

VORTEX-SCALE DATA ASSIMILATION WITH HEDAS IN THE 2013 SEASON and IMPACTS OF PARAMETER PERTURBATIONS

Presented for the HFIP Teleconference, 04 December 2013

by

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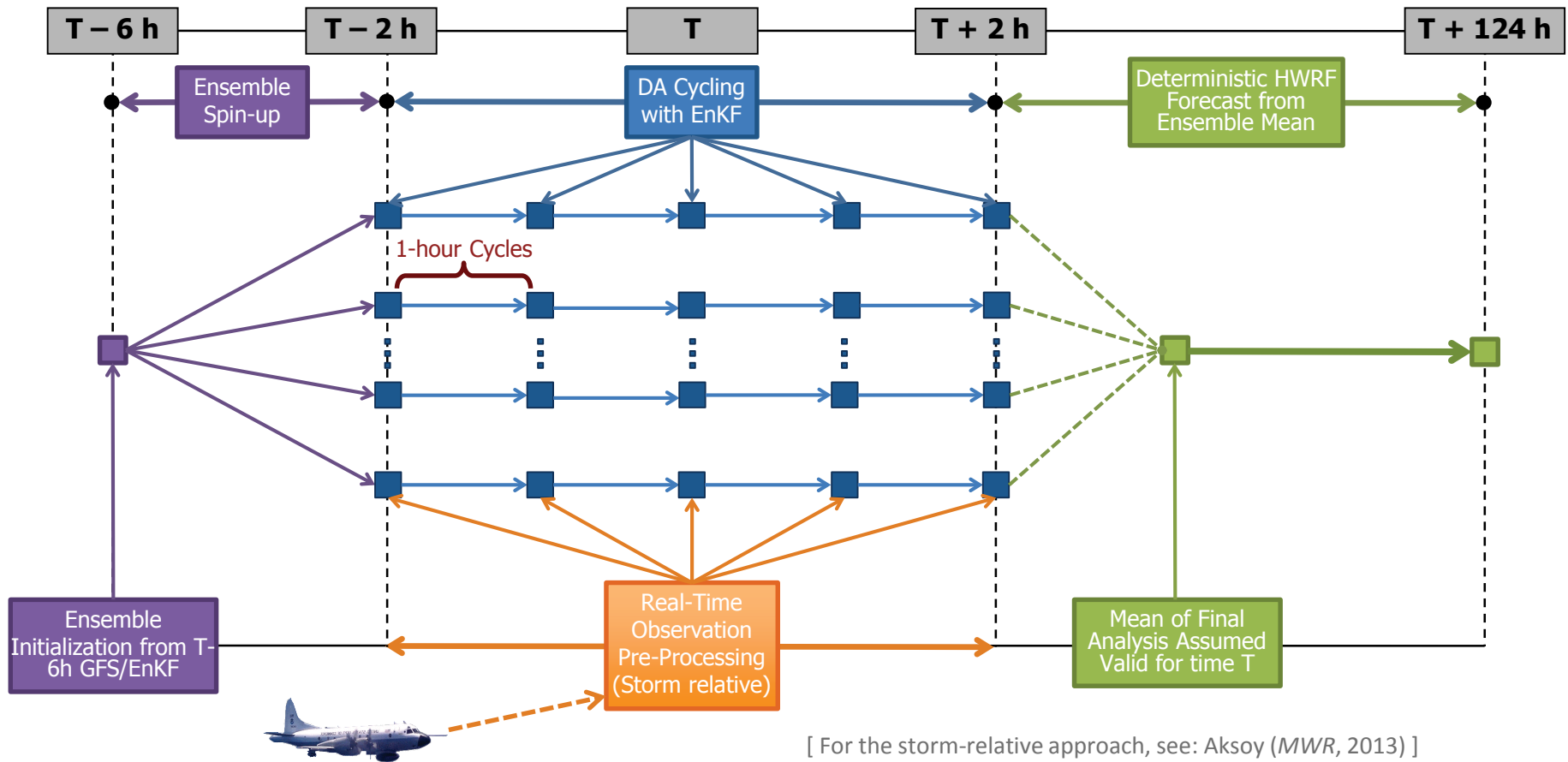
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HEDAS CONFIGURATION in 2013

- An ensemble-based **EnKF** data assimilation system **interfaced with NOAA's HWRF model (2012 version, no ocean)**
- Ran **near real time in 2013** on NOAA's Jet supercomputer (supported by **NOAA HFIP project**)
- Focuses on **data assimilation in the hurricane inner core** (in a 3-km inner nest)
- **Assimilates aircraft data** (radar, dropsonde, flight level, SFMR surface wind speed) from NOAA P-3 and G-IV, Air Force Reserve C-130, and NASA Global Hawk aircraft, **and satellite AMVs, AIRS and GPS-RO retrieved T/Q profiles**
- Published papers: Aksoy et al. (*MWR*, 2012 & 2013); Aksoy (*MWR*, 2013); Vukicevic et al. (*MWR*, 2013)



HEDAS CASES in 2013

STORM	DATE	FLIGHT LEVEL				SFMR			Dropsondes					Doppler Superobs			Satellite	Satellite	Satellite	Total
		P-3	Air Force	G-IV	Total	P-3	Air Force	Total	P-3	Air Force	G-IV	HS-3	Total	P-3	G-IV	Total	AMVs	AIRS Retrievals	GPS-RO Retrievals	
Fernand	2013082600	0	1,478	0	1,478	0	346	346	0	0	0	0	0	0	0	0	952	0	0	2,776
Gabrielle	2013082918	0	0	0	0	0	0	0	0	0	0	88	88	0	0	0	2,308	8,214	52	10,662
Gabrielle	2013083000	0	0	0	0	0	0	0	0	0	0	1,702	1,702	0	0	0	1,766	0	0	3,468
Gabrielle	2013083006	0	0	0	0	0	0	0	0	0	0	784	784	0	0	0	1,416	8,442	0	10,642
Gabrielle	2013083112	0	0	36	36	0	0	0	0	0	0	35	0	0	44	44	1,998	0	0	2,113
Gabrielle	2013083118	0	0	1,200	1,200	0	0	0	0	0	1,749	0	1,749	0	9,249	9,249	2,324	654	0	15,176
Gabrielle	2013090418	0	1,486	0	1,486	0	216	216	0	0	0	426	426	0	0	0	4,184	5,712	118	12,142
Gabrielle	2013090500	0	0	0	0	0	0	0	0	0	0	1,359	1,359	0	0	0	3,044	0	0	4,403
Gabrielle	2013090506	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,152	3,630	205	6,987
Gabrielle	2013090512	0	1,302	0	1,302	0	245	245	0	42	0	260	302	0	0	0	3,642	0	355	5,846
Gabrielle	2013090618	2,440	2,016	370	4,826	512	360	872	0	0	0	0	0	0	0	0	5,108	2,062	388	13,256
Gabrielle	2013090712	0	0	0	0	0	0	0	0	0	98	0	98	0	804	804	3,278	0	395	4,575
Gabrielle	2013090718	4,624	260	80	4,964	1,020	0	1,020	0	0	1,626	949	2,575	55,566	0	55,566	3,538	6,084	0	73,747
Gabrielle	2013090800	332	1,150	0	1,482	87	177	264	0	16	0	1,182	1,198	0	0	0	2,348	0	0	5,292
Gabrielle	2013090806	0	0	0	0	0	0	0	0	0	0	1,181	1,181	0	0	0	3,280	6,818	198	11,477
Gabrielle	2013091018	33	624	0	657	9	150	159	0	78	0	0	78	0	0	0	3,602	2,121	201	6,818
Eight	2013090518	0	868	0	868	0	202	202	0	0	0	0	0	0	0	0	1,876	2,986	29	5,961
Eight	2013090600	0	664	0	664	0	103	103	0	0	0	0	0	0	0	0	954	0	191	1,912
Ingrid	2013091218	0	816	0	816	0	166	166	0	0	0	0	0	0	0	0	804	1,586	31	3,403
Ingrid	2013091300	6	428	0	434	3	69	72	0	0	0	0	0	0	0	0	848	0	184	1,538
Ingrid	2013091312	0	1,778	0	1,778	0	357	357	0	13	0	0	13	0	0	0	1,261	0	195	3,604
Ingrid	2013091318	432	0	1,108	1,540	103	0	103	0	0	1,075	0	1,075	0	15,554	15,554	1,534	669	163	20,638
Ingrid	2013091400	1,194	1,691	0	2,885	311	245	556	157	18	0	0	175	20,372	0	20,372	1,067	0	0	25,055
Ingrid	2013091406	415	0	0	415	88	0	88	0	0	0	0	0	0	0	0	1,321	466	171	2,461
Ingrid	2013091412	1,546	1,808	204	3,558	391	353	744	226	84	80	0	390	26,089	2,071	28,160	1,527	0	364	34,743
Ingrid	2013091418	704	0	943	1,647	175	0	175	122	0	1,124	0	1,246	8,513	8,272	16,785	2,027	1,891	5	23,776
Ingrid	2013091500	1,476	1,904	0	3,380	350	446	796	191	31	0	0	222	10,683	0	10,683	1,883	0	0	16,964
Ingrid	2013091506	643	0	0	643	172	0	172	102	0	0	0	102	5,889	0	5,889	1,511	3,471	0	11,788
Ingrid	2013091512	1,318	2,304	207	3,829	327	532	859	244	226	52	0	522	19,603	1,793	21,396	1,641	0	200	28,447
Ingrid	2013091518	311	0	890	1,201	98	0	98	20	0	1,444	0	1,464	3,809	14,001	17,810	2,245	572	586	23,976
Ingrid	2013091600	2,593	1,927	0	4,520	581	377	958	307	103	0	0	410	16,430	0	16,430	1,626	0	0	23,944
Ingrid	2013091612	0	1,366	0	1,366	0	323	323	0	22	0	0	22	0	0	0	1,326	0	204	3,241
Karen	2013100218	0	1,588	0	1,588	0	330	330	0	0	0	0	0	0	0	0	2,500	2,196	366	6,980
Karen	2013100300	28	880	0	908	7	159	166	0	0	0	0	0	0	0	0	1,782	0	0	2,856
Karen	2013100306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2,060	5,446	0	7,506
Karen	2010100312	0	1,902	0	1,902	0	434	434	0	0	0	0	0	0	0	0	1,884	0	3	4,223
Karen	2010100318	1,024	1,881	0	2,905	242	367	609	123	57	0	0	180	6,082	0	6,082	4,030	2,281	196	16,283
Karen	2010100400	1,604	1,363	0	2,967	460	305	765	289	0	0	0	289	12,805	0	12,805	4,549	0	0	21,375
Karen	2010100406	1,126	1,410	641	3,177	279	410	689	134	99	985	0	1,218	7,429	0	7,429	4,089	1,471	0	18,073
Karen	2010100412	1,831	860	502	3,193	472	213	685	302	42	1,043	0	1,387	7,004	0	7,004	4,858	0	0	17,127
Karen	2010100418	985	1,935	0	2,920	236	441	677	108	64	0	0	172	1,929	0	1,929	4,925	6,661	0	17,284
Karen	2010100500	1,999	1,685	0	3,684	496	432	928	293	90	0	0	383	12,158	0	12,158	4,703	0	0	21,856
Karen	2010100506	1,214	1,452	0	2,666	285	296	581	163	64	0	0	227	1,054	0	1,054	3,197	5,879	0	13,604
Karen	2010100512	1,709	643	0	2,352	405	159	564	224	22	0	0	246	107	0	107	3,066	0	0	6,335
Karen	2010100518	0	2,067	0	2,067	0	483	483	0	102	0	0	102	0	0	0	2,667	1,277	192	6,788
		29,587	41,536	6,181	77,304	7,109	8,696	15,805	3,005	1,173	9,311	7,931	21,420	215,522	51,788	267,310	113,701	80,589	4,992	581,121

HEDAS CASES in 2013 - BREAKDOWN

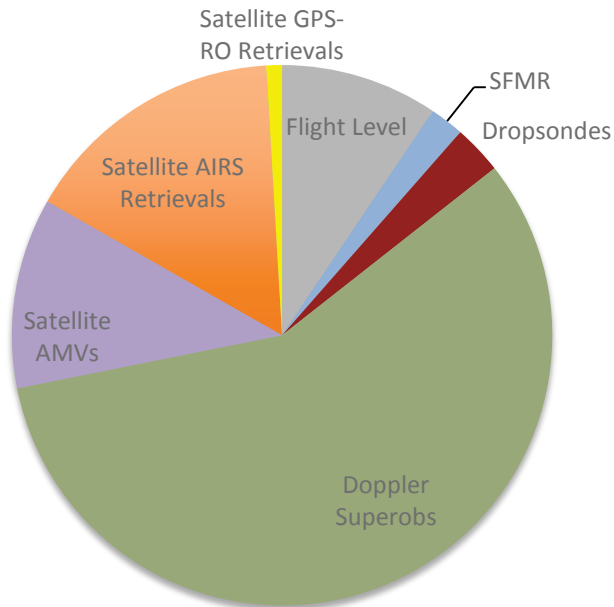
By Observing Platform

Platform	Num. Obs.	Num. Cases	Avg. Num. Obs.
Flight Level	77,304	37	2,089
SFMR	15,805	35	452
Dro sondes	21,420	33	649
Doppler Superobs	267,310	21	12,729
Satellite AMVs	113,701	45	2,527
Satellite AIRS Retrievals	80,589	23	3,504
Satellite GPS-RO Retrievals	4,992	24	208
Total	581,121	45	12,914

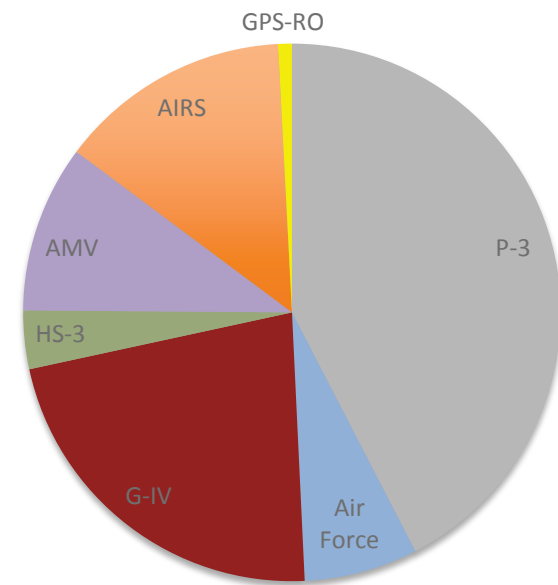
By Observing Aircraft

Aircraft	Num. Obs.	Num. Cases	Avg. Num. Obs.
P-3	255,223	24	10,634
Air Force	51,405	30	1,714
G-IV	67,280	12	5,607
HS-3	7,931	9	881
AMV	113,701	45	2,527
AIRS	80,589	23	3,504
GPS-RO	4,992	24	208
Total	581,121	45	12,914

Case-Averaged Number of Observations



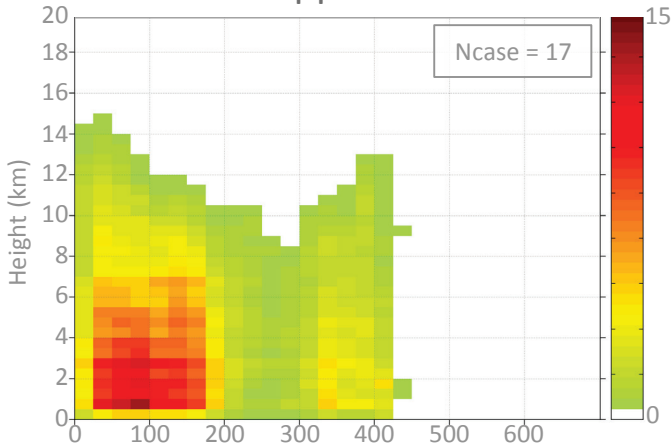
Case-Averaged Number of Observations



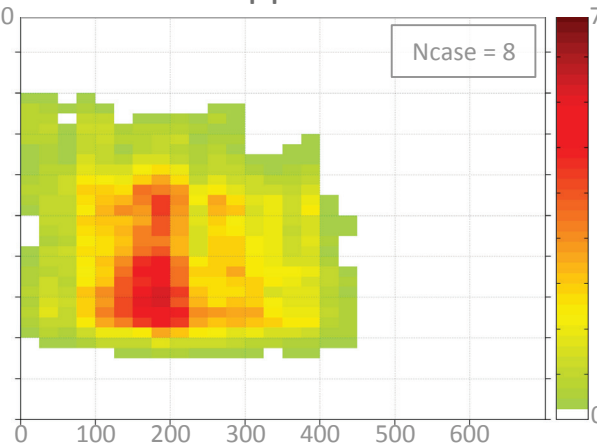
HEDAS CASES in 2013 – OBS. LOCATIONS

WIND OBS. (Case-averaged ob. density within 25 km radius, 0.5 km height)

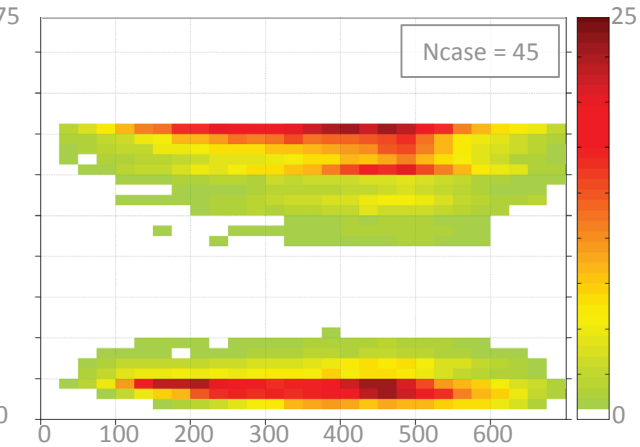
P-3 Doppler Radar



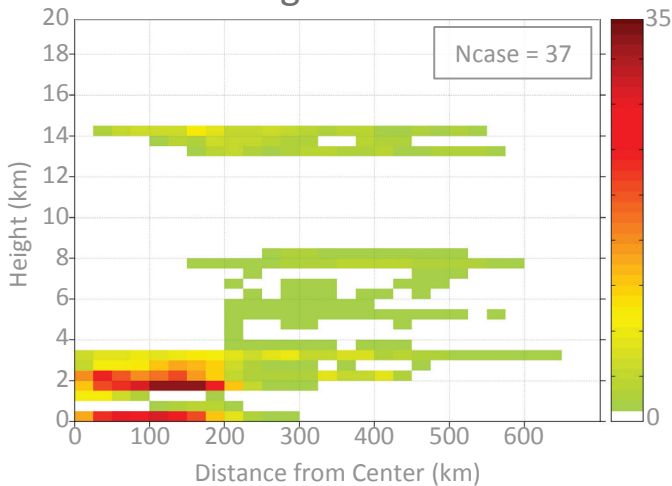
G-IV Doppler Radar



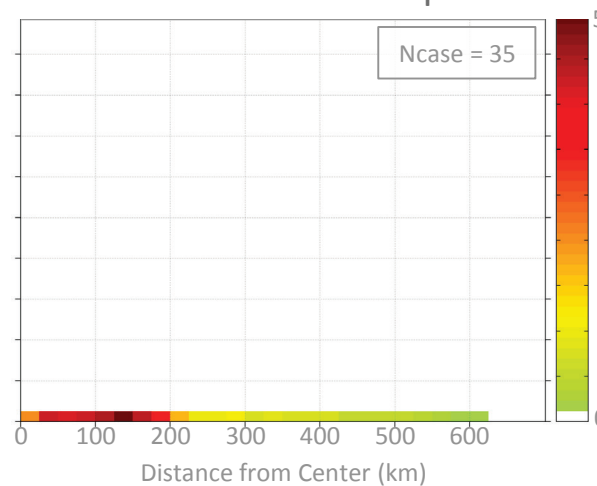
Atm. Motion Vectors



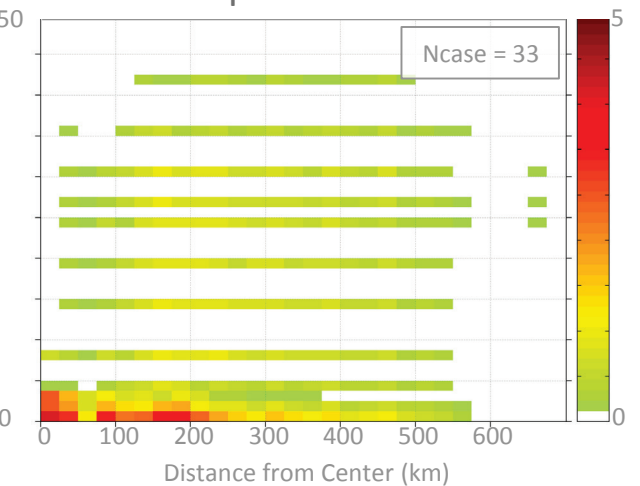
Flight Level



SFMR Surface Wind Speed

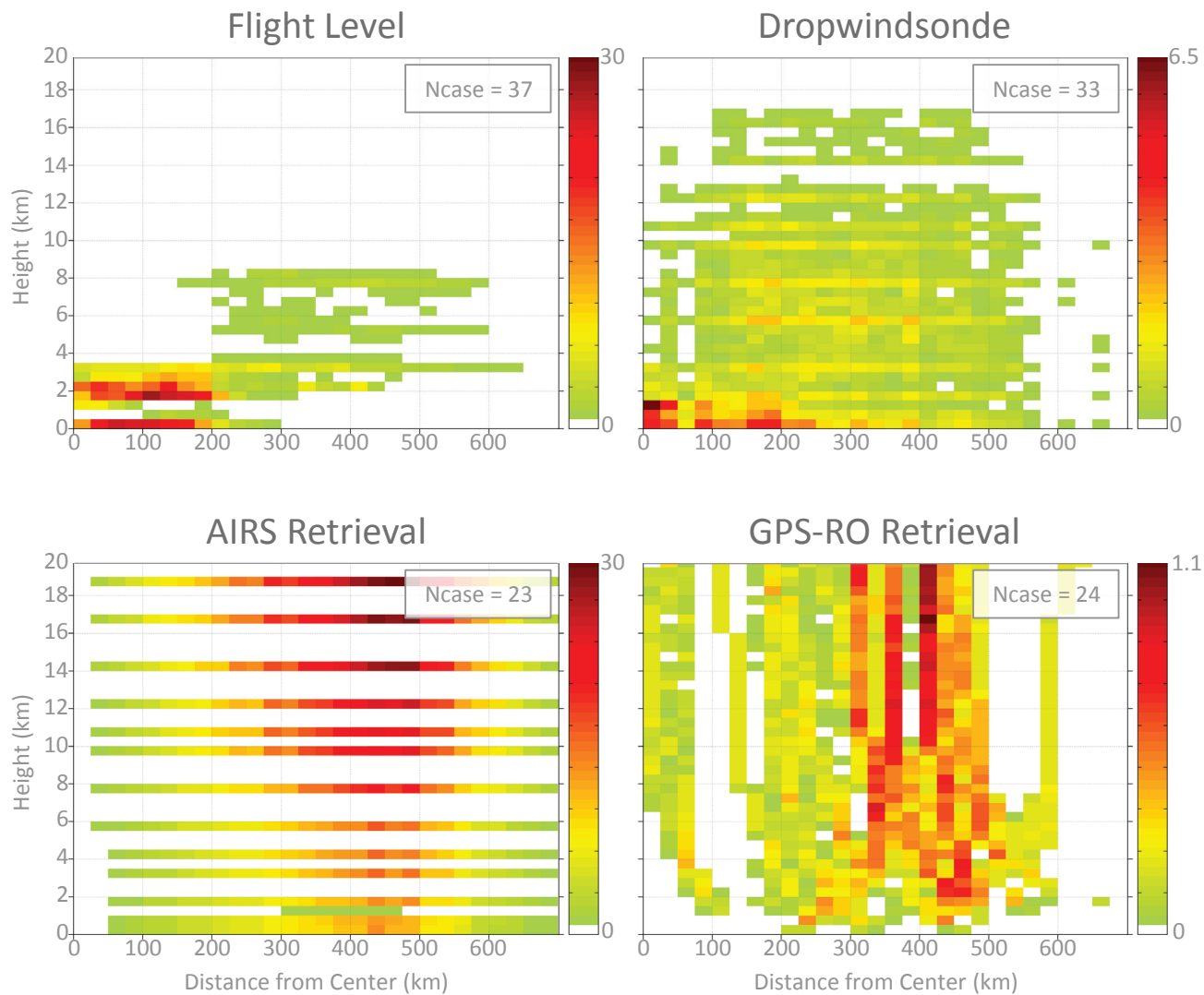


Dropwindsonde



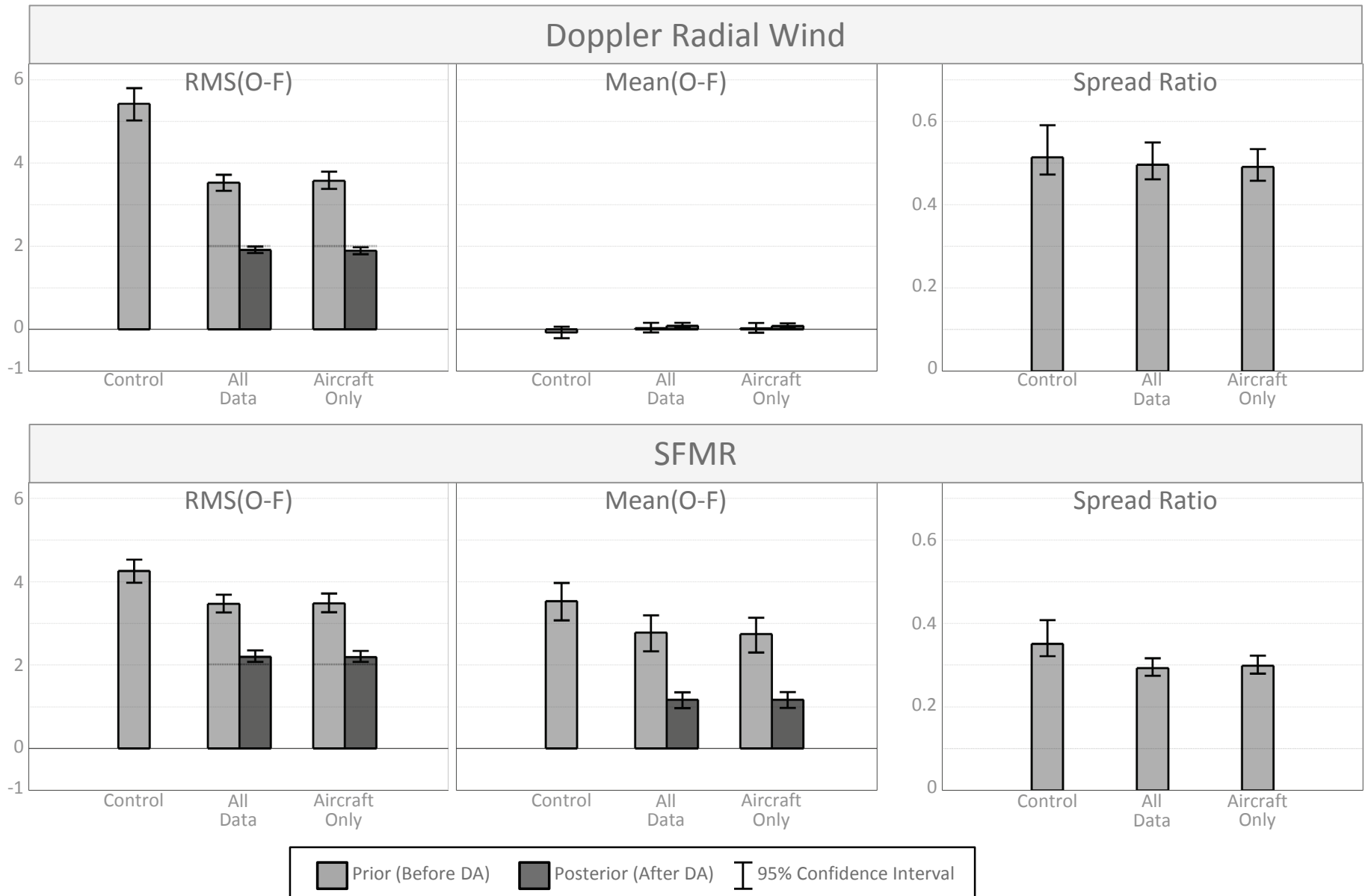
HEDAS CASES in 2013 – OBS. LOCATIONS

THERMO. OBS. (Case-averaged ob. density within 25 km radius, 0.5 km height)



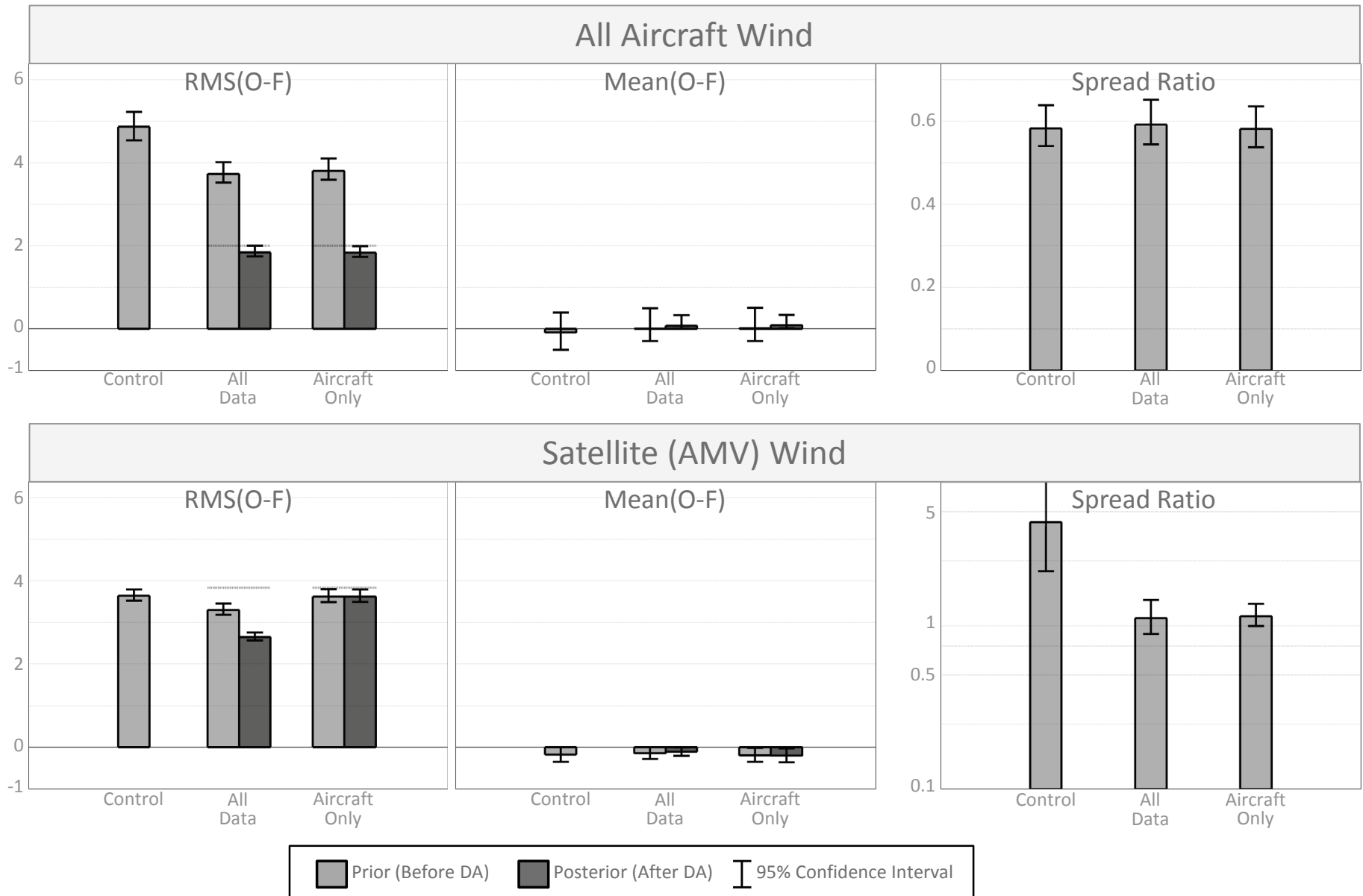
HEDAS CASES in 2013 – DIAGNOSTICS

INNOVATION (O-F) DIAGNOSTICS over CYCLES 2-5



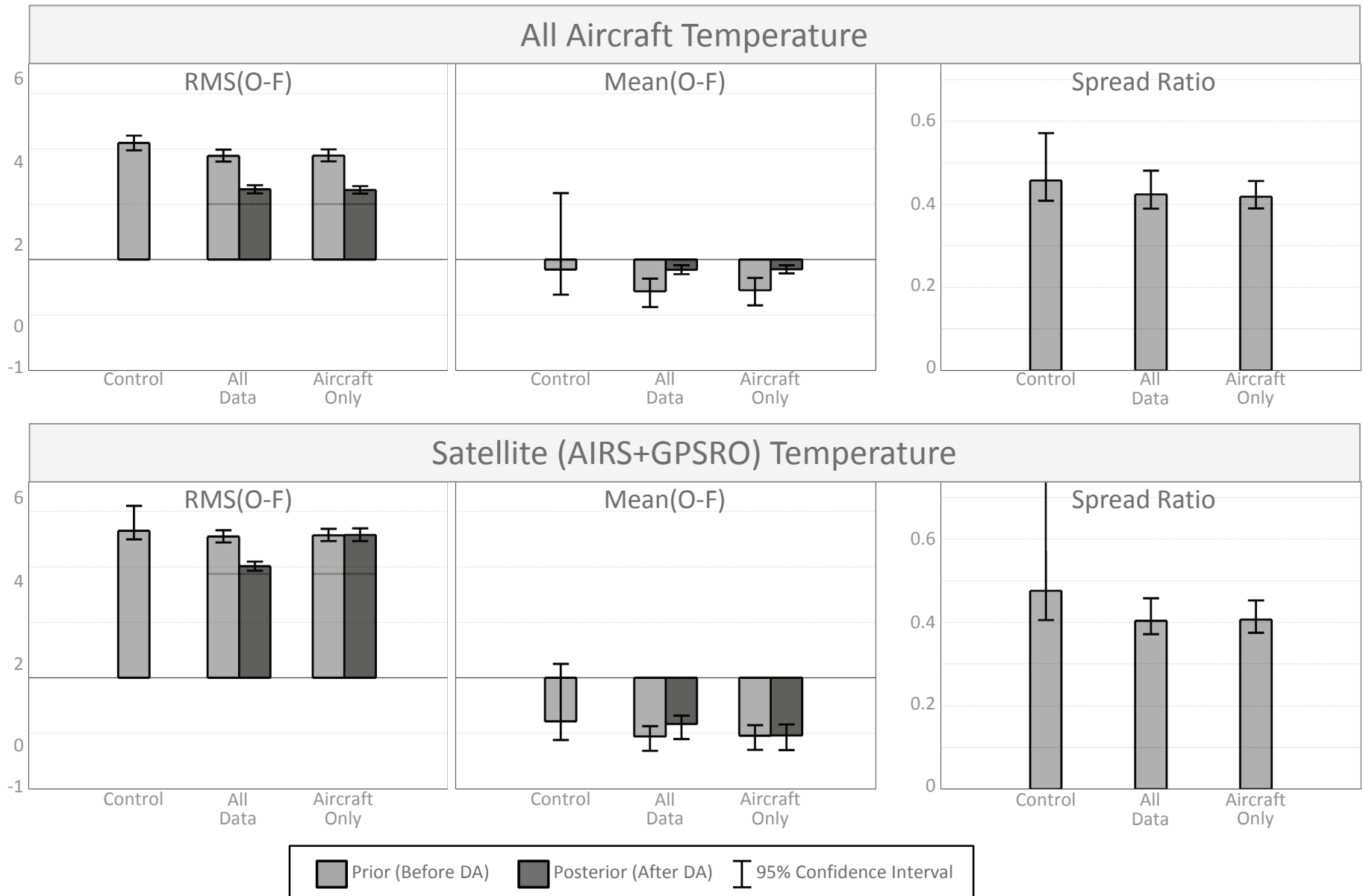
HEDAS CASES in 2013 – DIAGNOSTICS

INNOVATION (O-F) DIAGNOSTICS over CYCLES 2-5



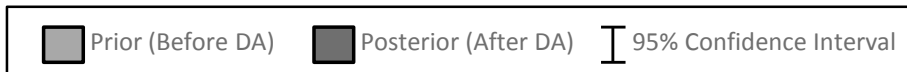
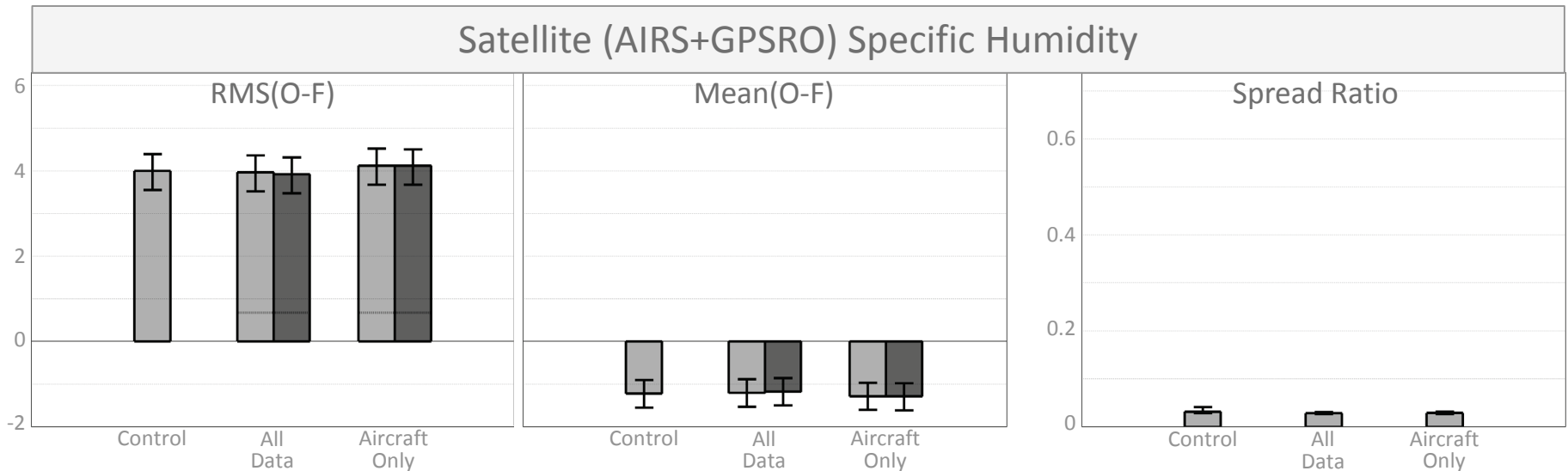
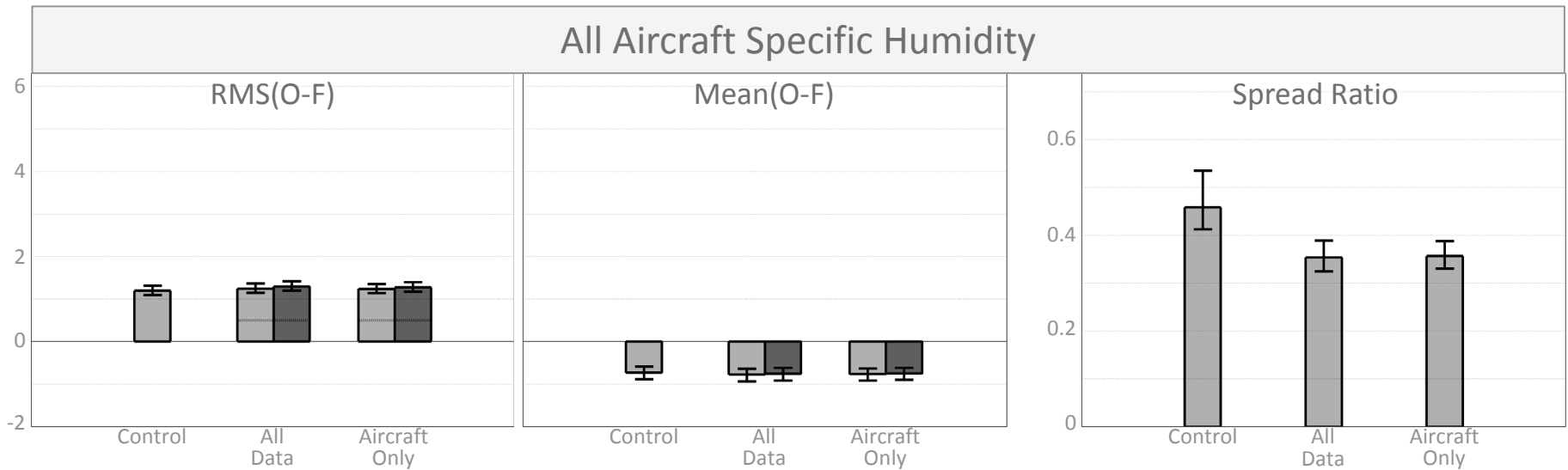
HEDAS CASES in 2013 – DIAGNOSTICS

INNOVATION (O-F) DIAGNOSTICS over CYCLES 2-5



HEDAS CASES in 2013 – DIAGNOSTICS

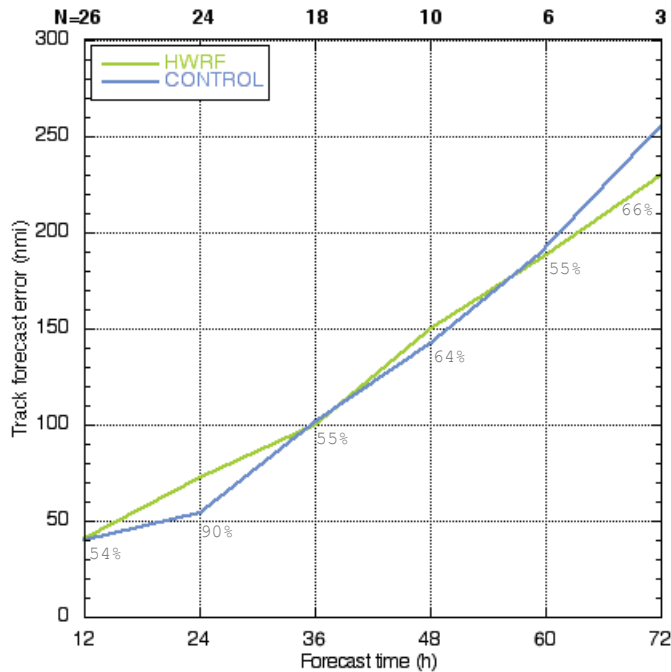
INNOVATION (O-F) DIAGNOSTICS over CYCLES 2-5



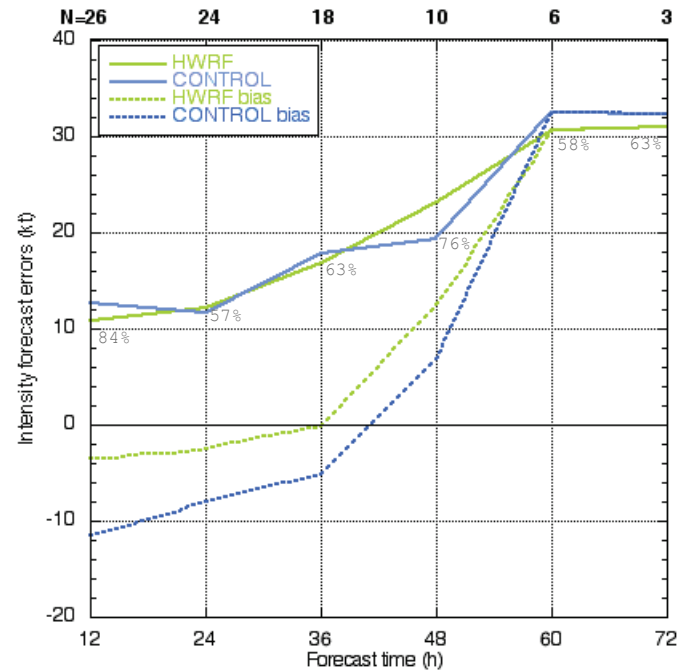
HEDAS CASES in 2013 – FORECAST RESULTS

TWO-WAY: CONTROL (NO DA) vs. OPERATIONAL HWRF

Track Error



Intensity Error

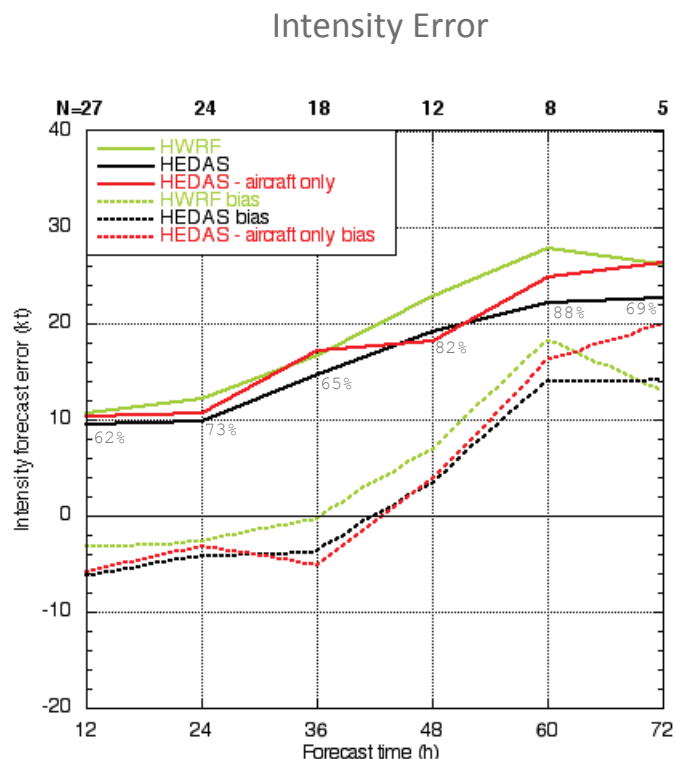
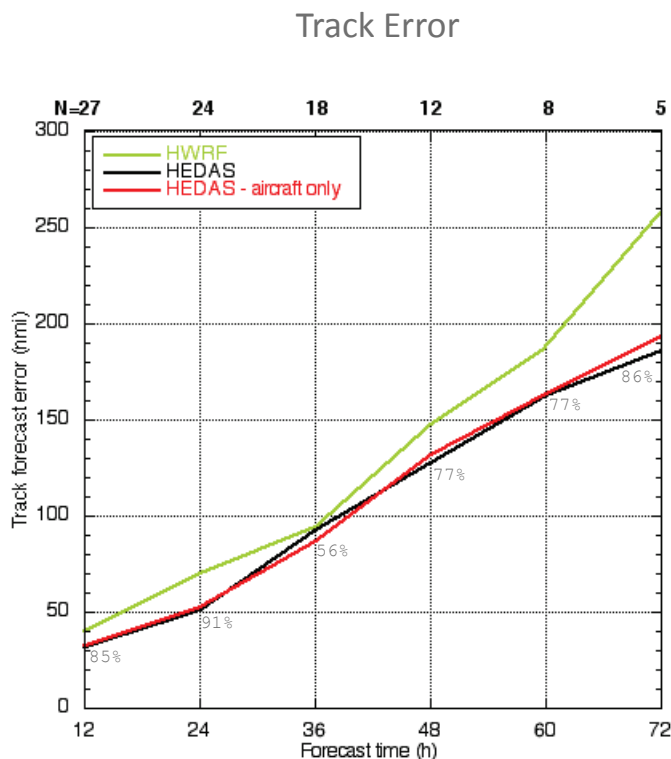


(Statistical Significance indicated as % underneath error curves)

While mean absolute errors of track and intensity are generally not very different, HWRf has smaller bias up to ~48 h.

HEDAS CASES in 2013 – FORECAST RESULTS

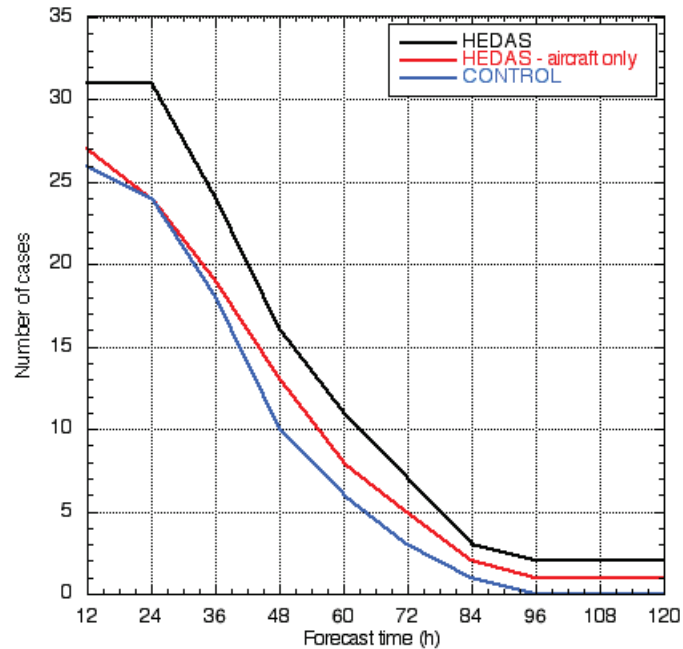
THREE-WAY: HEDAS ALL DATA vs. HEDAS AIRCRAFT ONLY vs. OPERATIONAL HWRF



(Statistical Significance indicated as % underneath error curves for HWRf vs. HEDAS)

Both HEDAS flavors performed better than HWRf for track (but low statistical significance). In intensity, HEDAS flavors performed better in terms of mean absolute error, but with higher negative bias out to ~36 h. Addition of satellite data to “traditional” aircraft dataset also improved HEDAS performance.

NUMBER OF CASES VERIFIED



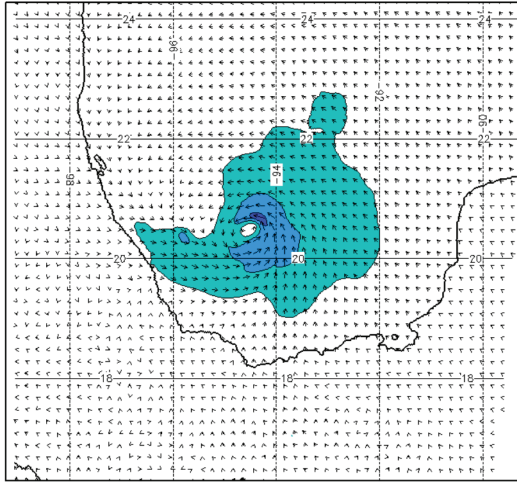
An additional benefit of satellite data was in the number of cases that were tracked, indicating that the initial vortex analysis with satellite data had a higher likelihood of “surviving” at later forecast times.

HEADAS CASES in 2013 – CASE STUDY 1

INGRID10L 09/14 12Z

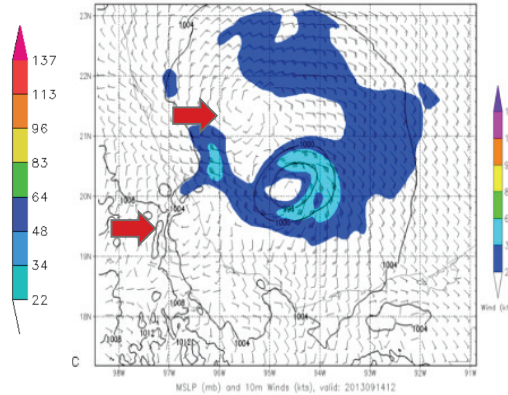
HEADAS

10-m wind-speed [kt]



HWRP

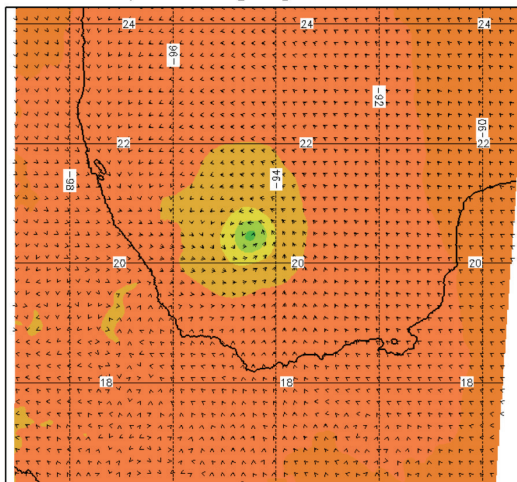
NCEP HWRP - INGRID10L 2013091412 - F000



Erroneous triple vortex structure in HWRP initial conditions.

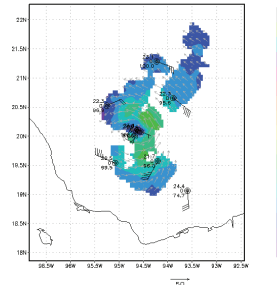
Maximum wind speed: 55.5273 kt Initial date: 2013091412

Mean sea-level pressure [mb]



RADAR

20130914H1 INGRID at 0.5 km (m/s)
Valid: 201309141029



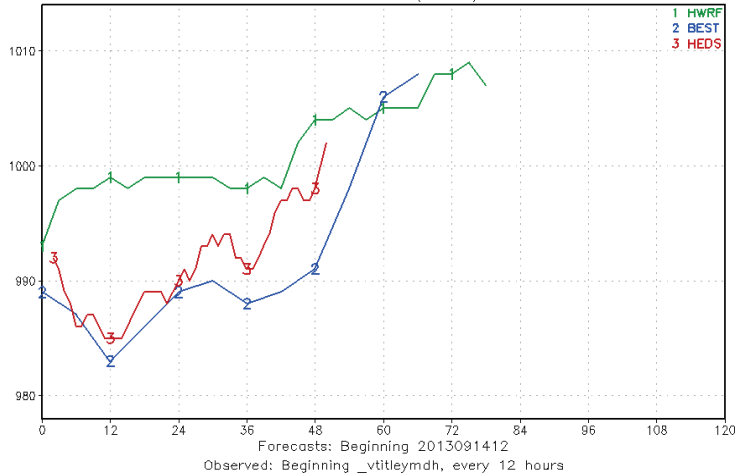
Minimum pressure: 991.524 mb Initial date: 2013091412

HEADAS CASES in 2013 – CASE STUDY 1

INGRID10L 09/14 12Z

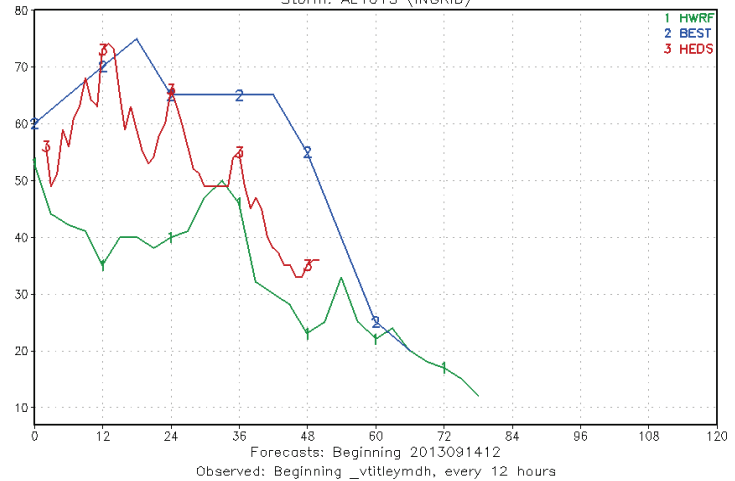
Intensity

2013 Tropical Cyclone Tracks
Storm: AL1013 (INGRID)



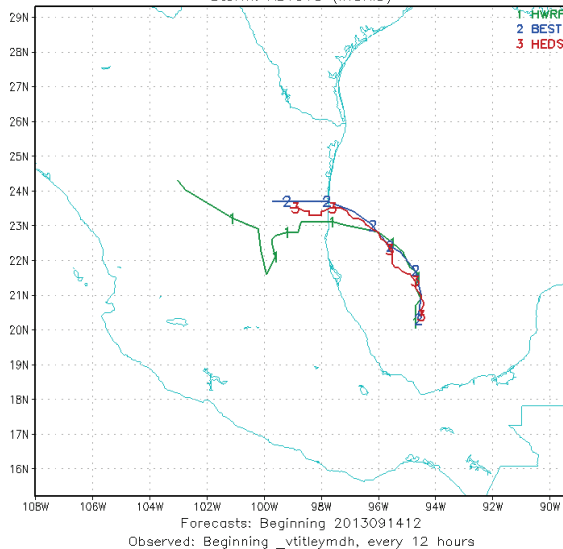
MSLP

2013 Tropical Cyclone Tracks
Storm: AL1013 (INGRID)



Track

2013 Tropical Cyclone Tracks
Storm: AL1013 (INGRID)

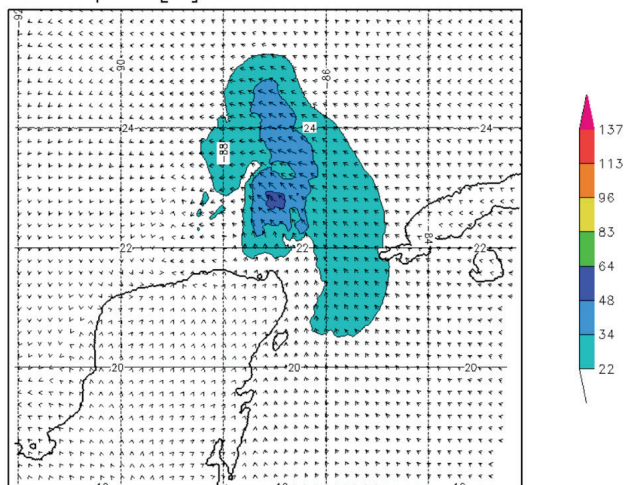


Structural improvements appear to have resulted in better track & intensity forecast in HEADAS

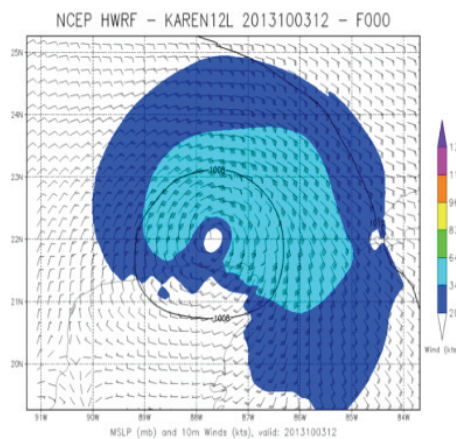
KAREN12L 10/03 12Z

HEADAS

10-m wind-speed [kt]

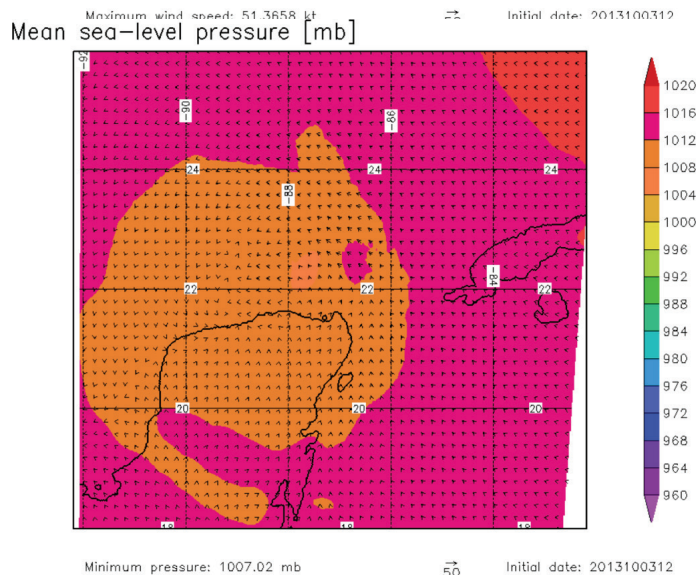


HWRF

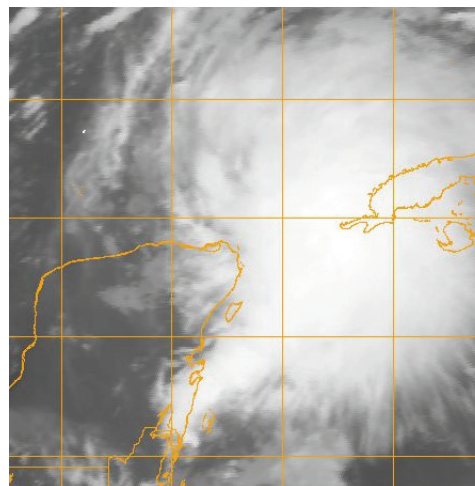


Symmetric vortex structure in HWRF initial conditions.

Mean sea-level pressure [mb]



Satellite IR



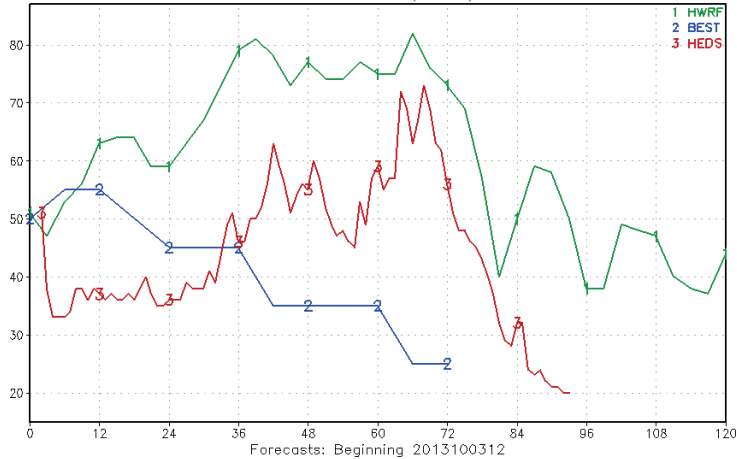
[Credit: Sim Aberson (HRD)]

HEADAS CASES in 2013 – CASE STUDY 2

KAREN12L 10/03 12Z

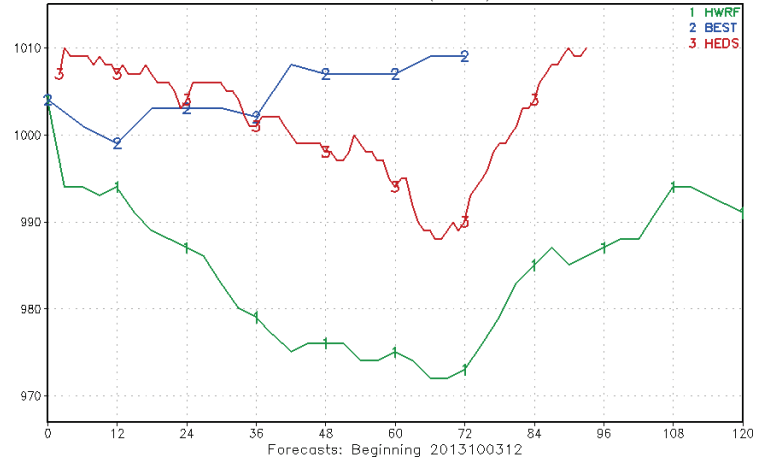
Intensity

2013 Tropical Cyclone Tracks
Storm: AL1213 (KAREN)



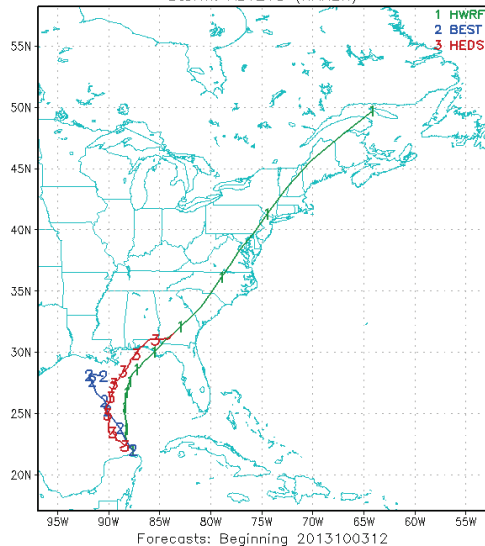
MSLP

2013 Tropical Cyclone Tracks
Storm: AL1213 (KAREN)



Track








2013 Tropical Cyclone Tracks
Storm: AL1213 (KAREN)









Structural improvements appear to have resulted in better track & intensity forecast in HEADAS for the first 36 h.

HWRF PARAMETER SENSITIVITY

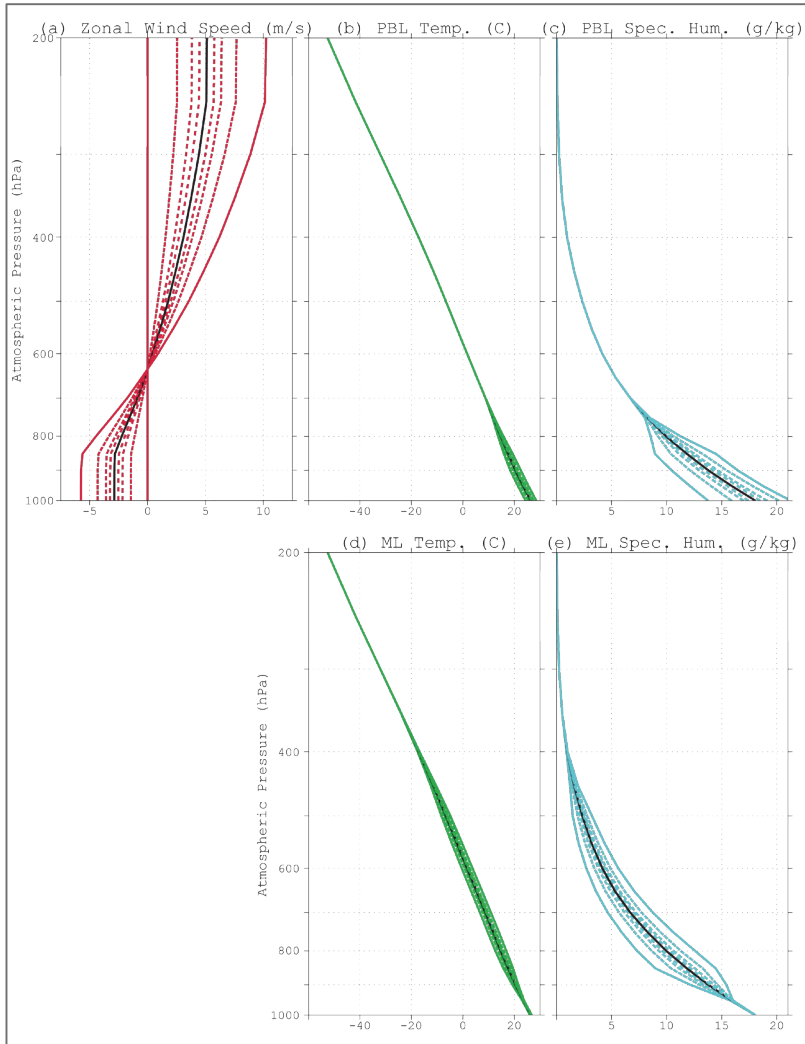
- An idealized version of HWRF is developed based on Gopalakrishnan et al. (2011, *MWR*) and Bao et al. (2012, *MWR*):
 - Repository version of idealized HWRF + 2012 operational physics configuration at 27/9/3 km resolution
 - Entire globe assigned Dunion (2011, *J. Clim.*) moist tropical sounding & mass adjustment in the meridional direction following Nolan (2011, *JAMES*) to balance westerly shear
 - Coupled with one-dimensional HYCOM ocean model [Credit: George Halliwell (AOML/PhOD)]
 - Initialized with observation-based composite vortex
 - 5-day simulations (13 parameters x 8 perturbation realizations + 1 control)

		PARAMETER PERTURBATION REALIZATIONS								
						Control				
1. Storm Environment										
- Zonal Westerly Shear (m/s)		0	4	6	7	8	9	10	12	16
- Westward Storm Speed (m/s)		0	2.5	3.75	4.375	5	5.625	6.25	7.5	10
- SST (C)		27	28	28.5	28.75	29	29.25	29.5	30	31
- Moisture Perturbations in PBL (%RH)		-20	-10	-5	-2.5	0	+2.5	+5	+10	+20
- Moisture Perturbations in ML (%RH)		-20	-10	-5	-2.5	0	+2.5	+5	+10	+20
- Temperature Perturbations in PBL (K)		-2	-1	-0.5	-0.25	0	+0.25	+0.5	+1	+2
- Temperature Perturbation in ML (K)		-2	-1	-0.5	-0.25	0	+0.25	+0.5	+1	+2

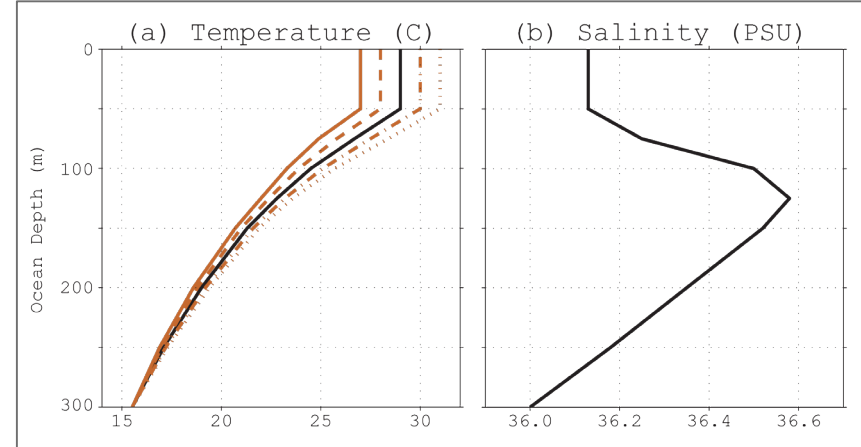
2. Initial Vortex										
- Vortex Size (RMW, km)		15	30	37.5	41.25	45	48.75	52.5	60	75
- Initial Intensity (kt)		65	75	80	82.5	85	87.5	90	95	105

3. Model Parameters										
- Vertical Eddy Diffusivity Multiplier		0.1	0.3	0.4	0.45	0.5	0.55	0.6	0.7	0.9
- Horizontal Diffusivity (namelist)		0	0.375	0.5625	0.6563	0.75	0.8438	0.9375	1.125	1.5
- Momentum Flux Multiplier		0.5	0.75	0.875	0.9375	1	1.0625	1.125	1.25	1.5
- Enthalpy Flux Multiplier		0.5	0.75	0.875	0.9375	1	1.0625	1.125	1.25	1.5

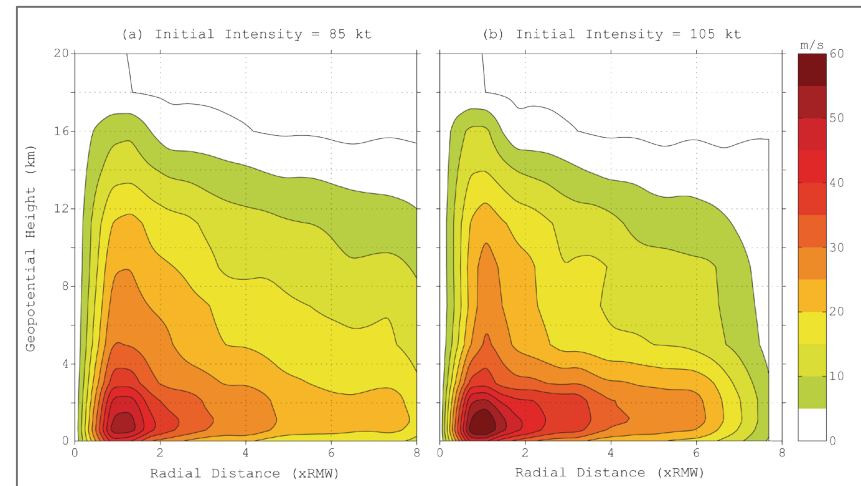
Atmospheric Environment Perturbations



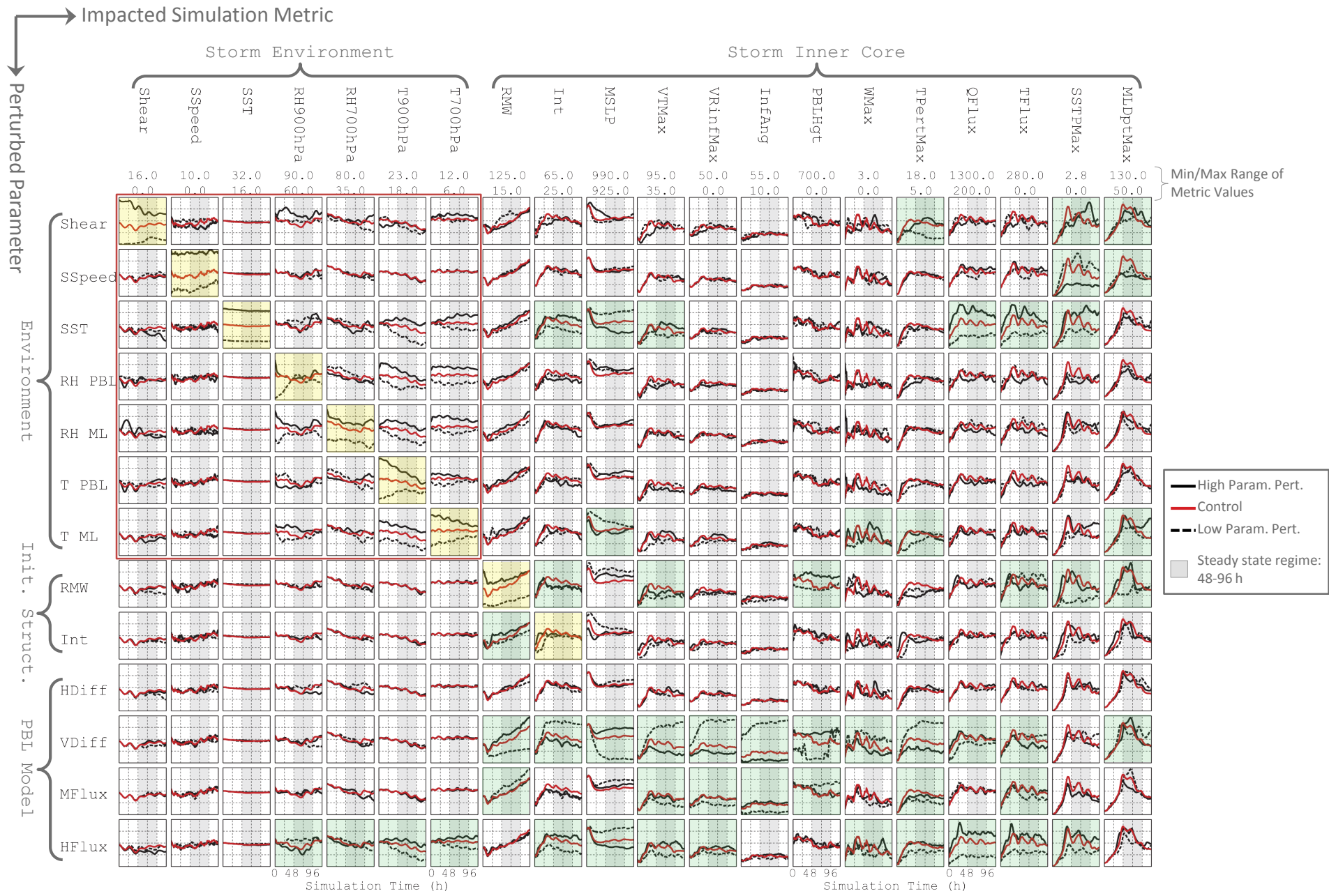
Ocean Perturbations



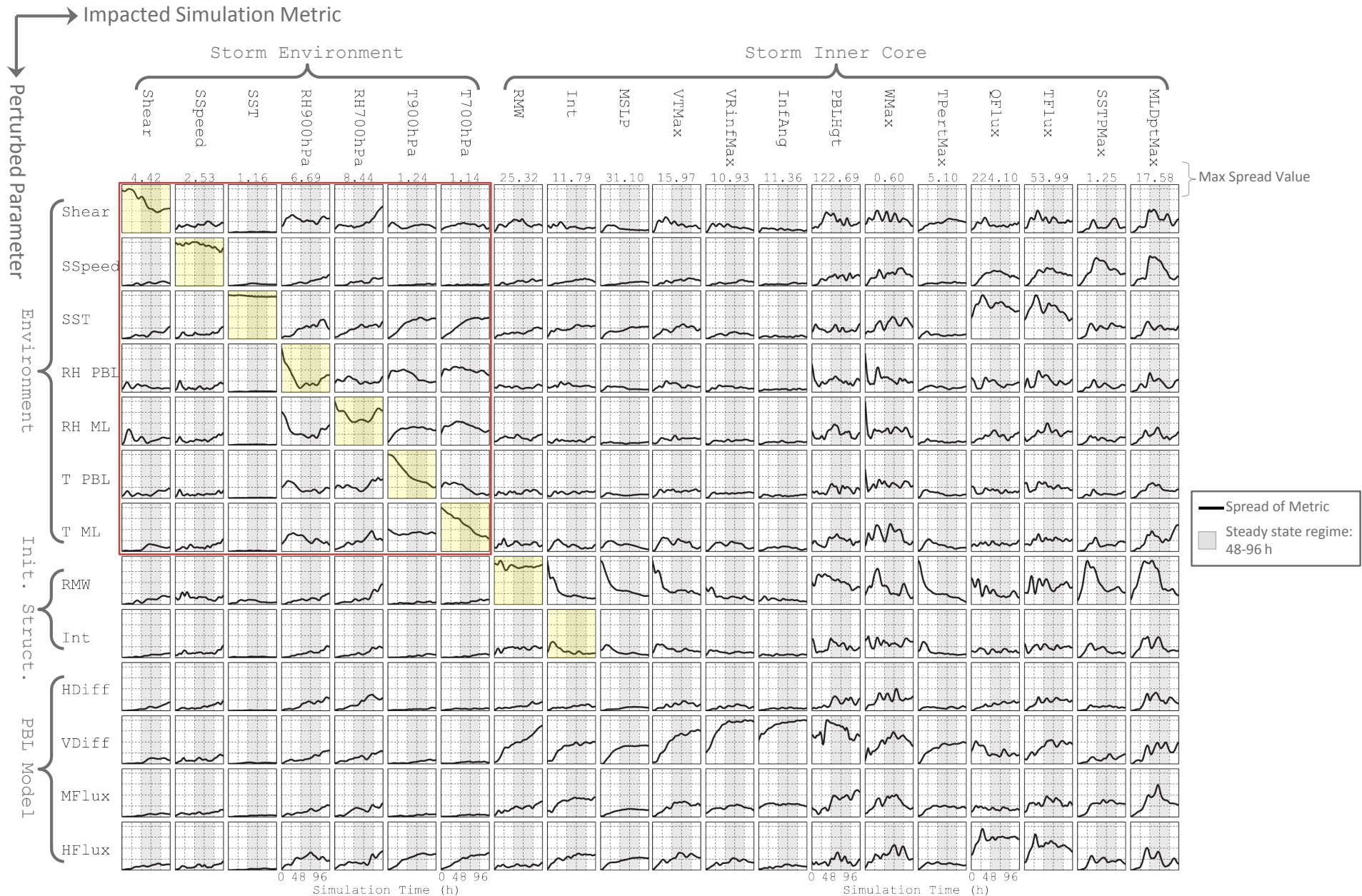
Initial Vortex Perturbations



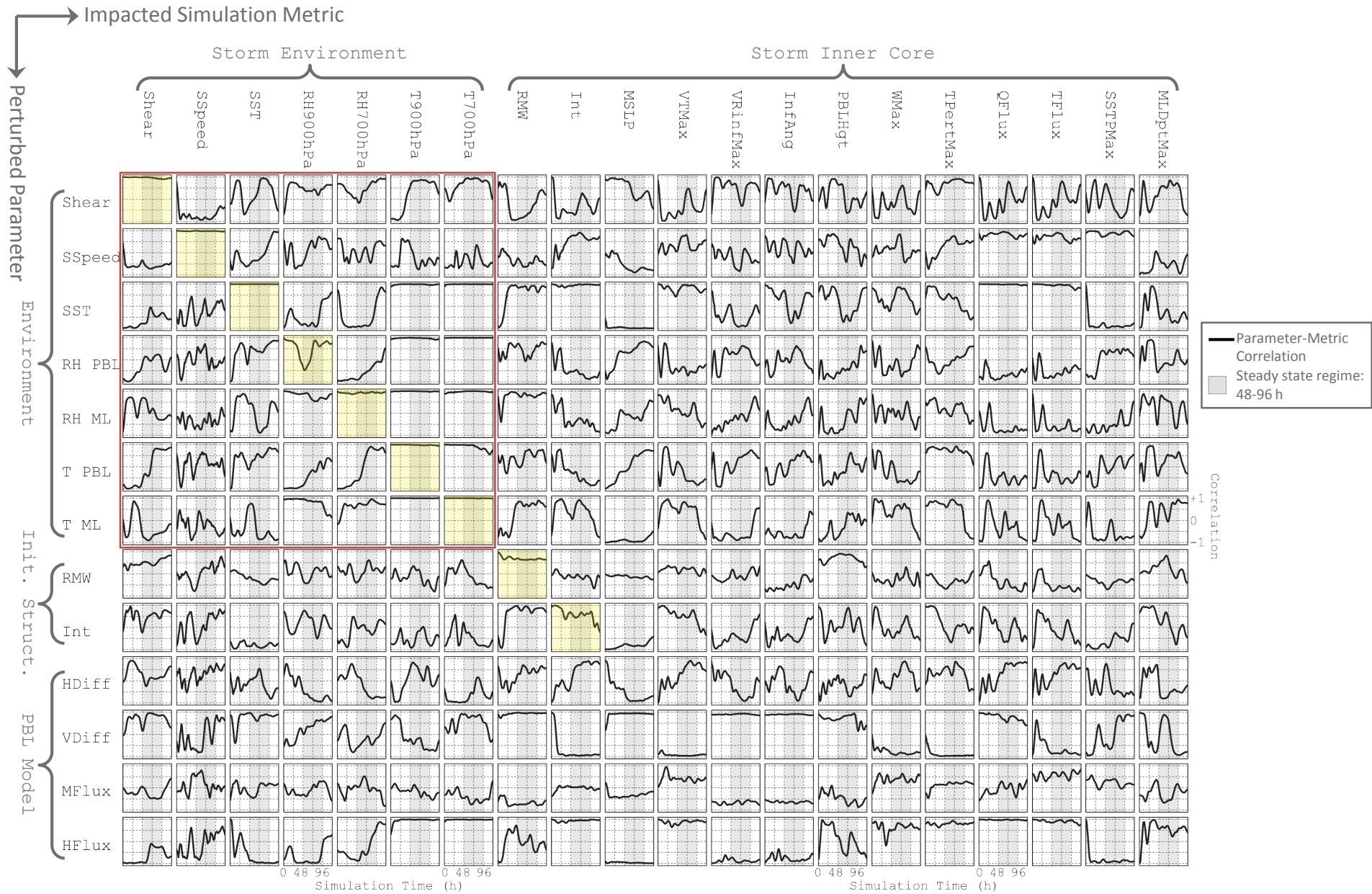
HWRF PARAMETER SENSITIVITY



SPREAD FROM PARAM. PERTURBATIONS



PARAMETER-SIMULATION CORRELATIONS



CORRELATION COEFFICIENT

- Indicates linear statistical relationship for a given metric and parameter combination
(example: metric = intensity, parameter = shear)
- For each available time frame, computes correlation based on available samples between metric and parameter as a result of perturbations in that parameter
- Differences are normalized by the variances

$$C_{p,M}^t = \frac{1}{N_r} \frac{\sum_{r=1}^{N_r} (M_r^t - \bar{M}^t)(p_r^t - \bar{p}^t)}{\sigma_M^t \cdot \sigma_p^t}$$

M: Metric (intensity, MSLP, etc.)

p: Parameter (shear, C_{dr} , etc.)

r: Specific realization of parameter perturbation

t: Time

- Correlation coefficient averaged over 48-96 h and multiple metrics for cumulative impact:

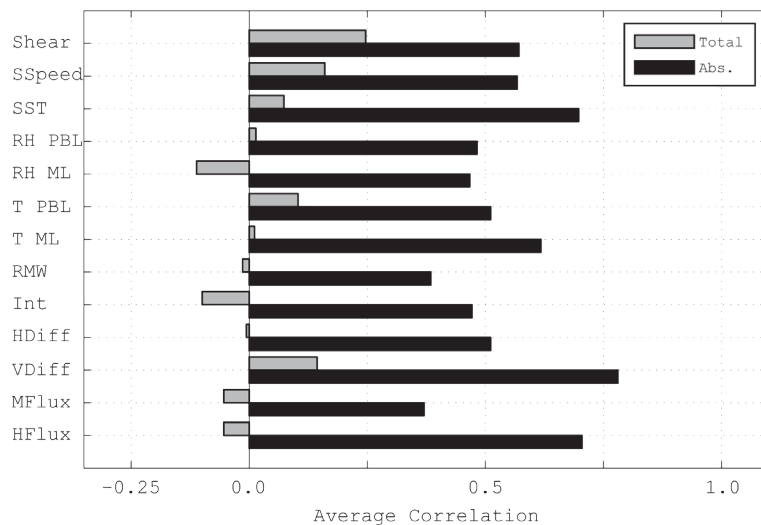
$$C_p = \frac{1}{N_m} \sum_{M=1}^{N_m} \left[\frac{1}{N_t} \sum_{t=1}^{N_t} C_{M,p}^t \right]$$

Metrics included in calculation:

Environment	Structure	
Shear magnitude	Intensity	Max. Core T Pert.
Shear direction	MSLP	RMW
Storm speed	Max. Vt	Latent heat flux
Storm direction	Max. Vr-Inflow	Sensible heat flux
SST	Inflow Angle	Max. SST Pert.
	PBL height	Max. Mixed Layer Depth
	Max. W	

↓ Perturbed Parameter

Cumulative Correlation Coefficient



Strongest Cumulative Correlations

Absolute	Total
VDiff	Shear (+)
HFlux	Sspeed (+)
SST	Vdiff (+)
T ML	RH ML (-)
Shear	Int (-)
SSpeed	

RESPONSE FUNCTION – Similar to Tong and Xue (2008, MWR)

- Works for a given metric and parameter combination
(*example: metric = intensity, parameter = shear*)
- Compares the time series of the metric from a run with a realization of the parameter perturbation vs. the control run
(*example: realization of shear = 12 m/s*)
- Differences are normalized by the variance of the control time series for fair comparison
- For display convenience, $\log_{10}(J)$ will be plotted

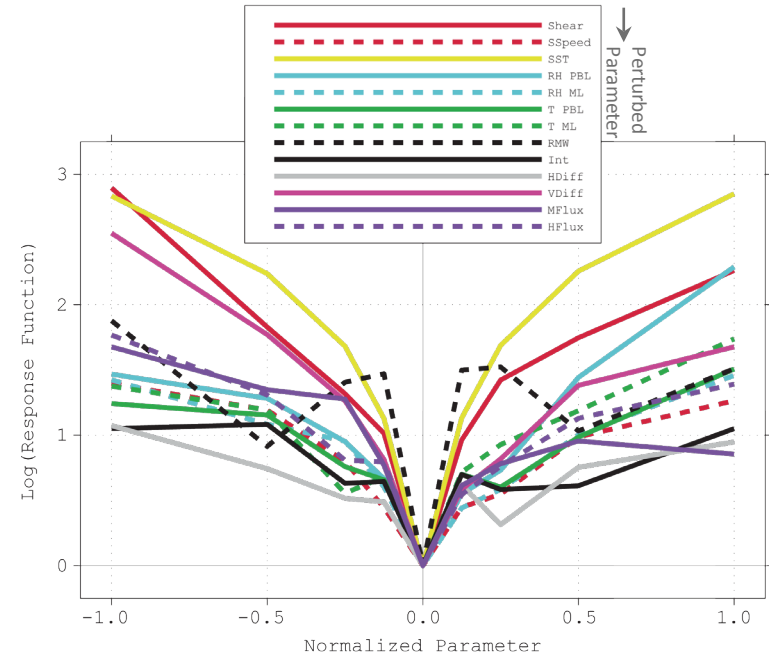
$$J_{M,p}^r = \frac{1}{\langle \sigma \rangle_{M,c}^2} \left[\frac{1}{N_t} \sum_{t=1}^{N_t} (M_p^{r,t} - M_c^{r,t})^2 \right]$$

M: Metric (intensity, MSLP, etc.)
p: Parameter (shear, C_d , etc.)
r: Specific realization of parameter perturbation
c: Control
t: Time -> 48-to-96-h hourly output

- Response function averaged over multiple metrics for cumulative impact:

Environment	Structure	
Shear magnitude	Intensity	Max. Core T Pert.
Shear direction	MSLP	RMW
Storm speed	Max. Vt	Latent heat flux
Storm direction	Max. Vr-Inflow	Sensible heat flux
SST	Inflow Angle	Max. SST Pert.
	PBL height	Max. Mixed Layer Depth
	Max. W	

Cumulative Response Function



Strongest Cumulative Correlations		Strongest Response Function
Absolute	Total	
VDiff	Shear (+)	SST
HFlux	Sspeed (+)	Shear
SST	Vdiff (+)	VDiff
T ML	RH ML (-)	HFlux
Shear	Int (-)	RH PBL
SSpeed		RMW

- How to incorporate the various measures of sensitivity in a well-calibrated ensemble?
- A natural starting point would be some measure of spread that can be compared for various perturbed parameters (plotted as “Total” in figure):

$$\tilde{\sigma}_p = \frac{1}{N_m} \sum_{M=1}^{N_m} \left[\frac{\frac{1}{N_t} \sum_{t=1}^{N_t} \sigma_{M,p}^t}{\bar{\sigma}_M^{\max}} \right]$$



For each perturbed parameter (p):

- Calculate time-averaged spread for each metric M
- Normalize by max. spread across all parameters (so that the relative impact of the parameter on that metric can be detected)
- Average over all metrics

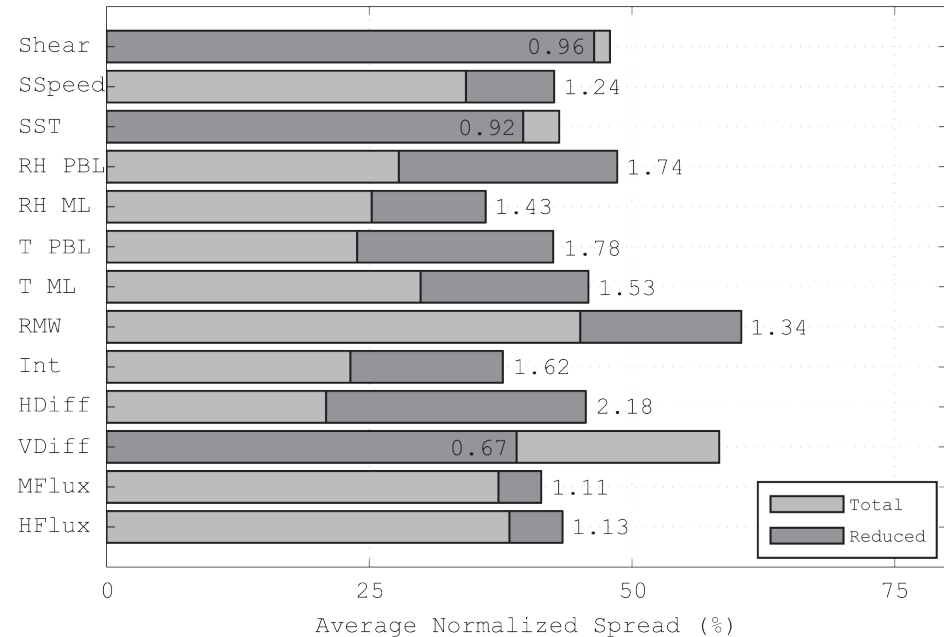
- But even when normalized, this is not a fair comparison of spreads, because the normalization factors themselves are also impacted by the (somewhat) arbitrarily chosen parameter perturbation magnitudes.
- Response function is hypothesized to be of value in accounting for the spread variability due to arbitrary nature of parameter perturbation magnitudes (plotted as “Reduced” in figure):

$$\bar{\sigma}_{M,p}^{red} = r_{M,p}^J \cdot \bar{\sigma}_{M,p} \quad \text{where} \quad r_{M,p}^J = \tilde{p}_{int} (\log_{10} J_p^M = 0.5)$$

For each (M,p) pair, apply a “reduction” factor to the time-averaged spread as follows:



- Calculate average “regressed” normalized parameter range that corresponds to $\log_{10}(J)$ value of 0.5 (this value chosen to ensure regression does not yield extrapolation)
- Use normalized parameter range as the reduction factor to modify spread values



Reduced spread shows much smaller variability across perturbed parameters, an indication of better-calibrated overall spread. (RMW spread reduction doesn't work well likely because of unusual response function behavior at small parameter perturbation values.)

- HEDAS ran near real time for 45 cases in 2013 (storm.aoml.noaa.gov/hedas)
- Assimilated satellite AMVs as well AIRS and GPS-RO retrieved thermodynamic profiles for the first time this year
- Overall, both aircraft-only and all-data HEDAS experiments demonstrated improved track and intensity errors compared to operational HWRF
- Two areas that remain unresolved:
 - Assimilation of thermodynamic information, especially moisture
 - Insufficient ensemble spread
- For ensemble spread, our results from perturbing model parameters indicate that they provide valuable ensemble variability comparable to “traditional” perturbations in environment or initial vortex
- We plan to utilize the response function approach to calibrate for spread from various sources
- Near-future plans:
 - Apply calibrated spread approach to simultaneous perturbations
 - Apply parameter perturbations in 2014 HEDAS ensemble
 - Apply better calibrated observation errors