JHT Final Progress Report

(1 September 2011 – 31 August 2013)

Improved Automation and Performance of VORTRAC Intensity Guidance

26 November 2013

Principal Investigators: Wen-Chau Lee, Earth Observing Laboratory, UCAR,
Paul Harasti, Marine Meteorology Division, NRL
Michael Bell, Department of Meteorology, UHM

Introduction:

This document gives the final JHT project report on the "improved automation and performance of Vortex Objective Radar Tracking and Circulation (VORTRAC) intensity guidance" for the performance period from 1 September 2011 to 31 August 2013. VORTRAC uses a series of algorithms to deduce the central pressure and radius of maximum wind (RMW) of a landfalling TC in near real time from WSR-88D Level II radar data and environmental reference pressure data from nearby coastal weather stations. The development of VORTRAC version 1 (hereafter, referred to as VORTRAC 1.0) was funded by JHT between 2005-2007 and it was officially accepted for operations at the National Hurricane Center (NHC) in 2008 (Fig. 1). In its previous operational form, VORTRAC 1.0 required specific WSR-88D level-II data ready on the JHT server and external scripts to fetch input data and user input of an initial TC position, RMW estimate, and radar selection. Although the algorithms were robust, these additional steps made the software vulnerable to failures and inefficient in real-time operations.

The purpose of this JHT project was to improve the real-time operational capability of VORTRAC 1.0 to automatically diagnose central surface pressure and its tendency from radar-derived wind fields at NHC as additional guidance for TC intensity change near landfall when a TC center is within the Doppler range of a coastal WSR-88D. Most aspects of the VORTRAC 1.0 operation have now been automated, and take advantage of operational data streams to form the basis of VORTRAC 2.0 software (Fig. 2). The accomplishments achieved during the performance period can be summarized in three categories: (1) improve and update the VORTRAC algorithms, (2) identify potential points of failure and improve the logic and robustness of VORTRAC 2.0 in real-time operations, (3) improve the functions and graphical user interface (GUI) based on inputs from NHC Point of Contacts (POCs).

A significant amount of effort was dedicated to re-establish communications with new NHC POCs for VORTRAC, Wallace Hogsett, who replaced the retired Colin McCadie in 2010. The PIs had a conference call with NHC and met Wallace at the IHC Conference in Charleston SC in March 2012 to discuss expectations of the project and obtain updates on the computer infrastructure at NHC for accessing vital datasets in real time during operations. Improvements to VORTRAC functions and GUI made in Year 1 were primarily based on the inputs from Wallace. Wallace left NHC prior to the 2012 hurricane season. Jose Salazar was able to run VORTRAC 2.0 in real-time continuously during two hurricane landfalls for Isaac and Sandy. The PIs continued to communicate and work with new VORTRAC NHC POCs Chris Landsea & Stacy Stewart to improve VORTRAC 2.0. The PIs made three visits to NHC during the performance period to demonstrate the VORTRAC 2.0 capabilities and receive feedback from NHC POCs. The PIs also made a presentation at NHC to update the progress of VORTRAC 2.0 and the recent development of new algorithms that may improve VORTRAC in the future.

This final report first provides a brief summary of the improvements in algorithms and user interface that were presented in previous progress reports. The remainder of this report will focus on the systematic studies of the 12 historical landfalling TC cases between 2005-2011 that spun a wide range of conditions (e.g., size, intensity, precipitation organization, range to the radar, etc) and the real-time tests. The results and statistics provide useful guidance to real-time operations including optimizing parameter selection and interpretation of the results.

Accomplishments:

1. Algorithm improvements/upgrades

   a) Remove all external scripts to handle necessary data feeds and transition to automate operations,
   b) Update VORTRAC to run on new Level II Message 31 format,
   c) Improved internal “robustness” to handle exceptions,
   d) Use of NOAA operational products as input data (storm location and RMW),
   e) Implement a multi-step dealiasing procedure,
   f) Objectively determine analysis quality,
   g) Automate principle component analysis (PCA),
   h) Include tropical cyclone eye tracking (TCET) algorithm to improve the center estimate, and
   i) Implement improved HVVP algorithm for better mean wind estimate.

2. Graphical User Interface (GUI) improvements/upgrades

During the PIs three visits to NHC during the performance period, the PIs discussed with NHC POCs to modify the parameters and add additional information to the GUI that may help the hurricane specialist to make real-time decisions. Examples are listed as follows:

   a) Add a radar reflectivity display,
   b) Change the unit of wind from m/s to knots,
   c) Change the unit of distance from km to nautical miles,
   d) Add a display summarizing the numerical data history,
   e) Modify the display of numerical data history by including only the time periods that VORTRAC produced useful results,
   f) Enable viewing past information,
   g) Display the measured maxima approaching and receding winds,
   h) Display the CAPPI altitude of the current VORTRAC run,
   i) Add the ability to change the CAPPI height for computing pressure deficit,
   j) Allow POC to run multiple versions of VORTRAC 2.0 for more than one altitude,

k) Add a maximum analyzed surface wind estimate using a reduction factor from VORTRAC estimated winds from 1-3 km altitude,

l) Add a display of maximum VORTRAC deduced wind with wavenumber one component when available.

Incorporation of NHC Feedback

Due to the departure of the NHC point of contact (POC) in the first 6 months of the project, one of the foci during the performance period was to interact with NHC point of contact (POC) to receive feedback on how VORTRAC performed during landfall events. The PI team visited NHC three times during the performance period and implemented changes/upgrades to VORTRAC 2.0 based on POC's inputs.

PIs (Lee and Bell) visited NHC from 19 August – 20 August 2013 to work with NHC POCs to further improve the VORTRAC 2.0 before the end of the performance period. The following topics were discussed: (1) improve the numerical table of storm history to the GUI and only show results when VORTRAC 2.0 was computed from a data distribution that exceeds the user specified threshold to ensure the integrity of the results, (2) add the ability to change the CAPPI height for computing pressure deficit and allow POC to run multiple versions of VORTRAC 2.0 for more than one altitude, and (3) add a maximum analyzed surface wind estimate using a reduction factor from VORTRAC estimated winds from 1-3 km altitude.

The PIs had extensive discussions with NHC POCs and James Franklin on the subject of how to interpret VORTRAC-derived winds and convert those winds down to the 10 m altitude. In addition, the PIs discussed the pros and cons of using 3 km CAPPI vs. 1 km CAPPI in computing pressure deficit to obtain surface pressure and the additional lead time for a good pressure estimated that could be gained. It was decided that getting a reliable surface pressure estimate at the earliest time would be valuable for the hurricane specialists. The PIs added the capability to allow NHC POC to choose the desired altitude for pressure deficit calculation.

The NHC POCs also requested the PIs to add several more parameters to the GUI and change the unit of wind speed from m/s to knots to be consistent with the operational convention at NHC. The PIs updated the GUI to include these parameters, including maximum approaching and receding Doppler winds, the CAPPI altitudes of the VORTRAC calculations, and the maximum VORTRAC-estimated tangential wind by including the wavenumber 1 component when available.

Additional improvements to the radar algorithms were also made in the performance period. The automation of the principle component analysis (PCA) method was enhanced and finalized during this performance period. The method estimates the circulation center and RMW from an analysis of range- and azimuth-referenced eigenvectors derived from a PCA of the Doppler velocity data. The enhancements of the algorithm were based on extensive testing and optimization using archived WSR-88D level II data of Hurricanes Erin (1995), Bret (1999), Charley (2004) and Katrina (2005). Improvements to the accuracy and robustness of the HVVP method were also finalized during this performance period. Lastly, improvements and updates to the documentation were conducted in the performance period. An updated User Guide will be delivered with the final report.

VORTRAC analysis of historical US landfalling TCs between 2005-2011

The PIs also selected 12 US tropical cyclone landfall events between 2005-2011 (Table 1) as test cases to systematically identify potential failure points in VORTRAC 1.0. These cases represented a spectrum of storm intensity (from tropical storm to Cat 5 hurricane), radius of maximum wind (RMW) (from small to large), storm structures (disorganized to well organized). Through this extensive testing process, the limitations and optimal range/parameters for VORTRAC were better understood and were implemented in VORTRAC 2.0. Improved VORTRAC 2.0 software performance was seen in the 2012 hurricane season. Fortunately for US coastal residents, there have been very few landfalling tropical cyclones in the US during the performance period to test the software. For the three landfall cases available during the performance period, TS Andrea, Hurricanes Sandy and Isaac, VORTRAC 2.0 ran continuously without failure.

Since VORTRAC uses a single volume of WSR-88D data to deduce all essential TC information, including the TC center, RMW, maximum axisymmetric tangential winds, and minimum central pressure, the quality of the VORTRAC results are subject to TC characteristics and several factors intrinsic to the VORTRAC algorithm (e.g., the size of the eye, the distance from the radar to the storm center, the earth curvature, etc.). As a result, volume-to-volume variations of VORTRAC results are expected. In addition, VORTRAC results are available every six minutes that is much higher than the period of reconnaissance aircraft visits to the TC center for NHC operational use. Hence, filtering the VORTRAC results in time may provide a better set of information for hurricane specialists for operational purposes. The VORTRAC results filtered in one-, three-, and six-hour period were examined and compared with the best track data and Air Force reconnaissance data (when available).

Due to the earth curvature, the altitude of a radar beam increases with range. Therefore, the ability to sample the TC eyewall circulation suitable for VORTRAC analysis is a function of range and elevation angle of the radar PPI. In general, the VORTRAC analysis can be performed on CAPPIs constructed from using the 0.5 degrees PPI scan which is best possible proxy of the “surface” information. However, the 0.5 degree beam goes above 1 km MSL beyond ~75 km which limits the lead time for obtaining information in landfalling TCs. Analyzing CAPPIs at 2 km and 3 km is an option to extend the range of obtaining vital TC information via VORTRAC. However, it is anticipated that the pressure gradient and other information will have larger biases from their surface values. We will show the VORTRAC results from 1 km, 2 km, and 3 km CAPPIs to examine the characteristics of the VORTRAC results at different altitudes and illustrate the caution one must take when blending these information to obtain the maximum possible information of a landfalling TC when running VORTRAC in real-time.

We will present four storms (out of 12) in this report. Three of them (Dennis 2005, Humberto 2007, and Dolly 2008) are successful cases and one of them (Ida 2009) is a case that did not provide useful information. Recommendations on how to optimize VORTRAC parameters and interpret the results are discussed.

1. Hurricane Dennis 2005

Hurricane Dennis was observed by KEVX and KMOB from 13-00 UTC 10 July. Figure 3 illustrates Dennis' best track (dotted line), Air Force reconnaissance centers (black squares), VORTRAC track filtered by 1-hour (thin solid line) and 3-hour (thick solid line) running mean at 1 km (blue), 2 km (green) and 3 km (red) altitude from the KEVX radar. It is evident that the Air Force reconnaissance centers with a frequency ~2 hours deviate from the best track reflecting a higher temporal variation of Dennis' track. It is very encouraging that the VORTRAC-derived Dennis' centers with 1-hour filtering follow the Air Force reconnaissance centers very well. These two tracks deviate near the end of the analysis period. Dennis' VORTRAC track took a right turn while Dennis moved away from the radar and degraded the VORTRAC analysis.

Figure 5 portrays Dennis' minimum surface central pressure from best track, Air Force reconnaissance, and VORTRAC. Symbols are the same as in Figure 3. The dots connected by the thinnest lines represent the pressure derived from the individual VORTRAC runs. The gray line indicates the distance of the center to the radar, and the gray dots indicate the RMW. Dennis made landfall at ~20 UTC (marked by a vertical black line). This example clearly illustrates the different information portrayed by different time scales. Although the 6-minute VORTRAC pressure estimates can fluctuate on the order of several hPa, the overall pressure trend was well represented by the data with a one-hour filter. As expected, VORTRAC had difficulties to deduce reasonable vortex structures while Dennis just entered the radar range (i.e., not enough data to perform a least-squares fit near the RMW). The difficulty is most apparent at 1 km altitude. It is evident that consistent results from VORTRAC were obtained after 15 UTC. As anticipated, the pressure estimates using 1 km CAPPI (blue) provided the deepest pressure compared with those deduced from the 2 km (green) and 3 km (red)

CAPPIs. More impressively, the VORTRAC pressure estimates were in fair agreement with the surface pressure trend shown in the Air Force reconnaissance data with a sinusoidal oscillation compared with the best track pressure between 17-20 UTC. However, the VORTRAC-derived pressure begins to deviate from the Air Force reconnaissance measurements after Dennis made landfall. This may be due to the decay of organized circulation after landfall that posed a challenge for VORTRAC.

2. Hurricane Humberto 2007

Hurricane Humberto rapidly intensified a few hours before it made landfall. The VORTRAC derived tracks from KHGX (Fig. 5) at different altitudes are consistent with the best track and compared well with several centers reported by the Air Force reconnaissance. A ~10 km difference is evident between the VORTRAC derived circulation center and the Air Force reconnaissance wind centers. Further studies will be conducted to examine the possible causes of this difference – one possibility is the effect of the mean wind on the apparent location of the wind center vs. the VORTRAC-derived circulation center. The VORTRAC-derived pressure from KHGX and KLCH (Fig. 6) shows a downward trend (intensifying) that is also consistent with the best track and Air Force reconnaissance. There is a ~6 hPa bias between the VORTRAC derived pressure and the Air Force dropsonde measurements. It is also evident that VORTRAC had difficulties to “lock-in” a center and a circulation while Humberto just entered the Doppler range (west of -94.9 degree in Fig. 5) as in Dennis described in previous subsection. During the rapid intensification period, the 1 and 2 km results from KLCH depict the intensifying trend well. Interestingly the deepening trend is not as pronounced at 3 km, suggesting a shallower circulation. The continued KHGX analysis shows some intensification as the storm left radar range, but indicated less intensification than KLCH that was able to view the low-level circulation more clearly later in the landfall period. Humberto’s example illustrates the caution one must be taken when using surface pressure estimated from the 3 km CAPPI.

3. Hurricane Dolly 2008

Hurricane Dolly was another intensifying storm at landfall. Figure 7 shows the VORTRAC derived track from the KBRO radar. The high-resolution track compares very well with aircraft reconnaissance, even capturing a short-lived southwest displacement from the best track. The intensification followed by slight weakening before landfall (Fig. 8) is well captured by the VORTRAC analysis, although with a high pressure bias similar to that seen in Humberto. The pressure trend is similar at all altitudes, but the bias is smallest at 1 km height. The VORTRAC analysis depicts more weakening than the reconnaissance pressures, likely due to a close approach to the radar.

4. Hurricane Ida (2009)

As an example of a poorly performing case, Figs. 9 - 11 show the VORTRAC analysis for Ida. The failure to identify a center is evident in Fig. 9, as the VORTRAC derived track meanders close to the radar at all analysis times. Given that the retrieved center is significantly displaced from the best track and is very close to the radar, the poor performance of the pressure trend (Fig. 10) is not surprising. The reason for the analysis failure was due to a strong asymmetry in the precipitation field, such that no Doppler velocity couplet was associated with the RMW. Instead, the algorithm keyed in on a couplet near the radar associated with the outer circulation (Fig. 11). The analysis failure provides a counter example for when the VORTRAC assumptions are not met, compared with the previous intensifying cases.

Statistical analysis

A summary of the error statistics for Hurricane Dennis compared to the Best Track is shown in Table 2 for a variety of heights and averaging times. Since the verification data has a six hourly resolution, averaging over a shorter time period yields larger discrepancies due to both error and real fluctuations in the intensity. Absolute pressure estimates have a high bias that increases with altitude, suggesting that the pressure gradient aloft is weaker than that found at the surface. A direct calculation of the root mean square error (RMSE) yields similar values as the pressure bias. After removing a constant, altitude dependent bias the RMSE deviations from Best Track are ~4 - 10 hPa for averaging times longer than 1 hour. The large 1 km bias and RMSE at the beginning of the analysis period is reduced with longer averaging time. One clear result from the statistics and analysis plots is that the intensification trend is reasonably well captured at all heights, as indicated by the correlation coefficient. Longer averaging periods have a higher correlation with the Best Track.

A summary of the error statistics for all 12 cases at 1 km height and 6-hour averaging time is shown in Table 3. The bias-corrected pressure RMSE are similar for most storms, although the biases can be large for the weaker and larger storms. For weak storms, the pressure gradient may not be well resolved within the radar echo. For large storms, the pressure gradient likely extends beyond the Doppler radar range. Correlation coefficients are high for most storms, but show high negative correlations for the weakest and largest storms that had steady central pressures at landfall. The high correlations indicate that the nearly steady pressure trends are captured, but the negative sign indicates that the exact slope of the trend can be wrong. The Ida (2009) example shown in Fig. 10 illustrates this point, as the slight intensification retrieved by VORTRAC is approximately linear but incorrect. The error for Irene is similar due to the weak radar presentation of that storm. Wilma also had a high negative correlation due to errors related to the very large RMW at landfall, but a very low bias-corrected RMSE. The pressures for Cindy and Gustav were basically not retrievable for similar reasons. Poor analysis quality was also associated with large discrepancies from the Best Track center position. The 6 storms with good analysis quality showed lower center errors, lower bias, and higher correlation coefficients.

VORTRAC analysis of real-time storms during the 2012-2013 season

A test of the VORTRAC 2.0 during Hurricane Isaac’s 2012 landfalls at Key West and New Orleans showed significant improvement over the Version 1 of the software. A further test of the software during Hurricane Sandy’s 2012 landfall in New Jersey also provided a good test of the operational aspects of VORTRAC, although the asymmetric, large hybrid storm structure did not meet the algorithm assumptions and produced limited guidance.

Tropical Storm Andrea made landfall in Dixie County, FL on June 8, 2013. VORTRAC 2.0 was run in real-time by the NHC POCs, providing a good test of the software. Screenshots of the display running on the PI's computer are shown in Figure 12. Since Andrea was relatively weak and asymmetric there was no significant intensification, but all of the operational data streams worked properly and the software ran properly during the landfall. The real-time analysis performed at NHC was reconstructed from the output files on the JHT server (Fig. 13). The initial RMW estimate obtained from the ATCF was particularly large, but switched to a smaller estimate a few hours before landfall. The software automatically updated the RMW range based on the updated ATCF estimate. An initial intensification trend changed to a weakening trend once the RMW was updated.

Summary and Recommendations

The upgrade from VORTRAC 1.0 to VORTRAC 2.0 has greatly improved the robustness, automation, and features of the software package, and has addressed many deficiencies related to real-time operations in VORTRAC 1.0. The software was run continuously during the three US TC landfalls in the performance period. Real-time tests suggest that the improved automation using operational data streams works well. Although these three landfalling TCs were not ideal for VORTRAC to obtain reliable surface central pressure and related parameters, they were good test cases to evaluate real-time operational aspects of VORTRAC 2.0. A major effort for upgrading VORTRAC 2.0 was to optimize operation parameters and characterize VORTRAC-derived TC structures. Without suitable US TC landfall cases, this was accomplished by testing VORTRAC 2.0 using 12 historical landfalling cases from 2005 – 2011 and comparing with Best Track and Air Force reconnaissance data when available. These results suggest that VORTRAC can retrieve intensification trends when the storm has sufficient organization and radar echo coverage. It is unclear how much of the higher frequency changes in the VORTRAC intensity are real or due to noise in the algorithms, given the lack of verification data on short timescales. However, the time-averaged output generally compared well with detailed reconnaissance data, and also with Best

Track on longer timescales. The two storms in the test set with significant intensification (Dolly and Humberto) were both well captured by the time-averaged analysis.

As anticipated, ***VORTRAC has difficulties with very large, weak, or highly asymmetric storms that violate the algorithm assumptions.*** However, these null cases provided valuable information for constraining VORTRAC parameters to filter out questionable results for operational use. The PIs also implemented many different options in VORTRAC 2.0 after extensive discussions with NHC POCs during the performance period. Subjective assessment of the radar presentation in the CAPPI display should be used to determine whether the analysis is representative of the primary circulation and RMW. If the automatic center tracking appears robust, and the primary maxima in the Doppler velocity are identified, then the guidance should be reliable. In contrast, if the center appears to be displaced from the primary Doppler velocity maxima, then the guidance may be unreliable. The proper interpretation of VORTRAC 2.0 results and their links to other well-established observing parameters, such as the reconnaissance in situ and dropsonde data will need further studies in the future. The PIs will work with NHC POCs on a time-available basis without a JHT project to ensure the success of VORTRAC if it is made operational.

Year	Max. Intensity (Kts)	Hurricane
2005	110	Katrina
2005	105	Dennis
2005	105	Wilma
2005	100	Rita
2005	65	Cindy
2005	65	Ophelia
2007	80	Humberto
2008	75	Dolly
2008	90	Gustav
2008	95	Ike
2009	60	Ida
2011	75	Irene

Table 1. The list of 12 hurricanes used in this study.

Storm and Height	Time Averaging	Number of Timesteps	Bias corrected Pressure RMSE (hPa)	Pressure Bias (hPa)	Pressure Correlation with Best Track	Mean Distance from Best Track (km)
Dennis 1 km	Raw	127	15.7	9.3	0.72	15.5
	1 hour	117	12.6	7.3	0.84	12.9
	3 hour	97	9.5	5.1	0.96	9.5
	6 hour	67	6.1	4.6	0.98	7.2
Dennis 2 km	Raw	116	9.7	8.8	0.96	13.2
	1 hour	106	9.1	8.4	0.98	10.9
	3 hour	86	7.8	8.3	0.997	8.7
	6 hour	56	4.9	8.3	0.999	7.8
Dennis 3 km	Raw	117	7.6	11.8	0.96	15.2
	1 hour	107	7.0	11.4	0.98	12.1
	3 hour	87	6.1	11.3	0.997	9.6
	6 hour	57	3.9	11.2	0.999	8.9

Table 2. Error Statistics for Hurricane Dennis (2005).

Storm	Height and Time Averaging	Number of Timesteps	Bias corrected Pressure RMSE (hPa)	Pressure Bias (hPa)	Pressure Correlation with Best Track	Mean Distance from Best Track (km)
Katrina	1km/ 6 hour	87	1.3	10.1	0.45	12.5
Dennis	1km/ 6 hour	67	6.1	4.6	0.98	7.2
Wilma	1km/ 6 hour	5	0.5	2.7	-0.99	38.5
Rita	1km/ 6 hour	77	2.9	28.6	0.98	25.5
Cindy	1km/ 6 hour	1	11.6	11.6	N/A	78.9
Ophelia	1km/ 6 hour	150	2.3	9.9	0.91	28.6
Humberto	1km/ 6 hour	151	2.2	8.9	0.98	27.1
Dolly	1km/ 6 hour	92	2.1	7.1	0.56	6.1
Gustav	1km/ 6 hour	N/A	N/A	N/A	N/A	N/A
Ike	1km/ 6 hour	33	1.9	22.7	-0.89	51.1
Ida	1km/ 6 hour	115	3.0	8.0	-0.98	116.7
Irene	1km/ 6 hour	9	7.2	27.4	-0.999	57.8

Table 3. Error statistics for 1 km analysis averaged over 6 hours.

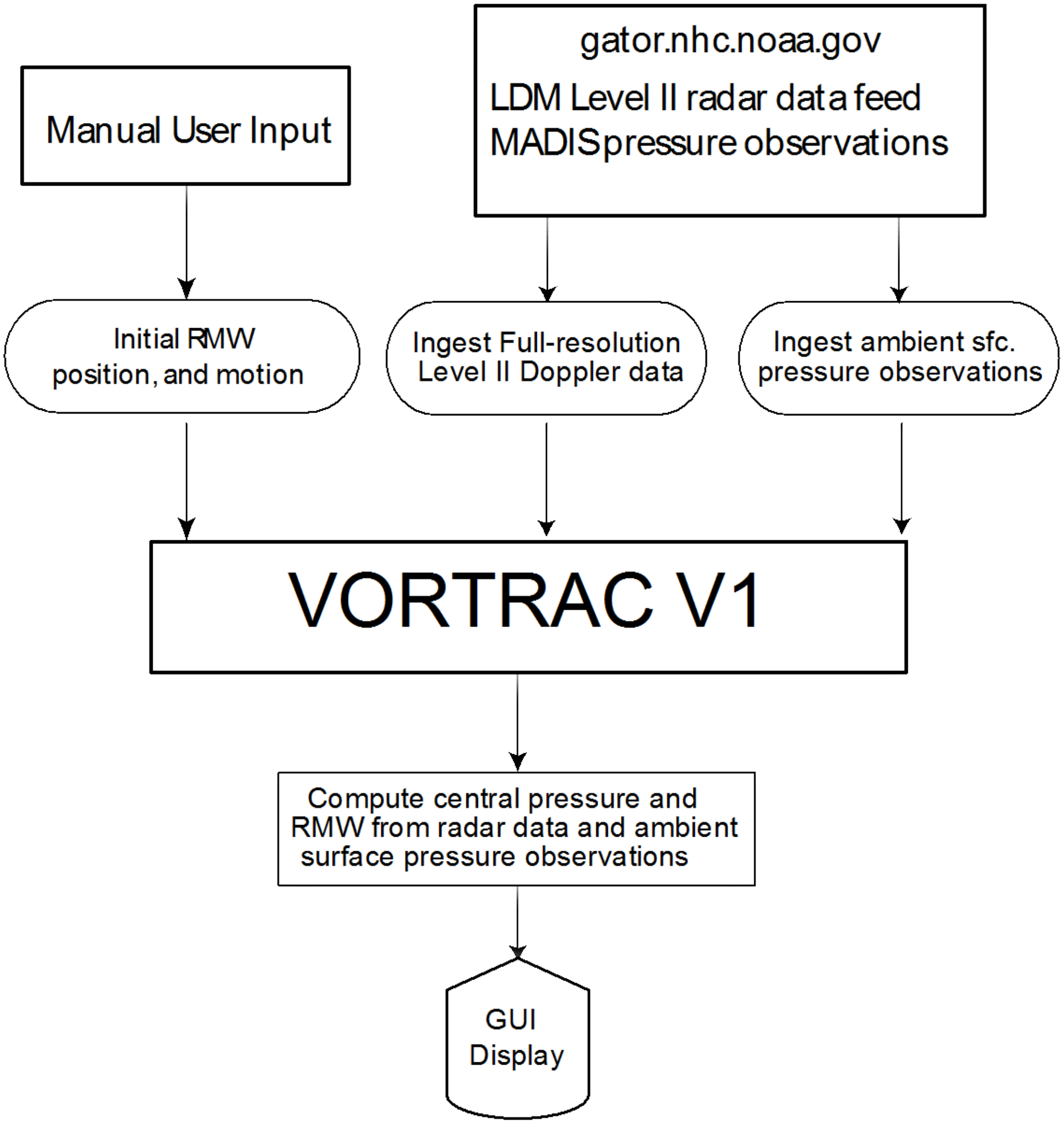


Figure 1. Software flowchart for VORTRAC Version 1 implemented in 2008.

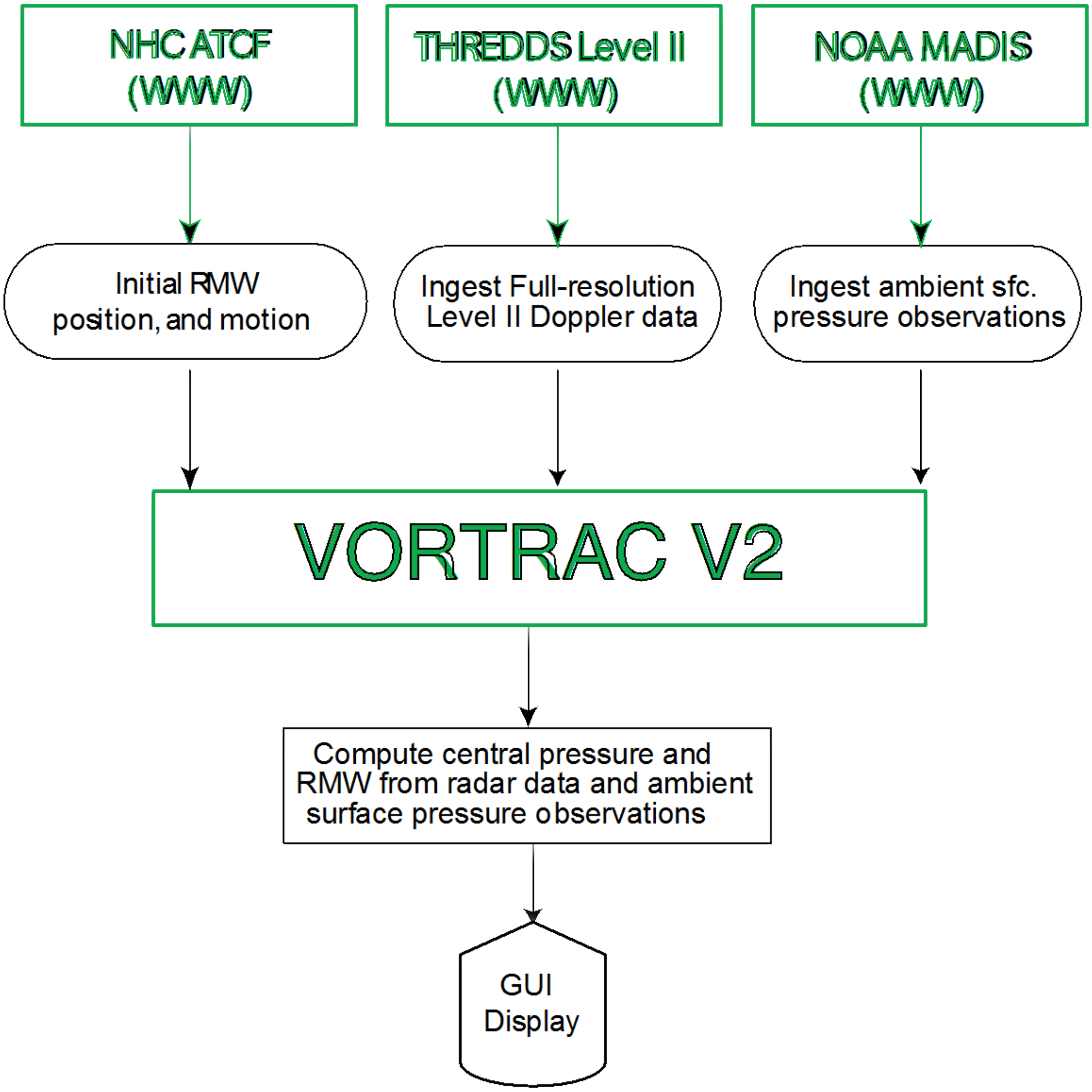


Figure 2. Software flowchart for VORTRAC Version 2 implemented for this JHT project.

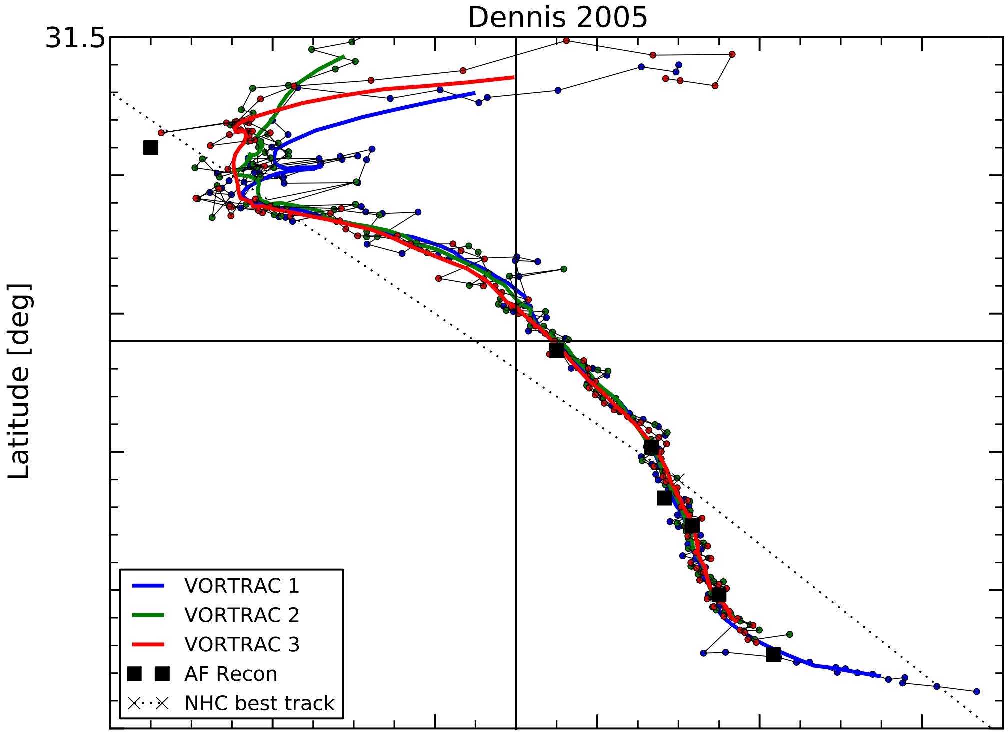


Figure 3. Hurricane Dennis (2005) VORTRAC-derived centers from KEVX radar. Thin lines with dots indicate individual radar centers at 1 km (blue), 2 km (green), and 3 km (red). Thick lines indicate 1-hour running mean. Black squares indicate U. S. Air Force reconnaissance centers, and dashed line with 'X's indicate NHC best track centers. Black solid lines indicate the center latitude and longitude at landfall.

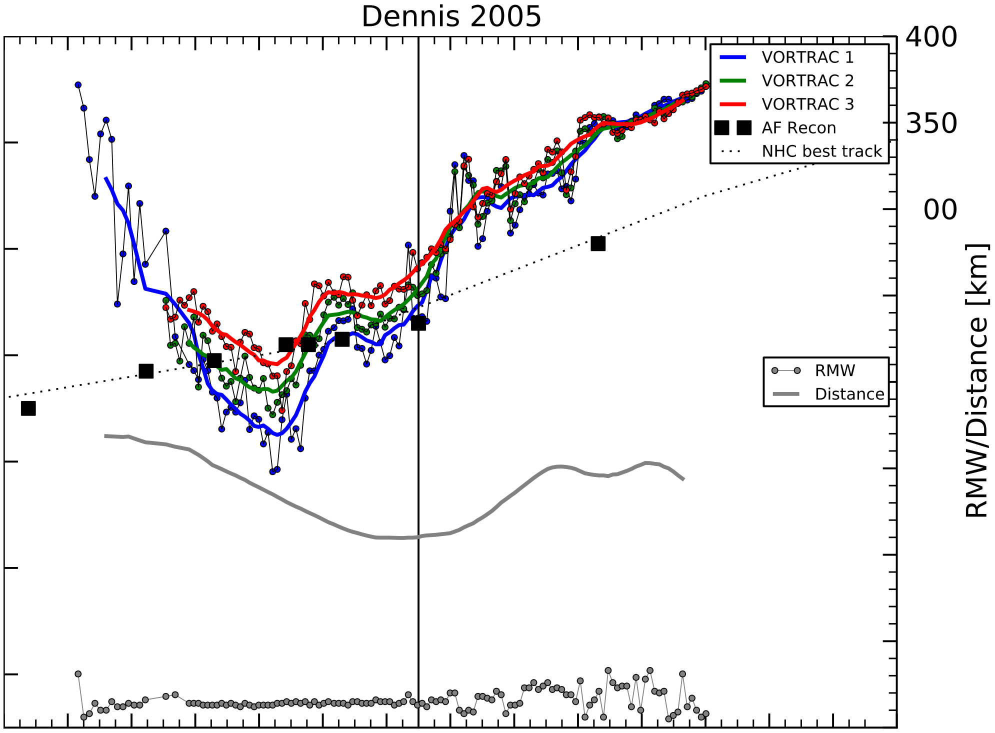


Figure 4. Hurricane Dennis (2005) VORTRAC-derived central pressure from KEVX radar. Colored lines and symbols are the same as Figure 3, but indicate central pressure as a function of time. The black solid line indicates time of landfall, the gray solid line indicates the distance of the center to the radar, and the gray dots indicate the RMW.

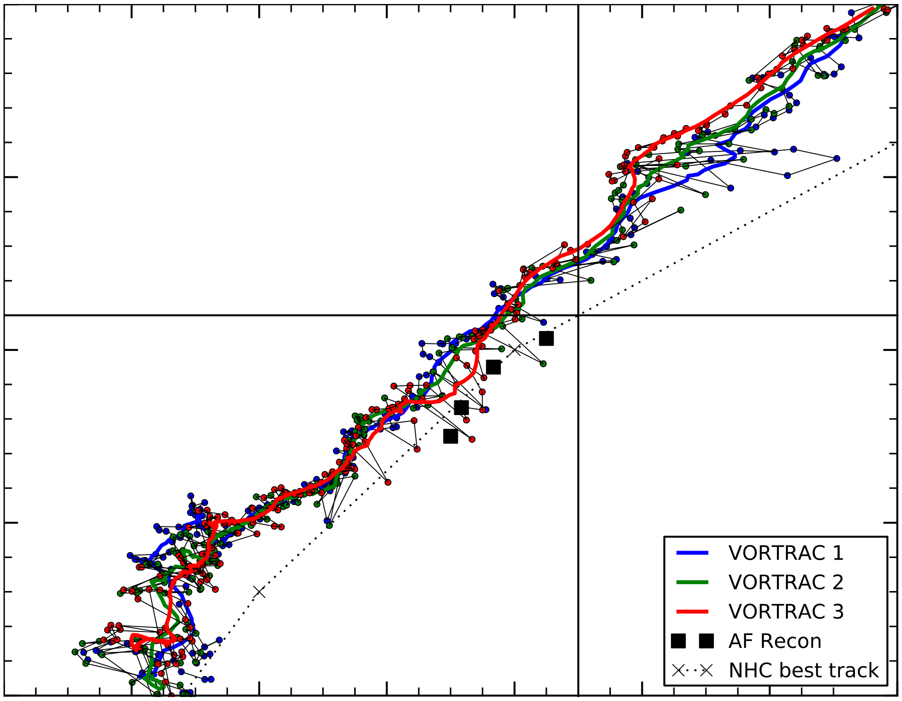


Figure 5. Hurricane Humberto (2007) VORTRAC-derived centers from KHGX radar. Symbols are the same as Figure 3.

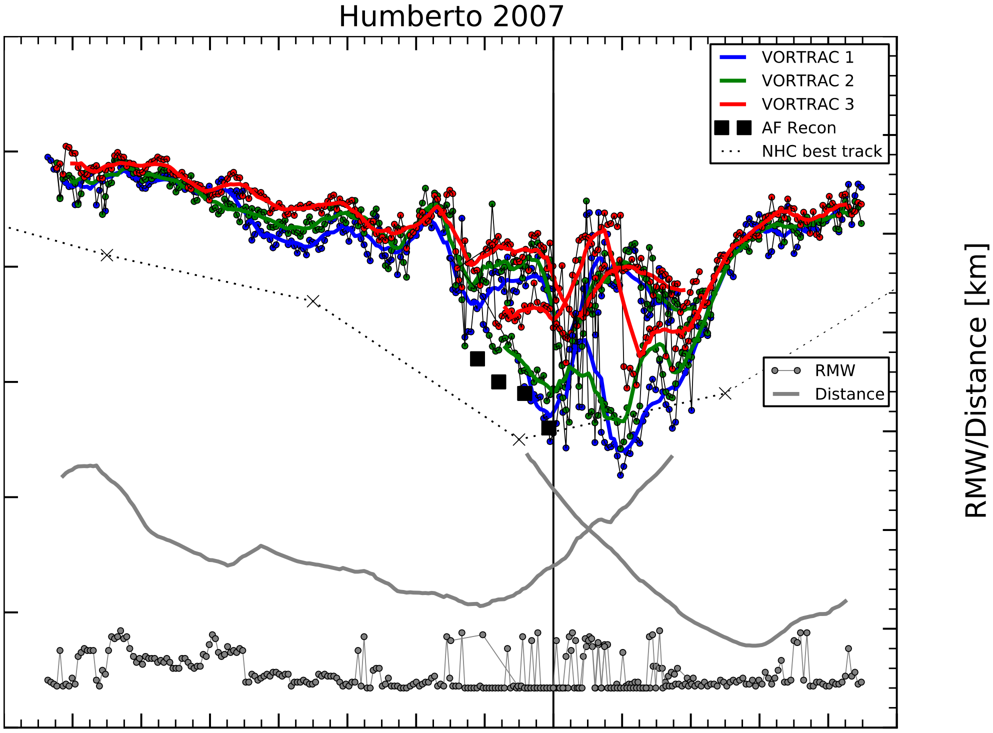


Figure 6. Hurricane Humberto (2007) VORTRAC-derived central pressure from KHGX and KLCH radars. KHGX analysis extends from 15 – 11 UTC, and KLCH analysis extends from 6 – 16 UTC. Symbols are the same as Figure 4.

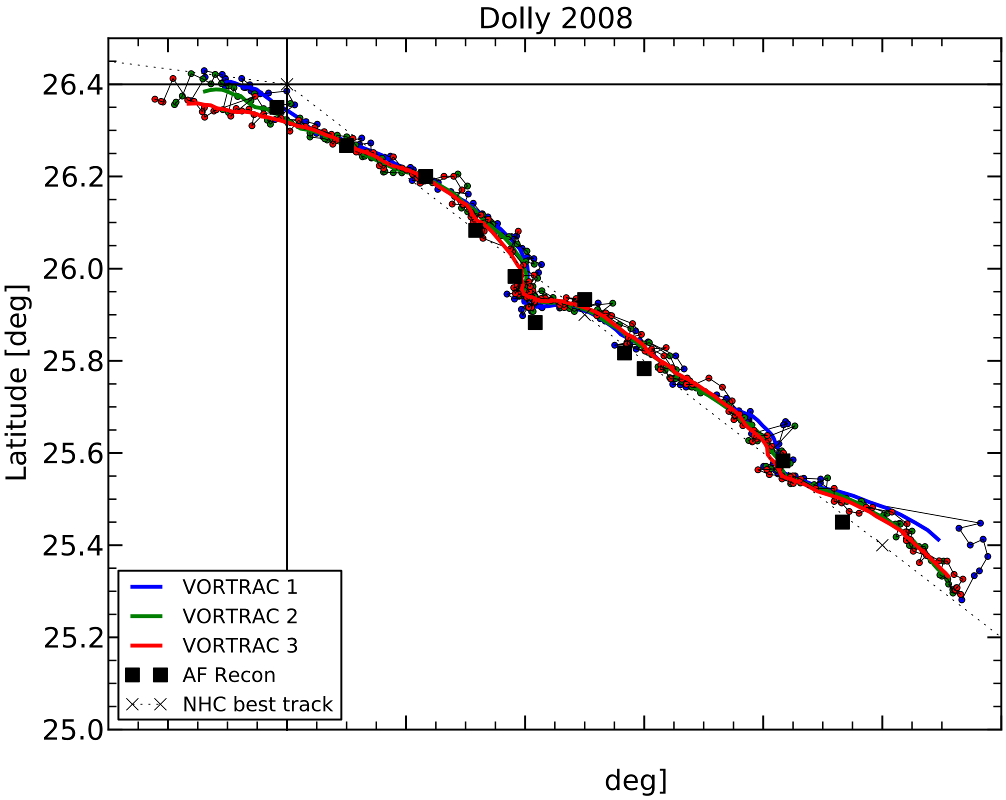


Figure 7. Hurricane Dolly (2008) VORTRAC-derived centers from KBRO radar. Symbols are the same as Figure 3.

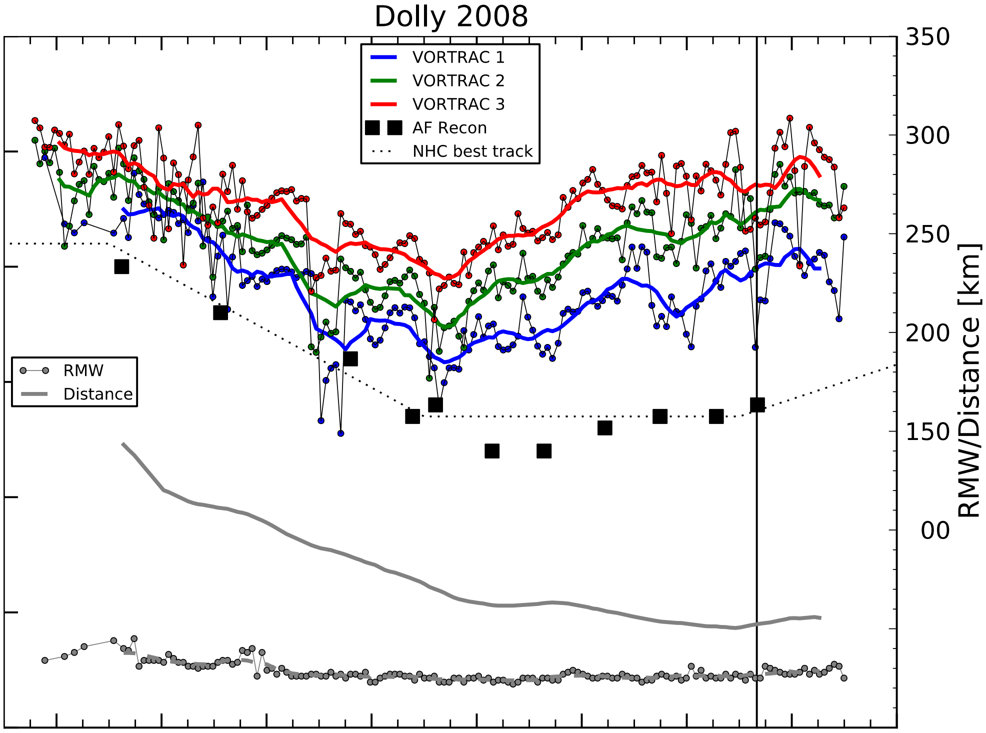


Figure 8. Hurricane Dolly (2008) VORTRAC-derived central pressure from KBRO radar. Symbols are the same as Figure 4.

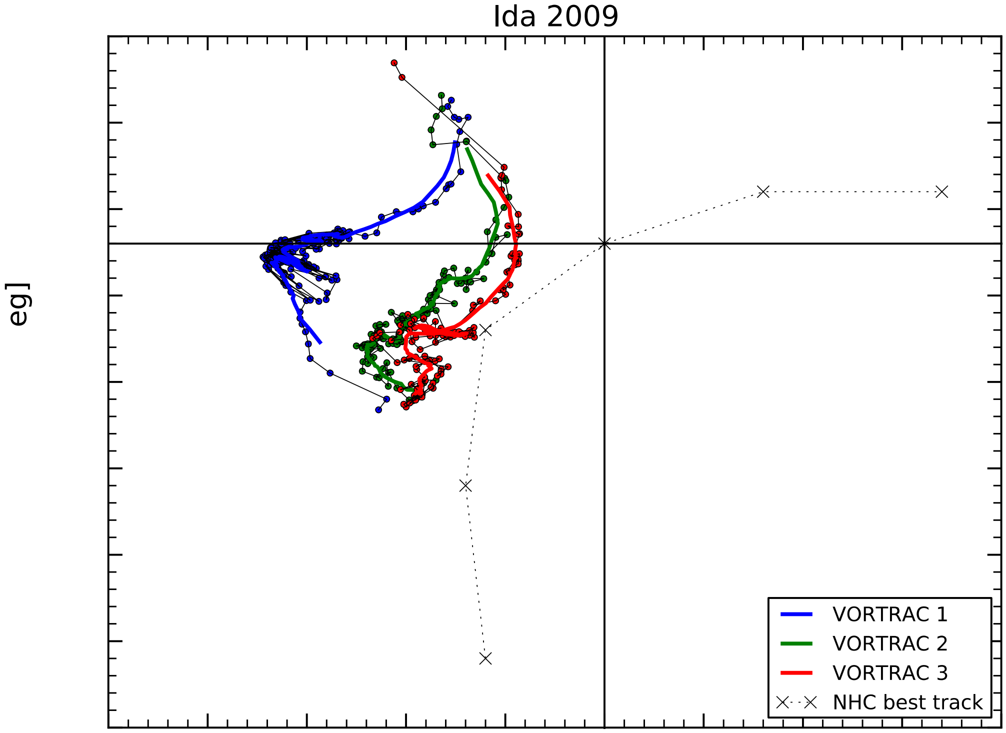


Figure 9. Hurricane Ida (2009) VORTRAC-derived centers from KLIX radar. Symbols are the same as Figure 3.

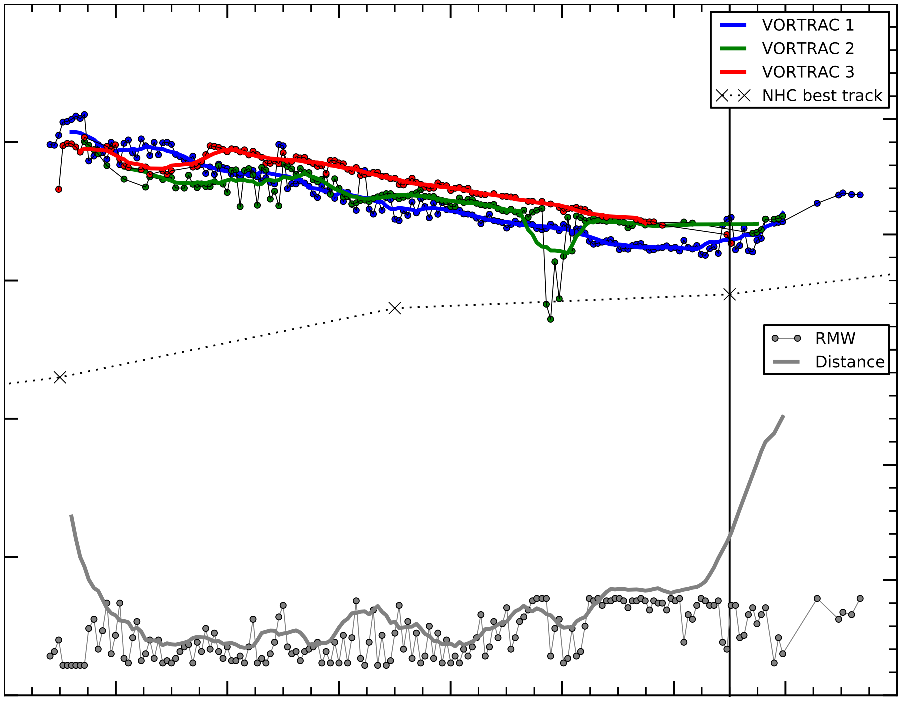
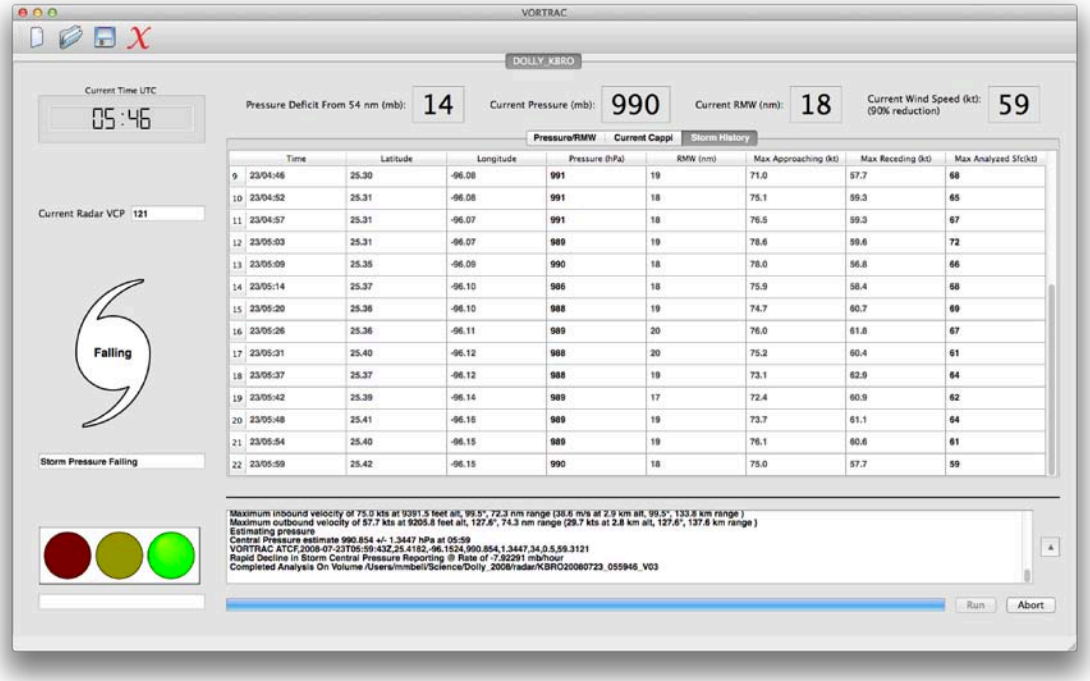


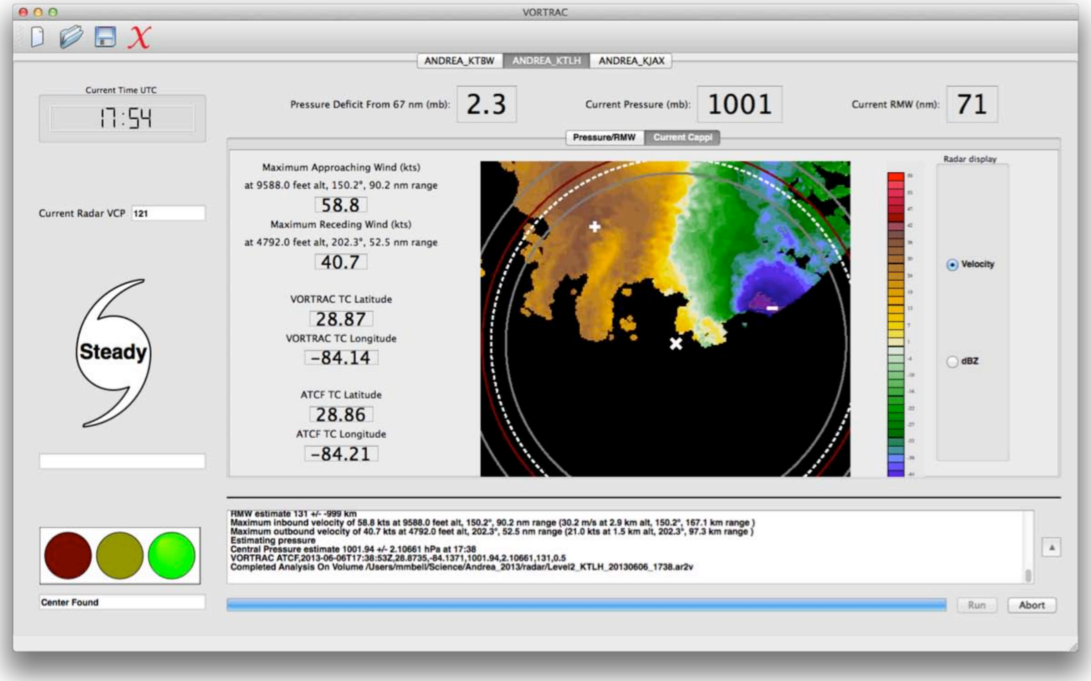
Figure 10. Hurricane Ida (2009) VORTRAC-derived centers from KLIX radar. Symbols are the same as Figure 3.



	Time	Latitude	Longitude	Pressure (hPa)	RMW (nm)	Max Approaching (kt)	Max Receding (kt)	Max Analyzed Sfc(kt)
9	23/04:46	25.30	-96.08	991	19	71.0	57.7	68
10	23/04:52	25.31	-96.08	991	18	75.1	59.3	65
11	23/04:57	25.31	-96.07	991	18	76.5	59.3	67
12	23/05:03	25.31	-96.07	989	19	78.6	59.6	72
13	23/05:09	25.35	-96.09	990	18	78.0	56.8	66
14	23/05:14	25.37	-96.10	986	18	75.9	58.4	68
15	23/05:20	25.36	-96.10	988	19	74.7	60.7	69
16	23/05:26	25.36	-96.11	989	20	76.0	61.8	67
17	23/05:31	25.40	-96.12	988	20	75.2	60.4	61
18	23/05:37	25.37	-96.12	988	19	73.1	62.9	64
19	23/05:42	25.39	-96.14	989	17	72.4	60.9	62
20	23/05:48	25.41	-96.16	989	19	73.7	61.1	64
21	23/05:54	25.40	-96.15	989	19	76.1	60.6	61
22	23/05:59	25.42	-96.15	990	18	75.0	57.7	59

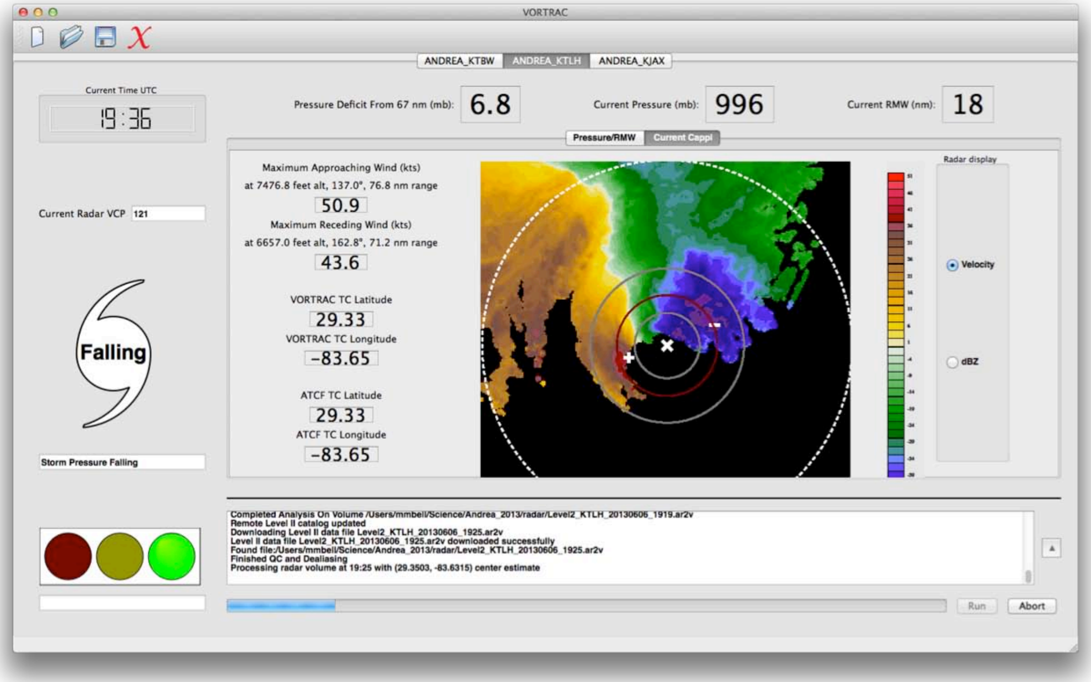
```
Maximum inbound velocity of 75.0 kts at 9391.5 feet alt, 99.5°, 72.3 nm range (38.6 m/s at 2.9 km alt, 99.5°, 133.8 km range )
Maximum outbound velocity of 57.7 kts at 9205.8 feet alt, 127.6°, 74.3 nm range (29.7 kts at 2.8 km alt, 127.6°, 137.6 km range )
Estimating pressure
Central Pressure estimate 990.854 +/- 1.3447 hPa at 05:59
VORTRAC ATCF,2008-07-23T05:59:43Z,25.4182,-96.1524,990.854,1.3447,34,0.5,59.3121
Rapid Decline in Storm Central Pressure Reporting @ Rate of -7.92291 mb/hour
Completed Analysis On Volume /Users/mmbell/Science/Dolly_2008/radar/KBRO20080723_055946_V03
```

Figure 11. Screenshot from real time VORTRAC showing new Storm History table and maximum analyzed wind speed reduced to the surface.



Current Time UTC: 17:54
Pressure Deficit From 67 nm (mb): 2.3
Current Pressure (mb): 1001
Current RMW (nm): 71
Current Radar VCP: 121
Maximum Approaching Wind (kts) at 9588.0 feet alt, 150.2°, 90.2 nm range: 58.8
Maximum Receding Wind (kts) at 4792.0 feet alt, 202.3°, 52.5 nm range: 40.7
VORTRAC TC Latitude: 28.87
VORTRAC TC Longitude: −84.14
ATCF TC Latitude: 28.86
ATCF TC Longitude: −84.21
Center Found

```
RMW estimate 131 +/- -999 km
Maximum inbound velocity of 58.8 kts at 9588.0 feet alt, 150.2°, 90.2 nm range (30.2 m/s at 2.9 km alt, 150.2°, 167.1 km range )
Maximum outbound velocity of 40.7 kts at 4792.0 feet alt, 202.3°, 52.5 nm range (21.0 kts at 1.5 km alt, 202.3°, 97.3 km range )
Estimating pressure
Central Pressure estimate 1001.94 +/- 2.10661 hPa at 17:38
VORTRAC ATCF,2013-06-06T17:38:53Z,28.8735,-84.1371,1001.94,2.10661,131,0.5
Completed Analysis On Volume /Users/mmbell/Science/Andrea_2013/radar/Level2_KTLH_20130606_1738.ar2v
```



Current Time UTC: 19:36
Pressure Deficit From 67 nm (mb): 6.8
Current Pressure (mb): 996
Current RMW (nm): 18
Current Radar VCP: 121
Maximum Approaching Wind (kts) at 7476.8 feet alt, 137.0°, 76.8 nm range: 50.9
Maximum Receding Wind (kts) at 6657.0 feet alt, 162.8°, 71.2 nm range: 43.6
VORTRAC TC Latitude: 29.33
VORTRAC TC Longitude: −83.65
ATCF TC Latitude: 29.33
ATCF TC Longitude: −83.65
Storm Pressure Falling

```
Completed Analysis On Volume /Users/mmbell/Science/Andrea_2013/radar/Level2_KTLH_20130606_1919.ar2v
Remote Level II catalog updated
Downloading Level II data file Level2_KTLH_20130606_1925.ar2v
Level II data file Level2_KTLH_20130606_1925.ar2v downloaded successfully
Found file:/Users/mmbell/Science/Andrea_2013/radar/Level2_KTLH_20130606_1925.ar2v
Finished QC and Dealiasing
Processing radar volume at 19:25 with (29.3503, -83.6315) center estimate
```

Figure 12. Screenshots from Tropical Storm Andrea (2013) landfall.

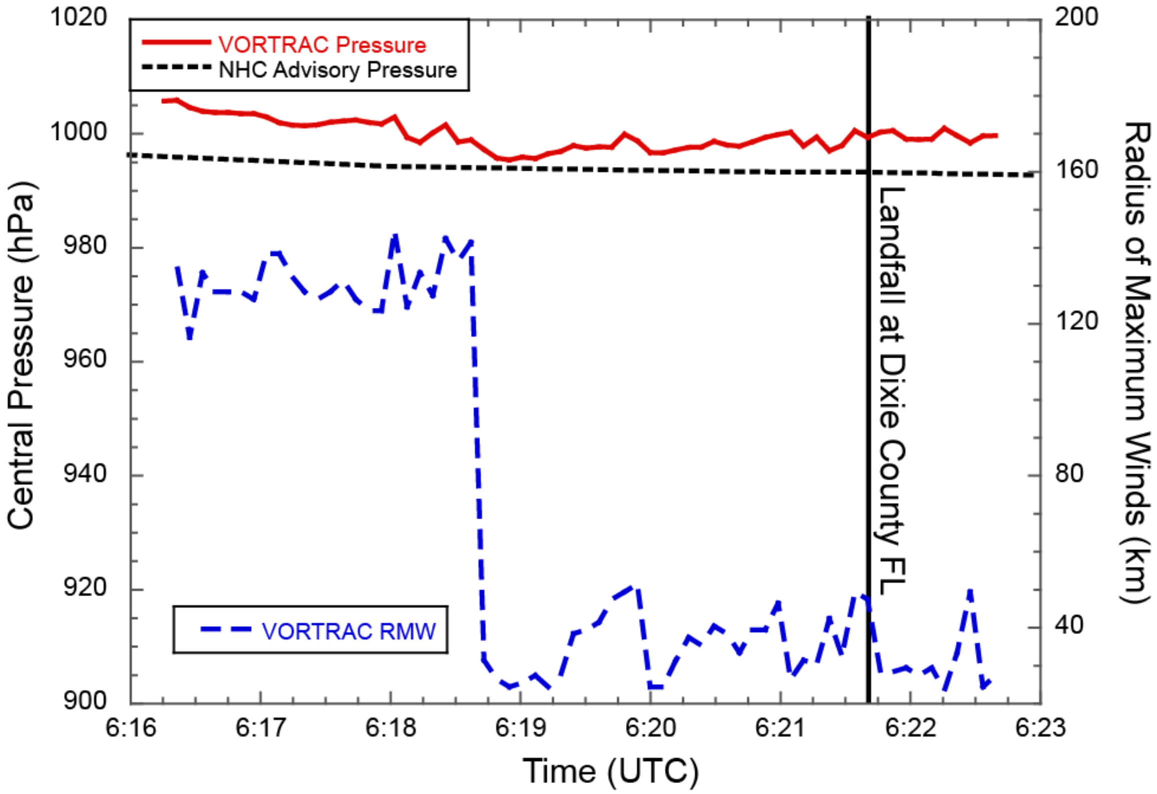


Figure 13. Real-time VORTRAC analysis of Tropical Storm Andrea (2013) calculated from NHC output files.