

A Consensus Approach for Estimating Tropical Cyclone Intensity from Meteorological Satellites: SATCON

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ABSTRACT

A consensus-based algorithm for estimating the current intensity of global tropical cyclones (TCs) from meteorological satellites is described. The method objectively combines intensity estimates from infrared and microwave-based techniques to produce a consensus TC intensity estimate, which is more skillful than the individual members. The method, called Satellite Consensus (SATCON), can be run in near-real time and employs information sharing between member algorithms and a weighting strategy that relies on the situational precision of each member. An evaluation of the consensus algorithm's performance in comparison with its individual members and other available operational estimates of TC intensity is presented. It is shown that SATCON can provide valuable objective intensity estimates for poststorm assessments, especially in the absence of other data such as provided by reconnaissance aircraft. It can also serve as a near-real-time estimator of TC intensity for forecasters, with the ability to quickly reconcile differences in objective intensity methods and thus decrease the uncertainty and amount of time spent on the intensity analysis. Near-real-time SATCON estimates are being provided to global operational TC forecast centers.


1. Introduction

The surveillance of tropical cyclones (TCs) by meteorological satellites has essentially mitigated the problem of detection. The global tropics are routinely scanned by a constellation of geostationary (GEO) and polar-orbiting platforms with increasing frequency and by sensors with improved spatial and spectral sampling. The location, genesis, occurrence and dissipation of TCs can be qualitatively tracked and cataloged via a myriad of multispectral imagery.

It is somewhat more difficult to estimate the current intensity [CI; which can be minimum sea level pressure (MSLP) or maximum sustained (1 min) near-surface (10 m) winds (MSW)] of TCs from space-based platforms. The analysis of TC cloud patterns from infrared (IR) imagery can be done subjectively using trained analysts and empirically based rules. The longstanding Dvorak technique (Dvorak 1975, 1984) has been employed

at operational TC centers for many decades and is heavily relied upon for analyzing the CI and anchoring TC intensity catalogs (“best tracks”) in the absence of in situ intensity observations. Even novice analysts can estimate the CI with a fair amount of accuracy as evidenced by crowdsourcing strategies (Hennon et al. 2015). However, IR-based cloud pattern recognition methods have their limitations (Velden et al. 2006b; Knaff et al. 2010) due to inherent subjectivity in the interpretation of the imagery and constraints on the ability to view organized convective structure underneath the typically large and dense TC cirrus canopy. Techniques that utilize cloud-penetrating microwave (MW) sensors can help in this regard (Brueske and Velden 2003; DeMuth et al. 2004; Bankert and Cossuth 2016; Jiang et al. 2019), but these methods also have their strengths and weaknesses.

Accurate estimates of the CI are important for several reasons: 1) The CI is the starting point of the operational TC forecast process; 2) It is one of the primary input variables used to initialize both dynamical and statistical TC forecast models; and 3) TC climatologies and trends rely on accurate best-track intensities. Forecasters (or best-track analysts) often face the problem of concurrent satellite-based CI estimates that exhibit a large

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degree of spread/uncertainty. To deal with this, an often-used conservative approach is to take the mean of the estimates (simple consensus). However, a “smarter” consensus method that further reduces the CI estimate uncertainty based on the situational performance of each consensus member is desirable.

In this paper, we report on the development of a consensus model to estimate TC CI from satellite-based methods first proposed in [Velden et al. \(2004\)](#) and [\(2006a\)](#). The approach draws on several independent and objective multispectral techniques that are routinely available and estimate the CI of TCs from satellites. These techniques are carefully characterized by situational performance to develop a weighted consensus algorithm that exploits the advantages of each individual technique. Called Satellite Consensus (SATCON), the algorithm can operate in near-real time, and it will be shown that SATCON CI estimates can notably improve upon estimates provided by the individual members and a straight average of those estimates, and are competitive with existing traditional approaches such as the Dvorak technique.

The SATCON method is described in [section 2](#), along with a brief review of the individual objective TC intensity estimation techniques that are currently used in the consensus approach. SATCON performance results are shown in [section 3](#), and the tendencies are discussed further with case study examples in [section 4](#). [Section 5](#) summarizes the findings and looks to the future with promising new satellite observations and novel methods to interrogate that data.

2. SATCON method and model members

The concept of applying a consensus of solutions to a problem or forecast is not new. Consensus or ensemble approaches have been developed for a wide range of meteorological applications, and they have been shown to be skillful in TC forecasting for quite some time ([Goerss 2000, 2007](#); [Sampson et al. 2008](#); [Krishnamurti et al. 1999](#); [Halperin et al. 2017](#); [Simon et al. 2018](#)). Recent forecast verification reports from the National Hurricane Center (NHC) routinely find that consensus models of forecast TC track and intensity yield the best skill (e.g., [Cangialosi 2019](#)). Pertinent to our study subject, forecasters at operational TC centers often take a simple average of divergent Dvorak CI estimates concurrently available from multiple agencies to assess the final CI in their bulletins and best tracks.

In this section, we describe a situationally weighted, variable (two or more members depending on availability) consensus method designed to retrieve a final “best estimate” of TC CI from several near-simultaneous

objective (fully automated) satellite-based CI techniques. The current configuration of SATCON includes members from mature and operationally tested objective algorithms that are briefly described below. Although it is certainly conceivable that the traditional analyst-based Dvorak estimates could be entrained into SATCON, for the purposes of this study we evaluate SATCON as an independent aid to complement and compare with the operational Dvorak estimates. As will be discussed in the last section, other existing and emerging new methods to estimate TC intensity from a growing suite of advanced satellite-based sensors could be candidates for becoming future SATCON members.

a. Current SATCON members

[Table 1](#) lists the current suite of sensors and satellites that make up the members of SATCON. A brief description of each current (as of early 2020) SATCON member is given below.

1) THE ADVANCED DVORAK TECHNIQUE (ADT)

The ADT is a computer-based algorithm designed to estimate the intensity of TCs using geostationary satellite IR imagery. It is employed by most operational TC analysis and forecasting centers worldwide to aid in determining the intensity of TCs, especially in oceanic basins where in situ measurements are not available. The initial versions of the algorithm ([Olander and Velden 2007](#)) were designed to closely mimic the Dvorak technique, which requires a trained analyst to apply pattern-matching and classification schemes to satellite imagery to estimate CI ([Fig. 1](#)). The primary goals of these early algorithm versions were to achieve the level of performance of the Dvorak technique while eliminating some of the inherent subjectivity through automation.

Since [Olander and Velden \(2007\)](#) first documented the ADT, development has continued in response to user feedback, new science, and improvements in satellite sensors. The enhancements include algorithm functionality improvements and an expansion of capabilities and precision ([Olander and Velden 2019](#)). In brief, the most notable advancements include: 1) finer tuning of the algorithm regression equations to aircraft-based TC intensity estimates using an expanded development sample, 2) the incorporation of satellite-based MW information into the intensity estimation scheme, 3) more sophisticated automated TC center-fixing routines, 4) adjustments to the intensity estimates for subtropical systems and TCs undergoing extratropical transition, and 5) addition of a surface wind radii estimation routine that is based on [Knaff et al. \(2016\)](#).

TABLE 1. Suite of current SATCON members as described in the text.

Method	Algorithm	Channels	Satellites	Years in use	Notes
LEO microwave sounder based	AMSU	6–8, 16	<i>NOAA-15, -16, -18, -19;</i> <i>Metop A-B</i>	2006– present	2014: <i>N-16</i> AMSU-A failure; 2008: <i>Metop-A</i> channel-7 failure
	SSMIS	3–5, 17	<i>F16–19</i>	2006–present	2015: <i>F-16</i> and <i>F-18</i> failures; 2016: <i>F-19</i> failure
	CIMSS ATMS CIRA ATMS	7–9 1–22	<i>SNPP/N-20</i>	2012–present	CIRA ATMS only used for TC eye > 40 km
GEO IR imager based	Advanced Dvorak technique	IR-W	<i>GOES-13–17; Himawari-7–8;</i> <i>Meteosat-8–11</i>	2006–present	Real-time ADT operates on latest available operational GEOs (after commissioning)

The ADT algorithm is now operationally implemented and supported by NOAA/NESDIS, and has become an established tool for providing real-time, objective TC intensity guidance at operational TC centers around the globe. Since the source imagery is provided by operational geostationary satellites, ADT CI estimates are nominally output and made available to SATCON every 30 min for active systems designated as TCs by Tropical Cyclone Regional Specialized Meteorological Centers or the Joint Typhoon Warning Center. For further details on the ADT and its performance results, see Olander and Velden (2019).

2) MEMBERS BASED ON LOW-EARTH ORBITER (LEO) MICROWAVE SOUNDERS

Complementing the geostationary satellite IR-based Dvorak and ADT approaches to estimating TC CI, many of the available meteorological LEO satellites offer instruments that sense in the MW. With the ability to penetrate the central dense overcast often associated with TCs, the MW sensors offer unique information on the TC thermal and convective structure, which through empirical algorithms (described below), can estimate intensity. The independent nature of the MW

structure observations versus the IR-based cloud pattern-recognition methods is ideal for consensus-based approaches. The downside is that the LEO satellites only provide sporadic spatiotemporal coverage over a TC, which is partially mitigated by a healthy operational fleet at present. Although this fleet is dwindling (see Table 1), it is hoped that future constellations of “smallsats” [e.g., Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS); Blackwell et al. 2018] will alleviate the temporal coverage issue.

There are several MW sounder-based methods to estimate TC intensity that are currently employed in the SATCON. They all share the fundamental concept of observing the upper-tropospheric thermal (warm) anomaly in the TC core region (Fig. 2), and relating its strength through hydrostatic principles to the TC center minimum surface pressure from which the storm’s maximum winds can also be deduced. There is a reasonable correlation between upper-tropospheric brightness temperature (T_b) anomalies observed by the microwave sounders and the TC surface pressure anomalies. However, none of the existing microwave sounders can fully resolve the TC

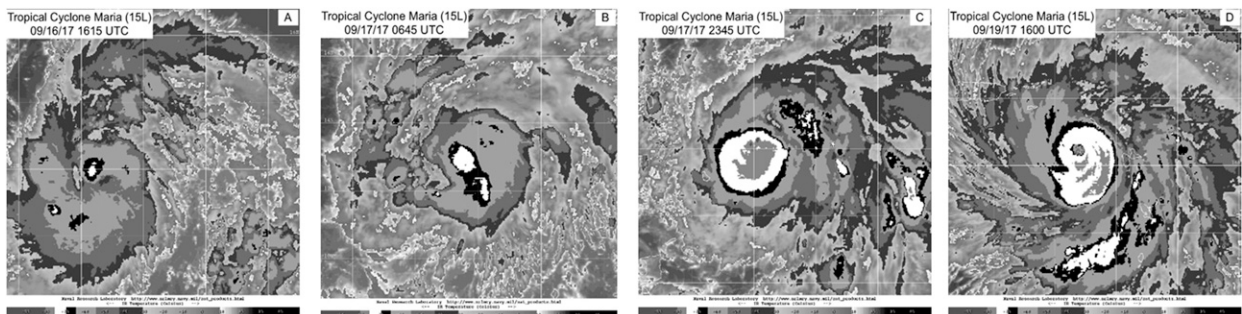


FIG. 1. Infrared “BD curve” enhancement from different stages of Hurricane Maria (2017) development that satellite analysts use for TC intensity estimation based on the Dvorak technique: (a) tropical depression (estimated maximum winds of 30 kt), (b) tropical storm (55 kt), (c) hurricane (75 kt), and (d) major hurricane (145 kt). (The satellite imagery is courtesy of the NRL-Monterey tropical cyclone site.)

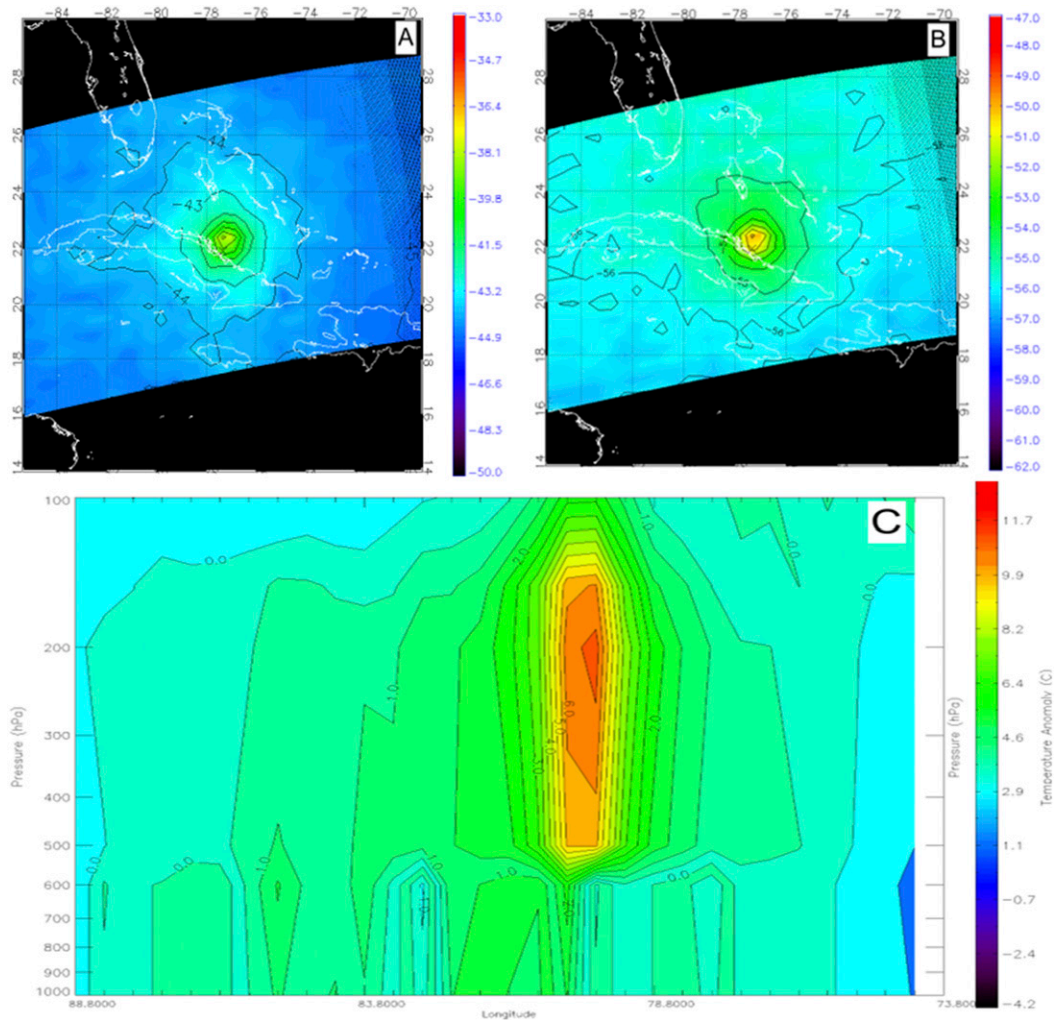


FIG. 2. Example of Hurricane Irma (2017) depicted by a LEO microwave sounder showing the typical signature of the upper-tropospheric warm core (yellow and orange colors): AMSU (a) channel-8 and (b) channel-7 brightness temperature plots ($^{\circ}\text{C}$, with 1° contour interval), and (c) resultant vertical cross section of brightness temperature anomaly derived from multiple channels (0.5° contour interval). (Source: <http://tropic.ssec.wisc.edu/real-time/amsu/>.)

thermal anomaly due to the relatively coarse horizontal and vertical resolution of their sensors, thereby requiring statistical adjustments to achieve the CI estimates. The MW sounder-based methods that are currently active in SATCON are briefly discussed below.

(i) AMSU

The Advanced Microwave Sounding Unit (AMSU) flown aboard the NOAA LEO satellite platforms is a cross-track scanning radiometer that utilizes two instruments to measure temperature (AMSU-A) and moisture (AMSU-B) at vertical resolutions determined by the weighting functions of each channel. A regression-based algorithm developed by researchers at the University of Wisconsin Cooperative Institute

for Meteorological Satellite Studies (CIMSS) utilizes the aforementioned upper-level Tb anomalies (warmest pixel Tb at center of the TC minus an average of environmental Tb surrounding the TC warm core at an annulus of 500 km) measured from AMSU-A channels 6–8 for an initial estimate of the TC MSLP anomaly (Herndon and Velden 2004). This estimate is then corrected to account for error sources from factors such as sensor field-of-view (FOV) position offset (TC center relative to the nearest sensor footprint center), undersampling of the warm anomaly due to the TC eye size relative to the footprint spatial resolution, and location of the TC core within the AMSU-A scan swath (near-nadir location versus near-limb). The MSW are then estimated using the derived

AMSU-based MSLP anomaly, the azimuthal mean AMSU-B 89-GHz Tb gradient near the TC inner core, storm translation speed and latitude. Objectively determined eye size estimates used by the AMSU algorithm can come from several sources: output from the Automated Rotational Center Hurricane Eye Retrieval (ARCHER) algorithm (Wimmers and Velden 2010), which employs MW imager channels calibrated to 89 GHz, or IR-based estimates (Kossin et al. 2007) that are output from the ADT when available, or estimates from operational TC analysis agencies, in that order of priority.

The largest source of error for the AMSU algorithm CI estimates results from undersampling of the TC upper-level Tb anomaly. AMSU has the coarsest FOV resolution of the current MW sounders with 48 km at nadir increasing to more than 100 km at the limb. Empirically determined bias corrections are applied to the CI estimates to account for the resolution limitation. However, the largest CI estimation errors from this method tend to occur for intense TCs with very small eye diameters, especially when the storm centers are located near the edge of the AMSU scan swath (FOVs adjacent to the swath edge are not used by the algorithm). SATCON is trained to recognize this situation, and the AMSU algorithm performance tendencies are built into its weighting scheme described in section 2c.

AMSU-based intensity estimates have been available since 1998 from *NOAA-15* through *NOAA-19*. As of early 2020, only *NOAA-15*, *NOAA-18*, and *NOAA-19* have functioning temperature sounders, and *NOAA-19* data are degraded by noise in channel 8. The European MetOp Series (A-C) also carries an AMSU instrument, and data from *MetOp-B* are currently processed into TC intensity estimates as well (*MetOp-C* is being added).

(ii) SSMIS

The Special Sensor Microwave Imager/Sounder (SSMIS) flown on the U.S. Department of Defense (DoD) DMSP series of LEO satellites became operational in 2005 (*F-16* satellite) with follow-on missions including *F-17*, *F-18*, and *F-19*. The primary instrument difference between the SSMIS and the AMSU is that the SSMIS employs a conical scanning strategy. This is advantageous for TC intensity estimation since the FOV spatial resolution of 37.5 km does not change across the scan. With an improved sensor spatial resolution, the SSMIS is less susceptible than AMSU to undersampling of the TC upper-level warm anomaly. The instrument also employs a high-resolution (~14-km FOV) MW imager channel near 85 GHz that provides important TC structure information such as eye diameter and eyewall strength when interrogated by the ARCHER algorithm.

The general approach for TC intensity estimation using the SSMIS is very similar to that of the AMSU algorithm described above. Unique regressions developed from SSMIS sounder channels 3–5 (mid- to upper tropospheric) Tb anomalies are used to estimate an initial MSLP anomaly, with possible corrections applied to account for TC size. The estimate of MSW is regressed from the MSLP anomaly, latitude, and storm size. The final MSW estimate can include adjustments based on the eyewall convective vigor as observed by the ARCHER algorithm organization scores, and to account for the storm translation speed. As of early 2020, only the *F-17* temperature sounder is still operating, with no MW sounder follow-on missions (DoD) planned.

(iii) ATMS

The Advanced Technology Microwave Sounder (ATMS) is the MW sounder for the new-generation LEO satellites as part of the Joint Polar Satellite System (JPSS). ATMS is similar to AMSU, with channels and weighting functions that are nearly identical for the purposes of TC intensity estimation. The primary improvement is a higher-FOV spatial resolution of 32 km at nadir, making ATMS the highest-resolution MW sounder (for near-nadir views) currently operating.

There are two methods to estimate TC intensity using ATMS that are part of the SATCON membership. The first one was developed at CIMSS and follows the same general strategy as the AMSU algorithm using the raw Tb anomalies from channels 7–9 (equivalent to AMSU channels 6–8) to arrive at an estimate of the TC MSLP anomaly. Corrections are applied for TC eye size, latitude, and storm size. The MSW estimation uses the ATMS-derived MSLP anomaly along with TC eyewall vigor as measured by ARCHER intensity scores, and the inner core Tb gradient (maximum of either channel 8 or 9).

The second ATMS-based method currently used in SATCON was developed at the Colorado State University Cooperative Institute for Research in the Atmosphere (CIRA) and differs from the CIMSS approach by using temperature retrievals instead of the raw Tb. The method was originally developed using AMSU data (DeMuth et al. 2004). Temperatures at 23 pressure levels derived from the ATMS retrievals are used in the TC intensity algorithm, and concurrent estimates of cloud liquid water are used to correct the temperature profiles from the effects of rain scattering. A second correction is applied to account for the effects of ice scattering, and the hydrometeor-corrected temperatures are then interpolated to a radial grid. Using global model (GFS) data for boundary conditions,

a downward hydrostatic integration is performed, a geopotential height field is derived and subsequently a 3D wind field is produced at standard pressure levels for a 12° TC-centered box. A statistical model is used to estimate TC MSLP and MSW from predictors derived from the temperature, pressure and wind retrievals. There are 13 predictors for the MSLP estimates and 12 predictors for the MSW estimates (Chirokova et al. 2017, 2018). Although the CIRA method produces the added benefit of a 3D wind field, the reliance on model data for the retrievals and boundary conditions can contribute to generally higher errors in the MSLP and MSW estimates when compared with the CIMSS approach.

3) SATCON PRESSURE>WIND MEMBER

An additional member to the SATCON TC MSW estimate is provided via a pressure–wind relationship model. The SATCON TC MSLP estimates (trained on solid observations from reconnaissance aircraft data and shown to be highly skillful in section 3) are converted to MSW using a regression of reconnaissance-based TC MSLP anomalies matched to storm-relative MSW values (motion component removed). In each case, adjustments to the MSW are made to account for storm characteristics such as latitude, eye size, and motion as further described in the SATCON method in the next section.

b. SATCON approach

The individual member weights used in the SATCON process of determining a CI are derived from their respective intensity estimation error distributions (discussed in the next section), from which each member has situational strengths and weaknesses. The performance behavior of each member can therefore be characterized into situational bins. For example, intensity estimation errors for the ADT depend on the objectively determined IR “scene type” (Olander and Velden 2019). The ADT method tends to perform best when there is a clear eye present in the IR imagery (EYE scene). However, the performance can be degraded when a TC eye is not easily resolvable in the IR (eye is too small or partially obscured by clouds), or when a TC encounters strong vertical wind shear (SHR scene). The MW sounder-based methods have errors that are correlated with the sensor FOV resolution and scan geometry with respect to storm eye size and location, respectively. In smaller storms or TCs with small eyes, the localized TC warm anomaly will not be fully resolved or the competing effects of eyewall hydrometeor attenuation (cooling) can lead to increased uncertainties in the representation of the anomaly, and hence the intensity estimates. SATCON makes use of this situational information to optimally weight all of the available intensity estimates

into a single superior consensus estimate. Unique performance characteristics exist for the two TC intensity metrics, MSLP and MSW, resulting in different SATCON weighting schemes for each metric.

Another element of the SATCON process involves cross-sensor information sharing. Each SATCON member contains unique parametric information that can be used by the other coincident members to assess the situational bins and possibly adjust the intensity estimates. For example, the ADT produces estimates of TC eye size when an eye is distinguishable in the IR (Kossin et al. 2007). Because the MW-sounder methods can suffer from undersampling issues when the TC eye diameter is less than ~50 km, the ADT eye size can be used to adjust the estimates accordingly. Conversely, the latest version of the ADT (version 9.0) makes use of input from passive MW sensors in the 85–92-GHz range when available using the ARCHER algorithm (Wimmers and Velden 2010). ARCHER estimates TC eye size and position in addition to eyewall vigor and completeness (Fig. 3). These parameters are used to create TC organization “scores” that are used as input to the ADT during cases when the ADT intensity may have a tendency to plateau prior to eye emergence in the IR. The CIMSS MW-sounder methods use the 85–92-GHz imagery and ARCHER analyses to determine FOV position offsets noted earlier, and this information can also be used to adjust the CIRA ATMS estimates. TC eye size estimates from ARCHER can also be used by the CIMSS MW-sounder-based methods to account for undersampling (in the absence of IR eye size information). Although ARCHER is not an explicit member of the SATCON model, it can provide integral input to the SATCON process.

Additional sources of input to the SATCON process can come from operational TC centers via the Automated Tropical Cyclone Forecasting system (ATCF; Sampson and Schrader 2000) and include the environmental pressure used in the pressure>wind member, as well as storm motion. Small adjustments can be made to the final estimated MSW values for storms that significantly deviate from an average TC motion of about 11 kt ($1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$) using the formulation from Schwerdt et al. (1979).

c. SATCON weighting scheme

All of the above factors can lead to empirically determined adjustments to the individual member intensity estimates of CI prior to producing a SATCON estimate. The estimates are then combined into a single SATCON CI estimate using appropriate weights based on situational performance as discussed below. Separate weights are used for estimating MSLP and MSW since

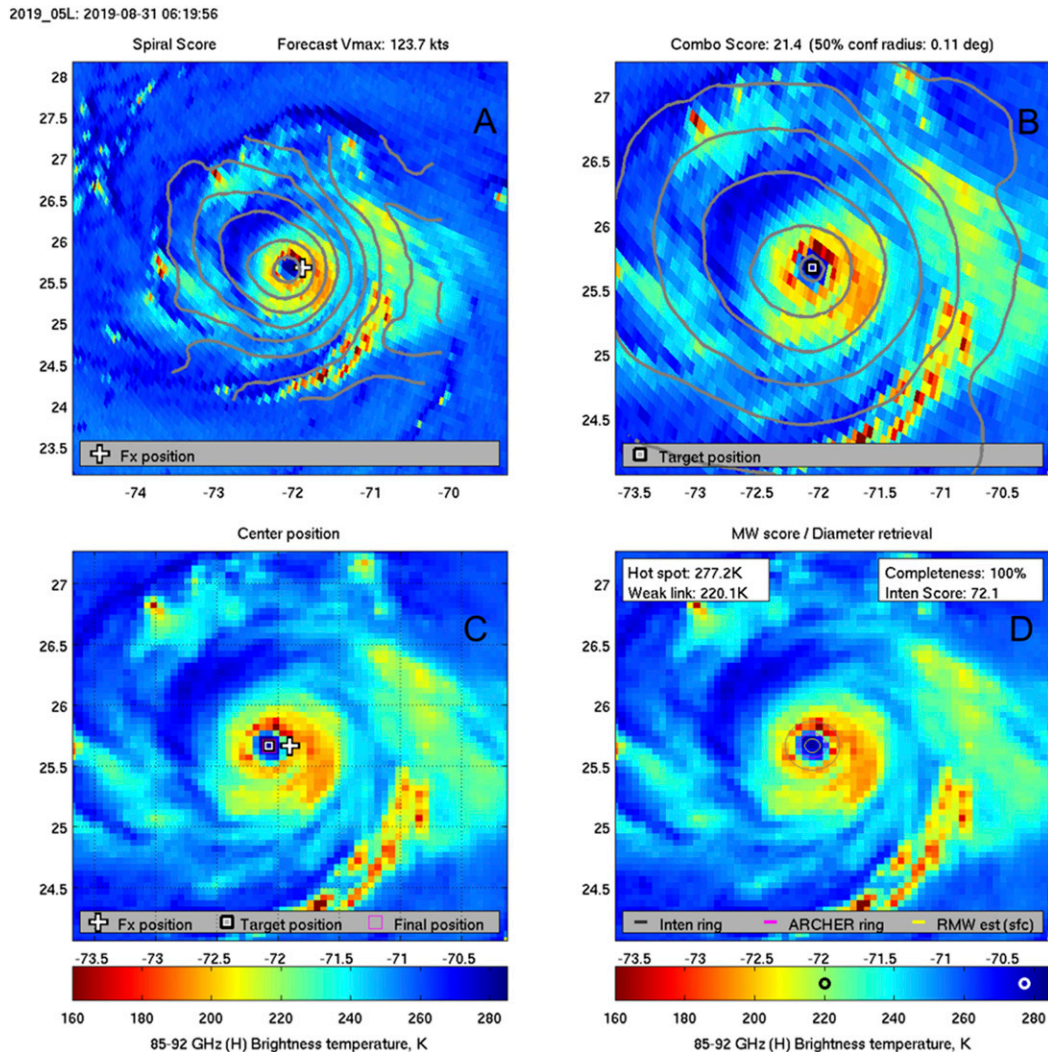


FIG. 3. Example of ARCHER output for Hurricane Dorian (2019) at 0600 UTC 31 Aug. ARCHER objectively centers and “scores” the organization of the storm in microwave imagery: (a) spiral score, (b) combination score (spiral plus eyewall ring scores), (c) center position, and (d) final score and diagnostics.

they can yield different situational error characteristics. At least two coincident members must be available to produce a SATCON estimate (the ADT is always one member), but relationships are determined for up to four coincident (within 2 h of each other) estimates.

The actual weights used by SATCON are based on the root-mean-square errors (RMSE) for intensity estimates of the individual members in given situations. For example, Fig. 4 shows typical MSW RMSE errors for SATCON members in given scenarios. From the top row of Fig. 4 it can be seen that the ADT performs comparatively better with “eye” scene types than other classifications. The bottom row of Fig. 4 show examples of TCs in 89 GHz imagery along with the location of the more coarse resolution MW sounder scan position

(FOV) used to determine the inner core thermal anomaly strength and produce the TC intensity estimate. Three scenarios are shown. In Fig. 4d, the TC eye is large and the sounder core FOV position nicely coincides with the true TC center. This represents an ideal scenario for the MW sounder-based methods and the lower RMSEs reflect this. Figure 4e presents the same case in which the TC eye is large, however, the MW sounder core FOV is offset from the true TC position resulting in some subsampling of the eye warming. The intensity estimate’s RMSEs in this situation are relatively higher. Finally, Fig. 4f represents a “worst case” situation in which both the TC eye is small (compared to the MW sounder spatial resolution) and the sounder core FOV position is offset from the true TC position.

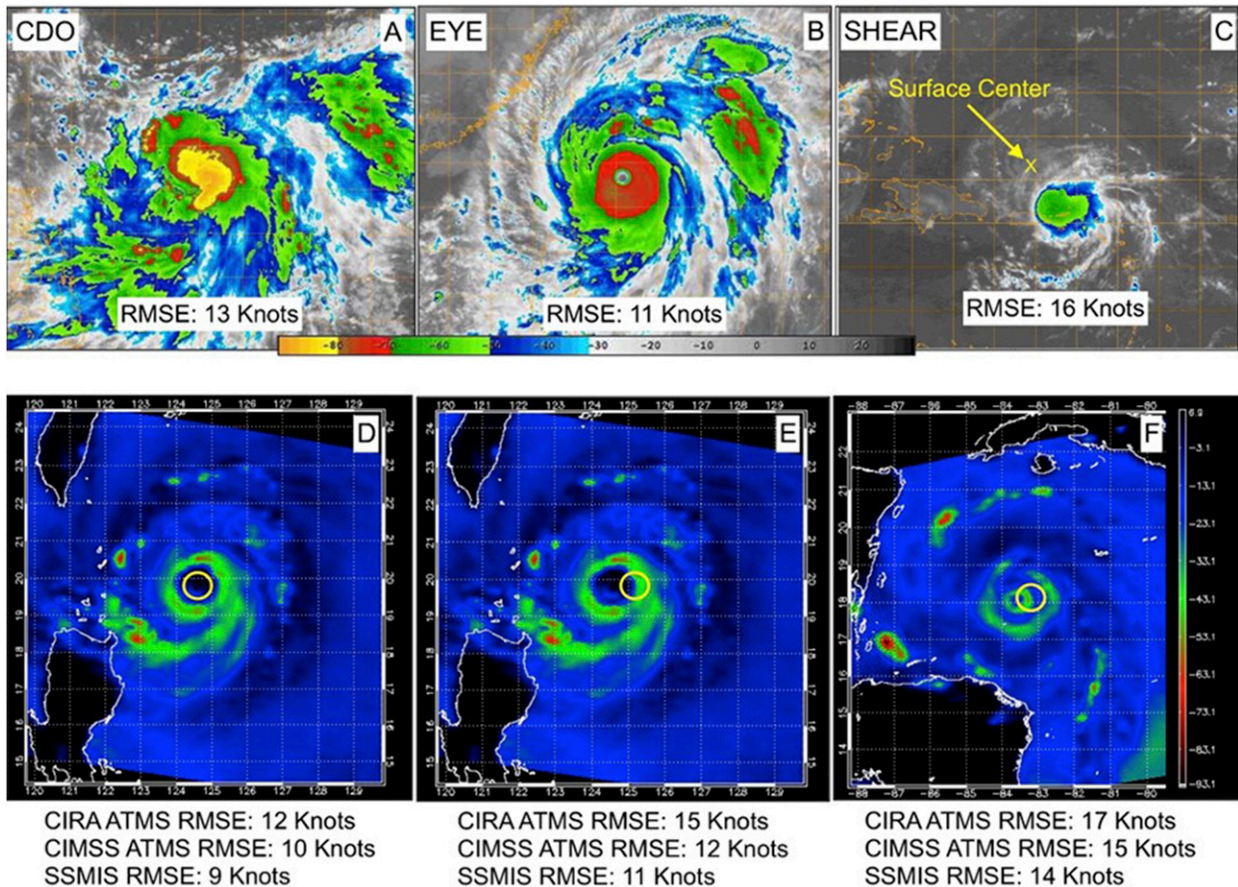


FIG. 4. Example weighting scenarios for selected members of SATCON. (a)–(c) IR images of TCs (courtesy of the NRL-Monterey tropical cyclone site) and the designated ADT scene types along with the associated MSW RMSE for those scene types. Also shown is AMSU-B 89-GHz imagery with yellow circles denoting the corresponding sounder scan position used to produce the intensity estimate, and the associated MSW RMSE for three of the sounder-based methods for each scenario: (d) a scenario for the AMSU-A scan position and FOV well within the TC eye, (e) a scenario in which the AMSU-A scan is offset from the TC eye center, and (f) a scenario in which the TC eye is small relative to the AMSU-A FOV resolution and is also offset from the TC center.

In this case, the RMSEs are high and would result in lower weights in the SATCON algorithm.

The members' RMSEs (and SATCON weights) are determined from a large development sample consisting of TC intensity estimates from all input members. For purposes of training the model with solid verification, the development sample only includes cases when near-coincident aircraft reconnaissance data are available within ± 3 h of the SATCON estimate (MSLP from dropsondes; MSW from agency

best track). This includes cases from 2006 to 2014 (AMSU and SSMIS from 2006 to 2014; ATMS from 2012 to 2014) in the Atlantic Ocean, eastern-central North Pacific Ocean, and (a few from the) western North Pacific (field experiment aircraft data) TC basins.

The SATCON weights are proportional to the member RMSE values for given scenarios, and an intensity estimate is derived from a set of equations depending on the number of available members. For example, the three-member equation is

$$\text{SATCON} = \frac{W_1 W_2 (W_1 + W_2) E_3 + W_1 W_3 (W_1 + W_3) E_2 + W_2 W_3 (W_3 + W_2) E_1}{W_1 W_2 (W_1 + W_2) + W_1 W_3 (W_1 + W_3) + W_2 W_3 (W_3 + W_2)},$$

where W_n is the weight of the member n (RMSE) and E_n is the intensity estimate of member n . The member

weights are the situational RMSE values for each of the members used to create the estimate. The formulation

of the SATCON weighting structure is designed to apply higher weights to the member with a situationally dependent, statistically determined superior performance (of the available members). For example, if E_3 is the best-performing member in a given situation, the equation above shows how higher RMSEs (weights) from E_1 and E_2 are applied to E_3 to give more weight to that estimate. Less weight (relatively lower RMSEs) is applied to the other more uncertain estimates (E_1 and E_2).

The weighted SATCON MSLP estimate is the final value; however, further corrections can be applied to the SATCON MSW estimate. As noted earlier, the highly skillful SATCON MSLP estimates (discussed in section 3) are used to create a new member for the SATCON MSW estimate: a pressure-wind-derived MSW estimate. This empirically derived, regression-based member (not a weighted member in SATCON) starts with the SATCON estimates of the MSLP anomaly to estimate the MSW with adjustments for storm latitude and motion along with eye size information provided from the ADT or ARCHER. The new SATCON MSW estimate is then: $0.75 \times \text{SATCON_MSW} + 0.25 \times P>W_MSW$. The final SATCON estimate of MSW can be further adjusted to account for a too-weak bias at the upper end of the intensity scale (>85 kt), and a too-strong bias at the beginning stage of TCs (initial ~ 36 h after first agency bulletin). These biases (on the order of 10 kt) were noted after independent performance testing.

d. Near-real-time operability

SATCON has been demonstrated in a near-real-time mode over all global TC basins for several years by the algorithm developers at CIMSS (Herndon and Velden 2018). The SATCON intensity estimates are derived at CIMSS and made available via a dedicated website interface (<http://tropic.ssec.wisc.edu/real-time/satcon>), and distributed to U.S. TC forecast centers via the ATCF. At the time of this article, the SATCON algorithm and associated members are being transitioned into a framework that will allow the real-time processing to take place in an operational environment such as at the National Hurricane Center. Similarly, the DoD is also aiming to make it operationally available to the Joint Typhoon Warning Center. In the meantime, the near-real-time SATCON estimates will continue to be provided at CIMSS, at least until the operational transition is completed.

The TC intensity estimates from SATCON are limited to times when estimates from more than one member are available. The ADT outputs real-time estimates every 30 min, but the LEO member estimates

are only available when one of the LEOs overpasses a TC and the storm core is reasonably covered (swath limb overpasses are not used). Another limitation for real-time use is that the LEO data can take time to be downloaded from the satellite, processed into Tb by the supporting agency, and distributed into user-ready files. This delay is typically 1–4 h after the overpass, meaning the SATCON estimates can become near-real time when they are finally made available to operational users. To partially ameliorate this time lag, the real-time graphical SATCON displays on the CIMSS site will extrapolate forward the sounder-based intensity estimates up to 2 h to match a more current ADT estimate.

Despite these limitations, our experience in working with operational forecasters is that the sporadic and sometimes delayed SATCON intensity estimates can still be very useful if they are available within their current 6-h forecast cycle, particularly given the SATCON estimates can be higher precision than other available satellite-based estimates (discussed in sections 3 and 4). Especially during active TC periods, SATCON can provide the analyst with the ability to quickly reconcile differences in objective intensity methods and serve as a comparative guidance tool for evaluating various TC intensity estimates.

e. Use in poststorm analyses

Another important way in which SATCON estimates can contribute to TC intensity analysis is in poststorm assessment and “best track” procedures. No longer limited by operational constraints such as data latency, the SATCON intensity estimates can be fully employed in the more rigorous postanalysis process of defining and archiving the final TC intensity record. In addition to actual SATCON estimates when LEO MW-sounder passes are available, the model also calculates interpolated MW-based intensity estimates between the temporally sporadic LEO observations (typically 2–5 h). These interpolated values are matched up with the routinely available ADT estimates at 30-min intervals to produce interpolated SATCON estimates. These 30-min estimates are stored in the SATCON storm history file and result in a much smoother transition between SATCON estimates for postanalysis purposes.

In addition to the SATCON deterministic estimates, the CIMSS SATCON site displays statistically based, two-standard-deviation error bounds around the estimates that are dependent on situational performance. These bounds provide the forecaster/analyst with a probabilistic tool: Statistically it is highly unlikely that the true TC intensity will fall outside of these bounds. In cases where the working best-track intensity does fall outside the bounds it may indicate to the forecaster that

TABLE 2. Performance of SATCON TC MSW estimates (kt) compared with coincident individual member estimates, verified against reconnaissance-aided best-track MSW for the development sample of cases during 2006–14. The AMSU and SSMIS/ATMS are interpolated to times of ADT estimates.

<i>N</i> = 3167	SATCON MSW	ADT MSW	AMSU MSW	SSMIS/ATMS MSW
Bias	0.1	0.9	−1.4	−1.6
Absolute avg error	7.2	9.8	9.6	9.2
RMSE	9.0	12.0	12.3	11.3

the operational approaches used to arrive at the intensity deserve increased scrutiny. An example would be cases of rapid intensity changes in which traditional methods such as the Dvorak Technique may lag the true intensity.

With regard to the potential use of SATCON estimates in longer-term TC trend studies, a possible limitation is the unavailability of the higher-resolution MW-sounder based estimates prior to 1998, and the nonuniformity of available estimates after that time. Lower-spatial resolution MW sounders were available prior to the launch of the first AMSU in 1998, but the effectiveness in being able to resolve TC warm cores was much more limited. From 1998 onward, the AMSU estimates became available along with the SSMIS in 2005 and the ATMS in 2012, but with undesirable (for trend analyses) heterogeneous sampling during this period as new satellites/instruments were added.

3. SATCON performance results

As noted earlier, the SATCON model is trained on a development sample consisting of TC intensity estimates from all input members and when aircraft reconnaissance is available within 3 h of the SATCON estimate. This includes a large sample of cases from 2006 to 2014 (AMSU and SSMIS from 2006 to 2014, ATMS from 2012 to 2014) in the Atlantic, eastern-central Pacific, and a few cases in the western Pacific (field experiment aircraft data) TC basins. Tables 2 and 3 show the dependent-sample performance statistics for estimates of MSW (vs reconnaissance-aided best track) and MSLP (vs reconnaissance dropsondes), respectively. In the aggregate, the SATCON estimation errors are significantly lower than the errors of its individual members in all error metrics.

As an independent test of the algorithm's performance, SATCON was run in near-real time at CIMSS during the 2015–19 TC seasons to simulate operational constraints. The intensity estimates were compiled and compared to those of its coincident individual members, and also to operational analyst-based Dvorak technique estimates that were available and coincident. As before, the comparisons shown in the tables below consist of a homogeneous sample of cases validated against reconnaissance-measured MSLP or best-track MSW coincident with reconnaissance (± 3 h). This requirement necessarily restricts the validation to mainly Atlantic TCs with a few eastern-central Pacific matches.

The comparisons presented in Tables 4–7 represent the results of the independent validation and confirm that SATCON notably outperforms its individual objective satellite-based members in all the statistical metrics presented. In Tables 6 and 7, the SSMIS and the ATMS MW sounder estimates are combined since their error characteristics and situational behaviors are similar. The largest SATCON MSW underestimate error in the sample is 30 kt too weak that occurred during Eastern Pacific Hurricane Patricia (2015) which had a tiny but very intense core. The largest overestimate is 30 kt too strong for Atlantic Hurricane Maria (2017), when Maria's actual maximum winds were as much as 20–30 kt lower than what would be derived from a standard pressure-wind relationship. This is mainly due to the expansion of the hurricane's circulation as it moved into higher latitudes. The largest SATCON MSLP errors in the sample are 32 hPa too weak (Patricia) and 17 hPa too strong for Atlantic Hurricane Matthew (2016).

Note the weak biases in the MSW metric that appear in this sample for all of the members. This bias was not

TABLE 3. Performance of SATCON TC MSLP estimates (hPa) compared with coincident individual member estimates, verified against reconnaissance MSLP data for the development sample of cases during 2006–14. The AMSU and SSMIS/ATMS are interpolated to times of ADT estimates.

<i>N</i> = 3167	SATCON MSLP	ADT MSLP	AMSU MSLP	SSMIS/ATMS MSLP
Bias	0.1	−0.8	−1.1	−1.5
Absolute avg error	3.9	7.5	4.7	5.9
RMSE	4.9	9.3	6.3	8.0

TABLE 4. Performance of SATCON TC MSW estimates (kt) compared with coincident ADT and AMSU estimates, verified against reconnaissance-aided best-track MSW for an independent sample of cases from 2015 to 2019.

$N = 568$	SATCON MSW	AMSU MSW	ADT MSW	Simple avg MSW
Bias	-1.5	-3.2	-4.2	-3.7
Absolute avg error	7.6	9.5	10.8	8.6
RMSE	9.8	12.3	12.9	11.0

present in the development sample, and does not have a counterpart in the MSLP metric. It is particularly striking at higher MSW speeds. It is hypothesized that the increased use of the Stepped Frequency Microwave Radiometer (SFMR; Uhlhorn et al. 2007) surface wind estimates (now available from all reconnaissance aircraft) in the NHC best-tracking procedure may be contributing to this particular attribute. It has been noted that SFMR wind speeds are often higher than other aircraft estimates (NHC storm reports). At the time of this article (early 2020), the issue is being addressed by NHC and SFMR personnel, and a recalibration and validation effort is underway (Klotz and Nolan 2018; M. Brennan, NHC, personal communication).

SATCON also performs better than a simple consensus (straight average) of the individual members, generally by about 10%–15%. This indicates that the situational adjustments, information sharing, and weighting logic in the SATCON model are making a positive impact.

It is also informative from a user perspective to break out the SATCON estimation errors by TC intensity bins in order to assess estimate confidence at various storm intensities (Fig. 5). In general, SATCON tends to have small MSW estimate biases except in the lowest and highest intensity bins. For weak-stage storms (MSW < 45 kt), SATCON tends to be a little too strong, primarily due to a high bias in the MW sounder methods at these intensities (not shown), and corrections for this bias are being explored. A notable weak bias exists for Category 5 TCs, and is also present with the ADT. A higher percentage of tiny (unresolved) eyes at these strong intensities could be a cause. However this bias could also at least in part reflect the SFMR issues noted above, as all of the individual satellite-based methods are trained on best tracks prior to 2015 that were less influenced by the availability of SFMR MSW estimates.

In terms of RMSE, SATCON bests the ADT in all intensity bins except for the weakest storms due to the aforementioned SATCON high bias. The SATCON RMSE profile across the intensity bins is reasonably flat, except for the category-5 storms (but still significantly better than the ADT and the other members not shown). This implies a high confidence in the SATCON estimates over the individual members for all TC intensities, with the possible exception of the weakest bin. However, it will be shown in the next section that individual TC intensity maxima, especially when they are strong with sharp peaks, can be underestimated by the consensus approach.

SATCON is also competitive with the coincident operational Dvorak-based estimates from multiple agencies, even after they are averaged as in Fig. 5. Only with the bin of hurricane category 1–2 do the Dvorak estimates show a slightly lower RMSE. This is an important result in that it indicates the multispectral information provided by the objective methods is adding skill beyond that of the Dvorak method when properly utilized in the SATCON process. Note that the operational Dvorak estimates also exhibit a notable weak bias in the strongest intensity bins.

Although the SATCON performance results presented above are primarily restricted to TC basins with reconnaissance aircraft data due to that being a validation requirement, there is reason to believe the SATCON performance extends to other TC basins as well. In 2008 and 2010, the U.S. Office of Naval Research in collaboration with international partners supported field experiments to study aspects of western North Pacific TC structure (Elsberry and Harr 2008). Aircraft reconnaissance missions were flown into several TCs during the field campaigns, permitting the opportunity to validate new satellite-based

TABLE 5. Performance of SATCON TC MSLP estimates (hPa) compared with coincident ADT and AMSU estimates, verified against reconnaissance-observed MSLP for an independent sample of cases from 2015 to 2019.

$N = 568$	SATCON MSLP	AMSU MSLP	ADT MSLP	Simple avg MSLP
Bias	0.3	2.2	-0.6	0.8
Absolute avg error	4.9	6.3	7.0	5.5
RMSE	6.5	8.6	9.6	7.5

TABLE 6. Performance of SATCON TC MSW estimates (kt) compared with coincident ADT and SSMIS or ATMS estimates, verified against reconnaissance-aided best-track MSW for an independent sample of cases from 2015 to 2019.

<i>N</i> = 400	SATCON MSW	SSMIS/ATMS MSW	ADT MSW	Simple avg MSW
Bias	−0.9	−0.7	−3.0	−1.8
Absolute avg error	7.5	10.0	10.1	9.1
RMSE	9.5	12.3	12.9	11.2

TC intensity methods in a basin other than the Atlantic or east-central Pacific. And although the number of verification cases is relatively small, the TC intensities observed during the reconnaissance missions did span a wide range of 35–160 kt (MSW). Validation statistics for this small western North Pacific sample (Table 8) again show that SATCON (in this case the ADT plus AMSU) intensity estimation errors are lower on average than the available Dvorak estimates.

Other testimony comes from operational TC centers that have been experimenting with the near-real-time estimates produced by CIMSS. The JTWC TC forecasters (with an area of responsibility outside the Atlantic and east-central Pacific) now include SATCON in their daily in-house analysis and public bulletin discussions. The Australian Bureau of Meteorology TC forecasters, who have provided excellent feedback during the development and testing phases of SATCON as it pertains to their region, routinely cite the SATCON estimates as part of their operational CI analysis and bulletin information.

4. Examples and discussion

In this section we present examples of TC cases that illustrate the situational performance of SATCON. Although a full tutorial on the use of SATCON intensity estimates is not possible here, some discussion is given to scenarios that lend higher or lower confidence in the estimates.

The first example is Atlantic Hurricane Florence (2018) presented in Fig. 6, which illustrates a case of a storm undergoing significant periods of intensification and weakening. There is generally good agreement between the SATCON MSW estimates and the NHC best-track intensity throughout the period despite

considerable variance in the individual objective intensity estimates at times. This implies that there is ample situational independence between the objective estimation methods to allow the SATCON model weights to resolve the differences. Of particular note is the correct identification of both rapid intensification and weakening by SATCON (the second phase is confirmed by reconnaissance data after 8 September), which is a stringent test for consensus-based approaches. Also in this case, the maximum intensity peaks are relatively well-captured. On the other hand, a short-lived rapid intensification (RI) depicted by SATCON early on 3 September is amplified relative to the NHC best track. This RI is supported by a couple higher MW sounder estimates as well as rapidly increasing ADT values, while the operational Dvorak estimates increased by a more modest 5–10 kt over 12 h. In this case NHC chose the weaker end of the estimates, and reconnaissance was not yet available to verify one way or the other. In practice, and given the relative independence of the objective member methods in deducing intensity, there is generally higher confidence in the SATCON estimates when there is objective method agreement, and lower confidence in situations with higher method scatter. Also, analysts using SATCON in real time should be wary of a single member estimate causing a significant SATCON deviation peak (in this case a high AMSU estimate that is not supported by previous estimates nor a concurrent SSMIS value that only supports a lower estimate), and may choose to conservatively wait for the next estimate to confirm it or reduce the deviation of the SATCON estimate if used in postanalysis.

The Florence case also exhibits some behaviors and uncertainties that can occur with the objective methods

TABLE 7. Performance of SATCON TC MSLP estimates (hPa) compared with coincident ADT and SSMIS or ATMS estimates, verified against reconnaissance-observed MSLP for an independent sample of cases from 2015 to 2019.

<i>N</i> = 400	SATCON MSLP	SSMIS/ATMS MSLP	ADT MSLP	Simple avg MSLP
Bias	0.2	0.3	0.6	0.5
Absolute avg error	4.6	6.5	6.6	5.2
RMSE	6.1	8.6	8.7	6.8

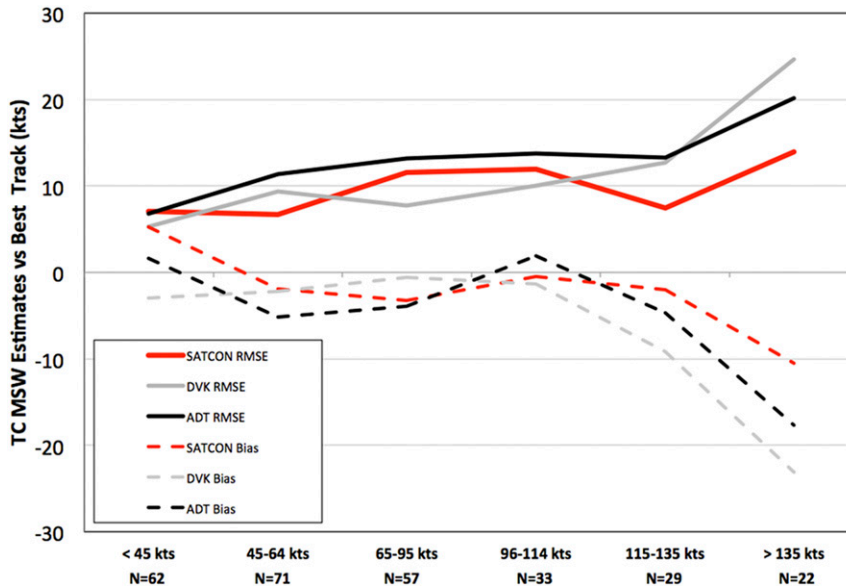


FIG. 5. Performance (vs reconnaissance-aided best track) of SATCON MSW (kt) estimates against subjective Dvorak (average of all agencies) and ADT estimates as a function of TC intensity (MSW) bins (kt; x axis). Solid lines represent the respective RMSE, and dashed lines represent the respective bias. The sample is from the 2015–19 independent dataset, with the number of matches *N* in each bin indicated at the bottom.

being considered. For example, the CIMSS ATMS estimates are generally on the high side during weak to moderate intensities, and the CIRA ATMS values are on the weak side during strong intensities. As noted in section 2, even though the parent instrument is the same, the methodologies that derive the intensities are different, resulting in contrasting biases. The SATCON model weighting scheme tries to account for these method performance behaviors. Another good example of SATCON’s value occurs during the intensity valley on 7–10 September, when Florence is being affected by a period of higher vertical wind shear and loses its eye structure. As shown in Fig. 4, the ADT becomes less reliable in these conditions and thus in this case exhibits a weak bias relative to the MW sounder-based methods and verifying best-track estimates. The SATCON weighting scheme makes allowances for this and draws closer to the sounder estimates for most of this period.

Figure 7 shows an example of SATCON indicating rapid intensification well before the operational Dvorak estimates, and greatly exceeding the JTWC working (real time) best-track values for western North Pacific Super Typhoon Halong (11W) in 2014. This case also highlights the potential usefulness of the 2-sigma (standard deviation) error bounds around the SATCON estimates in the CIMSS online displays. On 1 August, the objective method intensity estimates all increase

rapidly, and the SATCON MSW values become 30 kt higher than the working best-track estimates that fall outside the 2-sigma error bounds of SATCON. By definition this is highly unlikely and this, along with the congruence of the objective estimates, is an indication to the forecaster that something may be amiss with intensity estimation from the Dvorak method in this situation. In fact, a well-defined eye became apparent in MW imagery (information that was used in the ADT) but was not yet depicted in IR imagery, leading to Dvorak estimates that as a result are likely too weak.

Figure 8 illustrates a case in which SATCON likely underestimates peak intensity for multiple reasons. Atlantic Hurricane Danny in 2015 underwent a rapid rise and fall in intensity, which consensus methods (as natural averaging algorithms) can struggle with. Coupled with relatively infrequent MW sounder observations,

TABLE 8. Performance of SATCON TC MSW estimates (kt) compared with coincident ADT and operational Dvorak estimates, verified against reconnaissance-aided MSW estimates for a sample of TC cases from 2008 and 2010 in the western North Pacific.

<i>N</i> = 35	SATCON MSW	ADT MSW	Dvorak MSW
Bias	−1.6	−5.3	−2.0
Absolute avg error	7.7	11.0	9.4
RMSE	8.9	14.1	12.4

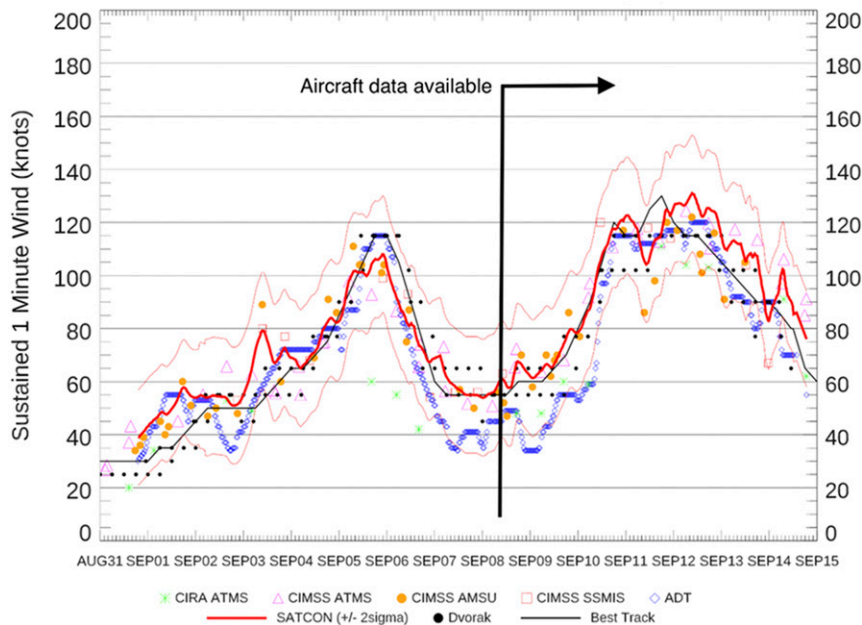


FIG. 6. Interpolated SATCON intensity estimates (MSW; thick solid red line) for Hurricane Florence (2018). Also plotted are the individual objective member estimates, the NHC Final best track (black line), the Dvorak operational estimates, and the SATCON 2-sigma confidence limits (thin solid red lines).

TC intensity peaks can often occur between SATCON estimates and therefore are not fully resolved. Danny was also a very small tropical cyclone with an eye diameter measured by MW imagers via ARCHER of only 5–10 km around the time of peak intensity. The very small storm size results in estimates that are too weak from the MW sounder-based methods even after appropriate corrections. Even the IR-based methods (subjective Dvorak and the ADT) struggle with the period of peak intensity, although the ADT is able to resolve a small ragged eye for a short time and performed the best. Despite the SATCON weighting adjustments, the anomalous combination of factors in this example lead to SATCON underestimates of the peak intensity.

Note that reconnaissance did not arrive into Danny until after the peak intensity indicated in the best track, and MSW estimates from that mission ranged from 95 to 105 kt. Therefore the 25-kt underestimate of peak intensity by SATCON may be overstated. Nevertheless, small, strong TCs with sharp intensity peaks are challenging for all satellite-based methods and SATCON as well. The Danny case serves as an example where some knowledge of intensity algorithm shortcomings can be useful in assessing the intensity methods even for algorithms such as SATCON that in the aggregate are very skillful but may underperform in certain storm structures.

One school of thought with consensus-based methods is why not just improve the individual objective algorithms rather than develop these approaches to derive better estimates? Though we strongly advocate for continued satellite-based algorithm development, the SATCON approach offers some advantages. SATCON takes the most likely solution that would be derived from a simple consensus mean value, and improves that likelihood further by weighting the known attributes of each member method. It offers a building platform for making future improvements to satellite-based TC intensity estimation if new instruments or methodologies become available. Last, and perhaps most important for use in operational TC forecast environments, it quickly shares and distills multiple information sources down to a single value for intensity analysis, with superior results. This can help to decrease the amount of time spent on the TC intensity analysis process allowing more time for the forecast.

The current membership of SATCON involves exclusively objective-based methods in order to provide intensity guidance to forecasters distinct from the subjective Dvorak technique. Yet this does not preclude the possible incorporation of operational Dvorak estimates into SATCON. In fact, experimental testing with limited weighting treatment has shown slightly better results are achieved with the inclusion of these estimates, but it is not clear if this result could be aided by a Dvorak

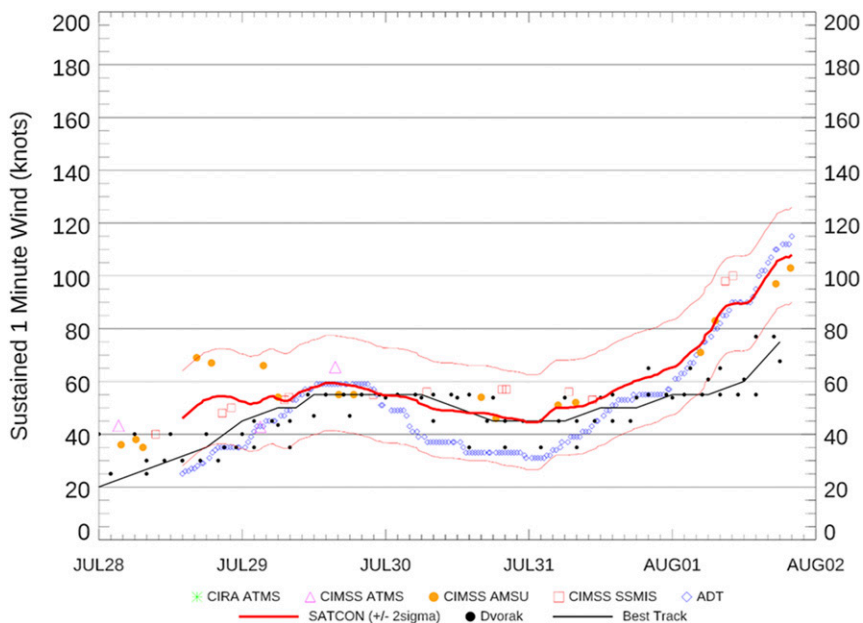


FIG. 7. Interpolated SATCON intensity estimates (MSW; thick solid red line) for Super Typhoon Halong (2014). Also plotted are the individual objective member estimates (ATMS was experimental at this time and not included in the SATCON estimates), the JTWC best track (black line), the Dvorak operational estimates, and the SATCON 2-sigma error limits (thin solid red lines).

influence on the verifying best-track records. The Dvorak estimates will also have many error characteristics that are similar to the ADT, thereby limiting the additional independent information that would be supplied to SATCON. Nevertheless, this option could be developed for poststorm analysis and best-track practices.

5. Summary and future directions

SATCON is a weighted consensus algorithm designed to optimize the strengths and minimize the weaknesses of objective satellite-based approaches to estimate TC intensity. It can provide the TC forecaster with the ability to quickly reconcile spread in objective intensity estimates thus decreasing the amount of time spent on the analysis of current intensity. The weighted consensus approach reduces estimate errors over those of the individual members, with the individual method weights in SATCON determined by situational performance.

Although it is shown that SATCON performs well in estimating TC intensity relative to other satellite-based methods, there are some limitations especially for real-time use. The estimates rely on LEO satellite inputs and thus are not continuous or always timely; 2–6-h time gaps are not uncommon, and normal latency is 1–4 h after the satellite overpass before the data are available for an intensity estimate to be derived. In addition, the

fully automated and objectively based algorithm can occasionally need user decision-making in the form of final quality control, as erroneous estimates can enter the model due to factors outside of the science algorithms.

Global, near-real-time SATCON estimates have been produced by the CIMSS developers and demonstrated to users for about the past 10 years via NOAA and DoD (Naval Research Laboratory) research and proving ground efforts. Given the encouraging demonstrated performance in estimating TC intensity, as of early 2020 the SATCON and associated member algorithms are being transitioned into a processing framework that will be supported by U.S. DoD and NWS operational environments. It is planned that these eventual operational SATCON estimates will also be made available to TC agencies outside the United States, as well as the TC research community.

The focus of future research will involve the continued evaluation of cross-platform parameter sharing, the development of quantitative or probabilistic SATCON estimate confidence indicators, and the testing/incorporation of potential new members. Other candidate objective satellite-based methods to estimate TC intensity exist (e.g., Piñeros et al. 2011; Kishimoto et al. 2013; Ritchie et al. 2014; Jiang et al. 2019; Xiang et al. 2019), and the emergence of Artificial Intelligence and Machine Learning approaches to TC

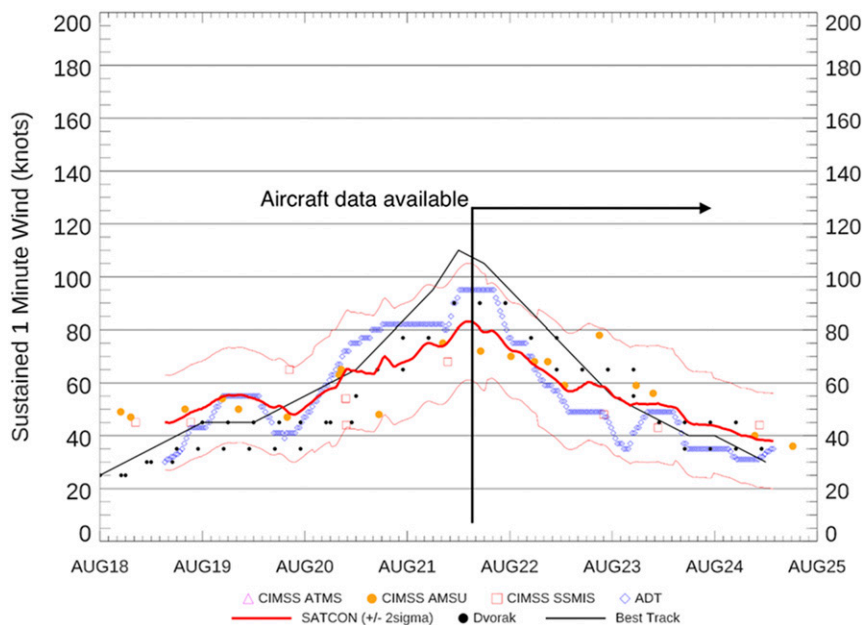


FIG. 8. Interpolated SATCON intensity estimates (MSW; thick solid red line) for Hurricane Danny (2015). Also plotted are the individual objective member estimates (ATMS was experimental at this time and not included in the SATCON estimates), the NHC best track (black line), the Dvorak operational estimates, and the SATCON 2-sigma confidence limits (thin solid red lines).

applications is promising (Bankert and Cossuth 2016; Chen et al. 2018; Pradhan et al. 2018; Wimmers et al. 2019). Upgrades to existing member algorithms, new satellite data sources, and inclusion of new members into the consensus will require periodic updates to the SATCON weighting scheme but will likely lead to further performance improvements.

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Data availability statement. Interested readers can obtain the datasets underlying the findings of this article by contacting coauthor Derrick Herndon (dherndon@sec.wisc.edu).

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