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Maximum hurricane intensity preceded by increase in lightning frequency

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Hurricanes are the Earth's most deadly storms, causing tremendous devastation around the globe every year. Forecasters are quite successful in predicting the pathways of hurricanes days in advance[1], but hurricane intensification is less accurately predicted. Here we analyse the evolution of maximum winds and total lightning frequency every 6 h during the entire lifetime of 56 hurricanes around the globe. We find that in all of these hurricanes, lightning frequency and maximum sustained winds are significantly correlated (mean correlation coefficient of 0.82), where the maximum sustained winds and minimum pressures in hurricanes are preceded by increases in lightning activity approximately one day before the peak winds. We suggest that increases in lightning activity in hurricanes are related to enhanced convection that increases the rate of moistening of the lower troposphere, which in turn leads to the intensification of hurricanes[2]. As lightning activity can now be monitored continuously in hurricanes at any location around the globe[3], lightning data may contribute to better hurricane forecasts in the future.

Hurricanes are the most deadly storms on the Earth, with evidence that the strength and number of intense hurricanes (category 4 and 5 of the Saffir–Simpson scale) may have increased in recent decades[4,5]. Hurricanes form over the warm oceans in the tropics, and develop from tropical depressions to tropical storms, and then hurricanes (in the Atlantic), cyclones (in the Indian Ocean) or typhoons (in the west Pacific). However, the physical nature of these storms is the same. These tropical cyclones can have total lifetimes from a few days to 2–3 weeks at most, and generally spend most of their lifetime over the oceans. In fact, the landfall of a hurricane results in the weakening and decay of the storm. Whereas the prediction of the trajectory of these storms is now quite accurate[1], the forecast of the future storm intensity is more difficult to predict. The reason for this is that storm tracks are primarily determined by the large-scale atmospheric environment surrounding the storm, but intensity changes are affected by many processes on a wide variety of scales. To first order, a fairly accurate short-term track forecast can be made simply by following a trajectory in the vertically averaged tropospheric flow in the storm environment. However, the intensity is affected by the convection near the storm centre, interactions with the underlying ocean and complex interactions with the storm environment, including the effects of vertical shear, trough interaction and moisture availability.

As hurricanes spend most of their lifetime over the oceans, it has always been a problem obtaining continuous, quality data from hurricanes before landfall. Satellites are used for some observations; however, *in situ* observations can be obtained only by using research aircraft that fly into these storms. These aircraft observations are extremely expensive, and are not available in all regions of the globe owing to range and safety limitations.

One way of looking within storms from great distances is to monitor the electrical activity within hurricanes. It has been known for many years that lightning activity is closely related to the microphysics and dynamics of convective storms. For charge separation on a microscopic scale, it is necessary to produce a mix of small ice particles together with graupel (small hail) particles growing in the presence of supercooled water[6,7]. However, these conditions become most efficient in supporting significant electric field build-up when updraft velocities are greater than 10 m s^{-1} in clouds. Hence, changes in lightning activity can signal changes in storm dynamics, organization, development and so on. In some hurricanes, rapid intensification is associated with updrafts greater than 20 m s^{-1}, accompanied by increased lightning activity[8]. In such cases, the mixed-phase regions of convective cells extend to higher altitudes than normal, with supercooled drops and graupel observed at altitudes much colder than the 0 °C isotherm. Hence, an increase in lightning activity within thunderstorms may provide some *in situ* information that can help improve the forecasts of enhanced convective growth of the storm's clouds and the subsequent hurricane intensification.

Although for many years hurricanes were believed to have little lightning activity, lightning has been observed within many hurricanes[9–14]. Even some historical anecdotes from sailors describe intense lightning in hurricanes[15]: "For one whole day and night it blazed like a furnace, and the lightning broke forth with such violence that each time I wondered if it had carried off my spars and sails; the flashes came with such fury and frightfulness that we all thought the ships would be blasted". Recently, lightning activity in tropical waves has also been related to the genesis of hurricanes[16].

To check the connection between hurricane intensification and electrical activity, we have collected data from all 58 category-4 and category-5 (Saffir–Simpson scale) hurricanes around the globe over a three-year period (2005–2007) (Fig. 1; see Methods). By definition, these storms have maximum sustained horizontal winds greater than 114 knots (210 km h^{-1}). The two main centres of hurricane activity occurred in the west Pacific and the west Atlantic. However, intense hurricanes also occurred in the Indian Ocean and southern/eastern Pacific.

Lightning activity around the globe can be continuously monitored from great distances using low-frequency or very low-frequency (VLF) electromagnetic networks on the ground. Such networks exist on regional scales in many countries (for example, the National Lightning Detection Network in the United States, Rede Integrada Nacional de Deteccao de Descargas Atmosfericas in Brazil, the Japanese Lightning Detection Network in Japan and the European Cooperation for Lightning Detection in Europe) and more recently efforts have been made to develop global networks, such as the World Wide Lightning Location Network (WWLLN; ref. 3). Although this network is primarily for research

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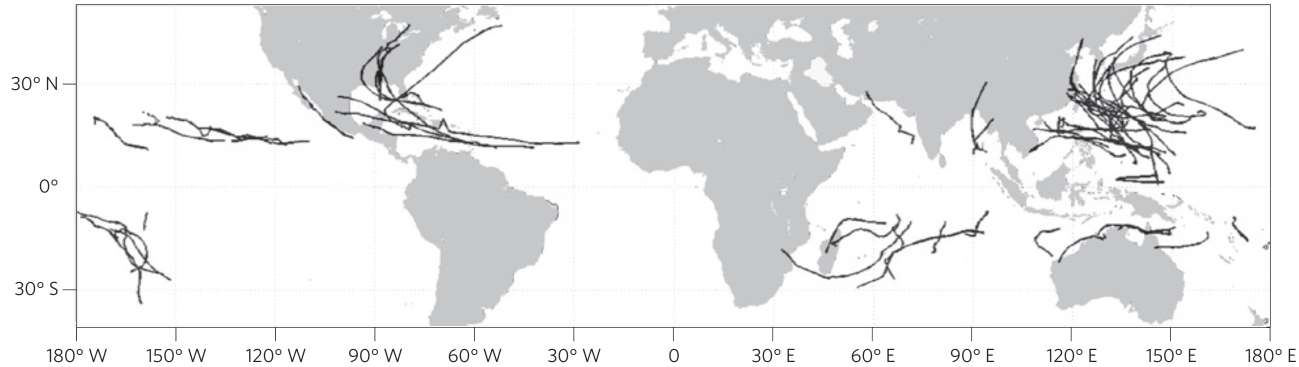

Figure 1 | Global distribution and paths of the 58 hurricanes used in this study. The category-4 and category-5 hurricanes included in this study are: 2005—Adeline, Bertie, Dennis, Emily, Haitang, Ingrid, Katrina, Kenneth, Khanun, Kirogi, Longwang, Mawar, Meena, Nabi, Nancy, Nesat, Olaf, Percy, Rita, Sonca, Talim, Wilma; 2006—Bondo, Carina, Chanchu, Chebi, Cimaron, Daniel, Durian, Ewiniar, Floyd, Glenda, Ioke, John, Larry, Mala, Monica, Saomai, Shanshan, Xangsane, Xavier, Yagi; 2007—Dean, Dora, Favio, Felix, Flossie, Gonu, Indlala, Kajiki, Krosa, Man-yi, Nari, Sepat, Sidr, Usagi, Wipha and Yutu.

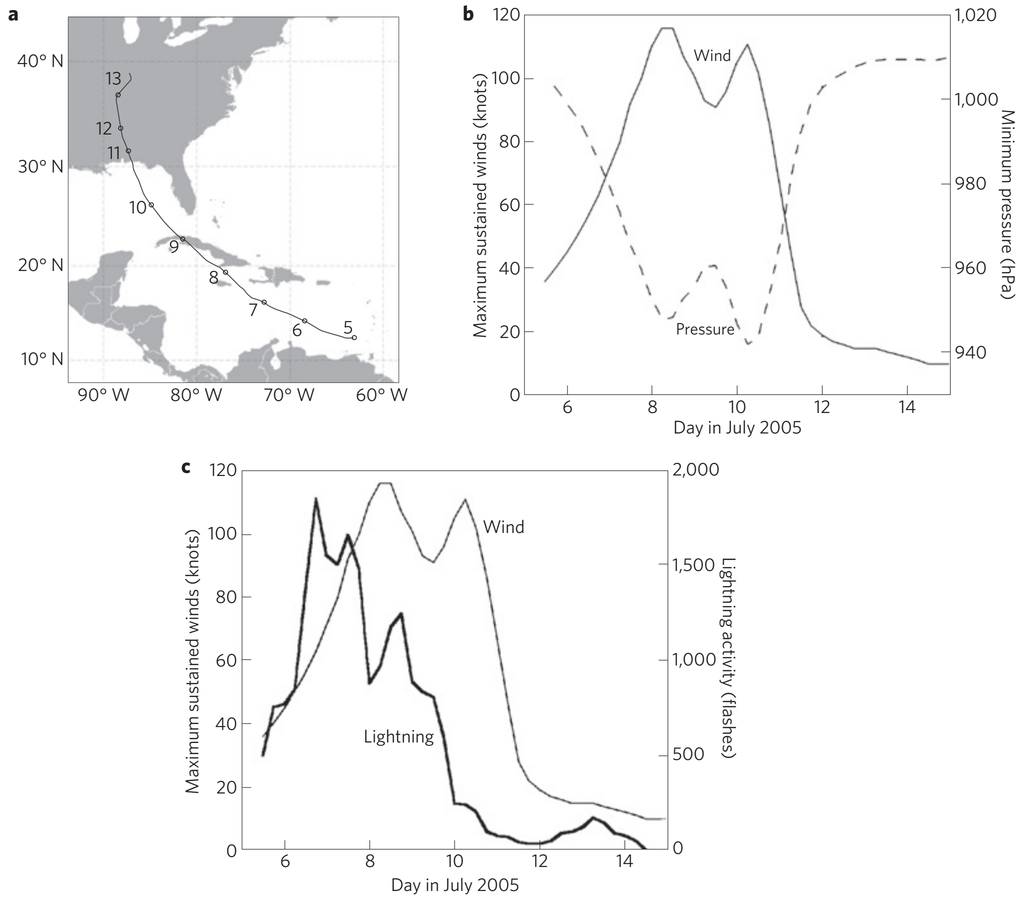

Figure 2 | Hurricane Dennis 5–14 July 2005. a, The path of Hurricane Dennis in the Atlantic Ocean, showing the location at 12:00 UTC every day. **b**, The minimum pressure at the centre of the hurricane (dashed curve) together with the maximum sustained winds (solid curve). **c**, The maximum sustained winds (solid thin curve) and the observed lightning frequencies within a 10° × 10° gridbox centred on the eye of the storm (solid bold curve).

purposes, the global lightning data detected by this network are updated in near real-time and can be used and viewed at http://webflash.ess.washington.edu/. The WWLLN has grown from 11 stations in 2003 to 30 stations in 2007, each station continuously receiving the VLF pulses (sferics) emitted by lightning discharges within a range of a few thousand kilometres (see Methods). The WWLLN network detects orders of magnitudes more lightning than polar-orbiting satellite detectors that detect only a few thunderstorms per orbit, and only for a fraction of the storm's lifetime[17]. The big advantage of the WWLLN network is that it is continuous in time and space, thus allowing global, real-time monitoring.

An example of our analysis for each of the hurricanes is shown in Fig. 2 for Hurricane Dennis in 2005. Figure 2a shows the trajectory of the centre (eye) of the hurricane from 5–14 July 2005, with the location of the hurricane eye at 12:00 UTC shown by the open circles. The central pressure and the maximum sustained winds are shown in Fig. 2b. As expected, there is a strong negative correlation between minimum pressure within the hurricane and the maximum wind speeds (Fig. 2b). The horizontal winds are a result of the intense pressure gradients between the eye of the storm and the surrounding regions. The bold curve in Fig. 2c represents the lightning activity detected by the WWLLN within a 10° × 10° grid box centred on the eye of the storm, and the thin curve showing the maximum

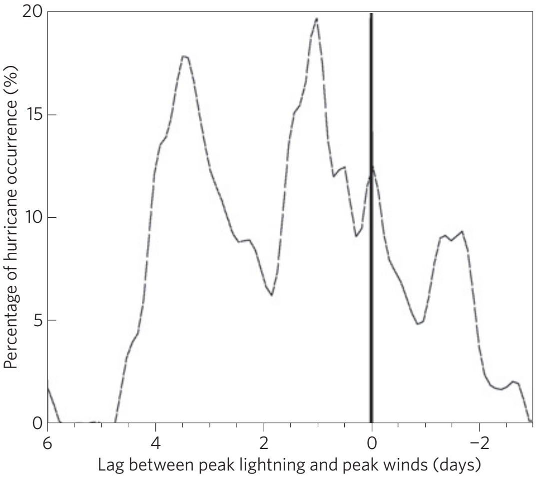

Figure 3 | Lag times between the maximum lightning activity and the maximum sustained winds in 56 hurricanes. Positive lags imply that the lightning activity peaked before the maximum intensity of the winds, and vice versa for negative lags.

sustained winds is the same as that in Fig. 2b. From Fig. 2c it can be clearly seen that the lightning activity follows the same pattern as the maximum wind speeds (or minimum pressures), with an approximate one-day lag between the peak lightning activity and the peak intensity of the hurricane. Hurricane Dennis had two periods of peak winds, both of which were preceded by maxima in lightning activity one day before the peak in the maximum sustained winds. The linear correlation between the lightning activity curve and the maximum sustained winds curve, taking into account the one-day lag, is 0.95, implying that lightning activity can explain 90% of the day-to-day variability of the maximum sustained winds in this hurricane. The correlation with the pressure curve (Fig. 2b) is −0.94.

The same analysis was carried out for all 58 category-4 and category-5 hurricanes that occurred during the years 2005–2007. Of these storms, 56 showed statistically significant positive correlations between lightning activity and maximum sustained winds. The summary of the results is presented in Figs 3 and 4. Figure 3 shows the distribution of the lag times between the maximum lightning activity and the maximum sustained wind speeds (or minimum pressure) in each hurricane. These lag times are obtained by shifting the lightning curves relative to the wind curves ±6 days, at 6-h intervals, and looking for the best correlation between the two data sets. More than 70% of the hurricanes analysed have the lightning activity peaking before the maximum wind intensities, with the most common lag being 30 h (both the mean and median). Whereas some storms had lightning activity peaking four days before the maximum winds, there are also some storms that show lightning activity peaking after the most intense wind speeds. This may be related to enhanced convection after landfall. It should be noted that hurricanes with no landfall showed even better results (see Supplementary information S1).

The statistical significance of these fits is shown in Fig. 4, where the linear correlation coefficients (r) between the lightning activity and wind speeds are shown for each hurricane, taking into account the lags shown in Fig. 3. The names of the 56 hurricanes are shown along the x axis, and the correlation coefficients are shown with different symbols depending on their statistical significance. The significance was calculated on the basis of the number of days used in the analysis for each hurricane. Hence, two hurricanes with the same correlation coefficient can have different statistical significance. All 56 hurricanes show significant correlations (>90%) between lightning activity and maximum sustained winds, with a mean of $r = 0.82$. This implies that daily lightning frequencies can explain more than 67% of the daily variability in maximum sustained winds, with an average lead time of 30 h.

As the WWLLN detects only a small fraction of total lightning[18], without any information about the type of lightning, its polarity, the peak currents and so on, future improved global lightning networks will probably improve these correlations, with enhanced spatial and temporal resolutions. Even better would be the installation of lightning detectors on geostationary weather satellites that will make uniform detection efficiencies and good coverage over the ocean possible, while being sensitive to total lightning, unlike the ground global networks that detect primarily cloud-to-ground

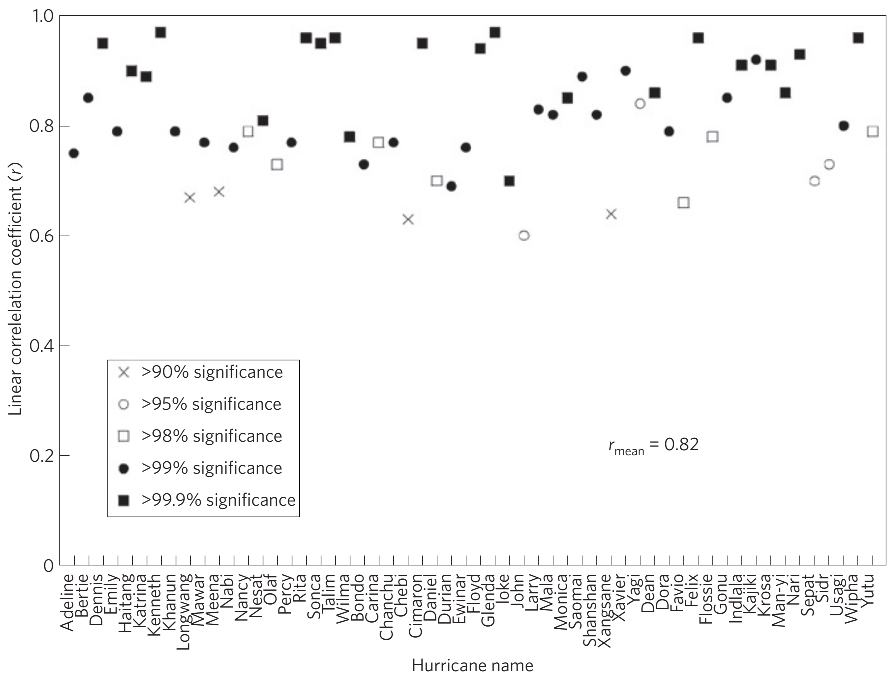

Figure 4 | The correlation coefficients (r) between maximum sustained winds and lightning activity. Each point represents one hurricane, and the symbols represent the level of statistical significance for a specific hurricane.

lightning discharges. Lightning detectors are planned on the next-generation Geostationary Operational Environmental Satellite as well as the Meteosat Third Generation satellites.

Of the 58 hurricanes analysed, only 2 showed no significant correlation between lightning and wind speed. One of these hurricanes (Ingrid 2005) showed no lightning at all, whereas the other (Kirogi 2005) had two maxima in the wind speeds and lightning, but the larger maxima in the wind speeds was correlated with the weaker peak of the lightning activity (see Supplementary information S2). Hence, only one event showed no relationship between lightning and maximum wind speed. If we consider a constant lag of 30 h between the lightning activity and the maximum winds in all hurricanes, we find that 31 out of 56 (55%) of the hurricanes show a positive correlation between lightning and wind speed, although only 19 out of 56 (34%) of the hurricanes show a statistically significant correlation for a fixed lag.

What could be the physical mechanism relating lightning activity to hurricane intensity? This is a topic for future research, although it has been suggested that the development of tropical cyclones is sensitive to the distribution and magnitude of moistening of the lower troposphere by convection[2]. The horizontal maximum sustained winds are very sensitive to changes in vertical convection that influences the rate of moistening of the lower troposphere. In addition, it has been shown that the time to maximum intensification in hurricanes depends on the intensity of the convection[2]. It has also been demonstrated that convection can generate potential vorticity anomalies that can lead to vortex intensification[19]. As lightning is an indicator of this convection, it follows that the lightning activity should precede the hurricane intensification.

This study shows the promise in using lightning data for understanding the processes related to hurricane intensification. If lightning can predict the intensification of hurricanes in advance, this provides a powerful tool for forecasters, especially in regions susceptible to considerable damage, and which lack proper early-warning capabilities. Furthermore, as lightning is directly related to thermodynamic processes that result in the release of latent heat in convective clouds, using lightning locations and intensities for data assimilation in atmospheric models[20] may markedly improve future hurricane intensity forecasts.

Methods

The hurricane data giving the location, time, maximum sustained wind speeds and minimum central pressure were obtained from the 6-h 'best track' estimations provided by the National Hurricane Center (http://www.aoml.noaa.gov/hrd/hurdat/) and the Joint Typhoon Warning Center (http://metocph.nmci.navy.mil/jtwc/best_tracks/index.html). For pressure and maximum winds, the data are available at 6-h resolution, but have been smoothed with a 24-h running average to agree with the lightning data.

The WWLLN lightning data are obtained by analysing the different time-of-arrival of the lightning pulses from a number of stations, where the location of each flash can be calculated combining at least five stations, with the condition that the time difference between pulses arriving at all five stations is less than 30 μs. This supplies a location accuracy of ~10 km (ref. 21). Owing to the data-processing limitations, together with the demand that numerous distant stations detect the same lightning flash, the network detects only a small fraction of the total lightning in a given region, with a bias to the discharges with large peak currents[22]. Furthermore, as the sensor coverage is not uniform around the globe, the detection efficiency changes for each location[18]. Moreover, because extra ground stations have been added over the past few years, the detection efficiency for a given location can also change over time. For these reasons, it is difficult to make quantitative comparisons of lightning activity between hurricanes, and between different regions in different years.

The 6-h lightning data from the WWLLN were collected and counted within a $10^\circ \times 10^\circ$ grid box centred on the eye of the hurricane. Owing to VLF propagation differences (and hence detection efficiency differences) between day and night, the lightning data were averaged with a 24-h running window (as was done for the wind data). It should be pointed out that smaller boxes were considered for the lightning data, but owing to the relatively low detection efficiency of the WWLLN, the number of lightning flashes detected drops markedly when the box is reduced to only $5^\circ \times 5^\circ$. As hurricanes often have horizontal diameters of 1,000 km, the use of a $10^\circ \times 10^\circ$ box around the eye of the storm is well justified.

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References

1. Shen, B. W. *et al.* Hurricane forecasts with a global mesoscale-resolving model: Preliminary results with Hurricane Katrina (2005). *Geophys. Res. Lett.* **33**, L13813 (2006).
2. Emanuel, K. The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. *J. Atmos. Sci.* **52**, 3960–3968 (1995).
3. Lay, E. H., Jacobson, A. R., Holzworth, R. H., Rodger, C. J. & Dowden, R. L. Local time variation in land/ocean lightning flash density as measured by the World Wide Lightning Location Network. *J. Geophys. Res.* **112**, D13111 (2007).
4. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**, 686–688 (2005).
5. Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H. R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**, 1844–1846 (2005).
6. MacGorman, D. & Rust, D. *The Electrical Nature of Storms* (Oxford Univ. Press, 1998).
7. Sherwood, S. C., Phillips, V. T. J. & Wettlaufer, J. S. Small ice crystals and the climatology of lightning. *Geophys. Res. Lett.* **33**, L05804 (2006).
8. Black, R. A., Bluestein, H. B. & Black, M. L. Unusually strong vertical motions in a Caribbean hurricane. *Mon. Weath. Rev.* **122**, 2722–2739 (1994).
9. Lyons, W. A. & Keen, C. S. Observations of lightning in convective supercells within tropical storms and hurricanes. *Mon. Weath. Rev.* **122**, 1897–1916 (1994).
10. Molinari, J., Moore, P. K., Idone, V. P., Henderson, R. W. & Saljoughy, A. B. Cloud-to-ground lightning in Hurricane Andrew. *J. Geophys. Res.* **99**, 16665–16676 (1994).
11. Samsury, C. E. & Orville, R. E. Cloud-to-ground lightning in tropical cyclones: A study of Hurricanes Hugo (1989) and Jerry (1989). *Mon. Weath. Rev.* **122**, 1887–1896 (1994).
12. Molinari, J., Moore, P. K. & Idone, V. P. Convective structure of hurricanes as revealed by lightning locations. *Mon. Weath. Rev.* **127**, 520–534 (1999).
13. Black, R. A. & Hallet, J. Electrification of the hurricane. *J. Atmos. Sci.* **56**, 2004–2028 (1999).
14. Shoa, X. M. *et al.* Katrina and Rita were lit up with lightning. *EOS* **86**, 398–399 (2005).
15. Ludlum, D. M. *Early American Hurricanes, 1492–1870* (American Meteorological Society, 1963).
16. Price, C., Yair, Y. & Asfur, M. East African lightning as a precursor of Atlantic hurricane activity. *Geophys. Res. Lett.* **34**, L09805 (2007).
17. Christian, H. J. *et al.* Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.* **108**, 4005 (2003).
18. Rodger, C. J. *et al.* Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study. *Annal. Geophys.* **24**, 3197–3214 (2006).
19. Montgomery, M. & Enagonio, J. Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model. *J. Atmos. Sci.* **55**, 3176–3207 (1998).
20. Papadopoulos, T., Chronis, G. & Anagnostou, E. N. Improving convective precipitation forecasting through assimilation of regional lightning measurements in a mesoscale model. *Mon. Weath. Rev.* **133**, 1961–1977 (2005).
21. Rodger, C. J., Brundell, J. B., Holzworth, R. H. & Lay, E. H. Growing detection efficiency of the World Wide Lightning Location Network. *Am. Inst. Phys. Conf. Proc.* (in the press).
22. Jacobson, A. R., Holzworth, R., Harlin, J., Dowden, D. & Lay, E. Performance assessment of the World Wide Lightning Location Network (WWLLN), using the Los Alamos Sferic Array (LASA) as ground truth. *J. Atm. Oceanic Tech.* **23**, 1082–1092 (2006).

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Author contributions

C.P. instigated and directed the research, analysed the hurricane data and wrote the manuscript. M.A. analysed the lightning data and was involved in the data interpretation. Y.Y. was involved in the project planning and data interpretation.

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to C.P.