

**¹ A quantitative re-examination of lightning as a
² predictor of peak winds in tropical cyclones.**

Ian C. Whittaker,¹ Emma Douma,¹ Craig J. Rodger¹ Timothy J. C. H.

Marshall,¹

Corresponding author: I. Whittaker, Department of Physics, University of Otago, PO Box 56,
Dunedin 9054, New Zealand. (ian.whittaker@otago.ac.nz)

¹Department of Physics, University of
Otago, Dunedin, New Zealand.

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

1. Introduction

1.1. Overview

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

26
27 Early studies on tropical cyclones gave no detail of their electrical activity [e.g., *Simpson*
28 *and Riehl*, 1981], while later studies observe lightning activity mainly in the rainbands
29 with occasional eyewall activity linked to supercell development [*Lyons and Keen*, 1994].
30 Lightning in the eyewall was later characterized as rare, requiring updrafts stronger than
31 10 ms^{-1} [*Black and Hallett*, 1999]. *Willis et al.* [1994] showed that a rapid electric field
32 gradient is formed when the tropical cyclone exhibits strong vertical velocities with charge
33 separation forming from the interaction of graupel and small ice particles. Recently
34 researchers have been investigating the lightning within tropical cyclones in an attempt
35 to better understand storm structure and the changes in wind intensity [e.g., *Thomas*
36 *et al.*, 2010; *Fierro and Reisner*, 2011; *Reinhart et al.*, 2014]. *Price, Mustafa and Yair*

37 [2009] performed an analysis of 56 category 4 and 5 tropical cyclones, and concluded that
38 lightning flash rates have a typical 30 hour lead on the maximum winds in a tropical
39 cyclone. In a similar style, *Pan, Qie and Wang* [2014] performed a study of super and
40 weak typhoons which resulted in lightning lead times of 30 and 60 hours respectively.
41 *Abarca and Corbosiero* [2011] showed that lightning flash density is higher when tropical
42 cyclone wind speeds are increasing, leading to a study of rapid intensification changes by
43 *DeMaria et al.* [2012], who concluded that lightning can be used to improve short term
44 (24 hour) predictions of wind intensification.

45

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

1.2. Data sources

50 We are using data from the International Best Track Archive for Climate Stewardship
51 (IBTrACS v03r05), a World Meteorological Organization Tropical Cyclone Programme
52 endorsed database for the wind, pressure and location of the tropical cyclones [*Knapp*
53 *et al.*, 2010]. We restrict our observations to those recorded by WMO endorsed stations.
54 We use lightning data (version Reloc-B) from the ground based World Wide Lightning
55 Location Network (WWLLN). WWLLN is a global network consisting of over 65 detection
56 stations using Very Low Frequency (3-30 kHz) receivers to detect lightning flashes using a

57 time-of-group-arrival technique. A recent description of the WWLLN network operation
58 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

59 *Price, Mustafa and Yair* [2009] (hereafter referred to as Price), investigated a dataset of
60 58 tropical cyclones for 2005 to 2007 said to be classified as category 4 and 5 (>114 kts) on
61 the Saffir-Simpson scale [*Saffir*, 1973; *Simpson*, 1974]. Their tropical cyclone subset was
62 mainly focused in the West Pacific (40%) but also included cyclones in the West Atlantic,
63 East Pacific and Indian Oceans. Price used WWLLN to determine the total lightning
64 within the tropical cyclone using a $10^\circ \times 10^\circ$ square window centered on the eye. The
65 maximum sustained wind and pressure data for each cyclone was taken from the National
66 Hurricane Center and the Joint Typhoon Warning Center with 6 hour resolution and then
67 smoothed using a 24 hour running average. The same averaging method was used on the
68 lightning data by collating the sub microsecond resolution lightning strike data into 6
69 hour totals and then applying a 24 hour running average. A comparison between average
70 wind speeds and lightning strike rate was then performed.

71
72 Price reported a positive correlation ($r = 0.82$) of strong significance (>90%) between
73 the variation in winds and lightning for 56 of the 58 cyclones. The peak correlation had
74 a variable time offset, with the lightning leading the winds by as much as 6 days in some
75 cases, and in others the lightning lagged the winds by up to 3 days. The mean and median
76 lead time of the lightning variability was reported as 30 hours. When each tropical cyclone

77 was compared using this 30 hour lead time, 31 events showed a positive correlation with
78 19 of these showing a statistical significance $> 90\%$. We begin by comparing the IBTrACS
79 database to the WWLLN lightning data for the Price storm set.

2.2. Reanalysis of the data

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

93
94 We begin, in a similar style to Price, with Hurricane Dennis. This tropical cyclone was
95 tracked between 5-15 July 2005. To perform the running average we initially attempted
96 using the average of 4 time bins (a 24 hour period), however an even number of bins
97 requires an interpolated time value to be used. This interpolation was tested and did not

98 reproduce the Price wind and pressure results. The number of bins was increased to 5 (a
99 30 hour period), allowing use of whole time bins and correctly reproducing the wind and
100 pressure variation. The wind and pressure variation in Hurricane Dennis is shown in panel
101 a) of Figure 1. However, the lightning strike variation using the same 30 hour average
102 approach produces different results from Price as shown in panel b) of Figure 2. We see a
103 similar shape in the smoothed lightning activity with the second peak at approximately
104 the same activity rate as Price. However, the initial lightning activity peak is lower
105 than Figure 2c in Price and the third peak is much higher. We have attempted multiple
106 methods to reproduce Price's values including: median averaging, larger and smaller time
107 windows to average over, different total lightning flash bin sizes, introducing bias to the
108 averaging and using older WWLLN products with no improvement. The reproduction
109 of hurricane Dennis has been independently performed by three of the authors and all
110 have reproduced the variability shown in Figure 1b. We perform a cross correlation of the
111 wind and lightning strike data seen in our Figure 1, taking the time difference associated
112 with the peak value, then shift the two data sets and perform a linear correlation. For
113 hurricane Dennis, we find the lightning leads the winds by 30 hours with a correlation of
114 0.96 and a statistical significance over 99.9%. This is very close to the Price values for
115 this storm of 24 hours and a correlation of 0.95. The small differences are most likely to
116 arise from our inability to perfectly reproduce the Price lightning curve. The direct wind
117 to pressure correlation was also calculated giving a linear correlation value of -0.98.

118

119 We repeated this process for all 58 tropical cyclones in the Price dataset, but included two

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

133
134 Panel d) of Figure 1 shows the distribution of the tropical cyclone lag data for comparison
135 to Price's Figure 3. Here a positive lag indicates that the lightning variation leads the
136 wind variation. The time resolution of the lag distribution is set to 6 hours (grey bars).
137 Again, the distribution does not match the specific values seen in Price. A summation of
138 the distribution in Figure 3 in Price exceeds 200%, suggesting some errors in this figure.
139 Despite the difference, we still find mean and median lag times close to the 30 hour values
140 reported by Price. The mean lag time for our analysis is +24 hours with a median value
141 of +27 hours. These average lag times are indicated on panel d) by the solid (mean) and

142 dashed (median) lines. As a final test the three cyclones with statistical significance less
143 than 90% are removed and the averages recalculated, giving little change to the mean lag
144 (+24 hours) and providing a median lag of +24 hours. Smoothing the lag distribution
145 data across 5 bins (30 hours, solid blue line) produces a distribution which looks closer to
146 Price's Figure 3.

147

148 We conclude that while there appear to be issues in the results presented by Price, their
149 approach does indicate that there is a moderate to strong correlation between lightning
150 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

151 The Price analysis approach is now extended to a larger and longer tropical cyclone
152 dataset. Classification of cyclones by wind intensity depends upon its basin of origin.
153 NOAA's Hurricane Research Division identifies 7 basins of origin for tropical cyclones
154 which can be split into 5 regions. These regions are Hurricanes (West Atlantic and
155 East Pacific north of the equator to the International Dateline), Typhoons (International
156 Dateline to 110° longitude north of the equator), Australian TC (100° eastwards to -
157 120° longitude, south of the equator), Indian TC (30° to 100° longitude both sides
158 of the equator), and any other location (including the Mediterranean). The intensity
159 classifications for each area are included in Table 1 with the maximum sustained wind
160 speeds converted to knots. The hurricane classification is from the latest update of the
161 Saffir-Simpson wind scale at the National Hurricane Center, the typhoon classification is

162 taken from the Hong Kong Observatory and the Australian classification is taken from
163 the Australian Bureau of Meteorology. The classifications for the Indian Ocean basins are
164 taken from the Indian Regional Specialized Meteorological Center, who use 7 categories
165 (1 to 4, 5(i), 5(ii) and 6) for tropical storms. These have been matched up to be consistent
166 with those of other agencies in Table 1. For our larger cyclone dataset only category 4
167 and 5 tropical cyclones (equivalent to 5(ii) and 6 in the case of those with Indian Ocean
168 basin of origin) will be included.

169
170 The basin of origin is determined by the latitude and longitude of the first maximum
171 sustained wind speed data point in the IBTrACS database for each cyclone. We find 144
172 tropical cyclones which can be classified as category 4 or 5 between January 2005 and
173 February 2013 (~20% of the tropical cyclone list for these dates). The initial position of
174 the 144 tropical cyclones are shown in panel a) of Figure 2. The color of each start position
175 represents the peak maximum sustained wind speed of the cyclone ranging from 85 to 160
176 kts. All 58 cyclones in the Price dataset passed the minimum sustained wind speeds to
177 be classed as a category 4 or 5 tropical cyclone using the classifications in Table 1 and
178 are included in this 8 year dataset.

3.2. Analysis of the 8 year tropical cyclone dataset

179 Panel b) of Figure 2 shows the 8 year dataset in a similar style to panel c) of Figure 1.
180 The x -axis indicates the start date of the tropical cyclone instead of the name of the storm.
181 Each data point symbol relates to the category of the tropical cyclone. The maximum
182 sustained wind speed, basin of origin and the mean/median/total lightning strikes in the

183 cyclone were examined and no relation to the linear correlation or optimal lag value was
184 found. There are two tropical cyclones not plotted which have a negative correlation value
185 (‘Carina’ in 2006, $r = -0.15$ and ‘Roke’ in 2011, $r = -0.35$). The mean (0.74) and median
186 (0.78) linear correlations are very close to the 3 year dataset of Price shown in panel c)
187 of Figure 1, indicating that the Price tropical cyclones are a fair sample of the larger
188 population. Panel c) of Figure 2 shows the distribution of lag times in a similar style to
189 panel d) of Figure 1. Once again the mean (29 hours) and median (30 hours) lags are
190 very similar to the ~ 1 day timescale discussed in both Price and *DeMaria et al.* [2012].

3.3. Lightning strike collection window

191 To collect the 6 hour lightning strike totals, Price used a $10^\circ \times 10^\circ$ square window. Up
192 to now we also used the same window size and shape but now investigate a window more
193 suited to the shape of a tropical cyclone. The $10^\circ \times 10^\circ$ square is changed to a circular
194 window with a radius set in km rather than degrees. At the equator 10° is ~ 1100 km so we
195 rerun the analysis on the 8 year dataset for radii ranging from 500 km down to 100 km in
196 100 km increments as well as a 50 km radius. A range of toroidal rings were also calculated.

197
198 A comparison of the circular to square window is performed by investigating the 500
199 km radius circular window centered on the cyclone. As expected there are only small
200 changes in the results between the 500 km radial and 10° square window. The circular
201 window giving both mean and median lags of 30 hours (in comparison to 29 and 30 hours
202 from the square window) and the median linear correlation was 0.76. In Section 2.2 we
203 described an initial condition limiting the cross correlation to +6 and -3 days to match

204 the Price approach. We now remove this limitation for analysis of the individual circular
205 lightning collection windows, the lag distribution smoothing (e.g., panel c of Figure 2) is
206 also reduced to a more conservative 3 bin distance (18 hours). The cross correlation and
207 linear correlation was performed for each cyclone and lightning radial distance window
208 described above. The 300 km radius window resulted in the highest linear correlation of
209 lightning to wind variability with $r = 0.80$, shown in panel a) of Figure 3. A full table
210 including each radial distance collection window with the average correlations and lags
211 are included in the supplementary material.

4. Discussion

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

225 large gradient in the 6 hour lightning strike total forced the cross correlation procedure
226 to match poorly and resulted in lags > 84 hours and < -84 hours (3.5 days).

227

228 In Section 3.3 we noted that a 300 km radius resulted in the best median linear correlation,
229 shown in panel a) of Figure 3. While the mean and median lags show a value similar to
230 that quoted by Price, the lags show a double peak distribution at +66 hours (2.75 days)
231 and 0 hours, with these average values sitting between them. Taking the average provides
232 little to no information in this specific case. We further investigate these peaks by looking
233 at radial distances smaller than 300 km. Panel b) of Figure 3 shows the < 50 km radial
234 distance which has only a single clear peak between 0 and +6 hours. *Molinari et al.* [1994],
235 used a distance less than 40 km as corresponding to eyewall lightning in hurricane Andrew,
236 while *Zhang et al.* [2012] determined lightning at < 60 km was eyewall lightning. We can
237 therefore assume that our < 50 km radial window is providing correlations predominately
238 for eyewall lightning. *Molinari, Moore and Idone* [1999] showed that lightning density
239 in tropical cyclones is bi-modal as a function of radial distance, with one distribution in
240 the eyewall and the other in the rainband region (150-300 km). Investigation of other
241 radial distances, including the 150-300 km region, provides no other single peaks in the
242 lag distribution. When looking at the < 300 km circular window in panel a) of Figure 3,
243 it is interesting to note that *Pan, Qie and Wang* [2014] found a modal lightning lag of
244 +60 hours (2.5 days) when looking at weak tropical cyclones in the Northwest Pacific
245 (using a < 600 km radius window). *DeMaria et al.* [2012] also determined that inner core

246 lightning outbreaks are “a signal that an intensification is coming to an end”, (i.e., the
247 peak winds have been reached).

5. Conclusions

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

263

264 These results suggest that the predictive timescale of lightning is highly dependent upon
265 which region of the cyclone is investigated. When using a spatially large lightning
266 collection window our results agree with other studies of high category tropical cyclones

267 [e.g., *Price, Mustafa and Yair*, 2009; *DeMaria et al.*, 2012; *Pan, Qie and Wang*, 2014] of
268 a ~ 1 day value. When we look at the region containing the eyewall we find a 0 day value,
269 indicating that eyewall lightning cannot be used to predict the wind evolution. When we
270 consider the < 300 km region (rainband and eyewall) we find a double peaked structure
271 at ~ 3 days (agreeing with *Pan, Qie and Wang* [2014] for weak tropical cyclones) and 0
272 days. This 0 day lag is independent of the eyewall correlation peak, confirmed by the
273 150-300 km window showing the same double peak structure.

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275 The tropical cyclone data was taken from the IBTrACS database and the lightning
276 data came from the WWLLN network, both described in the data sources section.
277 The information on tropical cyclone wind classification was taken from the following
278 websites: NOAA-National Hurricane Center (www.nhc.noaa.gov/aboutsshws.php),
279 Australian Bureau of Meteorology, (www.bom.gov.au/cyclone/faq), Regional Specialized
280 Meteorological Centre, New Delhi, (www.rsmcnewdelhi.imd.gov.in/), and the Hong Kong
281 Observatory, (www.weather.gov.hk/informtc/class.htm). Information on the splitting of
282 tropical cyclone identification regions was obtained from the NOAA-Hurricane Research
283 Division, (www.aoml.noaa.gov/hrd/tcfaq/F1.html). The authors wish to thank the World
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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)

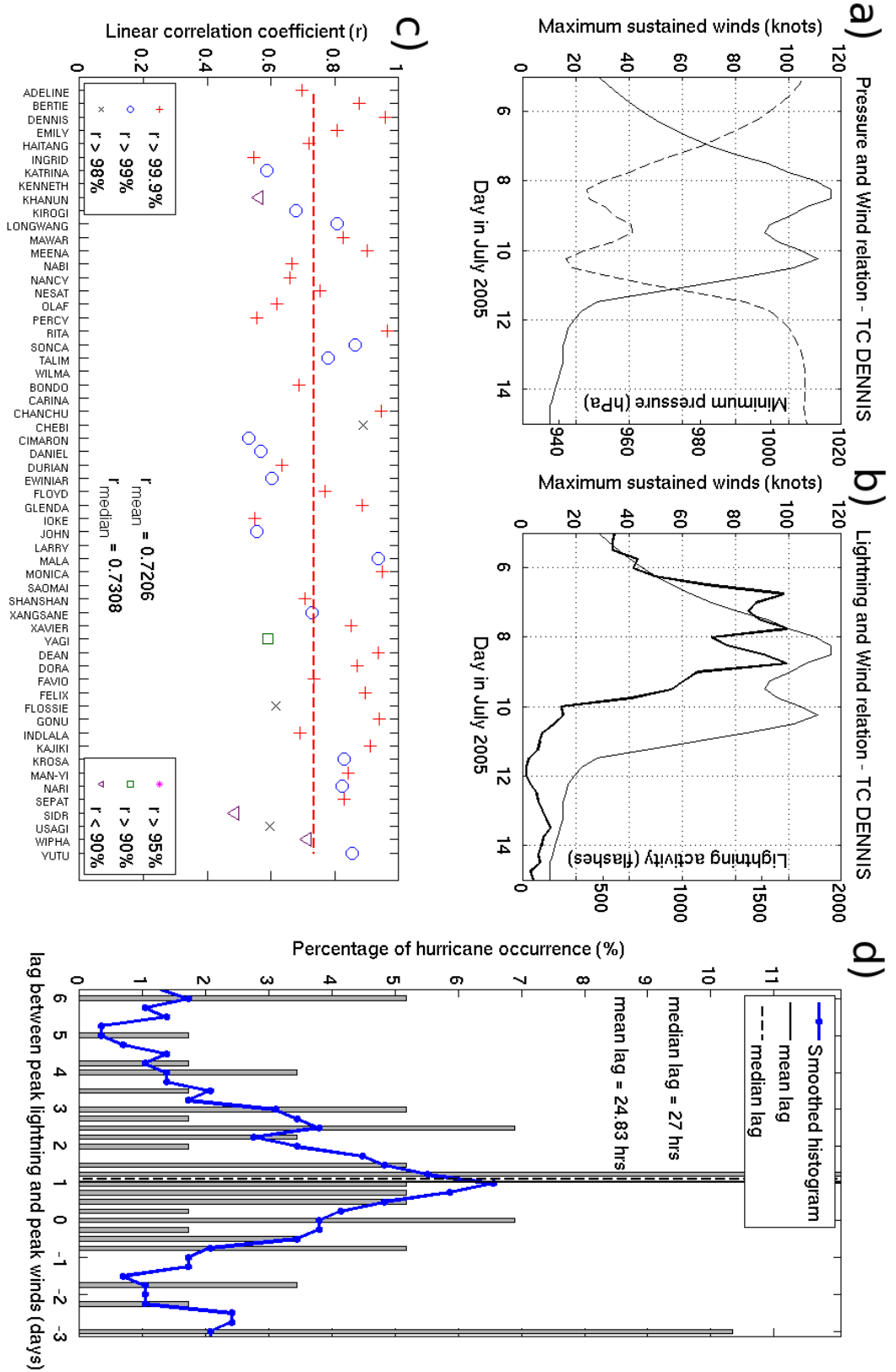


Figure 1: Recreation of the Price, Mustafa and Yair [2009] study using IBTrACS and WWLLN, with a 10° square window a) The wind (solid) and pressure (dashed) in Hurricane Dennis. b) Our processing of the wind (thin line) and lightning (thick line) in Hurricane Dennis. c) The linear correlation coefficients 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).

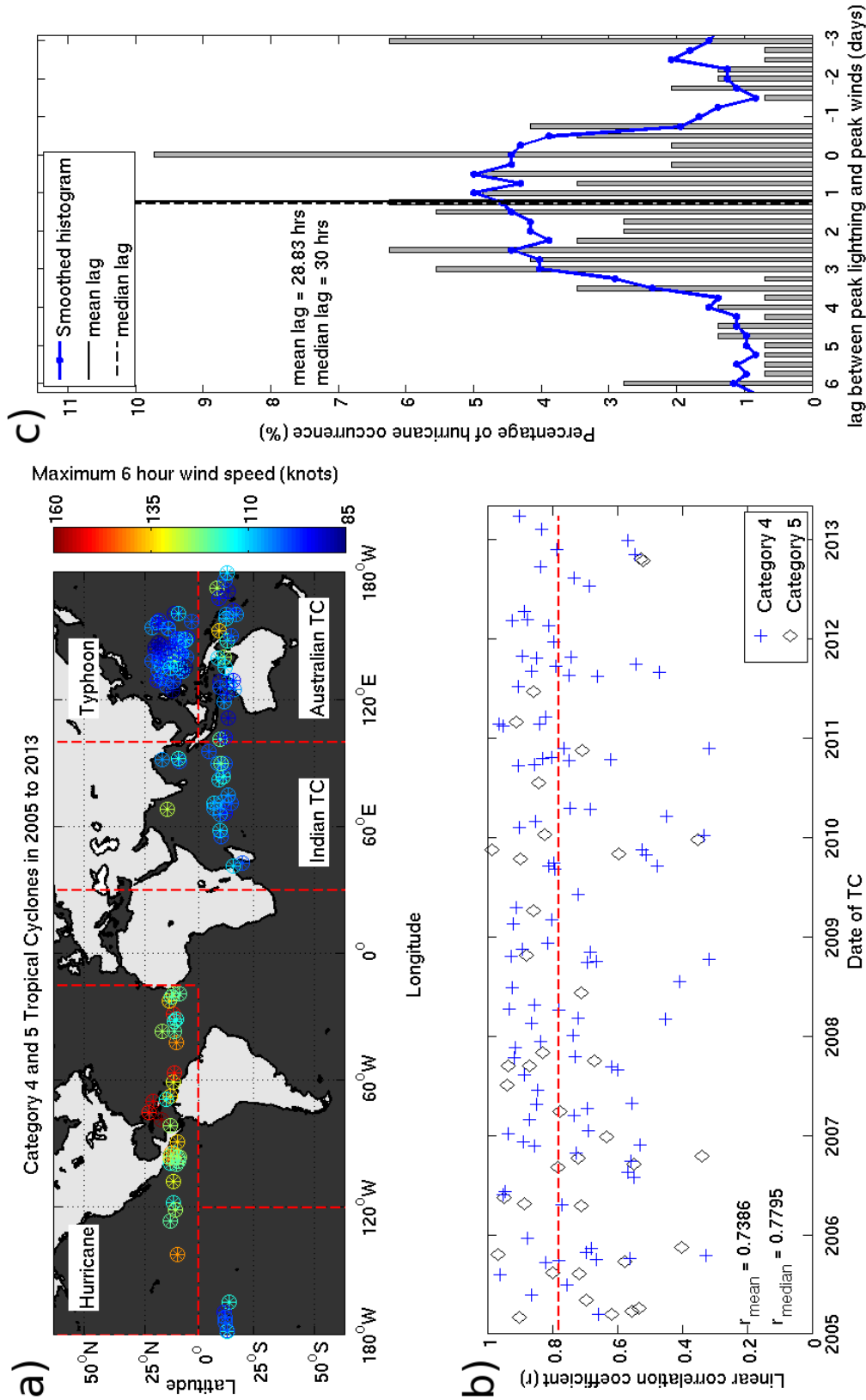


Figure 2: Data from the extended 8 year dataset covering January 2005 to February 2013, using the same 10° square window centered on the cyclone. **a)** A global map showing the starting point of each of the 144 tropical cyclones identified in this period. The color of the marker indicates the cyclone 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.

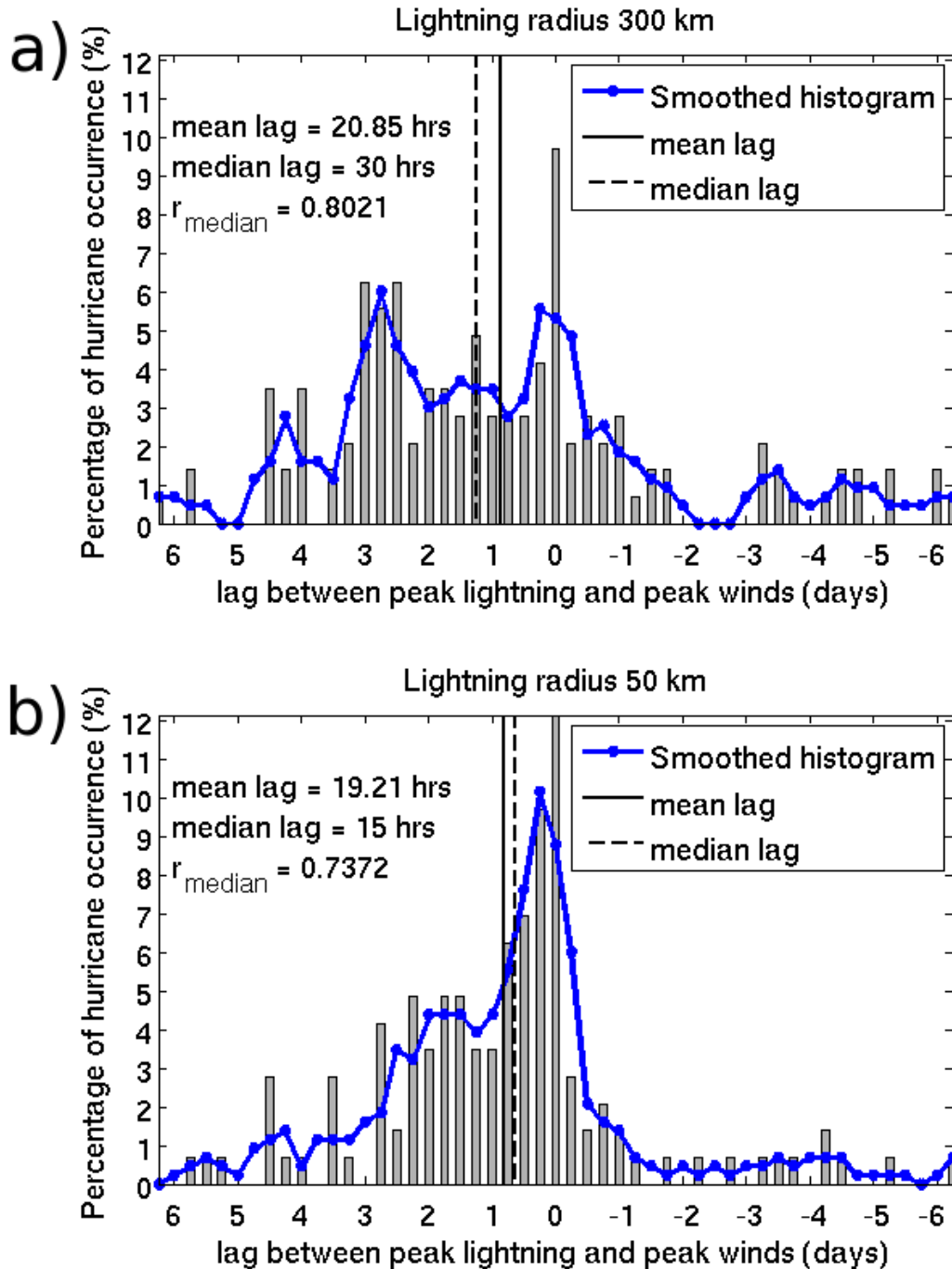


Figure 3: The 8 year dataset analysed using a circular window, in km rather than degrees, centered on the storm. **a)** The distribution of lags using a 300 km radial distance window for the lightning detection. **b)** The distribution of lags using a 50 km radial distance, this distance is most likely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