

Specification of Tropical Cyclone Parameters from Aircraft Reconnaissance

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1. Introduction

As part of the MORPHOS (Modeling Relevant Physics of Sedimentation in Three-Dimensions) project, the Oceanweather Tropical Planetary Boundary Layer (TropPBL) will be upgraded to reflect new knowledge of the physics of the cyclone surface boundary layer, especially vertical friction, based on the newer treatment of the transfer of momentum from sea to air at very high wind speeds (speeds greater than 30 m/s). In order to evaluate model modifications, accurate sets of azimuthally varying tropical parameters that fully exploit the double exponential description of the pressure gradient are required.

This paper describes the development and application of a workstation which is used to determine and track in time the parameter sets required to drive the TropPBL model. These inputs include easily obtainable parameters such as central pressure and track as well as the scale pressure radius (related to the radius of maximum winds) and so-called Holland's B parameter, which controls the peakedness of the wind and pressure profile.

2. Tropical PBL Model

The TropPBL model being applied is an upgraded version of the so-called TC96 (after Thompson and Cardone, 1996) model. A similar PBL model formulation was developed by Shapiro (1983) except in a cylindrical coordinate system. TC96 is an

application of a theoretical model of the horizontal airflow in the boundary layer of a moving vortex (Chow, 1970). That model solves, by numerical integration, the vertically averaged equations of motion that govern a boundary layer subject to horizontal and vertical shear stresses. The equations are resolved in a Cartesian coordinate system whose origin translates at constant velocity, V_f , with the storm center of the pressure field associated with the cyclone. Variations in storm intensity and motion are represented by a series of quasi-steady state solutions. The method starts from raw data whenever possible and includes an intensive reanalysis of traditional cyclone parameters such as track and intensity (in terms of pressure) and then develops new estimates of the more difficult storm parameters, such as the shape of the radial pressure profile and the ambient pressure field within which the cyclone is embedded. The time histories of all of these parameters are specified within the entire period to be hindcast. Storm track and storm parameters are then used to drive a numerical primitive equation model of the cyclone boundary layer to generate a complete picture of the time-varying wind field associated with the cyclone circulation itself. TC96 has been widely applied and validated mainly in terms of its success in forcing ocean response models. Many such studies have been reported (see e.g., Forristall *et al.*, 1978; Cardone and Resio, 1998; Jensen *et al.*, 2006).

The principle challenge in the application of the model to real storms is to describe the PBL pressure gradients in terms of the azimuthally dependent radial pressure profile, expressed in double exponential form:

$$P(r) = P_o + \sum_{i=2}^n dp_i e^{-\left(\frac{R_{pi}}{r}\right)^{B_i}}$$

where P_o is central pressure, and dp is the pressure differential between the eye pressure and the storm environment, R_p is a scaling radius related to (but not equal to) the radius of maximum wind and B is the profile peakedness parameter, usually called Holland's B after Holland (1980).

Previous variants of the TropPBL model (pre-1996) were restricted to Holland's $B=1$ and a single exponential pressure profile. The 1996 upgrade allowed a variable B as well as the specification of a double exponential pressure profile. The double exponential pressure profile was first applied in hurricane Gilbert (1988), but rarely used due to the difficulty in determining the combination of two R_p 's, two B 's and the dp associated with each pressure radii. Enhancements to the present TropPBL model include the specification of azimuthally varying inputs of dp and B which are used to represent the variation of environmental pressures in each quadrant and allow more refined B fits during landfall where an azimuthally average B may not describe the influences of land on the resulting wind field.

Given the changes in the model over time, it is not surprising that the existing archive of input parameters for historical storms varies with the model applied. Early storms were generally modeled with a $B=1$ and other model parameters modified to give the best

fit with observations given the B constraint. Tropical systems with double radial wind maxima or "flat" radial wind profiles which cannot be described with a single exponential profile were typically run with dp , R_p , and B parameters selected to give the best results in the storm inner core and then manual kinematic techniques applied to enhance the outer gradients. Storms with nearly equal double wind radii (such as Allen 1980) were analyzed kinematically from reconnaissance data and avoided the tropical model altogether. Thus, a new dataset of tropical parameters determined from aircraft reconnaissance data which fully exploit the azimuthally varying double exponential profile of the TropPBL model was required to evaluate possible physics changes to the model.

3. Aircraft Reconnaissance Datasets

3.1 Flight Level Data

Aircraft reconnaissance in the Atlantic basin started in the 1940's with Air Force and Navy missions into storms and continues today with planes from both NOAA (National Oceanic and Atmospheric Administration) and the 53rd Weather Reconnaissance Squadron of the U.S. Air Force. Early reconnaissance data is typically archived in microfilm form, and needs to be tediously scanned and typed for use in tropical analysis. Figure 1 shows a microfilm copy of data obtained during Donna 1960. Storms from the late 1970s onward are available in electronic form primarily from either National Hurricane Center/Tropical Prediction Center (NHC/TPC) or the Hurricane Research Division (HRD). Data availability and data formats vary in the archive, even within the same storm year. NOAA and Air Force data are generally in different formats and not consistently available from the same archive

source. Thus, the assembly and processing of reconnaissance data to a common format for tropical analysis is a tedious process requiring extensive manual work and quality control. All flight level data are processed to the common format shown in Table 1; not all data sets contain all the variables detailed. Additional data obtained in the vortex messages and data from dropsondes are also processed to common data format not detailed here.

Table 1. Tropical reconnaissance common data format

<i>Variable</i>	<i>Description</i>
Date/Time	Observation Time (GMT)
Lat	Latitude (deg)
Long	Longitude (deg)
StdPres	Standard Pressure (mb)
Zp	Height (m) of Standard Pressure Surface
Ws	Flight Level Wind Speed (m/s)
Wd	Flight Level Wind Direction (met)
Temp	Flight Level Temperature (C)
DewPt	Flight Level Dewpoint (C)
H2O	Liquid Water Content (g/kg)
RadarAlt	Height (m) indicated by radar
PresAlt	Height (m) indicated by pressure
Source	Data Source
StormLat	Latitude (deg)
StormLong	Longitude (deg)
Bearing	deg from storm
StmBear	Bearing relative to storm (45=Right Front Quadrant)
Range	km from storm
RadWind	Flight Level Radial component of wind (m/s)
TanWind	Flight Level Tangential component of wind (m/s)
VertWind	Flight Level Vertical component of wind (m/s)
SLP	Sea Level Pressure (mb)
SLPMeth	How SLP was obtained (measured/estimated)
SFCWs	Surface Wind Speed (m/s) 30-Min Average @ 10-meters
SFCWsMeth	How SFCWs was obtained (measured/estimated)

3.2 Surface Wind Estimates from SFMR

The Stepped Frequency Microwave Radiometer (SFMR), which estimates surface wind speeds, has been in use on NOAA/HRD aircraft since 1998. The SFMR provides a unique dataset due to its coverage of storms to a degree not available from either point wind estimates from GPS dropwindsondes or occasional direct tropical cyclone encounters with *insitu* measurement stations. Recently, the entire SFMR archive has been reprocessed using a new wind speed retrieval algorithm (Uhlhorn *et al.*, 2007) and made available by HRD. Most storms within the archive have multiple missions worth of data. A summary of SFMR measurements during Rita (2005) is shown in Figure 2.

Wind speeds retrieved from the SFMR have been extensively validated using GPS dropwindsonde data and are felt to represent the peak 1-minute wind at a 10-meter reference height. In order to compare SFMR estimates with output from the TropPBL model a conversion to a 30-minute average wind is required. The EDSU hurricane gust factor algorithm, as discussed in Vickery and Skerlj (2005), is applied to the median of observations every 30 seconds +/- 15 seconds from the source data. The median filter is applied to reduce sampling variability and remove spikes in the dataset. The median filter was not able to remove large spikes apparently caused when the SFMR beam was contaminated by land. A land removal algorithm was developed where observations within 30 seconds of exiting or entering land were removed from the archive.

To evaluate the 30-minute average SFMR wind estimates, a comparison of *insitu* buoy wind speeds from the NDBC (National Data Buoy Center) buoy archive was made. Buoy 10-minute averages available every 10 minutes were averaged +/- 10 minutes to

provide 30-minute wind estimates. All wind speeds were adjusted for height and stability to 10-meter reference level. Buoy observations from 1998-2006 within 10 km and 15 minutes of an SFMR observation greater than 10 km from the storm center (to prevent matches from differing quadrants) are shown in Figure 3. This figure indicates that the wind speeds measured by the SMFR converted to a 30-minute average are consistent with those obtained from buoy estimates up to 40 m/s.

4. Analysis Methodology

4.1 Basic TropPBL Parameters

The HURDAT archive provides the most basic storm parameters of track, maximum wind speed and central pressure (when available from aircraft/satellite estimates) at a 6-hourly time step for the Atlantic basin. While early periods of the HURDAT archive are known to have errors, the 1998-2006 portion of the database is of high quality. Tracks for individual systems are evaluated using historical radar, aircraft and satellite position fixes and modified as required. Most modifications are for sub-6 hour track wobbles and landfall positions that fall between 6-hour HURDAT data points. Figure 4 shows the hourly track modifications for hurricane Andrew (1992) with position estimates from aircraft vortex fixes. Forward speed and direction are computed from the modified track as input to the TropPBL model. Central pressure from HURDAT is also evaluated against fix data; again most modifications are made for sub-6 hourly changes and landfall conditions.

Environmental pressures, known in the model as P_{far} , have typically been estimated by hand using synoptic weather maps.

Knaff and Zehr (2007) presented an alternate method of obtaining environmental pressure from atmospheric model output by representing P_{far} as the average pressure in the 800-1000 km annulus surrounding the storm center. A comparison of manually estimated P_{far} 's and the annulus method derived from the NCEP/NCAR Reanalysis surface pressures show excellent agreement. Thus, the annulus method was applied for all storms. This method allowed the determination of multiple P_{Far} 's aligned along the axis of maximum pressure gradient to exploit new model capability which allows dp to vary by quadrant.

The remaining storm parameters of R_{p1}/R_{p2} (scale radii of the pressure profile), $B1/B2$ (Holland's B associated with each radius) and D_{p1}/D_{p2} (pressure drop associated with each radius) are determined from fits to aircraft reconnaissance and *insitu* data.

4.2 Fitted TropPBL Parameters

Willoughby and Rahn (2004) introduced a fitting scheme used to determine the radius of maximum winds (RMW) and Holland's B parameters from simultaneous fits of aircraft flight level tangential winds and heights measured from aircraft. The analysis technique applied a single exponential profile fit which minimized the following cost function:

$$S^2 = \sum_{k=1}^K \{ [v_o(r_k) - v_g(r_k, B)]^2 + g[z_o(r_k) - z(r_k, B)]^2 L_z^{-1} \}$$

This cost function attempts to minimize the difference between the computed gradient wind (v_g) and observed flight level wind (v_o) and scaled difference in the computed heights $z(r_k, B)$ and flight level heights (z_o) in order to determine B given a RMW estimated from the flight data with the best

fit. Figure 5 shows a series of fits from Willoughby and Rahn (2004) for Anita 1977, Mitch 1998, Hugo 1989, Edouard 1996 and Erika 1997 which show excellent agreement with the fitted maximum wind and varying success with the wind profile further from the storm center. However, when this methodology was attempted with storms that display concentric-eyewalls such as Allen 1980 (Figure 6) the fits to the second wind maxima were poor. In the second paper of the series (Willoughby *et al.*, 2006) a new sectionally continuous wind profile to overcome the limitations of the single exponential wind profile was introduced.

In this study, the double exponential pressure profile as implemented in the OWI TropPBL is used to fit the aircraft data much in the same way proposed by Willoughby and Rahn (2004) with some important differences. The gradient wind computed from the surface pressure parameters, rather than the cyclostrophic wind as applied in Willoughby and Rahn (2004) from aircraft heights is used for the wind speed comparisons. The gradient and cyclostrophic winds are nearly equivalent at the wind maxima (where Willoughby was comparing) but differ as a function of distance from the storm. Willoughby's cost function has been expanded to allow the use of surface pressure measurements either derived from the aircraft heights (hydrostatically reduced to the surface) or from *insitu* measurements such as buoys, CMAN stations, land stations and ship reports. Rather than rely on a purely objective determination of $Rp1$ and $Rp2$, an analyst workstation is used to iterate the values for a best fit based on both the snapshot of data being fit and well as maintaining time-continuity of the pressure radii. Figure 7 illustrates the ability of the double exponential pressure profile to fit the aircraft data during Allen (1980).

5. Initial Comparison in Lili 2002

Hurricane Lili (2002) provides an interesting test case since the storm was sampled by the SFMR instrument and passed close to two NDBC buoys on October 2nd and 3rd 2002 when the storm was its most intense (central pressure of 938 mb). Figure 8 shows the track of Lili and the positions of NDBC buoy 42001 (12-meter discus buoy) and buoy 42041 (3-meter discus buoy). Fits to the 700 mb flight level tangential winds and flight level heights along with surface pressure and resulting 10-meter wind field are shown in Figure 9. Fit parameters for each are detailed in Table 2. The primary radius $Rp1$ is in the 10-13 Nmi range during this period with pressure deficient increasing from 46 mb at the start of the 2nd to the maximum intensity at 21 GMT of 75 mb. The secondary radius $Rp2$ shows a tightening from 70 Nmi to 45 Nmi during the intensification of Lili, then broadens back out to 75 Nmi by the 3rd. The percentage of the total pressure drop associated with $Rp1$ remains at 73% with the remaining 27% associated with $Rp2$.

When the resulting TropPBL model output is compared to the SFMR data taken around 6:00 GMT (Figure 10) an approximate +5 knot bias in the resulting model winds is evident but with excellent agreement in the radius of maximum winds and overall distribution of the wind profile.

Comparisons at the NDBC buoys (Figure 11) also show some overestimation at the peak, but overall excellent agreement with the observations. The growth and decay cycle of the modeled winds are in near perfect agreement with the measurements.

Table 2 Fitted parameters during Hurricane Lili (2002)

<i>Date</i>	<i>Rp1</i> (<i>Nmi</i>)	<i>Rp2</i> (<i>Nmi</i>)	<i>B1</i>	<i>B2</i>	<i>Dp</i> (<i>mb</i>)	<i>%Dp</i> <i>Rp1</i>
Oct-02 00:00	13	70	1.50	0.90	46	73%
Oct-02 06:00	10	55	1.70	1.00	59	73%
Oct-02 12:00	10	50	2.00	1.10	60	73%
Oct-02 18:00	11	45	1.90	1.00	73	73%
Oct-02 21:00	11	55	1.85	0.90	75	73%
Oct-03 00:00	9	75	2.20	1.00	72	73%

6. Future Work

In order to fully apply the SFMR database for evaluation of model physics changes, a complete database of storm mission periods is required. A total of 15 storms during the period 1998-2006 have been completely reanalyzed using the storm fitting methodology outlined above. During the 15 storms, 33 individual aircraft missions have been identified where a) sufficient SFMR data were available to represent all quadrants in a composite field and b) the storm system was sufficiently away from the coast. Figure 12 shows one such composite mission taken during hurricane Ivan (2004). Raw SFMR data has been contoured using a simple objective analysis algorithm for illustrative purposes, and wind maxima along each flight leg have been identified. This dataset will serve as the basis of the model evaluation in terms of the placement of the maximum winds (radius at the surface and bearing relative to the storm motion vector), and the wind profile shape. Once model modifications based on SFMR data are complete, a further validation using *insitu* data and GPS dropwindsonde estimates will be performed before the updated model is delivered to the MORPHOS project.

Acknowledgements

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References

Cardone, V. J and D.T. Resio. Assessment of Wave Modeling Technology. Fifth International Workshop on Wave Hindcasting and Forecasting, 26-30 January, 1998, Melbourne, FL.

Chow, S. H., 1970: A study of the wind field in the planetary boundary layer of a moving tropical cyclone. MS Thesis, School of Engineering and Science, New York University, New York, NY.

Forristall, G. Z., E. G. Ward, V. J. Cardone, and L. E. Borgman. 1978. The directional spectra and kinematics of surface waves in Tropical Storm Delia. *J. of Phys. Oceanog.*, 8, 888-909.

Holland, G. J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Mon. Wea. Rev.* 108,1212-1218.

Jensen, R.E., V.J. Cardone and A.T. Cox, 2006: Performance of Third Generation Wave Models in Extreme Hurricanes. 9th International Wind and Wave Workshop, September 25-29, 2006, Victoria, B.C.

Knaff, J.A. and R.M. Zehr, 2007. Reexamination of Tropical Cyclone Wind-Pressure Relationships. *Wea. and Fore.*, vol 22, Feb 2007, pp-71-88.

Shapiro, L. J., 1983: The asymmetric boundary layer flow under a translating hurricane. *J. Atmos. Sci.*, 40, 1984-1998.

Thompson, E.F., and V.J. Cardone, 1996. Practical modeling of hurricane surface wind fields. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, July/August 1996, pp. 195-205.

Uhlhorn, E.W., P.G. Black, J.L. Franklin, M. Goodberlet, J. Carswell and A.S. Goldstein, 2007. Hurricane Surface Wind Measurements from an Operational Stepped Frequency Microwave Radiometer, *Mon. Wea. Rev.* vol 135, Sept. 2007, pp 3070-3085.

Vickery, P.J. and P.F. Skerlj, 2005. Hurricane Gust Factors Revisited. *Jour. Struct. Eng.*, vol 131, No.5, May 2005.

Willoughby, H.E. and M.E. Rahn, 2004. Parametric Representation of the Primary Hurricane Vortex. Part I: Observations and Evaluation of the Holland (1980) Model. *Mo. Wea. Rev.*, vol. 132, Dec 2004 pp. 3033-3048.

Willoughby, H.E., R.W.R. Darling and M.E. Rahn, 2006. Parametric Representation of the Primary Hurricane Vortex. Part II: A New Family of Sectionally Continuous Profiles. *Mo. Wea. Rev.*, vol. 134, Apr 2006 pp. 1102-1120.

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POST FLIGHT REPORT OF RESEARCH PLANE 39C.

HURRICANE DONNA LOCATED AT 22.2 N 72.4 W AT 1927Z AND AT 22.1 N
73.0 W AT 2152Z ACCURATE WITHIN 10 MILES. MAX FLIGHT LVL WINDS 150KTS
IN NE QUAD 134 KT IN SE QUAD 120 KT IN NW QUAD AND 99 KTS IN SW
QUAD. HURRICANE FORCE WINDS EXTND 40 MILES TO S AND W AND 60 MI
TO N AND E. MINIMUM 700 MB HT 8430 FEET. MIN KTP SLP 941 MBS.
11 DEG TEMP RISE IN CENTER. RADAR COVERAGE FEASIBLE. MANY LAYERS
OF CLOUDS IN EYE.

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Figure 1 Microfilm copy of aircraft reconnaissance obtained during hurricane Donna (1960).

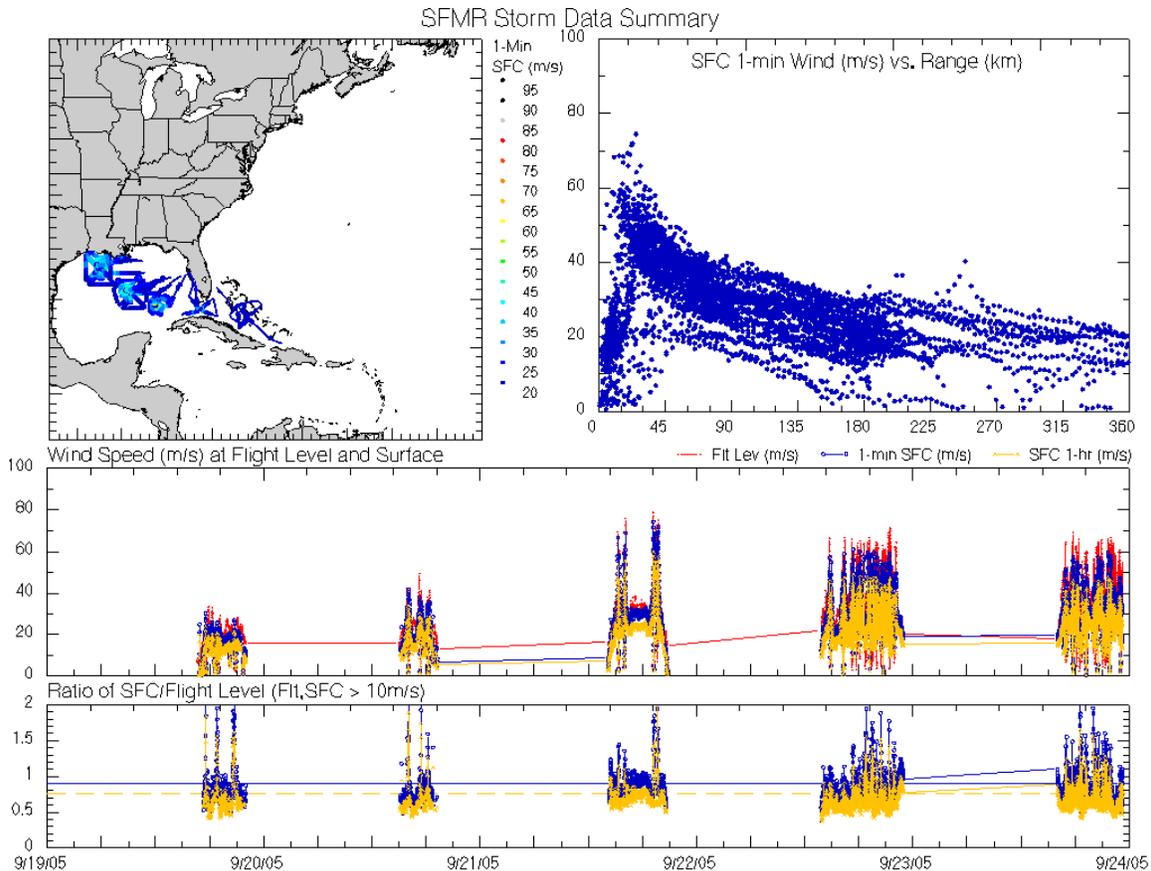


Figure 2 Summary of SFMR observations during Rita (2005). Geographic locations of the observations are shown in the upper left, 1-minute surface wind vs. range to storm center is shown in upper right and flight level, surface and 30-minute wind speeds along with there respective ratios vs. time are shown in the bottom figure.

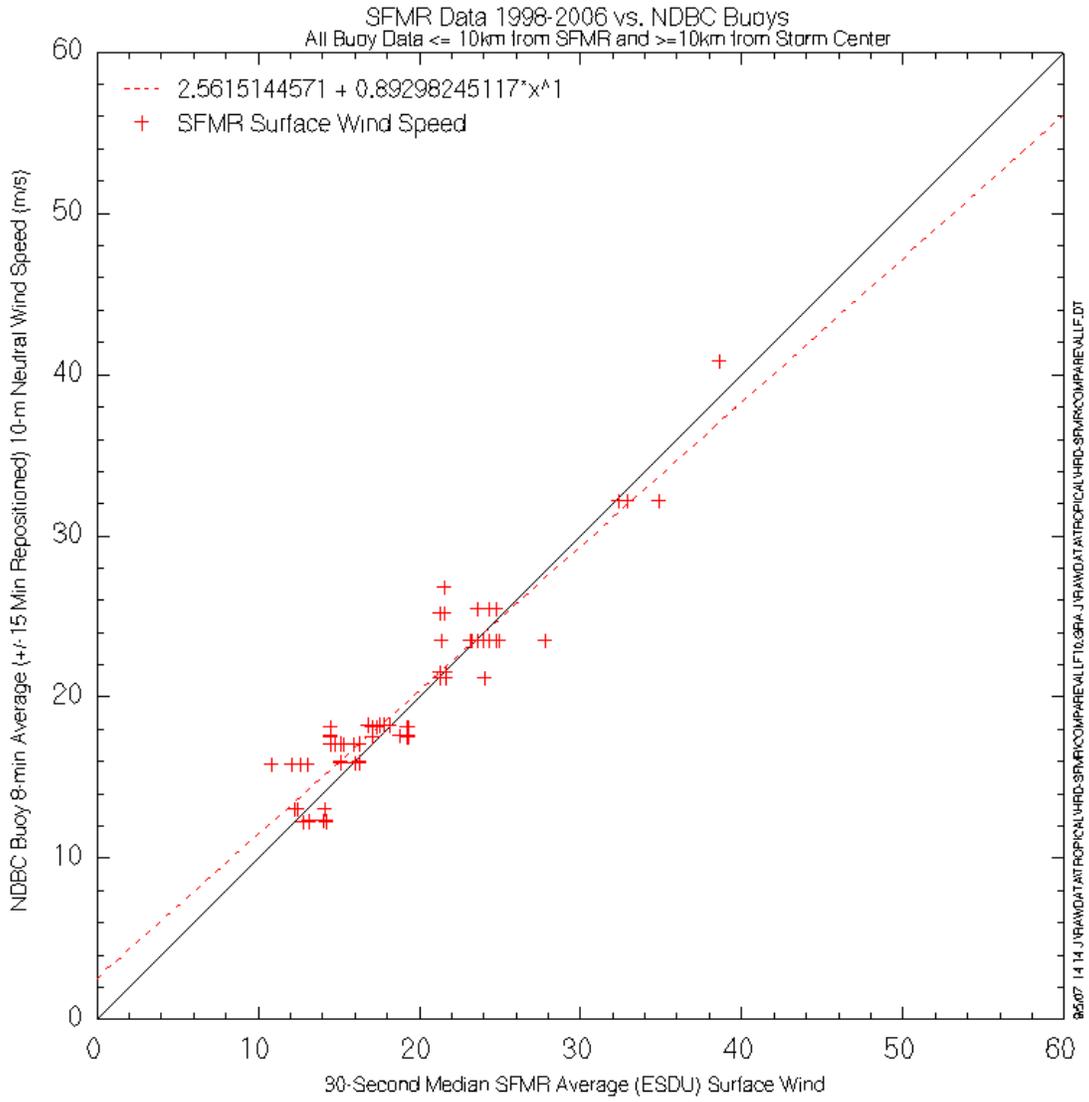


Figure 3 Comparison of SFMR and NDBC buoys within a 15 minute/10 km window (all winds 30-minute average, m/s)

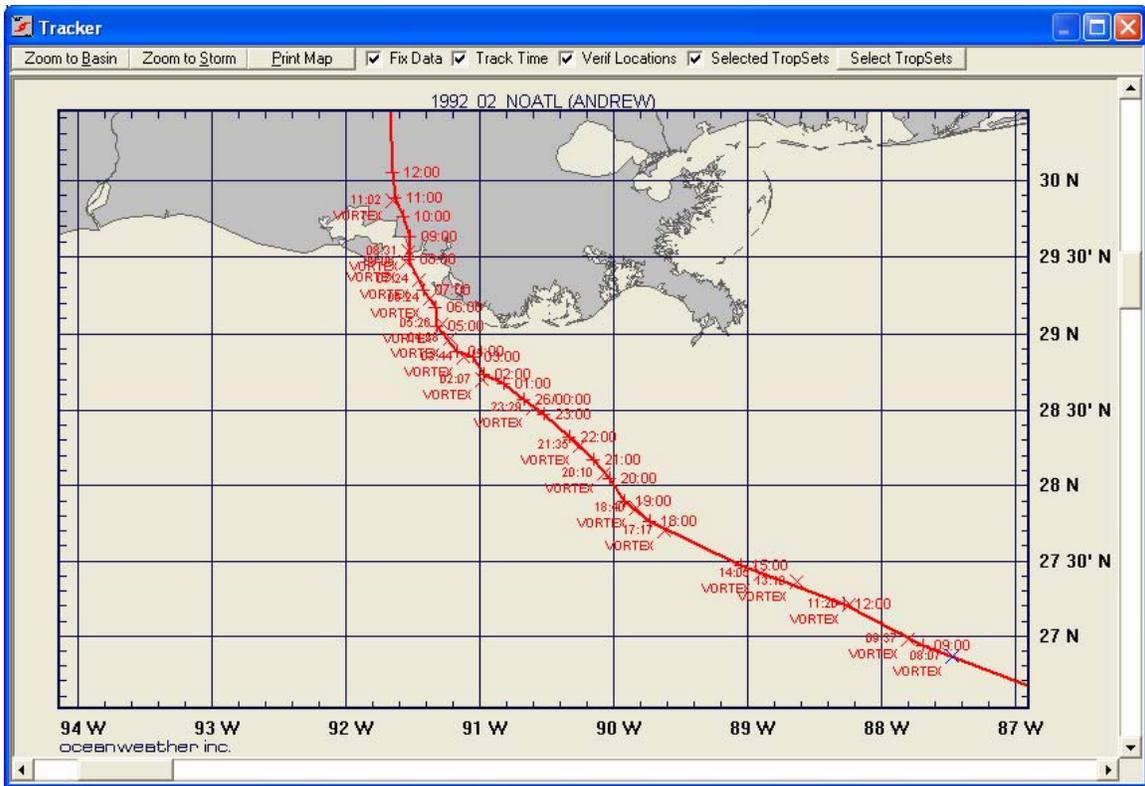


Figure 4 Modified HURDAT (red line) track of Hurricane Andrew (1992) shown with aircraft vortex center position estimates.

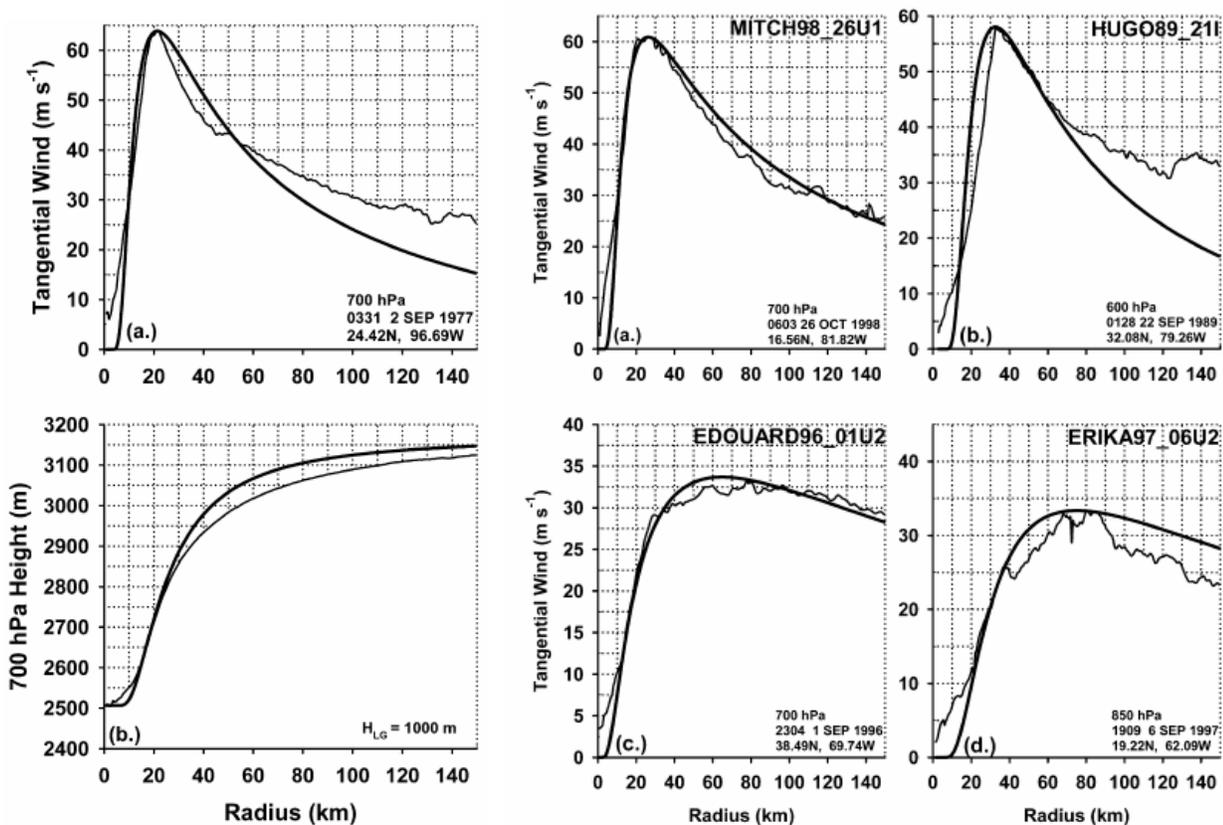


Figure 5 Example fits of a single exponential Holland profile fit to Anita (1977) (top left: flight level winds bottom left: 700mb heights) Mitch (1998) (top middle), Hugo (1989) (top right), Edouard (1996) (bottom middle) and Erika (1997) (bottom right) from Willoughby and Rahn (2004).

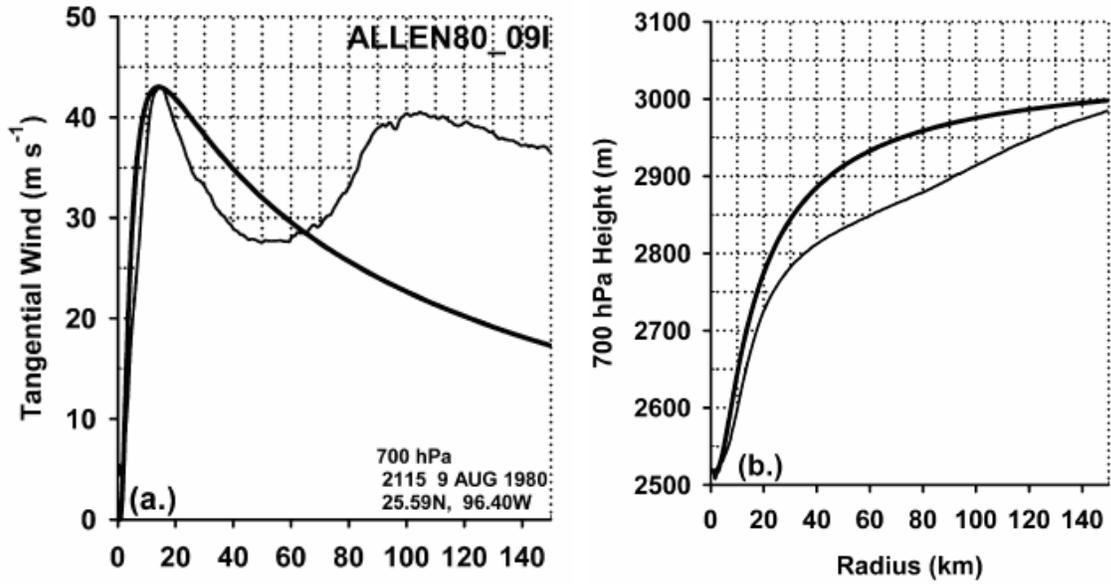


Figure 6 Single exponential fit for Allen (1980) from Willoughby and Rahn (2004) for flight level winds (left) and flight level heights (right).

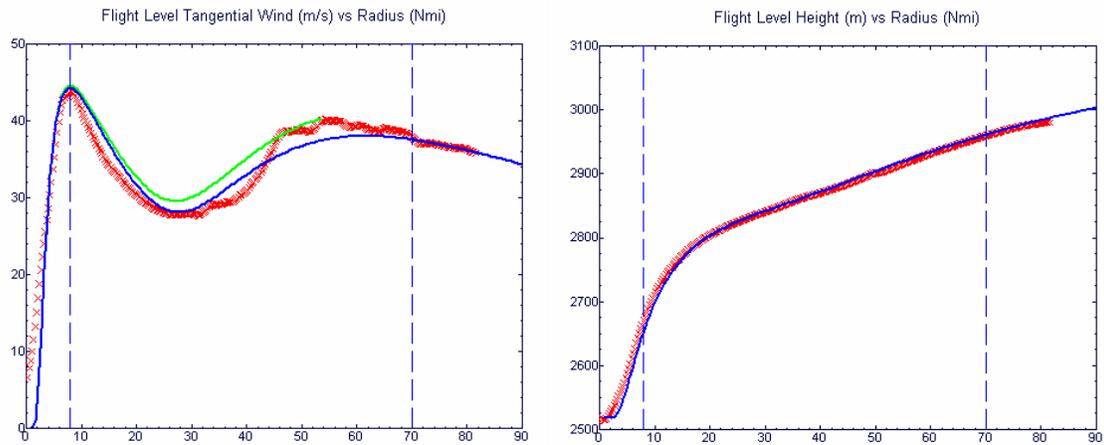


Figure 7 Double exponential fit (blue: gradient wind from surface pressure parameters, green: cyclostrophic wind from flight level heights as applied in Willoughby and Rahn) to 700mb flight level winds (red, left) and flight level heights (red data, blue fit) during Allen (1980) valid Aug-08-1980 21 GMT (data azimuthally averaged ± 60 minutes).

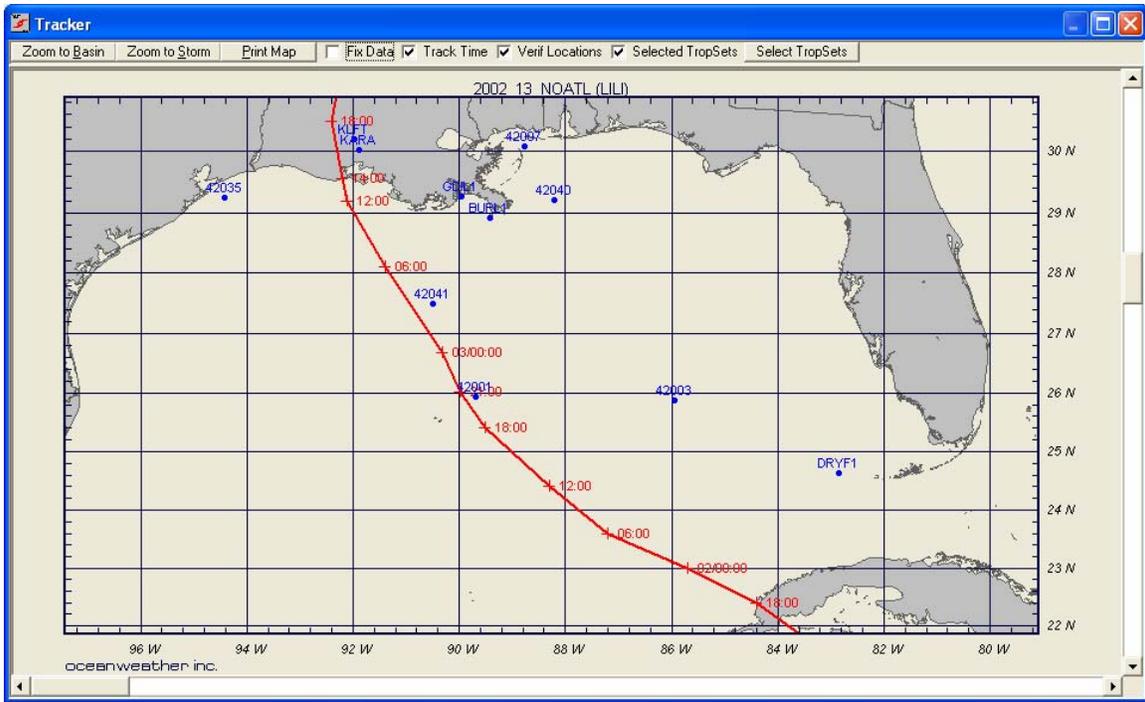


Figure 8 Track of Hurricane Lili (2002) showing insitu measurement locations.

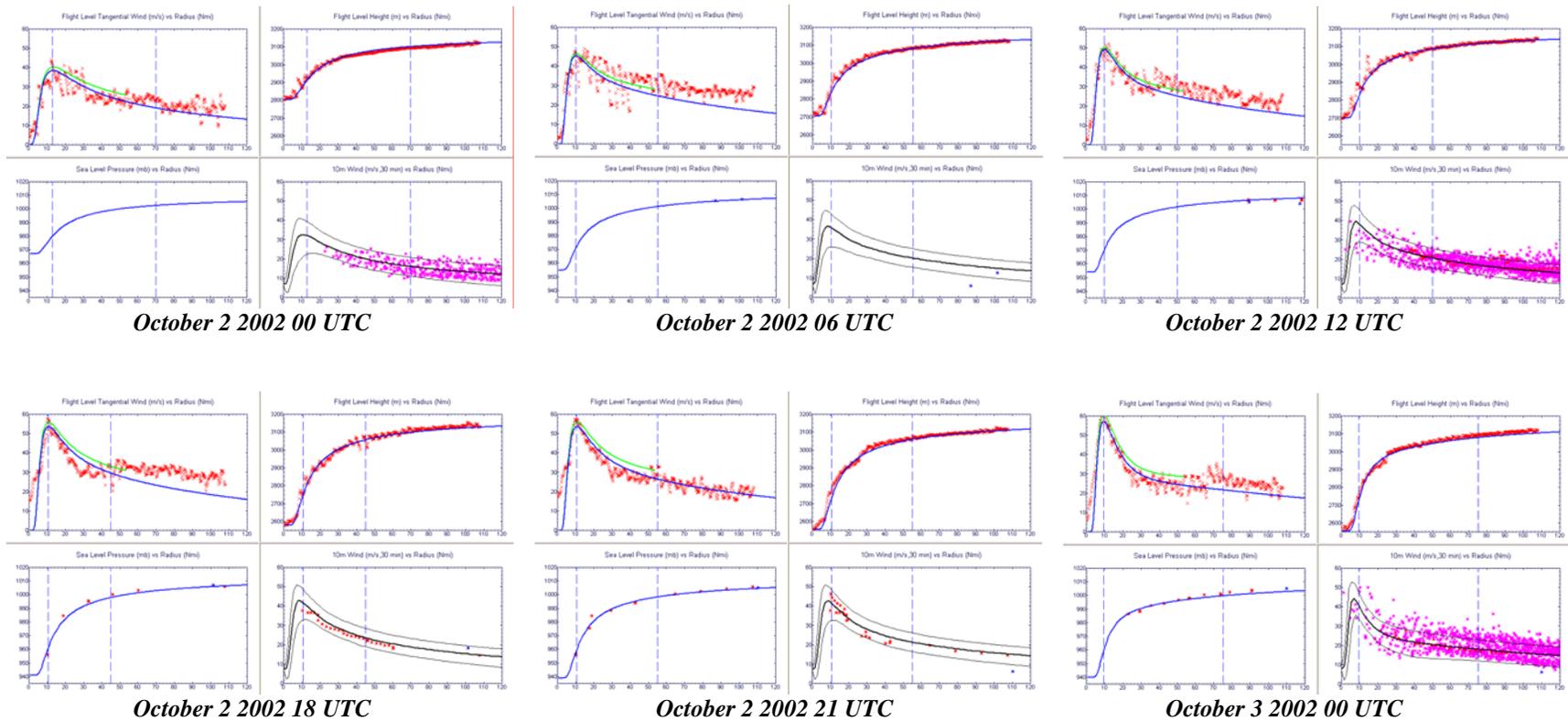


Figure 9 Tropical parameter fits during Hurricane Lili (2002) valid October 2nd 00:00, 06:00, 12:00, 18:00, 21:00 and October 3rd 00 GMT. Each 4-panel plot depicts the flight level tangential winds (m/s, top left), flight level heights (m at 700mb, top right), surface pressures from insitu data (mb, bottom left) and resulting 10-m 30-minute average wind speed (azimuthal minimum, maximum and average) with *insitu* data which includes 14 km QUIKSCAT data (m/s, bottom right).

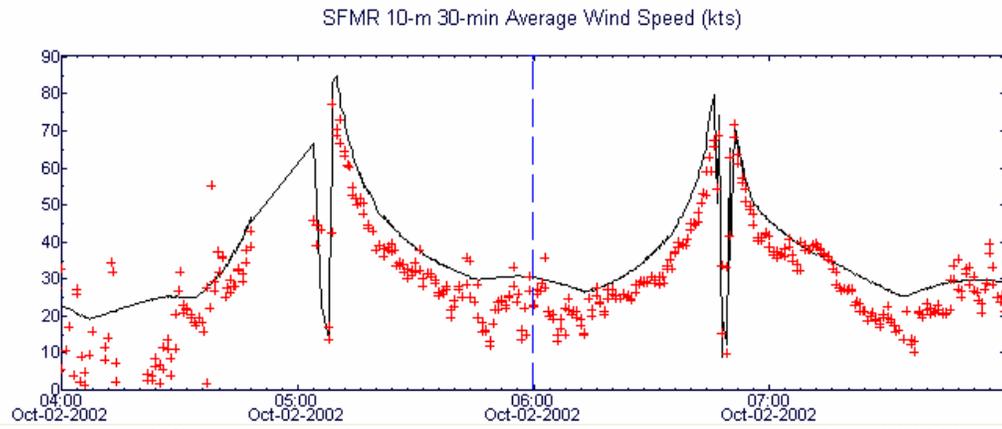


Figure 10 Comparison of SFMR observations and model output during Lili 2002

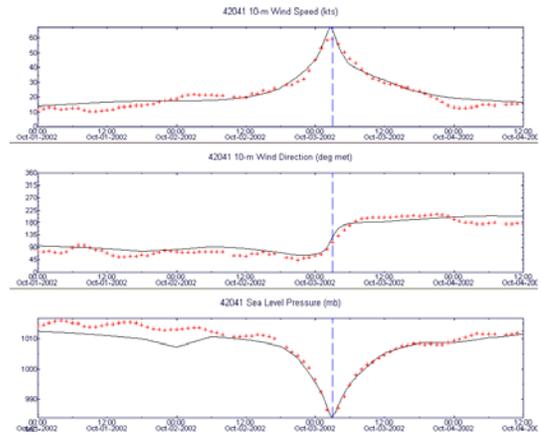
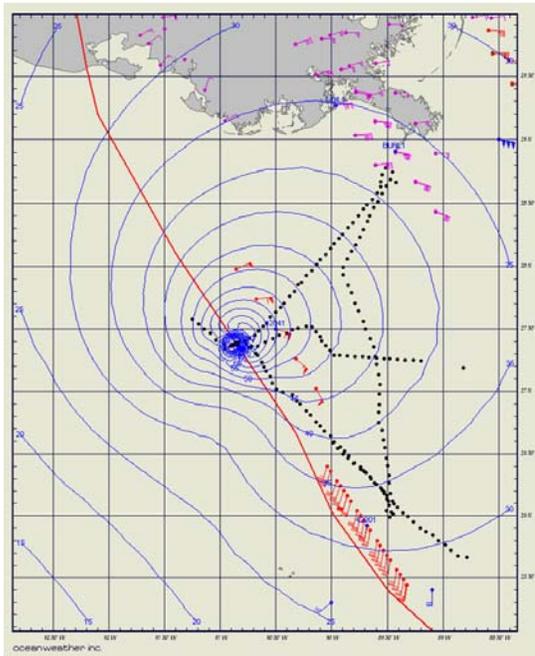
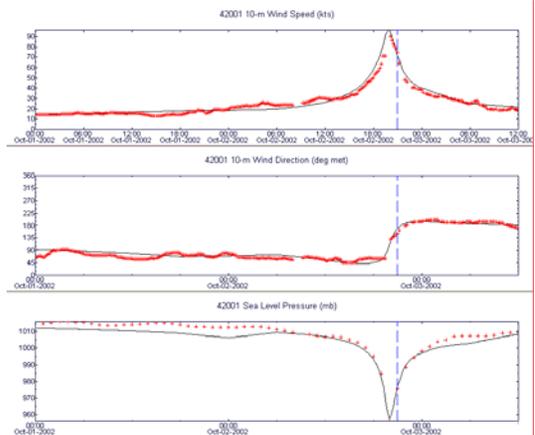
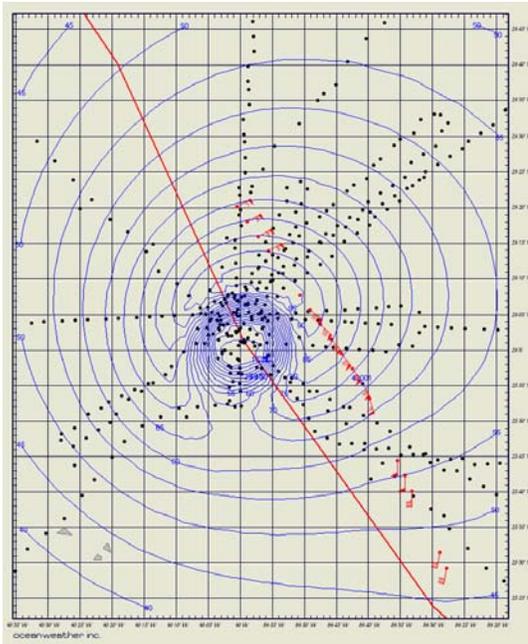


Figure 11 Comparison of modeled (black) and measured (red) wind speed, wind direction, and sea level pressure during Lili 2002 for NOAA buoy 42001 (top, right) and 42041 (bottom, right). Corresponding snapshot of measured winds and model isotachs (knots) are shown for October-2-2002 21 UTC (top, left) and October-3-2002 00 UTC (bottom, left)

MORPHOS 2004_09(IVAN) Mission Center Time: 200409142300 Includes Data from: 141947 to 150411
 Storm Latitude: 24 533 Storm Longitude: -86 917 Storm Heading: 336 Speed: 11

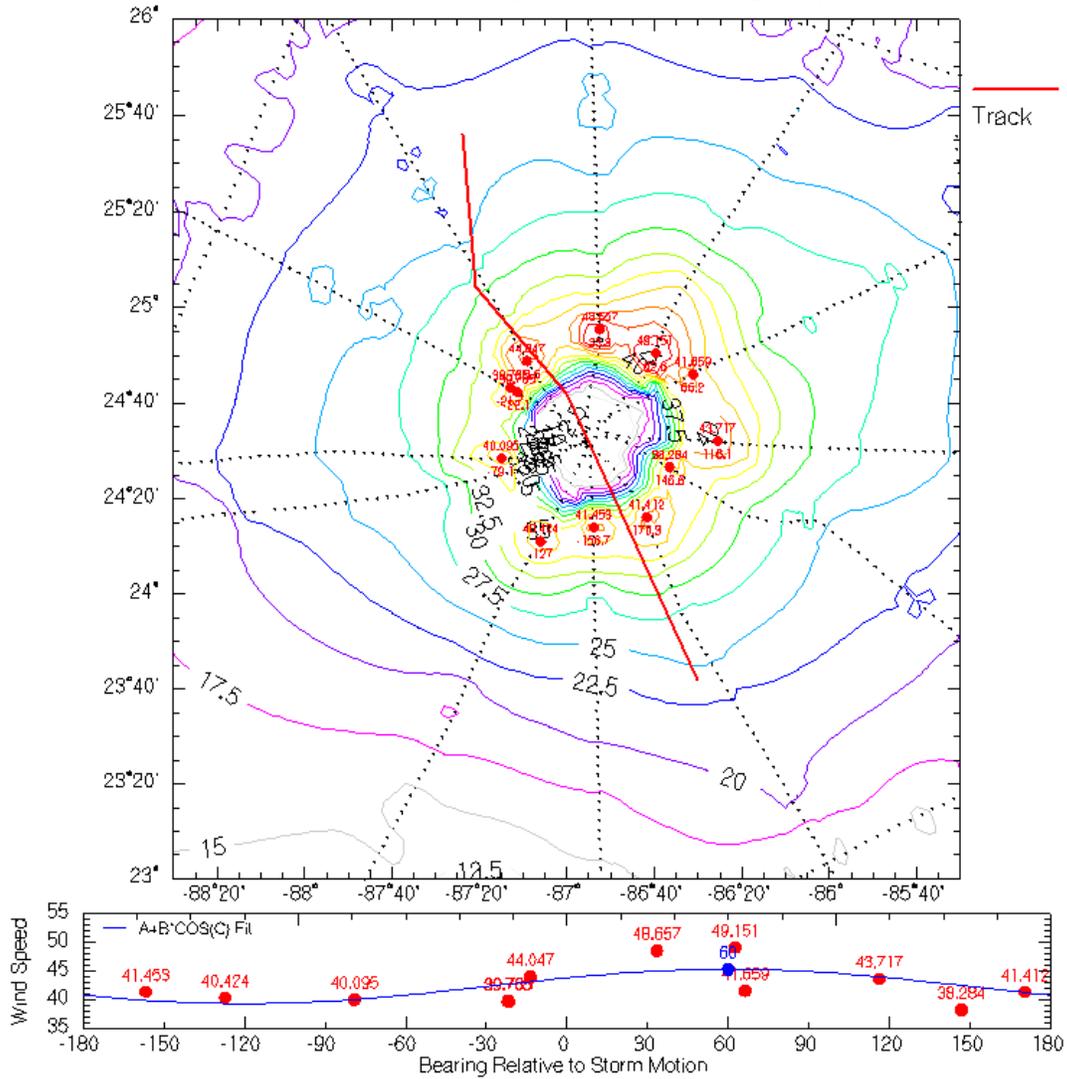


Figure 12 SFMR composite mission during Ivan 2004 (top) with wind leg maximum conditions (red, 30-minute average m/s) fitted to cos function (blue line) to estimate location of wind maximum relative to storm bearing (45° represents the right front quadrant).