km window showing the same double peak structure.

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Table 1: *The intensity classification for categories of tropical cyclones in different regions based upon maximum sustained wind speeds. The categories defined by the New Delhi RSMC are more numerous and the equivalent categories are included in brackets. Descriptions of the basin locations are given in the text. Wind speeds are converted to knots.*

Category	**Hurricanes**	**Typhoon**	**Australian TC**	**Indian TC**
1	> 64	> 34	> 34	> 34 (3)
2	> 83	> 48	> 48	> 48 (4)
3	> 96	> 64	> 64	> 64 (5i)
4	> 113	> 81	> 86	> 91 (5ii)
5	> 137	> 100	> 107	> 120 (6)

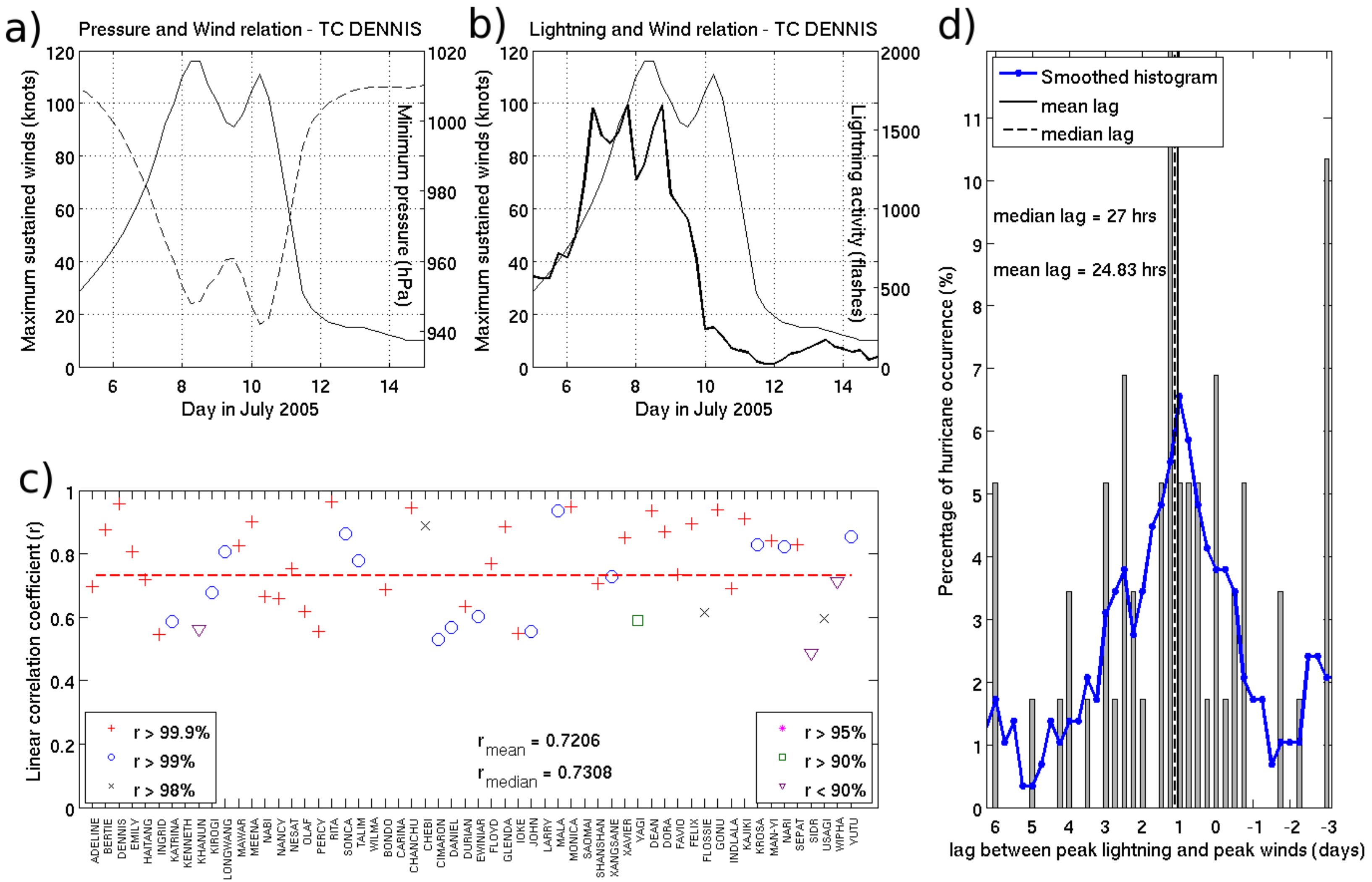

Figure 1: *Recreation of the Price, Mustafa and Yair [2009] study using IBTrACS and WWLLN, with a 10° square window.***a)** *The wind (solid) and pressure (dashed) in Hurricane Dennis.* **b)** *Our processing of the wind (thin line) and lightning (thick line) in Hurricane Dennis.* **c)** *The linear correlation coefficients for each of the Price 58 tropical cyclones. The symbol indicates the statistical significance.* **d)** *The distribution of peak correlation time lags (a 30 hour smoothing is shown by the blue solid line) showing a double peak around 0.75 days (18 hours).*

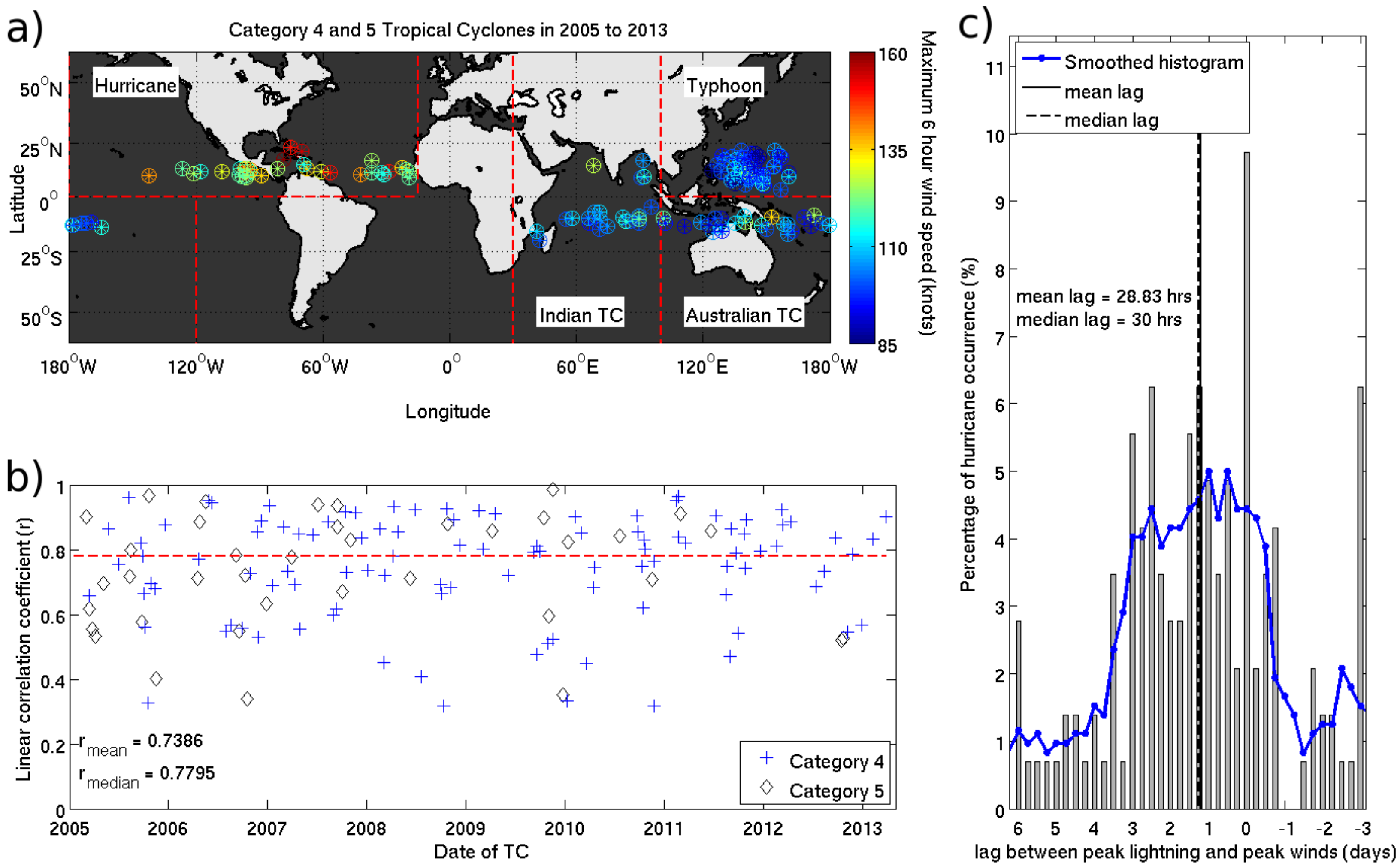

Figure 2: *Data from the extended 8 year dataset covering January 2005 to February 2013, using the same 10° square window centered on the cyclone.* **a)** *A global map showing the starting point of each of the 144 tropical cyclones identified in this period. The color of the marker indicates the cyclone maximum sustained wind speed.* **b)** *The optimal linear correlation of the wind to lightning for each of the 144 cyclones. Symbols correspond relate to the category of the cyclone.* **c)** *The distribution of peak correlation time lags.*

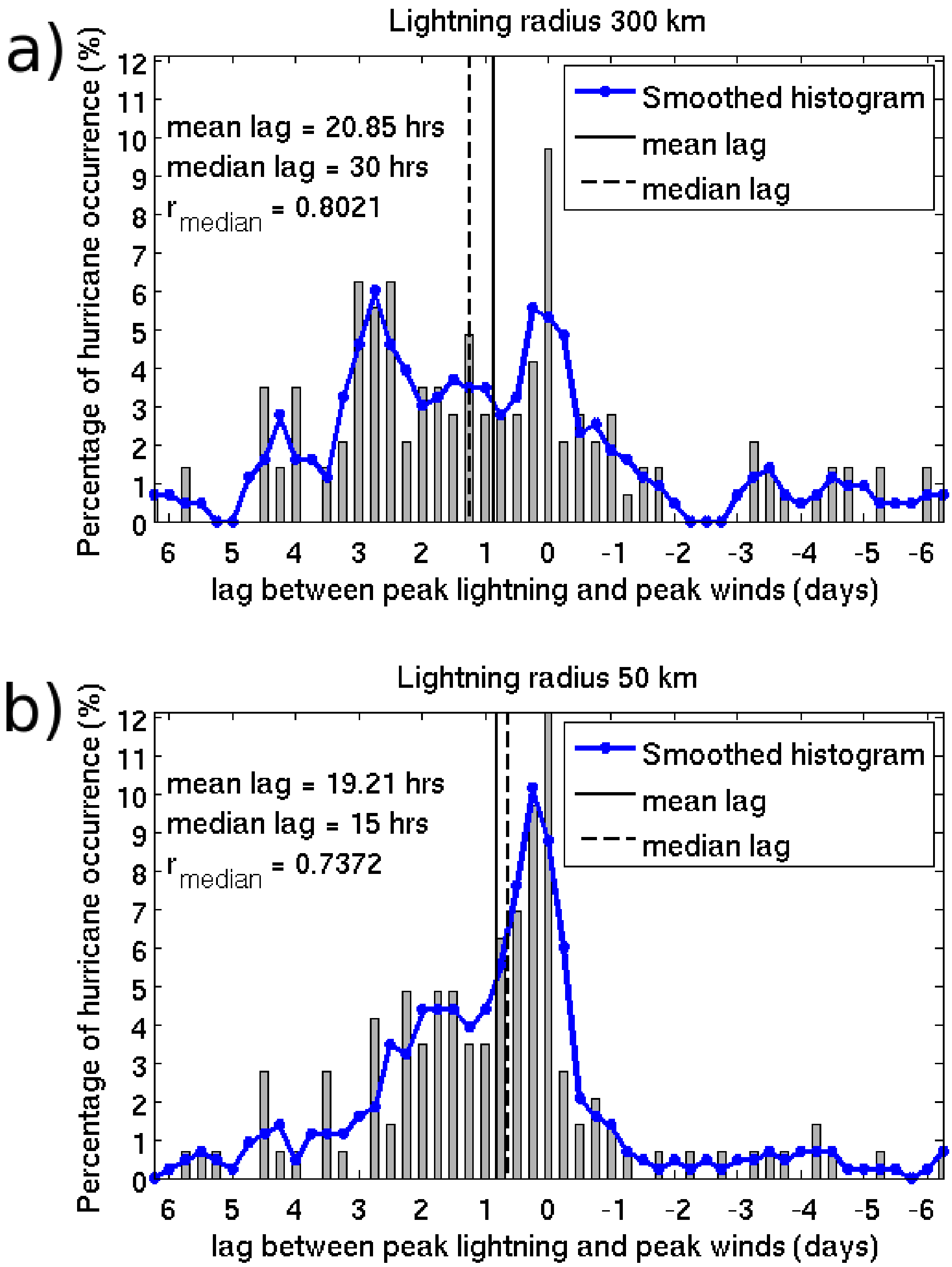

Figure 3: *The 8 year dataset analysed using a circular window, in km rather than degrees, centered on the storm.* a) *The distribution of lags using a 300 km radial distance window for the lightning detection.* b) *The distribution of lags using a 50 km radial distance, this distance is most likely comprised of eyewall lightning.*