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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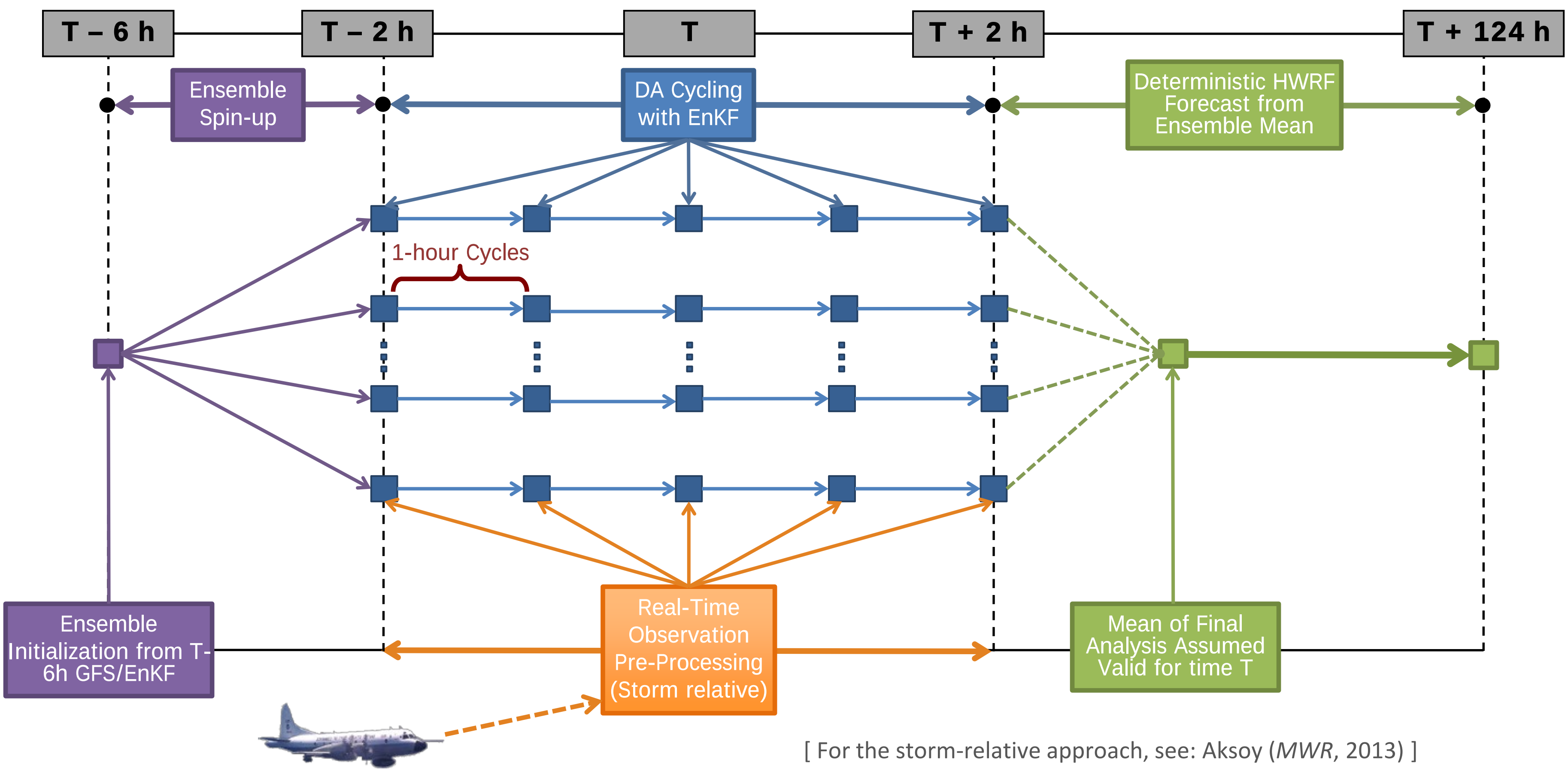
HEDAS CONFIGURATION in 2013

- 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)



[For the storm-relative approach, see: Aksoy (*MWR*, 2013)]

HEDAS CASES in 2013

		FLIGHT LEVEL				SFMR			Dropsondes					Doppler Superobs				Satellite	Satellite	
STORM	DATE	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	Satellite AMVs	AIRS Retrievals	GPS-RO Retrievals	Total
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	35	0	**35**	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

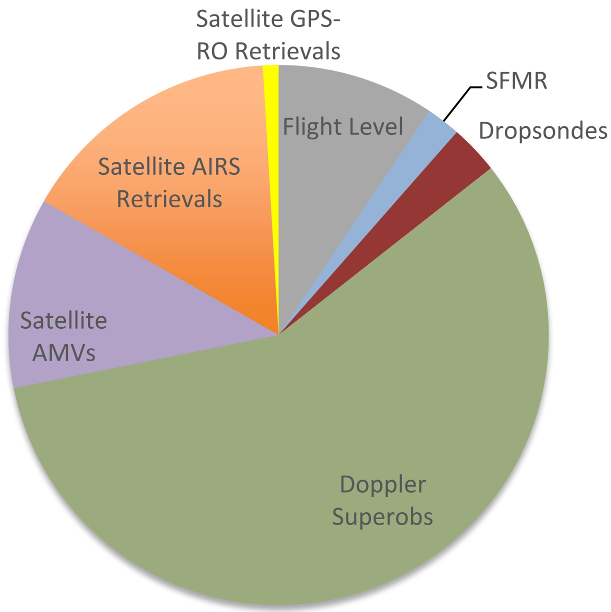
By Observing Platform

Platform	Num. Obs.	Num. Cases	Avg. Num. Obs.
Flight Level	77,304	37	2,089
SFMR	15,805	35	452
Dropsondes	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**

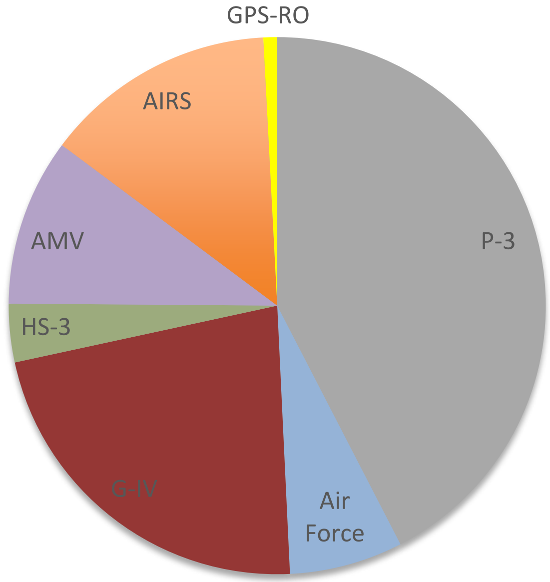
By Observing Aircraft

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

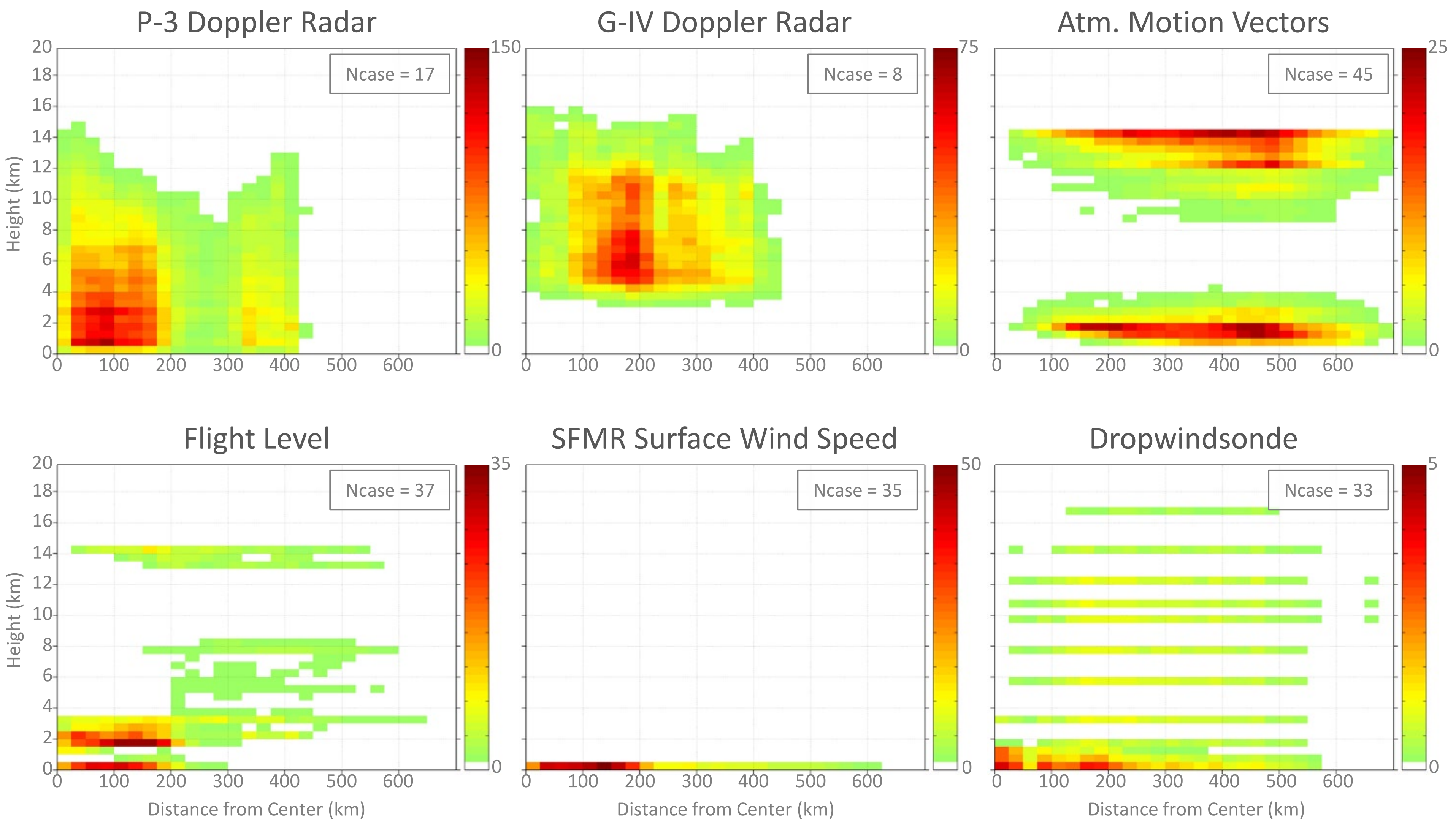


Case-Averaged Number of Observations



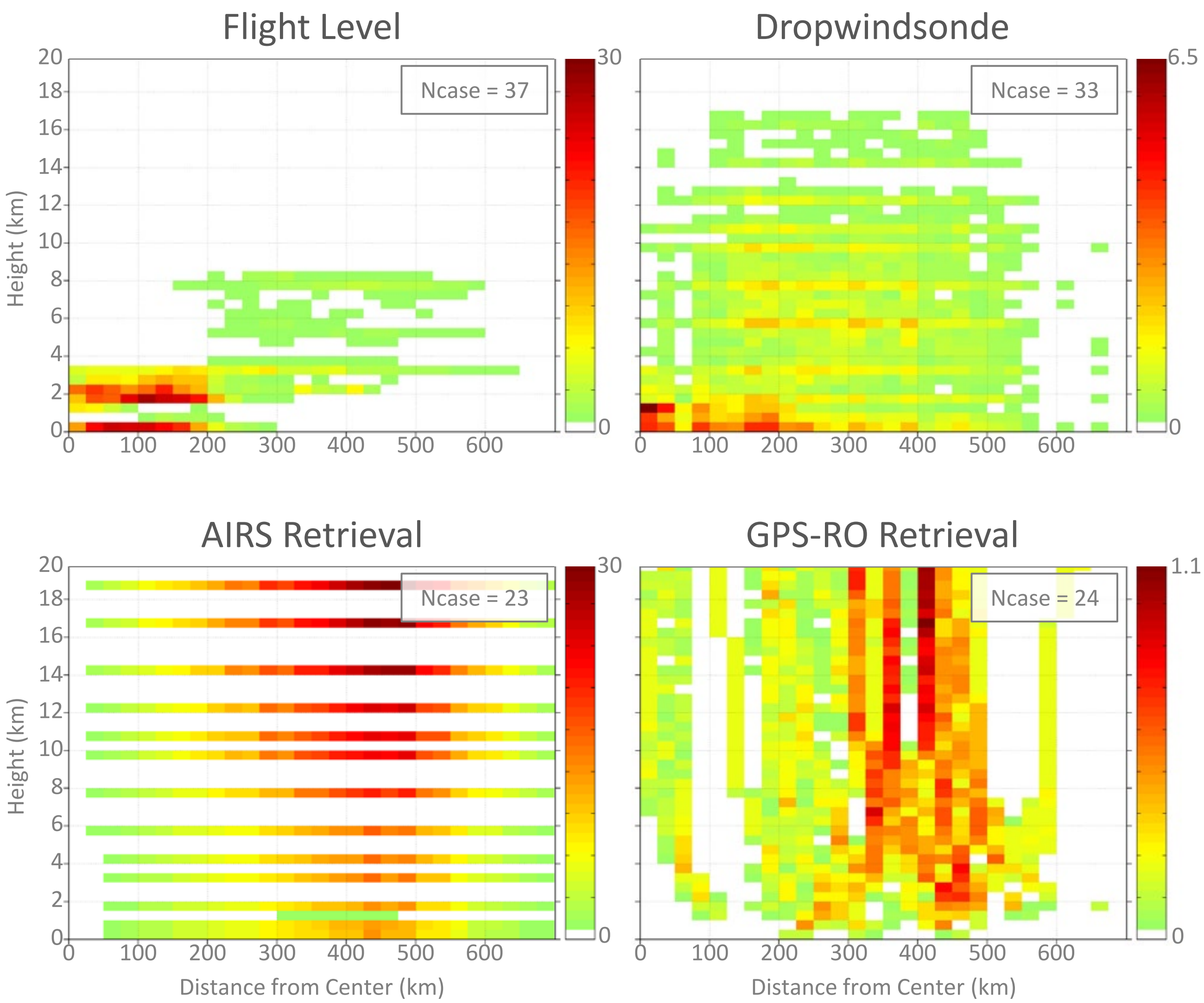
HEDAS CASES in 2013 – OBS. LOCATIONS

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



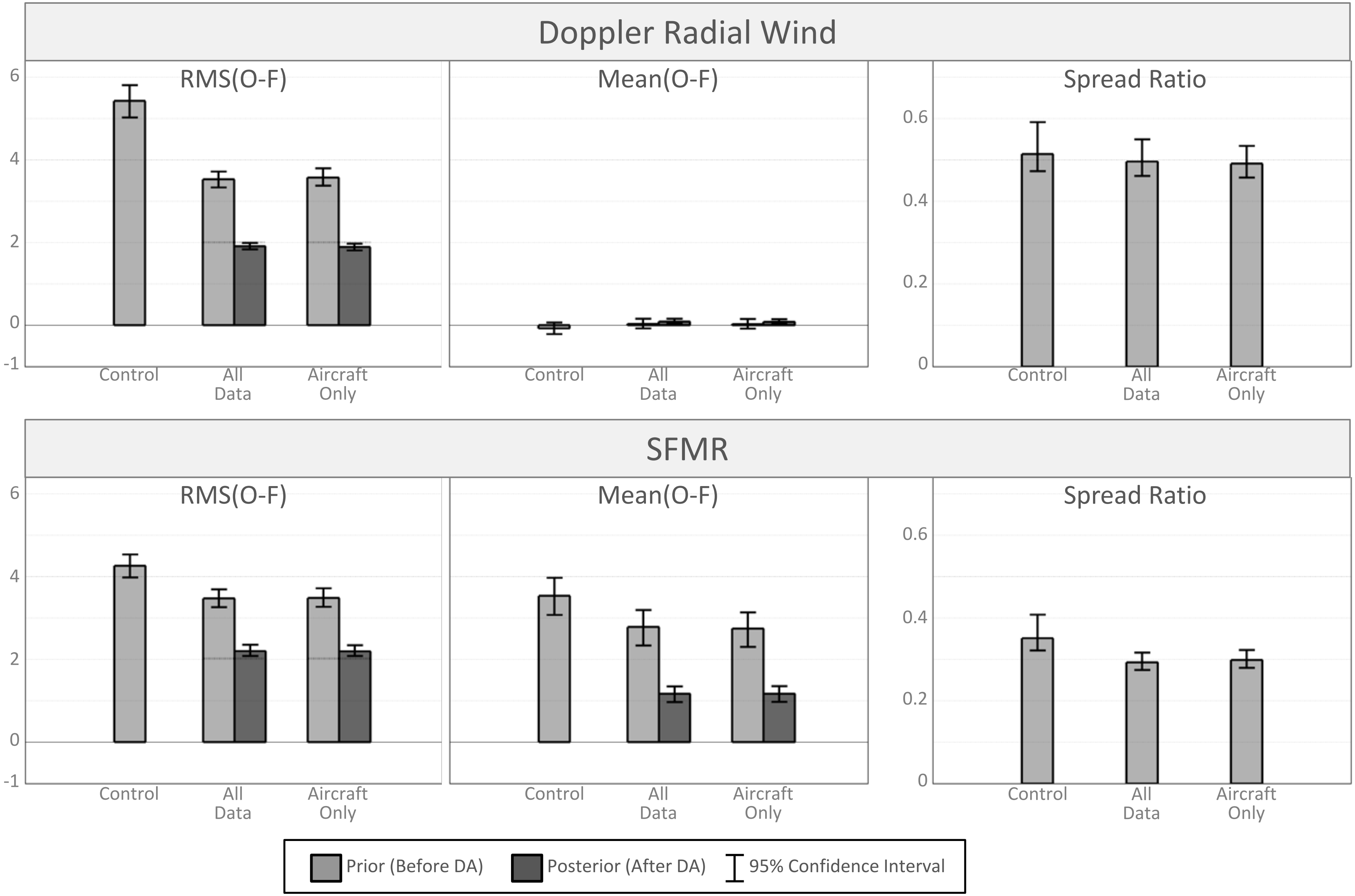
HEDAS CASES in 2013 – OBS. LOCATIONS

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



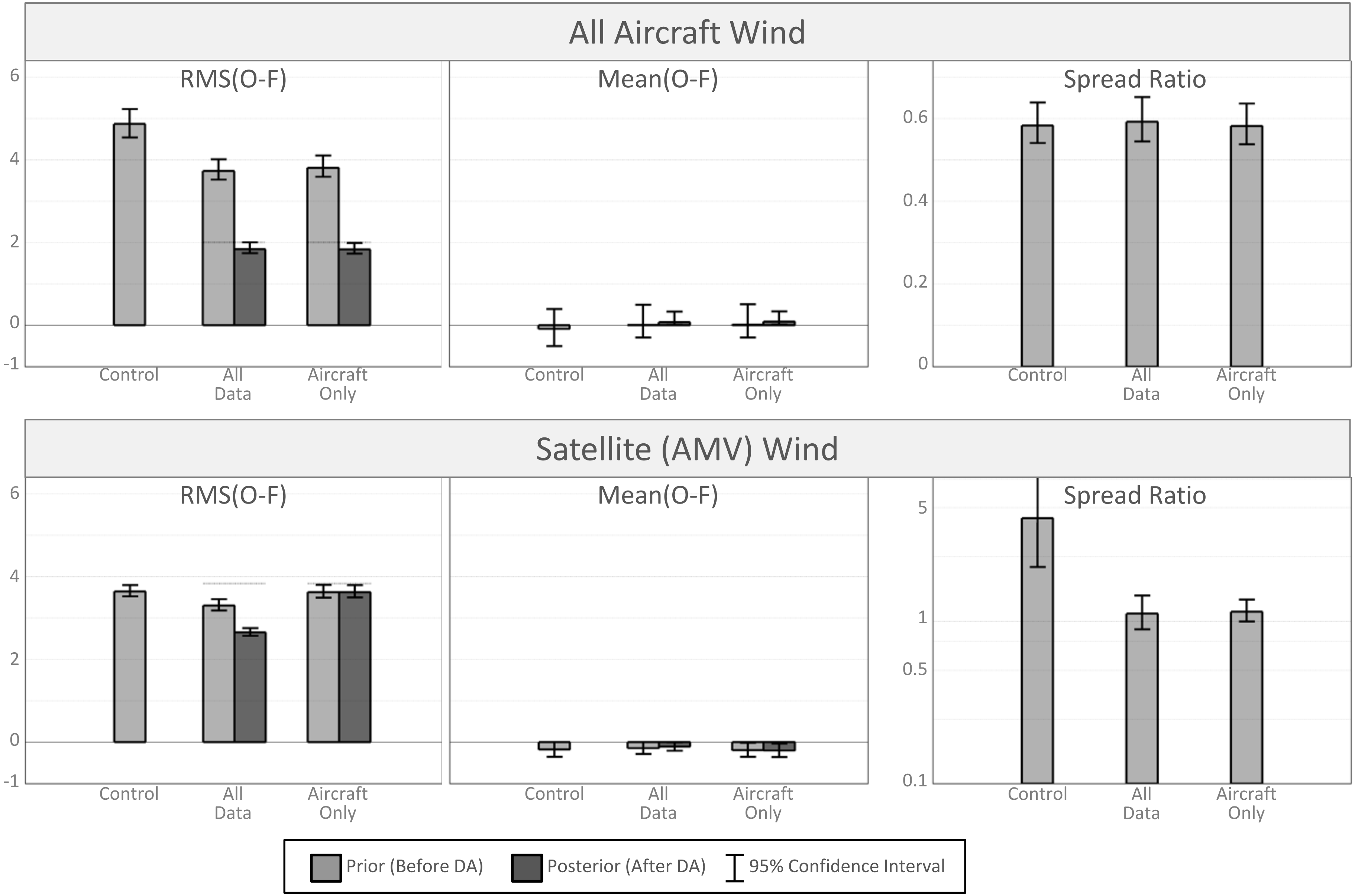
HEDAS CASES in 2013 – DIAGNOSTICS

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



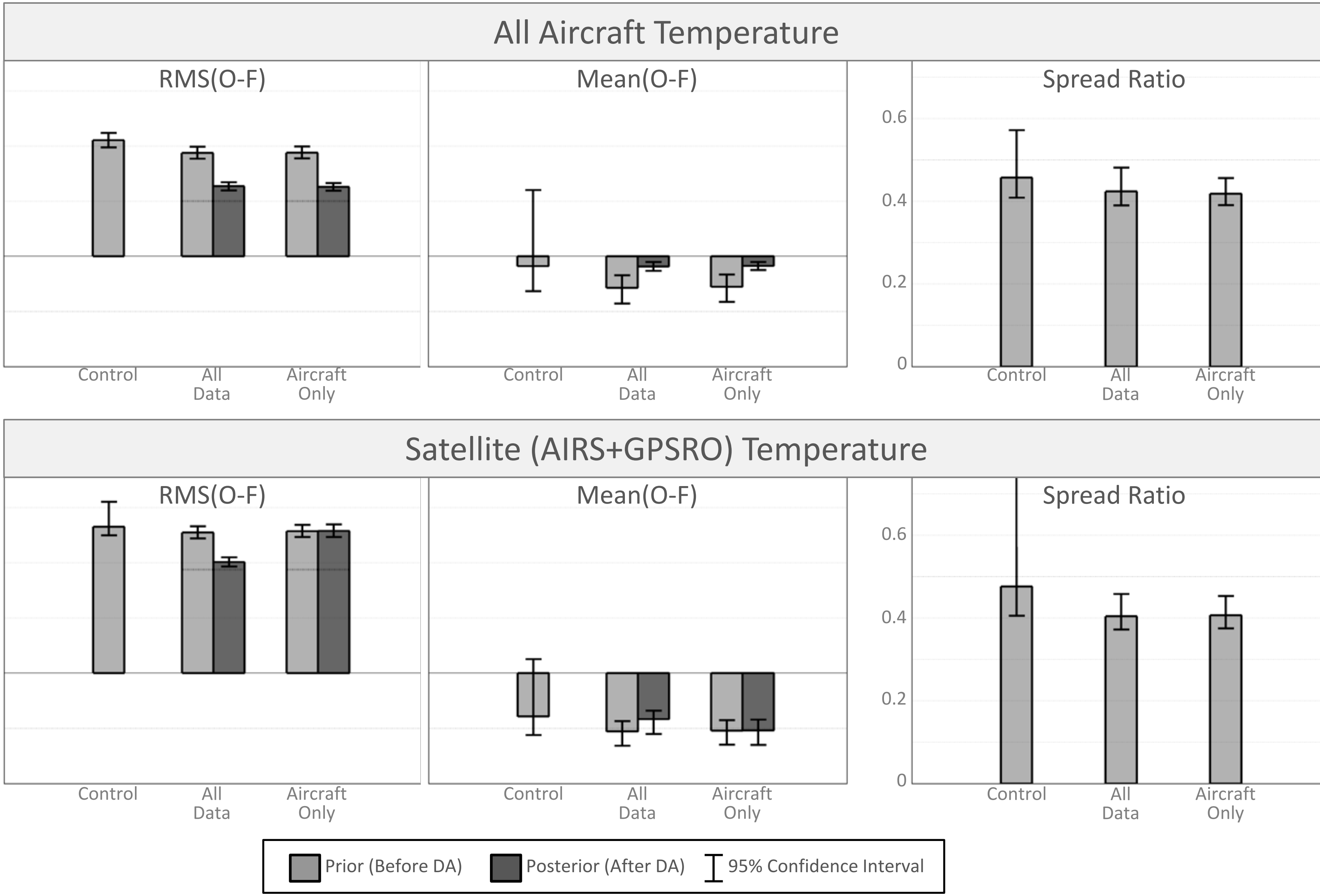
HEDAS CASES in 2013 – DIAGNOSTICS

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



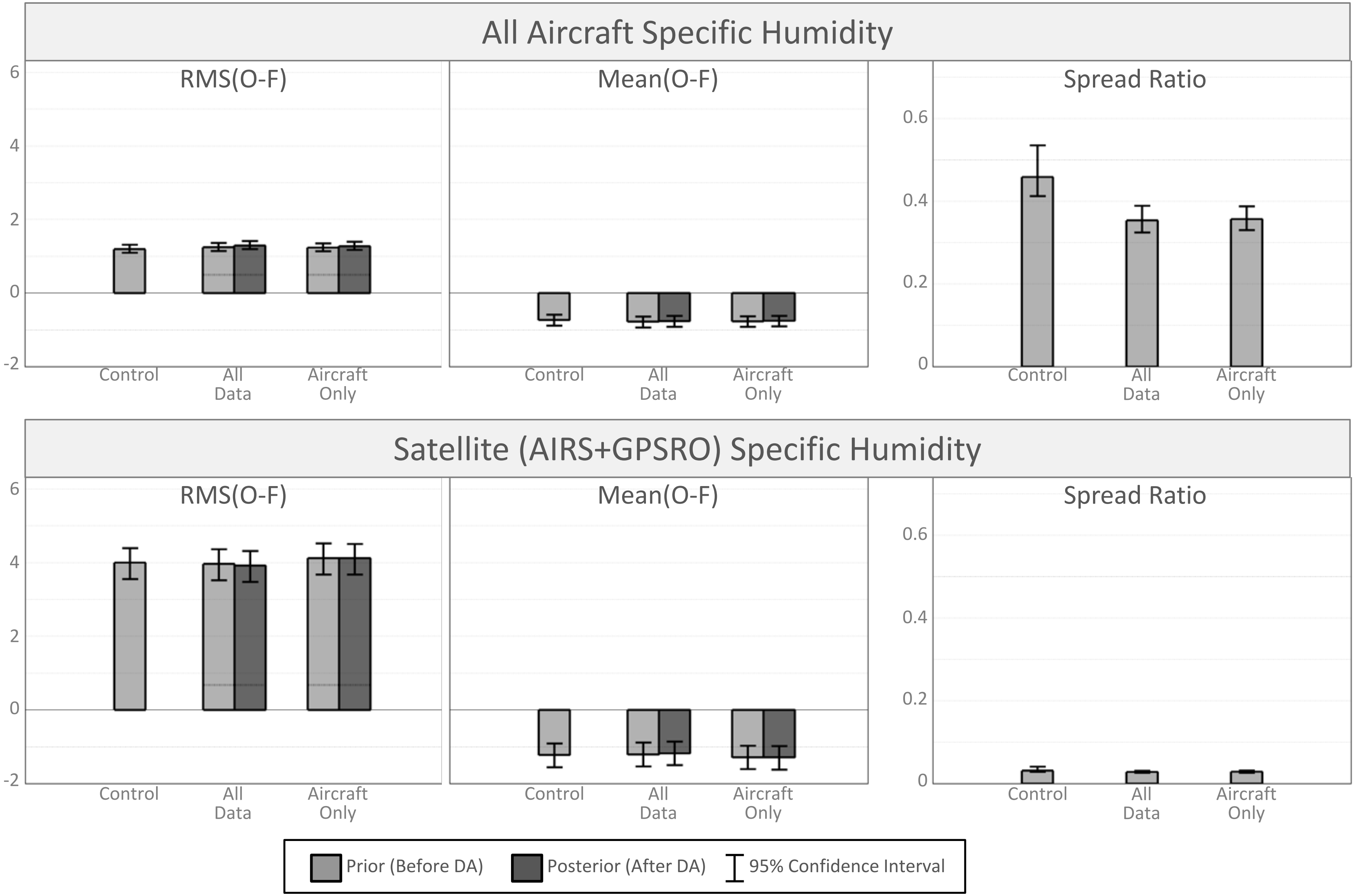
HEDAS CASES in 2013 – DIAGNOSTICS

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



HEDAS CASES in 2013 – DIAGNOSTICS

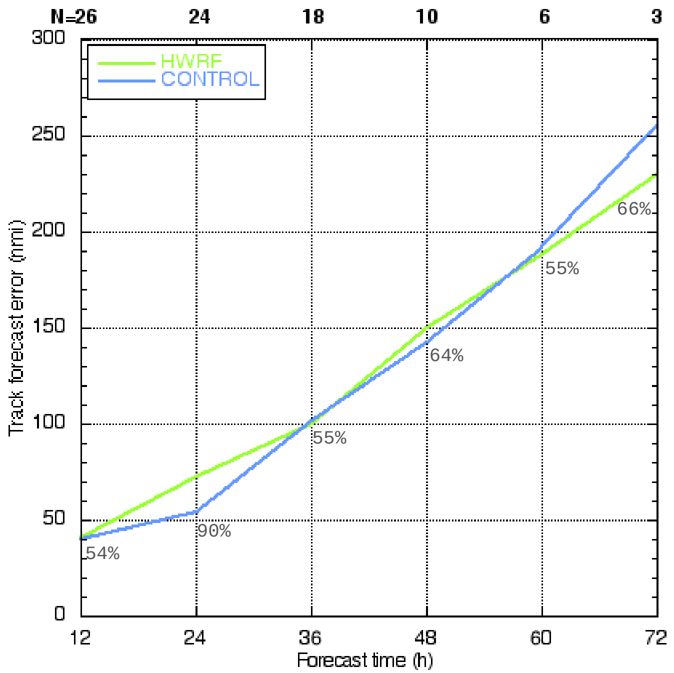
INNOVATION (O-F) DIAGNOSTICS over CYCLES 2-5



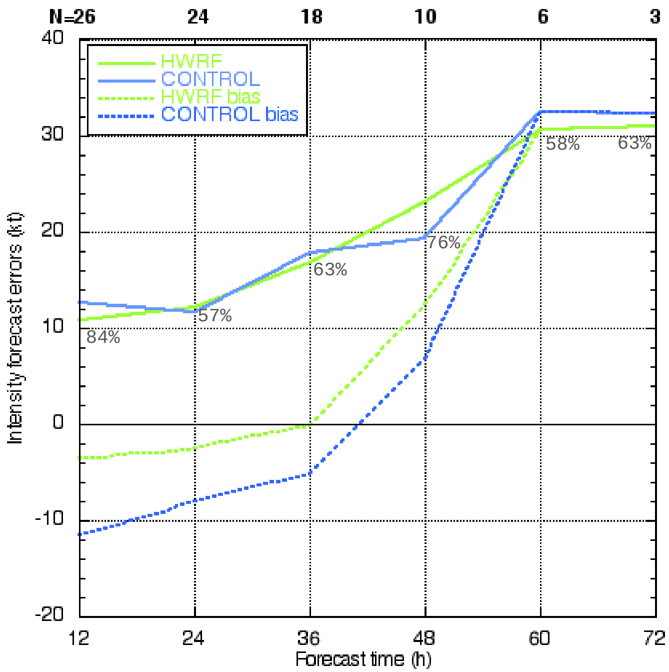
HEDAS CASES in 2013 – FORECAST RESULTS

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

Track Error



Intensity Error



(Statistical Significance indicated as % underneath error curves)

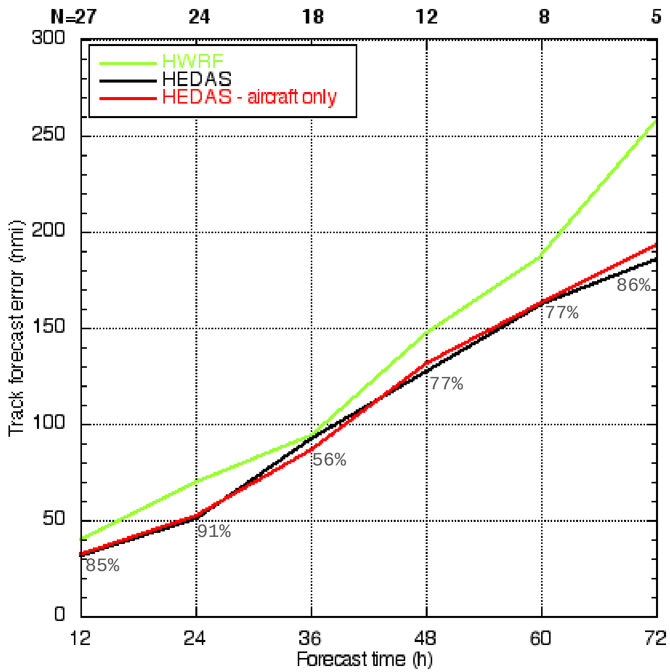
While mean absolute errors of track and intensity are generally not very different, HWRF has smaller bias up to ~48 h.

[Credit: Sim Aberson (HRD)]

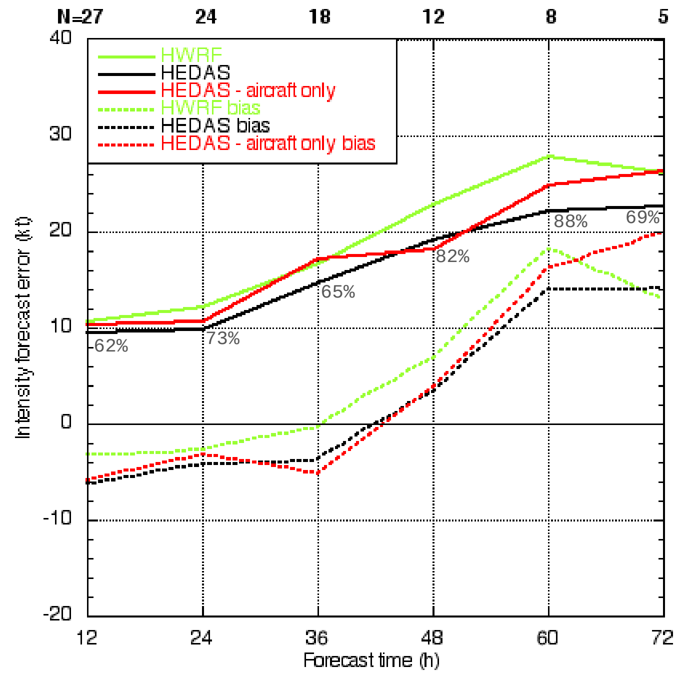
HEDAS CASES in 2013 – FORECAST RESULTS

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

Track Error



Intensity Error



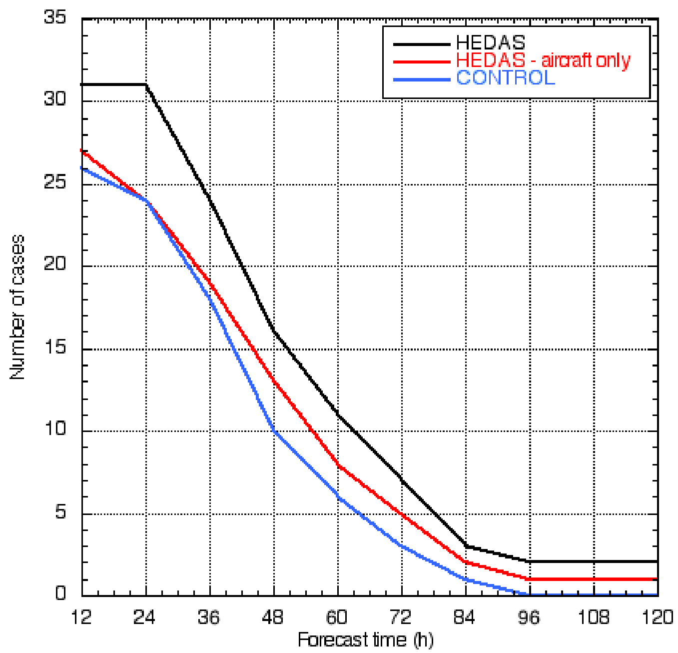
(Statistical Significance indicated as % underneath error curves for HWRF vs. HEDAS)

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.

[Credit: Sim Aberson (HRD)]

HEDAS CASES in 2013 – FORECAST RESULTS

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.

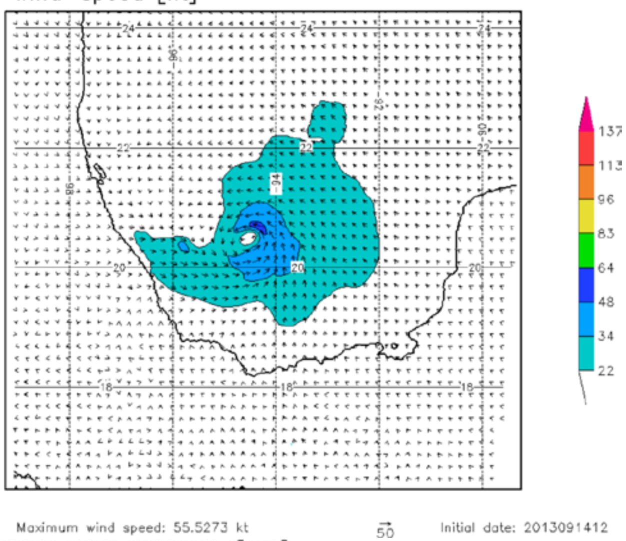
[Credit: Sim Aberson (HRD)]

HEDAS CASES in 2013 – CASE STUDY 1

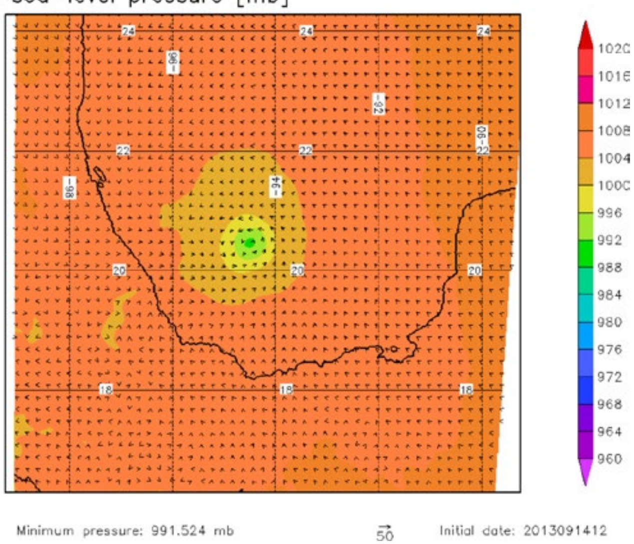
INGRID10L 09/14 12Z

HEDAS

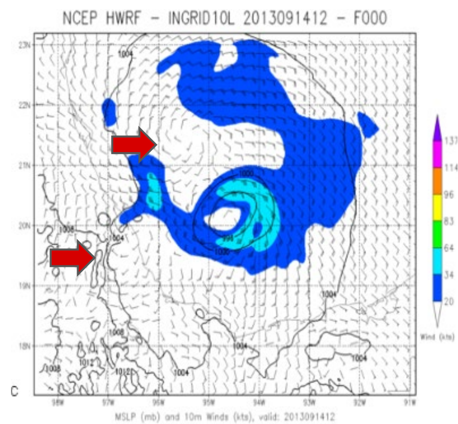
10−m wind−speed [kt]



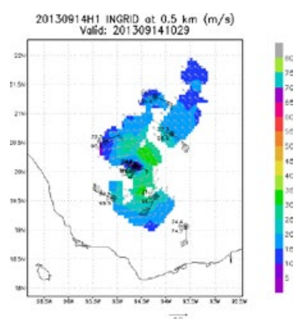
Mean sea−level pressure [mb]



HWRF



RADAR



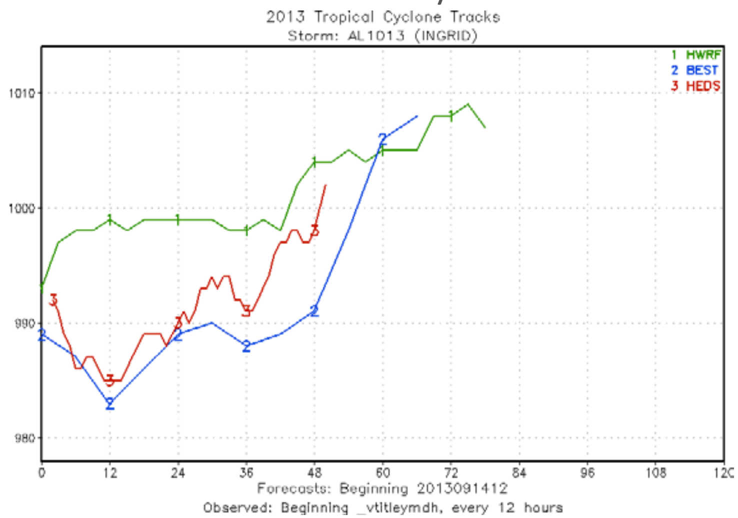
Erroneous triple vortex structure in HWRF initial conditions.

[Credit: Sim Aberson (HRD)]

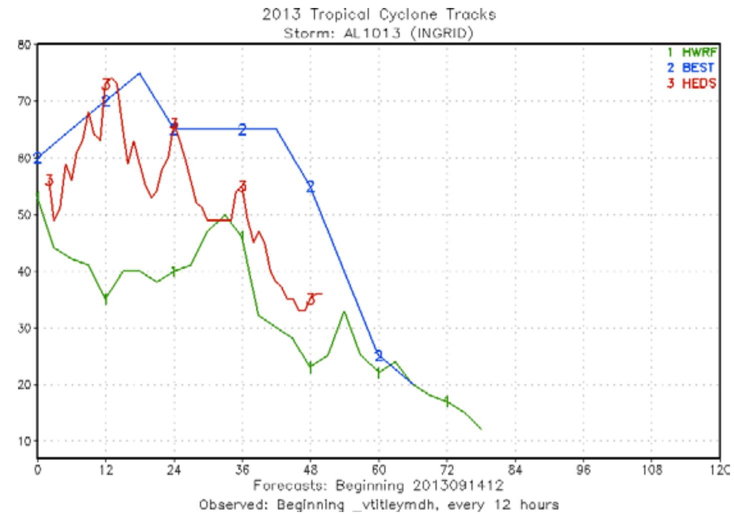
HEDAS CASES in 2013 – CASE STUDY 1

INGRID10L 09/14 12Z

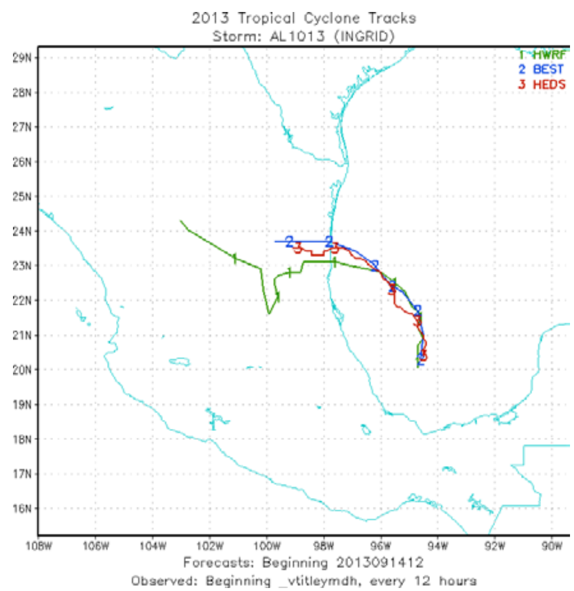
Intensity



MSLP



Track



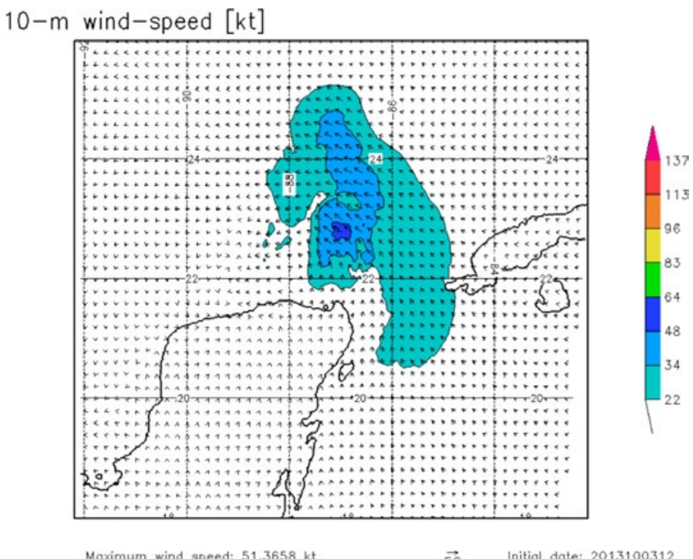
Structural improvements appear to have resulted in better track & intensity forecast in HEDAS

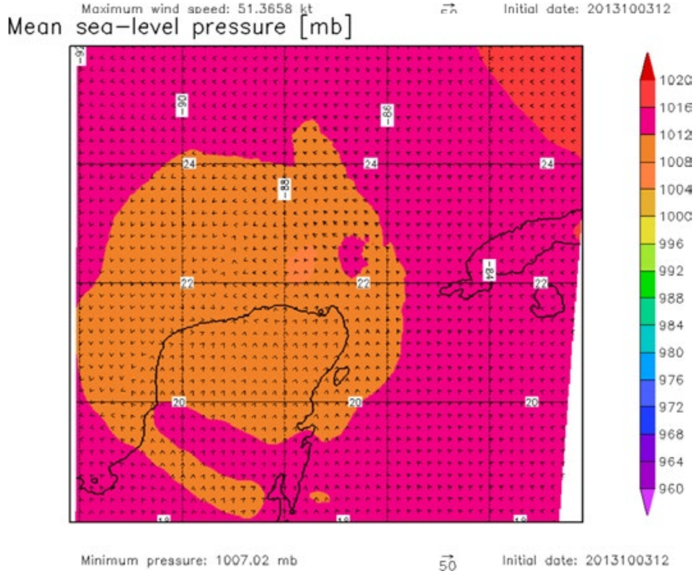
[Credit: Sim Aberson (HRD)]

HEDAS CASES in 2013 – CASE STUDY 2

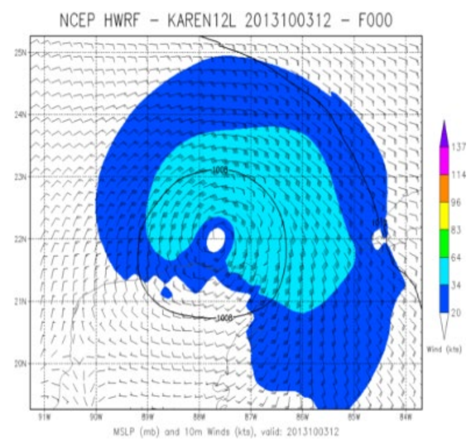
KAREN12L 10/03 12Z

HEDAS

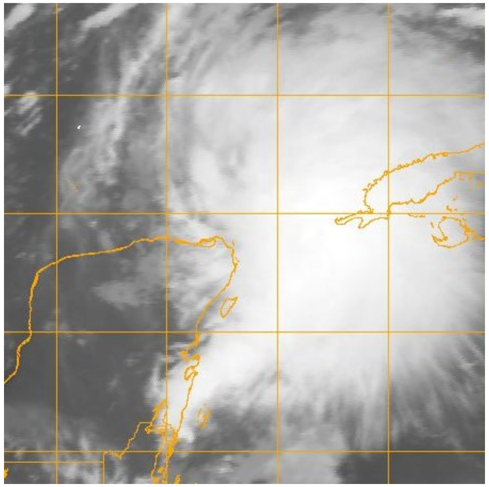




HWRF



Satellite IR



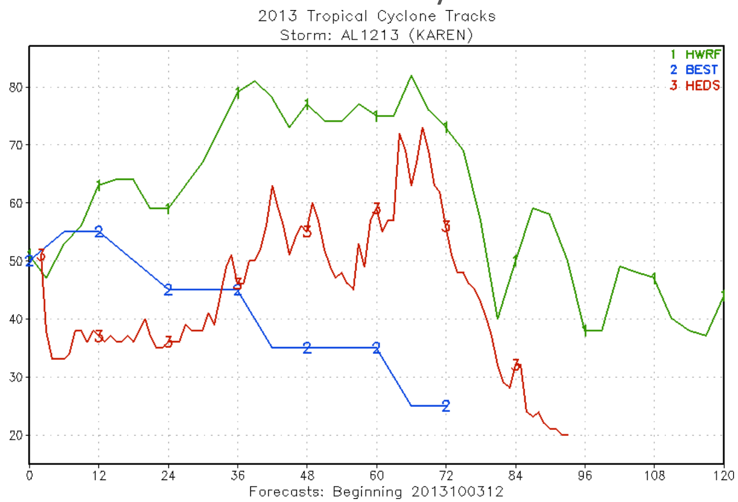
Symmetric vortex structure in HWRF initial conditions.

[Credit: Sim Aberson (HRD)]

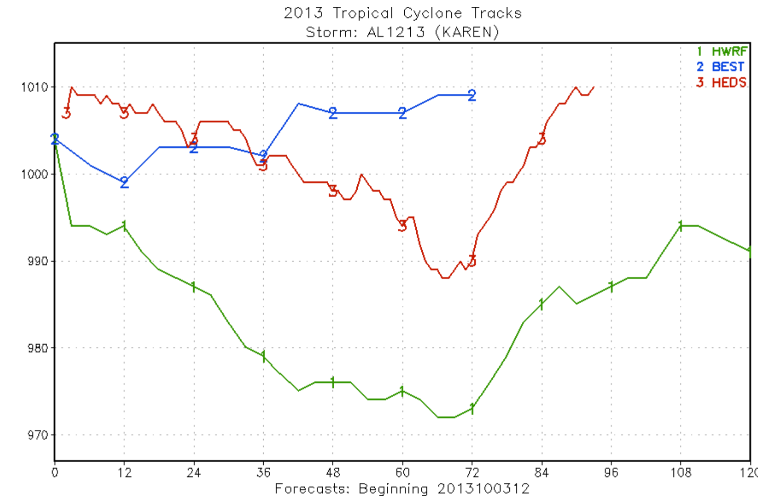
HEDAS CASES in 2013 – CASE STUDY 2

KAREN12L 10/03 12Z

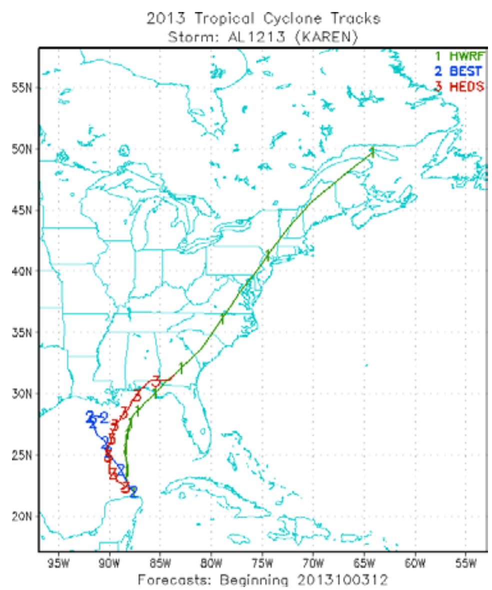
Intensity



MSLP



Track



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

[Credit: Sim Aberson (HRD)]

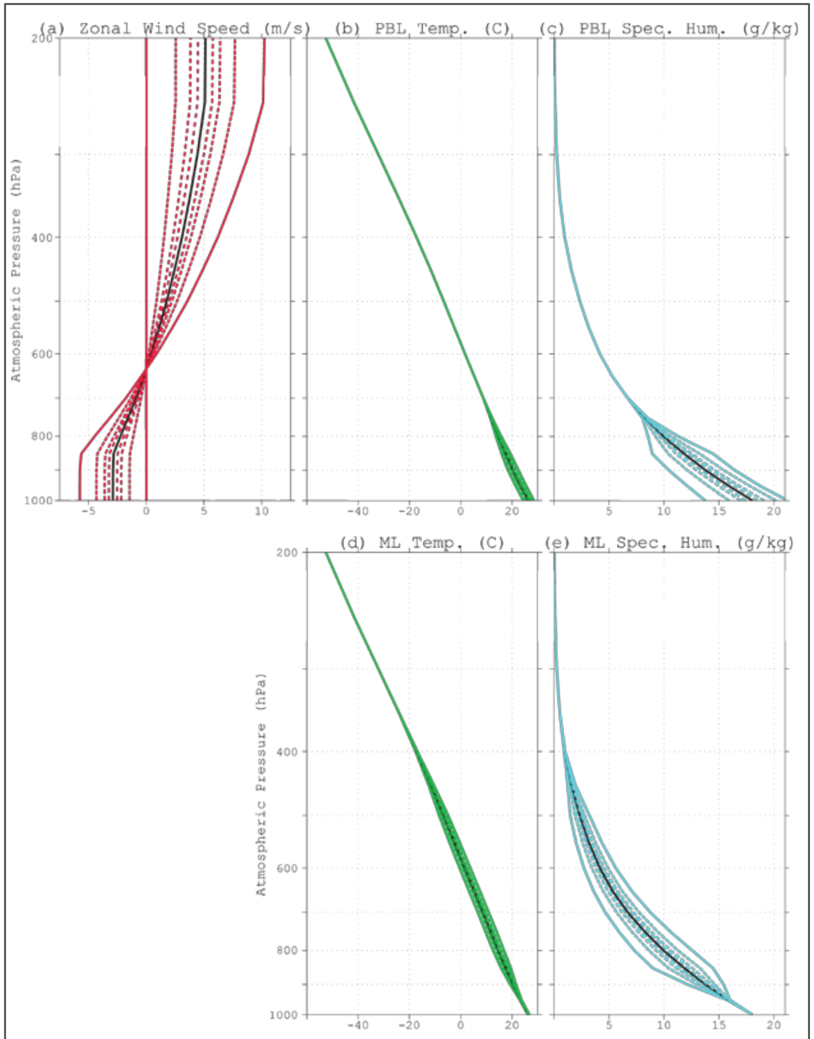
HWRF PARAMETER SENSITIVITY

- 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)

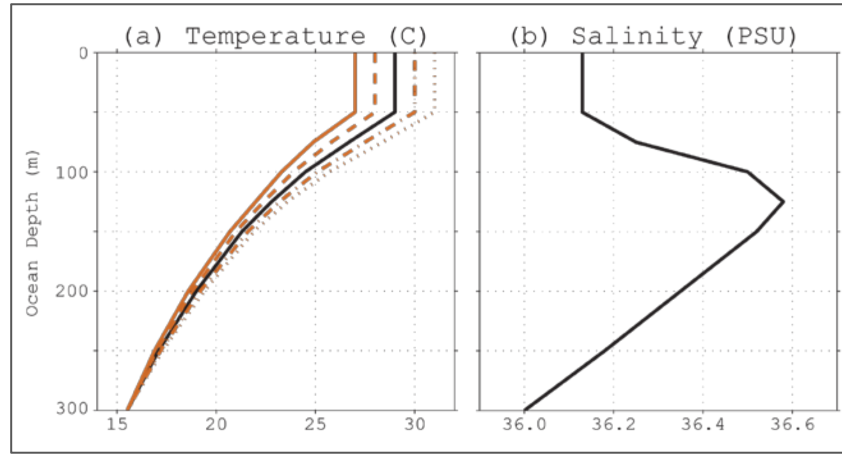
		PARAMETER PERTURBATION REALIZATIONS								
						Control				
1. Storm Environment										
- Zonal Westerly Shear (m/s)		0	4	6	7	8	9	10	12	16
- Westward Storm Speed (m/s)		0	2.5	3.75	4.375	5	5.625	6.25	7.5	10
- SST (C)		27	28	28.5	28.75	29	29.25	29.5	30	31
- Mositure Perturbations in PBL (%RH)		-20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

HWRF PARAMETER SENSITIVITY

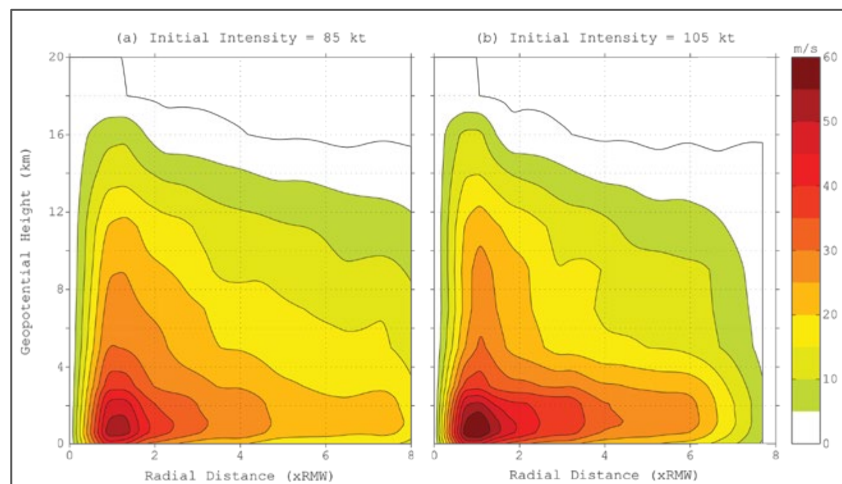
Atmospheric Environment Perturbations



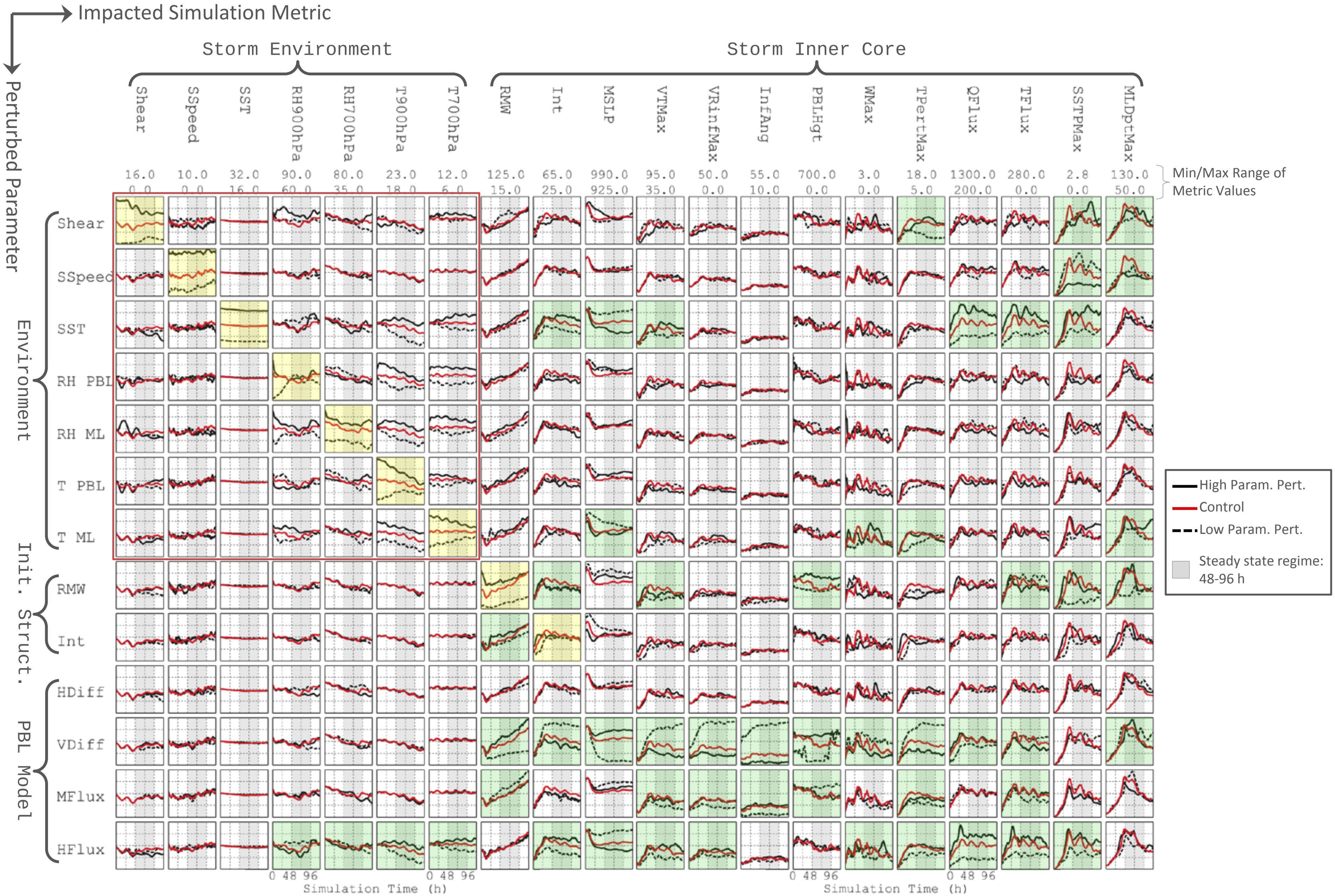
Ocean Perturbations



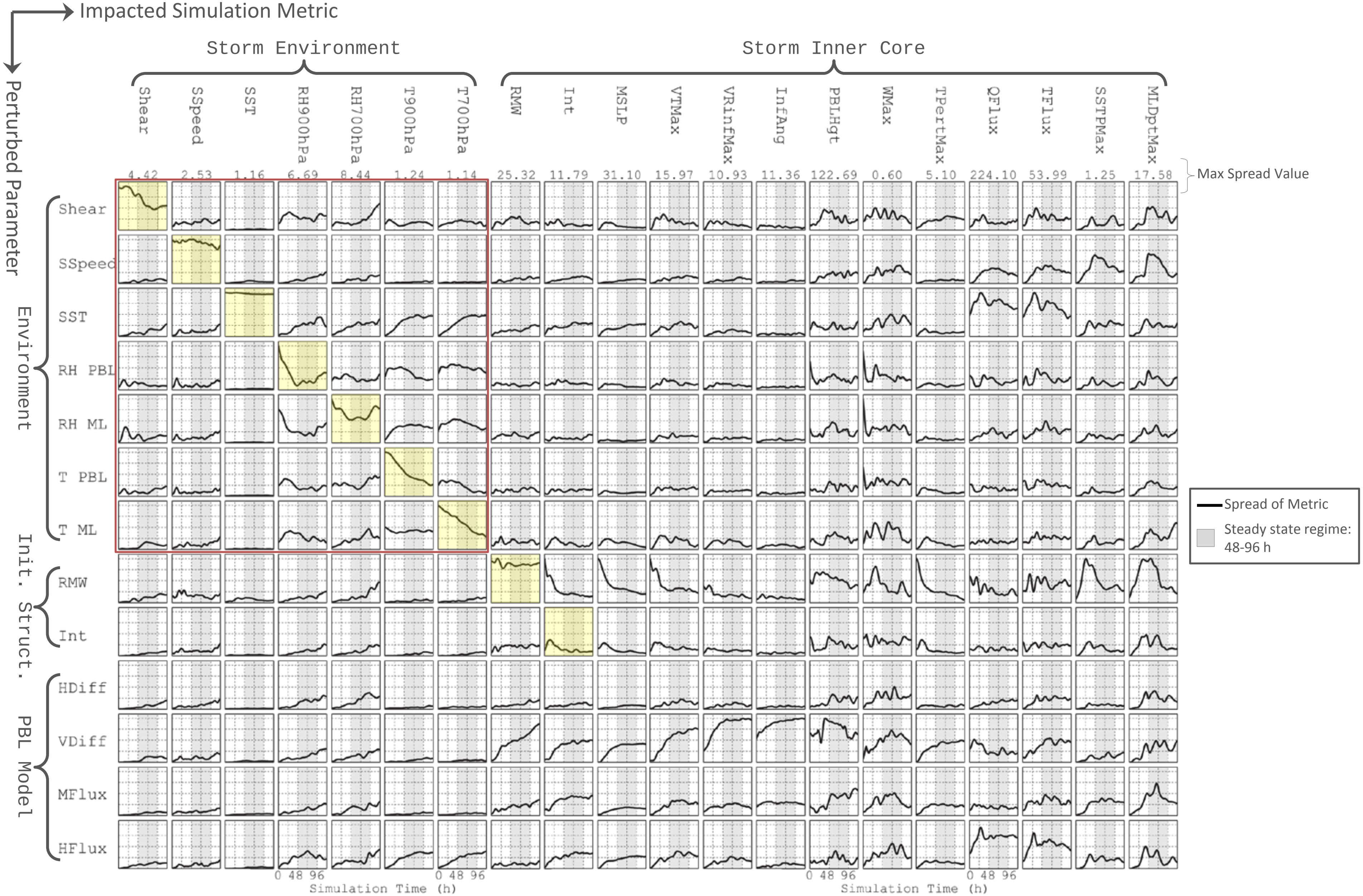
Initial Vortex Perturbations



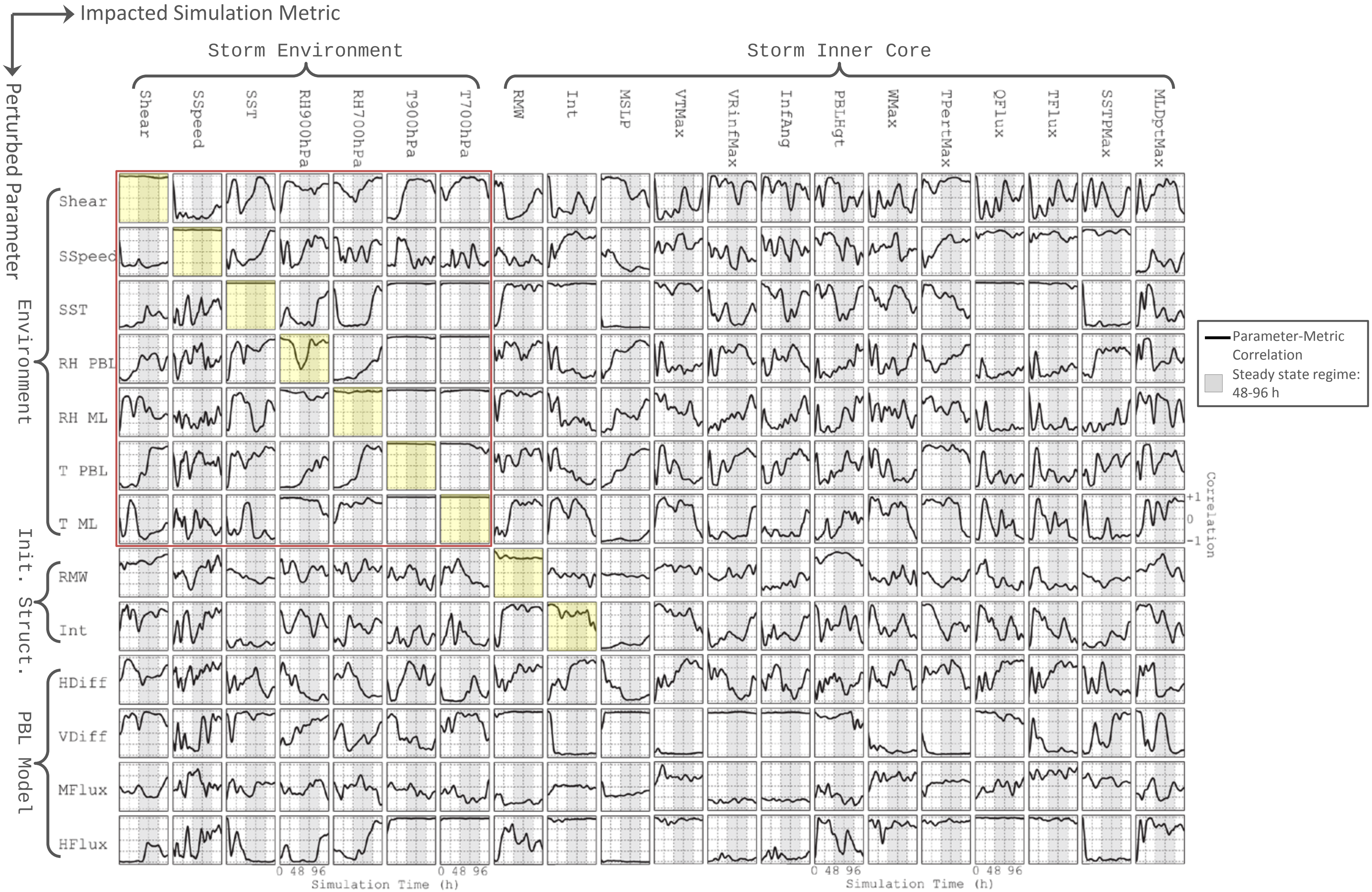
HWRF PARAMETER SENSITIVITY



SPREAD FROM PARAM. PERTURBATIONS



PARAMETER-SIMULATION CORRELATIONS



SENSITIVITY: 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

$$C^t_{p,M} = \frac{1}{N_r} \frac{\sum_{r=1}^{N_r} \left(M^t_r - \bar{M}^t\right)\left(p^t_r - \bar{p}^t\right)}{\sigma^t_M \cdot \sigma^t_p}$$

M: Metric (intensity, MSLP, etc.)
p: Parameter (shear, C_d, etc.)
r: Specific realization of parameter perturbation
t: Time

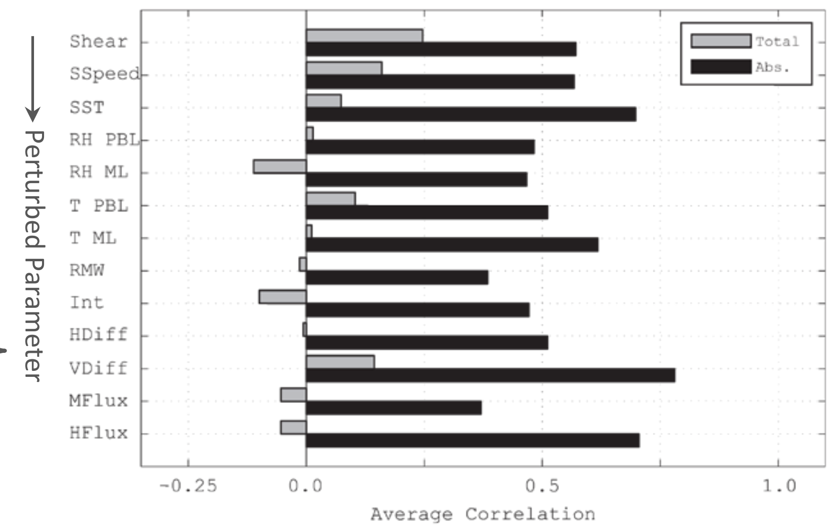
- Correlation coefficient averaged over 48-96 h and multiple metrics for cumulative impact:

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

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	

Cumulative Correlation Coefficient



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

SENSIVITY: RESPONSE FUNCTION

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

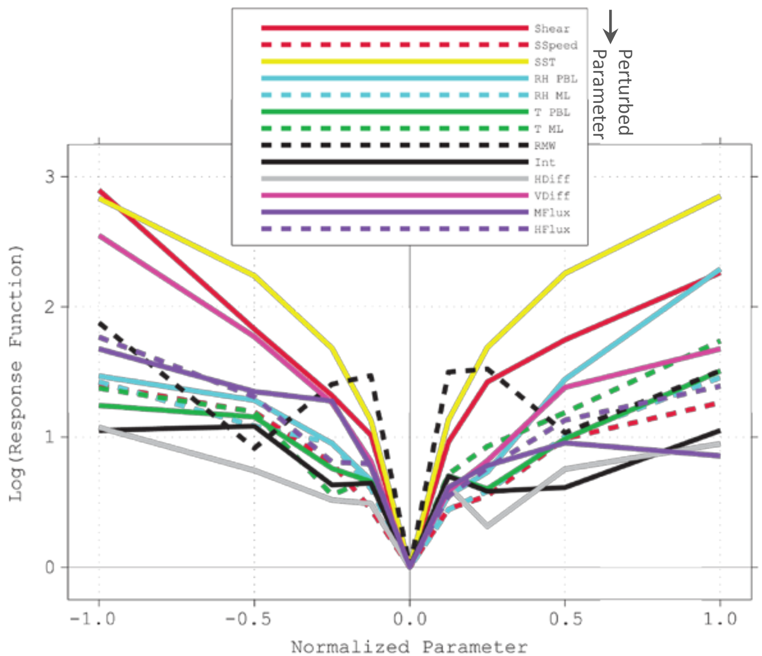
$$J^{r}_{M,p} = \frac{1}{\langle\sigma\rangle^{2}_{M,c}}\left[\frac{1}{N_t}\sum_{t=1}^{N_t}\left(M_p^{r,t} - M_c^{r,t}\right)^2\right]$$

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

TOWARD CALIBRATED PERTURBATIONS

- 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):

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

For each perturbed parameter (*p*):

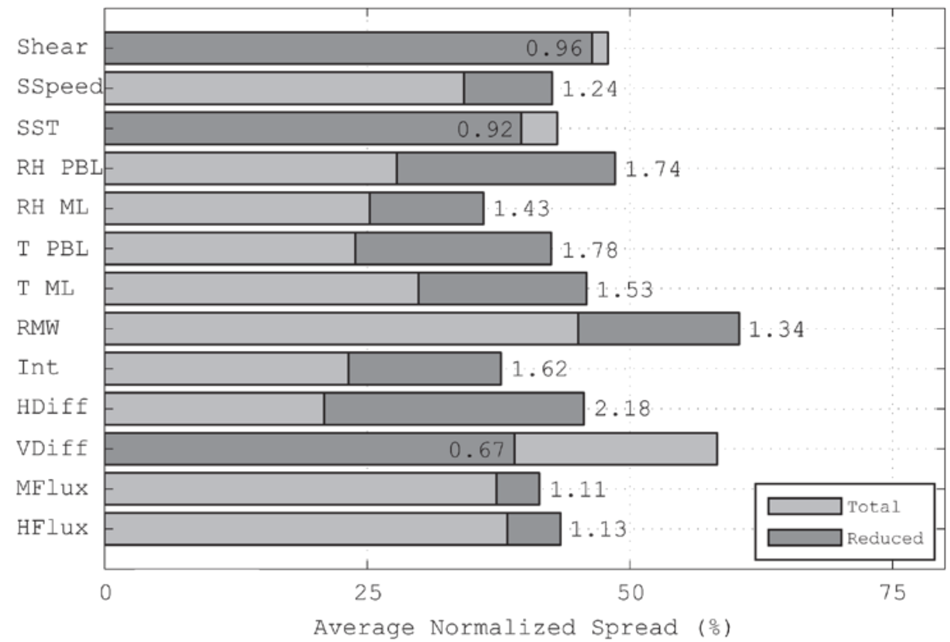
- Calculate time-averaged spread for each metric *M*
- Normalize by max. spread across all parameters (so that the relative impact of the parameter on that metric can be detected)
- Average over all metrics

- 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):

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

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 log10(*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.)

SUMMARY

- 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