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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 he Joint Typhoon Warning Centre (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, which then establishes the validity/utility of our technique.

WORK COMPLETED:

1. Further development of the DAV-based objective, automated system has been centered on reducing the high number of false alarms (cloud clusters detected that do not go on to become TCs), which not only improves the overall performance of the tracking system, but allows us to gather robust statistics on the detection system from which we can build a probabilistic genesis and intensity forecast system. Strategies include: modifying the DAV thresholds and applying a dual-threshold filter, which delays the time of detection; and applying edge-detection technology to properly group cloud features from a single cloud cluster. Furthermore, 12 days of IR imagery in 2010, which had high cloud cluster activity were manually examined to detect obvious patterns of false positives that could then be translated into rules for the automated tracking system. As a result a latitude filter to remove detections lower than 5 ºN and higher than 35 ºN in the western North Pacific was added. The testing also identified typical cloud cluster morphologies that were not pre-TC cloud clusters but were classified as false positives by the automated system. There is ongoing work to add this rule into the tracking algorithm.

2. Blended GOES-East/GOES-West IR images and DAV maps were generated for the 2009-2012 North Atlantic and eastern North Pacific hurricane seasons and for both genesis prediction and intensity forecasting. Preliminary code has been developed that creates and displays IR imagery and DAV maps in real time for the eastern North Pacific and the North Atlantic. The automated tracking algorithm was used in both the western and eastern North Pacific basins to generate genesis

statistics for 2009-2011 and the results were published in Wood et al. (2015). The Hurricane Satellite (HURSAT) dataset was used to generate 3-hourly tropical cyclone-centered DAV maps for 342 North Atlantic TCs and 468 eastern North Pacific TCs. These maps provide an opportunity to look at DAV-based parameters over a 30-year period and compare this consistent methodology with the best track intensity and size parameters.

3. Statistics have been collected for all cloud clusters tracked by the automatic tracking system to develop probabilities of genesis at lead times out to 120 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.

4. 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 upgraded. The details of the tracking system are reported in Rodríguez-Herrera et al. (2015). Developments this year include reducing the number of false positive cloud clusters detected by the system in order to improve the statistical analysis for the probabilistic genesis and intensity tool. Table 1 is a summary of the improvement in the number of false positive detection gained using: edge detection (ED); DAV thresholds; latitude filters (LF); and combinations of these. While the highest reduction in false alarms was accomplished by using a combination of all three strategies (LF-ED-DAV, > 50% reduction), the use of the DAV dual thresholds adds a delay in the time of cloud cluster detection. We plan on implementing the LF-ED, which reduces the false positive detection by ~36% over the four year period 2009-2012 without affecting our ability to detect all disturbances that developed into TCs in the JTWC database.

Approach	Threshold	2009		2010		2011		2012	
		#	%	#	%	#	%	#	%
UF		548		707		468		313	
ED									
	0.3529	496	-9.49	677	-4.24	447	-4.49	293	-6.39
	0.5686	528	-3.65	695	-1.69	460	-1.71	307	-1.92
ED–DAV									
	0.0397	541	-1.28	705	-0.28	466	-0.43	316	+0.96
	0.0471	365	-33.39	517	-26.87	335	-28.42	201	-35.78
LF	$\mathrm{Lat} \in (5^{\circ}, 35^{\circ})$	337	-38.50	444	-37.20	333	-28.85	223	-28.75
LF–ED									
	0.3529	326	-40.51	436	-38.33	320	-31.62	223	-28.75
	0.5686	326	-40.51	436	-38.33	320	-31.62	223	-28.75
LF–ED–DAV									
	0.0397	331	-39.60	443	-37.34	330	-29.49	227	-27.48
	0.0471	231	-57.85	329	-53.46	222	-52.56	147	-53.03

Table 1: Summary of the reduction in false positive detection by applying the different strategies. UF=unfiltered; ED=edge detection; DAV=DAV dual thresholds; LF=latitude filtering.

b) DAV-T genesis prediction in the North Pacific

The automated tracking algorithm was run in the western and eastern North Pacific for 2009-2012. The automated tracks were used to examine the inter-annual variability of cloud cluster activity in both basins (e.g., Figure 1) as well as develop the genesis statistics shown in Figure 2. Figure 1 shows density plots of the automated tracked cloud clusters by year for 2009-2012 along with the initial position 30-kt of all developing TCs in the JTWC (western) and NHC (eastern north Pacific) best track archives. In the eastern North Pacific, 92.9% of tropical cyclones were detected with a false alarm rate of 38.0% at a median time of 1.25 h prior to the first 30-kt time in the National Hurricane Center best track. In the western North Pacific, 96.8% of tropical cyclones were detected with a false alarm rate of 25.6% at a median time of 18.5 h prior to the first 30-kt time in the JTWC best track Wood et al. 2015).

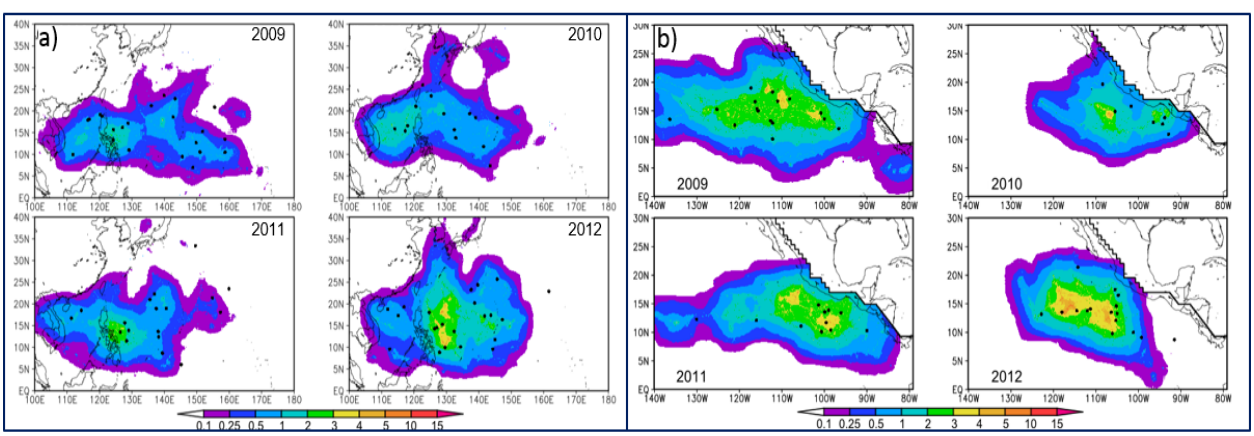

Figure 1: Density plots of automated tracked clusters that developed during 2009-2012 for (a) the western; and (b) the eastern North Pacific. Grid point values are calculated based on the inverse distance from the minimum DAV pixel for each cluster at each time it was tracked by the automated system. Black dots indicate the location at which a developing cloud cluster reached 30 kt in the JTWC best track.

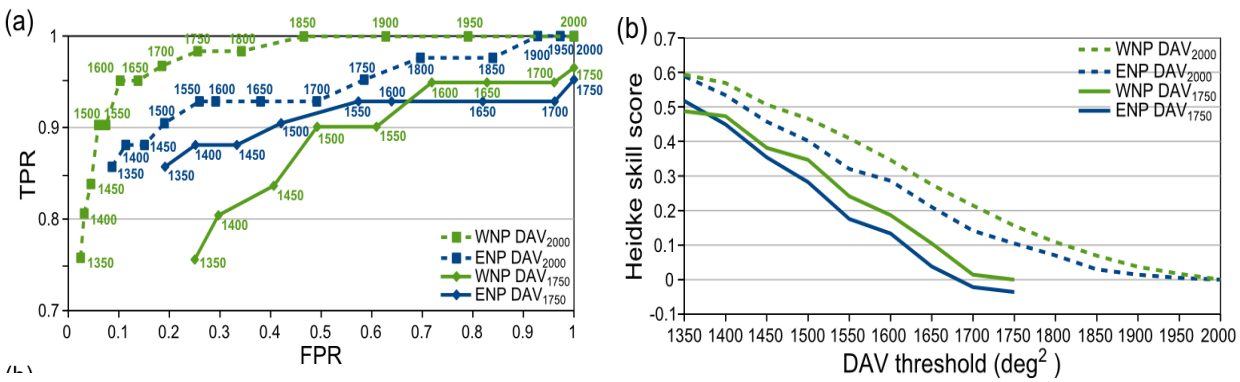

Figure 2. (a) Receiver Operator Characteristic (ROC) curves for cyclogenesis detections for various DAV threshold values in the western North Pacific (green) and the eastern North Pacific (blue) during 2009-2011; and (b) Heidke Skill Scores for the western North Pacific (green) and eastern North Pacific (blue). Positive (negative) values indicate forecasts that are better (worse) than chance. In both panels, the dashed line represents results from DAV_{2000} and the solid line from the stricter threshold (DAV_{1750}).

c) Probabilistic Genesis Prediction

A key reason for spending time to reduce the large number of false positive detections by the automated tracking system is to improve the fidelity of the statistical analysis being used to build a probabilistic model for genesis and intensity. The 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. 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.

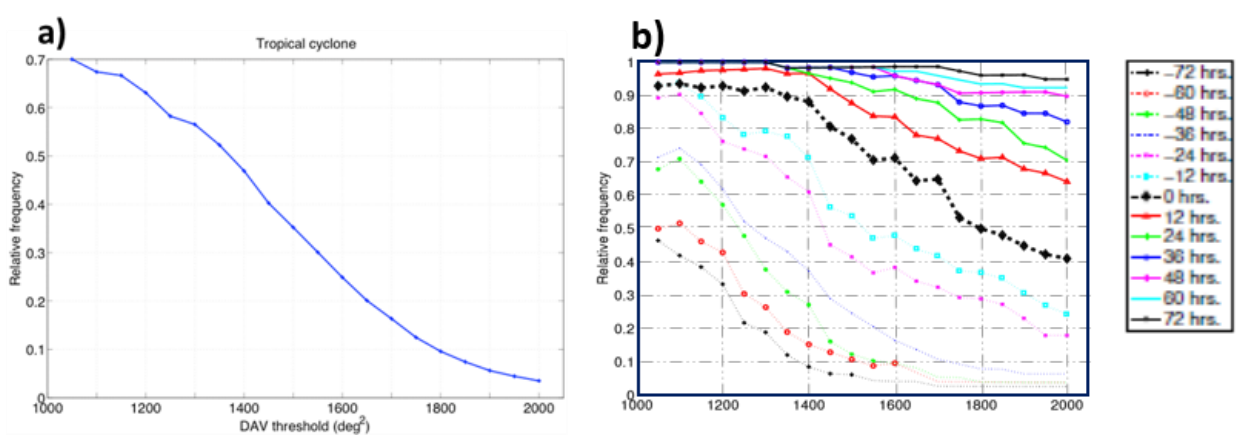

Figure 3: a) Relative frequency of a disturbance developing into a TC of any category as a function of the DAV value; and b) Relative frequency of a disturbance developing into a TD within a set time after (solid lines) or before (dotted lines) meeting the DAV value in the x-axis.

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 3a) 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 3b) 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.

A negative time to detection in Figure 3b 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 Figure 3b (i.e., -48 hrs., -24 hrs., etc.) corresponds to a maximum time to detection. For instance, the -12 hours curve is the relative frequency of disturbances for which the time to detection for each DAV threshold is less than or equal to -12 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 (-∞, -12] hours.

d) Wind field structure from the DAV parameter

Further analysis has revealed that the symmetric and asymmetric spatial patterns of the DAV maps correlate well with the corresponding spatial components of the surface wind field (Figure 4). 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 root mean square errors (RMSE) of 24.4, 14.8, and 10.0 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. 4. 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. Root mean square errors are 25-30%

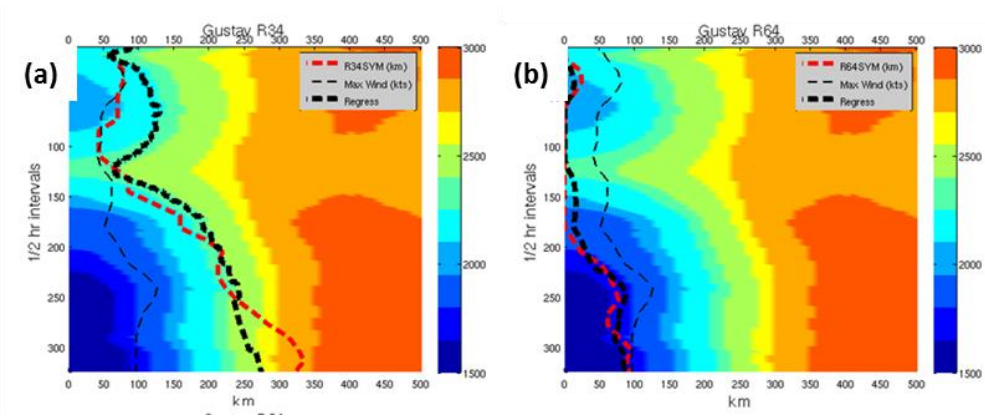

Figure 4: Hovmoller diagram of the azimuthally-averaged DAV signal plotted in color shading for TC Gustav. The red dashed line is the symmetric observed wind radii (km) and the thick black dashed line displays the regression line (km): (a) Observed wind radii and regression line for 34-kt winds; and (b) Observed wind radii and regression line for 64-kt winds. The thin black dashed line is the TC intensity (kts).

higher with the lowest errors typically in the southwest quadrant. Simple re-constructed 2-D wind fields are shown in Figure 5 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). Plans are to use the regression coefficients based on the North Atlantic training set to develop surface wind fields in the Pacific Ocean basins and compare to available observations.

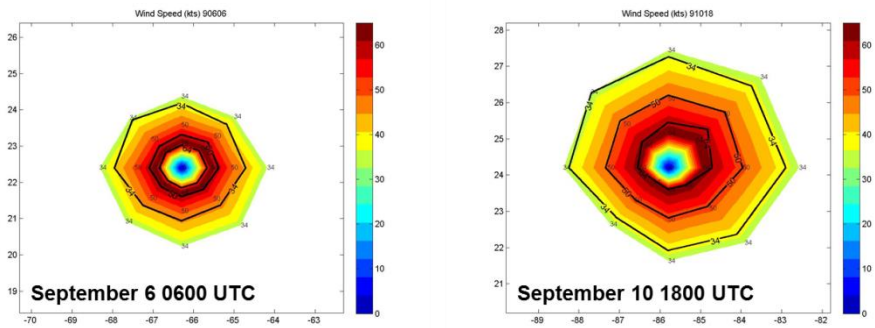

Figure 5: Re-constructed 2-D surface wind fields for TC Gustav based on the estimated R34, R50, and R64-kt winds in all four quadrants (shading). The same quantities from the extended best track database are overlaid (black contours) for comparison.

IMPACT/APPLICATIONS:

1) 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. While 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.

2) 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.

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