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Variability in tornado frequency associated with U.S. landfalling tropical cyclones

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[1] A statistical model for tornado frequency from Gulf of Mexico landfalling tropical cyclones (TCs) is developed using TC size, intensity, recurvature, and mid-level specific humidity data. New datasets are assembled for tornado frequency and for TC size at landfall as measured by the radius of outer closed isobar and distance of tornado from the TC center. Owing to systematic undercounting of tornadoes, the model is used to reconstruct the TC tornado climatology back to 1948, and further back to 1920 using a modified model that does not include mid-level specific humidity. Relative to the previous active period for Gulf TC landfalls of 1948–1964, the active period since 1995 has seen a statistically significant increase (95% level) in median TC tornadoes and in the frequency of large TC tornado outbreaks. These changes are linked to an increase in the median size and frequency of large Gulf landfalling TCs. **Citation:** Belanger, J. I., J. A. Curry, and C. D. Hoyos (2009), Variability in tornado frequency associated with U.S. landfalling tropical cyclones, *Geophys. Res. Lett.*, *36*, L17805, doi:10.1029/2009GL040013.

1. Introduction

[2] An often-overlooked impact from U.S. landfalling tropical cyclones (TCs) is that most TCs spawn tornadoes [*Gentry*, 1983]. Although a majority of these tornadoes are weak, there have been cases when significant death and destruction has resulted. Hurricane Ivan in 2004 generated an outbreak of 117 tornadoes that resulted in 47 injuries, seven deaths, and $96.9 million in property damage [*National Climatic Data Center*, 2009]. For the period 1970–1999, *Rappaport* [2000] found that TC tornadoes were responsible for 4% of all fatalities from U.S. landfalling TCs.

[3] Most TC tornadoes form in the outer rainbands typically 200 to 400 kilometers from the TC center with some tornadoes occurring in the inner core and eye wall [*McCaul*, 1991]. The right-front quadrant (RFQ) of a TC is typically the most favorable area for tornado formation since this region usually has the highest Bulk Richardson Number shear and deepest convection [*McCaul*, 1991; *Verbout et al.*, 2007]. Hence, TCs that make landfall from the Gulf of Mexico (where the RFQ is exposed over land for a longer time) are more likely to produce tornadoes in the continental U.S. than Atlantic landfalling TCs that strike the U.S. coastline obliquely.

[4] Recently, *Verbout et al.* [2007] provided statistical evidence indicating that TC recurvature is a better discriminating variable for a TC tornado outbreak than simply landfall location alone. Using synoptic composites of TCs that recurve versus those that do not, the authors showed that mid-latitude troughs provide additional deep-layer and low-layer vertical wind shear to recurving TCs, which favors mesocylogenesis and tornadogenesis, respectively. Other variables that have been identified in the literature to increase the propensity of a tornado outbreak include landfalling TCs with large horizontal size and TCs with significant mid-level dry air intrusions [*Hill et al.*, 1966; *McCaul*, 1991; *Curtis*, 2004].

[5] Since the identification of a TC tornado is determined by a variety of sources, e.g., Doppler radar, damage surveys, and eyewitness accounts, the climatology of TC tornado reports has a large undercounting bias especially prior to the mid-1990s. To avoid artificially correcting the inhomogeneous TC tornado record, a statistical model is developed for the TC tornado frequency produced by a landfalling TC using a set of *a priori* predictors for TC tornado formation including: TC size, intensity, mid-level specific humidity gradient, and TC recurvature. The statistical model is trained on the period 1998–2007 since the national network of NEXRAD (WSR-88D) weather radars was completed in 1997 and reflects a period of near homogeneous observational detection for tornadoes [*Simmons and Sutter*, 2005]. The utility of this model for TC tornadoes lies in its capability as a real-time, forecast tool as well as in reconstructing the climatology of TC tornadoes.

2. Data

[6] The HURricane DATabase (HURDAT) for the North Atlantic was used to determine the TCs that made landfall in the United States from 1920 to 2008 [*Neumann et al.*, 1999]. Maximum TC intensity at landfall was taken from HURDAT using the maximum 1-minute sustained wind speed. Based on HURDAT tracks for U.S. landfalling TCs, these systems were stratified into two groups: Gulf TCs and Atlantic TCs. For TCs with multiple landfalls such as Hurricane Katrina of 2005, these TCs were considered Gulf landfalls if the system made landfall at some point along the Gulf coast. Here, TC tornado statistics are examined for Gulf TC landfalls only, which account for 85% of all reported TC tornadoes [e.g., *McCaul*, 1991]. Using HURDAT and the Gulf TC landfall dataset, TC recurvature is calculated as the difference in 12–hour averaged storm heading at landfall from the 12–hour averaged storm heading at the last tropical advisory or the last tropical advisory while over the U.S. mainland, whichever occurs first.

[7] The National Climatic Data Center's (NCDC) Storm Events Database is used to identify all tornadoes that

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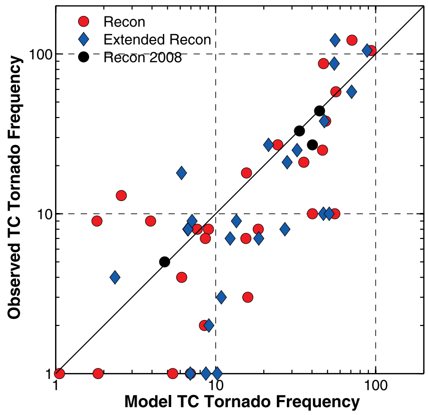

Figure 1. Log-log scatter plot of observed versus modeled tornado frequency per Gulf TC from the *Recon* (red circles) and *Extended Recon* (blue diamonds) models for the period 1998–2007. Black circles denote the observed versus modeled TC tornado frequency from *Recon* for 2008.

occurred in the U.S. prior to and after a TC's landfall during the period 1950–2008. Since tornado entries in the Storm Events Database are sometimes divided into multiple segments, tornado listings were compared to one another to ensure that no tornado was counted more than once. A TC tornado is defined to be any tornado that formed within 650 km of the center of circulation before the last tropical advisory was issued for a TC.

[8] A key predictor for the number of TC tornadoes is the horizontal size of the TC at landfall. Measures of TC size include: radius of the eye, radius of maximum winds, radius of hurricane force winds, radius of gale force winds, and radius of outer closed isobar [*Kimball and Mulekar*, 2004]. In this analysis, the radius of the outer closed isobar (ROCI) is used as a proxy for TC size, since ROCI is more closely related to the domain over which TC tornadoes may occur and since the ROCI analysis can be extended into the pre-satellite era. Details about the ROCI database are found in the auxiliary material.[1]

[9] The final predictor variable is the specific humidity gradient at 500 hPa (within 5° from the TC center) obtained from the NCEP/NCAR Reanalysis I dataset [*Kalnay et al.*, 1996]. It is hypothesized that the 500 hPa specific humidity gradient represents a measure for mid-level dry air entrainment. Physically, dry air intrusions in a TC's outer-rainbands induce convective downdrafts that then establish localized baroclinic boundaries in an otherwise moist, lower troposphere. These cold pools, which may be a source of horizontal vorticity [*McCaul and Weisman*, 1996], act in conjunction with enhanced low-level wind shear within the RFQ of a landfalling TC to increase the probability of a tornado outbreak [*Gentry*, 1983; *McCaul*, 1991; *Curtis*, 2004].

3. Methodology

[10] A statistical model for the TC tornado frequency per Gulf TC landfall is developed from the following equation:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + \varepsilon \qquad (1)$$

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2009gl040013. Other auxiliary material files are in the HTML.

where y is TC tornado frequency and x_1, x_2, x_3, and x_4 are ROCI, maximum wind speed at 10 m, 500 hPa specific humidity gradient, and TC recurvature, respectively. Integrated and scaled probability density functions for each predictor and TC tornado frequency were used to determine the power of each predictor variable (Figures S1a, S1b, S1c, and S1d). In equation (1), the ε term describes the model residuals, and the α_s terms are regression coefficients that were determined from the following operation. If the model residuals are ignored, then equation (1) may be written:

$$\mathbf{y}_n = \mathbf{X}\mathbf{A}_s \qquad (2)$$

This equation may be solved for the regression coefficients vector A_s:

$$\mathbf{A_s} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y_n} \qquad (3)$$

Two separate multiple regression models are developed: *Recon*, which employs all four predictor variables, and *Extended Recon*, which uses TC intensity, size, and recurvature as predictor variables. Both models are trained on the 1998–2007 period of observed TC tornado data and *Recon* (*Extended Recon*) is used to reconstruct the TC tornado climatology back to 1948 (1920). Statistical significance tests are used to assess whether changes in the reconstructed TC tornado data set are due to random chance. The 95% confidence level is determined by bootstrapping the *Recon* and *Extended Recon* model residuals for the period 1998–2007.

4. Assessment of Statistical Models

[11] To evaluate the *Recon* and *Extended Recon* models, Figure 1 shows a scatter plot of the observed and modeled TC tornado frequency for each Gulf landfalling TC during the period 1998–2007. Overall, the *Recon* and *Extended Recon* models explain 70% and 62%, respectively, of the total variance in the number of observed tornadoes per Gulf TC landfall from 1998 to 2008 (Table 1). Both models have the largest errors for TCs with the lowest and highest number of observed TC tornadoes, which is characteristic of least square statistic methods [*Wunsch*, 2006]. In the *Recon* model, the ROCI predictor explains the most variance in the observed number of tornadoes per Gulf TC landfall at 43%, followed by the 500 hPa specific humidity gradient (17%), maximum wind speed (8%), and TC recurvature (2%). For the *Extended Recon* model, ROCI explains 43% of the variance in the observed frequency of TC tornadoes with TC recurvature and TC intensity accounting for 11% and 8%, respectively. For the annual

Table 1. Performance of the *Recon* and *Extended Recon* Models in Terms of the Correlation Coefficient and Root Mean Square (RMS) Error for the 1998–2008 Period

1998–2008	Correlation (TC)	RMS Error (TC)	Correlation (Annual)	RMS Error (Annual)
Recon	0.84	16	0.95	26
Extended Recon	0.79	18	0.92	30

Table 2. TC Tornado Statistics for the Five Gulf Landfalling TCs From the 2008 Hurricane Season

Tornadoes 2008 Season	Observed	Recon	Extended Recon
HR Dolly	5	5	0
TS Edouard	0	0	0
TS Fay	44	45	18
HR Gustav	27	40	44
HR Ike	33	33	36
Total Tornadoes	109	123	98

number of TC tornadoes during the 1998–2008 period, both models performed very well in capturing the seasonal total of Gulf TC tornadoes as the variance explained by the *Recon* and *Extended Recon* models is 90% and 85%, respectively.

[12] An independent evaluation of both models was undertaken by applying them to the 2008 Atlantic hurricane season, which featured a record six consecutive TC landfalls on the U.S. mainland, five of which were Gulf TCs (Table 2). For four out of the five Gulf landfalling TCs from 2008, the *Recon* model captured the magnitude of the observed TC tornado outbreak that resulted post-landfall. Given the large mid-level specific humidity gradient at landfall for Tropical Storm Fay, *Recon* predicted an outbreak of 45 TC tornadoes would occur in comparison to a reported 44 TC tornadoes that ensued as Fay slowly moved inland. The accuracy in the TC tornado forecast for HR Dolly is attributed to the TC recurvature predictor as Dolly did not recurve to the northwest post-landfall but maintained a west-northwest storm heading. Overall, the *Recon* and *Extended Recon* models predicted a seasonal total of 123 and 98 TC tornadoes, respectively, in comparison to an observed value of 109 TC tornadoes.

5. Annual Variability of TC Tornadoes

[13] Due to a large undercounting bias throughout the historical record, the observed TC tornado dataset does not allow for an assessment of the interannual variability of TC tornado frequency due to Gulf landfalling TCs. Instead, examining the filtered seasonal reconstructions from *Recon* and *Extended Recon* reveals that the early 1930s and 1940s were likely associated with enhanced TC tornadic activity and the 1970s and early 1980s with reduced activity (Figure 2). The time period since 1995 has been marked by a high seasonal number of TC tornadoes, with 2004 and 2005 having reached unprecedented levels for annual TC tornado frequency according to the 95% confidence interval from the *Recon* and *Extended Recon* model reconstructions.

[14] Both the decadal scale fluctuations in seasonal Gulf TC landfalls and TC tornadoes reflect the same multi-decadal pattern of variability associated with the Atlantic Multidecadal Oscillation (AMO) [*Kerr*, 2000] with warm phases of the AMO in 1926–1964 and 1995–2008 corresponding to active periods for Gulf landfalling TCs. However, relative to the previous periods of peak Gulf TC activity, the number of Gulf TC landfalls during the period 1995–2008 is not unusual. Hence, the recent elevation of TC tornadic activity cannot be attributed to an increase in the number of landfalling TCs from the Gulf of Mexico.

[15] Since the variability in Gulf TC landfall frequency does not explain the high annual number of TC tornadoes in recent years, this result suggests that the number of tornadoes per TC landfall has changed between the two periods for Gulf landfalling TCs. To test this hypothesis, Figure 3a provides the probability density functions (PDFs) for the number of TC tornadoes per Gulf TC landfall from the *Recon* model for the two active periods, 1948–1964 (early active) and 1995–2008 (current active). The PDF for the current active period has broadened from the early active period and has seen a statistically significant increase (95% confidence level) in the frequency of large TC tornado outbreaks. In addition, the median number of tornadoes per Gulf TC landfall has significantly increased (95% confidence level) from 6 to 15 TC tornadoes.

[16] Since these changes in the PDFs for TC tornado frequency were determined using the *Recon* model, the analysis focuses on determining which predictors are responsible for these differences. The only variable that shows a statistically significant increase (95% confidence level) in the median and extreme values and makes an important contribution to the TC tornado predictions in the *Recon* model is ROCI (cf. Figures 3b, S2a, S2b, S2c). The median ROCI has increased from 195 km to 263 km between the two active periods. In addition, the frequency of large TCs (ROCI > 540 km) has significantly increased (95% confidence level) from the early active period. This change in the ROCI distribution is restricted to the years after 1995 as the PDF for Gulf landfalling TCs for the 1965–1994 period (not shown) exhibits a statistically similar structure to the 1948–1964 period in terms of median ROCI (205 km) and a lack of extremely large TC landfalls.

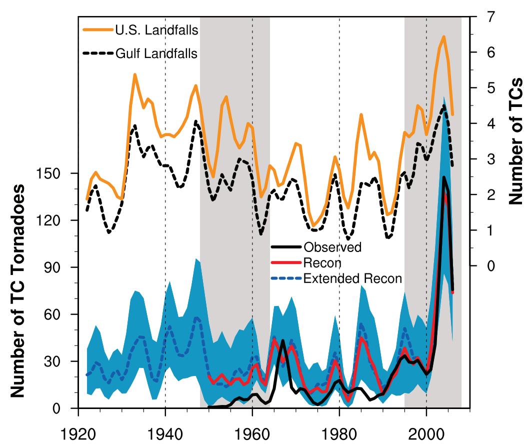

Figure 2. (top) Time series of the number of U.S. landfalling TCs (Gulf landfalling TCs) from 1920 to 2008 in orange (dashed black). (bottom) Time series of the annual number of TC tornadoes from *Recon* and *Extended Recon* in dashed red and blue for the periods 1948–2008 and 1920–2008, respectively, along with the observed TC tornadoes in black from 1950 to 2008. All time series have been filtered twice with a 1-2-1 filter. The 95% confidence interval is shaded in light blue, which for 1948–2008 (1920–1947) is determined by bootstrapping the *Recon* (*Extended Recon*) model residuals for the period 1998–2007. Gray boxes represent the two active periods for Gulf TCs: early active (1948–1964) and current active (1995–2008).

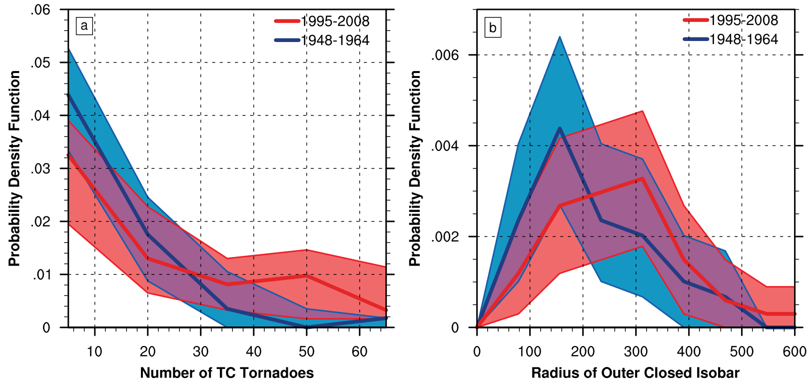

Figure 3. (a) Probability density functions of TC tornado frequency per Gulf TC landfall for the early active period (1948–1964) in thick blue and current active period (1995–2008) in thick red using the *Recon* model. The shaded regions of light blue (light red) indicate the 95% confidence interval of the early active (present active) PDF. Confidence interval determined by bootstrapping the *Recon* model residuals for the period 1998–2007. (b) Similar to Figure 3a, except for the radius of outer closed isobar (ROCI).

[17] To address whether the change in Gulf TC size is due to the methodology in determining a tropical cyclone's ROCI, another TC size metric was used which is the distance of tornado (DOT) from TC center (Figure S3). Consistent with the observed changes in the PDFs of ROCI, DOT observations exhibit a statistically significant increase (99% confidence level) in the median distance of tornado formation (289 km vs. 336 km) and in an increased frequency of TC tornadoes occurring at large distances from the TC center. These changes in DOT observations are physically consistent only if the size of Gulf TCs at landfall has increased between the two active periods.

6. Conclusions

[18] A new data set has been assembled for TC tornadoes associated with Gulf landfalling TCs that is used to develop a statistical model for TC tornadoes as a function of TC intensity, horizontal size, mid-tropospheric specific humidity gradient at landfall, and TC recurvature. Two forms of the statistical model are developed including *Recon*, which includes all four predictors, and *Extended Recon*, which does not include specific humidity data. For the period 1998–2008, the *Recon* (*Extended Recon)* model explains 70% (62%) of the observed TC tornado frequency per Gulf TC landfall and 90% (85%) of the seasonal number of TC tornadoes. Applying the models to the 2008 Hurricane Season, the *Recon* and *Extended Recon* models predicted an annual total of 123 and 98 TC tornadoes, respectively, in comparison to 109 reported TC tornadoes.

[19] In addition to its utility as a prediction tool for individual TCs, the *Recon* and *Extended Recon* models are used to develop a synthetic climatology of historical TC tornadoes back to 1948 and 1920, respectively. The reconstructions from the models along with the 95% confidence interval show that the high number of TC tornadoes during 2004 and 2005 is unprecedented in the historical record back to 1920. Also, the synthetic climatology of TC tornadoes clearly reflects the decadal scale variations in Gulf landfalling TC activity associated with the AMO. A comparison of the current warm phase of the AMO (1995–2008) with the previous warm phase period from 1948–1964 shows that the median number of TC tornadoes per Gulf TC landfall according to the *Recon* model has significantly increased (95% confidence level) from 6 to 15 TC tornadoes along with an increased frequency of large TC tornado outbreaks. PDFs of Gulf TC size show a 35% increase in median Gulf TC size along with an increased frequency of large Gulf landfalling TCs. These changes in TC size explain why the *Recon* model projects a significant increase in the median and extreme frequency of TC tornado events between the two active periods of Gulf TCs.

[20] The increase in TC size during the current active phase of North Atlantic TC activity raises the possibility that climate variability is modulating the change in Gulf TC size. Recent research by *Hill and Lackmann* [2009] has shown that environmental relative humidity places an important constraint on the horizontal extent of a developing TC. We hypothesize that increasing environmental moisture in the lower troposphere over a tropical cyclone's lifetime is responsible for the observed increase in median and/or extreme frequency of large Gulf TCs. Additional research on TC size including environmental influences and internal dynamics is clearly warranted for understanding and assessing their landfall impacts in the United States.

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