Feasibility of tropical cyclone intensity estimation using satellite-borne radiometer measurements: An observing system simulation experiment

Scott B. Sieron,[1] Fuqing Zhang,[1] and Kerry A. Emanuel[2]

Received 24 July 2013; revised 15 September 2013; accepted 17 September 2013.

[1] This study evaluates the potential of a proposed technique in using satellite-borne radiometer measurements and weather analyses to estimate the intensity of tropical cyclones. This theory shows that intensity is essentially directly related to the temperature deficit of cloud top versus sea surface, and the surplus in saturation entropy in the eyewall versus its surroundings. The eyewall entropy estimate comes from measurements of cloud top temperature and pressure, and the analysis provides the environmental saturation entropy. An Observing Systems Simulation Experiment was conducted, and the results were compared to those from previous studies using cloud-profiling radar altimetry measurements. The use of cloud top pressure measurements may produce more accurate results. Inherent challenges still require caution in considering operational implementation. **Citation:** Sieron, S. B., F. Zhang, and K. A. Emanuel (2013), Feasibility of tropical cyclone intensity estimation using satellite-borne radiometer measurements: An observing system simulation experiment, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50973.

1. Introduction

[2] There is great motivation to use satellite data to remotely estimate tropical cyclone intensity due to the sporadic nature of in situ measurements. The well-established Dvorak technique [*Dvorak*, 1975] for estimating maximum-sustained surface winds has been used and improved for decades, including the integration of newer observational products [*Velden et al.*, 2006].

[3] Some recently deployed sensors produce uniquely different observational products that are not all well suited to be integrated into the Dvorak technique but may otherwise provide useful information in determining tropical cyclone intensity. Two such new sensors are the cloud-profiling radar aboard CloudSat [*Stephens et al.*, 2002] and the Moderate Resolution Imaging Spectroradiometer (MODIS) [*Salomonson et al.*, 1989], both of which are part of the A-Train constellation of Earth-observing satellites [see *Stephens et al.*, 2002]. CloudSat provides cloud top height measurements and indications of the mode (convective or stratiform) of precipitation below cloud top in a vertical cross section. MODIS takes measurements in a 2330 km wide swath and provides various data products including brightness temperature and cloud top pressure [*Platnick et al.*, 2003; *Baum et al.*, 2012].

[4] With these measurement capabilities in mind, *Wong and Emanuel* [2007], hereafter WE07, developed a diagnostic equation for the maximum gradient wind:

$$V_m^2 \cong \frac{(T_S - T_0)(s_m^* - s_0^*) - \frac{1}{4}f^2 r_0^2}{\frac{R_d T_s}{36 p_0} - 1}, \quad (1)$$

where T_s and T_0 are the temperatures (in Kelvin) of the sea surface and at cloud top height in the outflow, respectively, r_0 is the outer radius at which the surface wind associated with the tropical cyclone is assumed to vanish, p_0 is the surface pressure at r_0, R_d is the gas constant for dry air, f is the Coriolis parameter, and s_m* and s_0* are the saturation entropy of the eyewall and the environment (at about r_0), respectively. s* is defined as

$$s^* \cong c_p \ln T - R_d \ln p + \frac{L_v q^*}{T}, \quad (2)$$

where c_p is the heat capacity at constant pressure, L_v is the latent heat of vaporization, R_d is the gas constant for dry air, T is temperature, p is pressure, and q* is the saturation-specific humidity. When the cloud top of deep moist convection is used both in the eyewall and the environment, the change in saturation entropy, ds*, can be converted to a change in saturation moist static energy (SMSE), dh*, by

$$T_0 ds^* = dh^*, \quad (3)$$

where T_0 is the cloud top temperature of the outflow, assumed constant between the eyewall and the "outer region" deep moist convection (henceforth, this will be referred to as the "SMSE substitution"). h* is defined as

$$h^* \equiv c_p T + L_v q^* + gz, \quad (4)$$

where g is the gravitational constant and z is the height above the surface; however, the moisture term can be neglected when at the high height of cloud top (as done in WE07) [*Luo et al.*, 2008b]. Cloud top altimetry measurements from CloudSat can be applied to determine SMSE because it uses height, z, whereas entropy uses pressure, p.

[5] The maximum gradient wind is assumed to exist at the top of the boundary layer, and the maximum-sustained surface wind can be crudely approximated from this with a simple reduction of 20% (as done in *Luo et al.* [2008b]; see also *Powell* [1980]).

[1]Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania, USA.
[2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Corresponding author: F. Zhang, Department of Meteorology, Pennsylvania State University, 601 Walker Building, University Park, PA 16802, USA. (fzhang@psu.edu)

0094-8276/13/10.1002/grl.50973

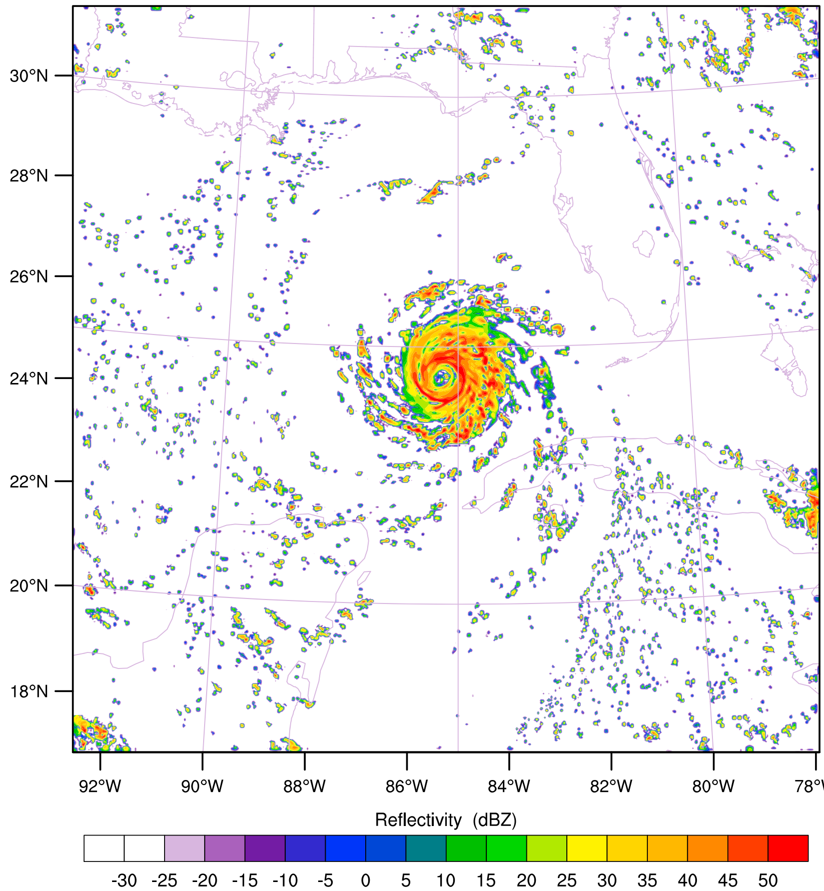

Figure 1. Near-surface reflectivity of innermost domain of Hurricane Katrina simulation at 00:00 UTC on 28 August.

[6] The WE07 study showed that equation (1) with the SMSE substitution (which forms their equation 15) generally works well with an axisymmetric tropical cyclone in a cloud-resolving model. The model output of cloud top height and temperature was used to determine the SMSE of the eyewall, but the environmental SMSE used at all forecast times was calculated from the initial environmental tropospheric thermodynamic profile.

[7] In a follow-up study, *Luo et al.* [2008b], hereafter Luo08, used a simplified version of equation (1) with the SMSE substitution:

$$V_m^2 \approx \frac{T_s - T_0}{T_0} \Delta h^*, \quad (5)$$

where Δ represents change from eyewall to environment. Luo08 presented positive, though preliminary, results of applying equation (5) to several CloudSat cases that have an eyewall interception. Their "direct estimate" method, i.e., using only satellite measurements to estimate Δh^*, used the cloud top of eyewall convection, and the cloud top of either outer region deep moist convection or the edge of the eyewall cloud shield. This method was found to produce better results and reduce the overall sensitivity to sea surface temperature than using sea surface temperature alone to estimate environmental SMSE [Luo08].

[8] The necessary inputs to use equations (1) with the SMSE substitution or (5) can be obtained from a combined use of CloudSat and MODIS brightness temperature data (in addition to a data source for sea surface temperature). However, the CloudSat cloud-profiling radar measurements leave most of the tropical cyclone unobserved. *Sieron* [2013] showed that there is much variability in the diagnosed wind speed depending on the selected eyewall and outer region deep moist convective cell chosen under the Luo08 methodological paradigm. However, MODIS and geostationary satellites such as GOES can provide cloud top pressure in a horizontal plane, and analysis data is given in three dimensions. Here we conduct a proof-of-concept Observing Systems Simulation Experiment (OSSE) to test the use of these data toward this proposed technique for tropical cyclone intensity estimation.

2. Methodology

2.1. The Simulation

[9] A convective-permitting Weather Research and Forecasting (WRF) V3.3.1 simulation of Hurricane Katrina for the period of 26 August 2005 00:00 UTC to 30 August 2005 21:00 UTC is used. There are three two-way nested

Table 1. The Relative Performance of the Two-Method Combinations of the Analyses

	Average Error (m/s)	Tuning Constant, C	Absolute Error with Tuning (m/s)
20% filtering	5.03	0.852	5.78
50% filtering	0.72	0.977	5.48

Table 2. Detailed Results From Using 50% Filtering for the Eyewall

Time (UTC)	Model (m/s)	Eyewall Radius (km)	Eyewall (K)	SST (K)	Entropy (J/K•kg), eyewall	Saturation Entropy (J/K•kg), env.	Diagnosed (m/s)	Error (m/s)	Diagnosed, $C=0.977$ (m/s)	Error with Tuning (m/s)
26 Aug 06:00	37.0	33	214.7	303.5	2596	2567	40.4	3.4	40.0	3.0
26 Aug 12:00	38.8	21	212.4	303.9	2597	2566	42.5	3.7	42.0	3.2
26 Aug 18:00	46.9	33	200.5	303.9	2605	2566	50.8	3.9	50.2	3.3
27 Aug 00:00	50.6	33	195.8	303.3	2629	2567	65.5	14.9	64.7	14.1
27 Aug 06:00	58.1	27	206.6	303.2	2622	2568	57.4	−0.7	56.7	−1.4
27 Aug 12:00	63.7	27	217.6	303.6	2627	2568	57.0	−6.7	56.4	−7.3
27 Aug 18:00	60.5	24	209	303.6	2636	2569	63.7	3.2	63.0	2.5
28 Aug 00:00	58.4	33	227.2	303.6	2625	2570	52.0	−6.4	51.4	−7.0
28 Aug 06:00	67.2	42	220.7	303.6	2635	2571	58.3	−8.9	57.6	−9.6
28 Aug 12:00	70.5	45	219	303.7	2643	2570	62.7	−7.8	62.0	−8.5
28 Aug 18:00	69.5	39	218.6	303.9	2654	2571	67.5	−2.0	66.7	−2.7
29 Aug 00:00	72.3	39	217.7	304	2657	2572	68.6	−3.7	67.8	−4.5
29 Aug 06:00	69.8	33	222.8	304.1	2663	2575	68.0	−1.8	67.2	−2.6
29 Aug 12:00	69.8	39	217.2	304.4	2670	2571	74.5	4.7	73.6	3.8
29 Aug 18:00	73.0	39	214.8	304.4	2683	2572	79.6	6.6	78.6	5.6
30 Aug 00:00	57.7	39	226.3*	299.3	2670	2575	66.9	9.2	66.1	8.4
							Average:	0.7	MAE:	5.5

model domains with horizontal grid spacing of 27, 9, and 3 km and integration time steps of 60, 20, and 6.67 s, respectively. The initial conditions are the same as in *Green and Zhang* [2013]. The output files from the innermost of the two nested domains (see Figure 1) at every 6 h between 26 August 06:00 UTC and 30 August 00:00 UTC are analyzed. This innermost domain is vortex tracking, has 561 × 561 grid points, and has 43 vertical levels. The WRF Single-Moment 6-Class microphysics scheme and the Yonsei University planetary boundary layer scheme are used in this domain. As in WE07, the cloud top is defined as the highest model level at which total liquid/ice water content is at least 0.2 g/Kg. The pressure, temperature, and cloud top data taken from the WRF output are treated exactly as if they are from satellite measurements or from a real-time analysis. The storm contains an eye at all of the analyzed times, and the eyewall is, for the most part, circular and symmetric at all but the earliest times.

2.2. Application

[10] For estimating the state of the environment, we use a predefined volume at a large radial distance from the storm center (see section 2.3). We use cloud top to estimate the state of the eyewall (see section 2.4). Since cloud top is not being used to estimate both the eyewall and environment, using equation (3) would be inappropriate because an assumed constant temperature, T_0, is invalid. Furthermore, cloud top pressure measurements, rather than height measurements, are used. Therefore, unlike in WE07 and Luo08, the SMSE substitution is not made and saturation entropy (equation (2)) is used.

[11] The diagnostic equation used is adapted from Luo08:

$$V_m^2 \approx C(T_s - T_0)\Delta s^*, \tag{6a}$$

where C is an optional tuning constant that removes bias in the diagnosed wind speeds from a given data set. The maximum surface (10 m) wind found within 99 km of the storm center is used as the truth metric, as it is the data most consistent with the National Hurricane Center (NHC) operational definition of maximum-sustained winds of a tropical cyclone. Since the diagnosed winds are being compared against surface winds, they should be reduced by 20% (see section 1). This adjustment can be made prior to applying the tuning constant for the sake of enabling a fair comparison of pretuned results from cases with different metric winds. For this analysis, the following equation, which is a modified version of equation (6a), is used:

$$V_{m,sfc} \approx .8 * \sqrt{C(T_s - T_0)\Delta s^*}. \tag{6b}$$

[12] The cloud top temperature of the eyewall is used for the cloud top temperature in equation (6), as is done similarly in WE07 and Luo08. The storm sea surface temperature in equation (6), T_s, is taken as the mean of the sea surface temperature (SST) at the storm center and the azimuthally averaged SST at 99 km radius.

2.3. State of the Environment From a Simulated Analysis

[13] The environment is defined as the free troposphere at a radial distance of 500 km from the center of the tropical cyclone (point of minimum surface pressure). All horizontal grid points at the 500 km radius that have a water surface are

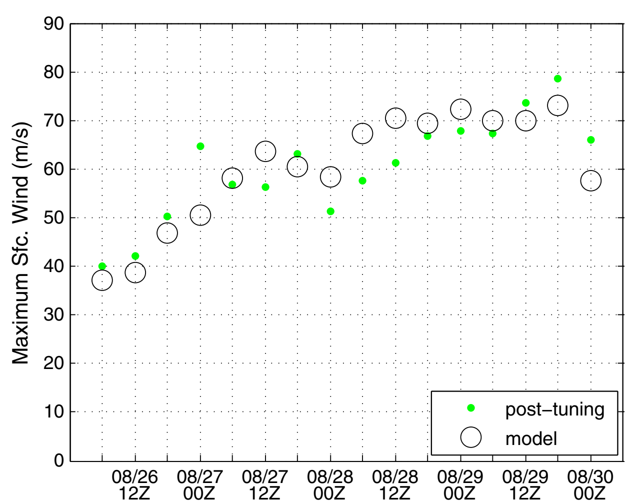

Figure 2. Diagnosed wind speeds post-tuning from using 50% filtering for the eyewall, compared to model wind speeds. Tuning constant $C = 0.977$.

identified. Considering each point individually, the vertical levels with a pressure between 850 hPa and 300 hPa are found. The saturation entropy at that point is the average saturation entropy at each of these vertical levels. If the model-simulated reflectivity at all of these levels is −30 dBZ (the minimum value in the output), then the point is included in the environmental average saturation entropy.

2.4. State of the Eyewall From Simulated Cloud Top Measurements

[14] A radially outward-directed search at 3 km intervals from the storm center to 99 km is done in locating the eyewall; the radius with the highest-estimated eyewall entropy is taken as the eyewall radius. At every point on a given radius, the cloud top is found, and the entropy is calculated from the pressure and temperature at that model level. Here the moisture contribution to entropy is disregarded (see section 1). The average cloud top entropy for the radius is determined using only the highest values of entropy found at that radius. The appropriate percentage of highest entropy points to use—the "eyewall-filtering percentage"—is to be determined in the analysis. The eyewall cloud top temperature for a given radius is the average of cloud top temperatures at the same set of points.

3. Results

[15] We examined two eyewall-filtering percentages for the azimuthal averaging in the eyewall identification process, 20% and 50%, respectively (that is, only the top 20% or 50% of points in terms of cloud top entropy are included in the average). Given that the final results for using these two percentages were quite similar (summarized in Table 1), no further tests of other filtering percentages were deemed necessary. The better performing analysis technique is the use of 50% filtering for the eyewall, and Table 2 and Figure 2 present more detailed results for this technique. The bias is only 0.7 m/s and the required tuning constant in equation (6b) $C = 0.977$. The mean absolute error both before and after tuning is 5.48 m/s. For reference, the average forecasters' perceived uncertainty in the NHC's Best Track maximum wind speed estimates for North Atlantic major hurricanes when aircraft data are absent is 7.2 m/s [*Landsea and Franklin*, 2013]. The results from nine CloudSat cases analyzed in Luo08 have a mean absolute error of 6.5 m/s.

[16] There is little variation throughout the time period (excluding the final forecast time when the storm is inland) in environmental saturation entropy and, especially, sea surface temperatures. For sea surface temperature, the range in values is only 1.2 K, or less than 1.5% of the average difference between eyewall cloud top temperature and sea surface temperature (hereafter "ΔT"). For environmental saturation entropy, the range is 8.8 J/K · kg, which is about 10% of the average Δs^* and about 10% of the increase in eyewall entropy from minimum to maximum intensity.

[17] As one would expect, the use of 50% filtering results in lower diagnosed wind speeds before any tuning constant is applied. Obviously, the entropy of the eyewall is lower, so the change in entropy from eyewall to environment, Δs^*, is reduced. Also, the eyewall cloud tops are warmer, and therefore, the ΔT is less. The reductions in ΔT and Δs^* have nearly equal impacts on reducing the wind speeds.

[18] The results from 50% filtering are superior both before and after tuning. The mean absolute error of the tuned results is about 5% less. However, the eyewall cloud top temperatures determined by the 20% filtering seem more realistic in general and are closer to those from the *Sieron* [2013] cross-section analyses; they are, on average, 6.0 K cooler.

4. Concluding Remarks

[19] This study seeks to evaluate the potential use of horizontal-planar satellite-measured cloud top temperatures and pressures of tropical cyclone eyewalls, together with analyses of the surrounding environment, to estimate tropical cyclone intensity. An Observing Systems Simulation Experiment (OSSE) was conducted with a high-resolution, nested domain WRF simulation of Hurricane Katrina in the Gulf of Mexico. Previous works [WE07 and Luo08] proposed to deploy this technique with cloud top altimetry measurements from cloud-profiling radar. However, the results of this study indicate that using cloud top pressure measurements from a scanning radiometer would not only provide more samplings than cloud-profiling radar but may also be more accurate as well [see *Sieron*, 2013].

[20] The theory does not account for virtual temperature, hydrometeor loading, biases in brightness temperature, or errors in satellite-derived cloud top pressure. This, together with other potential observational biases not considered here, would likely require a different tuning constant compared with the one used here and may introduce errors beyond those documented here.

[21] Other measures of storm intensity besides maximum point surface winds were tested, motivated by the fact that the technique pertains to the maximum gradient wind [WE07]. To account for this, we found the (radial and vertical) maximum azimuthally averaged tangential wind. These wind speeds are on average 3.8 m/s higher than the surface winds. However, since this wind is at the top of the boundary layer, there is no 20% reduction applied to the diagnosed winds; therefore, results before tuning have a substantial negative bias. After retuning, the mean absolute error is, on average, 1.9 m/s greater than using point surface winds as the metric.

[22] Other vertical locations in the troposphere could be used to define the environment. One tested in this study was above the boundary layer, which was approximated as the layer between 950 and 900 hPa. The saturation entropy is consistently higher here than in the free troposphere. The wind speeds have an average bias of −8.0 m/s before tuning and a post-tuning mean absolute error of 5.8 m/s.

[23] There are some other caveats with this study; the largest of which is that only one storm and one storm structure, the "eye storm," is analyzed. It is possible that the quality of results or the suitable methodological framework or both would differ for other, less organized tropical cyclone (TC) structures. Challenges for analyzing other TC structures include the need for a more rigorous procedure for center fixing and the investigation of validity of certain assumptions (such as undiluted moist ascent) made in the derivation of the technique. For the "embedded center" TC structure, the same methodological framework would probably be applicable, just that one would expect a small "eyewall radius" to be analyzed. However, a sheared TC may have not had sufficient angular coverage of convection for the framework developed here to be implementable. There is also variation among "eye

storms" with regard to symmetry and brokenness of the eyewall and the existence of concentric eyewalls. The suitability and implementation for TCs with other eye types or structures should be a focus for future work.

[24] This OSSE study is also simplified in assuming perfect observations, when in reality, brightness temperature is biased for some deep moist convection [*Luo et al.*, 2008a] and radiometer-based cloud top pressures are derived from algorithms [see *Baum et al.*, 2012]. However, it is possible that an eyewall identification process using the coldest IR or microwave brightness temperature, combined with a small eyewall-filtering percentage, could perform just as well and also reduce the impact of biased cloud top temperature measurements.

[25] If MODIS is used as the source of real observations, then one benefit as compared to this OSSE study is that the cloud top temperatures and heights are at three times the resolution as the model output when at nadir [*Baum et al.*, 2012]. However, the effects of partial sampling by MODIS when the swath does not encompass the entire core of the storm were not tested, and the resulting uncertainties in any diagnosed wind speed from using such measurements shall be considered in any future real-data testing of the proposed technique. Also, like this OSSE, MODIS sampling provides essentially a snapshot, with no time averaging, introducing sampling errors due to the transient behavior of the storm.

[26] The use of cloud top pressure products from GOES or other geostationary satellites would reduce this concern and allow for time-averaging procedures, such as those done for the Dvorak technique [*Velden et al.*, 2006]. Future work may include analyzing the WRF output at a time interval of 1 h or shorter and analyzing fluctuations in both the winds in the model and the diagnosed winds over such short time periods. Ultimately, real-data tests with a large-number sample of observed events in future studies are necessary to further evaluate the potential of the technique proposed in this study.

[27] **Acknowledgments.** This is an extension of the first author's master thesis research. We would like to thank Johnny Lou for explaining the method used in Luo08 and Eugene Clothiaux, Hans Verlinde, Dan Stern, and Ben Green for their constructive comments and suggestions on the thesis. This research is partially supported by NASA grant NNX12AJ79G and by the National Science Foundation Graduate Research Fellowship under grant DGE1255832. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

[28] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Baum, B. A., W. P. Menzel, R. A. Frey, D. C. Tobin, R. E. Holz, S. A. Ackerman, A. K. Heidinger, and P. Yang (2012), MODIS cloud Top property refinements for collection 6, *J. Appl. Meteorol. Climatol.*, *51*(6), 1145–1163.

Dvorak, V. F. (1975), Tropical cyclone intensity analysis and forecasting from satellite imagery, *Mon. Weather Rev.*, *103*, 420–430.

Green, B. W., and F. Zhang (2013), Impacts of air-sea flux parameterizations on the intensity and structure of tropical cyclones, *Mon. Weather Rev.*, doi:10.1175/MWR-D-12-00274.1, in press.

Landsea, C., and J. Franklin (2013), How 'Good' are the Best Tracks?—Estimating Uncertainty in the Atlantic Hurricane Database, *Mon. Weather Rev.*, doi:10.1175/MWR-D-12-00254.1, in press.

Luo, Z., G. Y. Liu, and G. L. Stephens (2008a), CloudSat adding new insight into tropical penetrating convection, *Geophys. Res. Lett.*, *35*, L19819, doi:10.1029/2008GL035330.

Luo, Z., G. L. Stephens, K. A. Emanuel, D. G. Vane, N. D. Tourville, and J. M. Haynes (2008b), On the Use of CloudSat and MODIS data for estimating hurricane intensity, *IEEE Geosci. Remote Sens. Lett.*, *5*, 13–16, doi:10.1109/LGRS.2007.905341.

Platnick, S. M., D. King, S. A. Ackerman, W. Paul Menzel, B. A. Baum, and R. A. Frey (2003), The MODIS cloud products: Algorithms and examples from Terra, *IEEE Trans. Geosci. Remote Sens.*, *41*, 459–473.

Powell, M. D. (1980), Evaluations of diagnostic marine boundary layer models applied to hurricanes, *Mon. Weather Rev.*, *108*, 757–766.

Salomonson, V. V., W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow (1989), MODIS: Advanced facility instrument for studies of the earth as a system, *IEEE Trans. Geosci. Remote Sens.*, *27*, 145–153.

Sieron, S. B. (2013), Exploring the feasibility of tropical cyclone intensity estimation using cloud radar and radiometer measurements, *M.S. thesis*, The Pennsylvania State Univ., State College, Pennsylvania.

Stephens, G. L., et al. (2002), The Cloudsat Mission and the A-Train, *Bull. Am. Meteorol. Soc.*, *83*, 1771–1790, doi:10.1175/BAMS-83-12-1771.

Velden, C., et al. (2006), The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years, *Bull. Am. Meteorol. Soc.*, *87*, 1195–1210, doi:10.1175/BAMS-87-9-1195.

Wong, V., and K. A. Emanuel (2007), Use of cloud radars and radiometers for tropical cyclone intensity estimation, *Geophys. Res. Lett.*, *34*, L12811, doi:10.1029/2007GL029960.