Retrieving Surface Wind Directions from Neural-Net Wind Speed Retrievals in Tropical Cyclones

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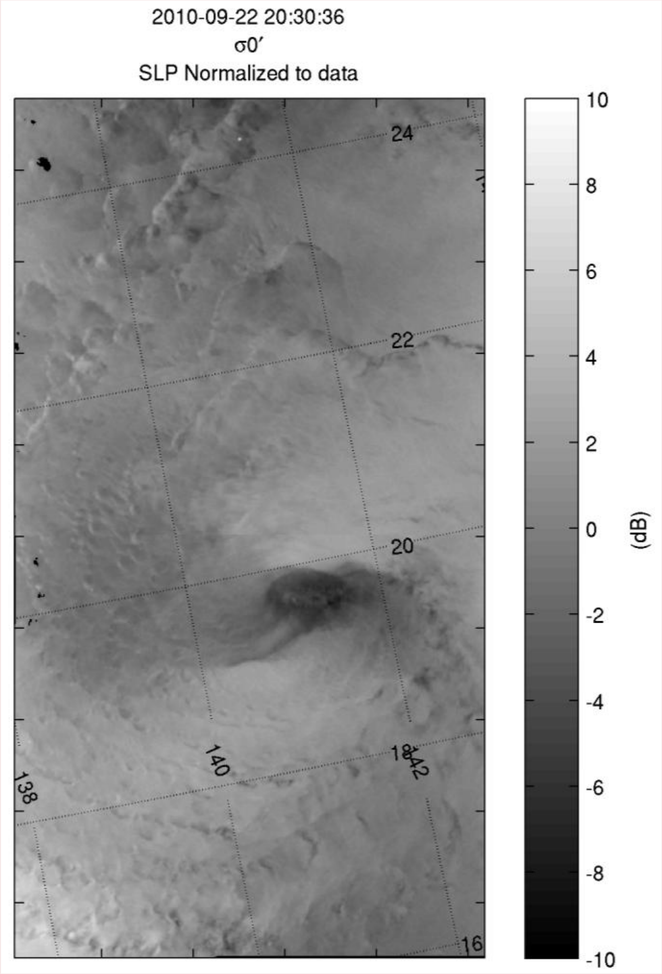
Based on SAR Tropical Cyclone (TC) Wind Retrievals (See Horstmann, 17:45)

- SAR: 1 km wind vector retrievals in TCs (Horstmann, Wackerman)
  - Wind directions from imprint of TC boundary layer (TCBL) roll vortices
  - Wind speeds from model functions (CMOD5N (co-pol), Cross-pol, X-band
  - ~ 5-6 m/s RMS at hurricane force (up to low Cat-3)
  - Directions ~ 20°RMS rel. drop sondes, QuikSCAT (no-rain flag)
  - Wind retrieval quality flags

Calculate Sea-Level Pressure (SLP) Patterns from SAR imagery



1. SAR σ_0

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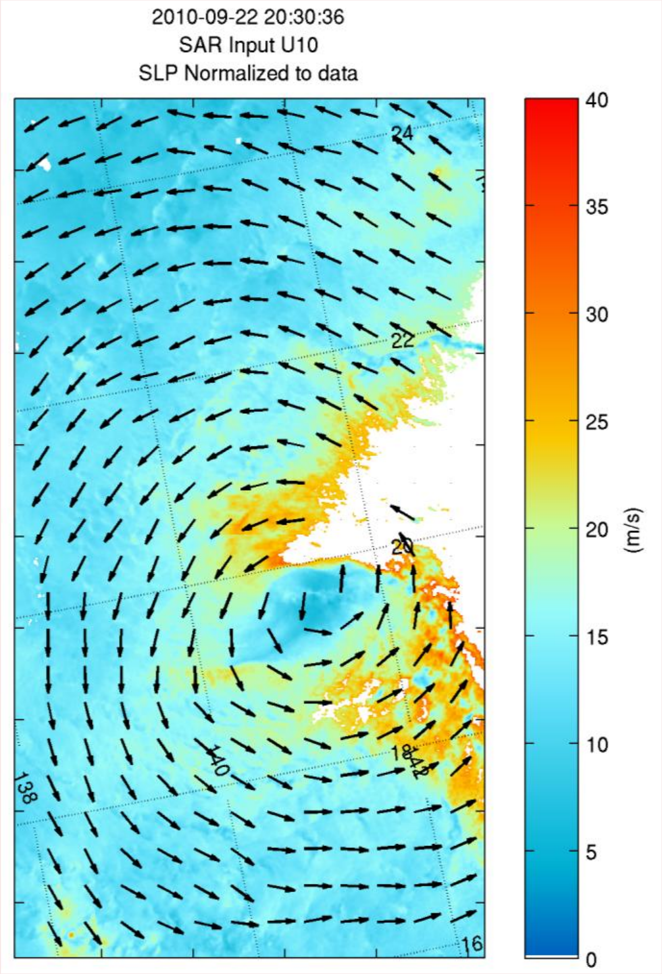

1. SAR σ_0
2. Standard U_{10} processing
   – Mask low confidence winds

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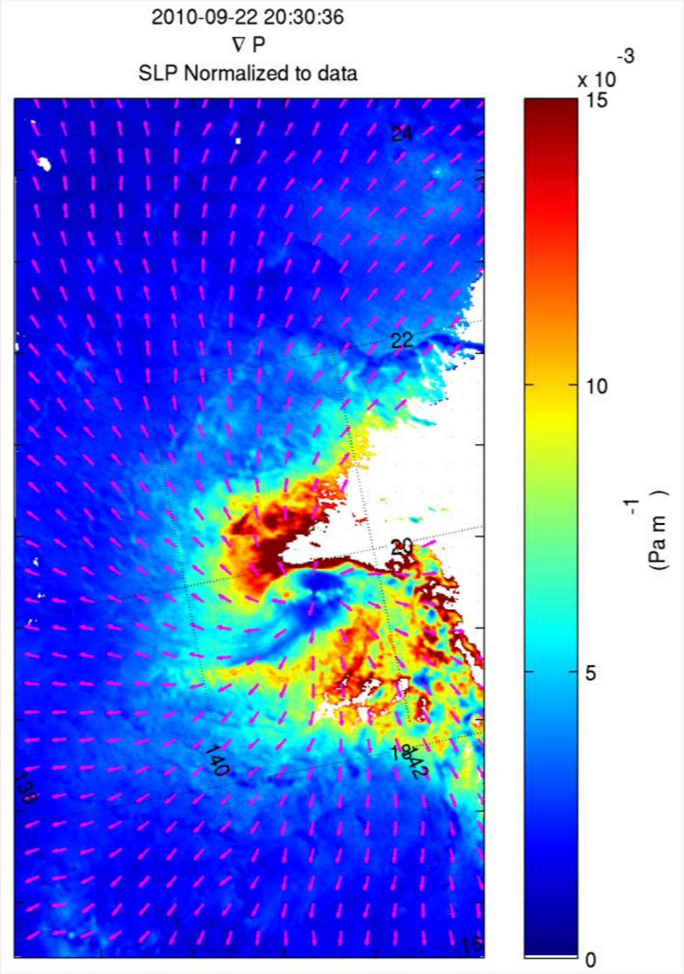

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3. Calculate pressure gradient vectors, $\overrightarrow{\nabla P}$, from $\overrightarrow{U_{10}}$ using Tropical Cyclone Boundary Layer (TCBL) model

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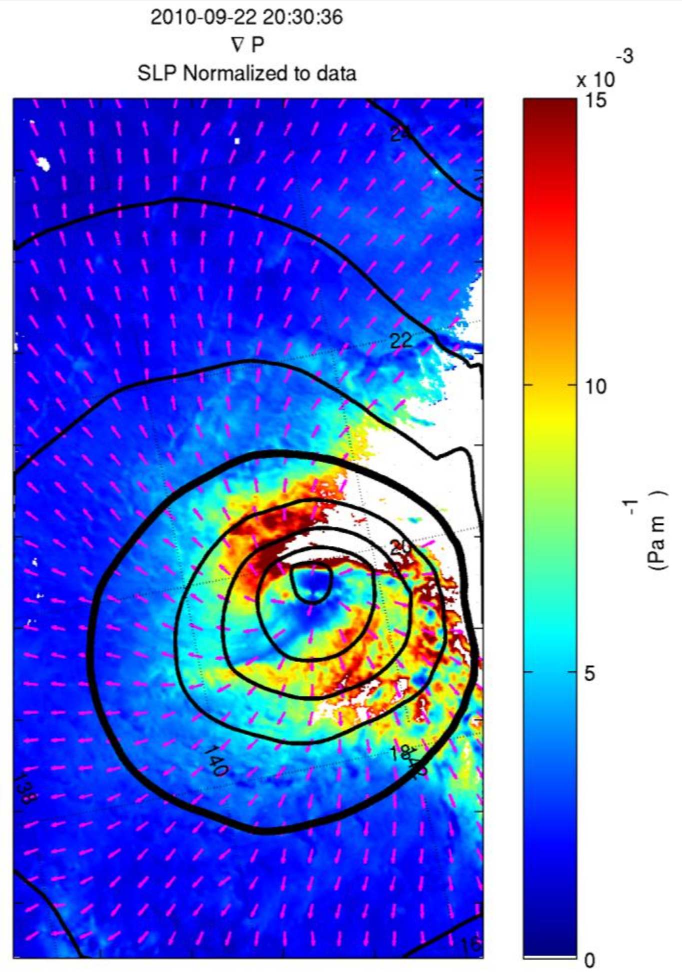

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3. Calculate pressure gradient vectors, ∇P , from $\overrightarrow{U_{10}}$ using Tropical Cyclone Boundary Layer (TCBL) model
4. Least-squares fit of pressure surface to ∇P vectors
   – Constraint: $\nabla \cdot \overrightarrow{V_{Geostrophic}} = 0$
   – Scene-wide dynamical consistency
   – Normalize to observations (optional)

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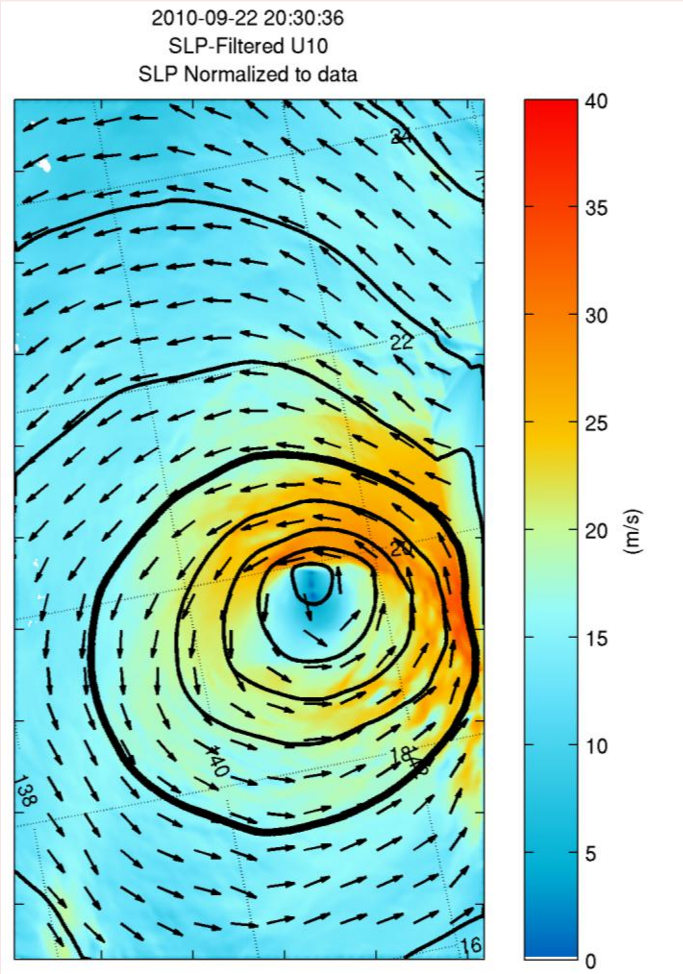

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   – Constraint: $\nabla \cdot \overrightarrow{V_{Geostrophic}} = 0$
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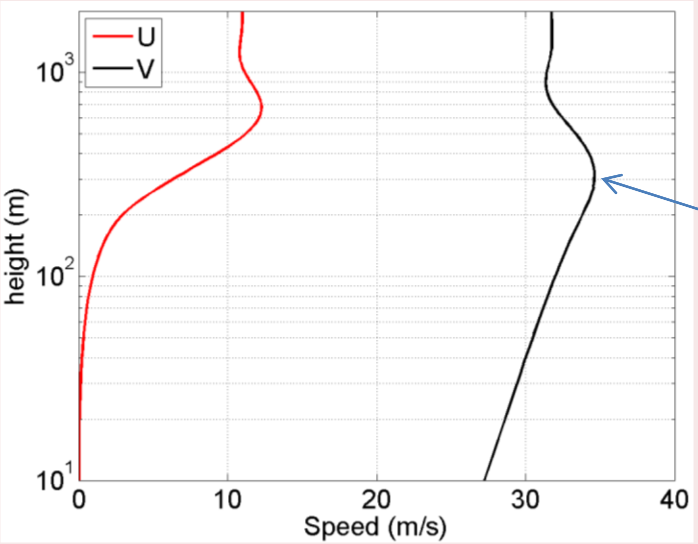
   – Normalize to observations (optional)
5. Use SLP pattern to force TCBL model and derive “SLP-filtered” surface wind vector field
   – Fill-in masked regions

TCBL: Nonlinear *Mean Flow* Dynamics are Important

- "Standard" PBL Scaling: $\boldsymbol{U} \cdot \nabla \boldsymbol{U} \ll \overline{\boldsymbol{u}' \cdot \nabla \boldsymbol{u}'}$
- Typhoon TCBL scaling: $\boldsymbol{U} \cdot \nabla \boldsymbol{U} \sim \overline{\boldsymbol{u}' \cdot \nabla \boldsymbol{u}'}$
- Fully nonlinear TCBL model (Foster, 2009) currently too costly

$$\boldsymbol{U}_{total} = \boldsymbol{U} + \boldsymbol{u}'$$

(rotated into surface wind coordinates)



V_g

Outer layer

Super-gradient jet

Inner layer

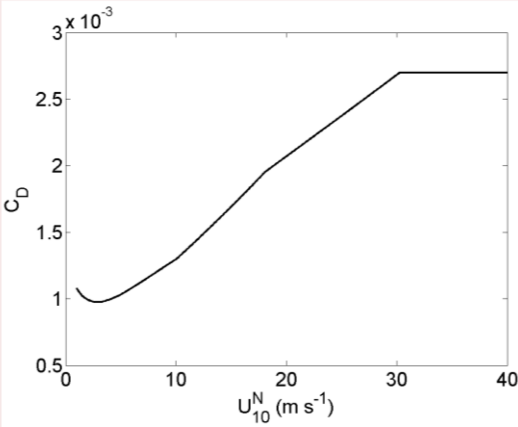
U_{10}

- Approximate nonlinear mean flow dynamics using gradient wind model
- Storm-relative correction

$$\frac{1}{\rho}\frac{dP}{dn} = fV_g\left(1 + \frac{V_g}{fR}\right)$$

$$R = \alpha r;\ \alpha \sim 0.65$$

Two-Layer TCBL Model:

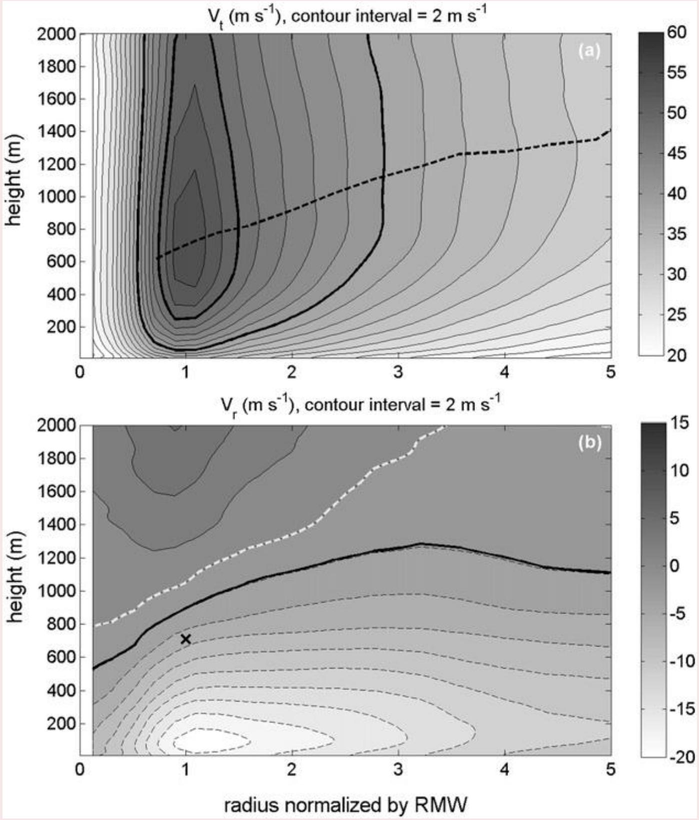


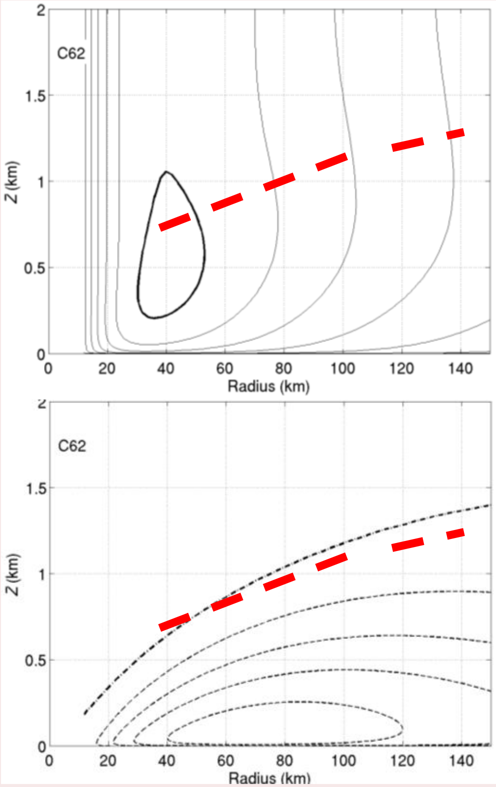
- Analytic match of inner and outer layers
- Inner (surface) layer
  - COARE/CBLAST-like surface layer
    - $C_{D_{max}} = 2.7 \times 10^{-3}$ for $U_{10} > {\sim}30\ ms^{-1}$
    - $C_H \sim const$, when stratification is included
- Outer layer
  - Nonlinear mean flow dynamics
  - TCBL depth increases with radius
- Assume TC interior close to gradient-wind, V_g, balance
  - $U_{10} = U_{10}(V_g)$ "direct model"
  - $V_g \;\; = V_g \;\; (U_{10})$ "inverse model"

TCBL: Mean boundary layer depth increases with radius

- Swirling flow:
  - Positive Rayleigh discriminant defines gradient wind-dependent time scale
- $I < f$, inner core; $I \to f$ as $r \to \infty$
- $\delta = \sqrt{2K_m/I}$

$$I^2 = \left(f + \frac{2V_g}{r}\right)\left(f + \frac{V_g}{r} + \frac{\partial V_g}{\partial r}\right)$$





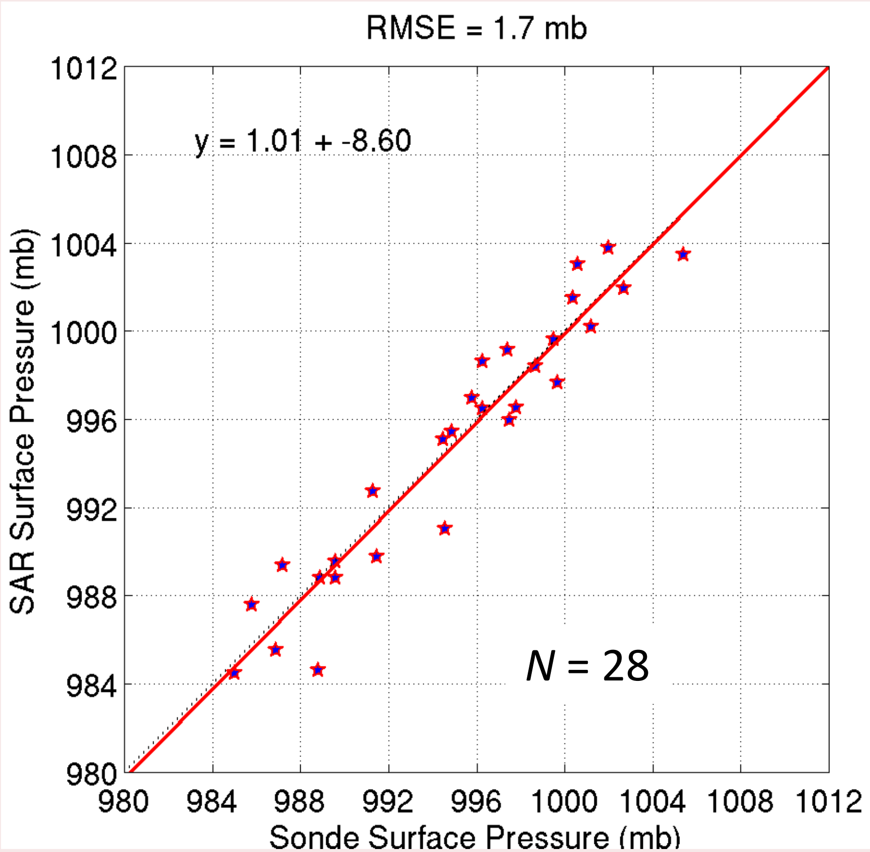
Observations: Zhang et al. 2011, *MWR*, 2011, **139**, 2523-2535

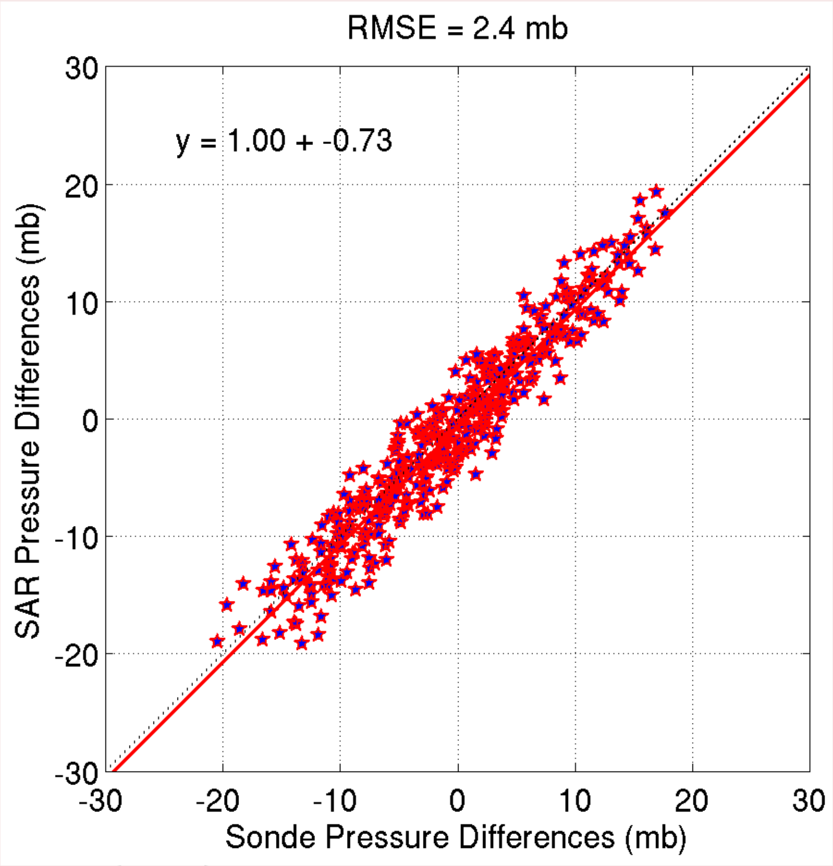
Nonlinear theory: Foster, 2009, *Boundary-Layer Meteorol.*, **131**, 321-344

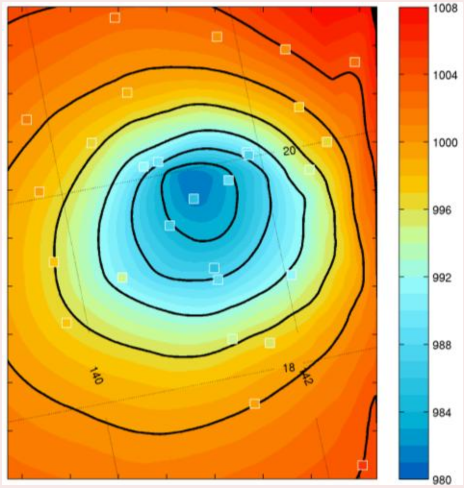
Cat-1 Typhoon Malakas

- Malakas 22 Sep, 2010, 20:30 UTC
- AF C-130J arrived 15 minutes after SAR overpass
- SFMR & 28 Drop Sondes

Malakas 22 Sep: Drop Sonde Surface Pressure



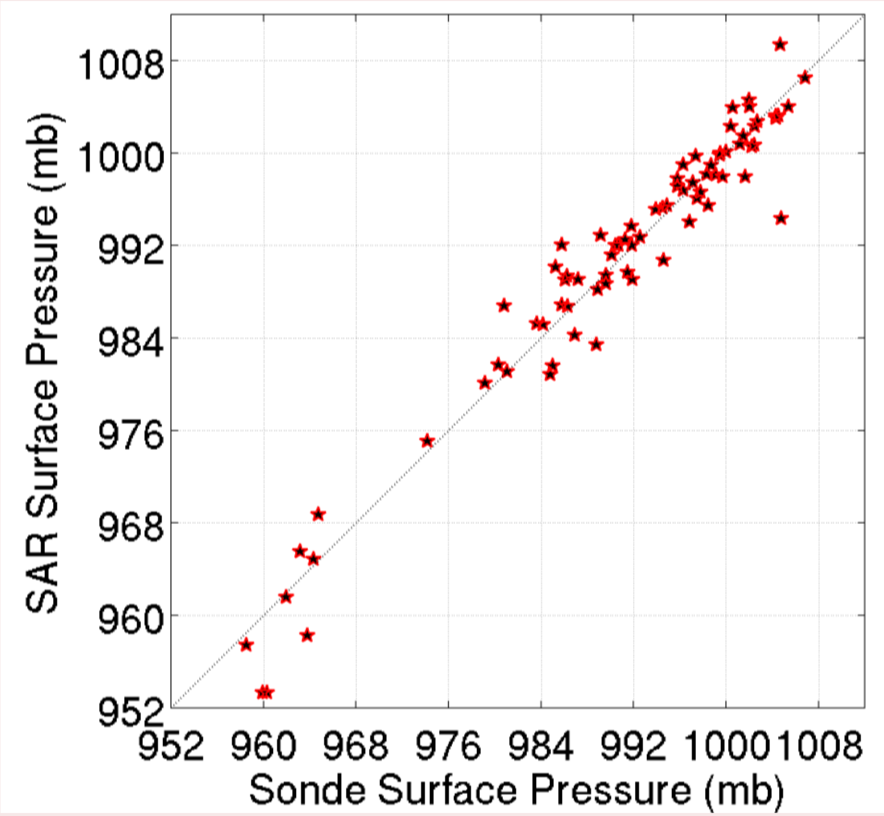


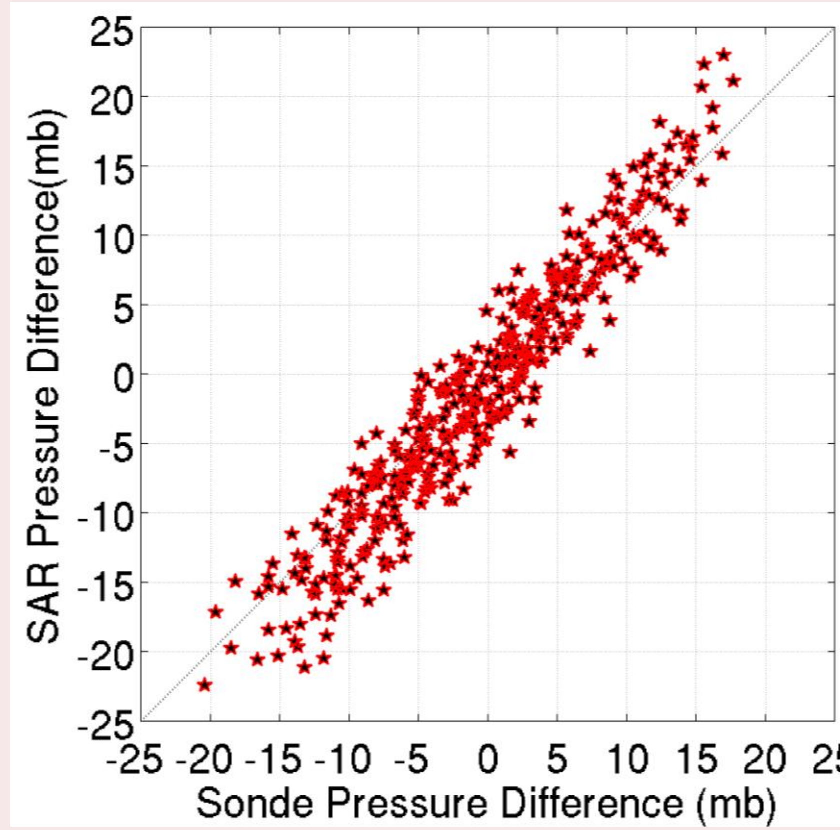


- $\frac{N(N-1)}{2} = 378$ pairs of sondes
- SLP pair-wise differences (PWD) give sense of SLP pressure shape retrieval

- SLP RMS < 2 mb
- SLP Pair-Wise Difference (PWD) RMS < 2.5 mb

Five SAR Scenes Compared to Drop Sonde Surface Pressure



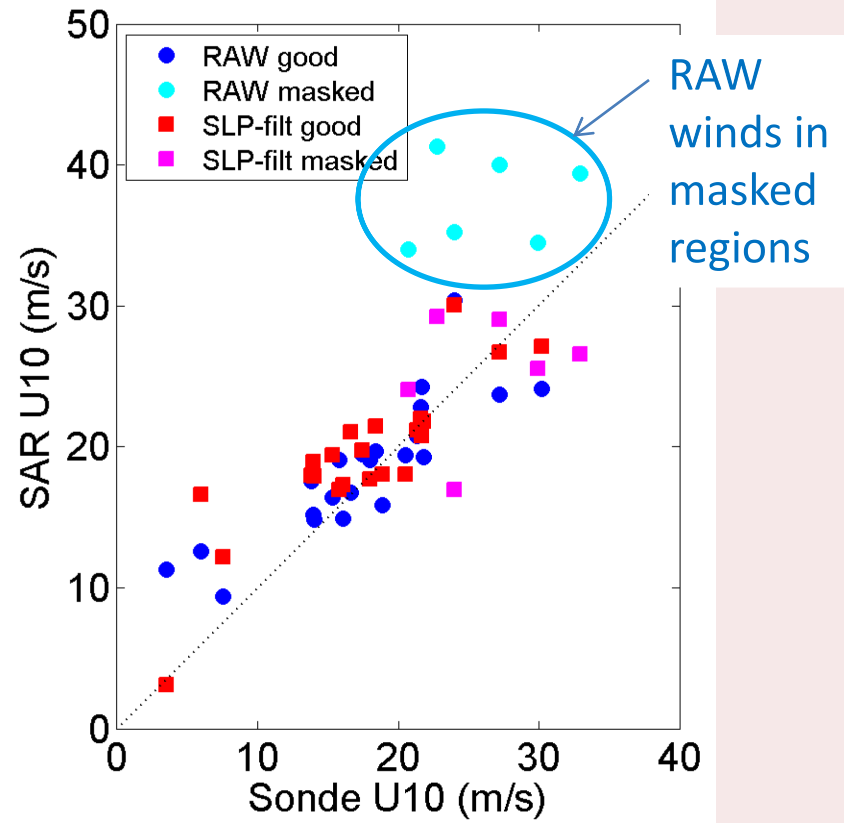


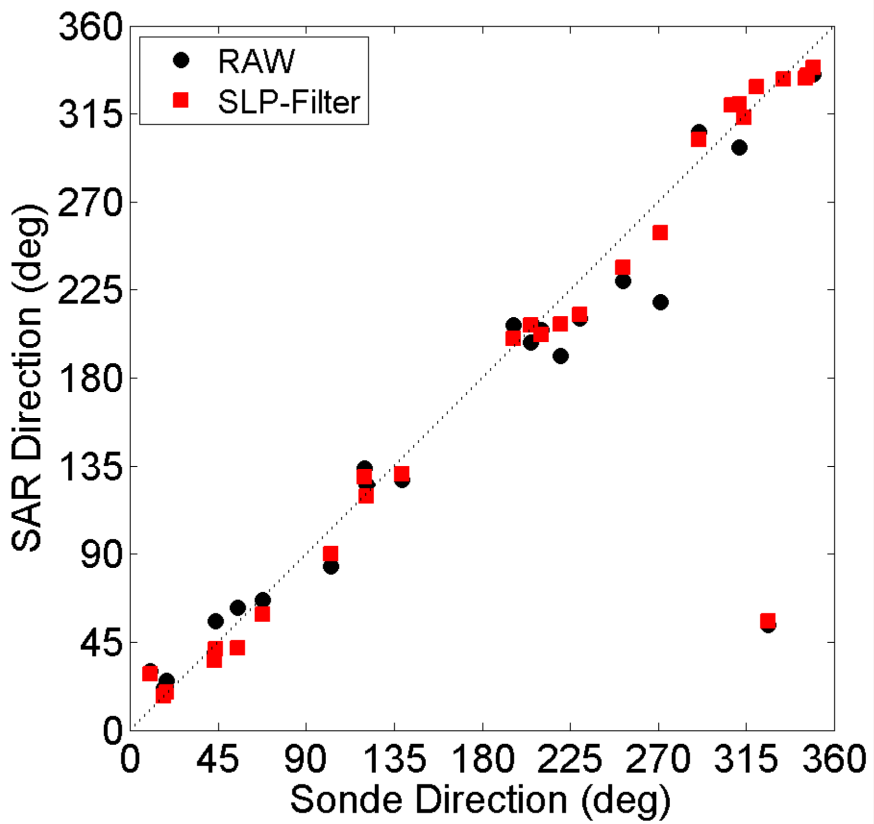
	SLP Bias (mb)	SLP RMS (mb)	PWD Bias (mb)	PWD RMS (mb)
SAR	0.1	2.8	0.6	2.9

Lili	30 Sep, 2002
Katrina	27 Aug, 2005
Helene	20 Sep, 2006
Ike	13 Sep, 2008
Malakas	22 Sep, 2010

- Overall ~3 mb RMS compared to drop sondes

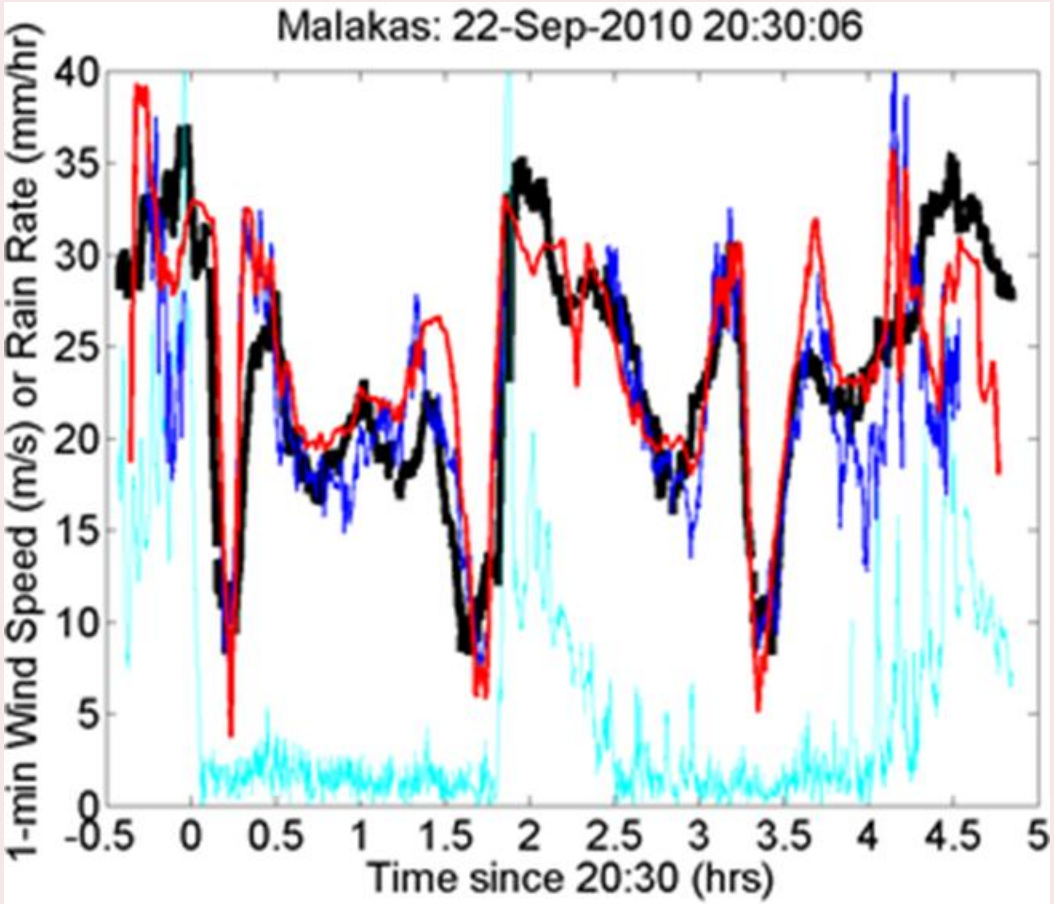
Malakas 22 Sep, 2010: Drop Sonde Surface Wind





	Speed RMS Good, N = 22 (m/s)	Speed RMS All, N = 28 (m/s)
RAW	3.3	5.6
SLP-Filter	3.2	3.9

Malakas 22 Sep, 2010 20:30: SFMR



Good Only N = 5,454	RMS (m/s)
RAW	3.4
SLP-Filter	3.4

Masked Only N = 4,427	RMS (m/s)
RAW	6.1
SLP-Filter	4.9

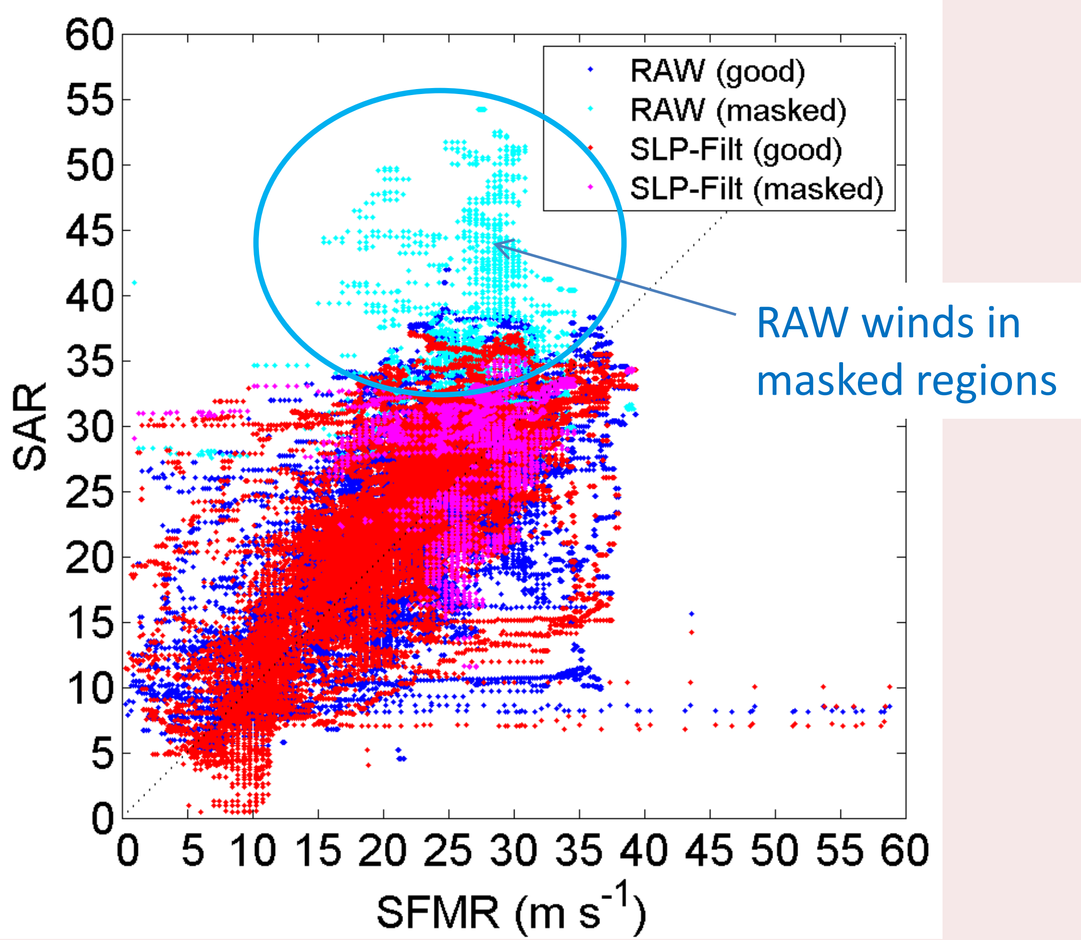
Not plotted

All Data N = 9,881	RMS (m/s)
RAW	7.8
SLP-Filter	4.2

Black: SFMR wind speed
Blue: RAW input wind (unmasked)
Red: SLP-filtered
Cyan: SFMR Rain Rate

- SLP-filtered and RAW winds are equal quality in good region
- SLP-filtered winds are better quality than RAW winds in masked region
- SLP-filtered winds have overall lower RMS

Five SAR Scenes Compared to SFMR



Good Only N = 31,292	RMS (m/s)
RAW	5.7
SLP-Filter	5.5

Masked Only N = 6,767	RMS (m/s)
RAW	8.6
SLP-Filter	5.4

All Data N = 38,059	RMS (m/s)
RAW	7.4
SLP-Filter	5.4

Lili	30 Sep, 2002
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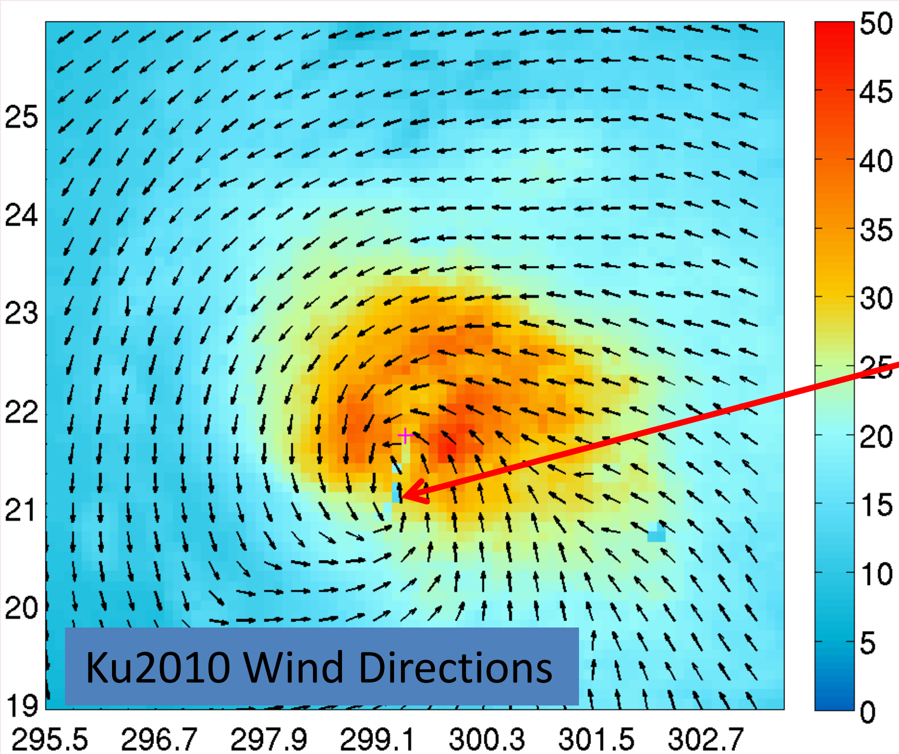
- SLP-filtered wind RMS is the same in good and masked regions
- RAW winds in masked region are lower quality than RAW winds in good region
- SLP-filtered winds has lower RMS overall

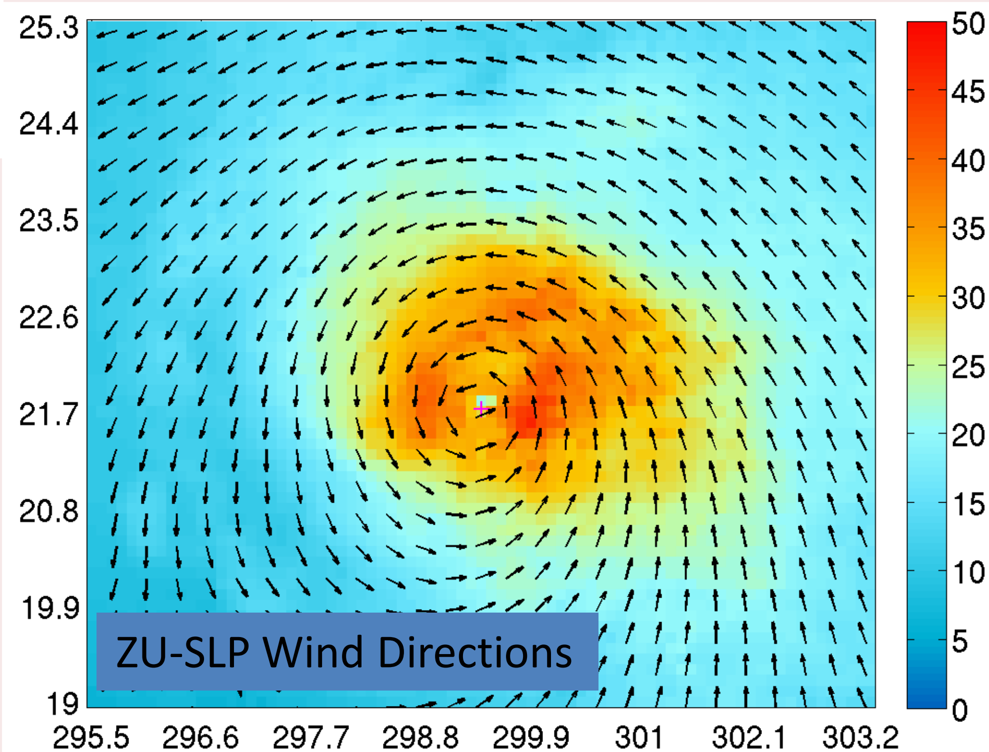
QuikSCAT Neural Net GMF (See Stiles, 17:00)

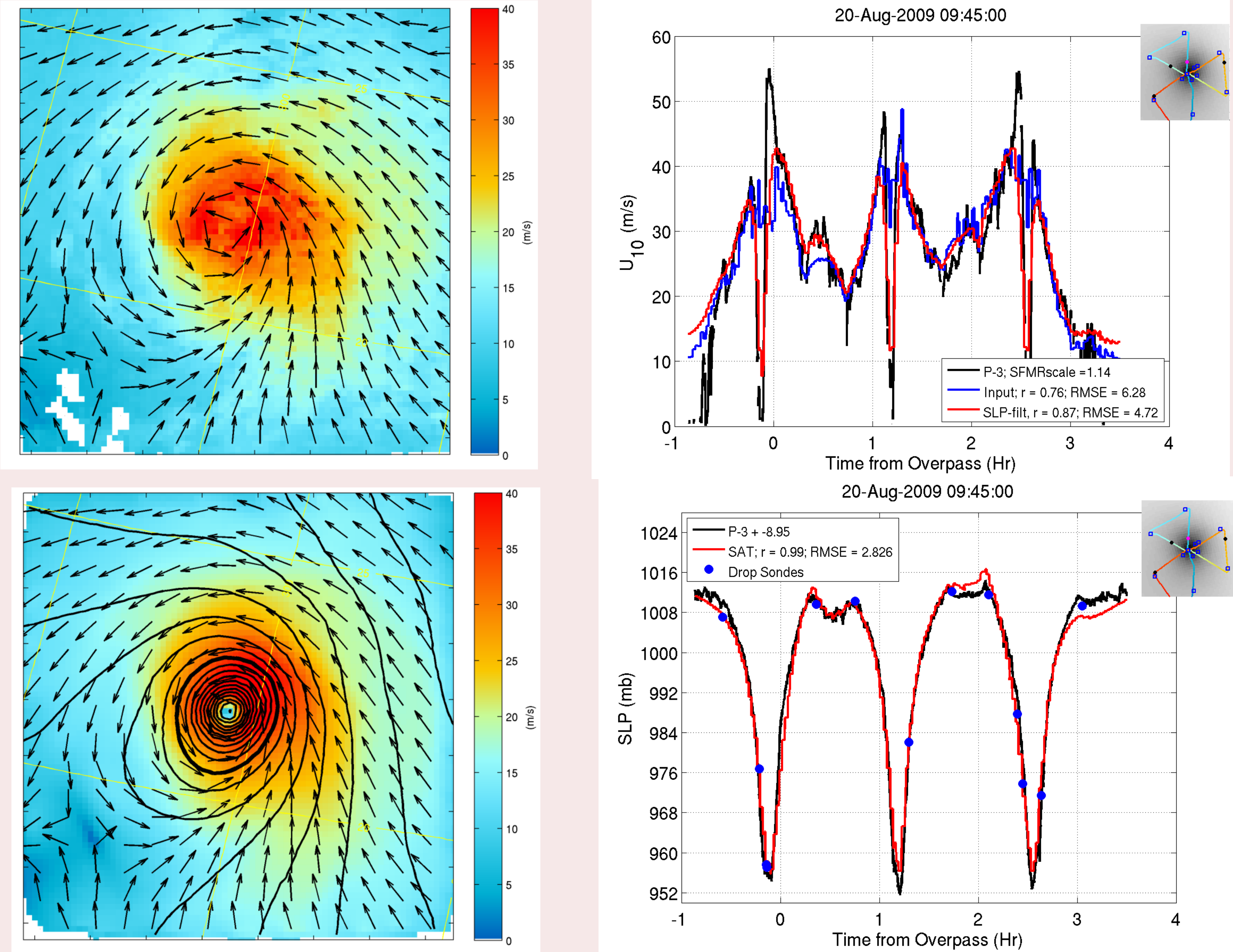
- Special Speed-only GMF for TCs
  - 10 years of data at JPL: http://tropicalcyclone.jpl.sa.gov/hurricane/gemain.jsp
  - NN trained to 2005 H*WIND
    - Stiles BW, RE. Danielson, W. Lee Poulsen, M J. Brennan, S. Hristova-Veleva, T-P.J. Shen, and Alexander G. Fore: 2013: Optimized Tropical Cyclone Winds from QuikSCAT: A Neural Network Approach, *TGARRS*, (**in press**)
  - 12.5 km pixels
- Scatterometer wind directions are <u>bad</u> in TC inner core
  - Fix with ZU-SLP retrieval iteration
    - Zhang, J. A., and E. W. Uhlhorn, 2012: Hurricane sea surface inflow angle and an observation-based parametric model. *Mon. Wea. Rev*., **140**, 3587-3605

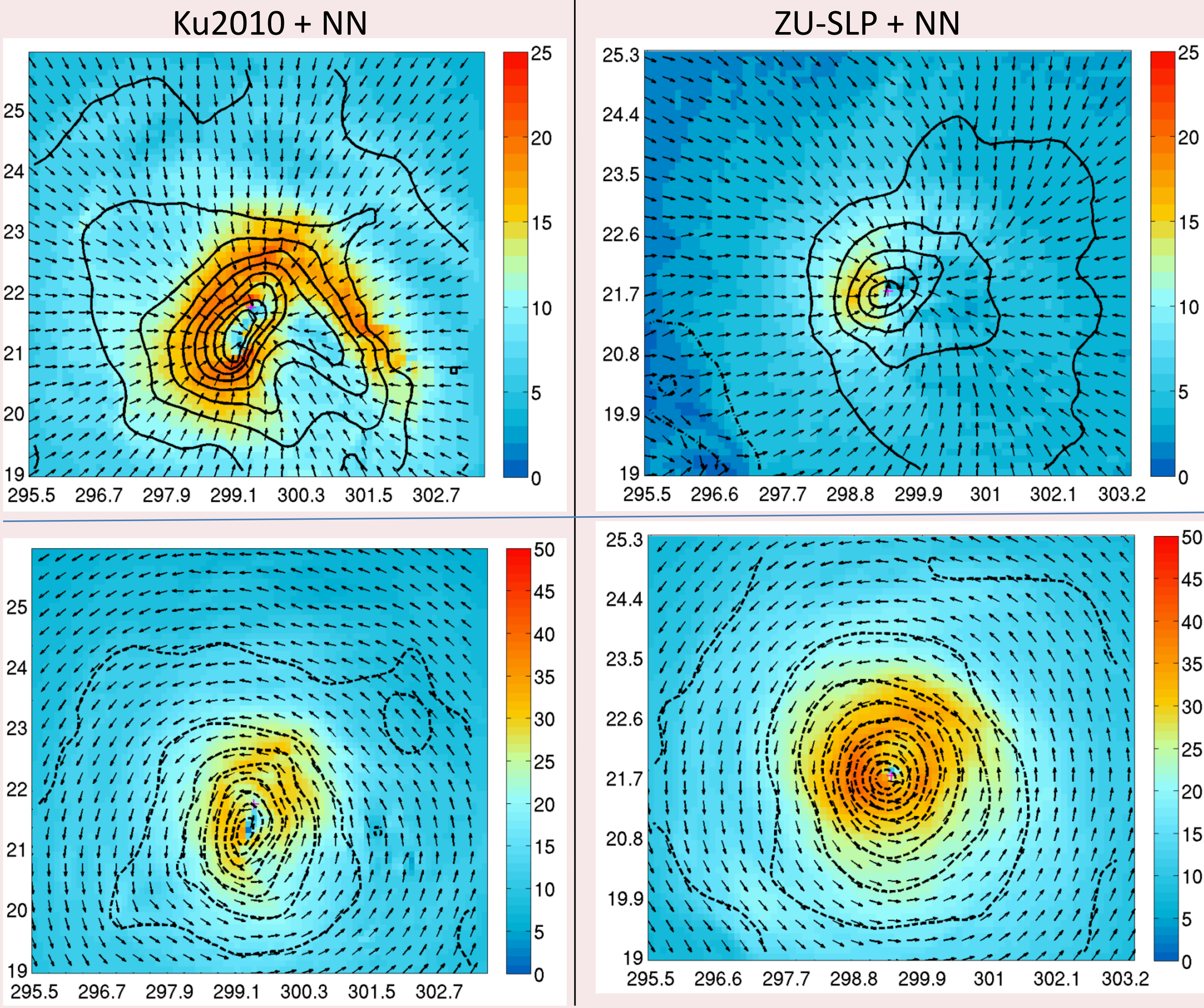
Hurricane Bill
20 Aug 2009, 09:45
QuikSCAT NN



Note: “squared-off” vortex shape & misplaced storm center




(m/s)
20-Aug-2009 09:45:00
U10 (m/s)
Time from Overpass (Hr)
P-3; SFMRscale =1.14
Input; r = 0.76; RMSE = 6.28
SLP-filt, r = 0.87; RMSE = 4.72
20-Aug-2009 09:45:00
SLP (mb)
Time from Overpass (Hr)
P-3 + -8.95
SAT; r = 0.99; RMSE = 2.826
Drop Sondes

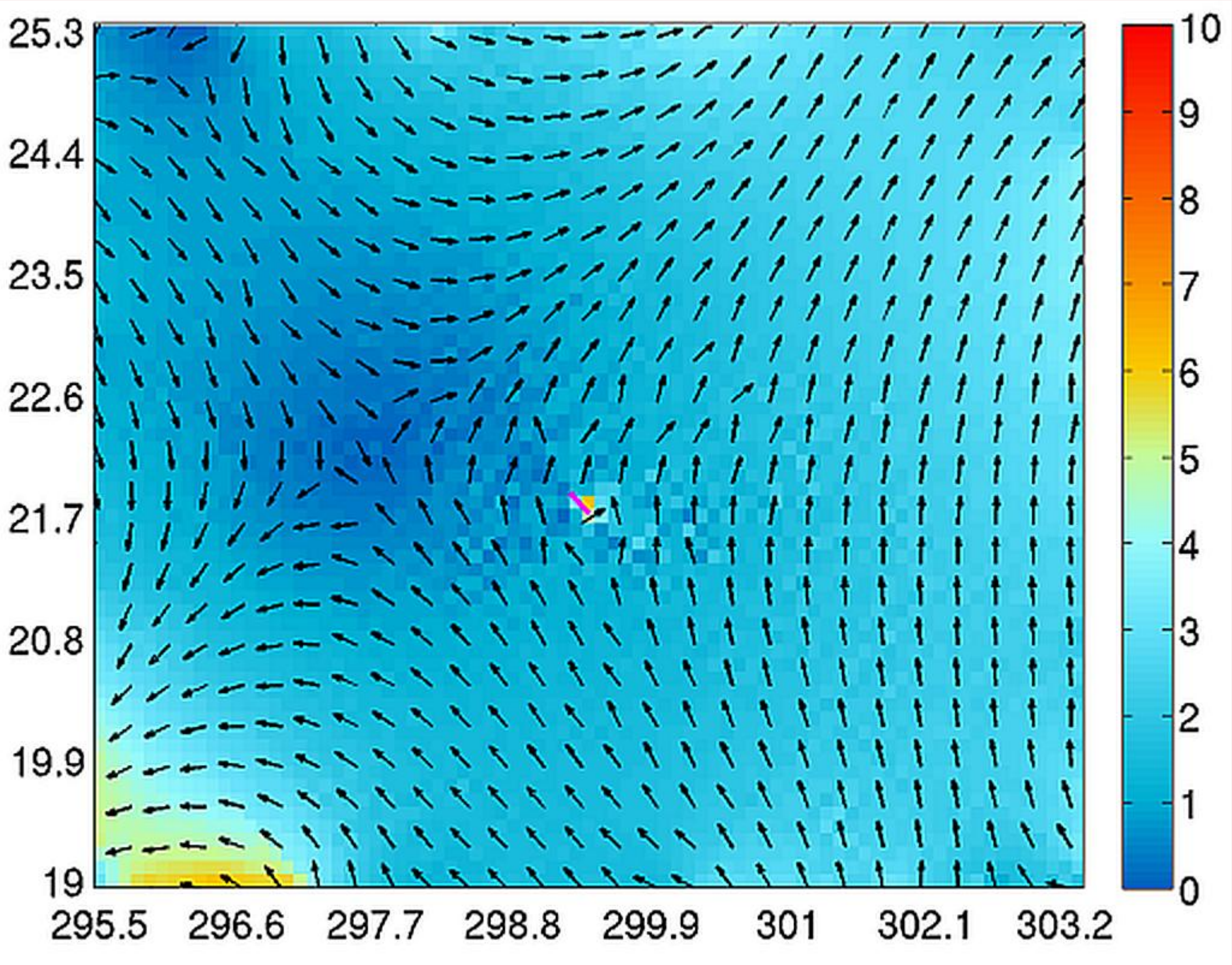


Irrotational Flow (Secondary Circulation, ***convergent***)

Nondivergent Flow (Primary circulation)

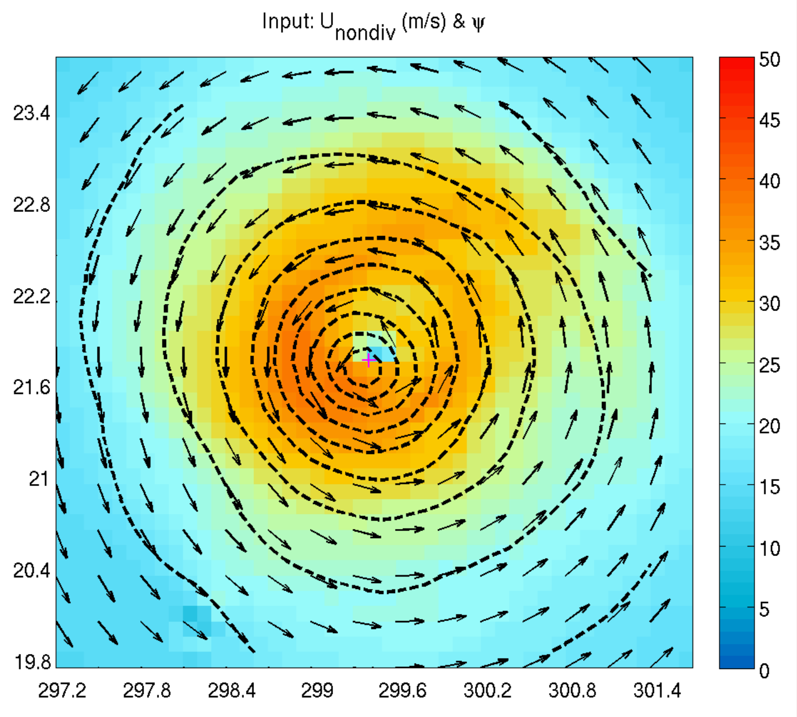
Bishop, C H., 1996: Domain-Independent Attribution. Part I: Reconstructing the Wind from Estimates of Vorticity and Divergence Using Free Space Green's Functions. *J. Atmos. Sci.*, **53**, 241–252.

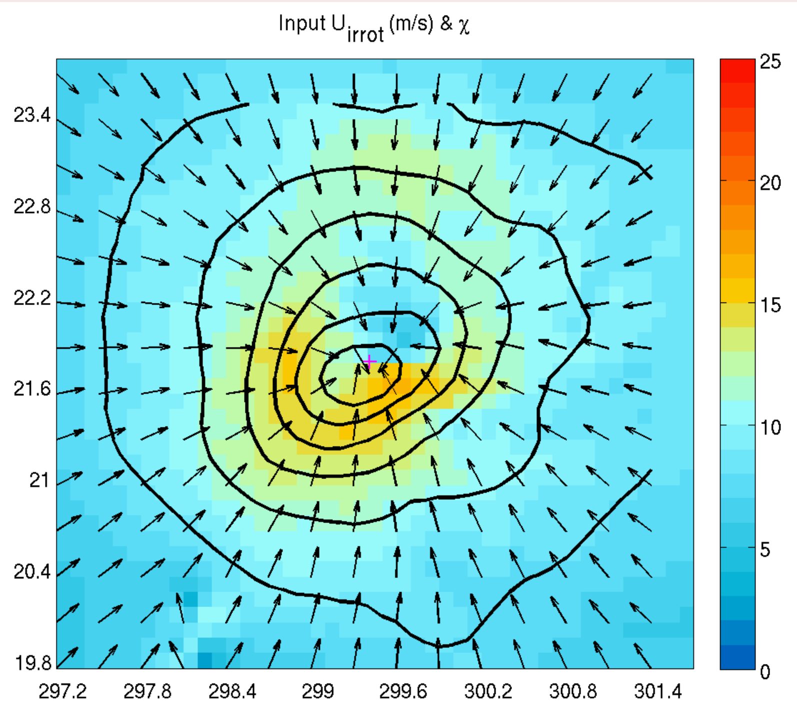
Deformation Flow from QuikSCAT ZU-SLP directions

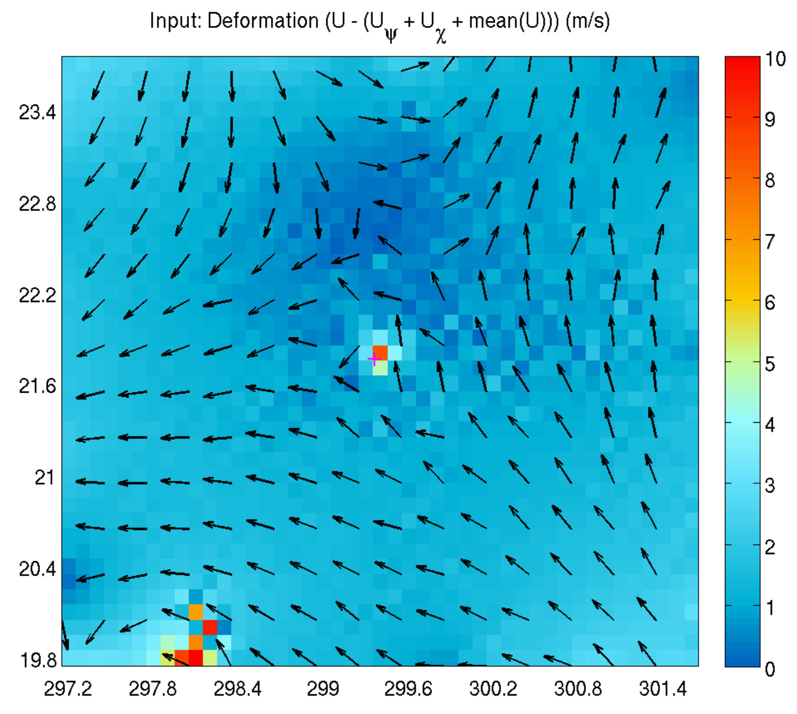


Investigation of Circulation Center

- Use initial guess at center (HRD, Best Track, etc.)
- Find metric based on circulation near RMW (radius maximum wind)
- Circulation center varies greatly over depth of TCs
  - Best track/HRD near flight level or “steering” level
  - Scatterometer data needs surface circulation center

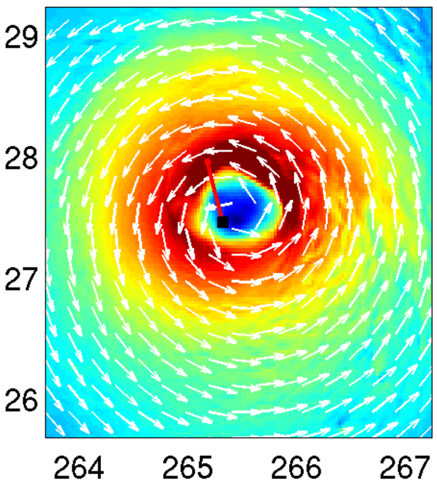




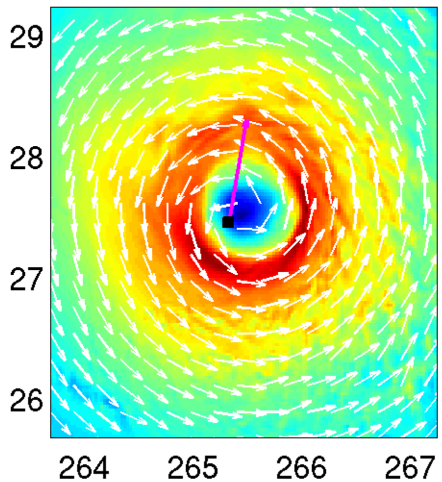


- Use flow partition analysis & SLP data to refine estimates of surface-level circulation center
- Best fit to SLP obs
- Find flow partition metrics e.g.:
  - Maximize circulation near RMW
  - Location of deformation cull
  - Comparison with numerical simulations (e.g. UMCM 3-way coupled model)

Uψ: 191.4 (m)

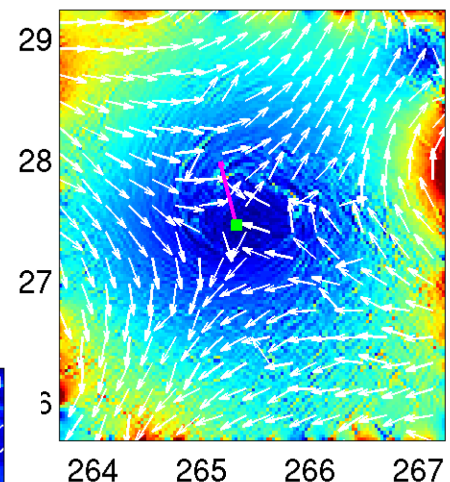


Uψ: 4568.2 (m)

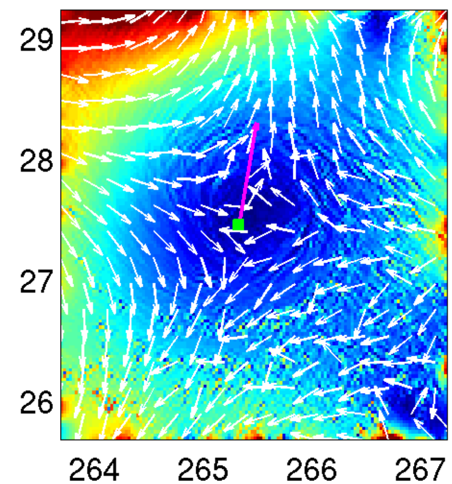


(First-look results of UMCM modeling system TCBL response to wave model)

Udef: 191.4 (m)

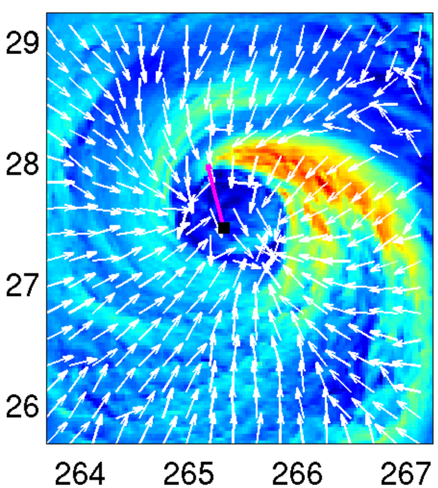


Udef: 4568.2 (m)

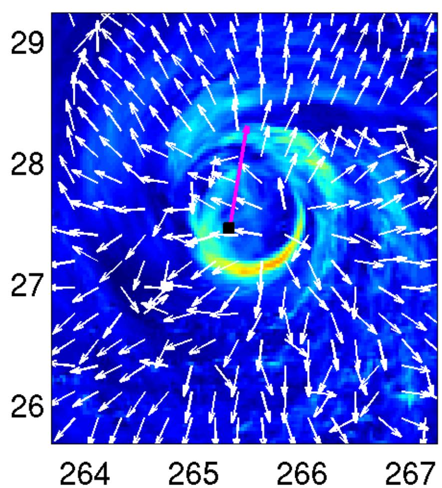


(Not rotated in rad/tan contributions)

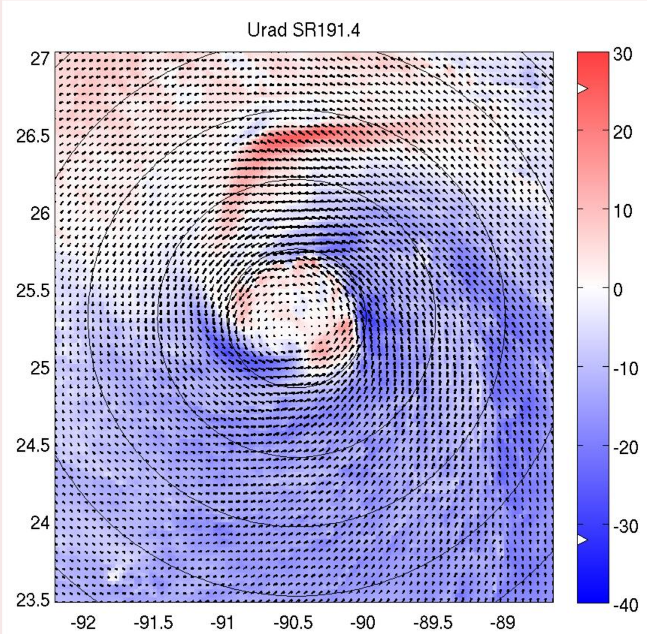
Uχ: 191.4 (m)

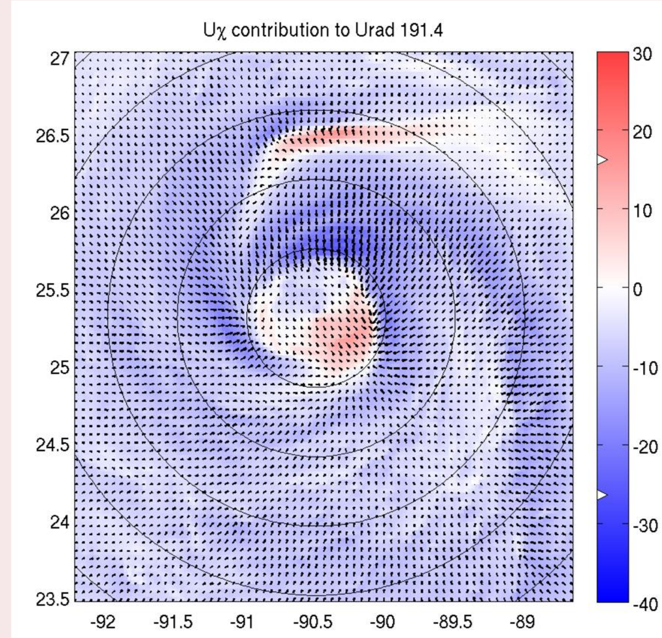


Uχ: 4568.2 (m)

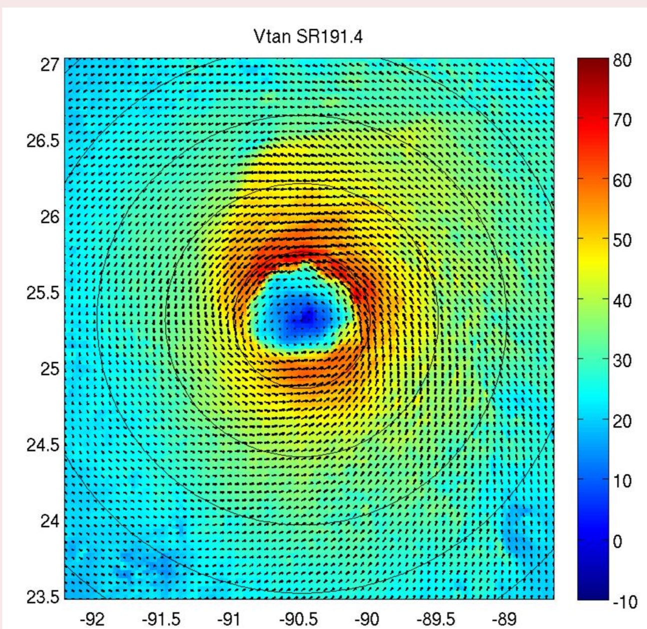


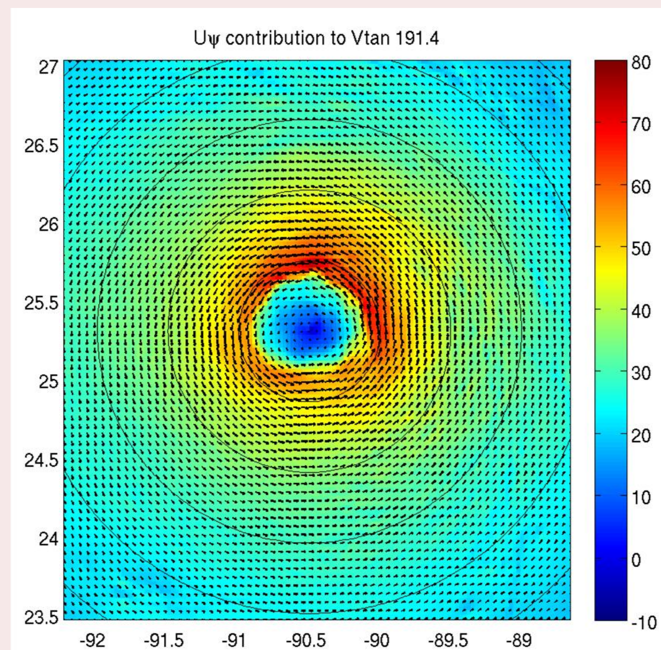
UMCM AWO (Ike, approaching landfall)





Note smaller Convergent radial flow Magnitudes Compared to SR Urad





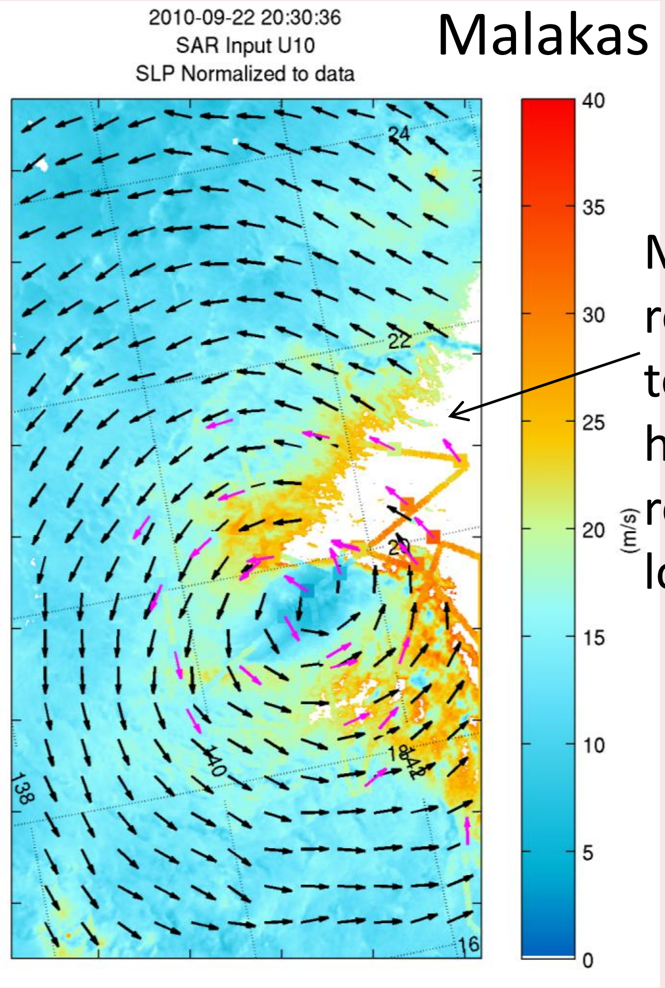
Future Research

- Upgrade TCBL model in SLP retrieval
  - Improve nonlinear dynamics ala Foster (2009)
- Use SLP to improve wind directions for scatterometers in TC conditions
  - Iterate SLP/partition analysis
- Combine with upper-level winds to study in→up→out TC-scale secondary circulation
  - Flow partitions at two levels
- Investigate TC TCBL roll vortices (SAR)
  - TCBL parameterization
  - Improve SAR wind directions

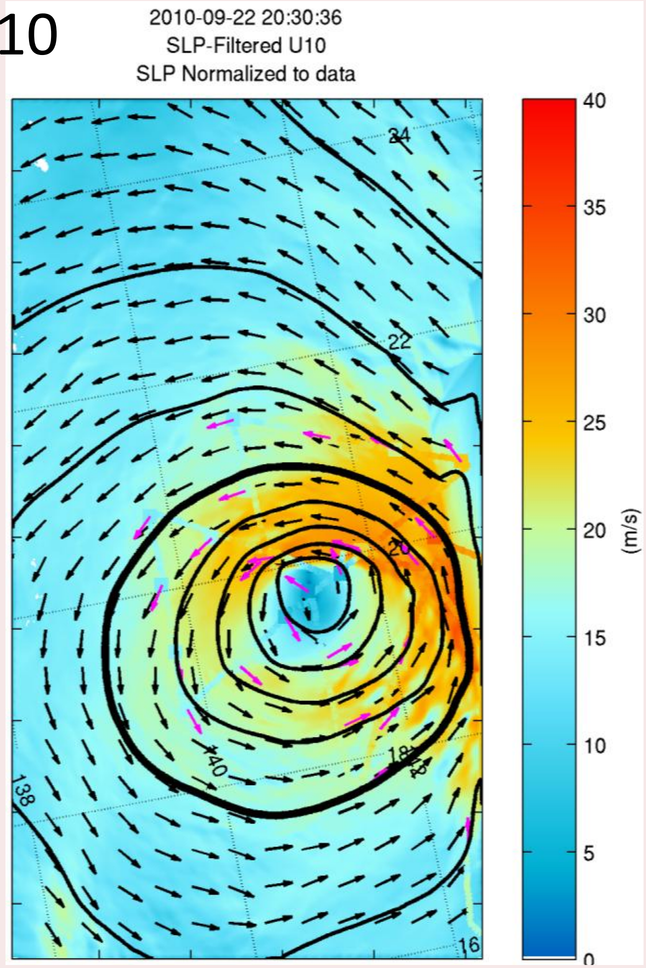
Summary

- Developed new methodology to calculate Sea-Level Pressure patterns from SAR images of Tropical Cyclones
  - 1 km pixels
  - <3 mb RMS compared to drop sondes
- Scene-wide SLP-filtered surface winds
  - Similar quality to RAW SAR winds in unmasked regions
  - Fills gaps where SAR winds are less certain (masked)
  - SAR wind speed comparable to SFMR RMS
    - SAR has more coverage
    - Cat2 + model functions not well established or tested
  - Dynamically consistent SLP and SLP-filtered U_{10}
- Apply to Scatterometer NN data sets
  - Coarser resolution
  - Longer and larger data set (QuikSCAT)
  - OSCAT & ASCAT scatterometers currently operational
  - RapidSCAT & HSCAT coming

Malakas 22 Sep, 2010



Masked regions tend to be high wind regions at low incidence



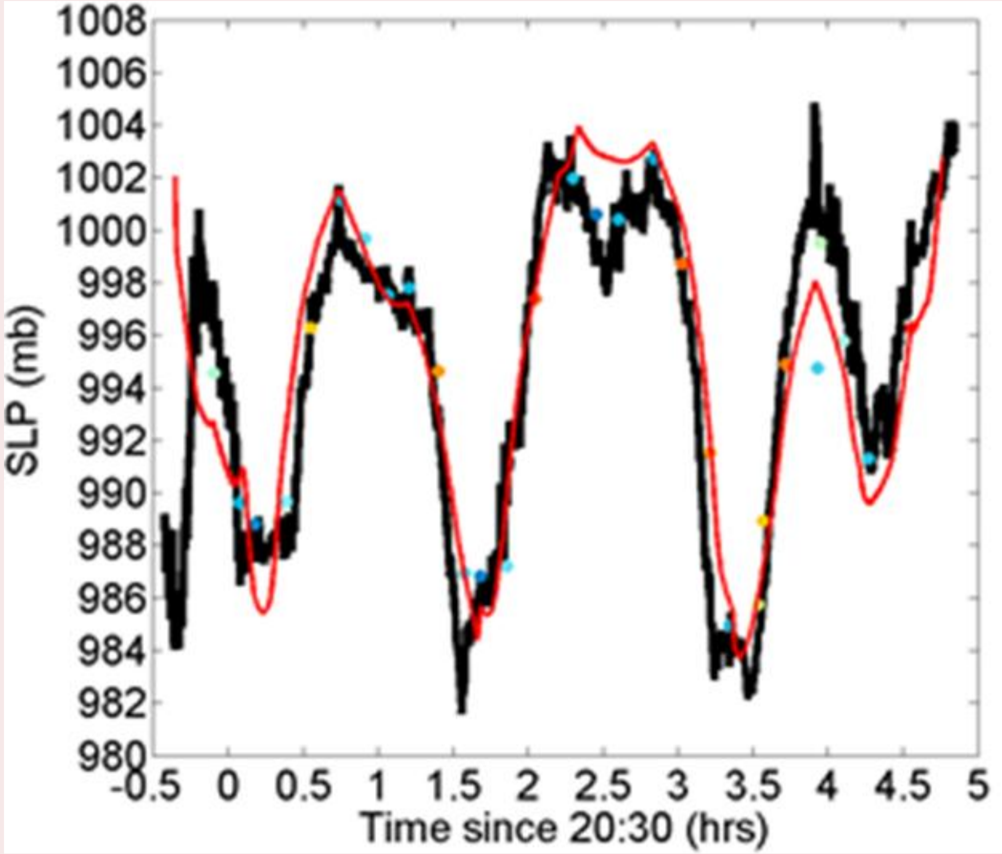
RAW SAR wind vectors
Mask less certain winds

SLP-filtered wind vectors
SLP contours (4mb interval)

Superposed (adjusted for storm translation):
SFMR wind speeds
Drop sonde U_{10} and directions

(directions every 40 km)

C-130J Surface Pressure



Black: C130 Sea-level Pressure from Flight Level Data

Red: SAR sea-level pressure

TCBL Model Development Needed for SLP Retrieval

- Approximated nonlinear mean flow dynamics
  - Storm-relative nonlinear dynamics corrections
  - Modified gradient wind correction
- Dynamical increase of TCBL depth with radius
  - Based on rotational "stiffness" of swirling flow
- High winds limit on ${C_D}^{max} = 2.5 \times 10^{-3}$