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MTrack

Improved Center Fix of Tropical Cyclones from SMAP Wind Observations

David Mayers and Christopher Ruf

ABSTRACT: MTrack is an automated algorithm that determines the center location (latitude and longitude) of a tropical cyclone from a scalar wind field derived from satellite observations. Accurate storm centers are useful for operational forecasting of tropical cyclones and for their reanalysis (e.g., research on storm surge modeling). Currently, storm center fixes have significantly larger errors for weak, disorganized storms. The MTrack algorithm presented here improves storm centers in some of those cases. It is also automated and, therefore, less subjective than manual fixes made by forecasters. The MTrack algorithm, which was originally designed to work with CYGNSS wind speed measurements, is applied to SMAP winds for the first time. The average difference between MTrack and Best Track storm center locations is 21, 36, and 46 km for major hurricanes, category 1–2 hurricanes, and tropical storms, respectively. MTrack is shown to operate successfully when a storm is only partially sampled by the observing satellite and when the eye of the storm is not resolved.

KEYWORDS: Remote sensing; Satellite observations; Numerical analysis/modeling

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Accurate knowledge of a tropical cyclone's (TC) center location, or the center fix, is critical for forecasting and reanalysis studies. The Dvorak technique, a frequently used TC monitoring method, requires a storm center fix as its first step (Dvorak 1975; Olander and Velden 2007). The accuracy of quadrant-specific wind radii estimates depends on storm center accuracy. For example, if the storm center is placed too far to the northeast, then the northeast quadrant's wind radii will be too small and the southwest quadrant's wind radii will be overestimated. Most TC simulation studies require a center location as input. However, the accuracy of the storm center location can vary between different meteorological agencies. There is need for an automated center fix algorithm that can perform with more consistency.

One automated technique is to fit spiral and ring shapes to satellite imagery of the TC (Wimmers and Velden 2016). This works best for well-organized storms with a clear eye, but only 12.6% of satellite imagery contain a detectable eye (Knapp et al. 2018). Another technique traces scatterometer wind vectors inward to the storm center, but the quality of these winds is known to degrade in heavy precipitation (Hilburn et al. 2006; Portabella et al. 2012). The method is most used in weak storms that are not well suited for spiral or ring fitting; however, scatterometer winds struggle with directional ambiguity at lower wind speeds (Lin et al. 2013). Ground-based radars and aircraft reconnaissance are the preferred data sources for storm center fixing, but the former can only be done at or near landfall, and the latter is only available for about 30% of storms in the Atlantic basin and even more rarely in the east and central Pacific (Rappaport et al. 2009).

MTrack algorithm

MTrack is an automated algorithm which determines the center location of a TC from a scalar wind field derived from satellite observations. The MTrack algorithm was first introduced, and is described in detail, in Mayers and Ruf (2019). This section will provide an overview of the algorithm as well as detailing changes made to the algorithm to accommodate a new type of satellite input. The foundation of MTrack is fitting a parametric wind model [Eq. (1)] to a satellite-observed wind field and computing the root-mean-square difference, or residual, between model and measurement. The converged model parameters and the residual depend on the assumed storm center location. The assumed TC center is varied systematically over a wide gridded domain containing the storm. The MTrack fix is the TC center location at which the residual is minimized.

The wind model used here is

$$\upsilon(r,\phi)=\left[\frac{2r\left(R_{\max}V_{\max}+0.5fR_{\max}^{2}\right)}{R_{\max}^{2}+ar^{b}}-\frac{fr}{2}\right]\left[1-A\cos\left(\phi-\phi_{\max}\right)\right], \tag{1}$$

where υ is the scalar wind speed at radial distance r and azimuth angle ϕ, expressed as a function of the six model parameters ($R_{\max}$, $V_{\max}$, a, b, A, and $\phi_{\max}$) as well as the Coriolis parameter f, which is a simple function of latitude. Parameters $R_{\max}$ and $V_{\max}$ are the radius of maximum wind and the maximum wind speed, respectively, and a and b control the roll-off rate of the winds from the maximum value.

The azimuthal scale factor, the term in (1) that includes A and $\phi_{\max}$, is a new addition to the previously published version. It accounts for the possibility of azimuthal asymmetry in the TC. These 2 additional degrees of freedom allow the parametric wind model to represent a wider range of TC wind fields, which reduces the residual and improves MTrack performance. The parameter A denotes the degree of asymmetry and $\phi_{\max}$ denotes the azimuthal direction of maximum winds. The maximum wind speed occurs at the point ($R_{\max}$, $\phi_{\max}$). From this point, the wind speed sinusoidally decreases with azimuth angle before reaching a minimum value of $V_{\max}(1-A)$ at the point ($R_{\max}$, $\phi_{\max}+180°$) on the diametrically opposite side of the

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storm from the maximum wind speed. The six parameters are chosen to minimize the root-mean-square difference between satellite observations and model given the assumed center location. An optimal set of parameters are determined using the gradient descent method. This approach modifies each parameter in the direction which improves the cost function. This continues iteratively until convergence. Note that only five of the six parameters in this model are free parameters. At each iteration, a is solved from the other five parameters by applying the constraint that the maximum wind speed is equal to the parameter $V_{\max}$, as is done in Morris and Ruf (2017). Also note that at each iteration the parametric wind field is smoothed using a Gaussian filter with standard deviation equal to the spatial resolution of the sensor. This is done so the model is more representative of the observations in general, and so it can better represent small storms where the eye is not resolved by the sensor.

An example of the process by which MTrack locates the TC center is shown in Fig. 1. The surface wind speeds are measured by the NASA satellite Soil Moisture Active Passive (SMAP), which is described in the next section. However, this explanation is valid for MTrack applied to near-surface wind speeds from any sensor. In the upper half of Fig. 1, an incorrect storm center is assumed which is about 150 km northeast of the correct location. The wind speed observations are highlighted in a 150-km radius around the assumed center. In the southwest quadrant, the wind speed increases out to 150 km with no sign of decay. This is not characteristic of a typical TC. The parametric model is fit to the measurements, but it does a poor job because the model is constrained to a radially decaying TC wind profile. This is seen in the top left of Fig. 1. The residual (root-mean-square difference) between the measurements and the model is 6.8 m s^{-1}.

Next, in the lower half of Fig. 1, a storm center is assumed which is close to the correct location. Again, all wind speed observations within 150 km of this assumed center are highlighted. Note that the algorithm uses all samples within $R_{\max}$ + 150 km to tune the parametric wind model to allow for large storms. Focusing on the northeast part of the storm in the lower-left part of Fig. 1, the wind speed is maximized around 50 km from the assumed center and decays radially out from there. This is representative of a typical TC wind field, and the parameters of the wind model can be adjusted to produce a model wind field that closely matches the observations. The residual in this case is 4.4 m s^{-1}, which is much lower than for the previous center.

The MTrack storm center search is performed over a grid of assumed centers around a first-guess location. Typically, this results in a grid of residuals which are lowest near the MTrack center, with a gradual increase in all directions away from it. A second search takes place over a finer grid centered on the lowest residual from the previous search. The minimum residual in the second search is the MTrack center. The assumed center in the lower half of Fig. 1 is the MTrack center.

Satellite input

MTrack was originally designed to work with surface wind speed data from the NASA Cyclone Global Navigation Satellite System (CYGNSS). CYGNSS, a constellation of eight satellites launched on 15 December 2016, measures wind speed by detecting GPS signals reflected from the wind-roughened ocean surface and relating the received power to wind speed (Ruf et al. 2016). Because the measurement location depends on positions of both the GPS satellites and CYGNSS satellites, the sampling pattern consists of pseudorandom tracks (one-sample-wide swaths) along the ocean surface. The resulting wind field consists of many narrow tracks of measurements with sizeable gaps in between. The MTrack parametric model approach was initially designed to handle gaps in the CYGNSS measurements; however, it can be expanded to work with TC wind speed measurements from any sensor.

SMAP. SMAP is a NASA satellite launched on 31 January 2015 which includes an L-band imaging radiometer. Its primary mission objective is to observe soil moisture and freeze/thaw state

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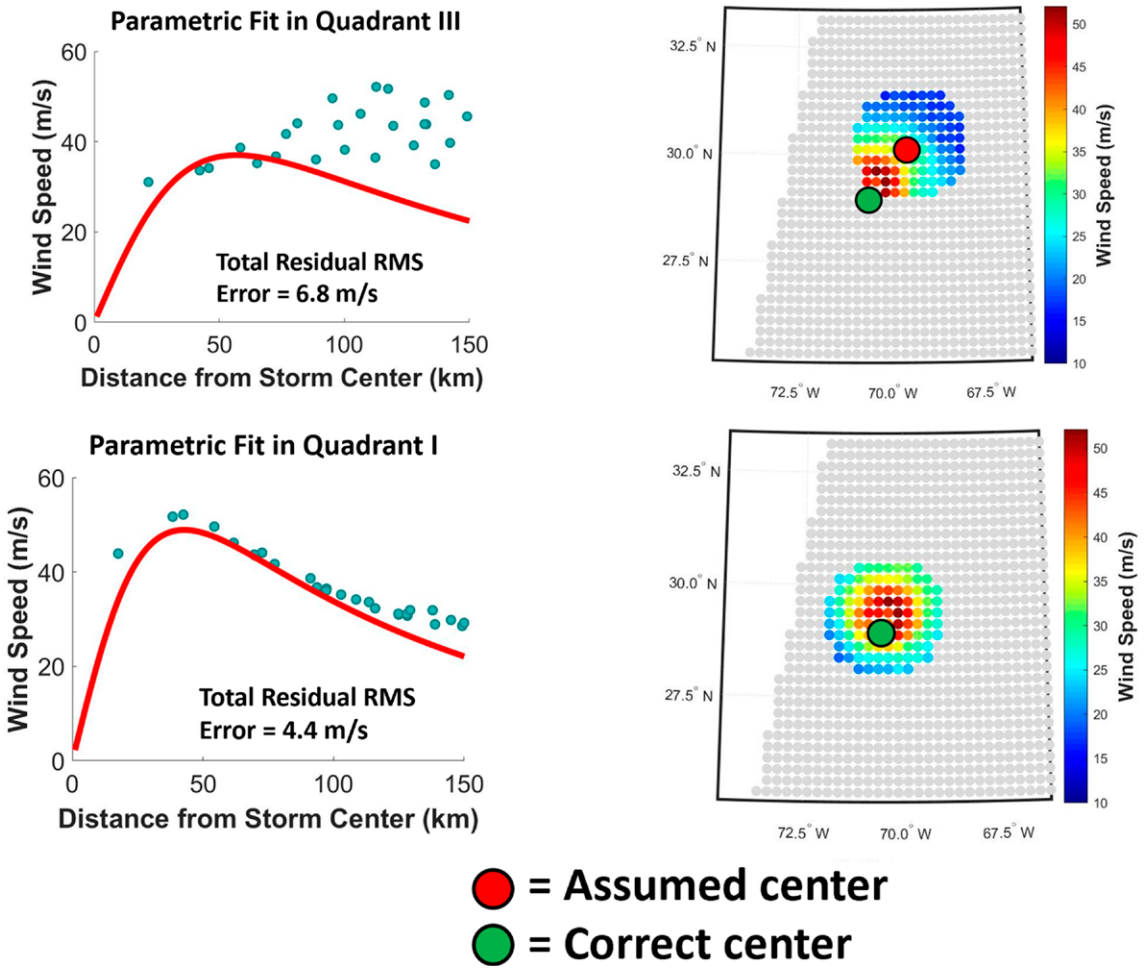


Fig. 1. The fundamentals of how MTrack works. (top) The result when a wrong location is assumed to be the storm center (red dot). Surface wind speeds highlighted around the assumed center are used to tune the parametric wind model. (top left) The blue dots are wind speed observations in the southwest quadrant and the red line is the best-fit parametric model. The residual (RMS difference between model and observation) is 6.8 m s^{-1}. (bottom) The assumed center is close to the correct location. The parametric model fits the wind observations much better and the residual is 4.4 m s^{-1}. Note that the parametric wind model varies continuously with azimuth angle. The red lines plotted above are approximated for the purpose of this visual and use the azimuth angle at the center of the selected quadrant.

from space to improve estimates of water, energy, and carbon transfers between the land and atmosphere (Entekhabi et al. 2010). SMAP also observes over the oceans and can estimate near-surface wind speed from the thermal emission of the wind-roughened ocean surface. This is done in all precipitating conditions and the measurements show no sign of saturation at high wind speed (Meissner et al. 2017). SMAP makes measurements in a 1,000-km swath with an orbit that repeats every 8 days (though a TC is measured by SMAP more frequently than this). Compared to CYGNSS, SMAP makes relatively infrequent measurements but provides more complete coverage since there are typically no gaps in the SMAP swath. Gap-free coverage allows MTrack to determine the storm center more accurately than with CYGNSS. Because MTrack was originally designed to handle data gaps, MTrack can operate with SMAP when there is missing data or when the storm is on the edge of the swath. Because SMAP often measures wind speed everywhere in the storm, there is more information available for the parametric wind model compared with CYGNSS input to MTrack. To be precise, it is often not possible to tune five free parameters with the incomplete CYGNSS wind field as input. The full storm coverage provided by SMAP allows for the parametric wind model to capture

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detailed information about the storm's wind field, including azimuthal variation and roll-off rate. The additional information in the wind field allows for a more accurate wind model and improved MTrack performance.

SMAP data used in this work were taken from the Remote Sensing Systems gridded product which is available at www.remss.com/missions/smap/.

Examples

Figure 2 shows MTrack results using SMAP wind speed measurements of well-organized category 4 Hurricane Florence at 1050 UTC 12 September 2018. The red dot in the figure represents the time-interpolated storm center generated in near–real time (NRT) and posted on the U.S. Naval Research Laboratory (NRL) website. (This is very similar to TCVitals center fixes. TCVitals storm centers are derived in part from these Navy fixes according to Buck Sampson at NRL.) For NRT processing there are often less data available for determining the storm center location compared with the reanalysis Best Track storm center fix. In this case, the NRT storm center does not agree with the position of the eye in the SMAP wind field. MTrack uses the NRT center as a first-guess location and estimates an improved center located about 50 km to the Southeast—in very good agreement with the Best Track center fix. The right panel of Fig. 2 shows the wind field constructed by the parametric wind model using the best-fit parameters and MTrack storm center location. The black circle is a 50-km radius centered around the Best Track center. A strong, organized storm with an eye visible in the satellite-measured wind field is the easiest case for MTrack or any center fix method. Unsurprisingly, MTrack finds the correct center, and the parametric wind model matches the SMAP wind field very well.

Figure 3 demonstrates that MTrack works well even when a storm is on the edge of the SMAP swath. This is also category 4 Hurricane Florence, but a day earlier than the previous example—11 September 2018 at 1014 UTC. In this case, the eye of the storm is about 30 km outside of the swath. The time-interpolated Best Track center is used as the first

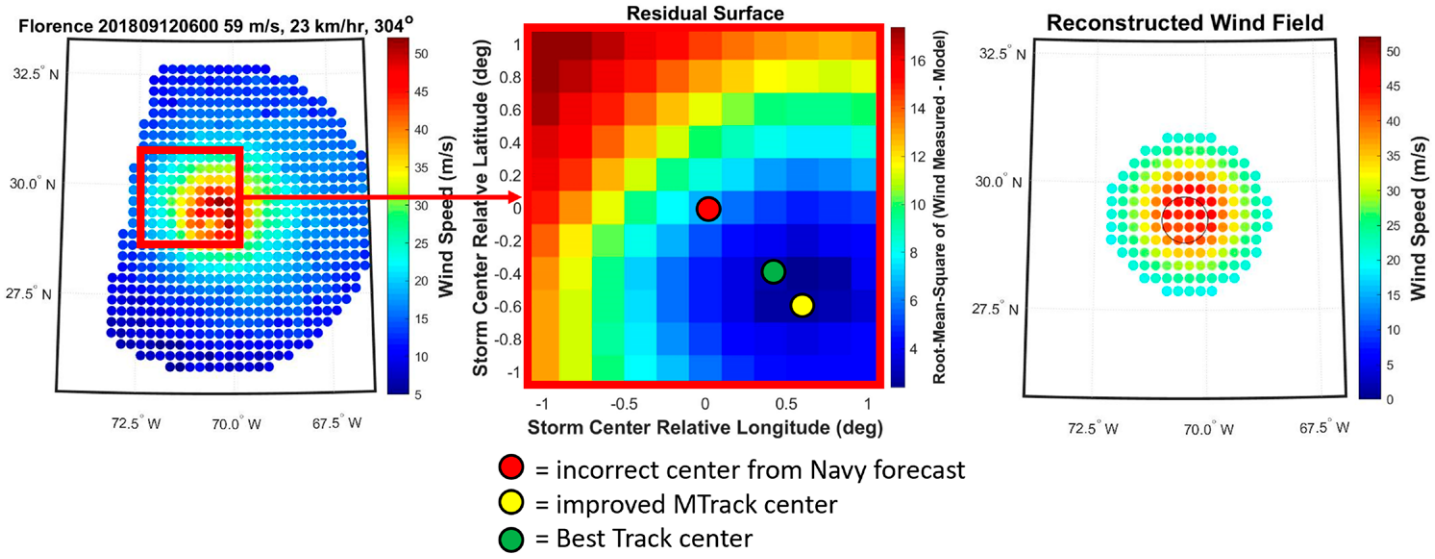


Fig. 2. (left) SMAP-measured wind field of category 4 Hurricane Florence at 1050 UTC 12 Sep 2018. The red box is the MTrack search grid. (center) Residual map that corresponds spatially to the red box in the left panel. Each grid cell is a location that is assumed to be the storm center. With this assumption in mind, the parametric wind speed model fits to SMAP observations and a residual is reported to the residual surface. The minimum residual is the MTrack center (yellow dot). This compares better with MTrack (green dot) than the near-real-time first-guess location from the Navy forecast (red dot). (right) Wind field that is constructed using the parametric wind model and best-fit parameters assuming the MTrack storm center. The MTrack wind field closely resembles the SMAP wind field meaning that this case can be well represented by the parametric wind model.

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guess instead of the NRT Navy center as in the last example. It is important to note that the MTrack center solution is independent of the first guess as long as the search grid is large enough to capture the storm center. Shifting the first guess simply shifts the search grid and the resulting storm center fix is unchanged. While MTrack iterates over the search grid (red box in Fig. 3), some assumed storm center locations are off the swath edge so there are no SMAP wind speed measurements in the immediate vicinity. In these cases, it is still possible to fit the parametric wind model to measurements and report a residual as long as there are measurements within a 150-km radius of the assumed center. MTrack finds a center about 40 km west of the swath edge, which is very close to the time-interpolated Best Track center, the best estimate of truth. The right panel of Fig. 3 shows that the MTrack wind field is very similar to the SMAP wind field. Again, this is a good way to check that MTrack is performing as intended.

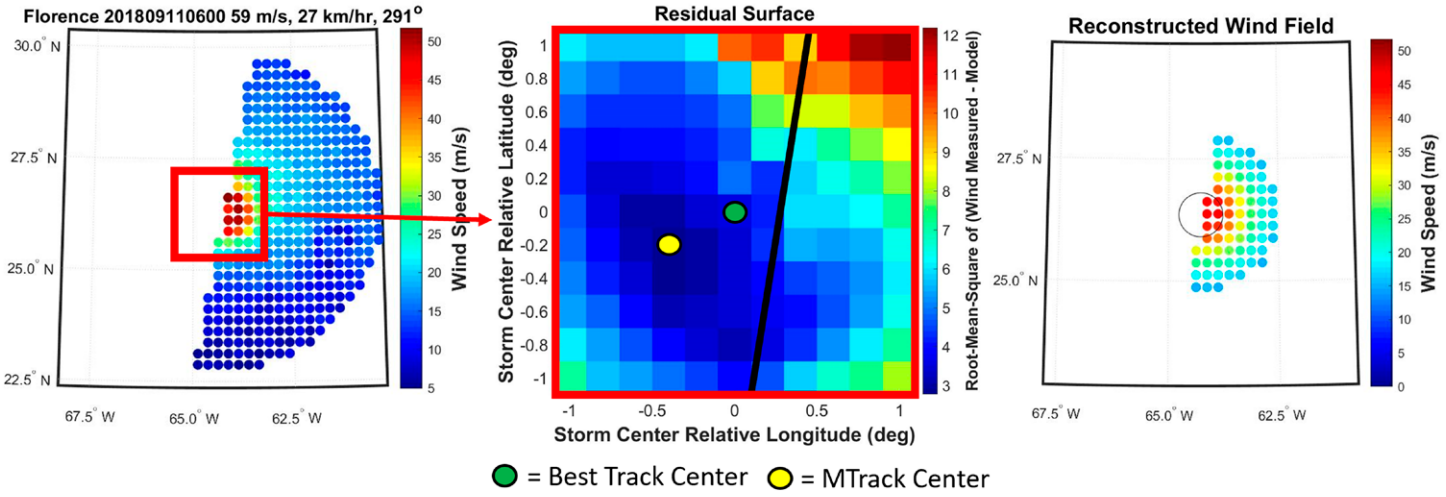


Fig. 3. (left) SMAP-measured wind field of category 4 Hurricane Florence at 1014 UTC 11 Sep 2018. The red box is the MTrack search grid. (center) Residual error map which corresponds spatially to the red box in the left panel. The first-guess storm center is Best Track (green dot), which is about 30 km from the SMAP swath edge (diagonal black line). The MTrack center (yellow dot), the location of lowest residual, is in good agreement with Best Track. (right) Wind field that is constructed from the parametric wind model and best-fit parameters assuming the MTrack storm center. The MTrack wind field closely resembles the SMAP wind field, which means that this case can be well represented by the parametric model, even though the storm is on the edge of the SMAP swath.

Figure 4 shows the SMAP wind field of category 3 Hurricane Dorian on 3 September 2019 when it was stalled over Grand Bahama. Much of the storm's core is not measured by SMAP in this case due to the presence of land. Despite the missing wind speeds, MTrack is able to find a storm center solution very close to the Best Track center, as seen in the residual error surface in the right panel of Fig. 4. The wind field in the middle panel is constructed from the MTrack parametric wind model using best-fit parameters and MTrack center location. The wind field that is "seen" by MTrack is very similar to the SMAP wind field, which suggests that MTrack is working as intended (the parametric wind model is able to represent the primary features of the SMAP wind field) and the storm center solution is reliable. In this reanalysis case, there is a Best Track fix available for comparison to confirm that the MTrack fix is accurate. However, comparison of the MTrack wind field to the SMAP wind field is a useful alternative way to determine how much confidence should be placed in the MTrack fix in NRT operation when a Best Track fix is not available.

Figure 5 shows a SMAP wind field of category 2 Hurricane Dorian on 30 August 2019. At this point, Dorian is very small and SMAP is not able to resolve the lower wind speeds in the

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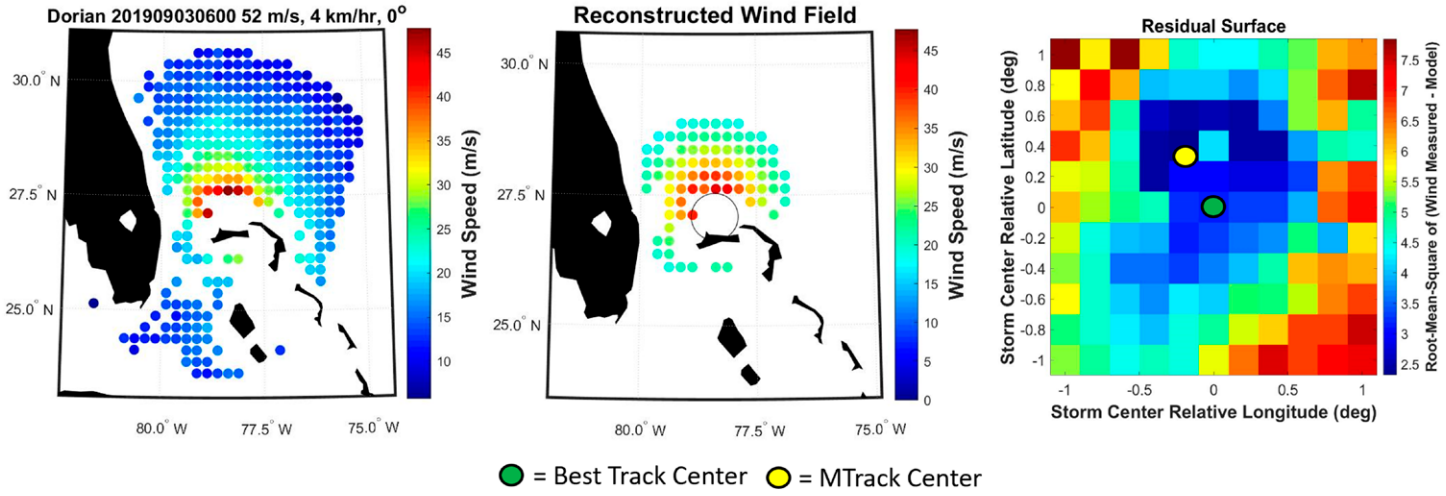


Fig. 4. (left) SMAP wind field of category 3 Hurricane Dorian on 3 Sep 2019. (center) MTrack wind field that is constructed from the parametric wind model using best-fit parameters and the MTrack storm center solution. The black circle is a radius of 50 km centered on the Best Track storm center location. The MTrack storm center agrees very well with the Best Track center, and the MTrack wind field closely resembles the SMAP-measured wind field. This is optimal MTrack performance, despite many missing wind speed measurements due to land. (right) The residual error map shows the MTrack center is close to the Best Track center.

eye. Although the eye is not visible in the SMAP wind field, MTrack is still able to operate successfully because of the spatial smoothing that is applied at each iteration. This allows the MTrack wind field to better simulate what SMAP sees at 40-km resolution. The right panel of Fig. 5 shows that MTrack finds a storm center location very close to the Best Track center. The center panel of the same figure shows that the parametric wind model is able to capture the behavior of this very small storm, with small R_{max}, a and b parameters tuned to match the roll-off rate, and the smoothing filter able to remove any evidence of the eye to match the SMAP measurements.

Figures 6 and 7 demonstrate some of the limitations of MTrack. Figure 6 shows category 1 Hurricane Dorian at a higher latitude on 7 September 2019. The SMAP wind field reveals an

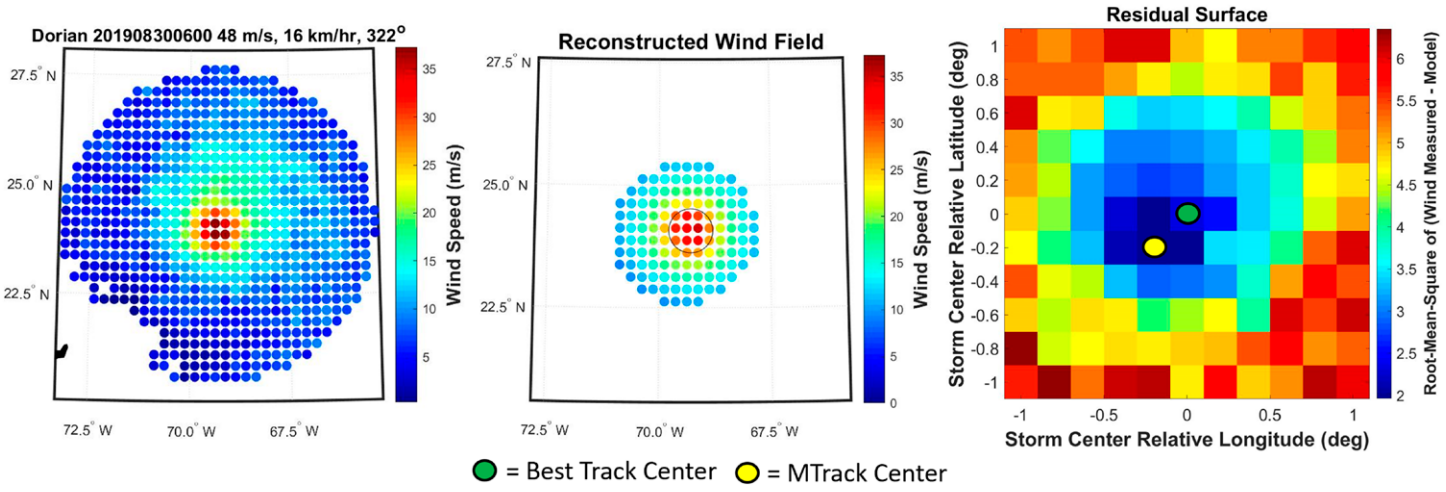


Fig. 5. (left) SMAP wind field of category 2 Hurricane Dorian on 30 Aug 2019. The storm is very small and the 40-km spatial resolution of SMAP is unable to resolve the lower wind speeds in the eye. (center) MTrack wind field that is constructed from the parametric wind model using best-fit parameters and the MTrack storm center solution. Because of the spatial averaging that is included in MTrack to mimic the resolution of SMAP, MTrack can represent a very small storm like this. (right) The residual error map of MTrack shows high confidence in a storm center location that is in good agreement with Best Track.

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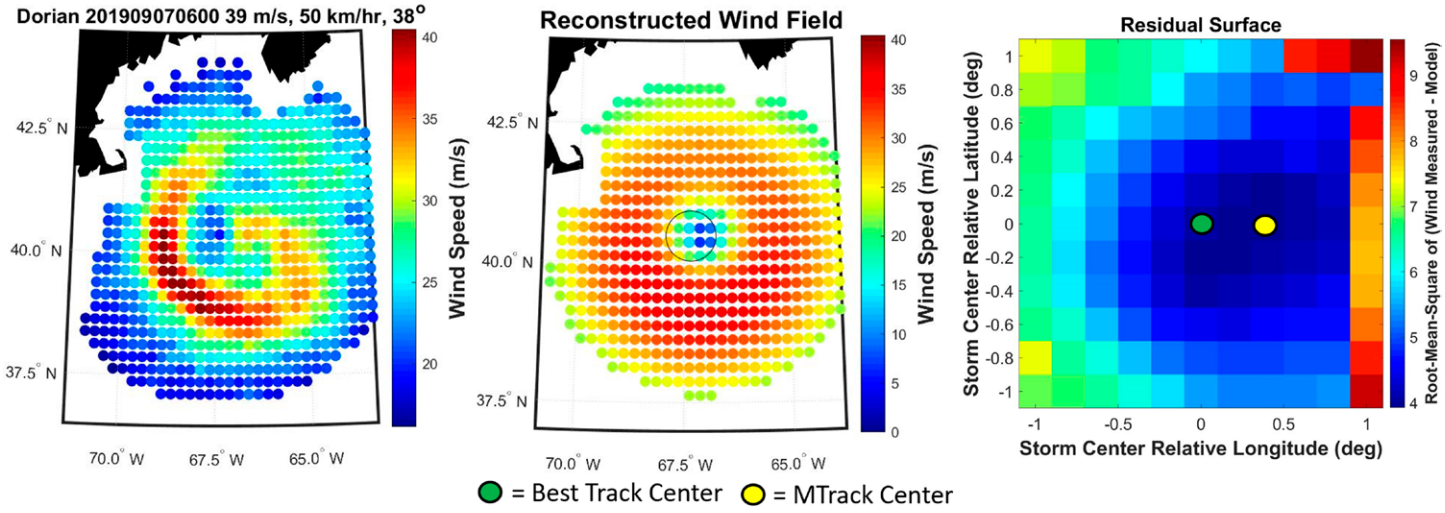


Fig. 6. (left) SMAP wind field of category 1 Hurricane Dorian on 7 Sep 2019.(center) MTrack wind field that is constructed from the parametric wind model using best-fit parameters and the MTrack storm center solution. The MTrack wind field is not complex enough to capture the spiral behavior of this storm. (right) Residual error map of MTrack. The MTrack center (yellow dot) is close to the Best Track center (green dot); however, this is just a coincidence. In cases where MTrack cannot capture main features of the measured wind field, the MTrack center is often unreliable.

unusual spiral shape which cannot be represented by the MTrack parametric wind model. When the primary features of the wind field cannot be captured by the wind model, the storm center solution generally cannot be trusted because MTrack is not operating as intended. However, in this case, the MTrack storm center solution is in good agreement with Best Track as seen in the right panel of Fig. 6. The center panel of Fig. 6 shows that the best-fit R_{max} is very large so that the MTrack wind field has high wind speeds almost everywhere in the domain. This does not represent the SMAP wind field very well, but this pattern has the lowest residual compared with SMAP when the assumed storm center is at the center of the spiral, which happens to be close to the Best Track center. In this case, MTrack is fortunate to be fairly accurate.

Figure 7 shows the SMAP wind field of a very weak and disorganized Tropical Storm Leslie on 9 October 2018. There is little discernible structure in the measured wind field, which makes it difficult for MTrack to function properly. As a result, the right panel of Fig. 7 shows that the MTrack residual error map does not have a clear minimum in the search domain, meaning that MTrack fails to find a storm center location. The MTrack search domain is large enough (2° × 2°) that a search initialized by a NRT center fix will always have the Best Track center contained within the

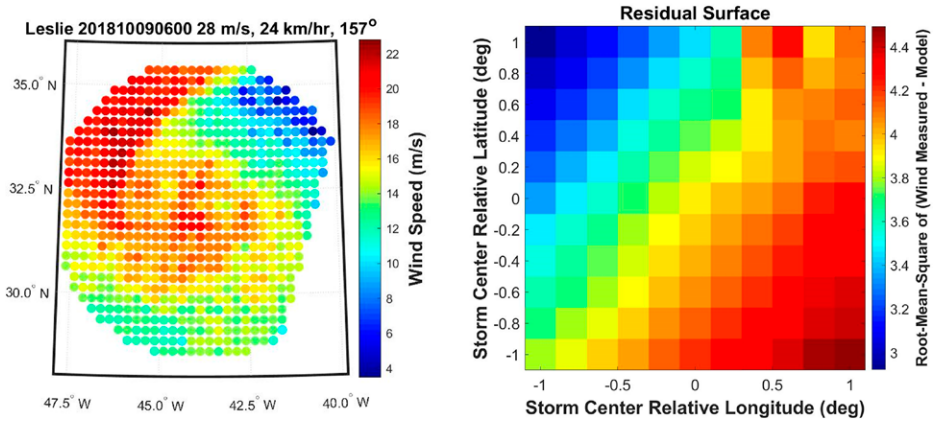


Fig. 7. (left) SMAP wind field of Tropical Storm Leslie on 9 Oct 2018. Leslie is very weak and disorganized at this time and there is very little discernible structure in the wind field. (right) MTrack residual error map. MTrack searched for a storm center location in a 2° × 2° grid centered around the Best Track center location. There is no clear minimum residual inside the search grid because the SMAP winds do not resemble the typical TC structure that is expected by the MTrack parametric wind model.

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search domain (Trahan and Sparling 2012). Therefore, storm center locations outside of the 2° × 2° search grid are not considered.

Accuracy assessment

To evaluate the accuracy of MTrack using SMAP winds as input, there must be a true storm center fix for comparison. However, there is no truth available for storm centers—the closest thing is Best Track, a 6-hourly reanalysis summary of all TCs. In 2012, Best Track storm center fix uncertainties were independently estimated by 10 experts, then the numbers were averaged together. According to Landsea and Franklin (2013), "the results obtained should be considered 'ballpark' estimates of uncertainty where virtually none have existed previously." MTrack storm center fixes are compared to Best Track and the average distance between the two can be considered an upper bound on the MTrack uncertainty (since a component of the difference is also due to Best Track error).

MTrack was run for all SMAP overpasses of 2018 storms in the Atlantic, west Pacific, and east Pacific basins (296 overpasses). First, overpasses with a minimum residual on the edge of the search grid were removed. When MTrack fails to find an optimal center due to a disorganized wind field, the lowest residual is most frequently on the edge of the search grid (as in Fig. 7). For tropical storms (<33 m s^{-1}), category 1 and 2 storms (33–49 m s^{-1}), and major hurricanes (>49 m s^{-1}), the percentage of cases removed for this reason is 18%, 4%, and 1%, respectively. The difference between the MTrack and Best Track center fixes are calculated for the remaining cases, binned by storm intensity, and averaged together. The results are displayed in Table 1. For tropical storms, category 1 and 2 storms, and major hurricanes, the MTrack error upper bounds are 46, 36, and 21 km, respectively. This is an upper bound on MTrack error because a component of the difference is due to Best Track error. Best Track uncertainties, binned the same way by intensity, are approximately 53, 40, and 27 km, respectively (Landsea and Franklin 2013). Both the MTrack and Best Track errors decrease with intensity because intense hurricanes are typically better organized with an easily identifiable eye, while weak storms are disorganized and do not have an obvious center of circulation. Note that MTrack errors are within the estimated Best Track uncertainty for all storm intensities.

Discussion

One expected use of MTrack is to create a database of TC properties. For example, each time a satellite makes an overpass of a TC, those wind speed measurements can be used as input to MTrack and a storm center location is automatically determined. Automatic quality control using the shape of the residual error map and the residual between satellite wind speeds and the best-fit model wind speeds can determine the confidence in the fix. Each MTrack center fix also generates parameters that characterize the TC wind field such as the maximum wind speed, radius of maximum wind speed, and azimuthal variation characteristics. These storm parameters can be reported along with the satellite wind speed product. They can also be

Table 1. MTrack performance broken down by storm strength. The success rate (percentage of time that MTrack can find a storm center solution) increases with storm intensity. MTrack is also more accurate for stronger storms, as is Best Track. MTrack uncertainty (mean distance from a Best Track fix when MTrack is successful) is within the Best Track estimated error for all storm intensities.

Storm strength	Best Track uncertainty (km) (only satellite observations available)	Average distance between MTrack and Best Track TC centers (km)	MTrack success rate (%)
Tropical storms	53	46	82
Category 1–2	40	36	96
Category 3–5	27	21	99

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used to generate a gridded wind speed product of the storm, even if the overpass coverage is incomplete. The above can be done at regular time intervals (e.g., every 6 h) using surface wind speed input from many different satellites for each MTrack fix.

MTrack can also assist expert forecasters at an agency such as the National Hurricane Center (NHC) to make a center fix decision. In this situation, MTrack would be one of many tools available to the forecaster. The MTrack center fix would be automated, but there does not need to be automatic quality control. Instead, an expert user could look at the satellite-measured wind field, the MTrack residual error map, and the MTrack reconstructed wind field. In a typical case, the MTrack residual error map has a well-defined minimum residual with increasing error on all sides (e.g., the center panel of Fig. 2). The depth and size of this minimum are indications of the confidence in the MTrack center fix solution. Next, the forecaster could compare the satellite-measured wind field to the MTrack reconstructed wind field. In a typical case, the MTrack wind field which is generated from the best-fit parametric wind model will look very similar to the measured wind field. If there are large differences in wind structure, it is likely that the complex wind field was not well represented by the parametric wind model (e.g., Fig. 6). In this case, it is possible that the MTrack center fix is accurate, but it is not a guarantee because the model does not agree with the measurements. In this way, an expert user can look at these three components of MTrack output to determine how much confidence to place in the storm center solution when comparing it to information from other available tools and data.

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