# Hurricane intensification detected by continuously monitoring tall precipitation in the eyewall

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[1] Previous studies show that a single observation of tall precipitation in a hurricane's eyewall is often associated with intensification of that hurricane's surface wind. Using WSR-88D radars, we show that repeated observation of precipitation height provides even more information about wind intensification. If the frequency of tall precipitation in the eyewall is at least 33% (1 in 3 radar volume scans), we find an 82% chance of wind intensification. If this threshold is not met, the chance of wind intensification drops from 82% to just 17%. We show that the WSR-88D height measurements are reasonable using the TRMM Precipitation Radar. **Citation:** Kelley, O. A., J. Stout, and J. B. Halverson (2005), Hurricane intensification detected by continuously monitoring tall precipitation in the eyewall, *Geophys. Res. Lett.*, *32*, L20819, doi:10.1029/2005GL023583.

## 1. Introduction

[2] Previous studies establish an empirical relationship between tall precipitation in the eyewall and hurricane wind intensification [*Kelley et al.*, 2004; *Simpson et al.*, 1998]. However, debate continues on a physical mechanism to explain this association and about whether the tall precipitation or the wind increase occurs first. *Smith* [2000] suggests that the wind increase may occur first, which could increase oceanic heat and moisture flux followed by more vigorous eyewall convection. Alternatively, *Heymsfield et al.* [2001] and *Rodgers et al.* [2000] suggest that vigorous eyewall precipitation may occur first, followed by latent heat release, forced subsidence in the eye, warming, lowered eye surface pressure, and finally, increased surface wind in the eyewall to maintain gradient wind balance.

[3] We seek to better quantify the empirical relationship between tall precipitation and hurricane intensification. In particular, we study the frequency of tall precipitation in the eyewall.

[4] To investigate this topic, we use the Weather Surveillance Radar – 1988 Doppler (WSR-88D). The WSR-88Ds generally observe a hurricane's eyewall every 4 to 6 minutes during several hours when the hurricane nears the United States coast.

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[5] Previous studies have shown that the coarse vertical resolution of a WSR-88D radar limits its usefulness for some applications [*Howard et al.*, 1997; *Brown et al.*, 2000]. In 80% of the volume scans that we examine, the vertical distance between radar sweeps is 2.2 to 4.3 km at a 15 km altitude in the hurricane's eye. In these volume scans, the eye is 100 to 290 km away from the radar.

[6] To explore whether the WSR-88D height observations are precise enough for our study, we compare them to observations from the Precipitation Radar on the Tropical Rainfall Measuring Mission (TRMM) satellite. The Precipitation Radar has a 0.25 km vertical resolution at nadir [*Kozu et al.*, 2001]. More specifically, we examine four eyewalls that were simultaneously observed by the TRMM Precipitation Radar and a WSR-88D. We find that the satellite and ground radars are in reasonable agreement with respect to the horizontal location and horizontal area of tall cells in the eyewall [see also *Heymsfield et al.*, 2000].

[7] Using WSR-88D precipitation height, we develop a threshold for detecting hurricane wind intensification. This threshold works when other techniques do not. Hurricanes too far away from a radar for doppler wind measurements may be close enough to the radar to estimate precipitation height. Precipitation cells in the eyewall are often too close together to estimate wind by tracking individual cells, but that does not interfere with estimating precipitation height.

## 2. Eyewall Precipitation and Wind

[8] We use a radar volume scan only if it sees the eyewall entirely over ocean, not over land. We establish this requirement because hurricane intensification is rare over land even though eyewall precipitation can be triggered when the eyewall encounters mountains or land/ocean gradients in surface friction and thermodynamic variables [*Geerts et al.*, 2000]. Before the eyewall reaches land, the same factors can trigger precipitation outside the eyewall. Our study, however, examines only eyewall precipitation because of the additional complication that would result from studying precipitation outside the eyewall and because we can identify a strong intensification signal looking at just the eyewall precipitation. In each radar volume scan, we define "extremely tall precipitation" as radar pixels with at least a 20 dBZ reflectivity and a pixel center at an altitude of at least 14.5 km [*Kelley et al.*, 2004].

[9] We linearly interpolate the maximum sustained surface wind intensity from the estimates that the NHC provides every six hours. This six hour interval prevents the present study from detecting wind fluctuations on

**Table 1.** WSR-88D Hurricane Observation Periods[a]

| | | | | | WSR-88D Volume Scans | | | | Intensification Predicted | |
|---|---|---|---|---|---|---|---|---|---|---|
| NHC I+ | Frequency (%) | $A_{33\%}$ ($km^2$) | Hurricane Name | WSR-88D Location | Start Date, yyyymmdd | Start Time (UT) | Duration, hh:mm | NHC Start/End Wind (kt)[b] | WSR-88D | NHC |
| y | 100 | 629 | Erika | Brownsville, TX | 2003/08/16 | 0715 | 03:45 | 60→65 | y | y |
| y | 87 | 181 | Earl | Eglin, FL | 1998/09/02 | 1428 | 03:32 | 76→85 | y | y |
| y | 72 | 33 | Irene | Miami, FL | 1999/10/15 | 0400 | 06:00 | 63→65 | y | y |
| y | 69 | 18 | Erin | Tallahassee, FL | 1995/08/03 | 0100 | 11:00 | 66→80 | y | - |
| y | 68 | 92 | Georges | Key West, FL | 1998/09/25 | 0717 | 10:43 | 86→90 | y | y |
| y | 67 | 187 | Bertha | Wilmington, NC | 1996/07/12 | 0851 | 04:49 | 77→86 | y | - |
| y | 48 | 20 | Alex | Morehead, NC | 2004/08/03 | 0312 | 09:48 | 60→82 | y | y |
| y | 46 | 18 | Irene | Wilmington, NC | 1999/10/17 | 1231 | 15:09 | 65→89 | y | n |
| y | 45 | 17 | Alex | Wilmington, NC | 2004/08/03 | 0120 | 10:11 | 57→78 | y | y |
| y | 37 | 8 | Bret | Brownsville, TX | 1999/08/21 | 1847 | 11:13 | 94→125 | y | y |
| y | 16 | 0 | Lenny | Puerto Rico | 1999/11/17 | 0418 | 09:13 | 104→120 | n | n |
| y | 12 | 0 | Claudette | Houston, TX | 2003/07/15 | 0331 | 07:29 | 61→65 | n | y |
| y | 9 | 0 | Charley | Key West, FL | 2004/08/13 | 0921 | 08:39 | 95→125 | n | y |
| n | 72 | 132 | Georges | Puerto Rico | 1998/09/21 | 1325 | 05:35 | 94→90 | y | y |
| n | 43 | 26 | Lili | New Orleans, LA | 2002/10/03 | 0100 | 07:45 | 122→94 | y | y |
| n | 26 | 0 | Frances | Miami, FL | 2004/09/04 | 1045 | 03:25 | 90→90 | n | n |
| n | 20 | 0 | Charley | Jacksonville, FL | 2004/08/14 | 0617 | 04:33 | 75→75 | n | y |
| n | 6 | 0 | Opal | Eglin, FL | 1995/10/04 | 1820 | 03:14 | 108→92 | n | - |
| n | 5 | 0 | Dennis | Morehead, NC | 1999/08/30 | 0826 | 11:47 | 88→83 | n | y |
| n | 4 | 0 | Gordon | Tallahassee, FL | 2000/09/17 | 1850 | 07:10 | 64→53 | n | n |
| n | 2 | 0 | Erin | Melbourne, FL | 1995/08/01 | 2320 | 03:10 | 75→75 | n | - |
| n | 2 | 0 | Fran | Wilmington, NC | 1996/09/05 | 1543 | 06:54 | 100→100 | n | - |
| n | 0 | 0 | Bonnie | Wilmington, NC | 1998/08/26 | 0840 | 07:25 | 100→100 | n | n |
| n | 0 | 0 | Danny | Mobile, AL | 1997/07/18 | 1700 | 05:00 | 70→70 | n | - |
| n | 0 | 0 | Floyd | Wilmington, NC | 1999/09/15 | 2122 | 06:40 | 92→90 | n | n |
| n | 0 | 0 | Georges | New Orleans, LA | 1998/09/27 | 1455 | 12:55 | 95→92 | n | n |
| n | 0 | 0 | Irene | Melbourne, FL | 1999/10/16 | 1616 | 08:33 | 65→65 | n | y |
| n | 0 | 0 | Isabel | Morehead, NC | 2003/09/18 | 0812 | 04:48 | 90→85 | n | y |
| n | 0 | 0 | Ivan | Mobile, AL | 2004/09/15 | 1620 | 11:17 | 115→115 | n | n |
| n | 0 | 0 | Jeanne | Melbourne, FL | 2004/09/25 | 1900 | 06:09 | 110→100 | n | y |

[a]Column one indicates if the hurricane's winds intensified ("y" for "yes" and "n" for "no") during the WSR-88D observation period based on the NHC wind estimates that were issued every six hours. Column two states the frequency of extremely tall precipitation, i.e., the percentage of volume scans with 20 dBZ $\geq$ 14.5 km in the eyewall. Column three states the horizontal area ($km^2$) of extremely tall precipitation that occurs in the thirty-third percentile of volume scans, sorted in order of increasing horizontal area. The next to the last column states if the height-frequency threshold is exceeded ($A_{33\%} > 5$ $km^2$), which would indicate a likelihood of hurricane intensification. The last column shows if the NHC advisory issued at the beginning of the WSR-88D observation period contained a 12 hour forecast that included hurricane intensification. Lacking NHC advisories, we leave the last column blank for hurricanes before 1998.

[b]1 m $s^{-1}$ = 1.94 kt.

shorter than six hour time scales or from determining if the wind increase occurs before or after the tall precipitation cells.

## 3. Observations Related to Tall Precipitation

[10] Hurricane Georges (1998) and the other hurricanes in Table 1 provide evidence that the WSR-88D radars correctly identify tall precipitation. Figure 1 shows a convective burst in Hurricane Georges, i.e., a persistent mesoscale region of convective precipitation in the eastern quadrant of the eyewall [*Heymsfield et al.*, 2001]. This convective burst occurred during a period of wind intensification: from 34 m $s^{-1}$ (65 kt) at 6 UT on September 24 to 46 m $s^{-1}$ (90 kt) at 12 UT on the next day. The WSR-88D data for other intensifying hurricanes in Table 1 lack the clear evidence of a convective burst present in Hurricane Georges, so later sections of this paper focus on individual convective cells instead of convective bursts.

[11] In Hurricane Georges, precipitation cells with a 20 dBZ WSR-88D signal at 14.5 km often have cold cloud tops, lightning strikes, and strong precipitation near the freezing level. In Figure 1c, the lightning detection efficiency for Hurricane Georges is around 40% because the hurricane was south of the Florida Keys [*Cummins et al.*, 1998]. In Figure 1d, the distinction between 5 km and 7 km altitudes should be considered approximate because the WSR-88D pixels are 2.5 to 3.5 km tall.

[12] In all hurricanes in Table 1, we find that most tall cells ascend from 5 km to 14.5 km in approximately $\sim$20 minutes, which is consistent with the 6 to 8 m $s^{-1}$ updrafts that *Black et al.* [1996, Figure 5a] found in the most vigorous 1% of observations in hurricane eyewalls. Our WSR-88D observations agree with *Heymsfield et al.* [2001] in that many tall cells maintain a 14.5 km height for only $\sim$30 minutes. In contrast, the precipitation cells that we observe in Hurricane Georges are well-separated and maintain a 14.5 km height for over 90 minutes. Well-defined, long-lasting precipitation cells may indicate the presence of mesovortices in the eyewall [*Braun et al.*, 2005].

## 4. Histograms of Precipitation Height

[13] We divide all WSR-88D volume scans into two populations: the 1224 that belong to intensifying hurricanes and the 1323 that belong to non-intensifying hurricanes. Figure 2a shows the Cumulative Distribution Functions (CDFs) for these two populations.

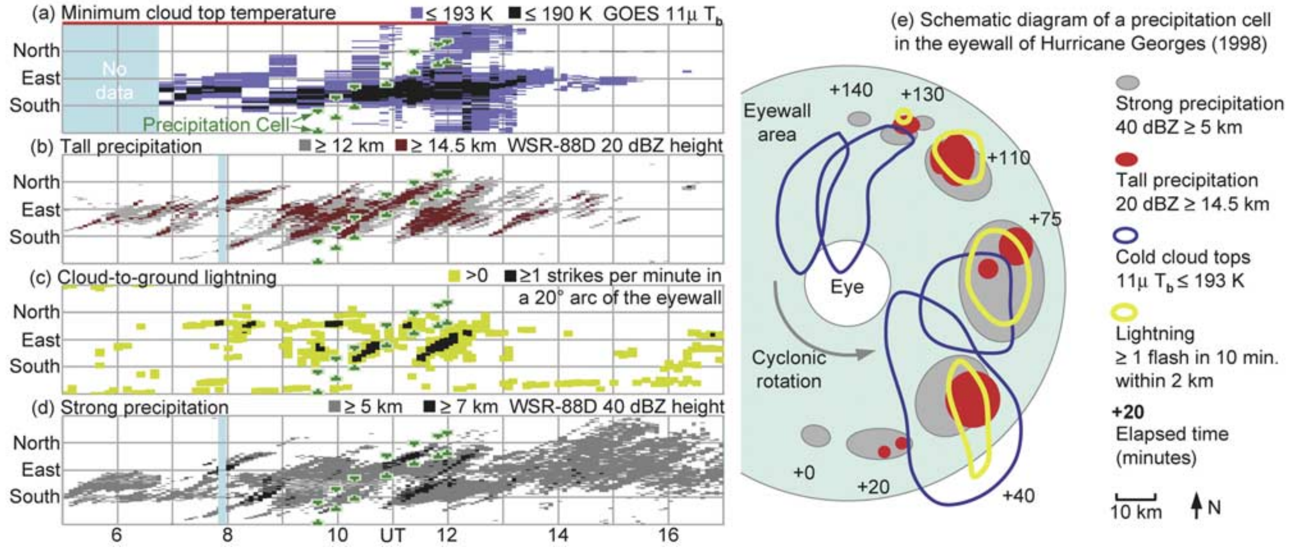


**Figure 1.** Time-azimuth plots of the eyewall of Hurricane Georges on 25 September 1998, as observed by the GOES satellite (a), the National Lightning Detection Network (NLDN) (c), and the WSR-88D radar at Key West, Florida (b and d). The vertical axis states the azimuth angle around the center of the hurricane. The time-azimuth plots include data observed 15 to 75 km from the center of the eye. The red bar at the top indicates when the hurricane's winds were intensifying according to the NHC. Panel (e) shows the evolution of a precipitation cell that formed in the eyewall at 0940 UT.

[14] The CDFs of WSR-88D near-land hurricane observations can be compared with CDFs calculated from TRMM Precipitation Radar overflights of tropical cyclones world-wide. From 1998 to 2003, the TRMM Precipitation Radar had 163 well-centered tropical cyclones overflight, only three of which occurred within range of a WSR-88D ground radar on the U.S. coast.

[15] The non-intensifying WSR-88D CDF stays close to the non-intensifying TRMM CDF. However, the intensifying WSR-88D CDF has taller precipitation on average than the corresponding TRMM CDF. This difference might be caused by the hurricanes near land having different properties than the world-wide population of tropical cyclones. Alternatively, the difference might be caused by the different observation geometries of the WSR-88D and TRMM Precipitation Radar. Suppose that intensifying hurricanes contained narrow cells that had a 20 dBZ signal covering only a 5 $km^2$ horizontal area at a 14.5 km altitude. In that case, the WSR-88D's narrow pixels ($0.5 \times 2.5$ km) could easily detect those cells while the TRMM Precipitation Radar's wider pixels (20 $km^2$ horizontally) would fail to detect them.

## 5. Predicting Hurricane Intensification

[16] We develop a threshold for detecting hurricane wind intensification. This threshold is based on the frequency of extremely tall precipitation in the eyewall. For a radar volume scan to be flagged as having tall precipitation in the eyewall, the eyewall must contain at least a 5 $km^2$ horizontal area with a 20 dBZ signal at least 14.5 km high. We do not try to count the number of precipitation cells because it is often difficult to distinguish between several adjacent cells and a single wide cell.

[17] The best frequency appears to be around 33% (1 in 3 volume scans) because many intensifying hurricanes have tall precipitation that often while few non-intensifying hurricanes do. Column 2 of Table 1 shows that the height-frequency threshold successfully identifies whether or not intensification is occurring in 83% of the observation periods (25 out of 30). About half of the intensifying periods experience a substantial wind increase of over 5 m $s^{-1}$ (10 kt) (Figure 2b).

[18] The success rate of our height-frequency threshold would be slightly lower than 83% if we assume that all WSR-88Ds have a ±2 dBZ calibration error or if we assume

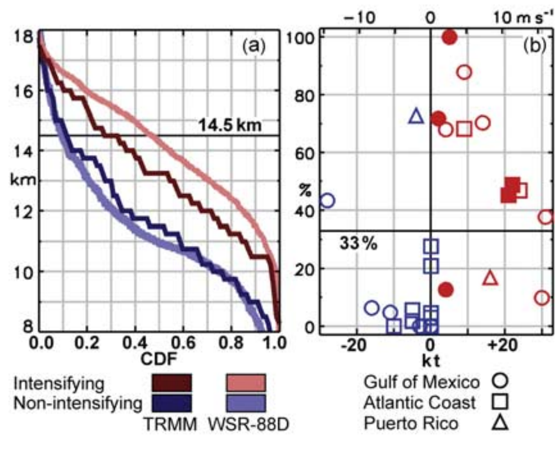


**Figure 2.** (a) For the WSR-88Ds and the TRMM Precipitation Radar, the CDFs of intensifying and non-intensifying hurricanes. The TRMM CDFs are reproduced from Figure 1a of *Kelley et al.* [2004]. (b) The change in the hurricane's sustained surface wind speed during each WSR-88D observation period. The vertical axis is the percentage of WSR-88D volumes scans that contain extremely tall precipitation in the eyewall. The five filled-in symbols are storms transitioning from tropical storm to hurricane during the WSR-88D observation period.

**Table 2.** TRMM Versus WSR-88D[a]

| Wind Intensity Increasing? | TRMM Overflights | | | WSR-88D Observation Periods | | |
|---|---|---|---|---|---|---|
| | Tower | No Tower | *Total* | Frequent Towers | Infrequent Towers | *Total* |
| Yes | 15% (25) | 31%[c] (51) | *47% (76)* | 31% (9) | 10%[c] (3) | *41% (12)* |
| No | 6%[b] (10) | 47% (77) | *53% (87)* | 7%[b] (2) | 52% (15) | *59% (17)* |
| *Total* | *21% (35)* | *79% (128)* | *100% (163)* | *38% (11)* | *62% (18)* | *100% (29)* |

[a]"Tower" refers to the height-only threshold, and "Frequent Towers" refers to the height-frequency threshold defined in Section 5. The number of cases is stated in parentheses.
[b]Type I error rate.
[c]Type II error rate.

that all estimates of wind speed change are in error by ±6 kt. Whether we add or subtract 2 dBZ from all of our reflectivity observations, we find that the height-frequency threshold correctly identifies the intensity change in 80% of the observation periods. *Anagnostou et al.* [2001] reported that the calibration of WSR-88D radars in the southeastern United States can vary by as much as 2 dBZ relative to the TRMM Precipitation Radar. To assess the effect of wind error, we identify the 13 observations periods whose intensifying/non-intensifying classification would not be altered by a 6 kt error in the wind speed change calculated from NHC wind estimates (i.e., periods with $|\Delta v| > 6$ kt). For these 13 observation periods, the height-frequency threshold has a 77% success rate in identifying whether or not intensification is occurring. Based on work by *Franklin* [2005, Table 11], errors in NHC wind estimates are likely to be approximately 6 kt.

[19] Table 2 shows that the 14.5km-33% height-frequency threshold is better at predicting intensification than the 14.5 km height-only threshold of *Kelley et al.* [2004]. Table 2 includes only the 29 independent WSR-88D observation periods. In contrast, Table 1 includes 30 observation periods, two of which cannot be considered completely independent because two radars simultaneously observed Hurricane Alex. Both the WSR-88D height-frequency threshold and the TRMM height-only threshold have similar type I error rates. A type I error is a "false alarm," which occurs when there is tall precipitation but no hurricane intensification.

[20] The WSR-88D height-frequency threshold has a much lower type II error rate than the TRMM height-only threshold. A type II error is "failure to detect." In this situation, failure to detect means the absence of tall precipitation when a hurricane does intensify. There is a simple explanation for why the WSR-88Ds have a lower type II error rate. With a single TRMM observation, it is impossible to know if a tall cell is about to form or if one just disappeared. In contrast, it is harder to miss a tall cell with a WSR-88D volume scan every 4 to 6 minutes.

[21] In summary, Table 2 indicates that intensification occurs during 82% of the independent WSR-88D observation periods that exceed our height-frequency threshold (9 out of 11). Intensification occurs during only 17% of the periods that do not exceed this threshold (3 out of 18).

[22] Consider the 12 hour hurricane intensity forecast issued by the National Hurricane Center (NHC) during a WSR-88D observation period. For the 24 NHC forecasts that we examine, the WSR-88D height-frequency threshold would have correctly raised suspicion about six inaccurate NHC forecasts and falsely raised suspicion about only two accurate NHC forecast (See the last two columns of Table 1). This result suggests that our height-frequency threshold could aid forecasters.

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## References

Anagnostou, E. N., C. A. Morales, and T. Dinku (2001), The use of TRMM Precipitation Radar observations in determining ground radar calibration biases, *J. Atmos. Oceanic Technol.*, *18*, 616–628.
Black, M. L., R. W. Burpee, and F. D. Marks (1996), Vertical motion characteristics of tropical cyclones determined with airborne Doppler radial velocities, *J. Atmos. Sci.*, *53*, 1887–1909.
Braun, S. A., M. T. Montgomery, and Z. Pu (2005), High-resolution simulation of Hurricane Bonnie (1998), Part I: The organization of eyewall vertical motion, *J. Atmos. Sci.*, in press.
Brown, R. A., V. T. Wood, and D. Sirmans (2000), Improved WSR-88D scanning strategies for convective storms, *Weather Forecasting*, *15*, 208–220.
Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. national lightning detection network, *J. Geophys. Res.*, *103*, 9035–9044.
Franklin, J. K. (2005), 2004 National Hurricane Center forecast verification report, NOAA, Silver Spring, Md.
Geerts, B., G. M. Heymsfield, L. Tian, J. B. Halverson, A. Guillory, and M. I. Mejia (2000), Hurricane Georges's landfall in the Dominican Republic: Detailed airborne Doppler radar imagery, *Bull. Am. Meteorol. Soc.*, *81*, 999–1018.
Heymsfield, G. M., B. Geerts, and L. Tian (2000), TRMM Precipitation Radar reflectivity profiles as compared with high-resolution airborne and ground-based radar measurements, *J. Appl. Meteorol.*, *39*, 2080–2102.
Heymsfield, G. M., J. B. Halverson, J. Simpson, L. Tian, and T. P. Bui (2001), ER-2 Doppler radar investigations of the eyewall of Hurricane Bonnie during the Convection and Moisture Experiment-3, *J. Appl. Meteorol.*, *40*, 1310–1330.
Howard, K. W., J. J. Gourley, and R. A. Maddox (1997), Uncertainties in WSR-88D measurements and their impact on monitoring life cycles, *Weather Forecasting*, *12*, 166–174.
Kelley, O. A., J. Stout, and J. B. Halverson (2004), Tall precipitation cells in tropical cyclone eyewalls are associated with tropical cyclone intensification, *Geophys. Res. Lett.*, *31*, L24112, doi:10.1029/2004GL021616.
Kozu, T., T. Kawanishi, H. Kuroiwa, M. Kojima, K. Oikawa, H. Kumagai, K. Okamoto, M. Okumura, H. Nakatsuka, and K. Nishikawa (2001), Development of Precipitation Radar on board the TRMM satellite, *IEEE Trans. Geosci. Remote Sens.*, *39*, 102–116.
Rodgers, E., W. Olson, J. Halverson, J. Simpson, and H. Pierce (2000), Environmental forcing of Supertyphoon Paka's (1997) latent heat structure, *J. Appl. Meteorol.*, *39*, 1983–2006.
Simpson, J., J. B. Halverson, B. S. Ferrier, W. A. Petersen, R. H. Simpson, R. Blakeslee, and S. L. Durden (1998), On the role of "hot towers" in tropical cyclone formation, *Meteorol. Atmos. Phys.*, *67*, 15–35.
Smith, R. K. (2000), The role of cumulus convection in hurricanes and its representation in hurricane models, *Rev. Geophys.*, *38*, 465–489.

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