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APPLICATIONS OF LIGHTNING OBSERVATIONS TO TROPICAL CYCLONE INTENSITY FORECASTING

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1. INTRODUCTION

The next generation geostationary satellite system starting with GOES-R will include a geostationary lightning mapper (GLM). The GLM will provide nearly continuous times and locations of total lightning with an accuracy of about 10 km over most of the field of view of GOES-east and –west. This coverage will include nearly all of the regions where tropical cyclones occur in the Atlantic and north Eastern Pacific. This lightning data will provide information about the convective structure in tropical cyclones and their environments.

Previous studies with ground-based lightning networks have revealed a number of interesting relationships between storm structure and the lightning distribution. Using data from the National Lightning Detection Network (NLDN) Molinari et al. (1999) have shown that the lightning density (strikes per unit area and time) tends to have a bi-modal structure as a function of radius from the storm center, with maxima near the eyewall region and in the rainband region (150-300 km radius) and a minimum in between. Their study and more recent analysis with the Long-range Lighting Detection Network (LLDN) (Squires and Businger 2008) indicate that the lightning near the storm center tends to be much more transient than that in the rainband region. Corbosiero and Molinari (2002) showed a strong relationship between the environmental shear and the azimuthal distribution of lightning, with a maximum in strikes on the down shear side of the storm.

Using the very simple argument that lightning is favored when the cloud updrafts are stronger (e.g., Black and Hallet 1999) it might be expected that increased lightning activity near the storm center would be correlated with short term intensification. However, previous studies with the NLDN and LLDN data have shown that this relationship is not straightforward, with peaks in lightning density occurring during the intensification, steady state and weakening stages of tropical cyclones. It is possible that the effect of vertical wind shear complicates the relationship with intensity changes. Also, Black and Hallet (1999) showed that the vertical electric fields in tropical cyclones are much weaker than those in continental convection suggesting that lightning outbreaks in the tropical cyclone inner core might be somewhat rare.

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In this study the relationship between lighting density and intensity changes will be investigated for a large sample of Atlantic tropical cyclone cases (2005-2007) using data from the World Wide Lightning Location Network (WWLLN). To help isolate the influences of vertical shear, the dataset is stratified into low- and high-shear regimes, where the shear is calculated from the NCEP global forecasting system (GFS) analysis fields.

2. THE WORLD WIDE LIGHTNING LOCATION NETWORK (WWLLN)

The experimental WWLLN uses a network of Very Low Frequency (VLF) detectors to estimate the time and location of global cloud to ground lightning strikes (Rodger et al. 2006). The network also detects some intracloud lightning. This data first became available in late 2003, although the number of stations has improved since that time. Because of the use of VLF and the limited station coverage (about 25 since 2006), the total lightning detection percentage is fairly low (a few percent). However, Solorzano et al. 2008 have shown that the detection rate is fairly constant over the Atlantic basin and can be used to investigate lightning structure in tropical cyclones. Also, the data since 2005 have been reprocessed with an improved algorithm. In this study, the reprocessed WWLLN data for 2005-2007 for Atlantic storms will be analyzed. Further details on the WWLLN are available from http://wwlln.net/ .

To provide a crude adjustment for the low detection rate, the annual average lightning density over the Atlantic region (0-50^{o}N, 100-0^{o}W) was calculated from the WWLLN data for each of the three years on a 0.5^o by 0.5^o latitude/longitude grid. This was then compared to the well-calibrated 0.5^o Optical Transient Detector (OTD)/Lightning Imaging Sensor (LIS) annual lightning climatology (Christian et al. 2003, Boccippio et al. 2002) over this same domain. The OTD data includes 1995-2000 and the LIS data includes 1998-2005. For this comparison, the lightning density was calculated in units of strikes per square kilometer per year. These units will be used for lightning density in the remainder of this paper.

The comparison of the WWLLN Atlantic basin lightning density to that from the OTD/LIS climatology resulted in conversion factors of 38, 24 and 23 for 2005, 2006 and 2007, respectively. This indicates that the WWLLN detection rate was 2.6%, 4.2% and 4.3% in each year. All of the WWLN lightning density data in the remainder of this paper includes the correction factors. Figure 1 shows the annual average lightning density over the Atlantic basin from the OTD/LIS climatology and from the adjusted WWLLN data from 2007. Although there are some differences, especially over Africa and the U.S., many of the general patterns over the ocean are the same in the upper and lower panels. Even with perfect data there would be some differences since the lower panel in Fig. 1 is from 2007 while the upper panel is from 1995-2005.

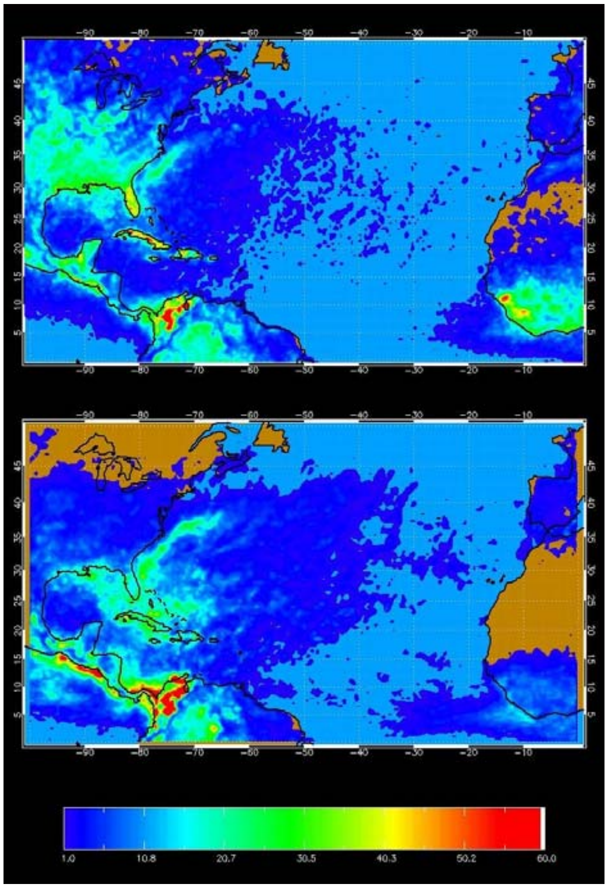

Figure 1. The annual average lightning density (strikes/km^2-year) from the OTD/LIS climatology (top) and from the 2007 WWLLN data (bottom). The WWLLN densities were adjusted by a constant factor of 23 to make the domain averaged values the same is for the OTD/LIS climatology.

3. DATA PROCESSING

The starting point for the lightning analysis is the National Hurricane Center (NHC) Atlantic tropical cyclone best track data that provides the latitude and longitude of the storm center, maximum surface winds and minimum sea-level pressure at 6 hour intervals from a post-storm analysis of all available information. The best track also includes a classification of the storm stage (tropical, sub-tropical, extra-tropical, remnant low, etc). Only those cases that were classified as tropical and subtropical were included. The sample was also restricted to cases where the storm center remained over the water for at least the next 24 h. With these restrictions, the sample includes 790 cases from 48 tropical cyclones. All intensity stages of each tropical cyclone were included (depression, tropical storm and hurricane).

The next step is to convert the lightning locations to a storm-relative cylindrical coordinate system. For each strike location, the 6 hourly best track latitudes and longitudes of the storm center were linearly interpolated to the time of the lightning strike. Then the radius and azimuth from the storm center to the strike location were calculated, where azimuth is measured counter clockwise relative to the eastward direction. Once the lightning positions were converted to cylindrical coordinates, the data was composited over 6 h intervals ending at each best track time. Then the lightning density was calculated over areas with a 100 km radial interval from 0 to 1000 km and a 45^o azimuthal interval.

To investigate the relationship with vertical shear, the lightning density dataset was combined with the developmental data for the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria et al. 2005). The SHIPS dataset includes vertical shear, sea surface temperature and many other storm-environment parameters for each 6 h best track point. The vertical shear is estimated by averaging the 850 and 200 hPa horizontal winds from the GFS model over a circular area with a radius of 500 km from the storm center, and then calculating the magnitude of the shear vector.

4. PRELIMINARY RESULTS

Figure 2 shows the azimuthal mean and standard deviation of the lightning density for the 2005-2007 Atlantic sample. The maximum density occurs at the smallest radii, with no evidence of a local minimum in the 100-300 km region. This is in contrast to previous studies that showed a local minimum for individual storms. The lack of a minimum is probably due to compositing data from many storms. The eyewall region is generally less than 100 km from the storm center, but the rainband locations are much more variable, and so the local maxima average out when many storms are combined.

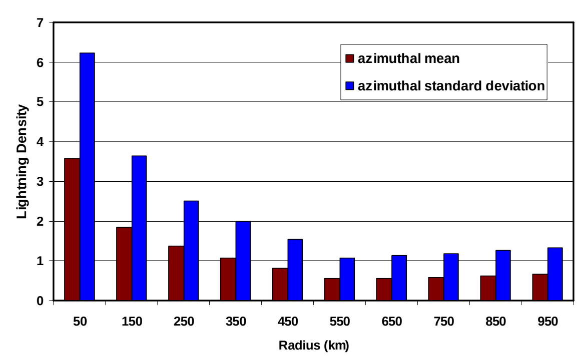

Figure 2. The azimuthal mean and standard deviation of the lightning density (strikes/km^2-year) as a function of radius for the 790 Atlantic tropical cyclone cases from

2005-2007. The x-axis labels are the centers of each 100 km radial interval.

The standard deviations in Fig. 2 are about twice the mean as most radii. This is qualitatively consistent with the results of Corbosiero and Molinari (2002), which showed a very large asymmetry in many storms, primarily with an azimuthal wavenumber one structure.

To illustrate the variability of the inner lightning activity, Fig. 3 shows a time series of the 0-100 km azimuthally averaged lightning density for all 790 cases. This figure shows that the inner core lightning activity is highly transient, consistent with previous studies. The vertical axis was restricted to 100 for clarity, although one of the points had a density of 239 (tropical storm Noel at 06 UTC on 01 Nov 2007).

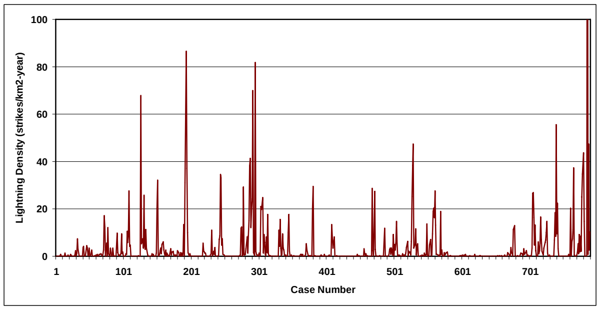

Figure 3. Time series of 0-100 km azimuthally averaged lightning density from all 790 cases. The data from each of the 48 storms are plotted consecutively.

To get a rough idea of the types of storms associated with large inner core lightning densities, Table 1 shows the cases with the 10 highest density values. All of the storms in Table 1 were at tropical storm intensity (max winds between 34 and 63 kt), and only three intensified in the following 24 hours. Philippe, Ingrid and Ernesto were weakening due to interaction with high shear, and Noel was beginning an extra-tropical transition. Only Maria was beginning a period of rapid strengthening. These results indicate that the vertical shear needs to be taken into account to better understand the relationship between lightning activity and intensity changes.

Table 1. The cases with the 10 highest inner core lightning density values.

Name	Date/Time	Density	Max Wind (kt)	t+24 h Max Wind
Noel	110107/06	239	50	70
Maria	090305/12	86	50	65
Philippe	092205/06	82	35	35
Philippe	092105/12	70	45	35
Irene	080805/06	68	35	30
Ingrid	091507/00	56	35	30
Ernesto	082606/18	47	55	45
Noel	110107/18	47	55	70
Noel	102907/00	44	50	45
Philippe	092005/12	41	60	45

To quantitatively determine the relationship between lightning density and intensity changes, the lighting density at each 100 km radial interval out to 600 km was correlated with the change in maximum winds in the next 24, 36 and 48 h. The correlation coefficients are shown in Fig. 4. The correlation between the inner core density and 24 h intensity change is weakly negative, which is not surprising 7 of the 10 cases with the highest density weakened in the following 24 h. However, the correlation coefficient was not statistically significant at the 95% level. There were statistically significant positive correlations for the densities in the intervals centered 150, 250 and 350 km, suggesting that lightning activity in the rainband region is related to subsequent intensification.

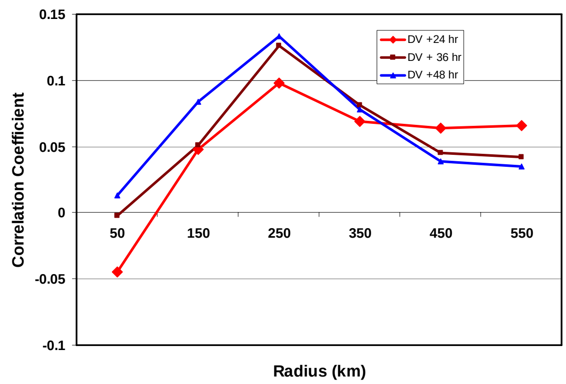

Figure 4. The correlation coefficient for the correlation of the lightning density at each 100 km radial interval from 0 to 600 km versus the change in the maximum winds in the subsequent 24, 36 and 48 h. The coefficients were statistically significant for the intervals centered at 250 km for the 24 h change, centered at 250 and 350 km for the 36 h change and at 150, 250 and 350 km for the 48 h change.

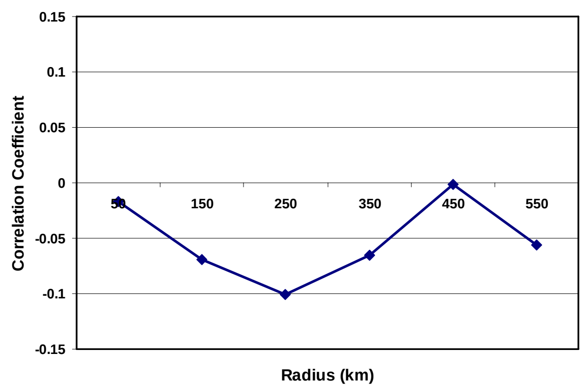

Figure 5. The correlation coefficient for the correlation of the environmental vertical shear and the lightning density as a function of radius. The coefficient for the radial interval centered at 250 km was statistically significant at the 95% level.

As described previously, there is a relationship between lightning activity and vertical shear. To further investigate this relationship, the vertical shear was correlated with the azimuthally averaged lightning density. Figure 5 shows that the correlation is negative at all radii out to 600 km, with the strongest correlation near 250 km. This indicates that the lightning density decreases as vertical shear increases. This result was somewhat surprising, especially in the storm environment, since environmental shear can sometimes increase convective vigor.

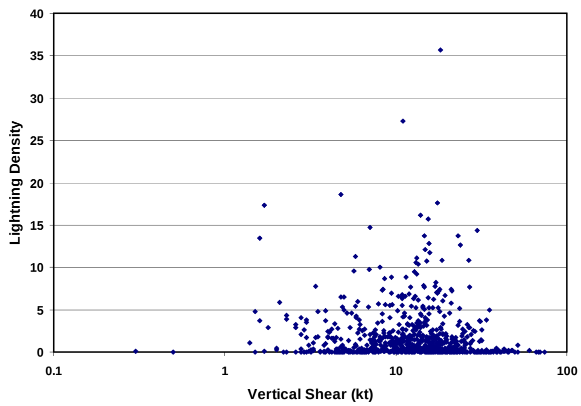

Figure 6. Scatter plot of 0-300 km lightning density as a function of vertical shear. Note that the x-axis has a log scale.

The above correlation results are a little misleading because there appears to be conflicting relationships between lightning density and shear, as can be seen in Fig. 6. This figure shows a scatter plot of the lightning density over most of the inner core and rainband regions (0-300 km) as a function of the shear. For low shear values (up to about 15 kt) the lightning density generally increases with increasing shear. However, for very large shear values, the lightning density appears to decrease. For the total sample, the correlation is weakly negative as was shown in Fig. 5. A possible explanation for this relationship is that as long as the shear does not become too large, the convective activity is enhanced. There is considerable evidence that the convection becomes more asymmetric as the shear increases (e.g. Zehr 2003), and the updraft speeds might be enhanced compared to those in the more organized symmetric convection that occurs in very low shear environments. However, if the vertical shear becomes too large, the tropical cyclone circulation itself is disrupted, and sometimes dissipates completely, as was the case for some of the storms listed in Table 1. Figure 7 confirms the variable relationship between shear and lightning density, with the maximum occurring for shear values between 12 and 16 kt. Figure 7 also shows a local maximum for the lowest shear values.

As a preliminary method to account for the effect of vertical shear, the dataset was divided into low- and high-shear regimes, where the median shear value (12.8 kt) was used to divide the cases. Figure 8 shows the correlation coefficients for the low and high shear regimes. Comparing Fig. 8 with Fig. 4 shows that the stratification by shear increases the correlation coefficient at the inner radii for the low shear regime and at outer radii for the high shear regime. A general rule in the SHIPS intensity model is that useful forecast information is obtained from predictors that explain more than 1% of the variance of the observed intensity changes (correlation coefficient > 0.1). Figure 8 shows that the lightning density satisfies this condition for several radii, and thus may be useful for improving statistical intensity forecasts.

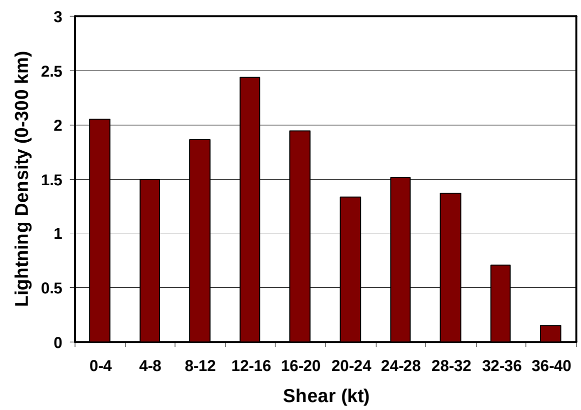

Figure 7. The 0-300 km average lightning density distribution as a function of vertical shear.

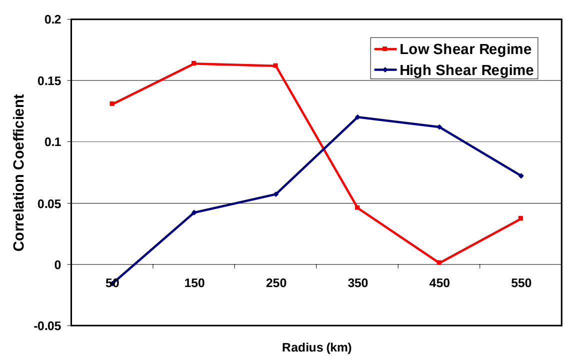

Figure 8. The correlation coefficient for the correlation of the lightning density in each 100 km radial interval from 0 to 600 km versus the change in the maximum winds in the subsequent 48 h. The coefficients were statistically significant for the intervals centered at 50, 150 and 250 km for the low shear regime, and centered at 350 and 450 km for high shear regime.

One of the most difficult aspects of intensity forecasting is the ability to prediction rapid intensity (RI) changes. As described by Kaplan et al. (2009), RI is often defined as a tropical cyclone where the maximum surface winds increase by 30 kt or more in 24 h. This roughly corresponds to the 95th percentile of the Atlantic intensity change distribution. Because of the difficulty in predicting RI, the only technique with even modest skill is the statistically based RI Index (Kaplan et al. 2009).

The RI Index uses a discriminant analysis technique using a subset of the input to the SHIPS model. The input variables are the vertical shear, 200 hPa divergence, maximum potential intensity (estimated from the sea surface temperature), intensity change in the previous 12 h, low-level moisture, oceanic heat content and predictors from GOES imagery. The ability of a predictor to discriminate between RI and non-RI cases depends on the difference in the mean of the predictor for the RI and non-RI cases. To get an idea of the utility of the lightning activity to help predict RI, the mean lighting density was calculated for the RI and non-RI cases for the low and high shear sub-samples. Of the 790 cases in the total lightning sample, 66 were RI cases, which is a slightly higher percentage (8.4%) than the 5% long term mean. As expected, most of the RI cases (55 of 66) were in the low shear sub-sample.

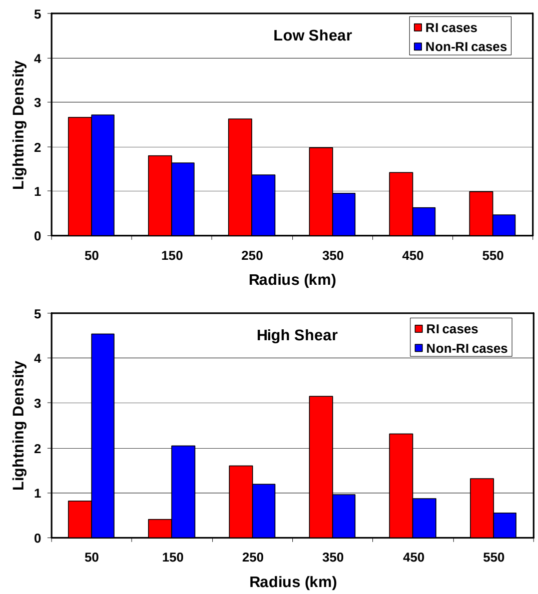

Figure 9. The average lightning density for the RI and non-RI cases as a function of radius for the low shear sample (top) and high shear sample (bottom).

Figure 9 shows the lightning density as a function of radius for the RI and non-RI cases for the low and high shear regimes. For the low shear cases, the RI and non-RI densities are about the same for radii from 0 to 200 km. However, for larger radii, the lightning density is much greater for the RI cases, indicating that it may be useful for prediction. For the high shear cases the lightning density at the inner radii is much higher for the non-RI cases. This is probably related to the cases like many of those in Table 10 that are undergoing extratropical transition or have shear-enhanced convection. However, at the larger radii (200-600 km), the RI cases have higher lightning densities, similar to the low shear cases. Thus, the lightning densities at the outer radii have the potential to improve the prediction of RI.

5. CONCLUSIONS AND FUTURE PLANS

The relationship between lightning activity and Atlantic tropical cyclone intensity change (measured by the maximum sustained surface wind) was examined using the World Wide Lightning Location Network (WWLLN) data. The WWLLN data were composited over 6 h intervals for all Atlantic tropical cyclones from 2005-2007. The intensity of each case was obtained from the NHC best track, and the environmental vertical wind shear (850-200 hPa) was determined using the database from the operational SHIPS intensity model. After restricting the cases to those where the storm center remained over the water for the following 24 h, the sample includes 790 cases from 48 tropical cyclones. The lightning density was calculated in a storm relative cylindrical coordinate system over areas with a radial increment of 100 km and an azimuthal increment of 45^{o}.

Preliminary results show that the lightning density decreases monotonically with radius out to 1000 km and the azimuthal standard deviation is about twice the mean. The local minimum in lightning density between the inner core and the rainband region identified in previous studies was not observed in the composite, probably because the rainband location is highly variable and the local maxima in individual cases averages out. Similar to previous studies, the inner core (0-100 km) lightning density is very transient. The 10 cases with the highest inner core lightning density were all of tropical storm intensity, and only 3 intensified in the following 24 h. Many of these cases were interacting with vertical wind shear or were beginning extratropical transition. This result indicates that the vertical shear needs to be taken into account when examining the relationship between lightning and tropical cyclone intensity change.

A correlation of the lightning density and the intensity change in the following 24, 36 and 48 h showed the correlation was weakly negative or near zero for the inner core, but was not statistically significant at the 95% level. However, statistically significant positive correlations between lightning density and intensity changes were found at radii between 100 and 400 km.

The relationship between lightning density (0-300 km average) and vertical shear was found to be nonlinear. For shear values between about 0 and 15 kt, the lightning density generally increased with increasing shear. For shear values greater than about 15 kt, the lightning density decreased with increasing shear. Thus, vertical shear near 15 kt appears to be optimal for tropical cyclone lightning activity. When the sample was stratified into low and high shear regimes, the correlation between lightning density and intensity change increased, and the correlation with the inner core lightning density became positive and statistically significant for the low shear sub-sample.

The relationship between lightning activity and rapid intensity change (maximum wind increase of 30 kt or more in the following 24 h) was also examined. It was found that the cases without RI had the same (low shear sample) or greater (high shear sample) inner core lightning than the RI cases. However, there was considerably greater lightning density at larger radii (200-600 km) for the RI cases in both the low and high shear regimes. These results suggest that lightning data may be useful for tropical cyclone intensity prediction, including rapid intensification.

This preliminary analysis will be expanded by adding the WWLLN data from the 2008 hurricane season. The relationships will also be examined for storms in eastern North Pacific tropical cyclone basin and compared with those in the Atlantic. The initial analysis focused on the azimuthally averaged lightning structure. In future work, the asymmetric structure will also be considered. Additional environmental parameters that are available from the SHIPS model database, including the distance to land and sea surface temperature will also be examined. In preparation for GOES-R, statistical intensity prediction algorithms that include the lightning input will also be tested. Finally, the detection efficiency of WWLLN may have a day-night difference. The dataset will be examined to determine if improved statistical relationships can be obtained by accounting for the diurnal variability.

ACKNOWLEDGMENTS

The research was partially supported by the NESDIS GOES-R Risk Reduction Project. The views, opinions, and findings in this report are those of the authors, and should not be construed as an official NOAA and or U.S. Government position, policy, or decision.

REFERENCES

Black., R.A., and J. Hallet, 1999: Electrification in hurricanes. *J. Atmos. Sci.*, **56**, 2004-2028.

Boccippio, D.J., W.J. Koshak, and R.J. Blakeslee, 2002: Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor. Part I: Predicted diurnal variability. J. Atmos. Ocean. Tech., 19, 1318-1332.

Christian, Hugh J., Richard J. Blakeslee, Dennis J. Boccippio, William L. Boeck, Dennis E. Buechler, Kevin T. Driscoll, Steven J. Goodman, John M. Hall, William J. Koshak, Douglas M. Mach, and Michael F. Stewart, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. J. Geophys. Res., 108(D1), 4004, doi:10.1029/2002JD002347, 2003.

Corbosiero, K.L., and J. Molinari, 2002: The effects of vertical wind shear on the distribution of convection in tropical cyclones. *Mon. Wea. Rev.*, **130**, 2110-2123.

DeMaria, M., M. Mainelli, L.K. Shay, J.A. Knaff, and J. Kaplan, 2005: Further Improvements in the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

Kaplan, J., M. DeMaria, and J.A. Knaff, 2009: A revised tropical cyclone rapid intensification index for the Atlantic and Eastern Pacific basins. Submitted to *Wea. Forecasting.*

Molinari, J., P. Moore, and V. Idone, 1999: Convective structure of hurricanes revealed by lightning locations. *Mon. Wea. Rev*., **127**, 520-534.

Rodger, C.J., S. Werner, J.B. Brundell, E.H. Lay, N.R. Thompson, R.H. Holzworth, and R.L. Dowden, 2006: Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): initial case study. *Ann. Geophys.,* **24**, 3197-3214.

Solorzano, N.N., J.N. Thomas, and R.H. Holzworth, 2008: Global studies of tropical cyclones using the World Wide Lightning Location Network. Extended Abstract, *AMS Third Conf. on the Meteorological Applications of Lightning Data*, Jan. 21-24, 2008, New Orleans, LA, 5 pp. [Available from http://ams.confex.com/ams/88Annual/techprogram/paper_134367.htm]

Squires, K., and S. Businger, 2008: The morphology of eyewall lightning outbreaks in two category 5 hurricanes. *Mon. Wea. Rev.* **136**, 1706-1726.

Zehr, R.M., 2003: Environmental vertical wind shear with Hurricane Bertha (1996), 2003: *Wea. Forecasting*, **18**, 345-356.