On the Use of CloudSat and MODIS Data for Estimating Hurricane Intensity

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Abstract—**This letter presents preliminary results concerning the use of new observations from the A-Train Constellation for testing a new technique of remotely sensing hurricane intensity from space based on modeling a hurricane as a balanced, convectively neutral vortex. The key observational requirements are simultaneous, accurate measurements of cloud-top height, cloud-top temperature, and cloud profiling information across the center of the storm, although there are ways to bypass the need for cloud-top temperature. In this letter, the Moderate Resolution Imaging Spectroradiometer onboard Aqua provides an estimation of the cloud-top temperature, and the near-simultaneous CloudSat observations provide the essential cloud-top height and cloud profiling information. Initial results indicate that the new technique is a promising method for estimating storm intensity when compared *post facto* to the best track database. Potential uncertainties and room for further refinement of the technique are discussed.**

Index Terms—**Radar applications, radar meteorological factors, satellite applications.**

I. INTRODUCTION

METEOROLOGICAL satellites have been used operationally for tropical cyclone surveillance since the mid-1960s, and practically no single hurricane or typhoon has gone undetected since that time [6]. Although these spaceborne observations have improved the surveillance of the movements these deadly storms, reliable estimates of their destructive power using the same spaceborne observations have proven to be much more elusive. Maximum sustained wind, defined as the 1-min average wind speed at an altitude of 10 m, is widely used to characterize the intensity of tropical cyclones and, thus, the potential for damage to property and life. It has proven to be difficult, however, to relate this measure of storm intensity to any existing satellite radiometric quantity. To deal with the situation, an empirical method was developed by [3] to estimate the maximum sustained wind using a cloud pattern recognition technique that is calibrated by aircraft reconnaissance data (see, e.g., [9] for review). Meanwhile, Kidder *et al.* [5] proposed a physical–statistical approach that related the warm anomaly of the microwave oxygen band brightness temperature ($\sim$55 GHz) to the hurricane surface pressure gradient and surface winds at the outer radius. Recent studies (e.g., [1] and [2]) further expanded and refined this approach using Advanced Microwave Sounding Unit data.

The model of tropical cyclones in [4] offers another physically based framework for estimating tropical cyclone intensity [10]. Approximating the hurricane as a vortex in gradient and hydrostatic balance, which is everywhere neutral to slantwise moist convection, Wong and Emanuel [10] (hereafter, the "WE07 Method") derived an expression for the peak wind speed in the storm,[1] i.e.,

$$V_m^2 \approx \frac{T_s - T_0}{T_0} \Delta h^* \tag{1}$$

where T_s and T_0 are the sea-surface temperature (SST) and cloud-top temperature, respectively, and Δh^* is the change in saturation moist static energy ($\equiv C_pT + gz + L_vq$) at cloud-top level,[2] from the eyewall h^*_{eyewall} to the outer region h^*_0. Note that V_m that was so estimated is the maximum gradient wind, which is considered valid at 1–2 km above the surface. The surface wind is then reduced by 20% as a crude means of accounting for the reduction of 10-m winds from the gradient wind, following WE07. Evaluating (1) requires simultaneous, accurate measurements of the cloud-top height and cloud-top temperature of the storm.[3] It was shown in WE07 that this new method works well in cloud-resolving model simulations, but it has only recently been possible to test it with satellite data. With the new observations now becoming available from the A-Train constellation [8], we are now able to quantify the defining parameters of (1) from satellite observations and thus evaluate how well the actual storm intensity might be estimated. The purpose of this letter is thus to outline how these new observations can be used and provide initial tests of the feasibility of this technique by comparing the results with the "Best Track" database.[4]

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[1] This is not to be confused with the upper bound of the maximum winds or the maximum potential intensity that is determined from the storm's environment only (see, e.g., [10] for details).

[2] T, z, and q refer to the temperature in Kelvin, height from the surface in meters, and specific humidity in kilograms/kilogram, respectively. C_p is the isobaric specific heat capacity of dry air, g is gravity, and L_v is the specific latent heat of vaporization.

[3] The contribution from water vapor to moist static energy is negligibly small at the height of hurricane tops, usually as cold as -70 °C.

[4] Although the "Best Track" data (obtained from Unisys Weather database) are not all from *in situ* measurements (so are not all "ground truth"), they are the best alternatives that are available for the current study. A similar premise was followed in the evaluation of other satellite-based method (e.g., [2]). When a much larger CloudSat hurricane database is developed, we will use the reconnaissance data for a separate evaluation.

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TABLE I

INFORMATION ON THE STORMS USED IN THIS LETTER. "Est1" REFERS TO THE ESTIMATION THAT IS BASED ON SST AND RH ASSUMPTIONS, WHEREAS "Est2" REFERS TO THE ESTIMATION THAT IS BASED ON SATELLITE DATA ALONE

Name	Date	Time(UTC)	Est1(m/s)	Est2(m/s)	Best Track(m/s)
Daniel	7/23/06	10:52	55.2	56.7	59.2
Ewiniar	7/4/06	4:43	62.3	53.3	56.6
Ileana	8/23/06	21:02	56.8	55.7	54.0
Prapiroon	8/2/06	5:53	44.3	33.6	33.4
Durian	12/4/06	6:16	43.5	34.7	25.7
Gordon	9/16/06	16:58	43.3	42.9	33.4
Helene	9/17/06	5:05	47.7	41.7	37.3
Clovis	1/2/07	10:33	55.4	41.2	33.4
Arthur	1/24/07	12:34	19.0	43.6	23.1

II. SATELLITE AND ANCILLARY DATA SOURCES

Moderate Resolution Imaging Spectroradiometer (MODIS) 11-μm brightness temperature data are used as a proxy for cloud-top temperature.[5] MODIS onboard Aqua flies in formation with CloudSat, being separated from each other by only an average of 60 s. Cloud-top height is obtained from the CloudSat radar observations. CloudSat was launched on April 28, 2006, carrying with it the first satellite-borne millimeter-wavelength cloud profiling radar (CPR) operating at 94 GHz. The effective vertical resolution of the radar is 480 m, with oversampling at 240-m resolution. The data that were used in this letter are from the 2B-geoprof product [7]. Since launch, more than 150 overpasses of tropical storms have been collected,[6] of which 75 reached hurricane/typhoon strength. However, the "WE07 Method" requires an eye or near-eye overpass, and at this time, nine such cases are available (Table I). For a complete archive of the CloudSat overpasses of tropical storms, please refer to the database that is hosted on the Naval Research Lab webpage http://www.nrlmry.navy.mil/tc_pages/tc_home.html.

Fig. 1 shows an example of both the CloudSat data (radar reflectivity) and the MODIS brightness temperature data for Hurricane Ileana over East Pacific, on August 23, 2006. According to the Best Track database, Ileana achieved the Saffir–Simpson Category 3 status with maximum sustained wind of 105 kn (~54 m/s) at the time of this observation. The eye was well developed, and the CloudSat track passed directly through the eye. Both the eyewall and the outer rainbands are also distinct in the MODIS plan view. From the CloudSat radar profiles, we can further see the bulging up of the eyewall clouds and the gradual downward slope toward the rainbands. This downward slope in cloud-top height can be understood as a manifestation of Δh^* in (1), i.e., the energy input into the storm, since 1) temperature variations with altitude are small in the lower stratosphere and 2) at these very low temperatures, the contribution of latent heat to moist static energy is negligible. The variations in moist static energy along the cloud tops will be dominated by variations in potential energy. Stronger hurricanes will thus usually have a steeper downward slope.

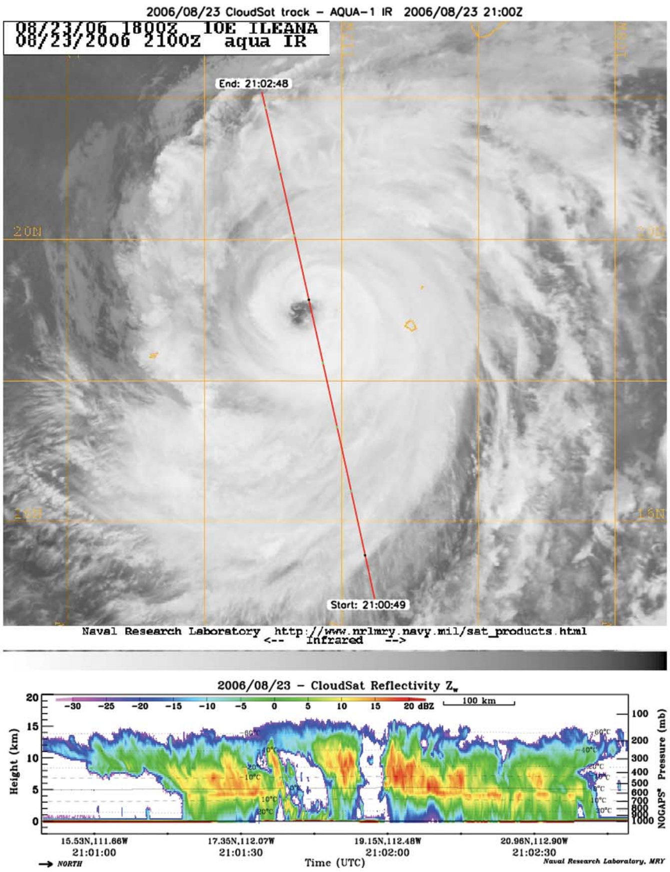

Fig. 1. MODIS (upper) and CloudSat (lower) depiction of Hurricane Ileana.

As evident in Fig. 1, the cloud-top altitude tends to be quite irregular in the outer region, and thus, it is sometimes difficult to assign a single meaningful value to the outer region saturation moist static energy. An alternative is to estimate this from the idea that the saturation moist static energy at the tops of the outer convective clouds h_0^* will be approximately equal to the actual moist static energy of undisturbed air in the boundary layer. In turn, we estimate this, assuming that the surface air temperature is equal to the SST, with a relative humidity (RH) of 80%. For this approach (i.e., indirect estimate of Δh^* across the hurricane top), SST data are also needed, in addition to the satellite data. For this letter, we use the Reynolds-weekly-average 1° latitude/longitude SST data to estimate the SST along each segment of the CloudSat and Aqua orbit under each tropical cyclone. Linear interpolation is performed to get the SST for the time of the overpasses.

III. PRELIMINARY RESULTS

Fig. 2 shows the estimated versus the "Best Track" hurricane intensity in terms of maximum sustained wind speed, based on the estimation of the environmental h_0^* using SST plus the RH assumption (solid symbols). Overall, the new technique has some skill in determining storm intensity, although we stress the caveat that the sample size is too small to draw a

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[5] To minimize error, only the thickest part of the eyewall clouds is examined to infer the cloud-top temperature. Furthermore, it is the brightness temperature difference between the eyewall and the outer rainband that really matters [see (1)].

[6] CPR data that are matched to MODIS cloud data and precipitation information from the Advanced Microwave Scanning Radiometer for EOS as well as best track storm information are being combined into a new A-Train data resource by the Naval Research Laboratory, Monterey, CA, for tropical storm research. Details of this new data resource will be provided in subsequent publications.

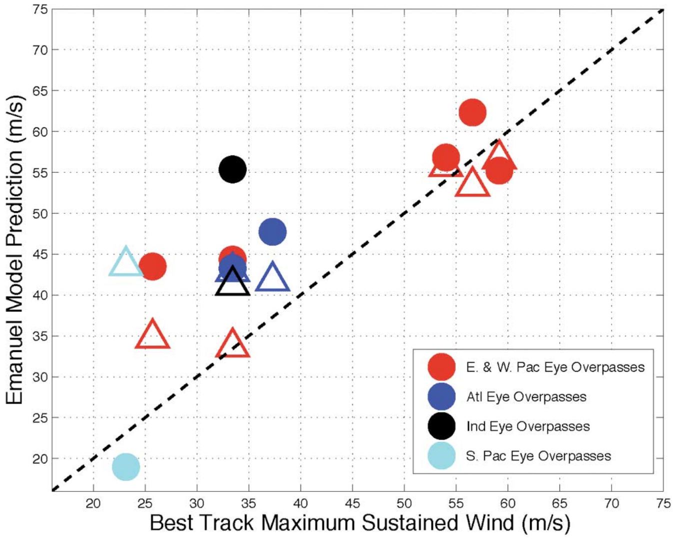

Fig. 2. Estimated versus best track "observed" tropical storm intensity. The dots are for the method that uses SST and 80% RH for estimating the environmental h_0^*, whereas the triangles are for the methods that use satellite data alone to estimate Δh^* (see text for details).

definitive conclusion. There appears to be some indication that better agreement is obtained for stronger hurricanes than for weaker storms. For weaker storms, the new technique tends to overestimate the maximum sustained wind.

The approach to estimate the environmental h_0^* that relies on SST and assumptions about the marine boundary layer (MBL) RH is a potential limiting factor in the application of the technique. The effect of uncertainties that are inherent to the assumptions of this approach can be understood as follows: Differentiating (1), under the assumption that $(T_s - T_0)/T_0$ is constant for small changes in SST, gives $dV_m/V_m = (1/2)d(\Delta h^*)/\Delta h^*$. Thus, one degree of error in SST is equivalent to 3.5 K or 3.5 KJ/kg error in Δh^* (mainly due to the moisture contribution) for an SST of 300 K. However, we estimate that Δh^* ranges from 5 to 10 KJ/kg for those cases that were observed by CloudSat. So, one degree of error in SST would then translate into 18% to 35% of error in the estimated V_m. For this reason, our ultimate goal is to move away from using SST as a basis for estimating the environmental h_0^* and Δh^*.

We try to make a direct estimate of the gradient of the cloud-top moist static energy as shown, for example, in the case of Typhoon Ewiniar in Fig. 3. This shows from top to bottom the 11-μm brightness temperature (MODIS), cloud-top height (CloudSat), estimated cloud-top moist static energy $(C_pT_c + gZ_c)$, and 2B-GEOPROF CloudSat radar reflectivity. Two convective plumes are identified by black arrows representing the eyewall and rainband convection. The cloud-top heights and temperatures of these convective regions are used to estimate Δh^*, which is calculated to be 9 K or 9 kJ/kg (as indicated by the green arrows). Substituting this value into (1), with T_s and T_0 already known, gives an estimated maximum sustained wind of 63 m/s, which is close to the value from the "Best Track," which is 58 m/s.

It is important to note that the validity of using rainband convection for estimating h_0^* and Δh^* depends on the identification of convective cores and that the emissivity of the clouds is similar between eyewall and rainband convection. Moving away from the eyewall to the rainbands is usually associated with a decrease in cloud emissivity, as the cloud tops get increasingly tenuous in the cirrus outflow. It is therefore important to ensure that the cloud top of the rainband convection is indeed that of deep, optically thick clouds with similar emissivity to that of the eyewall convection. CloudSat radar profile information provides an unprecedented ability to determine the nature of the cloud below the tops of thick clouds, thus making it possible to determine whether deep convective cores exist in the rainband and eyewall, as noted by the black arrows in Fig. 3. However, it is not always possible to identify representative convective cores in the outer spiral bands, as it is not always guaranteed that CloudSat will intersect such convection, given the limited sampling of the radar.

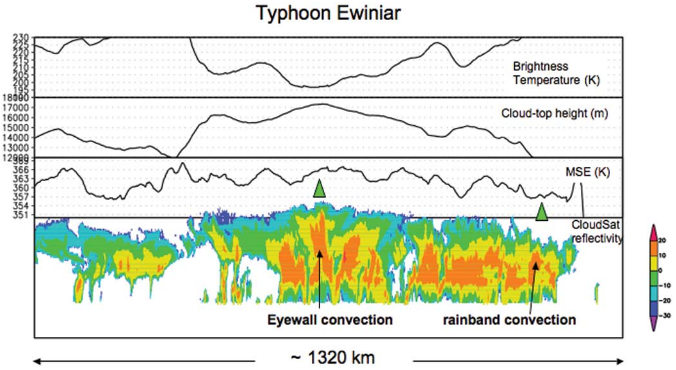

Fig. 3. Typhoon Ewiniar: (from top to bottom) 11-μm brightness temperature (in kelvins), cloud-top height (in meters), calculated moist static energy (in kelvins), and CloudSat reflectivity (in decibels referenced to zero).

To deal with the situation, Wong and Emanuel [10] suggested another way of estimating Δh^* using CloudSat data only. It is assumed that physical cloud-top temperatures across the hurricane top are roughly constant (because temperature variations with altitude are small in the upper troposphere/lower stratosphere region), so that the contribution to Δh^* comes mainly from the difference in cloud-top height (i.e., the downward slope of cloud top near the eye, as shown in Figs. 1 and 3). This is illustrated with another case: that of Hurricane Daniel, as shown in Fig. 4. The eyewall convection and rainband convection are identified through CloudSat radar profiles. The data suggest that there are different emissivities at the cloud tops (rainband convection is noticeably more tenuous, and the brightness temperatures increase quickly as one moves away from the eyewall); thus, the method that was discussed in the previous paragraph cannot be used. The assumption of constant cloud-top temperature in this case leads to a Δh^* that is only estimated from the difference in cloud-top height (the green arrows). For this case, we determine Δh^* to be about 10 K or 10 KJ/kg, which, upon being substituted into (1), gives an estimated V_m of 57 m/s, which is very close the "Best Track" value, which is 59 m/s.

Using cloud-top height alone to estimate Δh^* also has limitations. "Daniel" was a strong hurricane (Category 3) during the CloudSat overpass, and its cloud tops are relatively smooth. For weaker hurricanes or tropical storms, however, the fuzzy and sometimes even broken cloud tops make it difficult to obtain a good estimation of the downward slope. We therefore have to fit a smooth curve to the tops of the weak hurricanes. Moreover,

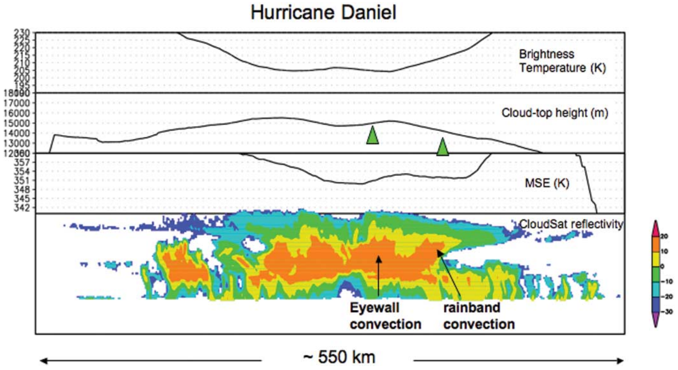

Fig. 4. Same as Fig. 3 but for Hurricane Daniel.

the constant cloud-top temperature assumption may not hold well if the rainband convection is too far away from the eyewall. For example, the rainband convection in Fig. 3 evidently has much higher cloud-top temperature than that of the eyewall convection. Nevertheless, combining the two approaches, as illustrated in Figs. 3 and 4, can increase the chance of finding a way of using satellite data alone for estimating hurricane intensity, toward eventually eliminating the dependence on SST and MBL RH assumptions.

Initial results using the two new approaches that use satellite data alone for estimating Δh^* are also shown in Fig. 2 as triangles. These new estimates significantly reduced the bias that is apparent in the SST-based method for weak storms.

IV. CONCLUDING REMARK

This letter presents preliminary results concerning the use of new observations from the A-Train Constellation for demonstrating and testing a new technique for remotely sensing hurricane intensity from space. The key observational requirements are simultaneous, accurate measurements of cloud-top height, cloud-top temperature, and cloud profiling information across the center of the storm, but there are ways to bypass the need for cloud-top temperature. In this letter, MODIS onboard Aqua provides an estimation of the cloud-top temperature, and CloudSat provides the cloud-top height and cloud profiling information.[7] More than 150 overpasses of tropical storms have been collected (and hosted at the NRL webpage) during the first half of the year of CloudSat mission, but since the new technique requires eye overpasses, the total number of usable cases is decreased to nine. Preliminary results show that the technique is a promising approach for estimating the hurricane intensity, although more data are needed to draw definitive conclusions about the method.

The analysis that was described in this letter is far from being mature enough to be converted to an operational algorithm for estimating storm intensity. However, the study is important in two ways: 1) it represents a unique and first-of-a-kind test of a theory of hurricane intensity that has not been verified against real-world data and 2) in a related way, the exploratory method for estimating intensity is physically based. The study is timely as the defining parameters of this technique are available from advanced satellite instruments such as those of the A-Train constellation, although the data are limited to the few intersections through the middle of the storms. There is also room for further refinement of this technique and, presumably, the theory itself. Specifically, there are a number of uncertainties that were involved that have been discussed, such as the dependence on ancillary SST data in one of the methods. This SST dependence can be avoided, as described by estimating Δh^* directly, through careful selection of eyewall and rainband convection. It proves to work as well for the cases that were analyzed so far, although it imposes extra requirements on satellite crossings. Clearly more cases accumulated over upcoming cyclone seasons will provide an opportunity for expanding the database and examining these issues further. CloudSat data support this kind of exploratory study, which has far-reaching implications for the design of future dedicated satellite observing systems of tropical storms. For example, the value of a scanning cloud radar and higher vertical resolution of cloud radar for improving the accuracy of the estimation of Δh^* would be a desirable benefit of any potential operational system.

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[7] It might appear that both cloud-top temperature and cloud-top height can be deduced from satellite infrared radiometer measurements, where as commonly done the latter one is inferred from the brightness temperature related to an environmental temperature profile. However, the wide-scale cloudy conditions and warm core of the hurricane make it difficult to accurately infer temperature profiles in the vicinity of the eyewall and other areas of deep convection. Collocated cloud radar or lidar is required to measure the height directly, although lidar cannot provide the important internal cloud structures of the storms.