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Article

Improving parametric cyclonic wind fields using recent satellite remote sensing data

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Abstract: Parametric cyclonic wind fields are widely used worldwide for insurance risk underwriting, coastal planning, or storm surge forecasts. They support high-stakes financial, development, and emergency decisions. Yet, there is still no consensus on the best parametric approach, or relevant guidance to choose among the great variety of published models. The aim of this paper is first and foremost to demonstrate that recent progresses on estimating extreme surface wind speeds from satellite remote sensing now makes it possible to select the best option with greater objectivity. In particular, we show that the Cyclone Global Navigation Satellite System (CYGNSS) mission of NASA is able to capture a substantial part of the tropical cyclones structure, and allows identifying systematic biases in a number of parametric models. Our results also suggest that none of the traditional empirical approaches can be considered as the best option in all cases. Rather, the choice of a parametric model depends on several criteria such as cyclone intensity and/or availability of wind radii information. The benefit of using satellite remote sensing data to better select a parametric model for a specific case study is tested here by simulating hurricane Maria (2017). The significant wave heights computed by a wave-current hydrodynamic coupled model are found to be in good accordance with the predictions given by the remote sensing data in terms of bias. The results and approach presented in this study should shed new light on how to handle parametric cyclonic wind models, and help the scientific community to conduct better wind, waves and surge analysis for tropical cyclones.

Keywords: Remote sensing; cyclones; parametric models; hurricanes; CYGNSS; ASCAT; storm surges; waves; winds

1. Introduction

Since the overview of Vickery et al. [1], numerical atmospheric models have been increasingly applied in storm surge prediction or coastal hazard assessment studies [2-5]. Nonetheless, parametric models deriving cyclonic wind fields from a few input parameters (pressure drop, maximum velocity, wind radii, location of the cyclone center, etc) are still widely used by the research and insurance communities, due to their simplicity, efficiency, and low-computational costs [6-12]. This is especially true for studies investigating storm surge hazards with statistical approaches, which require the construction of a large number of synthetic storms [13-16].

For a few decades (and still often today) the parametric surface winds were simply derived as the sum of an axisymmetric wind field and a uniform vector to mimic the asymmetry due to the storm translation speed. Vivid debates arose to determine the best way to estimate both components, which is a particularly relevant issue since large discrepancies of the synthesized wind field occur depending on the chosen method [17]. This kind of approach where the tropical cyclone (TC) size is generally determined by a single parameter (the radius of maximum winds), presents several drawbacks. In particular, it generally does not satisfactorily represent the TC wind asymmetry, which can be due to many factors such as blocking action by a neighbor anticyclone, boundary layer friction, or terrestrial effects [18].

To date, the increasing availability of satellite remote sensing data makes it possible to better depict and forecast the wind structure of TCs and its variations with azimuth. Whether they are based on infrared imagery and data [19-21], scatterometry [22-23], X-band, C-band and L-band radiometry [24-29], or global navigation satellite system-reflectometry (GNSS-R) [30-32], all these data can provide information about the 34-kt, 50-kt, and/or 64-kt wind radii in each TC quadrant. These radii are now commonly reported in advisories issued by warning centers.

Yet, to our knowledge, only very few studies investigating TC winds, cyclonic-induced waves, or storm surges through parametric models account for all this information, whether for forecasts or hindcasts. Besides, it is striking to see that even now, there is neither consensus nor even real debate on the best gradient wind model, i.e. the parametric model that will represent with the greatest accuracy the increase and decay of wind speed as a function of distance to the TC center. A vivid example of this is the Holland [33] vortex. Although known to present significant drawbacks [34], this model is still widely used by the research and insurance communities all over the globe. Other commonly used parametric wind models (for which there is room for improvement) include for example Jelesnianski and Taylor [35], or Emanuel and Rotunno [36]. New models are proposed almost every year [18,37], but the published studies also generally suffer from one or several drawbacks, including:

- a *lack of information about the parameters considered*. For example, the empirical surface wind reduction factor (SWRF [38]) used for computations is rarely indicated, although it is thought to play a significant role in the estimated surface wind speeds [17].
- *comparisons/validations with a limited number of observed data*. In-situ observations of surface wind speed are relatively sparse for TCs, as they spend most of their lifetime over the oceans, where the density of buoys able to record extreme winds is relatively small. Besides, the wind recorded by meteorological stations is often biased because of terrestrial effects, which makes it difficult to compare observations with parametric values in a consistent way. Although these issues are offset to some extent in the North Atlantic and East Pacific thanks to aircraft reconnaissance, it remains a major problem in all oceanic basins.
- *comparisons/validations with a limited number of parametric wind models*. Except the work of Lin and Chavas [17], we are not aware of any study investigating parametric wind models over a wide range of parameters and methods. New proposed models are often compared to the Holland [33] or Jelesnianski and Taylor [35] approaches to assess their quality, and disregard more recent models such as Willoughby et al. [39] or Emanuel and Rotunno [36].
- *comparisons/validations with parametric models which do not include all the available information about the TC wind structure.* As noted before, very few studies take into account all the available information about wind structure, such as the 34-kt, 50-kt, and 64-kt wind radii for each quadrant. Most of the time, only the hurricane-force (i.e. 64kt) wind radii are used, which potentially results in errors far from the cyclone center.

Yet, indirect surface wind speed measurements using remote sensing data are now expected to be mature enough to help us overcome most of these limitations. The recent availability of data from CYGNSS (Cyclone Global Navigation Satellite System), a spatial mission dedicated to wind speeds retrieval near the eye of TCs, is a promising example.

The main objective of this paper is to investigate the benefits of using recent satellite remote sensing data such as CYGNSS or ASCAT (Advanced Scatterometer) to help everyone selecting the most suitable parametric model, depending on his own case study.

After a short description of data and wind models used in the present study (section 2), we compare CYGNSS and ASCAT data with parametric models constrained by observations for 16 recent hurricanes (section 3). The aim is to provide a first evaluation of the usefulness of these remote sensing data as proxy for surface wind speeds. As we will show, these preliminary results suggest that CYGNSS and ASCAT might indeed provide reliable estimates for extreme and moderate wind speeds respectively. We then *hypothesize* that it is indeed the case, and check whether or not this assumption leads to consistent results. To this aim, we first compute the biases given by several parametric models to see if we can reproduce the findings of past studies (section 4). We then perform numerical hindcasts of hurricane Maria (2017) using several parametric formulas, and compare significant wave heights computed with real in-situ data to check, again, if the results are consistent (section 5). We finally discuss the main results of the manuscript and give concluding remarks (section 6).

2. Data and Methods

2.1. Cyclone selection

The Atlantic Ocean had a very active hurricane season in 2017, due to six major hurricanes and two in category 5. Thanks to aircraft reconnaissance, large quantities of high-quality in-situ data were collected and incorporated into models to better reproduce the hurricanes and their evolution for a wide range of intensities and sizes. Besides, the CYGNSS mission of NASA (dedicated to surface wind speed measurements in extreme conditions) was launched just in time to collect data for this season. These conditions are ideal for revisiting the structure of TCs, and the ability of parametric models to approximate it. In this study, we considered most of the hurricanes that occurred both in Atlantic (ATL) and East Pacific (EP) during the 2017 season. In all, 16 events were taken into account (Table 1).

Table 1. List and characteristics of the 16 hurricanes considered in this study. The minimum and maximum radii at 34-kt, 50-kt, and 64-kts (R34, R50, and R64 respectively) are given in nautical miles at the peak intensity. WS stands for wind speed.

Number	Name	Basin	Dates	TC Category (max WS)	Min/Max R34	Min/Max R50	Min/Max R64
1	Dora	EP	25/06 → 28/06	1 (80kt)	40/70	20/40	15/25
2	Eugene	EP	07/07 → 10/07	3 (100kt)	60/110	40/80	20/30
3	Franklin	ATL	07/08 → 10/08	1 (75kt)	60/130	30/50	NA/30
4	Gert	ATL	13/08 → 17/08	2 (90kt)	50/120	15/60	NA/30

5	Harvey	ATL	17/08 → 30/08	4 (115kt)	70/120	40/60	20/35
6	Hilary	EP	24/08 → 30/08	2 (90kt)	60/90	30/50	15/20
7	Irma	ATL	30/08 → 11/09	5 (160kt)	80/160	50/100	30/45
8	Irwin	EP	23/07 → 01/08	1 (80kt)	30/60	10/30	NA/15
9	Jose	ATL	05/09 → 22/09	4 (135kt)	50/120	30/50	20/30
10	Katia	ATL	06/09 → 09/09	2 (90kt)	60/60	20/40	15/20
11	Kenneth	EP	19/08 → 23/08	4 (115kt)	60/90	30/50	15/25
12	Lee	ATL	16/09 → 30/09	3 (100kt)	60/80	40/50	25/30
13	Maria	ATL	16/09 → 30/09	5 (150kt)	100/150	60/80	35/50
14	Max	EP	13/09 → 15/09	1 (70kt)	30/40	20/20	10/10
15	Norma	EP	14/09 → 19/09	1 (65kt)	70/80	30/50	NA/25
16	Otis	EP	16/09 → 19/09	3 (100kt)	40/60	20/40	10/20

For each of these events, we considered the following data provided by the NHC (National Hurricane Center) advisories: location of the cyclone center, minimum pressure, maximum wind speed, radii of the 34-, 50-, and 64-knot winds in the four quadrants at every 6 hours. Most of these data were calibrated using aircraft reconnaissance and are consequently expected to be reliable.

2.2. Remote sensing data

We also collected the full dataset distributed by the CYGNSS and ASCAT science team members for the 2017 hurricane season in Atlantic and East Pacific.

The CYGNSS mission [31] consists of a eight satellites-constellation in low-inclination circular orbit that receive direct and reflected GPS L1 (1.575 Ghz) signals to infer surface wind speeds and sea roughness, even for intense rainfalls typically observed during hurricanes. It allows for a good spatial and temporal coverage, with mean and median revisit times over the tropics of 7.2h and 2.8h respectively [32]. The 25km- resolution data considered here (v2.0) have been validated and calibrated using cyclones of the 2017 season, including most of the events considered in this study (Table 1). For the time being, the overall root mean square (RMS) error in the CYGNSS retrievals is about 1.4m/s and 17% for wind speeds lower and larger than 20 m/s respectively [40]. According to the CYGNSS team (personal communication), the bias explains approximately half of the high wind RMS (about 8.5%), the other half being random scatter. Generally speaking, we can thus expect maximum biases of a few meters per second, even for high wind speeds.

We tested here several Level 2-wind speed products:

- The "wind speed" (*ws*) product is derived from the best fit to both the normalized bistatic radar cross-section (NBRCS) and leading edge slope (LES) of the integrated delay waveform given by the delay-Doppler maps (DDM [41]), using a fully developed seas geophysical model function (GMF);
- The "yslf_les_wind_speed" (*les*) wind product is derived from only the LES of the DDM, using a young seas / limited-fetch GMF;
- The "yslf_nbrcs_wind_speed" (*nbrc*) product is derived from only the NBRCS, using the young seas / limited-fetch GMF.

ASCAT [22,42] consists of C-band scatterometers mounted on the satellites MetOp-A and MetOp-B, that were launched in 2006 and 2012 respectively. The emitting antennas transmit pulses at 5.255 GHz and extend on either side of the instrument, which results in a double 500km-wide swath of observations. These scatterometers are found to give reliable estimations of wind speeds up to at least 34-kt. However, they lose sensitivity in extreme conditions and are often plagued by rain contamination. We use here the 25km-resolution coastal product, which give more wind data close to the coast [43].

2.3. Parametric wind models

For a given cyclone and parametric gradient wind profile, we estimated the surface wind speed associated to each CYGNSS and ASCAT data point according to the following main steps:

1- From the NHC advisories, we estimated the surface background wind relative to the cyclone translation velocity at the time of acquisition of the considered CYGNSS/ASCAT data point. Following the approach of Lin and Chavas [17], we assumed that this wind is decelerated by a factor α=0.56 and rotated counter-clockwise by an angle β=19.2° from the free tropospheric wind.

2-We removed the translational portion of the wind speed from the maximum observed wind velocity and the 34-, 50-, and 64kt winds.

3-We converted surface velocities to velocities on top of the atmospheric boundary layer by applying an empirical surface wind reduction factor SWRF [38]. In the following sections, we specified SWRF=0.9. Other values were tested, but for the sake of simplicity results are not presented here (they add very little to the conclusions of this paper).

4-We estimated the maximum wind radii for the four quadrants, using the chosen parametric gradient wind profile, and the available wind radii information. For each quadrant, up to three radii of maximum wind are thus obtained: one from the 64-kt wind radius (R_{m64}), another from the 50-kt wind radius (R_{m50}), and a last one from the 34-kt wind radius (R_{m34}).

5-Depending on the available wind radii information considered, we computed R_{m64}, R_{m34} or all the radii of maximum winds (R_{m64}, R_{m50}, and R_{m34}) for the data point azimuth, using a spline interpolation.

6-We computed the wind speed values at the CYGNSS/ASCAT data point obtained using the chosen parametric gradient wind profile and the radii of maximum winds considered (R_{m64}, R_{m34}, or all three of them).

7-We assessed the wind speed at the CYGNSS/ASCAT data point, using a weighted average of the wind speeds obtained in the previous step. We followed the procedure proposed by Hu et al. [44], which ensures that all the wind radii information is satisfied.

8-We obtained the surface wind speed by multiplying the result by SWRF.

9-The wind speed obtained in the previous step was combined with the surface background wind computed in step 1 to get the final parametric wind speed at the CYGNSS/ASCAT data point considered.

This procedure is repeated for all the storms, gradient wind profiles, and CYGNSS/ASCAT Level 2-data points within a distance of 200km from the cyclone center. The parametric models considered here are given in Table 2.

Table 2. Parametric wind models considered in this study. For all of them, an empirical surface wind reduction factor [38] SWRF=0.9 was prescribed. Comparisons are only made for data within a distance of 200km from the cyclone center. The translation vector is reduced by a factor α=0.56 and rotated counter-clockwise by an angle β=19.2°, according to the findings of Lin and Chavas [17]. Here, V_m and R_m are the maximum wind speed and the radius of maximum winds. r refers to the distance to the TC center, and f to the coriolis coefficient.

Name	Main reference	Formula
E11	*Emanuel and Rotunno [36]*	$V(r) = \dfrac{2r(R_m V_m + 0.5 f R_m^2)}{R_m^2 + r^2} - \dfrac{fr}{2}$
E04	*Emanuel [45]*	$V(r) = V_m \dfrac{R_{0-r}}{R_0 - R_m}\left(\dfrac{r}{R_m}\right)^m \left(\dfrac{(1+b)(n+m)}{n+m\left(\dfrac{r}{R_m}\right)^{2(n+m)}} + \dfrac{b(1+2m)}{1+2m\left(\dfrac{r}{R_m}\right)^{2m+1}}\right)^{0.5}$ with b=0.25, m=1.6, n=0.9, R_0=420km
J92	*Jelesnianski et al [46]*	$V(r) = \dfrac{2rR_mV_m}{R_m^2 + r^2}$
H80	*Holland [33]*	$V(r) = \sqrt{\left(\dfrac{R_m}{r}\right)^B \dfrac{B\Delta P exp\left(-\left(\dfrac{R_m}{r}\right)^B\right)}{\rho} + \dfrac{r^2 f^2}{4}} - \dfrac{fr}{2}$

		with $B = \frac{V_m^2 e\rho + f V_m R_m e\rho}{\Delta P}$, $\rho = 1.15$, $e = \exp(1)$
H80c	*Holland [33] with cyclostrophic approximation*	$V(r) = \sqrt{\left(\frac{R_m}{r}\right)^B \frac{B\Delta P exp\left(-\left(\frac{R_m}{r}\right)^B\right)}{\rho}}$ with $B = \frac{V_m^2 e\rho}{\Delta P}$, $\rho = 1.15$, $e = \exp(1)$
M16	*Murty et al. [37]*	$V(r) = V_m \left(\frac{2rR_m}{(R_m^2 + r^2)}\right)^n$ with $n = 3/5$
W06	*Willoughby et al. [39]*	For $0 \leq r \leq R_m$: $V(r) = V_m \left(\frac{r}{R_m}\right)^n$ with $n = 0.79$ For $r \geq R_m$: $V(r) = V_m exp\left(-\frac{r-R_m}{X}\right)$ with $X = 243km$

3. Comparison of CYGNSS and ASCAT data

To get a preliminary idea of the usefulness of CYGNSS and ASCAT data as proxy for surface wind speeds, we computed the biases between these data and the mean (i.e. averaged over all empirical models) parametric winds for different cyclone categories and distances to the center (Figure 1). Computations were performed only when more than 30 data points were available for a given intensity/distance class. In practice, the comparison was possible for almost all cases, as hundreds or even thousands of space-borne observations were available for each class. Parametric models have been constrained by all the information provided by the NHC in the advisories, to ensure that they give the best approximation possible to real winds. In classes for which the biases are large, remote sensing data are not consistent with the mean parametric winds. We choose not to investigate further these data in the following sections, even if there is no evidence that the error is due to remote sensing rather than parametric models. On the contrary, small biases (in absolute terms) suggest that remote sensing data and parametric winds are consistent, so that they both give satisfactory results *a priori*. In the following, we will make the assumption that these CYGNSS/ASCAT data are indeed good proxies, and check whether or not this hypothesis leads to consistent results.

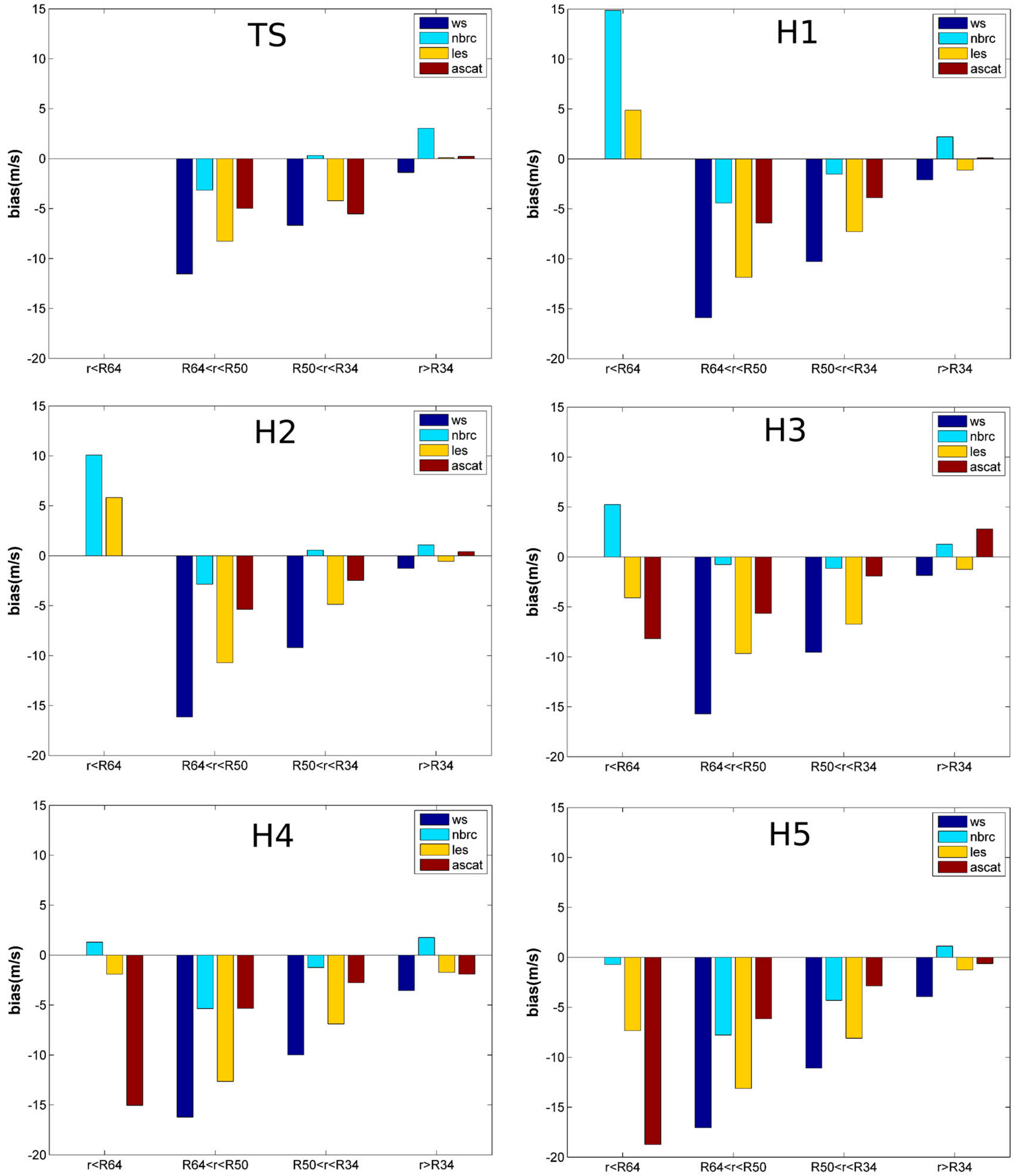

Figure 1. Bias between the remote sensing data and the parametric winds averaged over all empirical models (negative/positive values indicate that remote sensing data are negatively/positively biased compared to the mean parametric winds) . Different categories of distance to the cyclone center (r) and cyclone intensities are considered. TS stands for tropical storms, H1, H2, H3, H4, and H5 to the cyclone category (1, 2, 3, 4, and 5 respectively). R34, R50, and R64 are the radii for the 34-kt, 50-kt, and 64-kt winds. *ws*, *nbrc*, and *les* are three different CYGNSS products (see section 2).

Regarding ASCAT data, Figure 1 shows that the bias is low (less than about 2-3m/s in absolute value) for radius larger than R34, but becomes increasingly negative with cyclone category and decreasing distance to the cyclone center, up to almost -20m/s. These results suggest that ASCAT data are a good proxy for wind speeds lower than 34-kt, but that they underestimate extreme winds. This conclusion is consistent with previous published papers [47].

The "wind speed" (*ws*) product is found to give systematically more negative biases than ASCAT, and thus probably often underestimates the velocities (Figure 1). However, the absolute value of bias remains relatively low for radius larger than R34, which suggests that this product might still be a good proxy for moderate and (potentially even more) low wind speeds. As this product was developed for fully developed seas, these results were also expected.

Wind speeds derived from only the LES of the DDM ("*les*" in Figure 1) display, again, negative biases for r>R64. However, those remain smaller in absolute value compared to "*ws*", which makes sense since this product has been derived using a young seas / limited-fetch GMF that is expected to be more suitable for our test cases. Considering the potential errors on parametric models, it could be a proxy as good as ASCAT for radius larger than R34. Above all, this product shows significantly reduced biases for r<R64. This suggests that it yields better estimates of surface wind speeds than ASCAT close to the eyewall.

The wind speeds derived from only the NBRCS ("*nbrc*" in Figure 1) outperform the other products in most cases for radius lower than R34, with bias generally lower than 5m/s in absolute value. The main exception is the wind for radius lower than R64 for minor cyclones (category 1 or 2), where the bias reaches 10 to 15m/s. One plausible explanation is that the resolution of CYGNSS (25km) is too low to capture the surface wind speeds in these area, especially for weak cyclones where the 64kt radii are very close to the eyewall, i.e. to places where wind speeds vary quickly as a function of distance to the center. This problem is presumably less severe for major cyclones (category 3 or more) because of a larger extent of hurricane-force winds (Table 1).

Based on all these findings, we will *hypothesize* in the following section that the ASCAT and CYGNSS/NBRC products are the best surface wind speeds proxy for r> R34 and r<R34 respectively. However, we will not consider radii lower than R64 for weak (category 1-2) cyclones, as Figure 1 also suggest that none of the space-borne products tested here is reliable in these conditions.

We will check in sections 4 and 5 whether these preliminary results and assumptions give results consistent with previous work and in-situ data, to confirm or invalidate them *a posteriori*.

4. Performance of parametric wind models

Using the assumption made in the previous section, we computed the bias of the various parametric models as a function of storm intensity, distance to the cyclone center, and calibration method (using only radii at 34kt, only radii at 64kt, and all radii information for the left, middle and right panels respectively in Figure 2). The color bar shows the absolute value of bias. Blue colors correspond to small biases (in absolute value), and thus suggest that the parametric model should work well for the intensity/distance class considered. Conversely, red colors indicate that the model is expected to perform poorly. The aim is to see whether the assumption on which this figure is based ("ASCAT and CYGNSS/NBRC are good wind speeds proxy for r> R34 and r<R34 respectively") gives consistent results or not.

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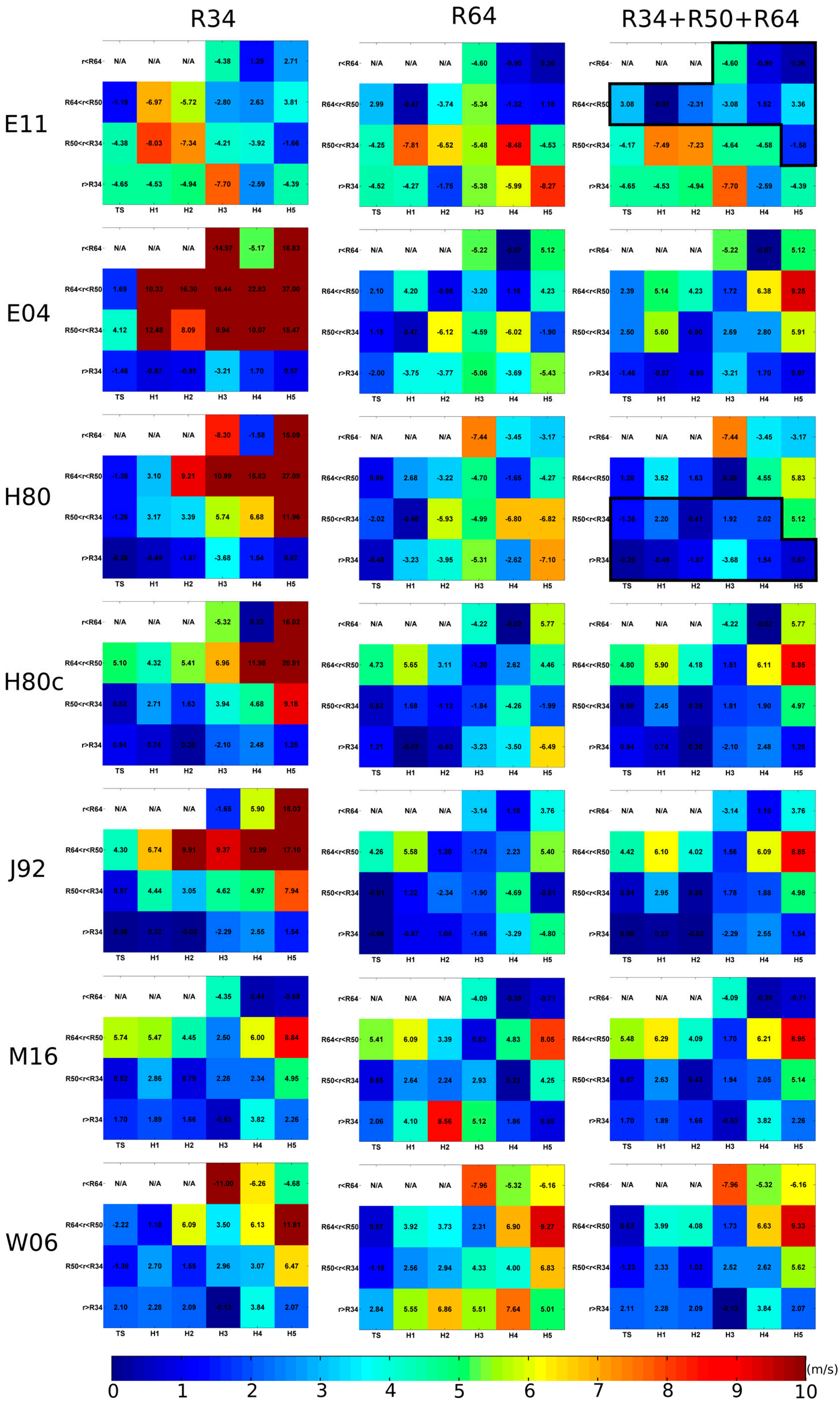

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Figure 2. Diagrams displaying the bias between various parametric models and the surface wind speeds estimated by CYGNSS/ASCAT data for all the events considered here, as a function of storm intensity and distance to the cyclone center (x- and y-axis respectively for each diagram), as well as calibration method (using only radii at 34kt, only radii at 64kt, and all radii information for the left, middle and right panels respectively). The color bar (the same for all diagrams) shows the absolute value bias. The values are displayed for each category/distance cell. The black contours indicate the category/distance classes for which we consider E11 and H80 models in section 5 (model E11H80).

First of all, it appears that the bias is significantly reduced in almost all cases for r<R64 and r>R34 when constraining the parametric models by R64 and R34 respectively. This suggests that not only the "mean" parametric wind values computed in section 3 are consistent with the CYGNSS/ASCAT data for these classes, but also most of the parametric models taken individually, as long as they are constrained by the 64-kt and 34-kt wind radii given by the NHC. This finding gives additional credit to the assumption we made in section 3. It may, however, be observed that biases are not always so much reduced (and can even be increased) when constraining the parametric models by R50 for very intense (category >3) cyclones. This issue appears also in Figure 1, where strangely the absolute bias of CYGNSS is larger for R64<r< R50 than for r<R64. There could be several explanations to this fact: an issue with the calibration of CYGNSS data for these conditions of course, but also a problem with the parametric models for extreme events in the "transition zone" (the area between the inner core/outer region). The latter cannot be dismissed, as most parametric models were built by focusing mainly on the inner and/or outer regions (e.g. [39]), whereas much less attention was paid to the transition zone between extreme and moderate winds. We will return to this point later on.

The results are also found to be consistent with most of the previous works. For instance:

- The inner region solution of Emanuel and Rotunno [36], E11, generally gives the smaller bias (hence the best results) close to the storm center (typically, for r<R50), especially for intense and well defined cyclones. It is also found to underestimate significantly the wind speeds far from the center as found in Lin and Chavas [17], even when prescribing the radii at 34-kt. E04 performs much better for the outer region, but poorly near the center. E11 and E04 can thus be merged to develop a complete TC radial wind structure as proposed by Chavas et al. [48];
- When solely constrained by radii close to the cyclone center (here R64), the Holland profile (H80) tends to underestimate the winds in the outer region, as noted by Willoughby and Rahn [34]. It can also lead to broad wind maximum, and thus wind overestimations at several dozens of kilometers from the center for extreme cyclones (for R64<r<R50 for example), as can be seen in the right and left panels notably. These findings, which are in accordance with the results of Willoughby and Rahn [34], confirm that the issue we identified earlier with the 50-kt wind radii could be partly due to flaws in parametric models such as H80 in the "transition zone".
- J92 tends to overestimate the wind speeds by a few m/s, as suggested by Lin and Chavas [17];
- The results are generally much better when considering a family of profiles with two characteristic lengths, as proposed by Willoughby et al [39]. For example, as stated above, the performance of the Holland model H80 is significantly increased when both radii at 34-kt and 64-kt are prescribed;
- Models such as W06 or M16 (which decay exponentially or as a power-law outside the eye) perform well in the outer region when the 34-kt radii are prescribed properly, which is consistent with the findings of Willoughby et al. [39] and Murty et al. [37].

The consistency of these results increases the confidence in our assumption that the ASCAT and CYGNSS/NBRC products are relatively good proxies for surface wind speeds, for r>R34 and r<R34 respectively (with the exception of the inner region for weak cyclones). To further build the confidence in this hypothesis, we also performed numerical hindcasts of hurricane Maria (2017), and compared computed significant wave heights with real in-situ data (section 5). The aim was also to

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investigate the potential of results such as those presented in Figure 2 to choose one parametric model rather than another, depending on the case study.

5. Comparison with in-situ data

Hurricane Maria was the deadliest storm of the 2017 Atlantic season. Recorded as a category 5 event, it caused catastrophic damages in Dominica and Puerto Rico, as well as widespread flooding and crop destructions in Guadeloupe. We tested here the ability of several parametric models to properly represent the wind pattern evolution during Maria by comparing the significant wave heights observed at buoys in the Lesser Antilles with those computed using a wave-current coupled model forced by a sub-set of the various parametric winds considered in the previous section. The model is based on the code SCHISM-WWM [49]. The computational domain is represented in Figure 3. Resolution spans from 10km far from the region of interest (where the bathymetry is derived from GEBCO), up to about 100m in Guadeloupe and Martinique where we have the best bathymetric data (ship-based soundings from the SHOM, the French Naval Hydrographic and Oceanographic Department). The model is forced by:

- astronomic tidal potential over the whole domain (12 constituents);
- 26 tidal harmonic constituents at the open boundaries, provided by the global FES2012 model [50] ;
- parametric pressure fields [33];
- parametric winds blended with CFSR (Climate Forecast System Reanalysis [51]) wind data. The parametric winds are prescribed for radii less than R34 , whereas CFSR data are imposed for r > 1.5 R34. In between, a smooth transition is ensured using a weighing coefficient varying with the radius r.

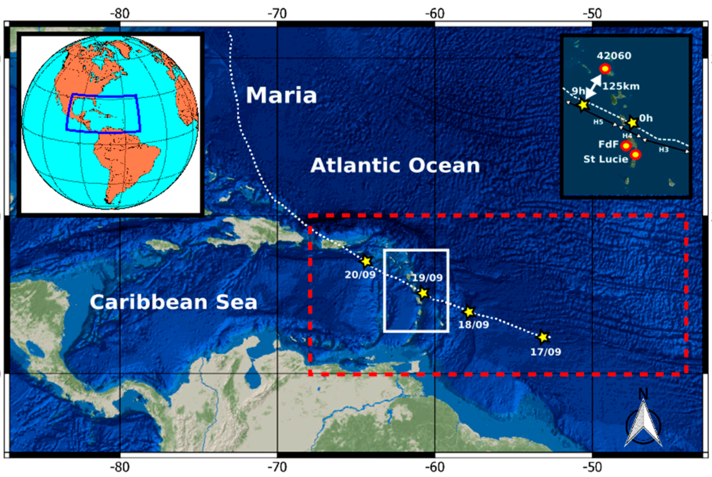

Figure 3. Study area. The computational domain is depicted with the dashed red contour. The dashed white line represents the track of hurricane Maria. The location of the buoys used for comparison is given in the upper-right corner box.

We considered here five parametric models:

- E11 and H80, constrained using the 64-kt wind radii only (E11(R64) and H80(R64) in Figure 4);
- E11 and H80, constrained using all the wind radii information (E11(All) and H80(All) in Figure 4);
- E11H80, for which we chose to blend the wind speeds inferred from E11 for the inner core area with those given by H80 for the outer region (see the black contours in Figure 2)

E11H80 was chosen to test whether results such as those presented in Figure 2 could be of benefit to build a better parametric model for the cyclone considered, using a combination of models that is expected to reduce the biases. We strongly insist on the fact that the new model tested here (E11H80) is just an example. In no way we consider this model as the best option. E11 combined with W06 or E04 could be also tested for instance.

The reader is referred to Krien et al [9] for greater details about the model and the numerical strategy. Here, we compared the significant wave heights (Hs) computed by the model with the Hs recorded by three buoys located in the Lesser Antilles (Figure 3): Fort de France (FdF) and Sainte Lucie, owned by Meteo France, as well as 42060, maintained by the National Data Buoy Center (NDBC). The latter went adrift during the peak of Maria, hence the decrease of Hs was unfortunately not captured.

Table 3. Bias, root mean square error (RMS) and normalized RMS (NRMS) obtained when comparing numerical simulations with in-situ significant wave heights.

		42060	Fort de France	St Lucie
H80 (R64)	Bias	0.1m	-0.85m	-0.43m
	RMS	1.2m	0.9m	0.55m
	NRMS	27.1%	41.8%	24%
H80 (All)	Bias	1.5m	0.9m	0.64m
	RMS	2m	1.06m	0.84m
	NRMS	46%	49.3%	36.6%
E11 (R64)	Bias	-1.4m	-0.8m	-0.44m
	RMS	1.5m	0.87m	0.56m
	NRMS	35%	40.3%	24.5%
E11 (All)	Bias	-0.9m	-0.21m	-0.19m
	RMS	0.9m	0.34m	0.43m
	NRMS	21.3%	15.8%	18.7%
E11H80 (All)	Bias	-0.7m	0.01m	-0.04m
	RMS	0.7m	0.31m	0.44m
	NRMS	17.4%	14.5%	19.2%

Results (Table3, Figure 4) show that:

- H80 and E11 constrained only by the 64-kt wind radii (R64) give the worst results, with Hs generally significantly underestimated, and NRMS ranging between 20% and 50% (Table 3).

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- Trying to improve these models by constraining all the 34-kt, 50-kt, and 64-kt wind radii (All) results in much better performances for E11, with reduced bias and NRMS (15 to 22% approximately). This suggests that E11 satisfactorily represents the TC structure, at least as long as the hurricane (here in category 4-5) remains relatively close to the buoys. It tends to underestimate Hs (in Sainte Lucie for example) when the storm moves further away.
- On the contrary, the H80 model strongly overestimates Hs when Maria is the closest to the storm, at a distance of about 120-200km (which corresponds roughly to the radii at 50-kt). This is also consistent with the results of Figure 2, and confirms, again, that the relatively significant biases obtained in Figure 1 for extreme cyclones and R64<r<R50 might be partly explained by flaws in parametric models such as H80 rather than errors in CYGNSS wind speeds. The prediction is better when Maria moves further away, which was also expected.
- The best results are obtained here for the model E11H80. The bias is found to be considerably reduced compared to E11constrained with all wind radii.

These results are all consistent with those presented in Figure 2 (keeping in mind that Maria is here a category 4-5 hurricane, and that it passes relatively close to the buoys, see Figure 3). Hence they also support our assumption that the ASCAT and CYGNSS/NBRC products are relatively good proxies for surface wind speeds, for r>R34 and r<R34 respectively (with the exception of the inner region for weak cyclones).

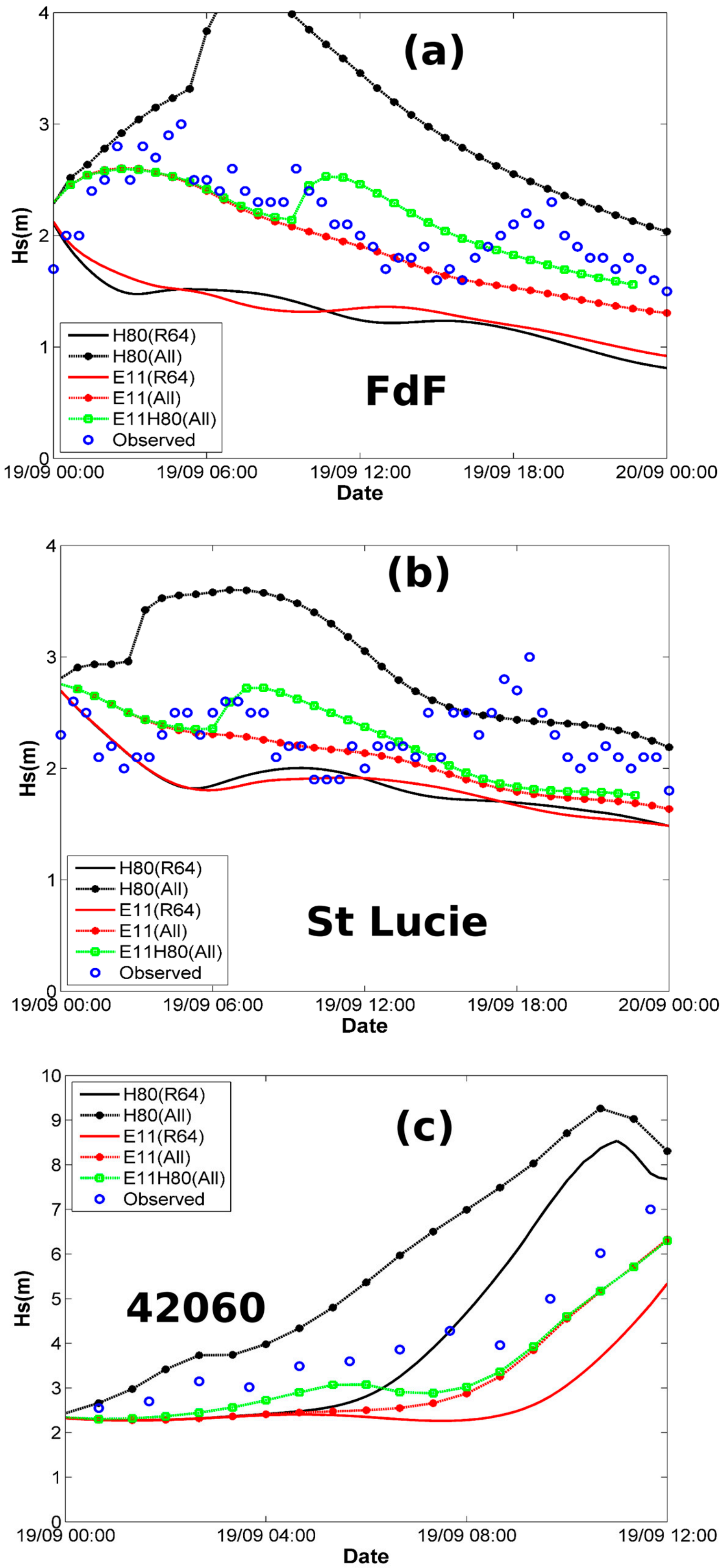

Figure 4- Significant wave height time series for different parametric models. "R64" denotes a model constrained only by the 64-kt wind radii. "ALL" indicates a model constrained with all the available information (34-kt, 50-kt, and 64-kt wind radii). E11H80 corresponds to a blend of the model E11 (for the inner core region) and H80 (for the outer region). Results for Fort-de-France, Sainte-Lucie, and the 42060 station are displayed in (a), (b), and (c) respectively.

6. Conclusions

Taking advantage of an extremely active 2017 hurricane season in the tropical Atlantic Ocean and the Eastern Pacific, we investigated the potential of using recent satellite remote sensing data such as CYGNSS and ASCAT to identify the advantages and drawbacks of several parametric wind models used for storm surge hazard assessment or prediction of cyclonic waves.

Under the assumption that ASCAT and CYGNSS/NBRC products can be considered as good proxies for surface wind speeds for the outer and inner regions respectively (with an exception for the core of weak cyclones), we were able to confirm the findings of a number of previous studies (e.g. Willoughby et al. [39], Lin and Chavas [17] or Chavas et al. [48]). Using a wave-current coupled numerical model, we also showed that remote sensing data such as CYGNSS/ASCAT are probably sufficiently accurate to be used to better select a suitable parametric model, depending on the case study considered. The choice will depend on several criteria such as cyclone intensity and/or availability of wind radii information. Indeed, our results suggest that none of the traditional empirical approaches can be considered as the best option in all cases.

We strongly insist on the fact that our aim here is not to encourage using or discarding a specific parametric model, and even less to propose a new one. First, because we did not test all the published models. Second, because each author uses a specific combination of parameters and approach to mimic the wind field, so that it would be presumptuous to draw definitive conclusions. Besides, there are still errors on remote sensing data, so that differences of 2-3m/s in terms of bias are probably not really significant.

The main finding of this paper is thus the following: satellite remote sensing is now mature enough to provide relevant information about the performance of parametric cyclonic wind models, even if further work is needed, especially to access to the full structure of TCs close to the eyewall. We focused here mainly on the CYGNSS mission, but there is little doubt that other type of data can also be valuable. Remote sensing has now become a powerful tool that should be used to validate or improve existing parametric approaches, in order to conduct better wind, waves, and surge analysis for TCs.

It is noteworthy to conclude by mentioning that even with the improved model tested here for Maria (see section 5), the NRMS remains relatively high (15-20%). Indeed, the temporal resolution (6-hours) is not sufficient to allow parametric models to reproduce the short-term variations of track, translation speed, or wind asymmetry. This stresses the need for higher temporal sampling of data (location of the cyclone center, maximum wind speed, wind radii, etc), and greater efforts to improve the efficiency of numerical atmospheric models.

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Author Contributions: Yann Krien conceived the idea and wrote most of the paper; Gaël Arnaud, Raphaël Cécé and Jamal Khan contributed to the development of the analysis tools; Gaël Arnaud, Ali Bel Madani and A.K.M.S. Islam arranged the figures and corrected a number of errors in the first version of the manuscript. Didier Bernard, Philippe Palany and Narcisse Zahibo prepared the project C3AF which funded about 66% of the work presented here. Fabien Durand, Laurent Testut and A.K.M.S. Islam played a major role for obtaining the IRD grant (about one third of total fundings). The manuscript also greatly benefited from their proofreading and suggestions.

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