Using satellite-based remotely-sensed data to determine tropical cyclone size and structure characteristics

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LONG-TERM GOALS:

To exploit remote-sensing observations for tropical cyclone genesis, intensity, and wind field structure information and use this information to develop objective, accurate multivariate analyses of tropical cyclone wind structure and intensity in oceanic regions where in situ observations are sparse.

OBJECTIVES:

The primary objective is to continue to use innovative signal-processing methodologies to extract tropical cyclone (TC) structure information, including genesis likelihood from clouds clusters, intensity information, and wind field structure information from remote-sensing platforms in oceanic regions where in situ observations are sparse. This information is used to develop accurate, objective analyses of tropical cyclone wind structure and intensity and to also detect early signs of development in tropical cloud clusters. Specific investigations include:

1. Developing a multivariate genesis parameter to create probabilistic forecasts of TCs within 24, 48, and 72 hours using the DAV signal in conjunction with other remote-sensing data including lightning flash rate data;
2. Developing methods using satellite observations to infer wind structure information;
3. Exploring improvements in TC model initialization using improved wind structure information; and
4. Exploring multi-variate, multi-temporal remote sensing data sets to provide structure and intensity information of TCs at different stages in their life cycles.
By leveraging our past work on objective peak intensity estimation and genesis potential of cloud clusters using geostationary satellite imagery, we will explore whether more detailed wind structure can be extracted from remote sensing data. We will begin with the geostationary visible and infrared observations that are the basis of our earlier results, but we will also explore the blending of spatially and temporally-limited data sets such as those available at microwave frequencies on polar orbiting platforms, as well as land-based remote-sensing information including the Vaisala Long-Range Lightning Detection network. We will also continue to improve the current techniques we have developed for genesis and intensity estimation/prediction working with our partners at JTWC to improve the utility and functionality of those techniques.

**APPROACH:**

This work has multiple aspects to it and so the approach is somewhat non-uniform in reaching each goal we have set. Most of the work includes analyzing remote sensing data for signals that prove to have high correlation with the TC parameter we are interested in, whether genesis, intensity trends, or size parameter trends. Because of our previous work in the DAV parameter (from IR imagery, Piñeros et al. 2008; 2010; 2011), our starting point is to analyze that signal for further information on TC size and structure. We then use validating observations to check and train our technique. For wind structure we are limiting the training set to within 6 hours of USAF reconnaissance data availability for the Atlantic. For validation and detailed analysis of the physical processes that link the signals we extract from remote sensing observations and the physical structures/processes they represent, we use statistical analysis, model simulation studies, or subjective evaluation then establishes the validity/utility of our technique.

**WORK COMPLETED:**

1. The DAV-based objective, automated system to track the location and evolution of TCs in satellite imagery has been tested in the western North Pacific basin for the 4 years 2009-2012 (Rodríguez-Herrera et al. 2014). Further development includes modifying the thresholds and applying edge-detection technology to properly group cloud features from a single cloud cluster, which reduces false positives and improves the overall performance of the system. In addition, the automated cloud cluster tracking algorithm has also been applied in the eastern North Pacific basin to track all cloud clusters during the 2009-2012 eastern North Pacific hurricane seasons and JRA-55 and NOAA SST data have been used to compare large-scale environmental patterns with cloud cluster activity (Wood et al. 2014). Code is being developed to display IR and DAV maps in real time for the eastern North Pacific basin, similar to that already in existence for the western North Pacific and North Atlantic basins. Finally, 2009-2013 GOES-E data in the North Atlantic are have been processed in preparation for use with the automated tracking system.

2. Statistics have been collected for all cloud clusters tracked by the automatic tracking system to develop probabilities of genesis at lead times out to 72 hours initially for the western North Pacific. The relative frequency of disturbances that develop into TCs of any category, after reaching a set DAV have been computed. That is, we have computed the ratio of the disturbances identified by the objective, automatic tracking system that develop into a TC, at any subsequent time, to the total number of disturbances identified that reach a set DAV value. We have also computed the relative frequency of the disturbances that develop into TD, TS, or TY within a set time interval. That is, we have computed the ratio of the identified disturbances that develop into any TC category within a set
time after meeting a given DAV value to the total number of identified disturbances that meet the same DAV value, whether they develop or not. This analysis required the development of new computer programs to process the large amount of data contained in the automated cloud tracking database, the JTWC invest database, and the JTWC best track archive.

3. The DAV technique (DAV-T) was applied to the eastern North Pacific basin for both genesis prediction and intensity forecasting. As neither GOES-E nor GOES-W provide full coverage of the eastern North Pacific, an algorithm was developed to stitch rectified satellite imagery together prior to applying the DAV-T. The parametric curve and two-dimensional parametric surface intensity algorithms were applied for the years 2005-2011 with overall root mean square (RMS) intensity errors of 13.4 kt and 12.7 kt respectively (Ritchie et al. 2014). The database of imagery is being updated to include 2012-2013 for the eastern North Pacific and 2011-2013 for the North Atlantic basins.

4. Lightning flashes were combined with the DAV-T signal for genesis to determine whether the DAV-T genesis prediction can be improved by incorporating other remote-sensing data that has shown genesis distinguishing properties. Previous work in the group has shown that Lightning flash rates are a discriminator of genesis (Leary and Ritchie 2009). Current work completed includes: transforming individual lightning flash counts to a grid at half-hourly intervals for the period May to October; and statistically analyzing the gridded flash counts with respect to DAV values and cloud top temperature in order to evaluate the potential for a combined genesis predictor product.

5. A methodology to objectively obtain the symmetric and asymmetric wind field structure of TCs from satellite imagery has been developed. From this, a multiple linear regression model has been developed using the axisymmetric DAV signal, variables from the best track data, and environmental parameters from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model in order to determine the radial extent of the axisymmetric 34-, 50-, and 64-kt winds. Furthermore, the analysis has been repeated for each individual quadrant (NE, SE, SW, and NW) in order to extract asymmetric components of the wind field. Recombination of the symmetric and asymmetric components has produced a good representation of the wind field for various test cases of TCs compared with either basic SHIPS R34, R50, R64 values or subjectively with the H*Wind product. A manuscript is in preparation for *J. Atmos. Sci.* reporting these results (Dolling et al. 2014).

RESULTS:

a) **Objective cloud cluster tracking algorithm**

The objective, automatic tracking system that was developed to improve the DAV-based genesis prediction technique continues to be improved. The details of the tracking system are reported in Rodríguez-Herrera et al. (2014). Figure 1 shows an IR image of the western North Pacific basin with a number of potentially developing cloud clusters being tracked by the objective, automated tracking system. The figure shows three types of current detections and the previous location of seven identified TCs with a latency time of 24 hours. The current detections, marked by a color circumference, are divided in blue new true detections (i.e., detections that satisfy all the thresholds in the tracking system and have not been previously identified), green true detections (i.e., detections that satisfy all the thresholds and are associated to a previously identified TC), and yellow track detections (i.e., detections that do not satisfy all the thresholds but have been associated to a previous true detection).
Table I shows the results of a tracking experiment carried out for the 2009-2013 seasons over the western North Pacific when compared with the Joint Typhoon Warning Centre (JTWC) invest database. As shown in the table, the results of the objective, automatic tracking system were in good agreement with the JTWC results, detecting almost all developing TCs. The largest differences were in the detected non-developing cloud clusters, and these mostly reflect differences in the JTWC operator tracking choices compared to the objective method. These differences are being analyzed in order to bring the automated system in line with JTWC practices. The performance of the tracking system with added cloud edge detection algorithms has also been analyzed and compared to the performance of the original implementation. Our analysis showed that the overall performance is similar in both cases. However, we have identified strategies that may be used to reduce the number of false positives identified by the system using the edge detection algorithm. The implementation of such strategies is part of the work that we plan to do during the next period.

Table 1. Summary of the objective, automatic tracking results obtained for the 2009-2013 seasons in the western North Pacific compared with the JTWC invest database.

<table>
<thead>
<tr>
<th>Tracking System</th>
<th>JTWC</th>
<th>Auto Tracking</th>
<th># that correspond</th>
</tr>
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<tbody>
<tr>
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<td># DEV</td>
<td># NDEV</td>
<td># DEV</td>
</tr>
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<td>44</td>
<td>23</td>
</tr>
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</tr>
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<td>2011</td>
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<td>44</td>
<td>19</td>
</tr>
<tr>
<td>2012</td>
<td>20</td>
<td>39</td>
<td>16</td>
</tr>
</tbody>
</table>

b) **DAV-T genesis prediction and estimation in the eastern North Pacific**

The DAV-T has been successfully applied to the eastern North Pacific basin over the period 2005-2011, for TC intensity estimation producing a best overall root mean square (RMS) error of 13.4 kt calculated using a radius of calculation of 200 km. Due to the variation in TC size found in the eastern North Pacific, the two-dimensional surface technique, which was developed for the western North Pacific was also applied to this basin. This technique uses the DAV value computed from two different
Figure 2: DAV intensity (kt; blue) and best track intensity (kt; red) for all storms in 2008. The DAV intensity estimates shown are made using 2005-2007 and 2009-2011 as the training set. 2008 had a best radius of 200 km and an associated RMS error of 10.0 kt.

Radii to then estimate the intensity of the TC. There was a slight RMS error improvement of 0.8 kt resulting from this methodology. The DAV-T estimated intensity (kt) compared to the National Hurricane Center best track estimates (red) for 2008 using 2005-2007 and 2009-2011 as the training set is shown in Fig. 2. The 2008 RMS intensity error is 10.0 kt (Ritchie et al. 2014).

Continuing work involves reducing the error made for high intensity estimates, as the performance of the DAV-T worsens as TCs become more intense. There are few samples for training at the high intensity end of the spectrum, and the sigmoid may not be the best parametric curve.

For genesis prediction in the eastern North Pacific, maps of the DAV parameter are created (Fig. 3) by calculating the DAV parameter with regions of lower DAV values that coincide with clouds signifying cloud clusters that are organizing into tropical cyclones. The objective tracking technique (Rodríguez-Herrera et al. 2014) is applied to the eastern North Pacific to follow and identify cloud clusters during 2009-2012. Statistics for both general cloud cluster climatology as well as the probability of correctly detecting a developing cloud cluster have been compiled (Wood et al. 2014).
c) **Probabilistic Genesis Prediction**

The large amount of tracking data produced by the tracking system includes time of detection, location, associated DAV value, and time spent by the disturbance below a set DAV threshold. That information has been used to perform a statistical analysis aimed at building a probabilistic model, which is one of the goals in this research. The reasoning behind the statistical analysis is that with a sufficiently large number of analyzed disturbances, the results of a relative frequency analysis will provide a good approximation to the probability density function of TC development, within a time window, as a function of DAV value. This idea is based on the well-known fact that the relative frequency approaches the probability in the limit of a very large number of observations.

![Figure 4](image)

**Figure 4:** a) Relative frequency of a disturbance developing into a TC of any category as a function of the DAV value; and b) Relative frequency of a disturbance developing into a TD within a set time after (solid lines) or before (dotted lines) meeting the DAV value in the x-axis.

The calculation of the relative frequency of a disturbance developing into a TC (of any category) at any subsequent time after meeting a set DAV value (Figure 4a) has been combined with the relative frequency of a disturbance developing into a TD, TS, or TY within a set time after meeting the same DAV threshold (Figure 4b) to estimate the “probability” of a disturbance developing into a TC of a given category a set number of hours after meeting a given DAV value. Note that the quantity computed using relative frequencies is not, strictly speaking, the actual probability. These results are still being validated; however, we present examples of the preliminary results herein.

The main challenge is that the computed “probabilities” are rather low even for very low DAV values. Recall that low DAV values correspond to very symmetric disturbances and are mostly obtained in already developed TCs. To obtain the curves in Fig. 4b, the difference between the time of first designation by the JTWC at TD category and the time at which the tracking system recorded the first instance of the disturbances meeting each DAV threshold was computed. This difference is the time to detection. A negative time to detection in Fig. 4b means that the tracking system recorded the first instance of the corresponding DAV threshold after the TD category designation time recorded in the best track. A positive time to detection means that the disturbance met the corresponding DAV threshold before the TD category designation time recorded in the best track. Each curve in Fig. 4b (i.e., -48 hrs., -24 hrs., etc.) corresponds to a maximum time to detection. For instance, the -6 hours curve is the relative frequency of disturbances for which the time to detection for each DAV threshold is less than or equal to -6 hours. Therefore, the time to detection for the disturbances used to compute the -6 hours curve, for each DAV threshold, can be any time in the interval (-∞, -6] hours.
d) Wind field structure from the DAV parameter

Maps of the DAV with respect to time display information on the axisymmetry of TC cloud structure. However, further analysis has revealed that the symmetric and asymmetric spatial patterns of the DAV correlate well with the corresponding spatial components of the surface wind field (Fig. 5). The spatial/temporal information in these maps along with information from the Best Track archive and the SHIPS model are utilized to create a multiple linear regression model, which is then utilized to estimate the radii of the 34-, 50- and 64-kt wind radii for both the axisymmetric and asymmetric components of the wind field. The symmetric model has mean absolute errors (MAE) of 20.8, 12.5 and 7.3 n mi for the 34-, 50- and 64-kt wind radii. An example of a TC with variable intensity and size is displayed in Fig. 5. The asymmetric component of the wind radii are also modeled using azimuthally averaged DAV in the NE, SE, SW and NW quadrants of the TC and the same predictors as the symmetric model. Mean absolute errors are of similar magnitude with the lowest MAEs typically in the southwest quadrant. Simple re-constructed 2-D wind fields are shown in Figure 6 for two times during TC Gustav. This objective technique for measuring the wind radii from GOES IR imagery allows for good approximations of the wind radii on ½ hourly time basis (Dolling et al. 2014).

Figure 5: Hovmoller diagram of the azimuthally-averaged DAV signal plotted in color shading for TC Gustav. The red dashed line is the symmetric observed wind radii (km) and the thick black dashed line displays the regression line (km): (a) Observed wind radii and regression line for 34-kt winds; and (b) Observed wind radii and regression line for 64-kt winds. The thin black dashed line is the TC intensity (kts).

Figure 6: Re-constructed 2-D surface wind fields for TC Gustav based on the estimated R34, R50, and R64-kt winds in all four quadrants (shading). The same quantities from the extended best track database are overlaid (black contours) for comparison.
IMPACT/APPLICATIONS:

1) Intensity Estimation: To estimate and predict the TC’s intensity, forecast centers make use of *in-situ* measurements that are expensive and not always available. On the other hand, satellite-based imagery provides a key, reliable source of measurements over the data-sparse tropical oceans (e.g., Ritchie et al. 2003). Several procedures have been developed to estimate the TC’s intensity from satellite imagery, among the most known ones are the Dvorak technique (Dvorak 1975), and the Advanced Dvorak Technique (ADT) developed by Olander and Velden (2007). Although the first technique is widely used, it is also subjective and produces quite different estimates depending on the operator. The second technique is well developed and while it has sensitive technical steps that can affect its performance (e.g. the TC pattern selection), it shows a lot of promise and is used by operational centers as additional information on current intensity. The technique being further developed in this research is simple, easy to implement, uses only infrared imagery, has a good performance, does not use pattern classification, and is a completely independent estimate of intensity. For this reason, this technique can enhance other TC intensity estimations generated by forecast centers around the world.

2) Genesis prediction: The ability to ascertain with some confidence that a particular cloud cluster will go on to develop into a tropical cyclone is a continuing issue for forecast centers. Again, there are techniques available to forecast centers to help with likelihood of genesis, putting concrete values or probabilities against the development of a particular cloud cluster is still more of a qualitative than a quantitative exercise. Here we are developing a fully objective, automated system that tracks cloud clusters and provides a probability of development into a tropical cyclone in a particular time frame that can be used in conjunction with other genesis techniques, or as a stand-alone tool.

3) Wind field structure: There are several potential applications for a good quality surface wind field. Currently we can produce a two-dimensional surface wind field of an existing TC, provide R34, R50, and R64 information by quadrant with a reasonable degree of accuracy. We can easily extend this to a three-dimensional wind field by using analytic profiles based on idealized models of TC vertical structure. However, we are exploring ways to extract vertical structure from satellite observations in order to produce a three-dimensional TC wind field that is physically based. This more realistic structure can be used to initialize forecast models.

RELATED PROJECTS:

None.

REFERENCES:


**PUBLICATIONS:**


