Signatures of Tropical Cyclone Intensification in Satellite Measurements of Ice and Liquid Water Content

SHUN-NAN WU AND BRIAN J. SODEN

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

(Manuscript received 28 February 2017, in final form 14 July 2017)

ABSTRACT

This study examines how the structure and amount of cloud water content are associated with tropical cyclone (TC) intensity change using the *CloudSat* Tropical Cyclone (CSTC) dataset. Theoretical and modeling studies have demonstrated the importance of both the magnitude and vertical structure of latent heating in regulating TC intensity. However, the direct observations of the latent heat release and its vertical profile are scarce. The CSTC dataset provides the opportunity to infer the vertical profile of the latent heating from *CloudSat* retrievals of cloud ice water content (IWC) and liquid water content (LWC). It is found that strengthening storms have ~20% higher IWC than weakening storms, especially in the midtroposphere near the eyewall. These differences in IWC exist up to 24 h prior to an intensity change and are observed for all storm categories except major TCs. A similar analysis of satellite-observed rainfall rates indicates that strengthening storms have slightly higher rainfall rates 6 h prior to intensification. However, the rainfall signal is less robust than what is observed for IWC, and disappears for lead times greater than 6 h. Such precursors of TC intensity change provide observationally based metrics that may be useful in constraining model simulations of TC genesis and intensification.

1. Introduction

The mechanisms that control tropical cyclone (TC) genesis and intensification remain a key area of research in TC prediction. There are several factors that govern the evolution of TC intensity and can be generally classified into either environmental effects or internal dynamical processes. Environmental effects, including ambient humidity, sea surface temperature, and vertical wind shear, have been well studied and have empirically established relationships with changes in TC intensity (DeMaria and Kaplan 1994; Kaplan and DeMaria 2003; Emanuel et al. 2004; Hendricks et al. 2010; Kaplan et al. 2010). However, our understanding of TC internal dynamics, such as eyewall dynamics (Montgomery and Kallenbach 1997; Schubert et al. 1999; Wu et al. 2016) and convection (Simpson et al. 1998; Kelley et al. 2004; Guimond et al. 2010; Rogers et al. 2013) remain poorly

understood. Given that TC is a highly nonhydrostatic system, vertical motions accompanied with latent heat release can be a key factor in the evolution of TC intensity (Nolan and Grasso 2003; Hendricks et al. 2004).

The latent heating from convection is a fundamental energy source of TC intensification. Theoretical studies (Schubert and Hack 1982; Hack and Schubert 1986) have shown that the radial and vertical location of latent heat release can also be critical to TC intensification. Specifically, Nolan et al. (2007) demonstrated that latent heating near the storm center at the warm core's height increases the efficiency of energy transformation. Using Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar measurements, Zagrodnik and Jiang (2014) investigated the impact of latent heating, rainfall, and convection distributions in TCs undergoing rapid intensification. They found that rapidly intensifying TCs tend to have a more symmetric distribution of rainfall and latent heating. However, a full understanding of the importance of convective heating in regulating TC intensification, and the fidelity of forecast models in reproducing this dependence remains unclear. This reflects, in large part, the lack of direct observations of latent heating.

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/MWR-D-17-0046.s1>.

Corresponding author: Shun-Nan Wu, sxw594@rsmas.miami.edu

Fortunately, satellite observations from NASA's *CloudSat* cloud profiling radar provide vertically resolved measurements of cloud liquid water content (LWC) and ice water content (IWC) that can serve as proxies of latent heating (Cecil and Zipser 1999). The *CloudSat* Tropical Cyclone (CSTC) dataset has collected over 8000 high-resolution overpasses of TCs since 2006 (Tourville et al. 2015).

In this study, we use the CSTC dataset to document signatures of future TC intensification in *CloudSat* measurements. By exploiting the high vertical and horizontal resolution of these measurements, we identify coherent features in the amount and distribution of cloud water content that exists up to 24 h prior to TC intensification. Section 2 introduces the dataset and methods adopted in this study. Section 3 compares composites of *CloudSat* measurement of LWC and IWC for strengthening and weakening storms, examines their dependence on lead time, and compares these results to composites of rainfall rates from AMSR. The last section summarizes the major findings and conclusions of our analysis.

2. Methodology

The CSTC dataset contains an archive of *CloudSat* overpasses that are within 1000 km of the TC center. Each overpass contains *CloudSat* measurements supplemented with select auxiliary variables on 125 vertical levels with a horizontal resolution of 1.1 km. The focus of this study is on the TC inner core; accordingly, we examine only those overpasses that are within 300 km of the TC center. Because *CloudSat* does not always pass directly over the TC center, we define the point of closest approach (PCA) of the overpass as the location of the overpass that is closest to the TC center. To ensure consistent sampling across storms, only those overpasses for which the along-track distance (i.e., the distance from the PCA to the end of the archived satellite swath) are greater than 500 km have been included in our analysis (see Fig. 1). These criteria reduce the total number of TC overpasses that are considered in this study to approximately 1500. We use the retrievals of IWC and LWC (2B-CWC-RO, P_R04 version) in this study. The CSTC dataset also includes rainfall observations from the AMSR-E instrument that have been collocated to the *CloudSat* overpass. For additional details regarding the CSTC dataset the reader is referred to Tourville et al. (2015).

To quantify changes in TC intensity, we use the best track archives from the Joint Typhoon Warning Center (JTWC) and the National Hurricane Center (NHC). Because the *CloudSat* overpasses are synoptic, the

FIG. 1. The overpass area between short black lines (reference A and B) is exclusively included in the calculation (long solid line crossing a big circle). The small unfilled circle is the point of closest approach and the solid dot is the TC center. The straight solid and dashed line represents the track of the overpass and the short dashed line is the distance from the overpass to the TC center.

intensity is linearly interpolated in time to match the time of the *CloudSat* overpass. The intensity change is then defined as the difference in maximum wind speed between the time of the *CloudSat* overpass and that reported 6 h later, which is also linearly interpolated (i.e., a 6-h intensity change). If the wind speed increases 1 kt (1 kt = 0.5144 m s^{-1}) or more, the storm is classified as strengthening (STN) and if the wind speed decreases 1 kt or more, it is classified as weakening (WKN). We note that our results are not sensitive to the choice of the 1-kt threshold and similar conclusions are reached if we use a 5-kt threshold. Considering the quantity of the data available, the 1-kt threshold is adopted here. Both STN and WKN have approximately 500 overpasses each, and there are approximately 500 cases of no intensity change. Table 1 summarizes the sampling characteristics of this dataset. To account for differences in TC size, the radius of maximum wind for every storm is obtained from International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. 2010). All storms stay over the ocean in the first 6 h after the *CloudSat* overpass. However, after the first 6 h, it is possible that some TCs move over land.

Next we examine how far in advance of the 6-h intensity change a signature is present in the IWC. To do so, we extend our analysis associated with a 6-h intensity change out to 12, 18, and 24 h after the time of the

TABLE 1. The average RMW and the number of overpasses included in the analysis as a function of storm category and future (+6 h) intensity change (MTN represents storms with the intensity change less than 1 kt).

Category	RMW (km)			No.		
	STN	WKN	MTN	STN	WKN	MTN
Tropical depression (<30 kt)	78.7	67.2	63.0	93	67	164
Tropical storm (30–55 kt)	66.9	63.5	63.1	246	212	216
Minor TC (55–100 kt)	39.9	42.1	43.5	147	168	64
Major TC (>100 kt)	29.9	32.2	29.7	43	52	14

CloudSat overpass. That is, we calculate the 6-h intensity change that occurs 6, 12, 18, and 24 h after the same composites of IWC. Thus, the composites for a 12-h lead time correspond to a TC intensity change that occurs 6–12 h after the *CloudSat* overpass; composites for an 18-h lead time correspond to a TC intensity change that occurs 12–18 h after the *CloudSat* overpass, and the composites for a 24-h lead time correspond to a TC intensity change that occurs 18–24 h after the *CloudSat* overpass.

3. Results

Figure 2 shows a cross-sectional composite of *CloudSat* retrievals of IWC for all strengthening storms (Fig. 2a) and all weakening storms (Fig. 2b). The *CloudSat* profiles are composited using the PCA of the overpass,

so that the center of the composite indicates the location of the overpass that is closest to the TC center. The unit of the ordinate is the distance to the PCA in kilometers. To account for the influence of TC size on the radial structure of the storm, we also normalize the axial (along track) distance of the overpass by the radius of maximum wind (RMW) of each storm before compositing. The units of the ordinate are thus dimensionless and express the along-track distance in terms of the number of RMW to the PCA instead of the storm center (all composites with normalized ordinate are included in the online supplemental material).

a. Ice water content

For composites in IWC of STN (Fig. 2a) and WKN (Fig. 2b), both maximums are located near the PCA and

FIG. 2. Composites of IWC for (a) STN, (b) WKN, and (c) the difference between STN and WKN. The x axis is the axial distance from the PCA in km and the y axis is height in km. Shadings represent IWC (mg m^{-3}).

FIG. 3. Composites of IWC for STN in (a) tropical depression, (b) tropical storm, (c) minor TCs, and (d) major TCs. The x axis is the axial distance from the PCA in km and folded by a zero point, which is defined in section 2. The y axis is height in km. The units of IWC are mg m^{-3} .

between 5 and 10 km. However, on average STN storms have about 50% higher IWC than WKN storms. The difference between STN and WKN storms (STN – WKN; Fig. 2c) highlights the pervasively higher IWC in STN storms, with the largest differences occurring within 70 km (about one averaged RMW) of PCA. Thus, storms with higher IWC are more likely to intensify over the next 6 h.

To investigate the dependence of this result on the initial storm intensity, we repeat the same analysis and stratify the results by TC category. The TCs are separated into four categories based on the storm intensity at the time of the *CloudSat* overpass: tropical depressions (<30 kt), tropical storms (30–55 kt), minor (55–100 kt), and major (>100 kt) TCs. To simplify the presentation, the results are symmetrized by the PCA. We repeat this analysis for *CloudSat* retrievals of LWC in section 3b and AMSR-E retrievals of surface rainfall rates in section 3c.

Figures 3 and 4 compare composites of IWC for the four different categories of STN and WKN storms, respectively. The maximum IWC is located near the PCA between 5- and 10-km altitude for all categories, and

increases as intensity category increases. Composites for WKN depict a similar pattern to those for STN; however, IWC is up to 50% less than that in STN for all categories except for major TCs. The difference, STN – WKN (Fig. 5), further highlights the robustness of the larger IWC in STN storms. For all categories except major TC, STN storms have higher IWC throughout most of the storm, with the largest differences located near the PCA (within two averaged RMW based on the number in Table 1) and between 5 and 10 km. It is worth noting that the signature of elevated IWC tends to be most pronounced near the PCA.

Our analysis thus far is based on the distance to the PCA instead of the true radial distance from the storm center. To address this problem, two methods for averaging IWC are adopted. First, we calculate the areal mean IWC within 100-km segments from PCA for each overpass and then plot the results against the distance from PCA to the storm center using 10-km bins. This method can be visualized as using a rectangular box 200 km wide and 10 km long to average the vertical profiles of TC overpasses (Fig. 6a). The analysis starts from TC center and repeats with the box moving

FIG. 4. As in Fig. 3, but for WKN.

outward in 10-km intervals. Next, the vertical mean IWC is calculated for each *CloudSat* profile and composited as a function of the distance to the TC center in 10-km intervals. This result can be visualized as using a 10-km-wide averaging radius to composite the profiles (Fig. 6b). The average begins from TC center and repeats with the ring expanding outwards at 10-km intervals. The areal averages from these two methods are plotted against the distance to TC center for each of STN and WKN storms (Fig. 7). For the rectangular box (Fig. 7a), the relationship is noisier as the signal near the storm center becomes contaminated by observations from a range of distances from the storm center. Whereas for circular averaging radii (Fig. 7b), the inner averages may be less representative due to a smaller sampling area (i.e., fewer profiles). Despite these differences in sampling, the results from both averaging boxes indicate similar differences in the radial distributions of IWC between STN and WKN storms.

Both STN and WKN storms exhibit larger IWC as one approaches the storm center. However, near the storm center, STN storms have roughly twice the IWC as WKN storms with this difference diminishing as radial distance approaching 300 km. The solid line in Fig. 7 shows the linear fit between IWC and radial distance.

The higher slope for STN storms reflects the higher IWC near the inner core, confirming that the largest difference in IWC between STN and WKN storms tends to occur near the storm center. This result is consistent with the study of Nolan et al. (2007), which suggests that the release of latent heating near the center is crucial in regulating TC intensify.

b. Liquid water content

Figure 8 shows the difference in cloud LWC between STN and WKN storms for all four categories. In contrast to the IWC, the LWC tends to be lower prior to intensification, particularly in the lowest 2 km. One possible interpretation of this result is that WKN storms tend to have more shallow convection, and thus higher LWC, than STN storms. This interpretation would also be consistent with the tendency for STN storms to have larger LWC in the upper levels of the LWC profile (3–5 km), but lower values below that level. However, the decrease in LWC could also be an artifact of the attenuation of the radar beam associated with the higher IWC at upper levels for STN storms. That is, the higher IWC associated with STN storms may deplete the radar beam enough to limit the reflectivity signal from the underlying cloud liquid droplets. Like the IWC analysis,

FIG. 5. Difference in IWC between STN and WKN for (a) tropical depression, (b) tropical storm, (c) minor TCs, and (d) major TCs. The x axis is axial distance from the PCA in km and the y axis is height in km. Colors represent the difference in IWC of STN–WKN storms (mg m^{-3}).

there is no clear signature of LWC differences between STN and WKN cases for the major TCs category.

Figure 9 compares the areal mean LWC (for both averaging methods) as function of the distance to TC

center for both STN and WKN storms. STN storms have higher LWC as one departs the storm center, while WKN storms demonstrate larger amount of LWC as one approaches the storm center. WKN storms have about

FIG. 6. An illustration of the two different averaging methods used for calculating the areal mean of the satellite retrievals. (a) The rectangular box with 200-km width and 10-km length that moves outward from TC center in a 10-km interval. (b) The circular averaging radii with 10-km width, and the ring expands by 10 km with constant width. The gray area depicts what each averaging box looks like and how it is aligned.

FIG. 7. Circles are the average IWC and error bars are standard error based on (a) rectangular box and (b) circular averaging radii. The solid lines represent the least squares linear regression of mean IWC vs radial distance. Results are shown separately for STN (red) and WKN (blue) storms. The x axis is the radial distance from storm center and the y axis is the areal mean IWC (mg m^{-3}).

twice as much LWC as STN storms, with the largest difference near the storm center. As mentioned before, the attenuation of the radar beam associated with IWC could account for the lower amount of LWC in strengthening storms. If this explanation is correct, then the attenuation-induced bias in LWC should decrease as the IWC decreases. (However, comparison of Figs. 7, 9,

and 11 indicates relatively little spatial correlation between the IWC or precipitation in strengthening storms and the difference in LWC between strengthening and weakening storms.) While we cannot rule out that this result could be an artifact of attenuation of the radar beam, such explanation would require that the bias in LWC introduced by beam attenuation vary systematically

FIG. 8. As in Fig. 5, but for LWC.

FIG. 9. As in Fig. 7, but for LWC.

with distance from the storm center and be largely independent of the corresponding changes in IWC or precipitation.

c. Rainfall rates

Figure 10 shows composites of AMSR retrievals of rainfall rates in all four categories for STN and WKN storms, respectively. Similar to the analysis for IWC, the rainfall rates are, on average, higher in STN storms than that in WKN storms, especially within two averaged RMW of PCA. However, the difference in rainfall rates between STN and WKN storms is not consistent in all four categories, particularly for tropical storms and major TCs where the differences between STN and WKN are small.

The areal averages of rainfall rates are plotted against the distance to TC center for each of the STN and WKN (Fig. 11). Unlike IWC, the results compiled by the two shapes of averaging methods are different in the distribution of areal mean rainfall rates. Using the rectangular box (Fig. 11a), the rainfall rates in STN storms are constantly 1 mm h^{-1} higher than what is observed in WKN storms from the TC center to the outer radius based on the linear fitting. Using the circular averaging radii (Fig. 11b), the difference in rainfall rates is about 1.5 mm h^{-1} around the TC center, but the difference gradually disappears as one moves outward to 300 km. However, the areal averages of rainfall rates between STN and WKN do not exhibit any systematic differences in their radial distribution, and more than half of the differences in rainfall rates between STN and WKN are smaller than standard error. The inconsistent differences imply that the rainfall rates may not be as reliable of an indicator for TC future intensification as IWC. One possible explanation for this is that the vertical distribution of latent heat release, which can be inferred from IWC, may be much more important in determining

future TC intensification than the vertically integrated amount of condensate, which can be inferred from rainfall rates.

d. Dependence on lead time

The analysis so far demonstrates that a signature of elevated IWC in STN storms is detectable for up to 6 h prior to an intensity change. In this section, we examine the dependence of the IWC signal on lead time by extending our analysis out to 24 h prior to the TC intensity change. Figure 11 shows the areal mean IWC within 100 km of the PCA for both STN and WKN storms. Results are shown for all four categories and four different lead times: 6, 12, 18, and 24 h (i.e., the TC intensity change between 0–6, 6–12, 12–18, and 18–24 h, respectively, based on the time of *CloudSat* overpass reported). In Fig. 12, the vertical bars depict the standard error for each composite and provide a measure of the uncertainty in the composite mean due to sampling. Similar to the cross-sectional analysis, in the 6-h lead time, the areal mean IWC in STN storms is $\sim 50\%$ greater than that in WKN storms. The difference in IWC between STN and WKN storms exceeds the standard error for all intensity categories, except for major TCs. This may reflect both the weaker signal and smaller sample size for this storm category. Note that the difference in IWC between STN and WKN storms decreases as the intensity of the storm category increases. As the lead time is extended, the difference in IWC between STN and WKN storms diminishes. However, elevated IWC is observed in STN storms out to 18 h in all categories except for major TCs. At a lead time of 24 h, IWC is still higher in STN storms in each category (except major TCs), although the difference is only larger than the standard error for tropical depressions. In major TCs, lack of the signal in IWC for intensity evolution may be due to the stronger initial storm intensity

FIG. 10. Solid lines are composites of AMSR rainfall rate and shading is the standard error for STN (red) and WKN (blue) storms. Results are shown for each storm category: (a) tropical depression, (b) tropical storm, (c) minor TCs, and (d) major TCs. The x axis is the axial distance from the PCA in km and the y axis represents the rainfall rate in mm h^{-1} .

in WKN storms, which also governs the IWC and thus dilutes the signal of elevated IWC in STN storms.

The same analysis is repeated for rainfall rates (Fig. 13). For a 6-h lead time, elevated rainfall rates for STN storms are observed for each category (except

major TCs). However, beyond 6 h these differences are not consistently larger than the standard error. Therefore, the rainfall rates, which can be regarded as the proxy for gross latent heating, may not be a good parameter for determining future TC intensity as there is

FIG. 11. As in Fig. 7, but for AMSR rainfall rate in mm h^{-1} .

FIG. 12. The areal mean IWC for each category of storm intensity as a function of lead time. Red and blue bars are the areal mean of IWC for STN and WKN, respectively. (from dark to light) The different brightness represents different categories of TC intensity: tropical depression, tropical storms, and minor and major TCs (in sequence, from left to right). Error bars are the standard error. The results are shown for four different lead times: 6, 12, 18, and 24 h.

no robust and consistent difference between STN and WKN storms.

4. Conclusions

This paper addresses how *CloudSat* retrievals of IWC and LWC are related to future TC intensification. It is shown that STN storms have higher cloud IWC than WKN storms in all storm categories except for major TCs; more specifically, TCs with elevated IWC tend to intensify in the following hours, and this signature of elevated IWC can be observed in *CloudSat* measurements up to 24 h prior to intensification.

Similar analyses are performed for LWC and rainfall rates. In terms of the signal of TC intensification, LWC tends to be lower in STN storms, particularly in the lowest 2 km, than that in WKN storms, although the significant difference only exists up to 12-h lead time. Differences in rainfall rates, however, are less pronounced than in IWC and LWC, and disappear for lead time beyond 6 h.

A key question to ask based on these results is why STN storms tend to have higher IWC and lower LWC near the storm center. One interpretation is that STN storms usually have more deep convection, and thus higher IWC in the midtroposphere, while WKN storms have more shallow convection, resulting in higher LWC in the low troposphere. However, we cannot rule out that the lower LWC in STN storms may be an artifact due to the attenuation of the radar signal. The greater signal for IWC compared to rainfall implies that the

FIG. 13. As in Fig. 12, but for AMSR rainfall rate.

vertical distribution of latent heating may be more important in determining TC intensification than vertically integrated amount of condensates. Such relationships suggest that *CloudSat* measurements of IWC can also provide useful information for evaluating and constraining model simulations of TC intensity change.

This study shows that insight into future TC intensity can be gained from satellite measurements of cloud IWC and LWC. Consistent with previous theoretical studies, we find observational evidence that both the proximity to the storm center and the altitude of condensate influences TC intensity. In particular, storms that intensify tend to have greater IWC within two averaged RMW of the storm center and between 6 and 10 km. The precursors found in this study provide observationally based metrics for improving our understanding of how latent heat release within the storm modulates TC intensity.

Acknowledgments. We thank Dr. David Nolan for helpful discussions and comments on this manuscript. *CloudSat* overpasses were obtained from the *CloudSat* Tropical Cyclone Overpass dataset. This work is supported by Grant NNX14AB19G from the NASA *CloudSat*/CALIPSO Science Team program.

REFERENCES

- Cecil, D. J., and E. J. Zipser, 1999: Relationships between tropical cyclone intensity and satellite-based indicators of inner core convection: 85-GHz ice-scattering signature and lightning. *Mon. Wea. Rev.*, **127**, 103–123, doi:10.1175/1520-0493(1999)127<0103:RBTCIA>2.0.CO;2.
- DeMaria, M., and J. Kaplan, 1994: A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin. *Wea. Forecasting*, **9**, 209–220, doi:10.1175/1520-0434(1994)009<0209:ASHIPS>2.0.CO;2.

- Emanuel, K. A., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental control of tropical cyclone intensity. *J. Atmos. Sci.*, **61**, 843–858, doi:[10.1175/1520-0469\(2004\)061<0843:ECOTCI>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<0843:ECOTCI>2.0.CO;2).
- Guimond, S. R., G. M. Heymsfield, and F. J. Turk, 2010: Multiscale observations of Hurricane Dennis (2005): The effects of hot towers on rapid intensification. *J. Atmos. Sci.*, **67**, 633–654, doi:[10.1175/2009JAS3119.1](https://doi.org/10.1175/2009JAS3119.1).
- Hack, J. J., and W. H. Schubert, 1986: Nonlinear response of atmospheric vortices to heating by organized cumulus convection. *J. Atmos. Sci.*, **43**, 1559–1573, doi:[10.1175/1520-0469\(1986\)043<1559:NROAVT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1986)043<1559:NROAVT>2.0.CO;2).
- Hendricks, E. A., M. T. Montgomery, and C. A. Davis, 2004: The role of “vortical” hot towers in the formation of Tropical Cyclone Diana (1984). *J. Atmos. Sci.*, **61**, 1209–1232, doi:[10.1175/1520-0469\(2004\)061<1209:TROVHT>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<1209:TROVHT>2.0.CO;2).
- , M. S. Peng, B. Fu, and T. Li, 2010: Quantifying environmental control on tropical cyclone intensity change. *Mon. Wea. Rev.*, **138**, 3243–3271, doi:[10.1175/2010MWR3185.1](https://doi.org/10.1175/2010MWR3185.1).
- Kaplan, J., and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecasting*, **18**, 1093–1108, doi:[10.1175/1520-0434\(2003\)018<1093:LCORIT>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<1093:LCORIT>2.0.CO;2).
- , —, and J. A. Knaff, 2010: A revised tropical cyclone rapid intensification index for the Atlantic and eastern North Pacific basins. *Wea. Forecasting*, **25**, 220–241, doi:[10.1175/2009WAF2222280.1](https://doi.org/10.1175/2009WAF2222280.1).
- Kelley, O. A., J. Stout, and J. B. Halverson, 2004: Tall precipitation cells in tropical cyclones eyewalls are associated with tropical cyclone intensification. *Geophys. Res. Lett.*, **31**, L24112, doi:[10.1029/2004GL021616](https://doi.org/10.1029/2004GL021616).
- Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neuman, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone data. *Bull. Amer. Meteor. Soc.*, **91**, 363–376, doi:[10.1175/2009BAMS2755.1](https://doi.org/10.1175/2009BAMS2755.1).
- Montgomery, M. T., and R. J. Kallenbach, 1997: A theory for vortex Rossby-waves and its application to spiral bands and intensity changes in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **123**, 435–465, doi:[10.1002/qj.49712353810](https://doi.org/10.1002/qj.49712353810).
- Nolan, D. S., and L. D. Grasso, 2003: Nonhydrostatic, three-dimensional perturbations to balanced, hurricane-like vortices. Part II: Symmetric response and nonlinear simulations. *J. Atmos. Sci.*, **60**, 2717–2745, doi:[10.1175/1520-0469\(2003\)060<2717:NTPTBH>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<2717:NTPTBH>2.0.CO;2).
- , Y. Moon, and D. P. Stern, 2007: Tropical cyclone intensification from asymmetric convection: Energetics and efficiency. *J. Atmos. Sci.*, **64**, 3377–3405, doi:[10.1175/JAS3988.1](https://doi.org/10.1175/JAS3988.1).
- Rogers, R., P. Reasor, and S. Lorsolo, 2013: Airborne Doppler observations of the inner-core structural differences between intensifying and steady-state tropical cyclones. *Mon. Wea. Rev.*, **141**, 2970–2991, doi:[10.1175/MWR-D-12-00357.1](https://doi.org/10.1175/MWR-D-12-00357.1).
- Schubert, W. H., and J. J. Hack, 1982: Inertial stability and tropical cyclone development. *J. Atmos. Sci.*, **39**, 1687–1697, doi:[10.1175/1520-0469\(1982\)039<1687:ISATCD>2.0.CO;2](https://doi.org/10.1175/1520-0469(1982)039<1687:ISATCD>2.0.CO;2).
- , M. T. Montgomery, R. K. Taft, T. A. Guinn, S. R. Fulton, J. P. Kossin, and J. P. Edwards, 1999: Polygonal eyewalls, asymmetric eye contraction, and potential vorticity mixing in hurricanes. *J. Atmos. Sci.*, **56**, 1197–1223, doi:[10.1175/1520-0469\(1999\)056<1197:PEAECA>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<1197:PEAECA>2.0.CO;2).
- 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. *Meteor. Atmos. Phys.*, **67**, 15–35, doi:[10.1007/BF01277500](https://doi.org/10.1007/BF01277500).
- Tourville, N., G. Stephens, M. DeMaria, and D. Vane, 2015: Remote sensing of tropical cyclones: Observations from CloudSat and A-Train profilers. *Bull. Amer. Meteor. Soc.*, **96**, 609–622, doi:[10.1175/BAMS-D-13-00282.1](https://doi.org/10.1175/BAMS-D-13-00282.1).
- Wu, C.-C., S.-N. Wu, H.-H. Wei, and S. F. Abarca, 2016: The role of convective heating in tropical cyclone eyewall ring evolution. *J. Atmos. Sci.*, **73**, 319–330, doi:[10.1175/JAS-D-15-0085.1](https://doi.org/10.1175/JAS-D-15-0085.1).
- Zagrodnik, J. P., and H. Jiang, 2014: Rainfall, convection, and latent heating distributions in rapidly intensifying tropical cyclones. *J. Atmos. Sci.*, **71**, 2789–2809, doi:[10.1175/JAS-D-13-0314.1](https://doi.org/10.1175/JAS-D-13-0314.1).