Hurricane Sea-surface Inflow Angle from GPS Dropsonde Composites and an Observation-based Parametric Model

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Acknowledgements

Support from NOAA Hurricane Forecast and Improvement Program (HFIP)

Scientists from HRD and other agencies, researchers, and crew members form AOC who participated HRD's field programs and helped with collecting and maintaining the Dropsonde data

Outline

1. Introduction and motivation

2. Data and analysis method

3. Data analysis result

4. A simple parametric model for Inflow angle and model validation

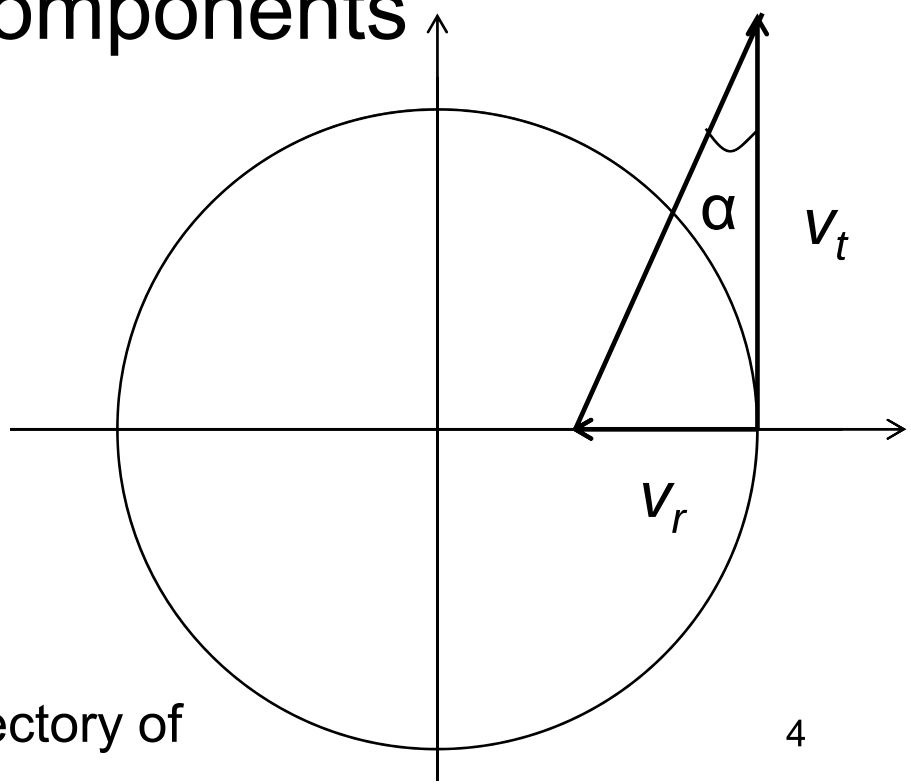
5. Applications of the parametric model

What is the Inflow angle in hurricanes?

The inflow angle (α) is defined as the arctangent of the ratio of radial (v_r) and tangential (v_t) wind components

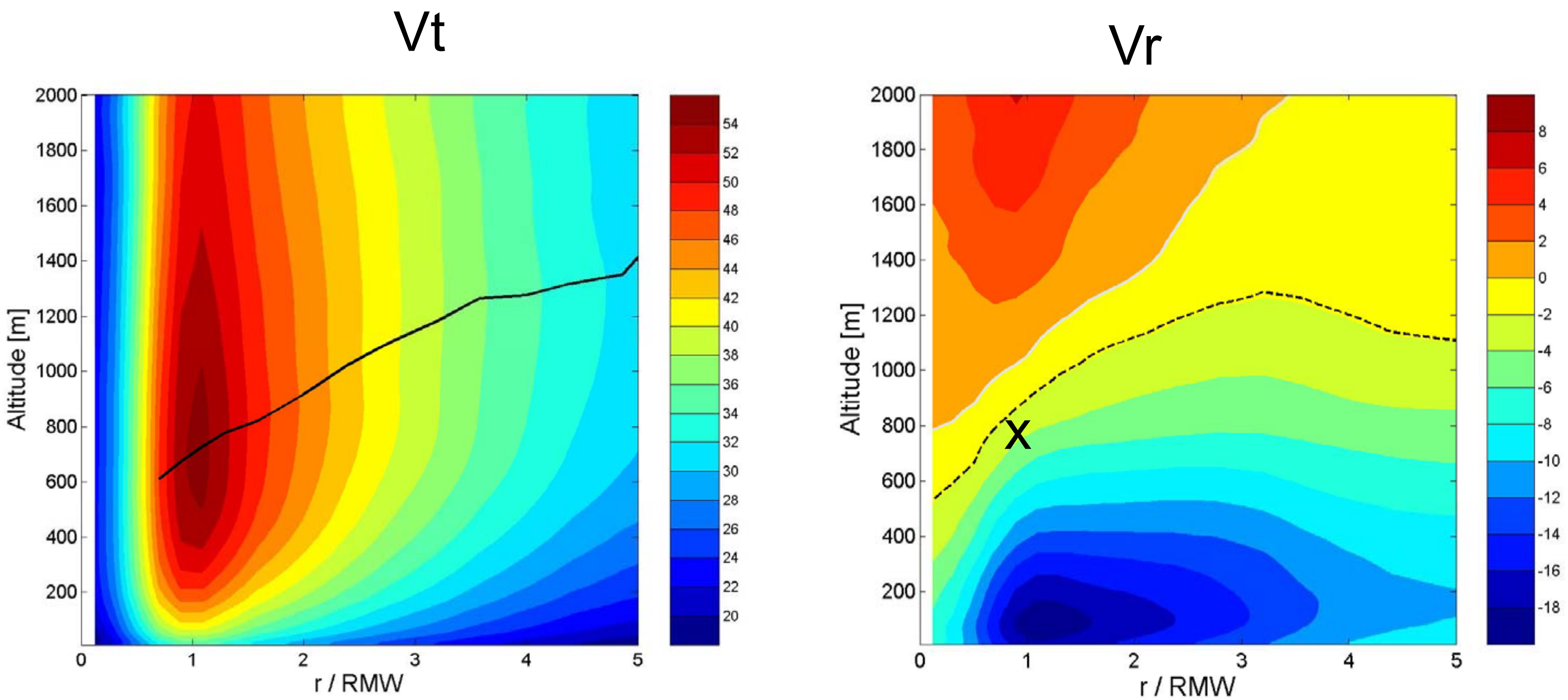
$$\alpha = \tan^{-1}(v_r / v_t)$$

Negative v_r represents radial inflow



The inflow angle represents the local trajectory of mass transport to the storm center

Tangential and radial wind speed (m/s) in the hurricane boundary layer



Composite analysis using hundreds of GPS dropsondes from 13 hurricanes (J. Zhang et al. 2011)

Why is the inflow angle important in hurricanes?

On the Dynamics and Energy Transformations in Steady-State Hurricanes

By J. S. MALKUS, Woods Hole Oceanographic Institution[1],
and H. RIEHL, The University of Chicago.

(Manuscript received May 5, 1959)

Abstract.

A dynamic model of the inflow layer in a steady mature hurricane is evolved, relating wind speed, pressure gradient, surface shearing stress, mass flow, and convergence. The low-level air trajectories are assumed to be logarithmic spirals. With this hypothesis, properties such as maximum wind and central pressure are determined through choice of a parameter depending on the inflow angle: a moderate hurricane arises with inflow angles of about 20°, while 25° gives an intense or extreme storm.

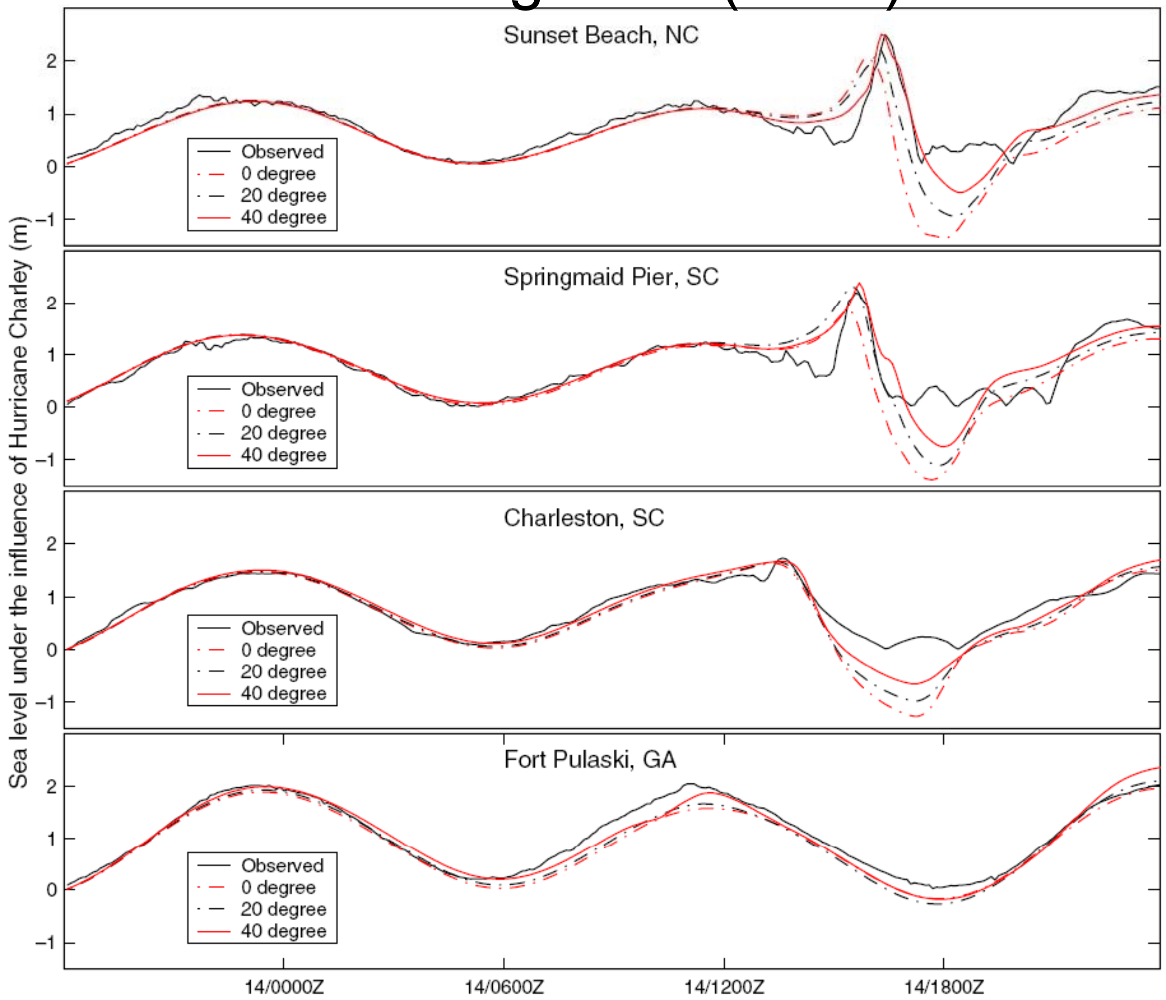
Most of this study treats the moderate storm. In order to maintain its core pressure gradients, an oceanic source of sensible and latent heat is required. As a result, latent heat release in the inner hurricane area occurs at higher heat content (warmer moist adiabats) than mean tropical sub-cloud air. The heat transfer from the ocean and the release of latent heat in the core determine the pressure gradient along the trajectory, and this prescribes the particular trajectory selected by the air among an infinite number available from the logarithmic spiral family.

This selection principle is evolved using recent work on "relative stability" of finite amplitude thermal circulations. Of an infinite number of dynamically possible spirals, the one is realized which maximizes the rate of kinetic energy production under the thermodynamic constraints, here formulated in terms of the relation between heat release and pressure gradient.

Finally, rainfall, efficiency of work done by the storm, and kinetic energy budgets are examined in an attempt to understand the difference between the hurricane—a rare phenomenon—and the common sub-hurricane tropical storm.

Inflow angle and storm surge modeling

Peng et al. (2006)



Sea surface elevation simulations forced by the Holland (1980) parametric wind model with different inflow angles

Inflow angle and wave modeling

Zhao and Hong 2011

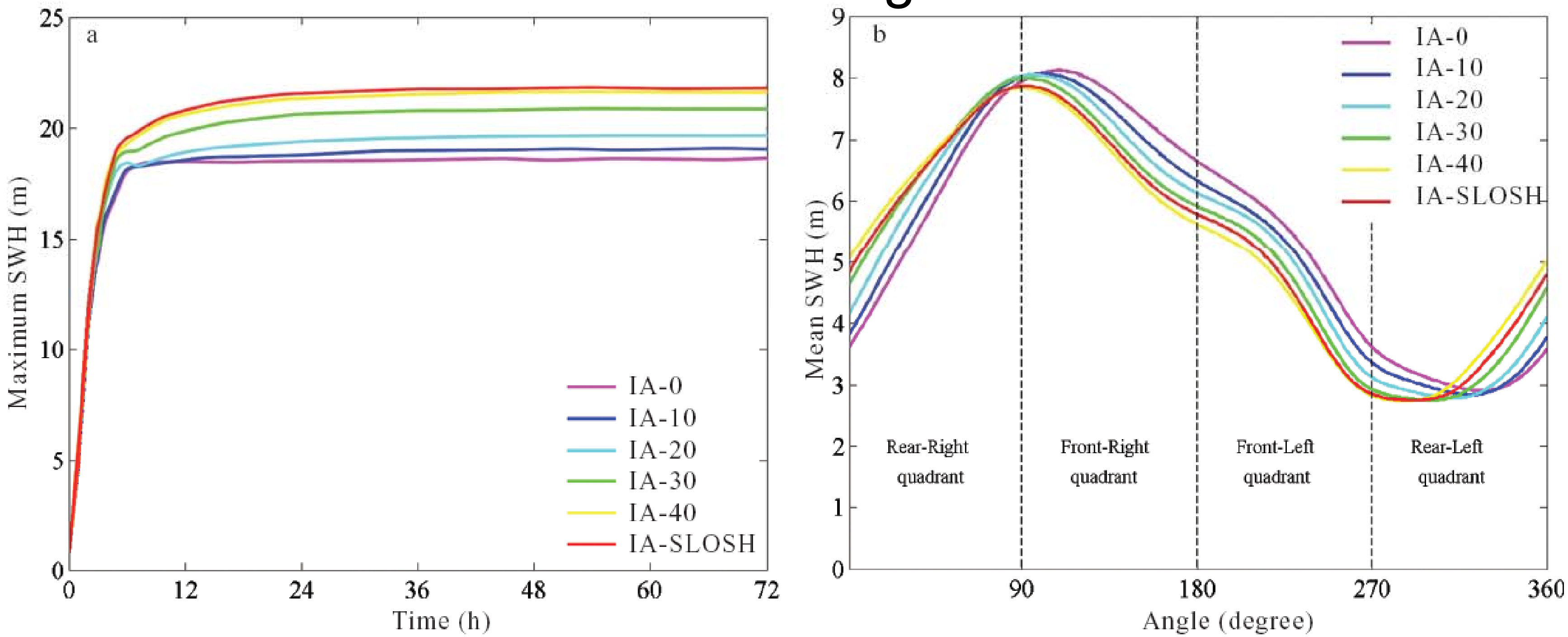
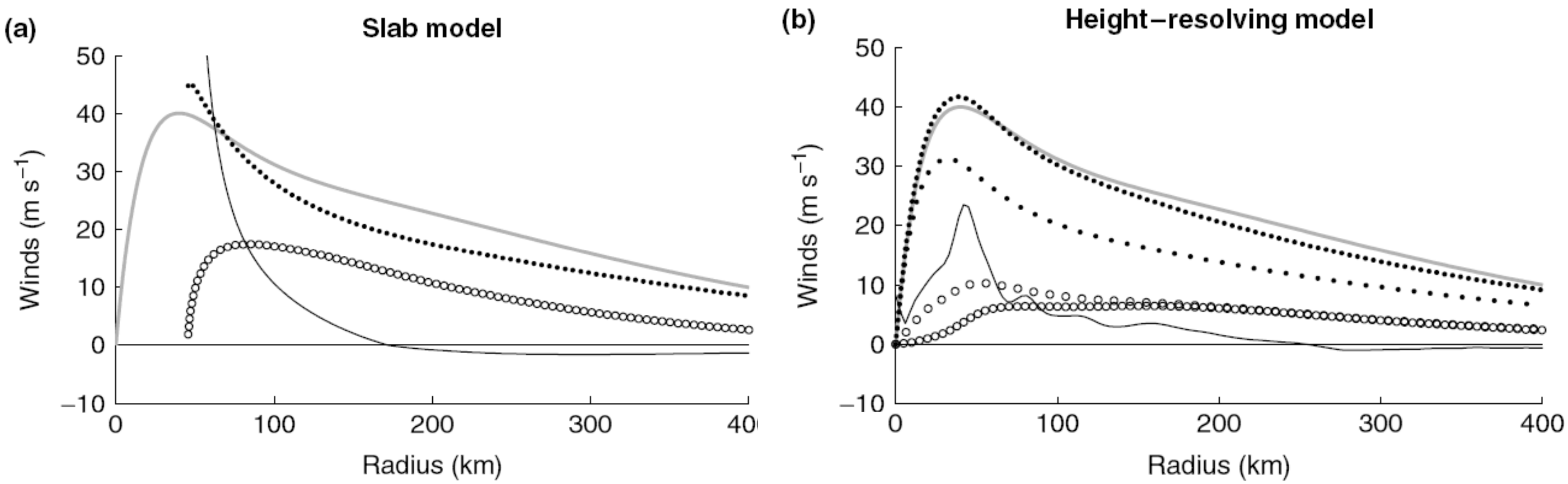


Fig.3 Impacts of different TC inflow angles on (a) the maximum SWH and (b) the mean SWH

WAVEWATCH III simulations forced by Willoughby et al. (2005) parametric wind model with different inflow angles

Inflow angle is a key dynamical parameter for boundary layer theory verification

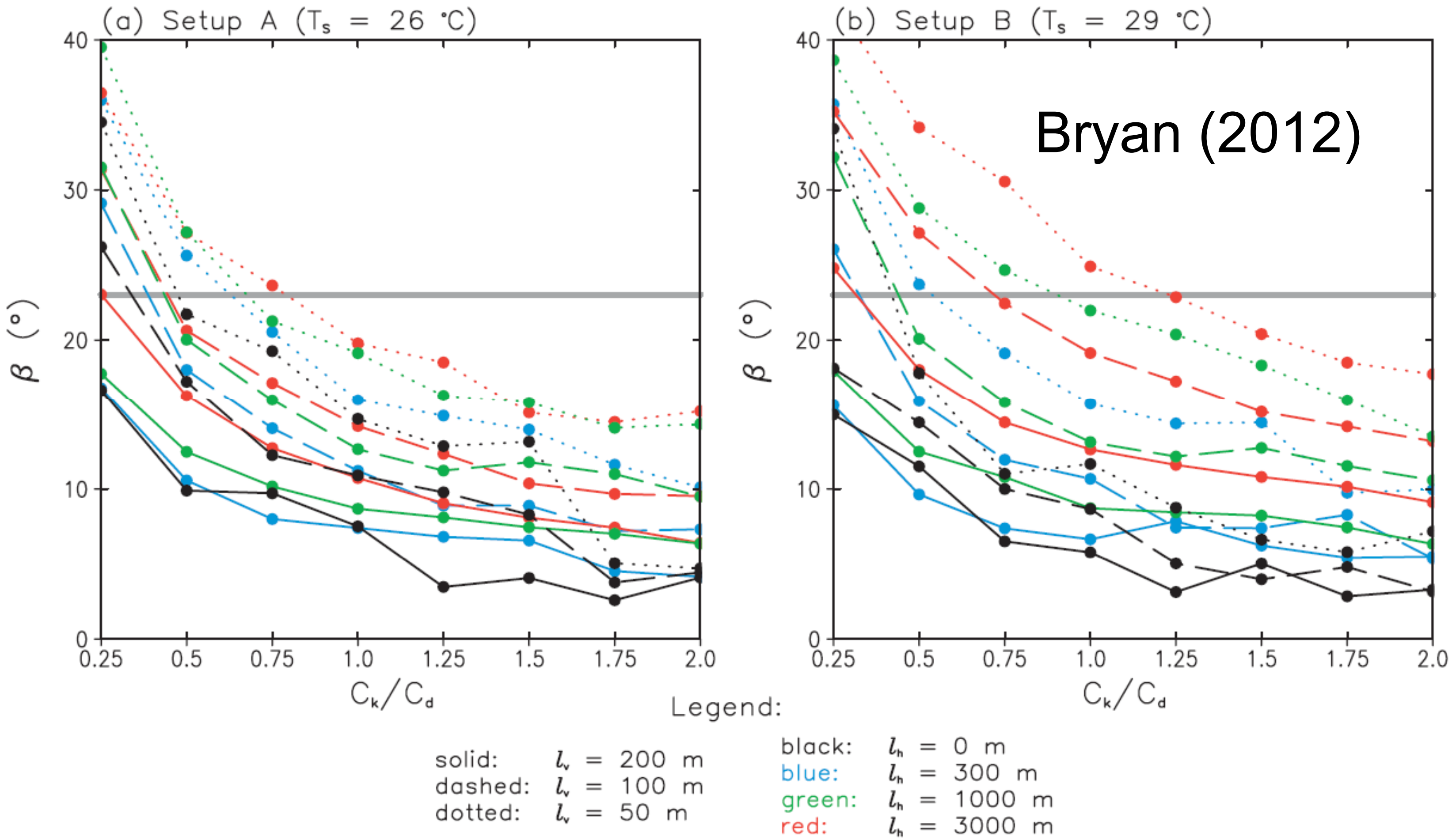


Kepert (2010)

Figure 3. (a) Axisymmetric boundary-layer flow according to the slab model. Gradient wind (thick grey), boundary-layer mean azimuthal (dots), inwards (open circles) and upwards (thin black, multiplied by 100) flow components. Parameter values are as in Smith and Montgomery (2008), including the boundary-layer height which is fixed at $h = 800$ m. (b) Simulation of the same vortex as in (a), except with the height-resolving model, as already shown in Figure 1. Curves with closely spaced symbols are averaged over the lower 800 m, while those with less dense symbols show the flow at 10 m height. The vertical velocity is at 800 m height.

The slab-model inflow angle exceeds 20◦ between 70 and 360 km radius and exceeds 30◦ from 90–220km radius, which seems unrealistically large.

Inflow angle and Model evaluation



The gray line represents the average value from dropsonde observations reported by Powell et al. (2009)

Very limited observational studies on hurricane surface Inflow angle

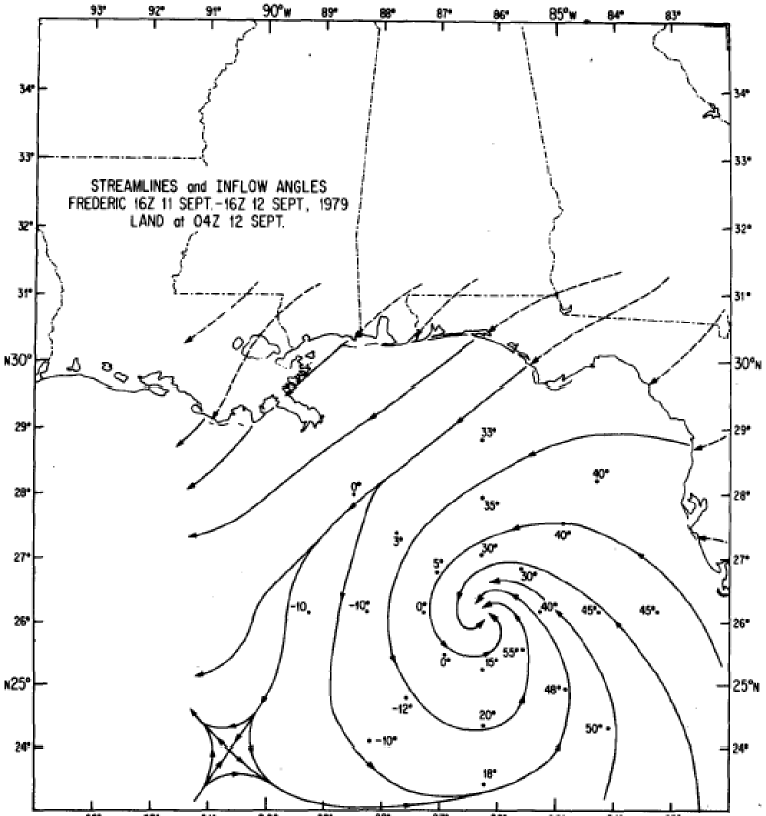


FIG. 6. Streamline analysis and inflow angles (degrees) for the overwater composite. Streamlines are dashed over land. Storm motion is 333° at 5 m s^{-1}.

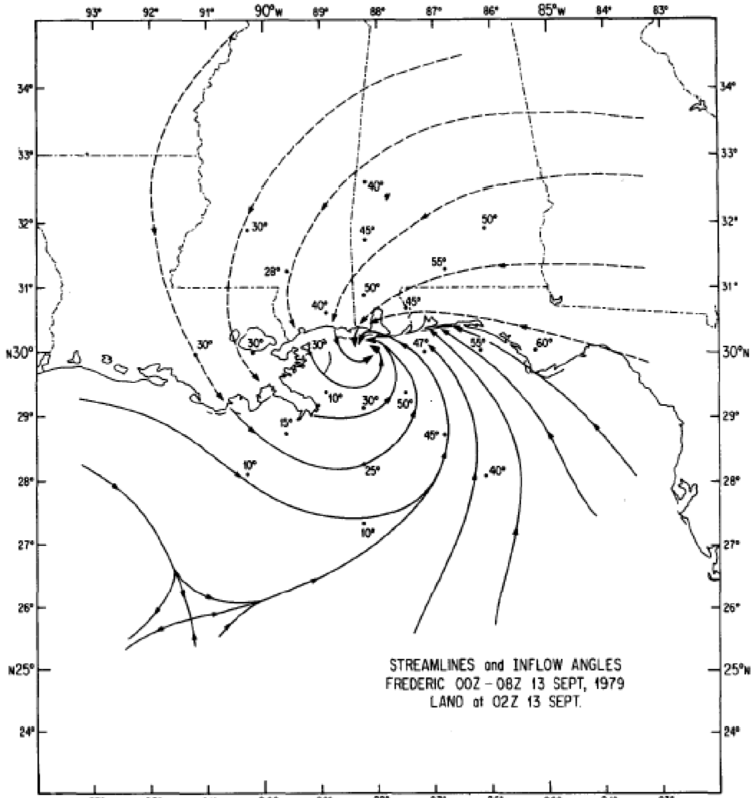


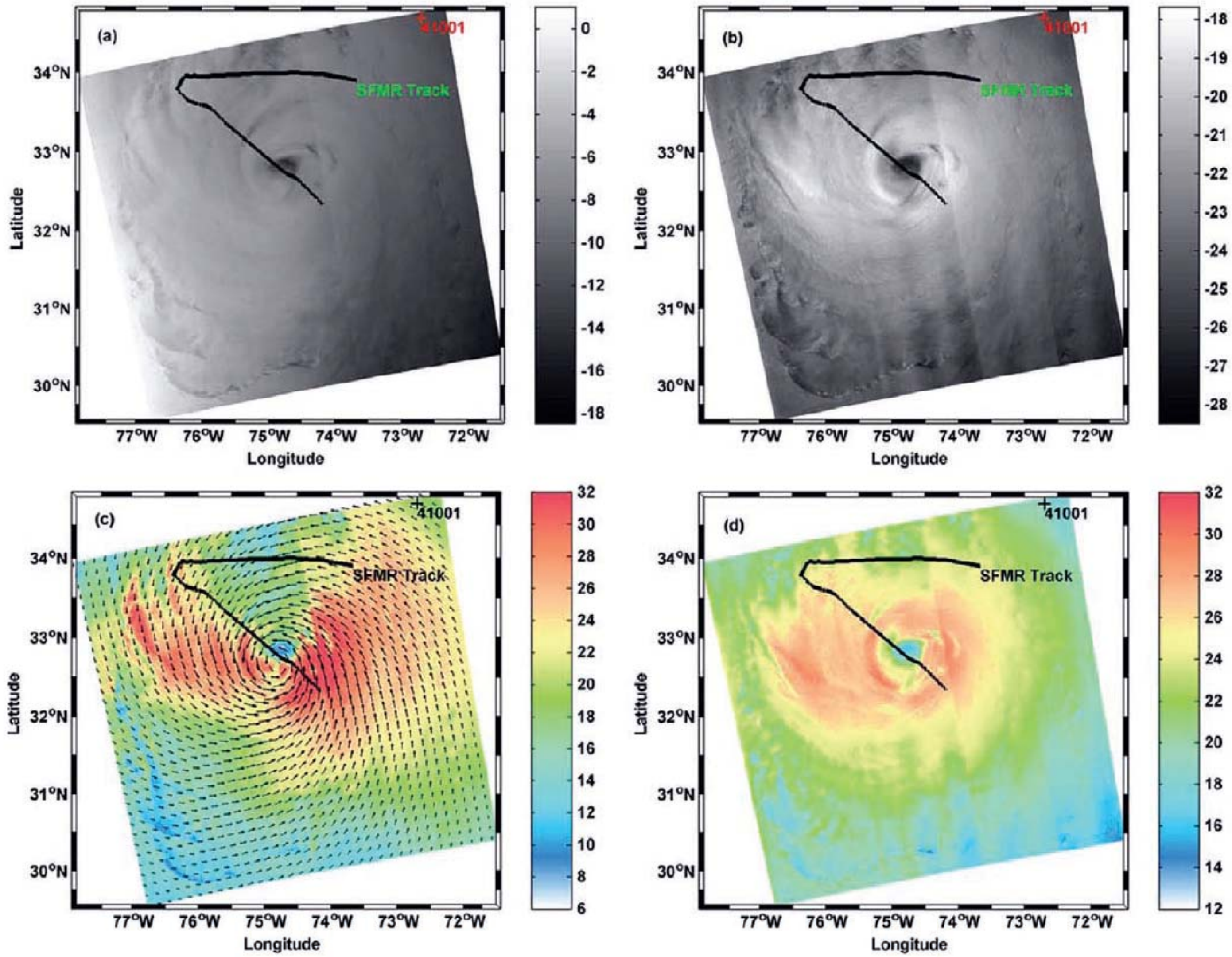
FIG. 10. Streamline analysis and inflow angles (degrees) for the landfall composite. Streamlines are dashed over land. Storm motion is 345° at 6.5 m s^{-1}.

The only observational study by Powell (1982) showing inflow angle asymmetry in Hurricane Fredric (1979)

Remote-Sensing Observation of Wind Vector in Hurricanes

- Nadir-viewing passive microwave radiometer is insensitive to wind direction (e.g., SFMR);
- Active microwave sensors (e.g. Scatterometers) attenuate in heavy rain with limited resolution;
- High resolution synthetic aperture radar (SAR) observed wind direction has ambiguous problem

SAR wind retrieval is sensitive to wind direction



B. Zhang and Perrie (2011 BMAS)

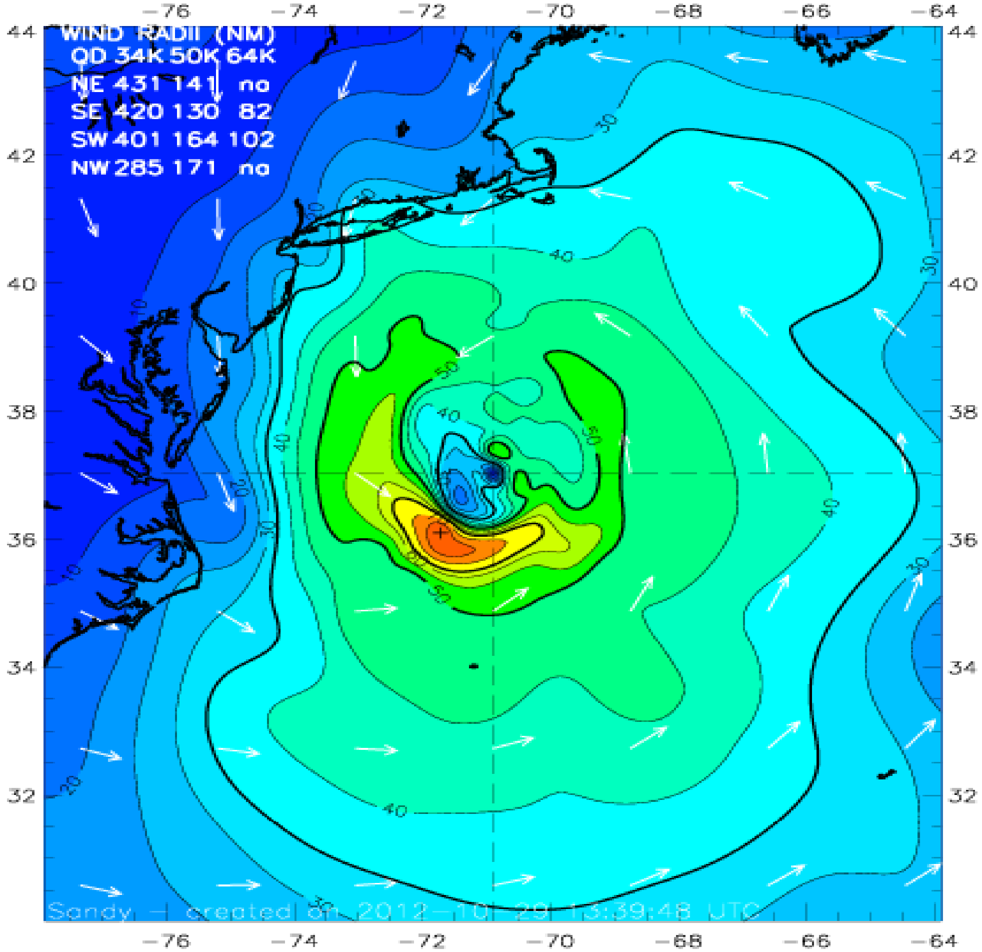
Hurricane Sandy 1330 UTC 29 OCT 2012

Max 1-min sustained surface winds (kt)

Valid for marine exposure over water, open terrain exposure over land

Analysis based on SFMR_AFRC from 1723 – 1325z; MADIS from 0602 – 1232z; GPSSONDE_WL150 from 0656 – 1306z; GPSSONDE_SFC from 0656 – 1306z; GOES_SWIR from 0702 – 1002z; TTUHRT from 0600 – 1230z; MOORED_BUOY from 0600 – 1310z; METAR from 0600 – 1335z;

1330 z position interpolated from 1200 ATCF_CARQ; mslp = 946.0 mb



Integrated Kinetic Energy: for Winds > TS force: 329 TJ, for Winds > Hurricane Force: 12 TJ
Destructive Potential Rating(0–6) Wind: 2.9 , Surge/Waves: 5.8

Observed Max. Surface Wind: 79 kts, 76 nm SW of center based on 1206 z SFMR_AFRC
Analyzed Max. Wind: 79 kts, 72 nm SW of center

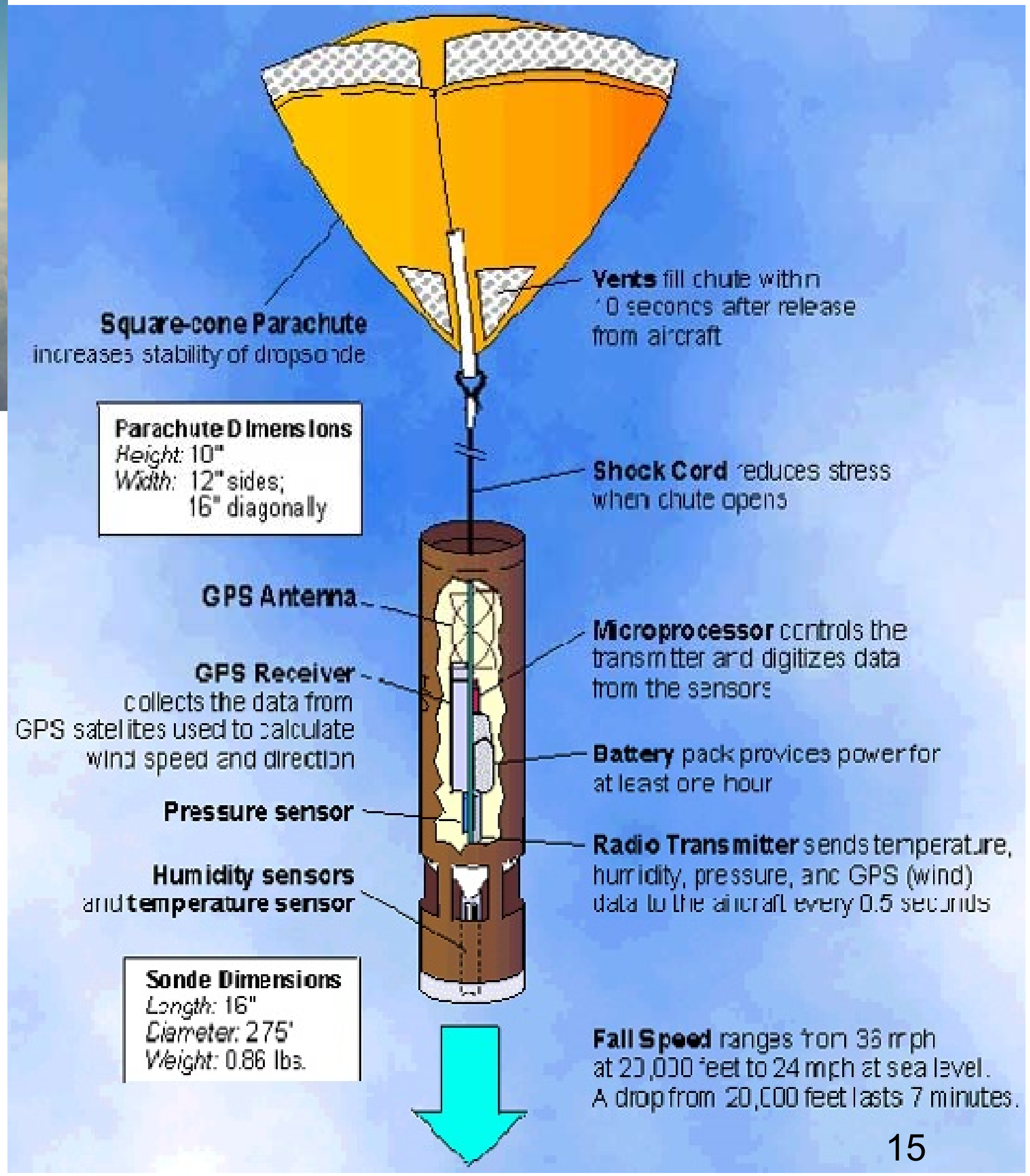
Uncertainty –> mean wind speed error: –0.78 kt, mean direction error: –0.18 deg
rms wind speed error: 4.90 kt, rms direction error: 9.81 deg

Research product of NOAA / AOML / Hurricane Research Division

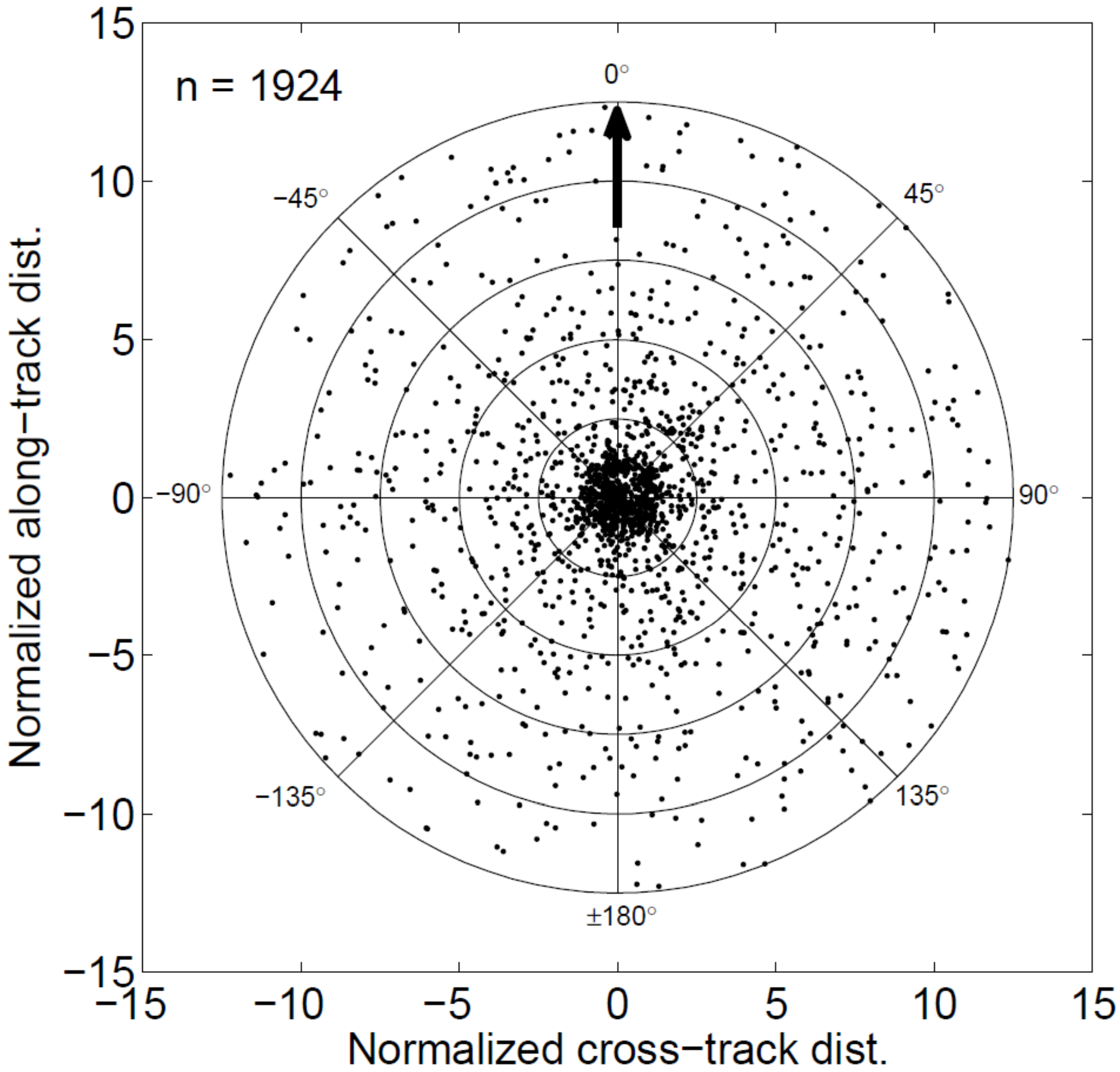
H*WIND Analysis

Surface wind direction is corrected from flight-level winds

GPS dropsonde



Dropsondes from 18 hurricanes (1997-2010)

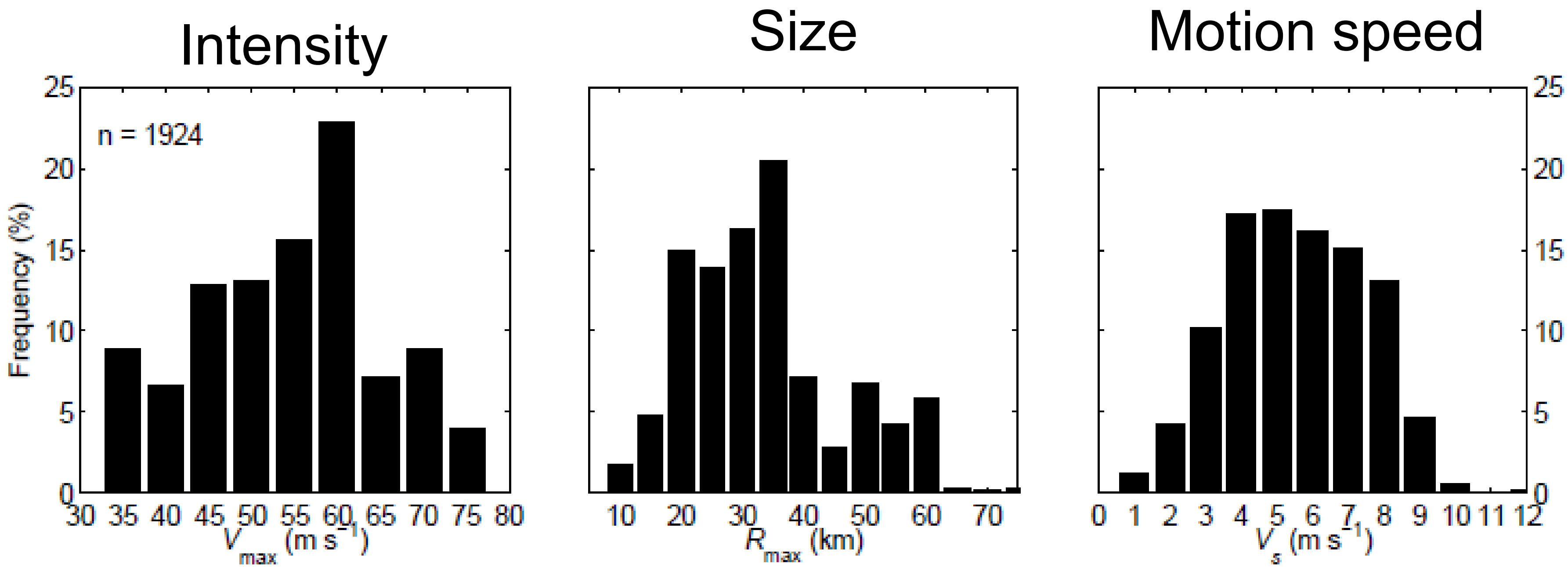


The center positions have been determined using the flight-level data to fix the storm center using the algorithm developed by Willoughby and Chelmow (1982).

Values of radius of maximum wind speed (Rmax) are determined using the SFMR surface wind profiles.

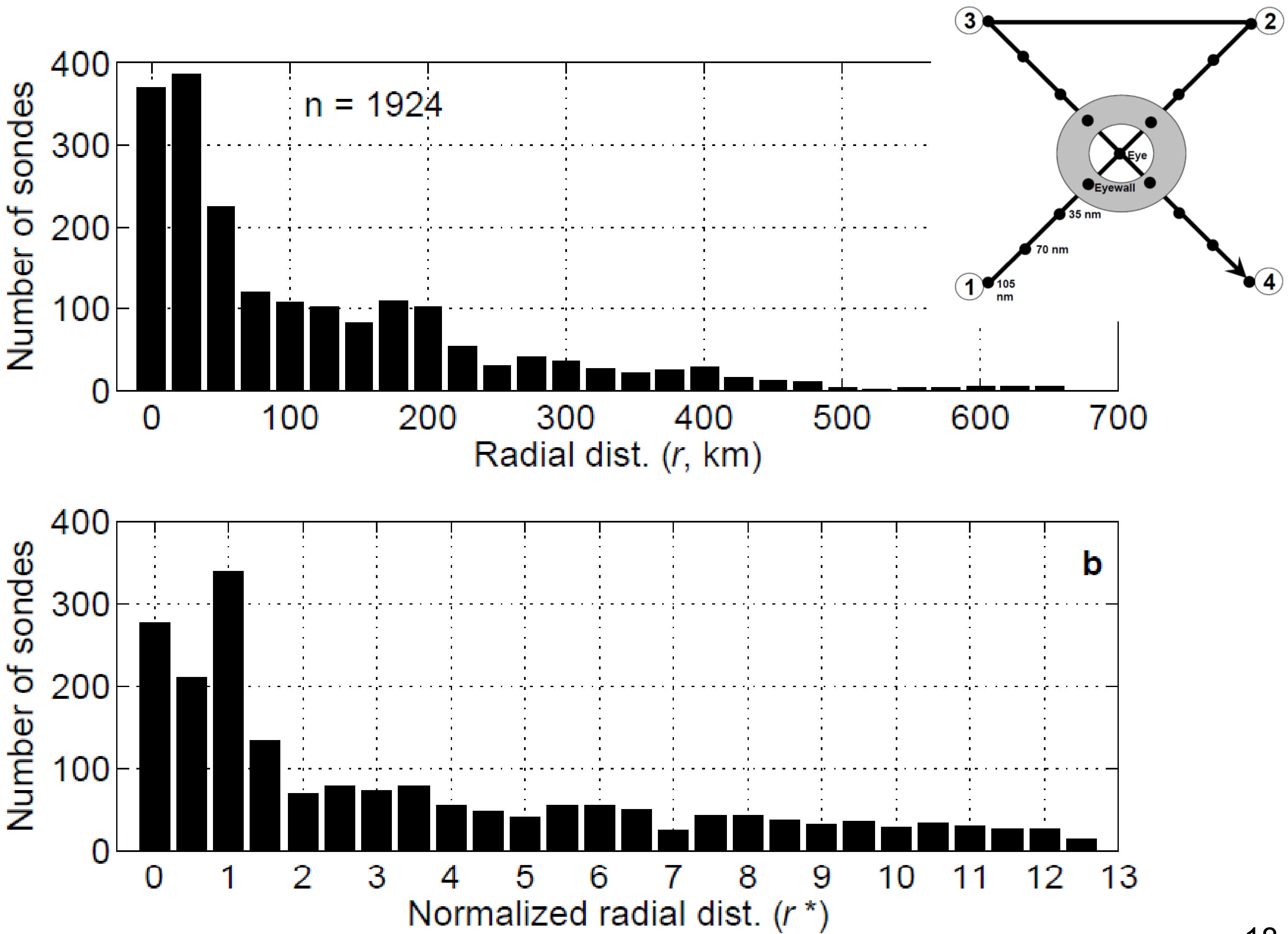
Zhang and Uhlhorn 2012

Storm information

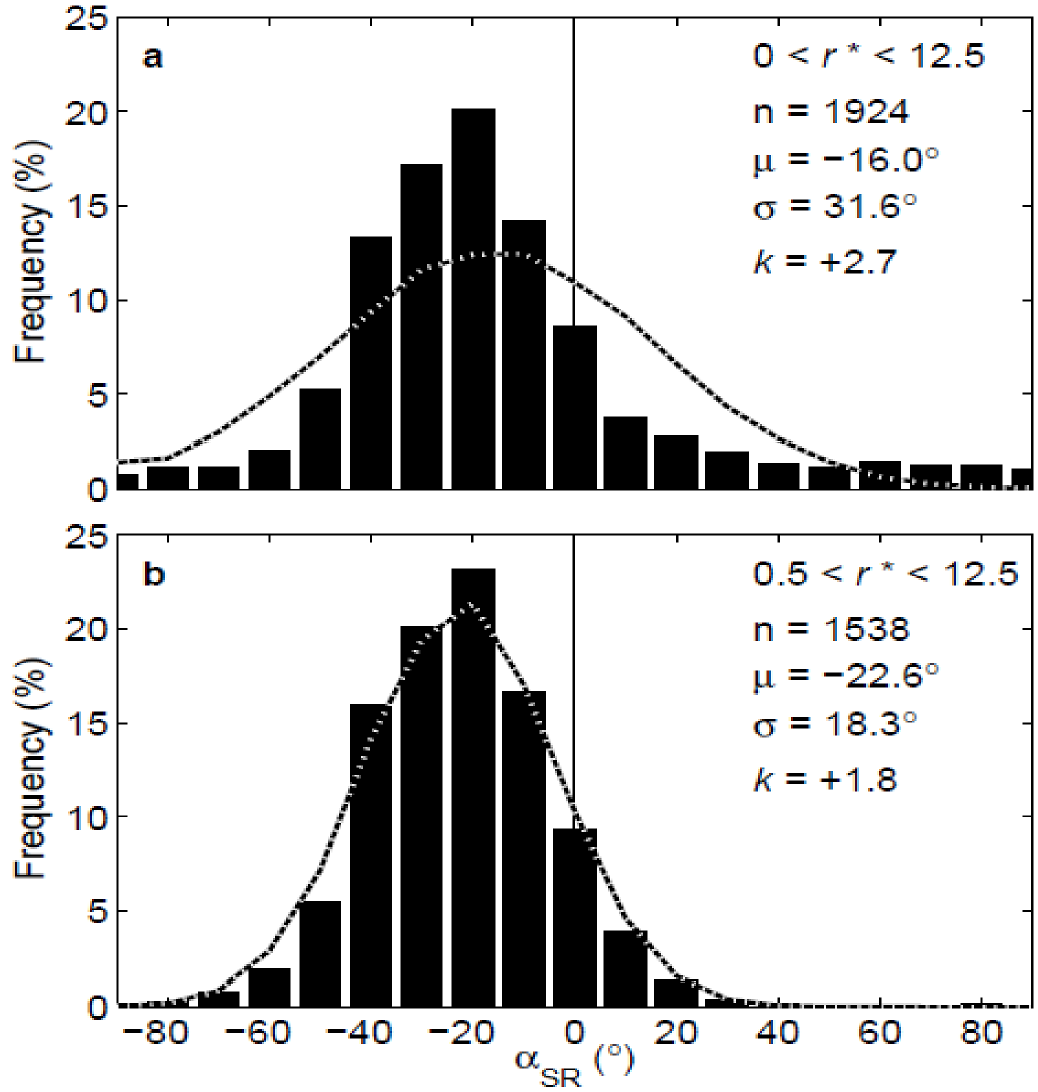


Median Vmax = 56.7 m/s
Median Rmax = 31.8 km
Median Vs = 5.5 m/s

Data distribution

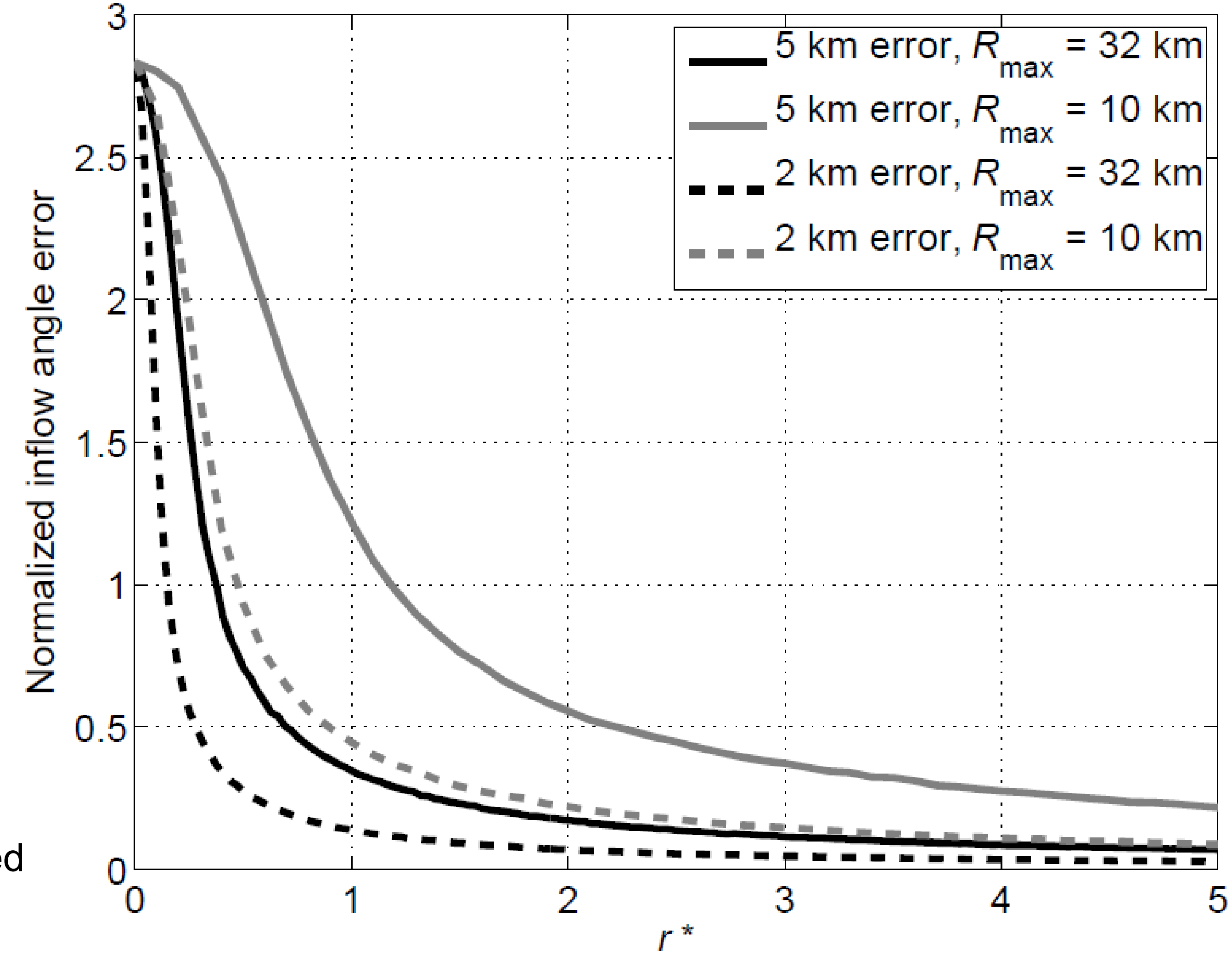


Inflow angle distribution and quality control



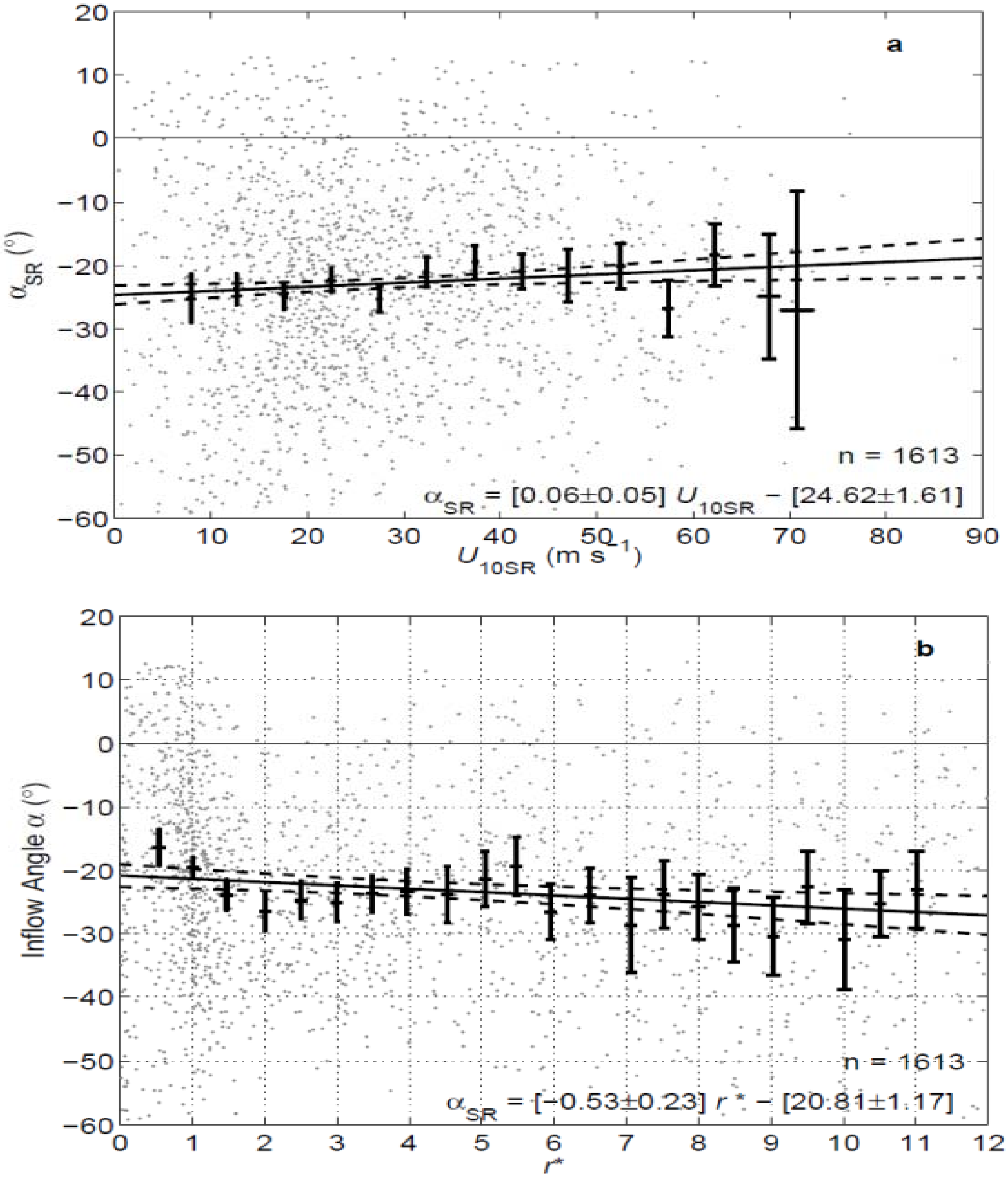
Impact of storm center position on the uncertainty of inflow angle calculation

Monte Carlo simulation of 1000 realizations



Error is Normalized by std(α)

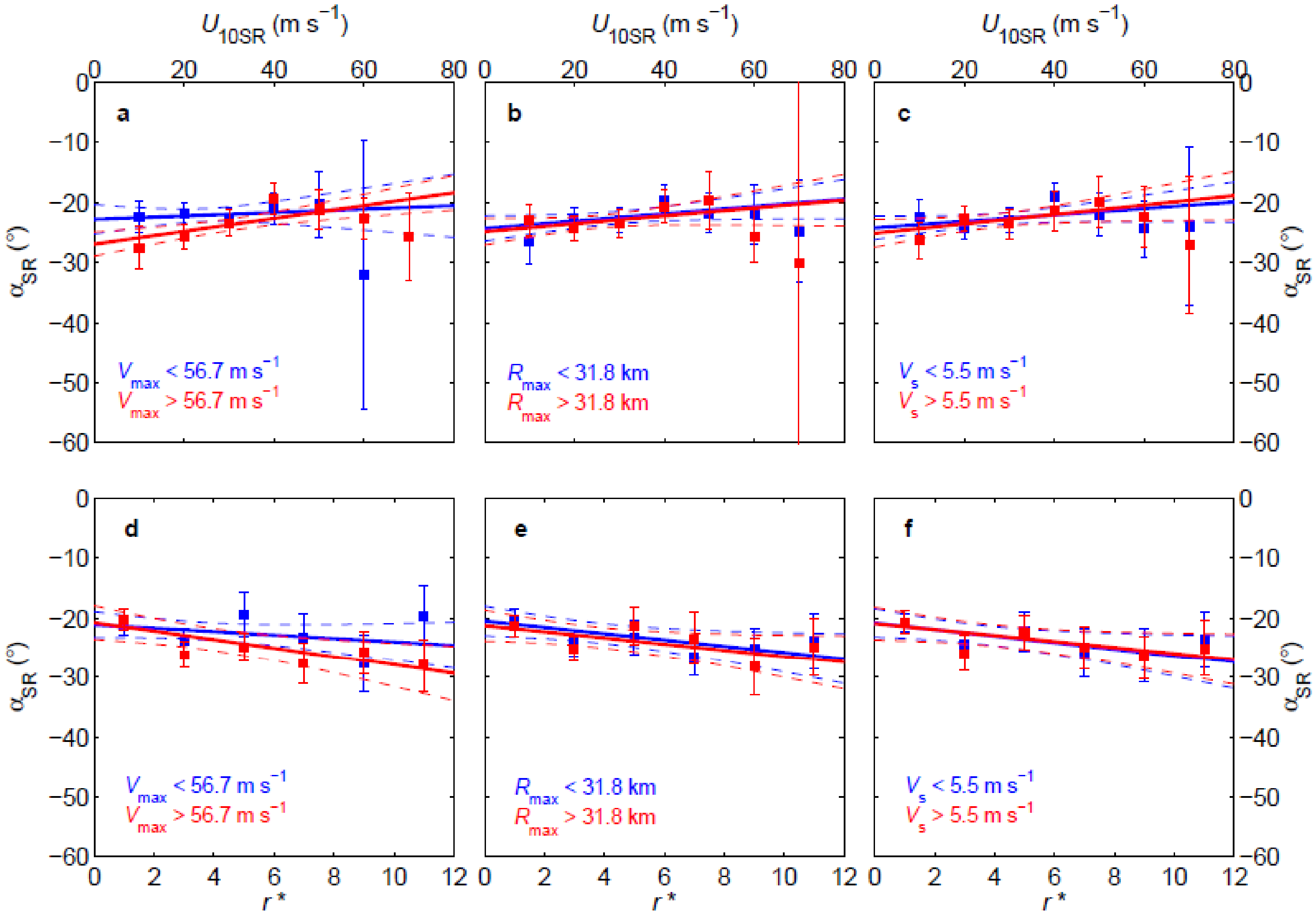
Inflow angle vs 10 m wind speed and distance



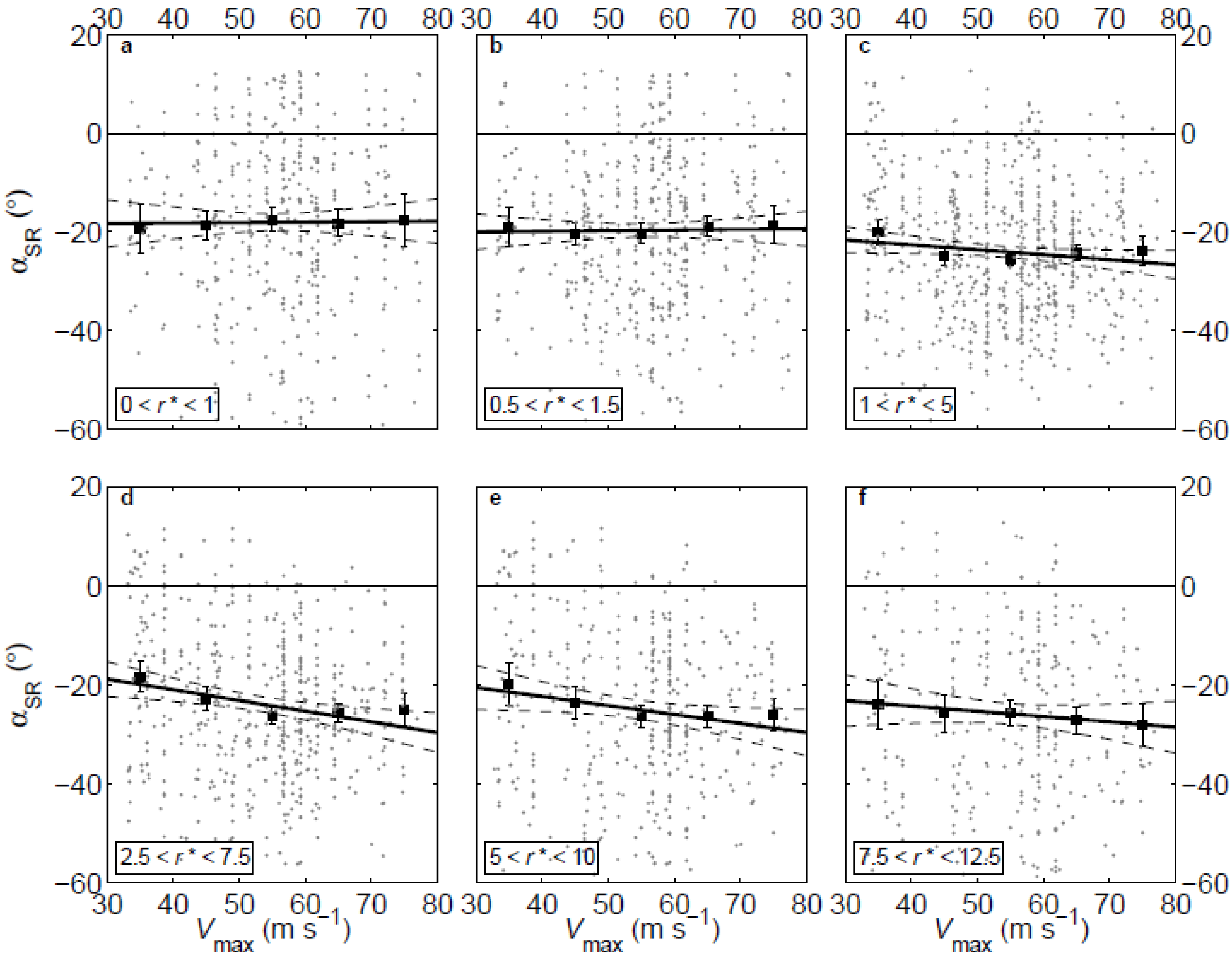
Little dependence of axisymmetric inflow angle on local surface wind speed;

A weak but statistically-significant dependence on the radial distance.

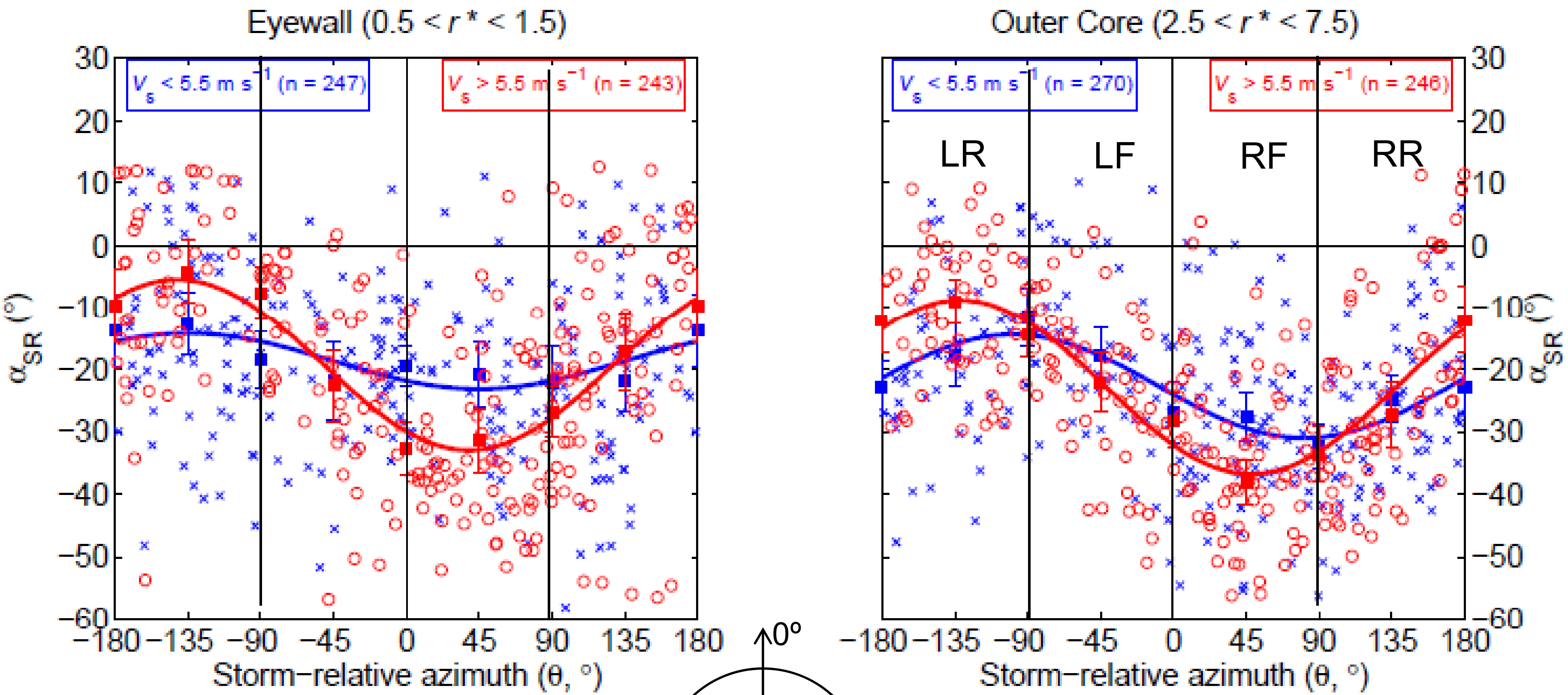
Axisymmetric Inflow angle vs storm intensity, size and motion speed

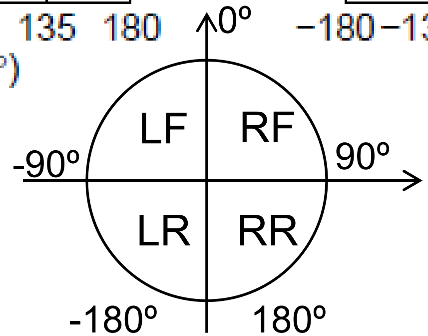


Inflow angle vs storm intensity by distance



Inflow angle asymmetry and storm motion speed

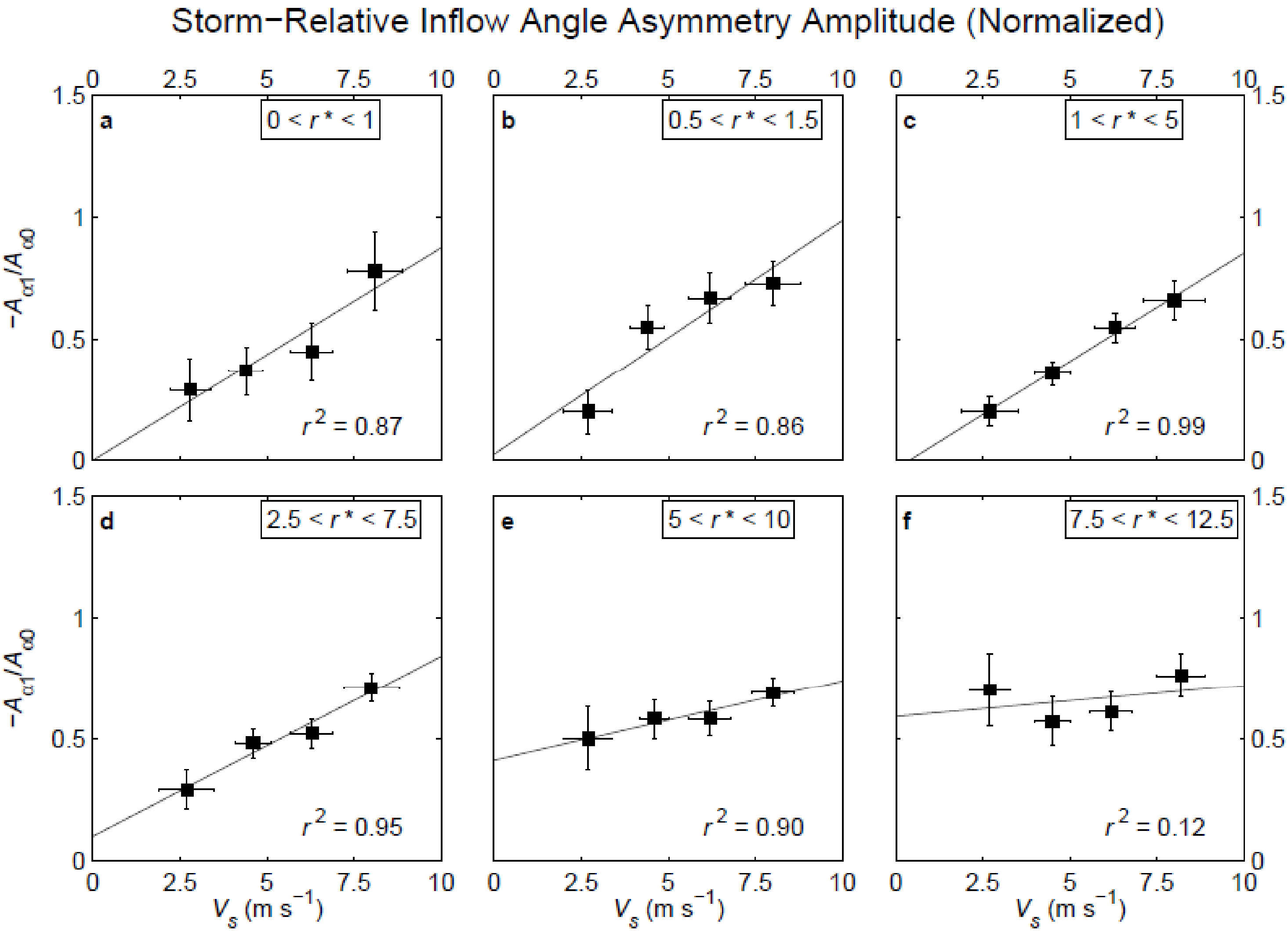




0º is pointed to the storm motion direction

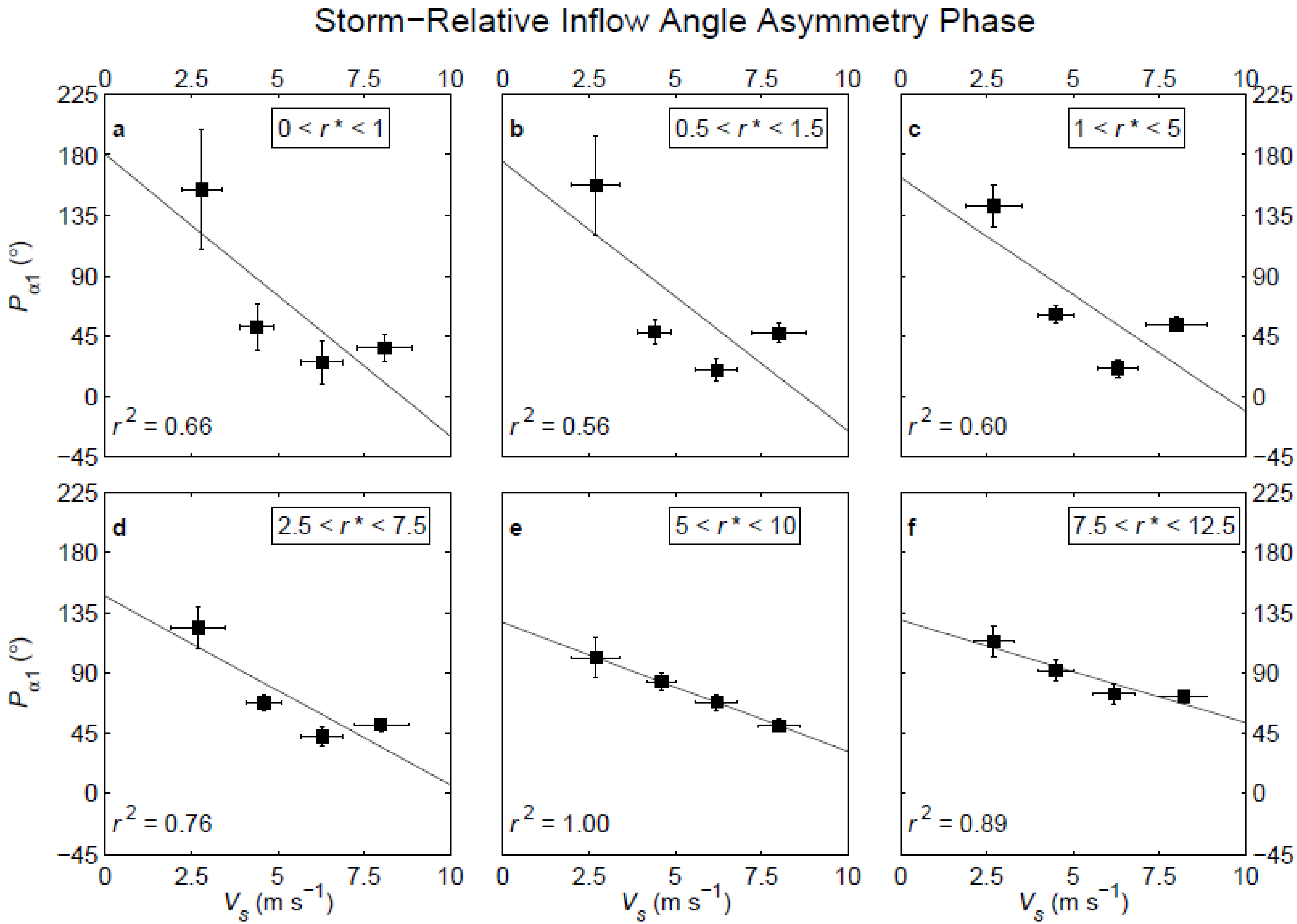
Inflow angle asymmetry - normalized amplitude

$$\alpha\_asy = A_{\alpha 1}\cos[\theta - P_{\alpha 1}]$$



Inflow angle asymmetry - phase

$$\alpha\_asy = A_{\alpha 1}\cos[\,\theta - P_{\alpha 1}]$$



Parametric inflow angle model

$$\alpha_{SR}(r^*,\theta,V_{\max},V_s)=A_{\alpha 0}(r^*,V_{\max})+A_{\alpha 1}(r^*,V_s)\cos[\theta-P_{\alpha 1}(r^*,V_s)]$$
$$+\varepsilon$$

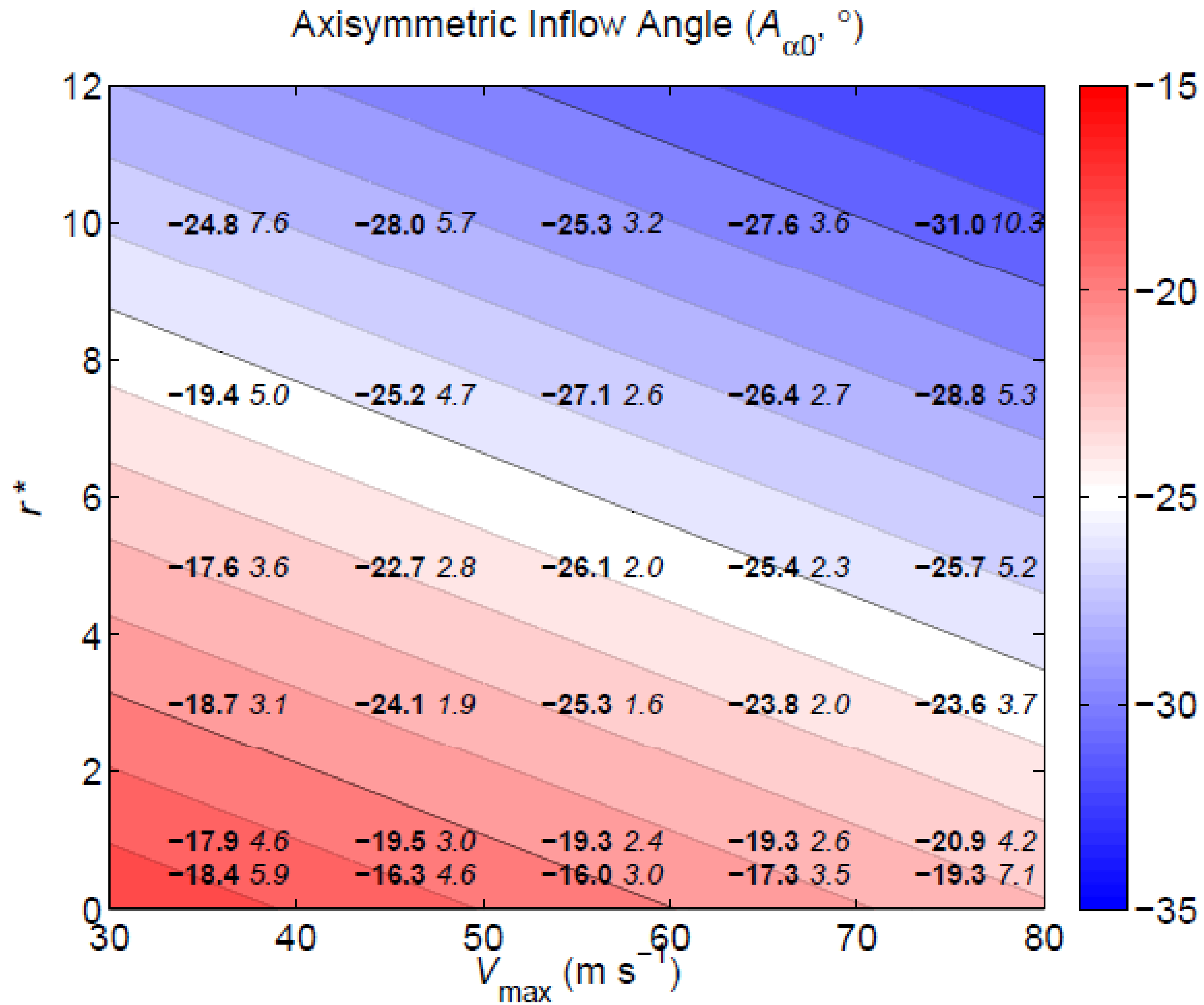
$$A_{\alpha 0}=a_{A0}r^*+b_{A0}V_{\max}+c_{A0}$$

$$-\frac{A_{\alpha 1}}{A_{\alpha 0}}=a_{A1}r^*+b_{A1}V_s+c_{A1}$$

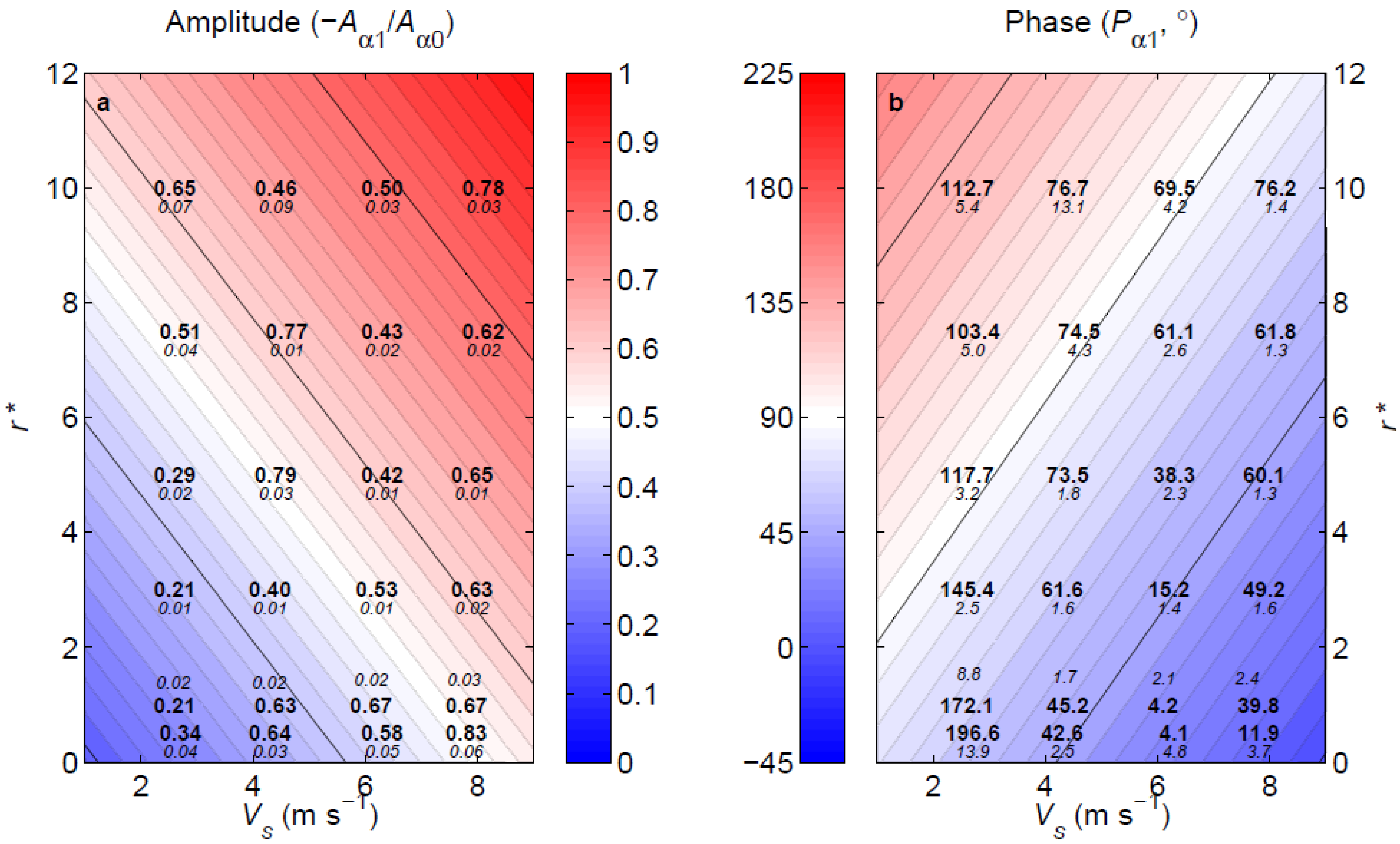
$$P_{\alpha 1}=a_{P1}r^*+b_{P1}V_s+c_{P1}$$

Coefficients are determined through multiple least square regression.

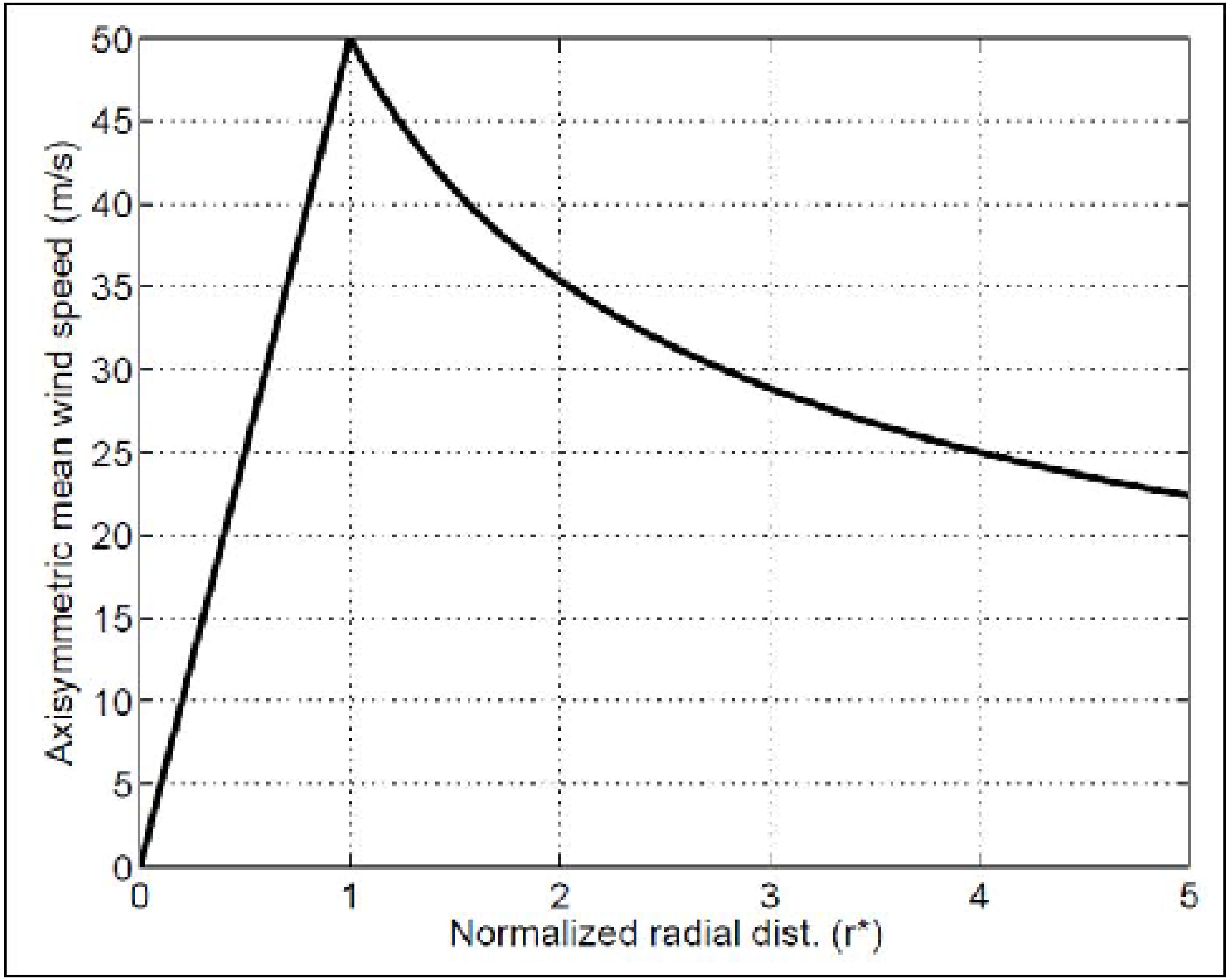
Axisymmetric component



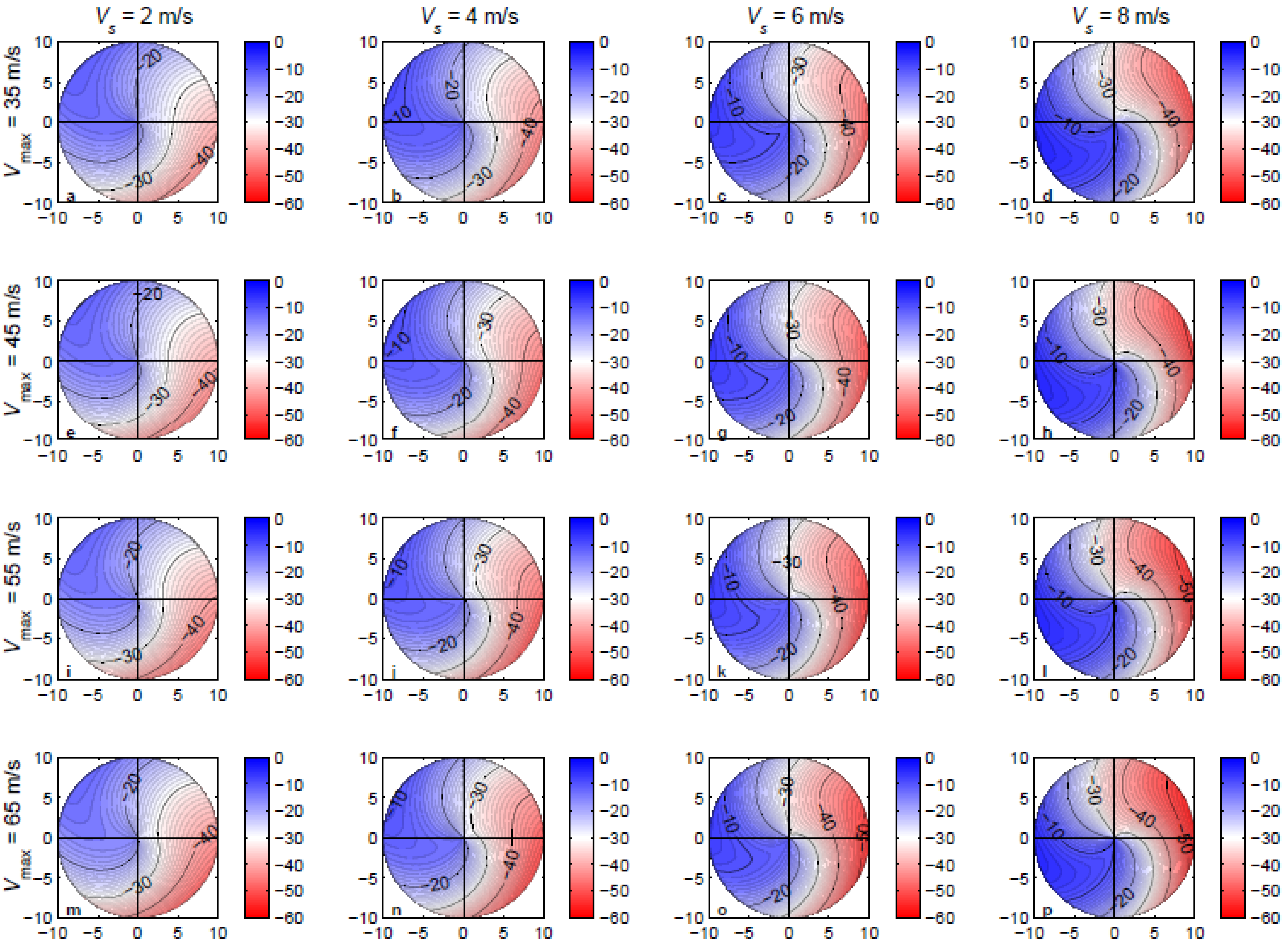
Asymmetric component



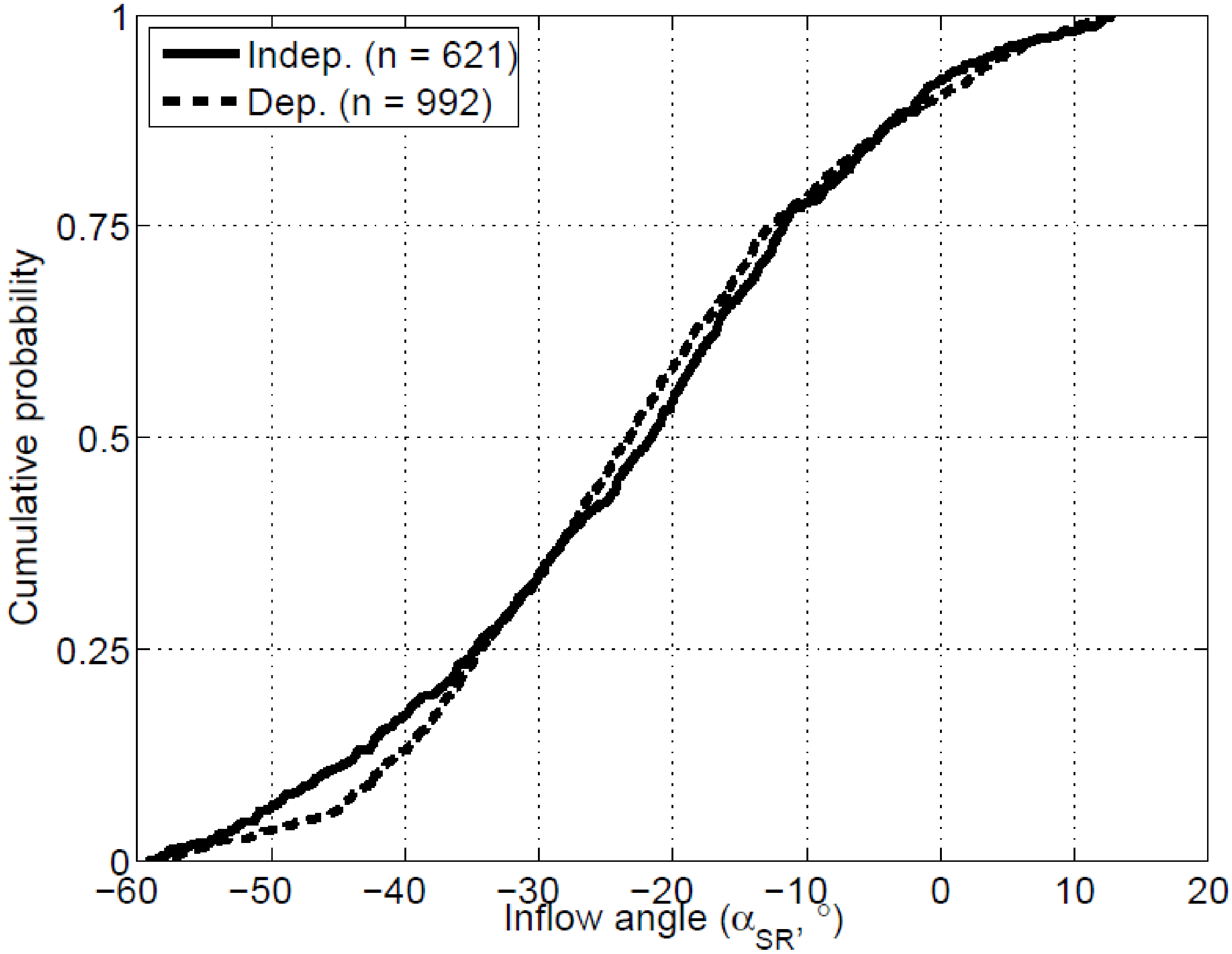
Given a radial wind profile



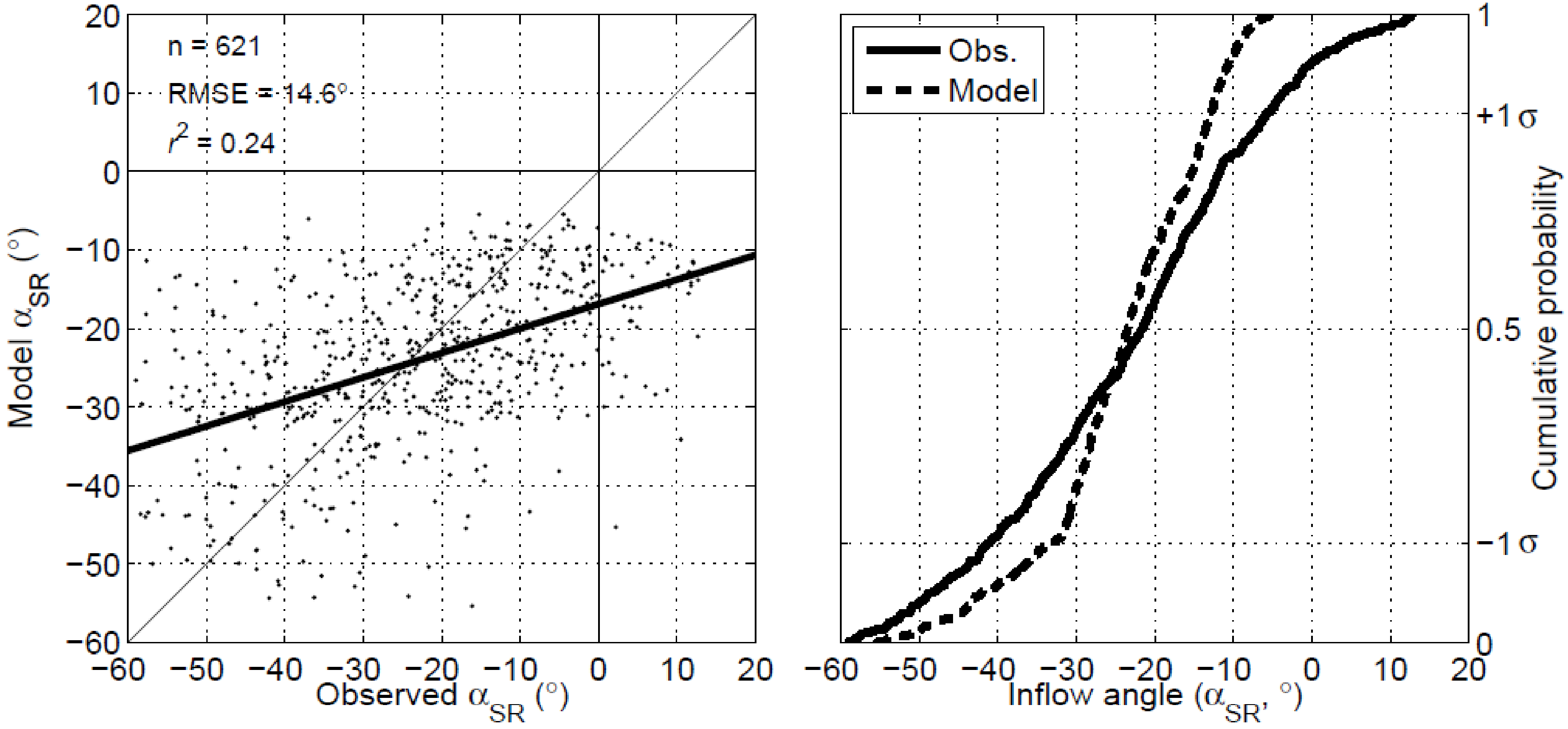
Model output of the Inflow angle



Two random samples for model development and evaluation



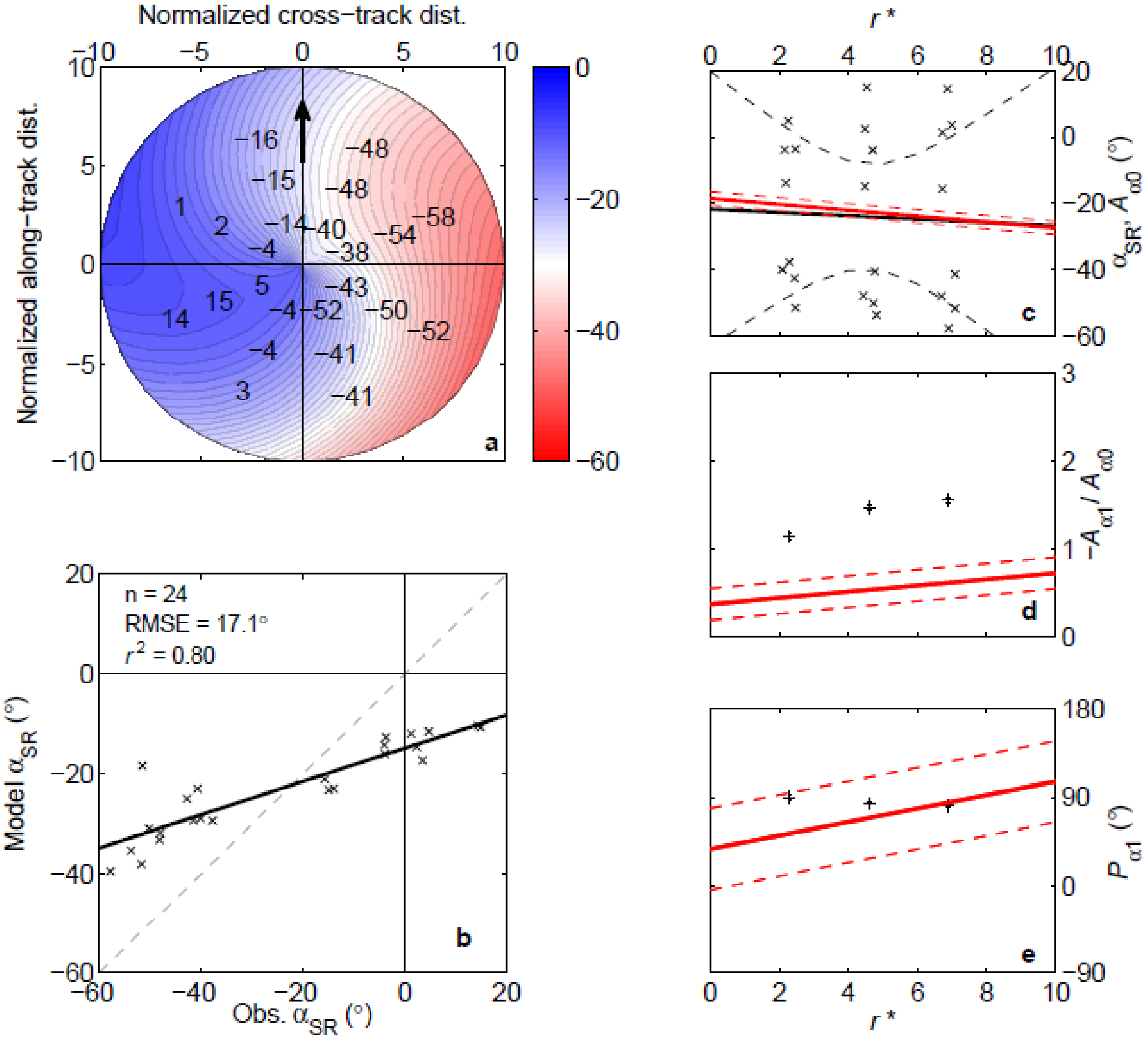
Model validation



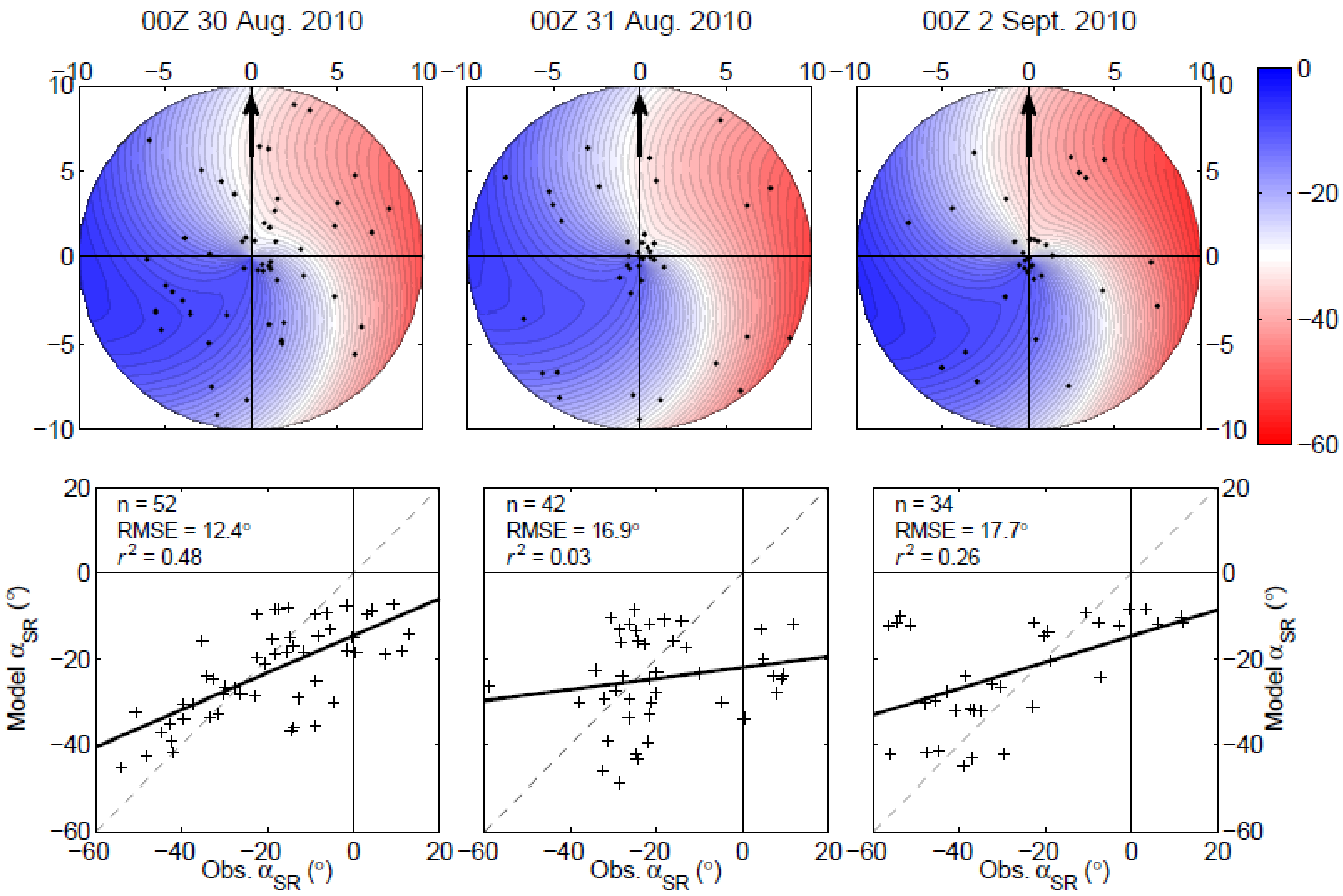
24% variance can be explained by the storm motion induced asymmetry.

Possible sources of errors: 1) storm center position; 2) randomness of the turbulent nature.

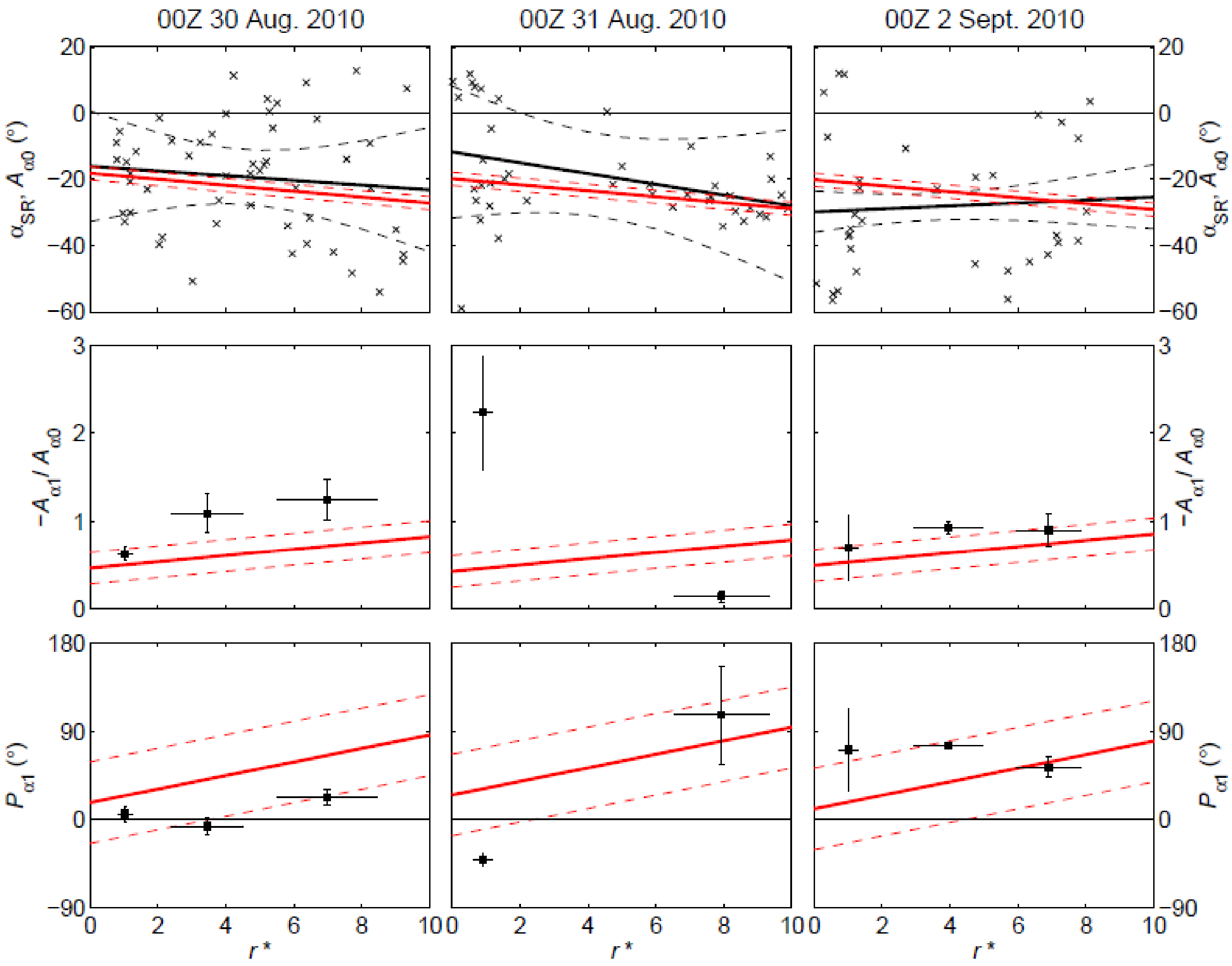
Model Verification using Hurricane Frederic data from Powell (1982)



Model verification using data from Hurricane Earl (2010)

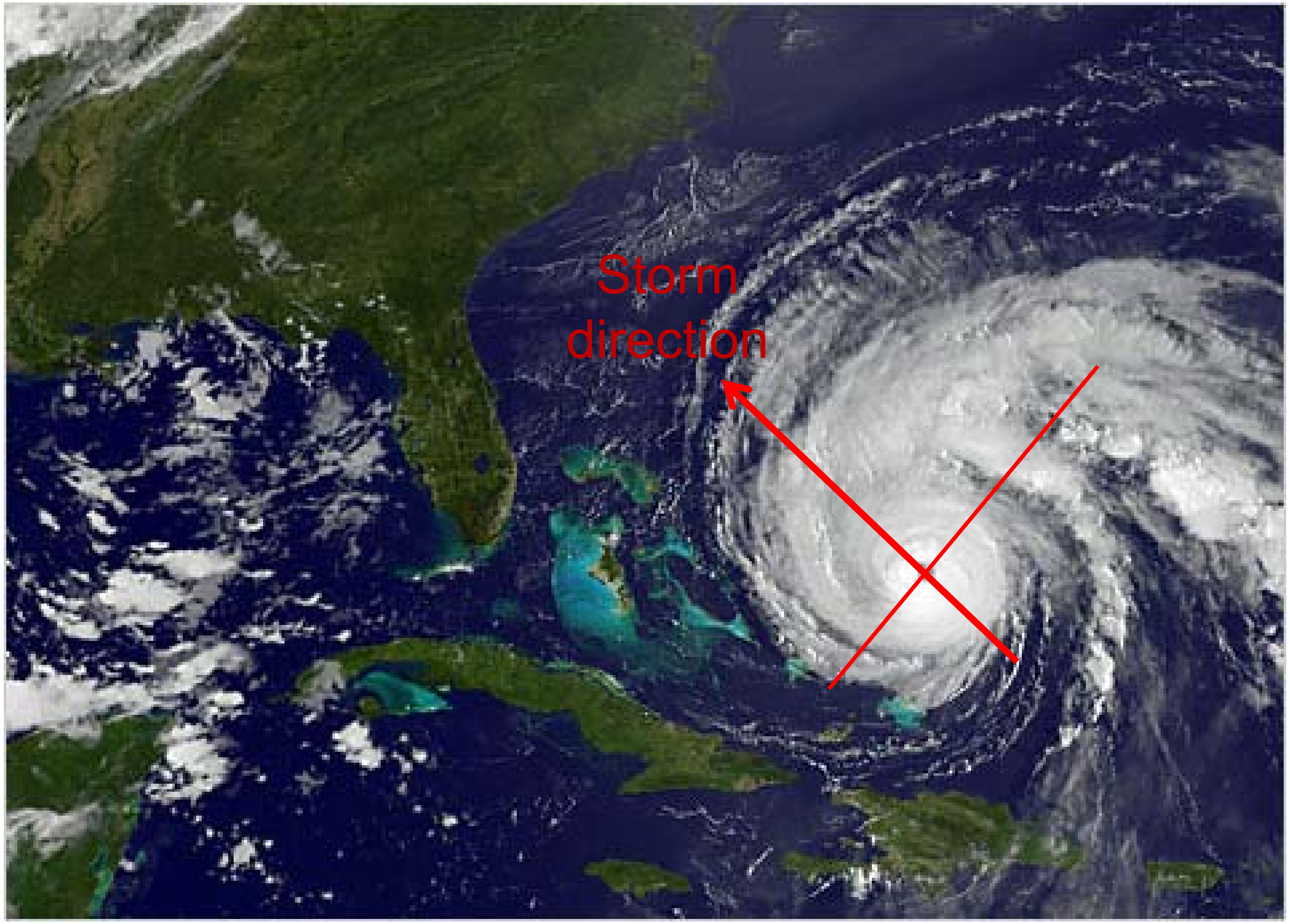


Model verification using data from Hurricane Earl (2010)



Hurricane Earl (2010/08/29)

storm motion speed ~ 7m/s

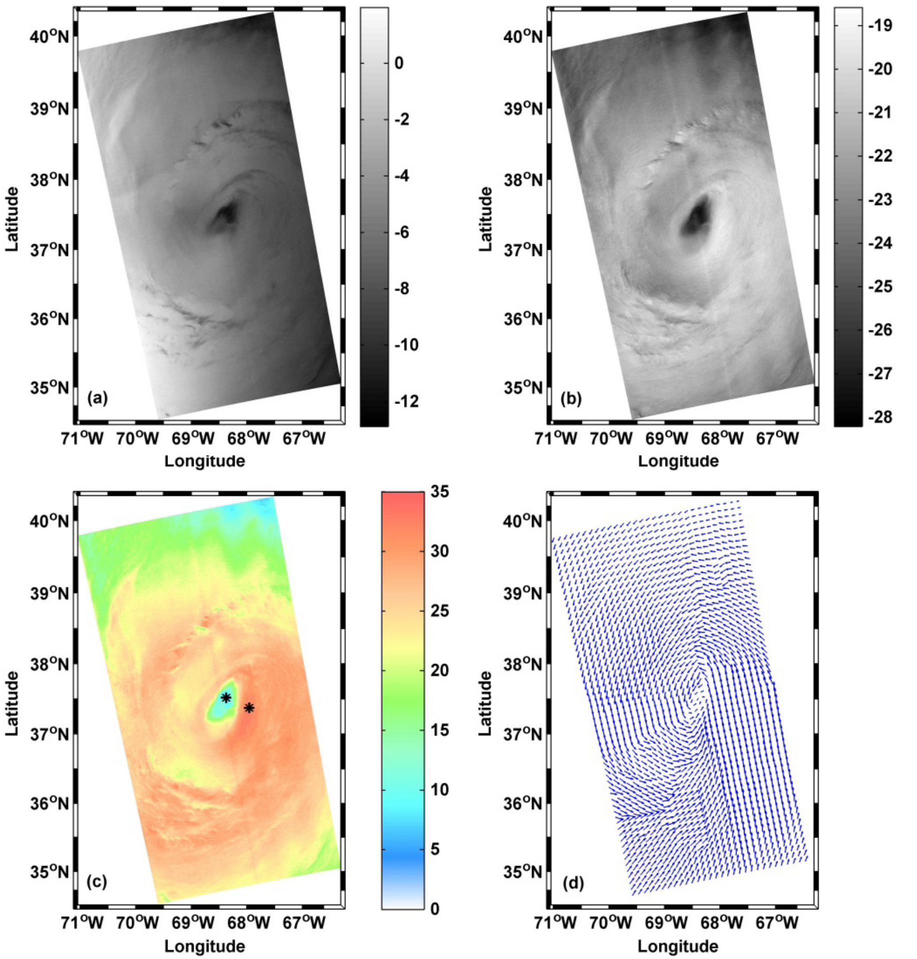


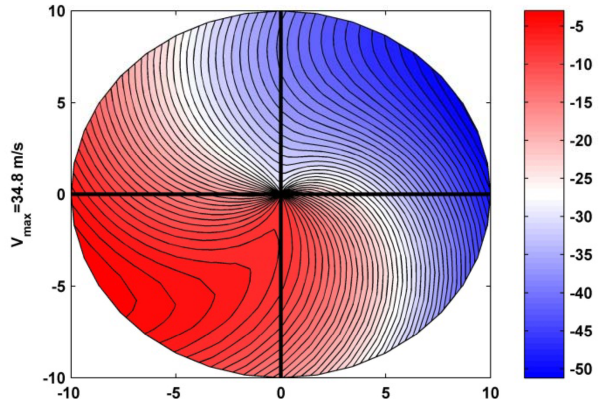
Possible applications of the inflow angle model

- Remote sensing: SFMR, QuickSCAT/SeaWinds, SAR
- H*WIND
- Model evaluation
- Model initialization
- Forcing ocean, wave and storm surge models that requires parametric wind model

Improve SAR wind retrieval with the inflow angle model

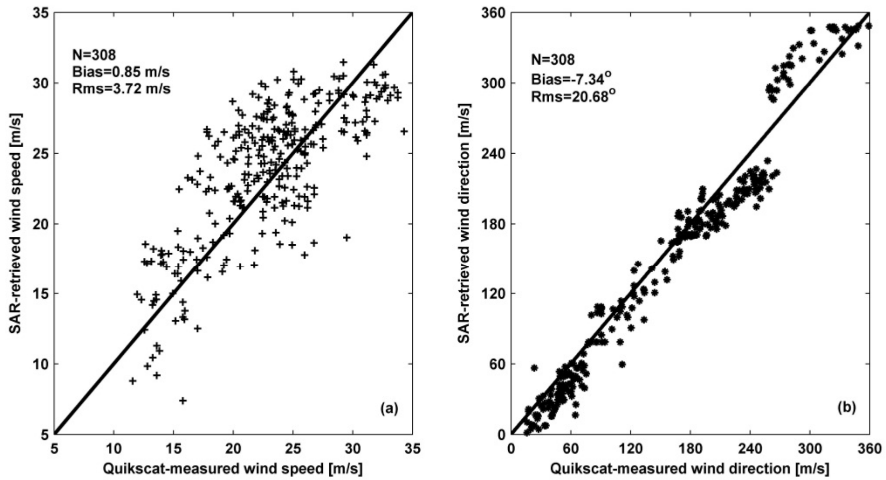
RADARSAT-2 *dual*-polarization SAR image over Hurricane Bill on August 22, 2009





Vs=9.4 m/s

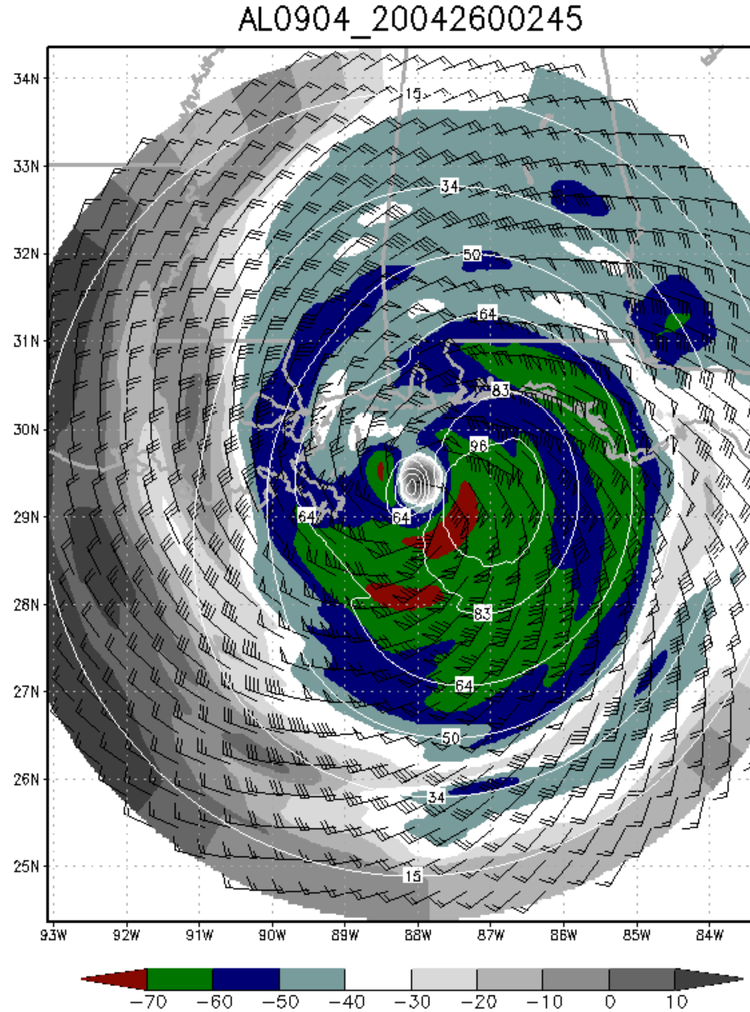
Vmax=35m/s



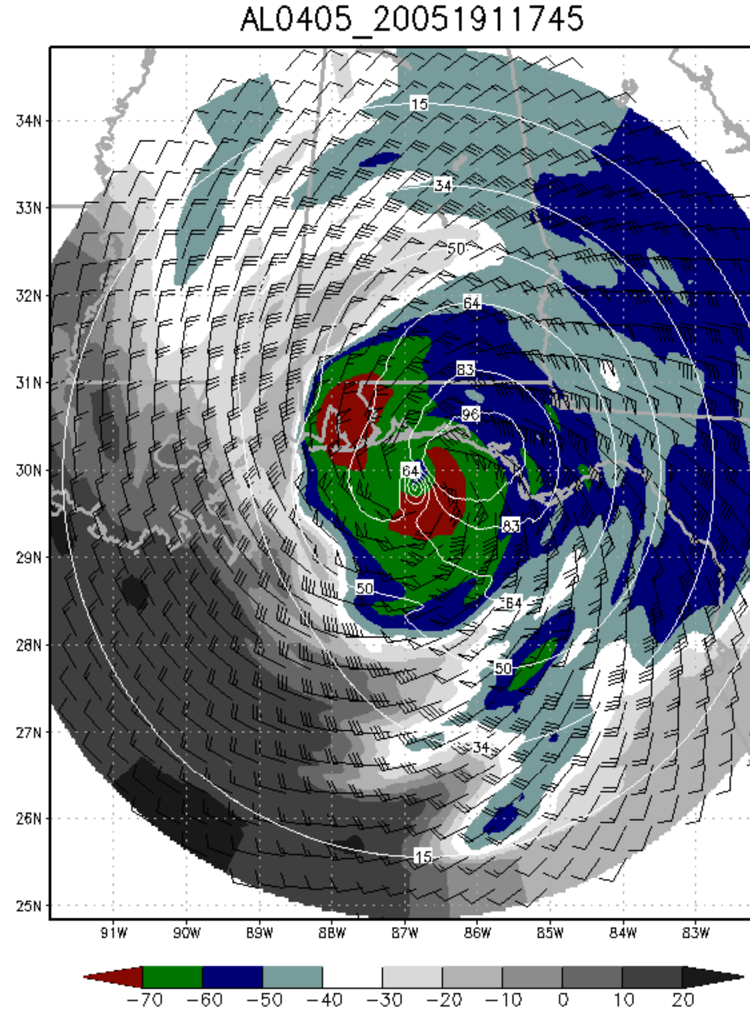
B. Zhang et al. 2013

Application: Infrared-based tropical cyclone surface winds

Hurricane Ivan (2004)



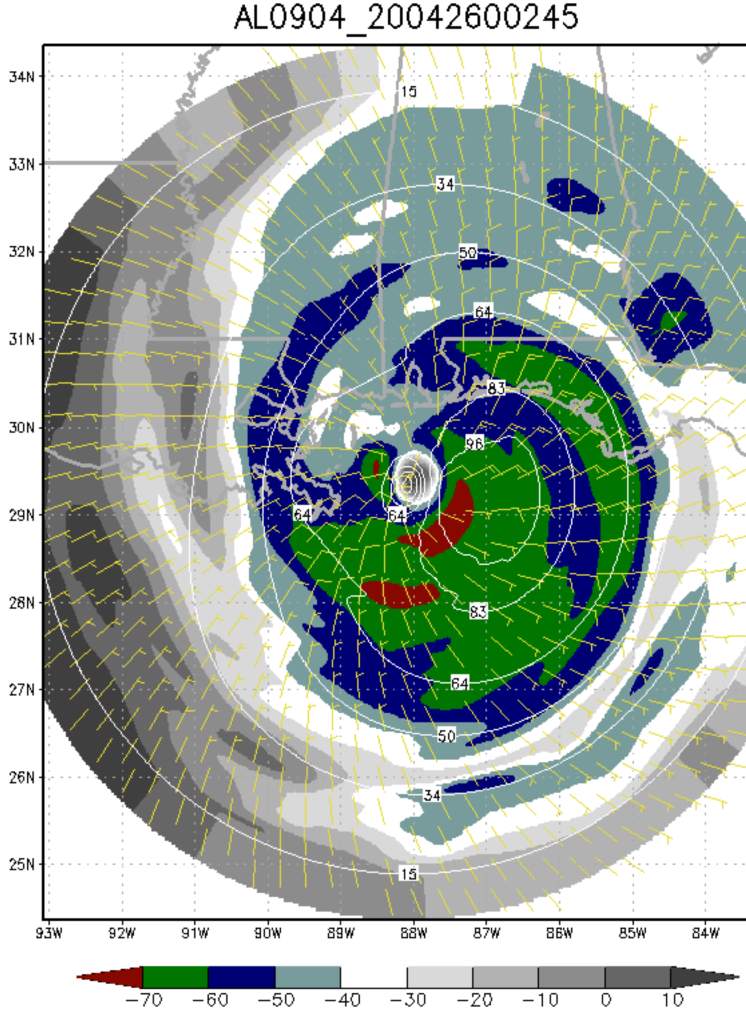
Hurricane Dennis (2005)



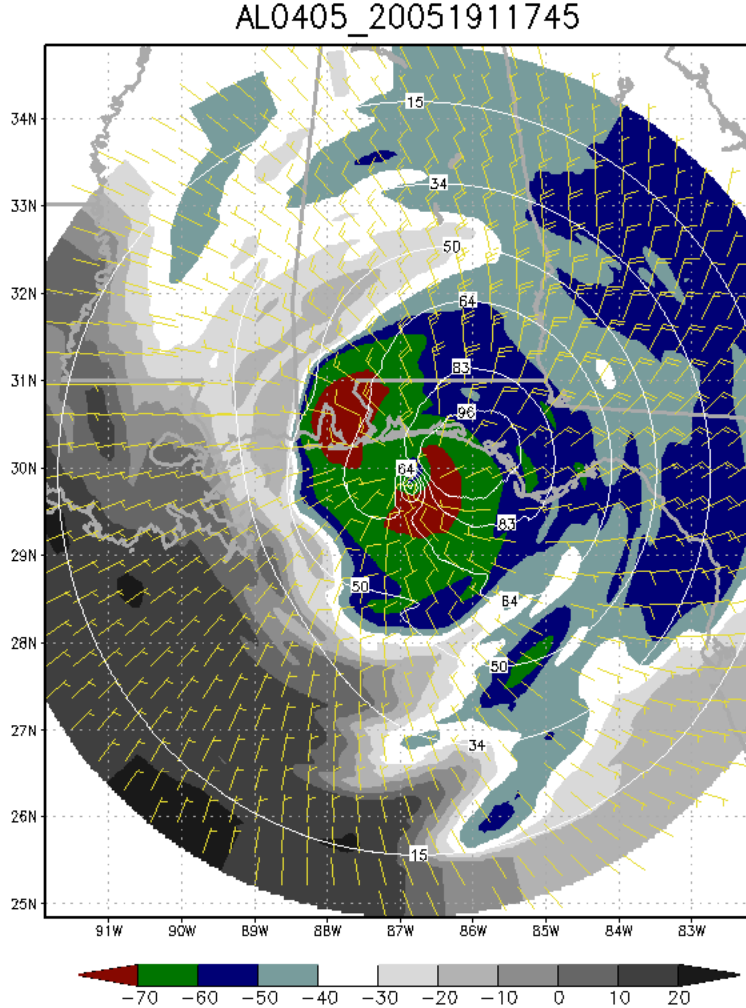
Credit: J. Knaff, NOAA Center for Satellite Applications and Research

Application: Infrared-based tropical cyclone surface winds

Hurricane Ivan (2004)

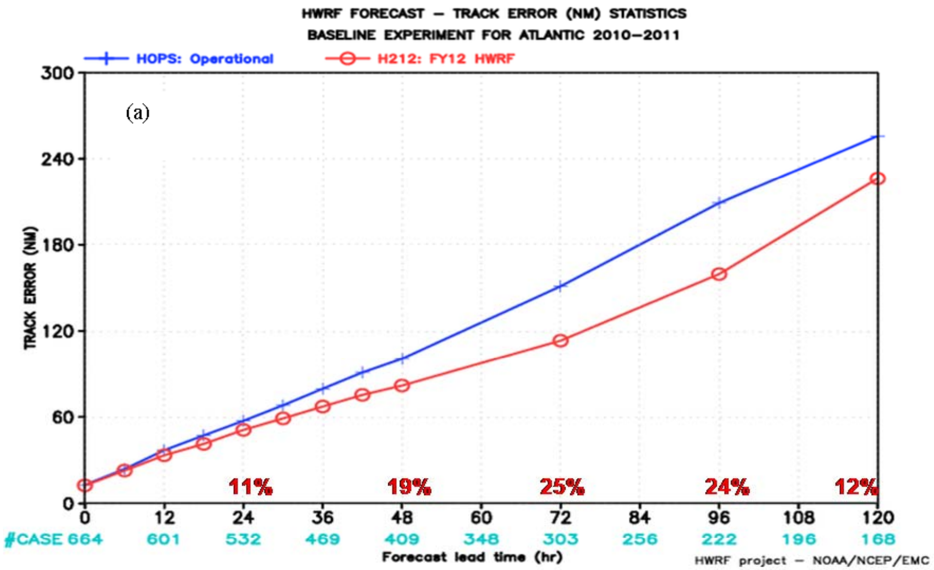


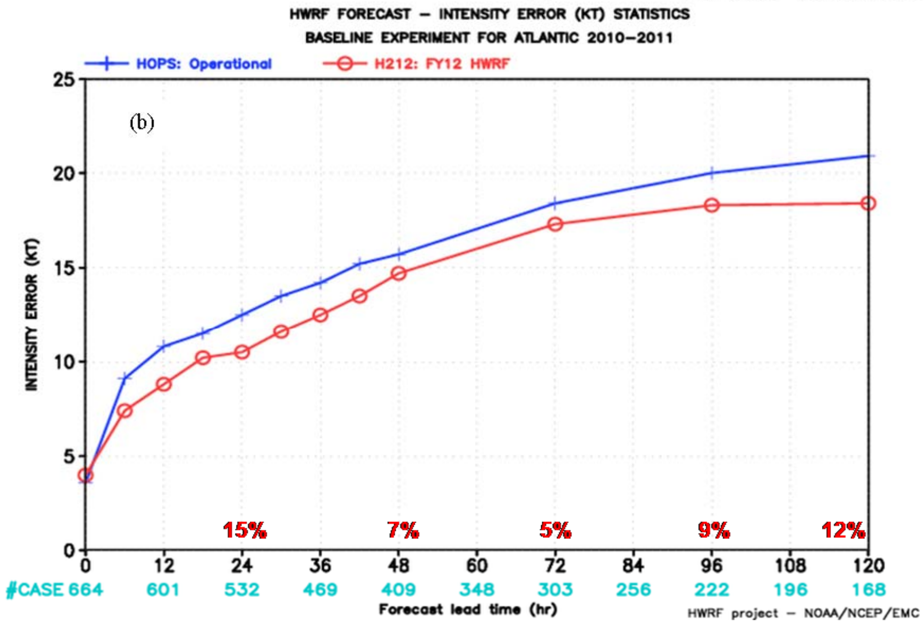
Hurricane Dennis (2005)



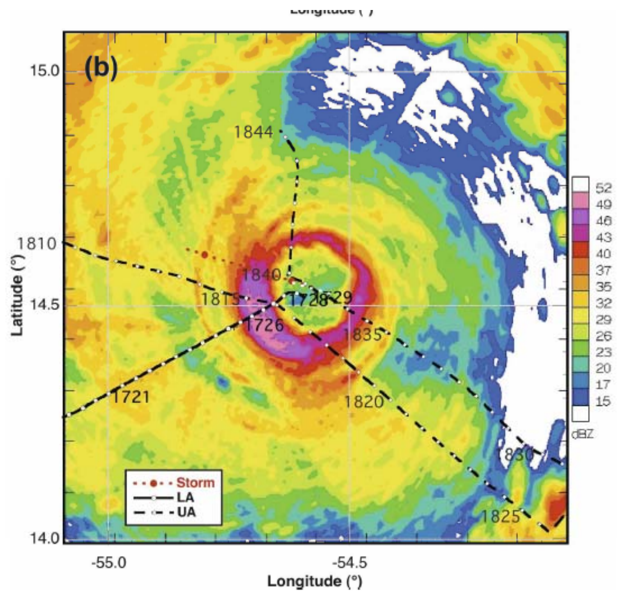
Credit: J. Knaff, NOAA Center for Satellite Applications and Research

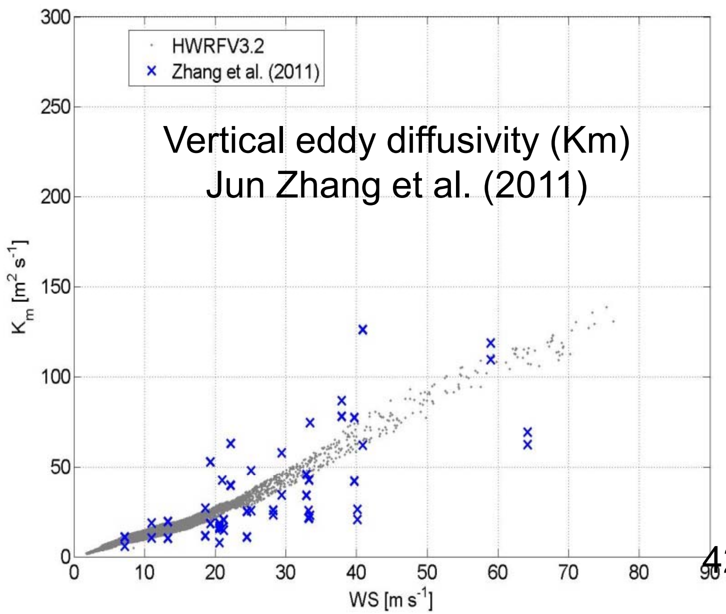
Observation-based physics upgrade leads to improvement in intensity forecast





Hurricane Hugo (1989) flight
Marks et al. (2008); J. Zhang et al. (2011)



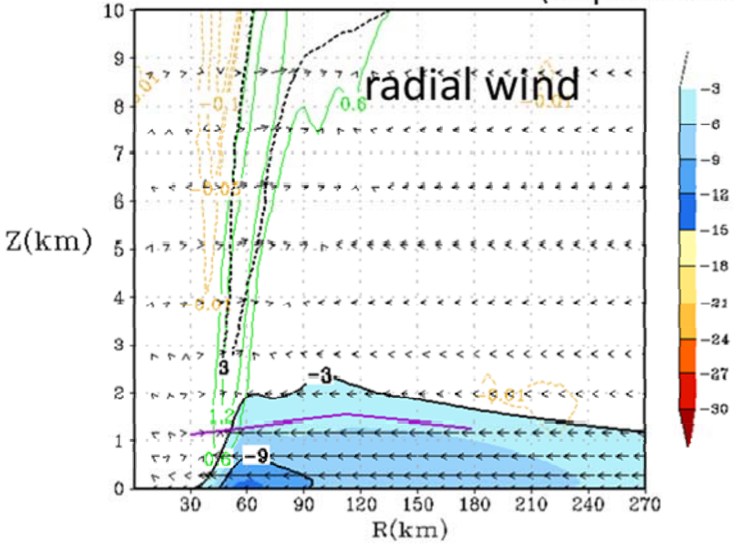


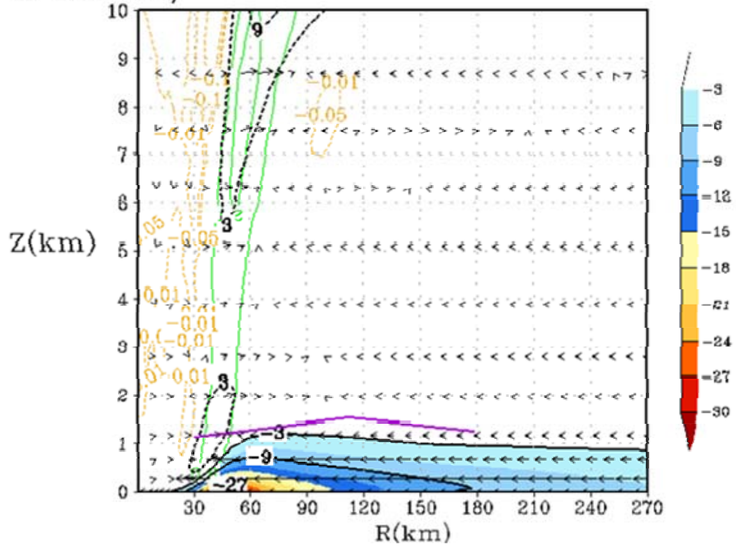
Model evaluation after physics upgrade in 2012-version operational HWRF

Original Km in HWRF

HWRF with modification of Km based on Obs

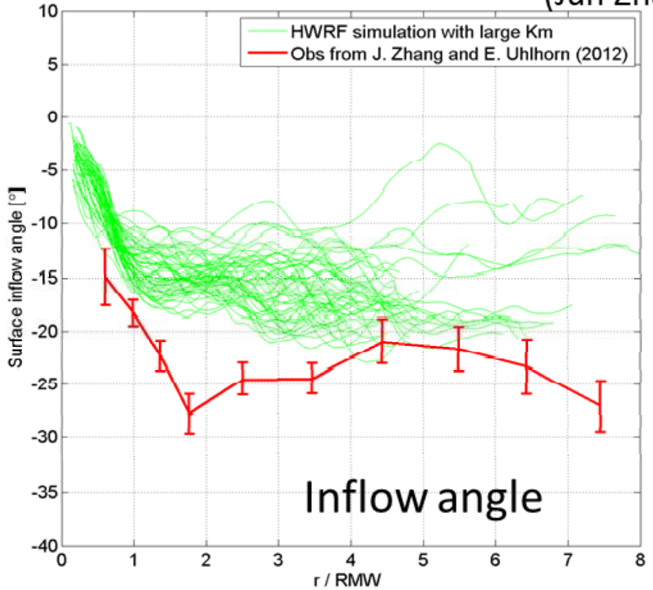
(Gopalakrishnan et al. 2012)

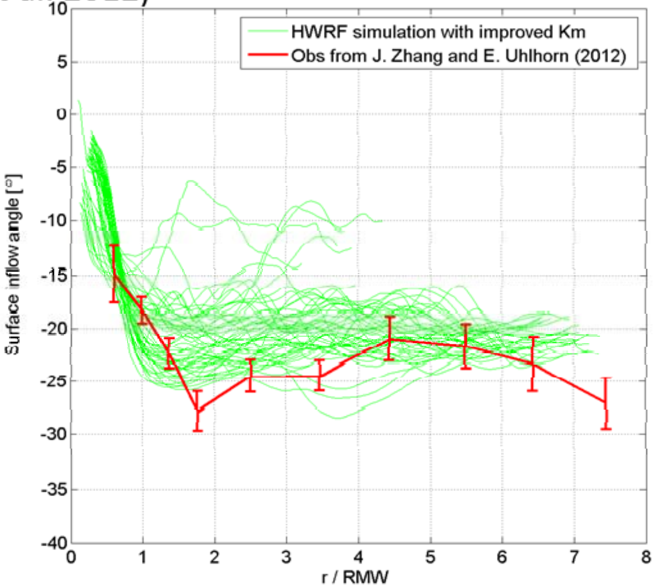




The purple line is the inflow layer depth from dropsonde observations reported by J. Zhang et al. (2011)

(Jun Zhang et al. 2012)





The red line is the axisymmetric inflow angle from dropsonde observations reported by J. Zhang and E. Uhlhorn (2012)

Inflow angle used in SLOSH and some storm surge models

Phadke et al. (2003)

$$\beta = 10^\circ\left(1 + \frac{r}{R_{\mathrm{mw}}}\right) \text{ for } 0 \le r < R_{\mathrm{mw}}$$

$$\beta = 20^\circ + 25^\circ\left(\frac{r}{R_{\mathrm{mw}}} - 1\right) \text{ for } R_{\mathrm{mw}} \le r < 1.2R_{\mathrm{mw}}$$

$$\beta = 25^\circ \text{ for } \ge 1.2\ R_{\mathrm{mw}}$$

The Zhang and Uhlhorn (2012) model can provide the asymmetry of the inflow angle

Summary

1. Data from over 1800 dropsondes were analyzed to study the distribution and variability of surface inflow angle in hurricanes;

2. The mean inflow angle is found to be –22.6 $\pm$ 2.2° (95% confidence).

3. Composite analyses show little dependence of axisymmetric inflow angle on local surface wind speed, and a weak but statistically-significant dependence on the radial distance from the storm center and storm intensity.

4. Significant inflow angle asymmetries are found to depend on storm motion speed.

5. A parametric model of low-wavenumber inflow angle variability as a function of radius, azimuth, storm intensity and motion speed, is developed.

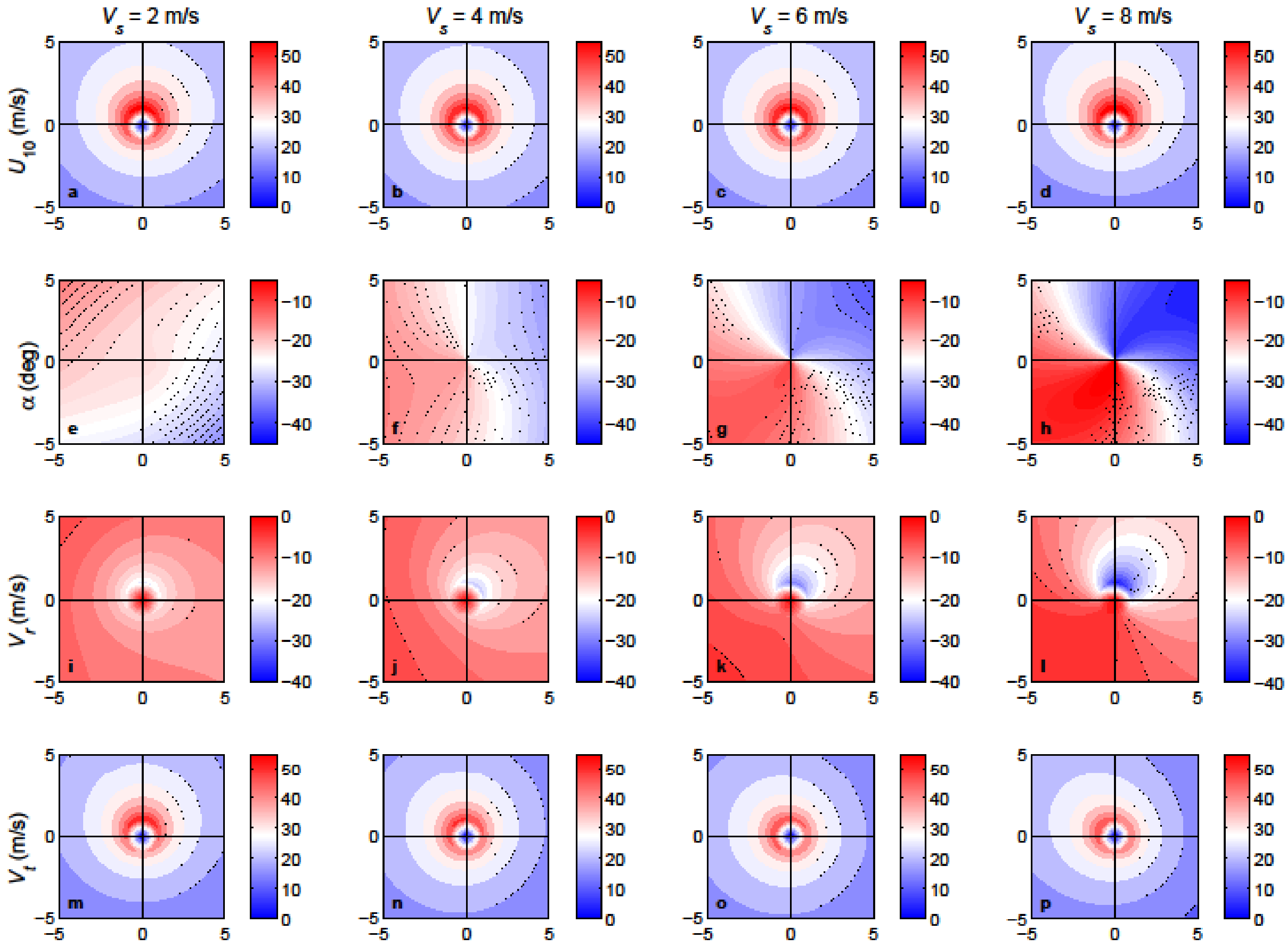

End
Thanks!
Questions?

Does hurricane intensity depend on inflow angle?

Table 2. Moderate Model Hurricane.

r km	v_ϑ m/sec	v_r m/sec	β degrees	$v_r r \cdot 10^{-9}$ c.g.s.	div. 10^5 cm^{-1}	w cm/sec	v m/sec	τ_0 $dynes/cm^2$	p_s mb
800	3.4	1.2	20	9.6	1	− 1.1	3.6	0.18	1011.8
700	6.9	2.5	20	17.55	0.6	− 0.66	7.3	0.71	1011.7
600	9.9	3.6	20	21.6	0.2	− 0.22	10.5	1.65	1011.5
500	12.4	4.5	20	22.5	− 0.1	+ 0.11	13.2	2.61	1011.2
400	15.0	5.5	20	22.0	− 0.65	+ 0.72	16	3.84	1010.5
300	18.1	6.6	20	19.8	− 1.1	+ 1.2	19.2	5.53	1009.5
200	23.3	8.5	20	17.0	− 2.3	+ 2.5	24.8	9.23	1007.2
100	37.2	13.5	20	13.5	−29.6	+32.6	39.6	23.5	997.7
90	40.0	11.9	17.3	10.7	−25.3	+27.9	42.0	26.5	996.0
80	42.7	10.7	14.6	8.6	−26.5	+29.7	44.2	29.3	993.8
70	46.0	9.4	11.8	6.6	−28.4	+31.3	47.2	33.4	991.0
60	49.6	7.9	9.2	4.7	−30.7	+33.8	50.3	38.0	987.35
50	53.8	6.1	6.5	3.05	−33.6	+37.0	54.0	43.8	982.4
40	57.7	3.9	3.6	1.6	−33.4	+36.7	57.9	50.2	975.35
30	55.4	1.3	1.3	0.39	−25.5	+28.0	55.4	46.0	966.0
26	39.4	0.2	0.25	0.05			39.4	23.3	962.85

Malkus and Riehl (1960)



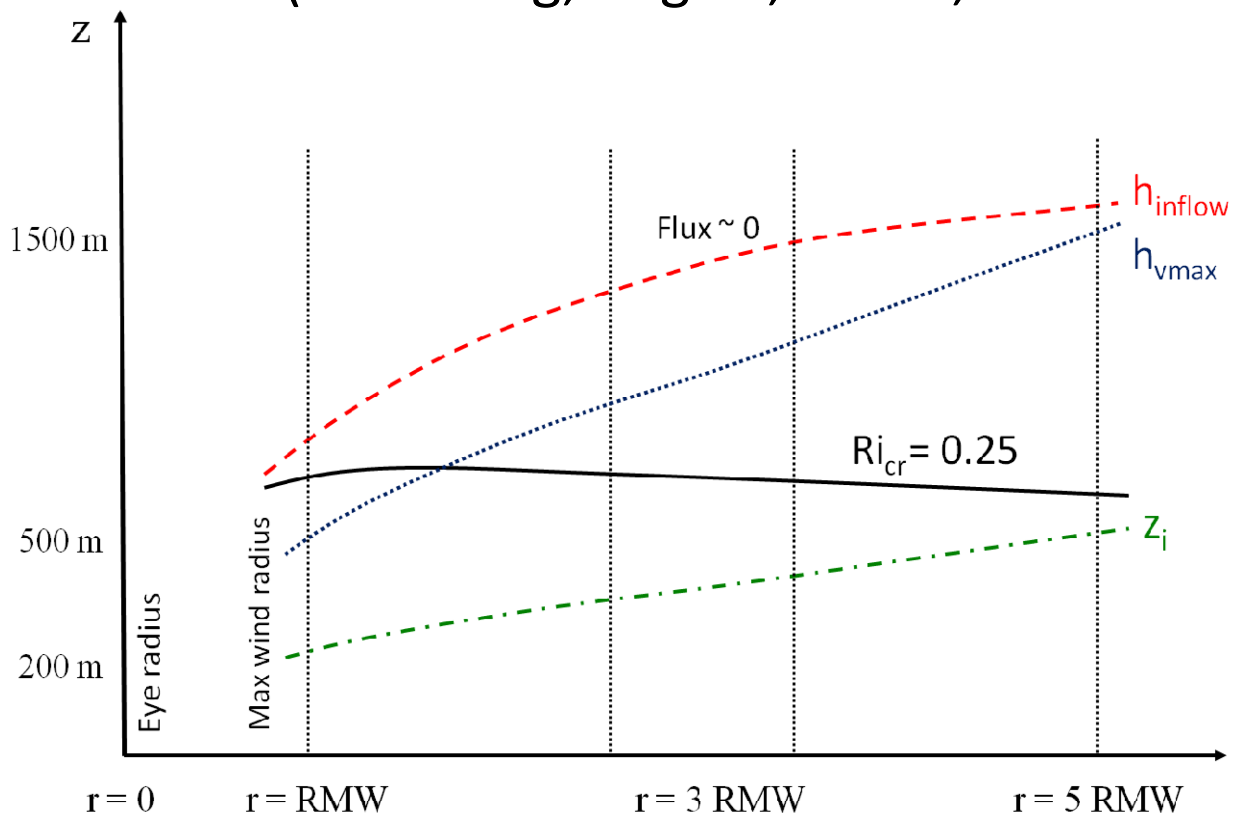
V_s = 2 m/s
V_s = 4 m/s
V_s = 6 m/s
V_s = 8 m/s
U_{10} (m/s)
α (deg)
V_r (m/s)
V_t (m/s)
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p

Theoretical explanation

- Shapiro (1983)
- Kepert (2001) : PBL height and Inertial stability

Defining PBL height in hurricanes

(Jun Zhang, Rogers, Nolan, and Marks, 2011 MWR)



h_{inflow} – inflow depth

h_{vmax}- height of the maximum tangential wind speed (Vt)

Z_i - mixed layer depth from the virtual potential temperature profile

Ri_{cr}-critical Richardson number defined as buoyancy to shear forcing

Flux – momentum flux from CBLAST-hurricane exp

Max Vt in storm rel coordinates occurs well within the inflow layer and within the frictional boundary layer associated with strong inflow that arises in part because of the departure from gradient wind balance.