Reprocessing the Most Intense Historical Tropical Cyclones in the Satellite Era Using the Advanced Dvorak Technique

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ABSTRACT

In recent years, a number of extremely powerful tropical cyclones have revived community debate on methodologies used to estimate the lifetime maximum intensity (LMI) of these events. And how do these storms rank historically? In this study, the most updated version of an objective satellite-based intensity estimation algorithm [advanced Dvorak technique (ADT)] is employed and applied to the highest-resolution (spatial and temporal) geostationary satellite data available for extreme-intensity tropical cyclones that occurred during the era of these satellites (1979–present). Cases with reconnaissance aircraft observations are examined and used to calibrate the ADT at extreme intensities. Bias corrections for observing properties such as satellite viewing angle and image spatiotemporal resolution, and storm characteristics such as small eye size are also considered.

The results of these intensity estimates (maximum sustained 1-min wind) show that eastern North Pacific Hurricane Patricia (2015) ranks as the strongest storm in any basin (182 kt), followed by western North Pacific Typhoons Haiyan (2013), Tip (1979), and Gay (1992). The following are the strongest classifications in other basins—Atlantic: Gilbert (1988), north Indian Ocean basin: Paradip (1999), south Indian Ocean: Gafilo (2004), Australian region: Monica (2006), and southeast Pacific basin: Pam (2015). In addition, ADT LMI estimates for four storms exceed the maximum allowable limit imposed by the operational Dvorak technique. This upper bound on intensity may be an unnatural constraint, especially if tropical cyclones get stronger in a warmer biosphere as some theorize. This argues for the need of an extension to the Dvorak scale to allow higher intensity estimates.

1. Introduction

Tropical cyclones (TCs) are well known for their occasional devastating impacts on human life and property, as well as ecological zones. Also known over various parts of the global tropics as hurricanes, typhoons and cyclones (for the remainder of this paper, they will all be referred to as TCs), TCs only rarely reach their full intensity potential. However, when they do, TCs represent simultaneously one of nature's most wondrous accomplishments and formidable threats.

The quest for identifying and ranking the most intense storms on our planet is more than a scientific curiosity. Human populations and infrastructure built along coastlines are growing, and thus are prone to an increasing threat from landfalling TCs. Entities such as the insurance and reinsurance industries are now developing sophisticated models to assess risk of extreme meteorological events. These models benefit from accurate historical data on TC tracks and intensities. Reanalysis efforts are under way in several regions to provide a more accurate assessment of return-event probabilities (e.g., Landsea and Franklin 2013). And with the warming biosphere, the preeminent question ''are TCs getting stronger?'' can only be assessed with a well-calibrated historical dataset (Landsea et al. 2006; Kossin et al. 2013).

The difficulty in determining the actual intensity of a TC, whether in real time or as part of a reanalysis, is a function of the observing system, which is nonconstant over time. The most representative data are provided by in situ platforms. TC-penetrating aircraft can yield the most detailed information on properties such as the

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minimum sea level pressure (MSLP) and radial distribution of the wind field surrounding the center. However, these observations are sporadic, and are confined to selected TC basins and periods that have varied during the aircraft reconnaissance era.

Satellite-based estimates of TC intensity are relied on heavily by regional specialized meteorological centers (RSMCs) tasked with conducting postanalyses of ''final best tracks'' (historical records of TC track and intensity). The Dvorak technique (Dvorak 1975, 1984) is the primary satellite tool utilized by RSMCs for analyzing TC intensity, and it does a reasonable job in most cases. But the method is not without limitations and depends somewhat on analyst judgement (Velden et al. 2006). When developing his technique, Dvorak did not have the full complement of satellite capabilities that exist today, leading to inherent biases in the empirically driven method's estimates, particularly notable at the very strong end of the TC intensity spectrum (Knaff et al. 2010).

The advanced Dvorak technique (ADT; Olander and Velden 2007) is an objective approach to estimating TC intensity that operates on geostationary satellite imagery and builds on the principles of the Dvorak technique, but has also been enhanced by rigorous statistical analysis and additional capabilities that fully exploit the improved qualities of satellite data available today. The ADT is fully automated and runs operationally at the NOAA/NESDIS Satellite Analysis Branch, where it serves as a practical tool for aiding TC forecasters in real-time and postanalysis intensity estimation. An earlier version of the ADT was used by Hoarau et al. (2004) to examine recent intense typhoons in the western North Pacific in relation to the standing-record intensity of Typhoon Tip (1979). In another study, a more contemporary version of the algorithm was applied to a homogenized satellite data record (partially reduced spatiotemporal resolution) to create a more consistent global record of TC intensity (Kossin et al. 2013). However, the primary intent in this application was to investigate the robustness of intensity *trends*, rather than focus on absolute maximum intensities.

In this study, we employ the most updated and fully capable version of the ADT and apply it to the highest-resolution (spatial and temporal) geostationary meteorological satellite data available for selected extreme-intensity TCs that occurred over the globe during the era of these satellites (1979–present). Cases with reconnaissance aircraft observations of intensity are carefully examined and used to help calibrate the ADT at extreme intensities. Bias corrections for observing properties such as satellite viewing angle and image spatiotemporal resolution, and storm characteristics such as small eye size are also considered. The results are an objective satellite-based assessment of lifetime maximum intensity (LMI) and a relative ranking of the most powerful TCs observed in the satellite era.

2. Case selection

Geostationary meteorological satellites became operational in the latter part of the 1970s, which therefore marks the start of our TC case selection. It should be noted that imagery from polar-orbiting satellites was available before this period; however, our study does not utilize these data for reasons discussed later. Infrared (IR) imagery (the ADT only employs the IR window channel) from the GOES (United States), Meteosat (Europe), and GMS/Multifunctional Transport Satellite (MTSAT)/Himawari (Japan) series of satellites at native spatiotemporal sampling was obtained from archives at the University of Wisconsin Space Science and Engineering Center for each selected TC case. Early GMS data were kindly provided by the Australian Bureau of Meteorology. Prior to 1998, the Indian Ocean TC basins were only viewed at the limbs of available operational geostationary satellites. Therefore, to avoid extreme viewing angle difficulties, the reanalysis period for these basins begins in 1998.

The global TC cases to be reanalyzed with the ADT were selected based on a thorough literature search and requested input from experts/historians in the TC community. The minimum requirement to be considered for the list was a LMI reaching category-5 status on the Saffir–Simpson scale (≥140-kt maximum sustained 1-min surface wind) as determined from best-track records.[1] The only exceptions were a couple of borderline category-5 storms in relatively less-active regions [e.g., TC Hellen (2014) in the Mozambique Channel and TC Gwenda (1999) in the Timor Sea] that were included based on the suggestions of regional experts. In more prolific TC basins such as the western North Pacific, not all category-5 TCs were considered for reprocessing given the large number of storms, and after a qualitative review of their satellite signatures. While our selections could have been curtailed further by more even stringent intensity criteria, we chose the conservative

[1] Best-track records provided by the Joint Typhoon Warning Center are used in this vetting process as they are available for all basins outside the North Atlantic and eastern North Pacific and consistently provide 1-min Vmax intensity estimates (compatible with the advanced Dvorak technique used in this study which also outputs 1-min Vmax estimates). The National Hurricane Center best-track data are used in the North Atlantic and eastern-central North Pacific.

TABLE 1. Tropical cyclones during the geostationary satellite era with extreme lifetime maximum intensities selected for reanalysis using the ADT. The named storms include the year of occurrence and are sorted by basin. Indian Ocean basins span the period 1998–2016; all other basins span 1979–2016.

North Atlantic	Eastern-central North Pacific	Western North Pacific	North Indian	South Indian (west of 90°E)	Australian region	South Pacific (east of 180°)
Allen (1980)	Linda (1997)	Tip (1979)	Paradip (1999)	Gafilo (2004)	Orson (1989)	Susan (1997)
Gilbert (1988)	Kenna (2002)	Elsie (1981)	Sidr (2007)	Bruce (2013)	Gwenda (1999)	Ron (1998)
Hugo (1989)	Ioke (2006)	Bess (1982)	Gonu (2007)	Hellen (2014)	Inigo (2003)	Zoe (2002)
Andrew (1992)	Rick (2009)	Mac (1982)		Eunice (2015)	Monica (2006)	Olaf (2005)
Mitch (1998)	Patricia (2015)	Abby (1983)		Fantala (2016)		Percy (2005)
Ivan (2004)		Forrest (1983)				Pam (2015)
Katrina (2005)		Vanessa (1984)				Winston (2016)
Rita (2005)		Dot (1985)				
Wilma (2005)		Flo (1990)				
Dean (2007)		Ruth (1991)				
		Yuri (1991)				
		Gay (1992)				
		Angela (1995)				
		Ivan (1997)				
		Joan (1997)				
		Zeb (1998)				
		Nida (2009)				
		Megi (2010)				
		Sanba (2012)				
		Jelewat (2012)				
		Bopha (2012)				
		Lekima (2012)				
		Haiyan (2013)				
		Vongfong (2014)				
		Nuri (2014)				
		Hagupit (2014)				
		Noul (2015)				
		Soudelor (2015)				

approach in the event that some TCs were severely underrepresented in the best-track records. We are reasonably sure that during the chosen period, the most intense TCs on record (based on either MSLP or maximum sustained surface wind, Vmax) were represented in our selection process. Unsurprisingly, the western North Pacific basin dominates the list of 60 extreme intensity TCs (Table 1), even after our filtering process.

There are a number of curiosities illuminated in Table 1 when viewed in terms of basin-relative intensity trends. For example, prior to 1997 the North Atlantic has only 4 cases while the western North Pacific is by far the most prolific basin with 13. Subsequently during the period 1998–2008, the situation remarkably reverses with an uptick in extreme intensity TCs in all basins except the western North Pacific, which yields only one case (TC Zeb). And most recently (2010–16), the Atlantic and eastern-central North Pacific have only 1 entry (TC Patricia) while the western North Pacific becomes prominent again with 11.

Some of this sporadic interbasin behavior is likely due to large-scale decadal oscillations. However, the historical best-track nuances also open the question of whether they may be influenced by the presence (or lack) of reconnaissance aircraft data, or the availability and changing quality of satellite data (including the addition of microwave imagery), and/or the sometimes subjective nature of the operational Dvorak technique as it evolved during our period of interest. To address these questions and rank the LMIs of the TCs listed in Table 1 in a consistent manner, a reanalysis based on a well-calibrated satellite-based algorithm (objective) operating on the native image resolutions is essential.

3. Approach

a. *Analysis tool (advanced Dvorak technique)*

The Dvorak enhanced infrared (EIR) technique (Dvorak 1984) is widely considered the ''gold standard'' for estimating TC intensity from satellite imagery. However, the technique relies on expert human analysis, and inherent subjective decision-making means that it is not always consistently applied from one specialist to the next, or one forecast office to the next, or one TC season to the next. A thorough review of this technique's strengths and weaknesses can be found in Velden et al.

(2006), and identified biases with Dvorak intensity estimates in Knaff et al. (2010).

To help ameliorate the subjective decision-making issues, the computer-based ADT was developed. The chronology of the ADT evolution and its ability to objectively estimate TC intensity can be found in Velden et al. (1998) and Olander and Velden (2007). Since the last formal publication, there have been numerous upgrades to the algorithm that have enhanced the performance and reliability (Olander and Velden 2012). The current version (v8.2) is fully automated and is now run operationally in real time at NOAA/NESDIS for TCs in all global basins. The ADT-derived intensities are used alongside the subjective Dvorak technique estimates provided by satellite analysts. (Details on how the ADT operates, its limitations, performance metrics, and a user's guide can be found online at http://tropic.ssec.wisc.edu/misc/adt/.)

The basis for the ADT analysis methodology retains key elements of the original Dvorak technique, including the output of intensity in the form of tropical numbers (T#s), which are then related to estimates of Vmax from the Dvorak conversion tables. The ADT operates in a similar way to the Dvorak EIR technique by identifying a ''scene type'' (such as ''curved band'' or ''eye'' scenes) in the imagery, and then applying various statistical–empirical-based models according to scene type. ADT modifications include the addition of regression equations for eye and central dense overcast scene types (curved band and shear scene types still mimic the Dvorak EIR methodology) to calculate the T#s, adjustments to the rules that modulate the allowable intensity ranges, and implementation of a new wind–pressure relationship (Courtney and Knaff 2009) to estimate MSLP from the Vmax.

The regression equations that determine the ADT T#s have been empirically and statistically tuned from many years of comparisons with ground truth observations and best-track data. It was found that the IR signatures in western North Pacific TCs varied slightly in their relation to intensity from TCs in the Atlantic and eastern North Pacific. Better ADT intensity estimates are achieved with separate sets of equations for these two regions. Other TC basins are generally lacking in ground truth data, making it more difficult to assess and apply region-dependent equations. Therefore, the western North Pacific equations were adapted for the South Pacific and Indian Ocean basins after extensive discussion with Dvorak analysis experts in the community. This is an open question, however, and illustrates the need for observational campaigns in TC basins lacking in regular reconnaissance missions.

As successfully demonstrated in Kossin et al. (2013), the ADT is well suited for major TC reanalysis projects. Being fully automated and easily adaptable to various satellites and image formats can make large global TC reanalysis projects quite tractable. The fact that every available image (e.g., every 30 min) can be quickly analyzed instead of 6-hourly as with the operational and subjective Dvorak technique means intensity records can be better represented (i.e., best tracks, which are now 6-hourly). This is particularly important in our study since we seek the absolute TC LMI peaks, which can often fall between the 6-h best-track intensity records. Finally, the ADT benefits from years of research-driven upgrades and calibrations with reconnaissance aircraft ''ground truth'' data. It has a proven track record in operational applications, and for comparative studies it can homogenize interbasin TC intensity estimates by means of an entirely objective approach.

b. Data

The highest available resolution operational geostationary satellite IR imagery was accessed from archives for the lifetime of each TC case in Table 1. For western Pacific cases, this includes *GMS-1* through *Himawari-8*; for Indian Ocean cases, *Meteosat-5* and *-7*; for Atlantic and eastern Pacific cases, *GOES-3* through *-13*. In cases when a TC was in view of two satellites, the imagery with the best viewing angle was chosen. Over the period of interest, the image spatial resolution varies from 8 km with early GOES, to 2 km with the recent *Himawari-8* satellite, and image update frequency also varies from 3-hourly (early GMS) to 30-min (all satellites now). It should be noted that more frequent scans are available from some of these satellites (i.e., rapid-scan modes), but were not used for reanalysis consistency and general nonimpact on the ADT estimates. The effects of the varying spatiotemporal sampling noted above on the ADT performance are discussed later.

The ADT operates primarily on longwave IR window channel imagery. During the period of interest, several of the available satellites have multiple sensing channels in the band centered near 11 μm. When this occurs, the channel closest to this central wavelength is selected and used for consistency; all fall between 10.7 and 11.5 μm. This variation was tested and found to yield insignificant differences on the ADT's intensity estimates.

Passive microwave imagery from low-Earth-orbiting (LEO) satellites is also employed in the ADT analysis when it is available. Higher-resolution microwave imagers first appeared in the late 1980s on the Defense Meteorological Satellite Program (DMSP) satellites, and were later augmented by the Tropical Rainfall Measuring Mission (TRMM) satellites starting in 1998 and lasting until 2015. The Advanced Microwave Scanning Radiometer (AMSR, -E and -2) has provided imagery since 2002. While only some of the 60 cases listed in Table 1 have microwave data available to the ADT reanalyses, it is not deemed a crucial aspect for the purposes of this study. The reasons for this are that the ADT only uses the microwave information in the developing stages of an eye, prior to an eye scene emerging in the IR. Since the LMI of extreme TCs typically occurs well after this eye formation period, the effects of the microwave data on the ADT intensity analysis at the time of LMI are negligible.

The ADT begins the reanalysis of each storm based on best-track information (see footnote 1). TC center fix estimates for each image to be analyzed are obtained from interpolated best tracks and used as "first guess" locations for centering each ADT analysis. The ADT then conducts its own center-finding analysis, which may override the first-guess value. The best-track information is also used (along with surface analyses) to calculate the storm MSLP values once the Vmax is determined by the ADT (described later).

c. TC reanalysis methodology

For each selected TC listed in Table 1, the ADT v8.2 was run on the full-resolution (spatial and temporal) IR imagery for the duration of the event. As with the Dvorak technique, the current intensity number (CI#) is normally used as the final analyzed intensity by the ADT. However, the ADT has a couple of intermediate T# steps before settling on a final CI# value, which includes a 3-h average of "adjusted T#" (adjT#), which are the initial raw ADT T# (akin to the Dvorak technique data T#) plus any rule adjustments that modulate allowable intensity fluctuations–trends. This procedure is effective in smoothing out occasional noisy T# behavior that comes with rapid sampling, particularly when scene types are changing. In our particular application, we seek the absolute intensity peak, and since the LMI in most of these extreme TCs is normally achieved after a solid eye scene has been established for an extended period of time, the scene type is in quasi–steady state. Therefore, the adjT# values are used for determining the final ADT maximum intensities in this study. Sans 3-h averaging, the ADT adjT# are allowed to more quickly "catch up" to the higher raw T# at peak intensity and therefore more properly represent the LMI. The ADT adjT# values at LMI are typically 0.1–0.2 T#s higher than the ADT CI# (3–6 kt for Vmax) at the extreme TC intensities.

The next step in the reanalysis process was to compare the ADT estimates (focusing on the higher peak-intensity values) with any available coincident reconnaissance aircraft estimates of Vmax and/or the associated "recon-aided" best-track values. This was necessary to assess if bias corrections to the ADT estimates would be needed at these extreme intensities, recalling that the ADT has its roots with the Dvorak technique and it was found by Knaff et al. (2010) that the operational Dvorak intensity estimates have a weak bias for intense TCs. Since the ADT uses two sets of basin-specific regression equations in the determination of T#s (one for the western Pacific, Indian, and Southern Hemisphere basins, and one for the eastern-central North Pacific and Atlantic basins), this calibration step was treated separately for the two regions.

For the eastern North Pacific/Atlantic region, aircraft validation–calibration opportunities are numerous. However, only recon data from the early 1990s onward are used after which the surface wind observations became more reliable with improved dropsonde technologies and the step frequency microwave radiometer. The data from TC Patricia (2015) were quite insightful, as were observations from TC Wilma (2005) and other cases on the list in Table 1. Overall, the coincident recon data and associated best tracks from NHC confirmed that the ADT estimates of Vmax were quite good in the extreme intensity regimes. Only an upward adjustment of 0.1T# (~3 kt at these extreme intensities) to the ADT adjT# value at LMI is warranted based on the comparisons.

The western Pacific–Indian Ocean region is more problematic. The authors are not aware of any recon aircraft flights into extremely intense TCs in the Indian Ocean, Australian, or southeast Pacific regions. Rare validation data from in situ surface reports are sketchy, and as a result the confidence was too low to assign any calibration adjustments to the ADT estimates in these basins. In the western North Pacific, the routine Air Force recon flights that ended in 1987 provided generally less reliable estimates of surface winds, especially in extreme events. However, there were many good observations of MSLP [Elsie (893 hPa) in September 1981, Abby (888 hPa) in August 1983, Forrest (876 hPa) in September 1983, Vanessa (879 hPa) in October 1984, Dot (893 hPa) in October 1985, and Betty (891 hPa) in August 1987] from which Vmax can be estimated using pressure–wind relationships (e.g., Courtney and Knaff 2009). And since 1987, there have been occasional aircraft missions flown in this region with updated technologies [flight data from TC Megi (2010) was particularly insightful]. All of these observations (and associated best tracks) were employed in the ADT comparisons–calibrations. After careful analysis, it was found that the ADT exhibits a weak bias at these intensities of −0.3T#s (~−9 kt). Therefore, the maximum adjT#s at LMI for all western North Pacific TCs are given an upward correction of 0.3 T#.

Finally, the calibrated ADT adjT# estimates were considered for further bias corrections based on a case-by-case assessment at LMI. The ability of the ADT to determine T#s in storms with eye scenes is a function of satellite scan angle, image spatial resolution, and eye size. ADT-determined eye temperatures (and hence T#s) will be reduced in storms at higher view angles (>40°), with small eyes (<12-km radius), and viewed with lower-resolution IR imagery (e.g., 8 km pre-1994 in eastern Pacific/Atlantic). Undersampling due to less frequent images being analyzed can also lead to a small low bias in estimating LMI (e.g., 3-hourly from GMS satellites pre-1986). All of these factors are tested for their impact on the ADT intensity estimates.

Comparing coincident recon-aided BT estimates of Vmax in intense TC cases with ADT adjT#s, it was found that satellite scan angle started to become an issue with view angles > 40°. Beyond that, eye size was also a factor, resulting in the following regression-derived relationships (only for cases >40° view angle):

$$\begin{aligned}\text{adt\_err(kts)} &= 39.4 + [-0.98 \times \text{ScanAng(deg)}] \\ &\quad + 0.49 \times \text{ADT\_EyeSize(km)} \\ &\quad \text{using 4 to 5 km IR imagery, and} \\ \text{adt\_err(kts)} &= 54.0 + [-1.39 \times \text{ScanAng(deg)}] \\ &\quad + 0.19 \times \text{ADT\_EyeSize(km)} \\ &\quad \text{using 8 km IR imagery.}\end{aligned}$$

Two relationships are necessary since the ability for the ADT to detect an accurate eye temperature will also depend on the IR image spatial resolution. The only storms in our study sample that were significantly affected by this bias correction are Atlantic TCs Allen, Hugo, and Andrew, and central North Pacific TC Ioke. In the case of TC Allen (1980), the LMI occurred at a wide view angle from *GOES-3* (54°) and necessitated an upward bias adjustment of 18 kt.

Even at near-nadir viewing angles, TCs with very small eyes can have resolvability issues when observed in the IR imagery. While an eye scene was analyzed by the ADT at every LMI instance for all 60 cases in our sample, it was found that those with a radius of 12 km or less merit an upward bias correction of 0.1 T# to the maximum adjT#, and with a radius of 8 km or less an upward bias correction of 0.2 T#. The ADT has an automatic adjustment to the T# for cases when it analyzes a "pinhole" eye scene type; however, for the 60 TC in our sample there were no such cases of this at LMI (although they did frequently occur during rapid intensification stages).

The fidelity of the input IR imagery used by the ADT to calculate estimates also needs to be considered. The vast majority of the IR data employed in this study have a native spatial resolution of 4–5 km. However, for GOES data prior to 1994, that resolution was 8 km. This difference was examined for the effects on the ADT intensity estimates by reducing some of the 4–5 km data to 8 km (as was done in Kossin et al. 2013). A small weak bias in the ADT estimates is noted when the 8-km resolution data is employed, necessitating an upward 0.1T# bias adjustment (~3 kt) to the ADT adjT# estimates at LMI for the four affected Atlantic storms prior to 1994 listed in Table 1.

With regards to image temporal sampling, the majority of cases were analyzed using 30–60 min image frequency. We found no significant differences between these sampling rates with regard to impacts on ADT LMI values. However, the *GMS-2/3* satellites prior to 1986 provided only 3-h image updates, which we found generally results in a small weak bias of 0.1–0.2 T#s [~(3–6) kt]. This bias adjustment is added to the ADT adjT#s at LMI for the affected western North Pacific TCs prior to 1986 that are listed in Table 1.

4. Results

It should be noted up front that the LMI rankings below are based on relatively small differences in the final ADT adjT#s, from which the ADT intensity estimates are based. Mean ADT intensity estimates are on the order of 8–10 kt (Vmax) for eye scenes. Even though we have sought to correct for some of the biases that lead to this mean error, it is arguable that given the estimate uncertainties, the absolute rankings should not be interpreted as based on solid measurements (i.e., in situ aircraft data). Nevertheless, we present the findings as our best assessment based on the objective ADT reanalyses, with the caveat that the differences between the intensity estimates presented below are generally within the standard error.

a. Overall rankings

The LMIs for all 60 TCs in Table 1 as determined by the ADT are ranked by the strongest Vmax estimates. The TCs at the top of the rankings are shown in Table 2 (for brevity, only the top 12 are shown here, but a full list is available from the corresponding author). Eastern North Pacific TC Patricia (2015) is analyzed by the ADT to be the strongest TC in the geostationary satellite era using Vmax as the metric for intensity (182 kt, 1-min sustained wind). The ADT maximum adjT# for Patricia after an upward bias correction of 0.1 T# for a very small eye at peak intensity was 8.4, the highest ever observed by the current version of the ADT. This exceeds the 8.2 adjT# for western North Pacific TC Haiyan (2013). TC

TABLE 2. Rank of the most intense (in terms of maximum sustained 1-min wind) global tropical cyclones in the geostationary satellite era as determined by the objective, satellite-based ADT.

Rank: (ADT Vmax)	Tropical cyclone name (year)	ADT final adjT#[a]	ADT estimated Vmax (1-min avg, kt)	ADT estimated MSLP (hPa) [rank][b]	Best track Vmax (1-min avg, kt)[c]	Best track MSLP (hPa)[c]	Operational Dvorak estimate (CI#)[d]
1	Patricia (2015)	8.4	182	876 [2]	185	872	7.0–7.5
2	Haiyan (2013)	8.2	176	878 [3]	170	895	8.0
3	Tip (1979)	8.1	173	873 [1]	165	870	7.5
3	Gay (1992)	8.1	173	883 [4]	160	872	7.5
5	Gilbert (1988)	8.0	170	887 [8]	160	888	7.5
5	Yuri (1991)	8.0	170	887 [8]	150	885	7.5
5	Nida (2009)	8.0	170	892 [12]	155	907	7.5
8	Linda (1997)	7.9	167	884 [5]	160	902	7.5–8.0
8	Allen (1980)	7.9	167	886 [6]	165	899	7.5
8	Vanessa (1984)	7.9	167	886 [6]	155	880	7.0
8	Wilma (2005)	7.9	167	888 [10]	160	882	6.5
8	Angela (1995)	7.9	167	889 [11]	155	879	7.5

[a] After all bias corrections based on reconnaissance aircraft calibrations, TC eye size, satellite view angle, IR image spatial resolution, and frequency.
[b] Based on Knaff–Zehr–Courtney wind–pressure relationship.
[c] NHC best tracks in Atlantic and eastern North Pacific. All other basins, JTWC best tracks.
[d] If more than one agency's estimate is available, the range is given if there is disagreement.

Tip (1979), which holds the record for the lowest ever measured MSLP, comes in a close third place tied with TC Gay (1992). A summary of the bias corrections applied to the ADT LMI adjT#s for each storm to arrive at the final Vmax estimates is shown in Table 3.

As Table 2 shows, the relative rankings for TCs Patricia, Haiyan, and Tip as the top three in intensity agree with the best-track rankings based on Vmax. Except for TC Patricia, the ADT Vmax values are higher than all of the best-track counterparts and the associated operational Dvorak estimates at the time of LMI. The reasons for this could be twofold: 1) the ADT T#s are measured in tenths, whereas the operational Dvorak technique's T#s are limited to 0.5 stratifications, and 2) the ADT analyzes at 30–60-min intervals, whereas the Dvorak technique fixes are historically done only every 6 h. There is ample evidence from Atlantic reconnaissance data in TC cases with frequent core penetration sampling that peak intensities can be achieved over very short durations (e.g., TCs Patricia and Wilma). Therefore, the ADT can gain some precision in these two ways that could more effectively capture the peak intensities. A possible third factor is the weak bias noted by Knaff et al. (2010) in the operational Dvorak estimates at high intensities; much of the operational best-track intensity information is heavily influenced by the Dvorak estimates. The bias corrections to the ADT estimates for scan angle and eye size as well as "high-end intensity" aircraft calibration are all likely contributing to the relatively higher Vmax T#s in most cases.

There are some intriguing findings with regards to the ADT versus best-track Vmax values in Table 2. While most of the values are within about 12 kt of each other, two notable differences are TCs Nida and Yuri. These storms had much lower best-track Vmax estimates by 15 and 20 kt, respectively, versus the ADT estimates. These lower estimates of Vmax are curious, as their signatures in the IR BD enhancement look quite robust, with big warm eye features (see Fig. 1). TC Yuri did not have any reconnaissance aircraft missions, and the JTWC report states the final best-track intensities were based on satellite analysis. TC Nida was a relatively small system and it appears from an examination of the 30-min ADT intensity listing that the LMI may have occurred between best-track estimate times. There were also fairly extreme deepening rates for both TCs, which due to constraints may have held down the operational Dvorak final intensities (Velden et al. 2006) and thus the associated best-track estimates.

While the eastern North Pacific basin gets the crown jewel (TC Patricia), the western North Pacific dominates the "top 12" with 7 entries. TC Gilbert (1988) edges out TCs Allen (1980) and Wilma (2005) for the strongest ADT-estimated Vmax in the Atlantic. There are no entries from the north Indian Ocean or any Southern Hemisphere basins (discussed in the next section). In terms of distribution over the analyzed period, most of the events (eight) occurred in the first half (1979–97); however, three of the top five (including the top two TCs Patricia and Haiyan) have occurred since 2009. Other

TABLE 3. Summary of bias corrections applied to the ADT adjT#s. All corrections are in units of T#.

Rank: (ADT Vmax)	Tropical cyclone name (year)	ADT final adjT#[a]	Aircraft calibration correction	Image resolution correction	Image frequency correction	Viewing angle correction	Eye size correction
1	Patricia (2015)	8.4	+0.1				+0.1
2	Haiyan (2013)	8.2	+0.3				
3	Tip (1979)	8.1	+0.3		+0.1		
3	Gay (1992)	8.1	+0.3				
5	Gilbert (1988)	8.0	+0.1	+0.1			
5	Yuri (1991)	8.0	+0.3				
5	Nida (2009)	8.0	+0.3				
8	Linda (1997)	7.9	+0.1				
8	Wilma (2005)	7.9	+0.1				+0.2
8	Vanessa (1984)	7.9	+0.3		+0.1		
8	Allen (1980)	7.9	+0.1	+0.1		+0.6	
8	Angela (1995)	7.9	+0.3				

[a] Final adjT# after all bias corrections have been applied. (Note: 0.1 T# equates to ~3 kt–3 hPa at extreme intensities.)

TCs just missing the top 12 include western North Pacific TCs Elsie (1981), Dot (1985), Megi (2010), and Nuri (2014).

TC Patricia merits a place at the top of our rankings, and this agrees with the best track in terms of Vmax. However, it is noteworthy that operational Dvorak estimates, likely held down by constraints during the rapid intensification, peaked at 7.0–7.5 T#, which equates to 140–155 kt. The ADT's real-time estimate was 8.2 T# (176 kt). The NHC analysts usually take a blend or consensus of satellite intensity estimates for the final best track (sans recon). Therefore, it is very possible that had reconnaissance aircraft not been observing the storm near LMI, the TC's final best-track intensity would have been analyzed much lower than the historical 185 kt, and possibly weaker than previous record-holders TCs Haiyan and Tip. In fact based on operational Dvorak comparisons alone, Table 2 shows that the other eastern North Pacific TC Linda (1997) might have been analyzed with a higher intensity. The bias-corrected estimate of 182 kt from the ADT reanalysis, and corroborated by the aircraft observations, provides some confidence for other analyzed extreme cases that did not have reconnaissance observations.

Up until 2013, TC Tip was considered the strongest storm to have formed in the western North Pacific since the beginning of the reconnaissance era. The MSLP was measured at 870 hPa (Dunnavan and Diercks 1980), but the Vmax of 165 kt was estimated from the pressure–wind relationship developed by Atkinson and Holliday (1977). The operational Dvorak estimates at the time (7.5 T#, 155 kt) were at the highest limit allowed by the technique without the addition of a prominent band factor (BF). In a study by Hoarau et al. (2004), it was suggested that TCs Yuri, Gay, and Angela might have intensities higher than TC Tip. Using an earlier version of the ADT (the ODT; Velden et al. 1998) and manual Dvorak estimates, they concluded that these three storms could be classified slightly higher than TC Tip. Our reanalyses suggest that in terms of bias-corrected ADT Vmax-based LMIs, TC Gay could be classified as Tip's equal, but that TCs Yuri and Angela are slightly lower.

When TC Haiyan occurred in 2013 and made a devastating landfall in the Philippines, there was much debate on whether the storm's LMI exceeded the gold standard of TC Tip (Masters 2013). Since there were no reconnaissance observations, the final best-track values relied on satellite estimates and a few sketchy surface reports at landfall. Operational Dvorak estimates reached 8.0 T#s for the first time ever, although it is unclear how these were achieved. The Dvorak rules for adding a BF (usually 0.5 T#) using EIR imagery are a little vague, and operational Dvorak analysts are very constrained in their application of this adjunct to the method. Nonetheless, the JTWC best track lists TC Haiyan with an LMI of 170 kt, which exceeds TC Tip as the strongest TC on record for the western North Pacific in terms of Vmax. Within the estimate uncertainties of the ADT, our reanalysis supports this, with an estimated LMI of 176 kt.

The ADT also outputs MSLP as a function of Vmax and formulas developed by Knaff and Zehr (2007) and Courtney and Knaff (2009), which relate the TC maximum winds to MSLP factoring in storm size, translation speed, latitude, and environmental pressure. Utilizing this metric for LMI, Table 2 indicates that TC Tip retains its longtime ranking as the strongest TC ever measured. The ADT MSLP estimate using the Courtney and Knaff (2009) equation yields 873 hPa, which is within 3 hPa of the aircraft-produced record of 870 hPa.

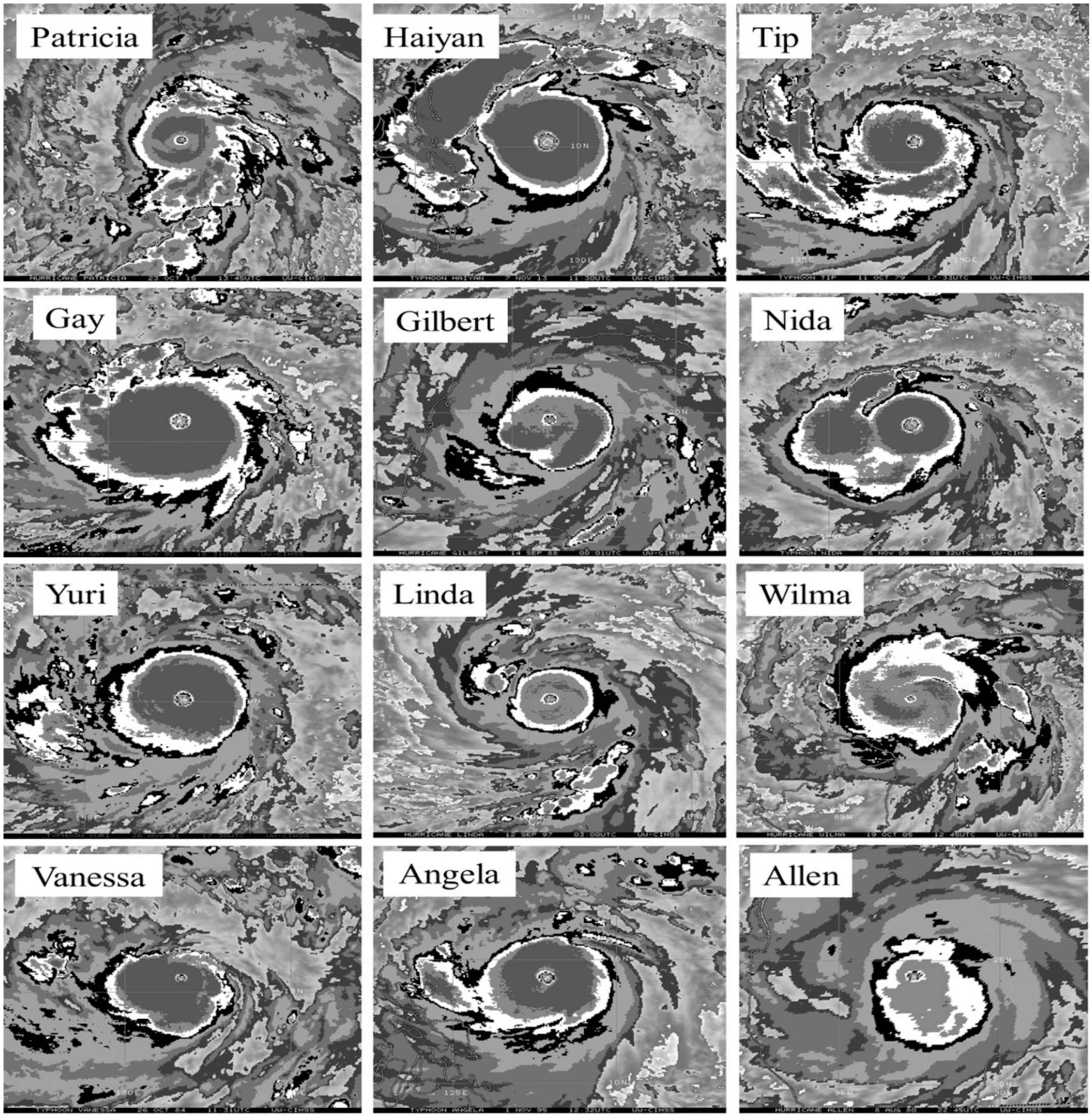

FIG. 1. IR images with the Dvorak BD enhancement applied to the 12 TCs in Table 2 at their respective maximum intensities, remapped to a common projection and scale.

However, there are notable differences between the ADT and best-track MSLP values with TCs Linda and Haiyan. Part of these discrepancies appears to be due to the wind–pressure relationships employed. The Knaff–Zehr–Courtney relationships were not fully developed at the time of these two events, and storm size parameters may not have been adequately captured in the operational best tracks.

It is informative to compare the 12 most intense TCs by their respective satellite signatures at LMI. Figure 1 presents the IR signature of the 12 storms (all in Mercator projections and at the same scale), enhanced with the standard Dvorak BD curve. This enhancement is used with the Dvorak technique to estimate T#s and current intensity (Dvorak 1984), and facilitates those analysts estimating TC intensity by highlighting the differences between the eye temperature and that of the

TABLE 4. The most intense (in terms of maximum sustained 1-min wind) tropical cyclones in the geostationary satellite era by regional TC basin as determined by the ADT. The Indian Ocean basins span the period 1998–2016, while all other basins span the period 1979–2016.

TC basin	TC name (year)	ADT final adjT#[a]	ADT estimated Vmax (1-min avg, kt)	ADT estimated MSLP (hPa)[b]	Best track Vmax (1-min avg, kts)[c]	Best track MSLP (hPa)[c]	Operational Dvorak estimate (CI#)[d]
Atlantic	Gilbert (1988)	8.0	170	887	160	888	7.5
East Pacific	Patricia (2015)	8.4	182	876	185	872	7.0–7.5
Central Pacific	Ioke (2006)	7.5	155	906	140	915	7.0
West Pacific	Haiyan (2013)	8.2	176	878	170	895	8.0
North Indian	Paradip (1999)	7.2	146	910	140	912	7.0
South Indian	Gafilo (2004)	7.3	149	901	140	898	7.0–7.5
	Fantala (2016)	7.3	149	920	155	910	7.0–7.5
Australian	Monica (2006)	7.6	158	904	155	879	7.5
Southeast Pacific	Pam (2015)	7.6	158	890	155	896	7.0–7.5

[a] After all bias corrections based on reconnaissance aircraft calibrations, TC eye size, satellite view angle, IR image spatial resolution, and frequency.
[b] Based on Knaff–Zehr–Courtney wind–pressure relationship.
[c] NHC best tracks in Atlantic and eastern North Pacific. All other basins, JTWC best tracks.
[d] If more than one agency's estimate is available, the range is given if there is disagreement.

surrounding cold cloud ring by performing contrast stretches in both warm and cold portions of the enhancement curve. At extreme intensities, darker gray shades surrounding the eye indicate colder cloud tops and more intense eyewall convection. This premise is used as the basis for the Dvorak intensities, along with the temperature of the eye.

It is evident from the signatures in Fig. 1 that the western North Pacific TCs are generally colder than their Atlantic/eastern North Pacific counterparts. This would seem to imply that a straight application of the Dvorak EIR method would yield higher T#s in the western North Pacific cases, and thereby stronger intensities. And in fact, based on agency TC reports and best tracks, the operational T#s are generally about 0.5 higher for extreme intensity events. Yet, the rankings in Table 2 based on the ADT are not so clear cut. As briefly described in section 2, the ADT employs regression equations to derived T#s. These equations not only take into account the eye and surrounding eyewall cloud-top temperatures, but also the difference between them. They are also tuned separately for the western North Pacific basin and the eastern North Pacific–Atlantic basins based on aircraft calibrations. Therefore, regional differences can be accounted for with the ADT whereas the basic Dvorak procedures to derive T#rs are globally applied.

There is anecdotal evidence to suggest the IR BD signatures may not be suitable for cross-basin TC intensity comparisons. Velden et al. (2006) notes there are regional variations on how the Dvorak technique is applied based on local expert analysis. Reconnaissance aircraft wind observations also support the high intensities and rankings in Table 2 for the eastern North Pacific and Atlantic cases. Finally, Fig. 1 also shows that the western North Pacific TCs are generally larger, as evidenced by the comparative sizes of the cold central dense overcasts (CDOs). Given comparable eye sizes, this would imply expanded surface pressure fields and relatively weaker gradients associated with western North Pacific TCs that would reduce the maximum winds compared to a smaller TC with a similar central MSLP in the Atlantic.

b. Regional rankings by TC basin

Table 4 lists the most intense (in terms of maximum sustained 1-min wind) TCs by regional basin as determined by the ADT. As already discussed, TCs Patricia (eastern North Pacific), Gilbert (Atlantic), and Haiyan (western North Pacific) take the honors in their respective basins. In the central North Pacific, TC Ioke in 2006 rates by far the most intense. The ADT final adjT# was aided by a small bias correction for viewing angle as TC Ioke was near the date line at LMI. The northern Indian Ocean spawned three extremely intense storms, with TC Paradip (1999) barely edging out TC Sidr (2007) and Gonu (2007). In the south Indian Ocean (west of 90°E), the ADT analyzes TC Gafilo (2004) and Fantana (2016) as the strongest events. Tops in the Australian region (defined as 90°E–180°) is TC Monica (2006). Finally, in the eastern South Pacific (east of 180°), TC Pam (2015) rates as the most intense, edging out TC Winston (2016).

Generally all of the ADT LMI Vmax estimates in Table 4 are a bit higher and within 10 kt of the corresponding best-track values. The exception is TC Ioke, for which the best-track estimate of LMI is 15 kt lower than the ADT estimate. Since there were no reconnaissance flights during TC Ioke, the best-track intensities are based on operational satellite estimates. It is unclear if these estimates accounted for the relatively large viewing angle (~53°), but the associated Dvorak CI# was 0.5 T# lower than the ADT. The best-track (JTWC) estimate of MSLP for TC Monica appears to be far too low. An analysis by the Australian Bureau of Meteorology using an earlier wind–pressure relationship puts the estimate at 916 hPa (Australian Bureau of Meteorology 2006).

c. *Analysis caveats and additional notes*

The results above were intentionally restricted to the use of geostationary satellite IR imagery alone in order to keep the reanalysis consistent as possible over the 37-yr period of study. Other satellite spectral bands are (or became) available such as visible, near-IR, and water vapor imagery, but these resources are used mainly in a qualitative way by satellite analysts to assess TC properties and structure. Since our study aims to reduce subjective interpretation, this information was not included into the reanalysis performed here. It was mentioned previously that the ADT will use microwave imager scores as input to help the analysis through developing eye phases. However, once the TC develops an eye in the IR, the microwave data are not used, and the LMI stages in extreme TC events are not significantly impacted. Methods have been developed to utilize microwave sounder information (outside the ADT) to deduce the TC warm core signal and relate that to intensity (Herndon and Velden 2012; Chirokova et al. 2013). But the higher-resolution sounders are not available throughout the entire period of our study, so for consistency sake those data were also not considered.

This study did not make use of the higher-resolution IR imagery available from LEO satellites. The spatial resolution associated with sensors on board these spacecraft ranges from 0.5–2.0 km, which is much better than any of the geostationary imagery until very recently. However, the data are not time continuous, and in fact often sporadic over a TC in the tropics where refresh rates (even if multiple satellites are considered) are on the order of 6–12 h. It is possible to derive a Dvorak data T# from the LEO IR imagery, and the higher resolution may add fidelity to the analysis. However, Dvorak did not base his empirical method on such high-resolution data, so it is unclear if these data T#s would translate directly to his intensity conversion tables. Also, the data T# is not necessarily used as the final intensity determination, since there are time-based rules and constraints to consider as part of the technique. The lack of continuous LEO observations makes the application of the Dvorak rules and constraints more difficult. Finally, the LEO satellite scan angles can be an even greater issue despite the higher spatial resolution, thus necessitating potentially large adjustments for extreme scan angles. Therefore, LEO imagery is not used here, but could merit future investigations.

As discussed earlier, the ADT utilizes the same regression equations to calculate intensity for Indian Ocean and Southern Hemisphere TCs as in the western North Pacific. Evidence to support the validity of this choice is limited to the rare verification opportunities in these basins. However, there is not enough direct, empirical, or anecdotal evidence to support the same bias correction (+0.3 T#) for extreme intensities that was warranted for western North Pacific TCs. The caveat being that if this correction were applied to TCs Monica and Pam, they would rank with the other TCs achieving an ADT adjT# of 7.9. However, the careful damage assessments and postanalyses from these two storms as they made landfalls do not support such intensities (Australian Bureau of Meteorology 2006; WMO 2015).

TC Allen merited extra attention. At the time of LMI, the viewing angle from *GOES-3* was near 54°. Coupled with relatively coarse IR imagery of 8-km spatial resolution, the signature for accurately estimating intensity was not optimal. Figure 1 indicates that Allen's core central dense overcast is not as cold as the other analyzed TCs. The ADT eye temperature is also not as warm, likely a result of the lower-resolution data and oblique-viewing angle. The operational Dvorak estimate yielded a T# of 7.5. Applying the bias corrections get Allen to an ADT adjT# of 7.9, but confidence in this estimate is lower than with the other TCs.

TC Wilma was another unusual TC. The measured (recon) pressure over a 30-h period dropped from 982 hPa to the Atlantic record low of 882 hPa, while the winds increased to 160 kt. During this intensification, the hurricane's eye shrank to as small as 3.7 km in diameter, becoming the smallest eye ever observed in a TC. Shortly thereafter, the storm rapidly lost intensity as part of an eyewall replacement cycle. The Dvorak technique rules do not allow for such a rapid intensity fluctuation (max T# achieved was 6.5 per Table 2), nor does the ADT. Therefore, the ADT adjT#s never achieved the values of the maximum raw T#s (8.2), such as is the case in nearly every other TC in our sample. For the sake of consistency, the ADT rules were not relaxed for Wilma, and the LMI estimate allowed to stand as an adjT# of 7.9 after a correction for the extremely small eye.

Finally it should be noted that the rankings in Table 2 are based on relatively small differences in the final

ADT adjT#s. The ADT mean intensity errors for eye scenes are on the order of 8–10 kt for Vmax. It is arguable that given the estimate uncertainties, the absolute rankings should not be interpreted as based on solid measurements (i.e., in situ aircraft data). Nevertheless, we present the findings as our best assessment based on the objective ADT reanalyses, with the caveat that the differences between the intensity estimates in Table 2 are generally within the standard error.

5. Summary

Historical accounts of tropical cyclones often come with inconsistencies in observations, operational analysis methodologies, and quality of data used to assess intensity. The nuances in best-track records in particular are influenced by the presence (or lack) of available reconnaissance aircraft data, the availability and changing quality of satellite data (including the addition of microwave imagery), and the subjective nature of the Dvorak technique as it evolved during our period of interest. The Dvorak technique relies on expert human analysis, and inherent subjective decision-making means that it may not always be consistently applied from one specialist to the next, or one forecast office to the next, or one TC season to the next.

To address these issues in a quest to rank the lifetime maximum intensities of the most intense TCs in the geostationary satellite era in a consistent manner, a reanalysis based on an objective, well-calibrated satellite-based algorithm operating on the native image resolutions is deemed essential. In this study, we employ the most updated and fully capable version of an objective satellite-based algorithm (the advanced Dvorak technique) and apply it to the highest-resolution (spatial and temporal) geostationary meteorological satellite data available for selected extreme-intensity tropical cyclones over the globe during the era of these satellites (1979–present). Cases with reconnaissance aircraft verification of intensity are carefully examined and used to calibrate the ADT at extreme intensities. Bias corrections for observing properties such as satellite viewing angle and image spatiotemporal resolution, and storm characteristics such as small eye size are also considered.

The results are an objective satellite-based assessment of lifetime maximum intensity for the most powerful TCs observed in the geostationary satellite era (1979–present). By these estimates and chosen intensity metrics (maximum sustained 1-min wind), eastern North Pacific TC Patricia (2015) ranks as the strongest storm in any basin (182 kt) during the period of analysis, followed by western North Pacific TCs Haiyan (2013), Tip (1979), and Gay (1992). TC Gilbert (1988) is ranked just ahead of TCs Allen (1980) and Wilma (2005) for the Atlantic basin crown. In the north Indian Ocean basin, TC Paradip (1999) edges out TC Sidr (2007), while in the south Indian Ocean, TC Gafilo (2004) ranks as the most intense. In the Australian region, TC Monica (2006) is classified as the strongest event while in the southeast Pacific basin, TC Pam (2015) edges out TC Winston (2016).

It is emphasized that these TC rankings are in terms of lifetime maximum sustained surface winds and not minimum surface pressure values. If MSLP is instead considered, TC Tip retains its ranking as the strongest TC on record. Our study chose to highlight the maximum winds, since that is what the Dvorak technique and the ADT actually estimates; MSLP is inferred from the maximum winds. Our reasoning is also supported by the fact that TC extreme winds better reflect the hazard to society than MSLP.

The results confirm previous best-track analyses that TCs Patricia and Haiyan are slightly stronger than any prior TCs in the geostationary satellite era when all storms are analyzed in a consistent, objective manner. In addition, ADT LMI estimates for four TCs exceed the maximum allowable limit of 8.0 T# imposed by the operational Dvorak technique. This upper-bound on intensity may be an unnatural constraint, especially if TCs get stronger in a warmer biosphere as some theorize. At the very least, this argues the need for an extension of the Dvorak scale to allow intensity estimates up to at least 8.5 T#.

These findings should be treated as a best attempt to utilize available satellite data in a consistent way, and ameliorate the subjective elements of operational intensity monitoring noted above. However, it is acknowledged that the estimates are based on one chosen algorithm. The ADT-estimated lifetime maximum intensities should not be taken alone as final assessments, rather they should be viewed as potential guidance for more thorough reanalysis efforts that take into account all available observations. It is also important to remember that the rankings are not to be considered ''all time,'' as the study period of consideration only spans the geostationary satellite era.

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REFERENCES

Atkinson, G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western North Pacific. *Mon. Wea. Rev.*, **105**, 421–427, doi:10.1175/1520-0493(1977)105<0421:TCMSLP>2.0.CO;2.

Australian Bureau of Meteorology, 2006: Severe Tropical Cyclone Monica (17–25 April 2006). Australian Bureau of Meteorology Rep., accessed 10 August 2016. [Available online at http://www.bom.gov.au/cyclone/history/monica.shtml.]

Chirokova, G., M. DeMaria, R. DeMaria, and J. Dostalek, 2013: Applications of JPSS imagers and sounders to tropical cyclone track and intensity forecasting. *Joint EUMETSAT Meteorological Satellite Conf./19th Satellite Meteorology, Oceanography, and Climatology Conf.*, Vienna, Austria, EUMETSAT/Amer. Meteor. Soc. [Available online at http://www.goes-r.gov/downloads/ScienceWeek/2013/posters/03-18/Galina-Chirokova.pdf.]

Courtney, J., and J. Knaff, 2009: Adapting the Knaff and Zehr wind–pressure relationship for operational use in Tropical Cyclone Warning Centres. *Aust. Meteor. Oceanogr. J.*, **58** (3), 167–179.

Dunnavan, G., and J. Diercks, 1980: An analysis of Super Typhoon Tip (October 1979). *Mon. Wea. Rev.*, **108**, 1915–1923, doi:10.1175/1520-0493(1980)108<1915:AAOSTT>2.0.CO;2.

Dvorak, V., 1975: A technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures. *Mon. Wea. Rev.*, **103**, 420–430, doi:10.1175/1520-0493(1975)103<0420:TCIAAF>2.0.CO;2.

——, 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 47 pp. [Available from NOAA/NESDIS, Washington, DC 20233.]

Herndon, D., and C. Velden, 2012: Estimating tropical cyclone intensity using the SSMIS and ATMS sounders. *30th Conf. on Hurricanes and Tropical Meteorology*, Ponte Vedra Beach, FL, Amer. Meteor. Soc., P1.21. [Available online at https://ams.confex.com/ams/30Hurricane/webprogram/Paper205422.html.]

Hoarau, K., G. Padget, and J. Hoarau, 2004: Have there been any typhoons stronger than Super Typhoon Tip? *26th Conf. on Hurricanes and Tropical Meteorology*, Miami, FL, Amer. Meteor. Soc., 16C.1. [Available online at https://ams.confex.com/ams/pdfpapers/75465.pdf.]

Knaff, J. A., and R. M. Zehr, 2007: Reexamination of tropical cyclone wind–pressure relationships. *Wea. Forecasting*, **22**, 71–88, doi:10.1175/WAF965.1.

——, D. P. Brown, J. Courtney, G. M. Gallina, and J. L. Beven, 2010: An evaluation of Dvorak technique–based tropical cyclone intensity estimates. *Wea. Forecasting*, **25**, 1362–1379, doi:10.1175/2010WAF2222375.1.

Kossin, J., T. Olander, and K. Knapp, 2013: Trend analysis with a new global record of tropical cyclone intensity. *J. Climate*, **26**, 9960–9976, doi:10.1175/JCLI-D-13-00262.1.

Landsea, C. W., and J. L. Franklin, 2013: Atlantic hurricane database uncertainty and presentation of a new database format. *Mon. Wea. Rev.*, **141**, 3576–3592, doi:10.1175/MWR-D-12-00254.1.

——, B. A. Harper, K. Hoarau, and J. A. Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science*, **313**, 452–454, doi:10.1126/science.1128448.

Masters, J., 2013: Wunderground Blog: Super Typhoon Haiyan: Strongest Landfalling Tropical Cyclone on Record. Accessed 12 August 2016. [Available online at https://www.wunderground.com/blog/JeffMasters/super-typhoon-haiyan–strongest-landfalling-tropical-cyclone-on-recor.]

Olander, T. L., and C. S. Velden, 2007: The advanced Dvorak technique: Continued development of an objective scheme to estimate tropical cyclone intensity using geostationary infrared satellite imagery. *Wea. Forecasting*, **22**, 287–298, doi:10.1175/WAF975.1.

——, and ——, 2012: The current status of the UW-CIMSS Advanced Dvorak Technique (ADT). *32nd Conf. on Hurricanes and Tropical Meteorology*, San Juan, Puerto Rico, Amer. Meteor Soc. [Available online at https://ams.confex.com/ams/32Hurr/webprogram/Paper292775.html.]

Velden, C. S., T. L. Olander, and R. M. Zehr, 1998: Development of an objective scheme to estimate tropical cyclone intensity from digital geostationary satellite infrared imagery. *Wea. Forecasting*, **13**, 172–186, doi:10.1175/1520-0434(1998)013<0172:DOAOST>2.0.CO;2.

——, and Coauthors, 2006: The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.*, **87**, 1195–1210, doi:10.1175/BAMS-87-9-1195.

World Meteorological Organization, 2015: Post-Tropical Cyclone Pam expert mission to Vanuatu. Mission Rep., 47 pp. [Available online at http://www.wmo.int/pages/prog/dra/documents/WMO-Pam-mission-Apri-2015-FinalReport.pdf.]