Model Sensitivity in Idealized, Ocean-Coupled Hurricane Simulations

Perturbations of Environment, Structure, and Model Physics Parameters

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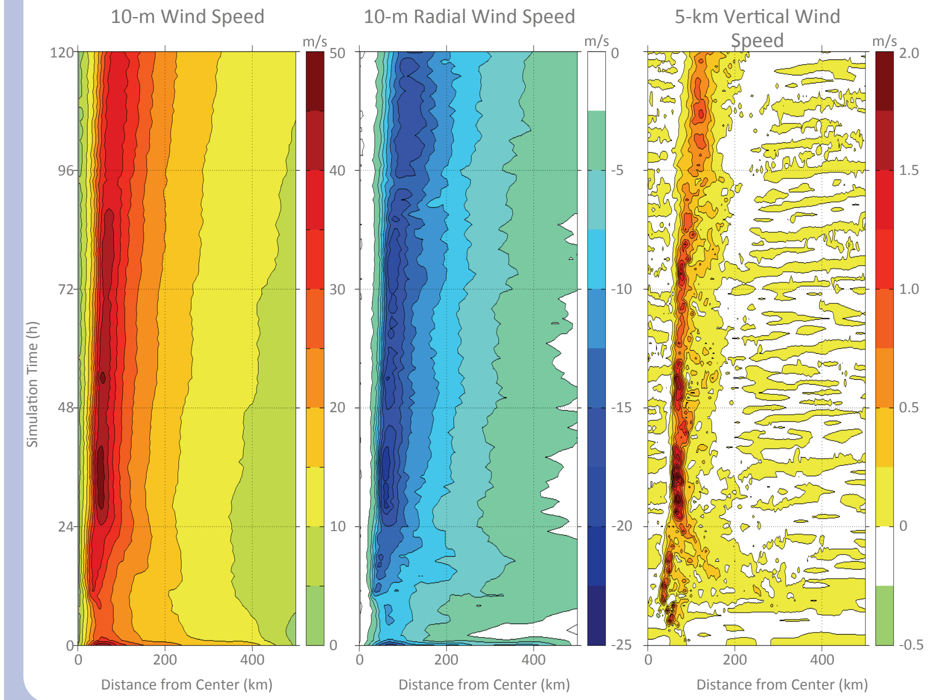
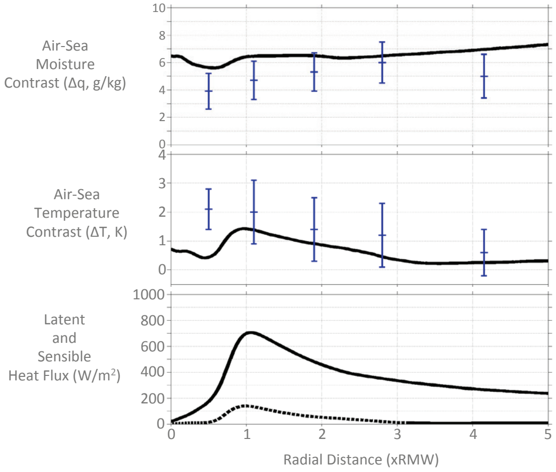
Introduction: The Control Run

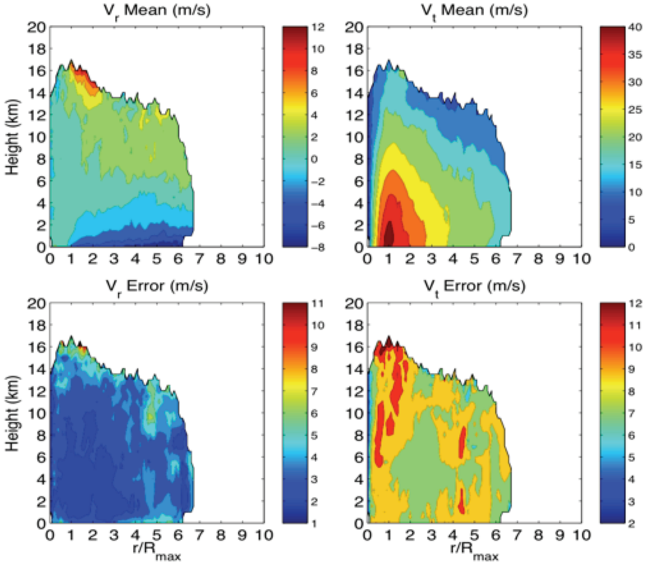
Idealized HWRF Coupled with 1-d Ocean

- 27/9/3 km, 10x10 degree inner nest
- 2012 operational HWRF physics settings
- *Entire globe* initialized with uniform Dunion (2011) moist tropical sounding
- Pure easterly flow with specified 850-200 mb shear & meridional mass adjustment
- No column-averaged mass transport (to keep the simulated storm near the center of domain)
- Coupled with HYCOM one-dimensional ocean model with specified initial 1-d temperature and salinity profiles; constant westerly ocean current (to mimic easterly storm motion relative to ocean)
- Composite, observation-based azimuthally averaged initial vortex

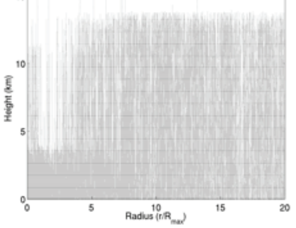




Doppler Radar Coverage



Dropsonde Coverage



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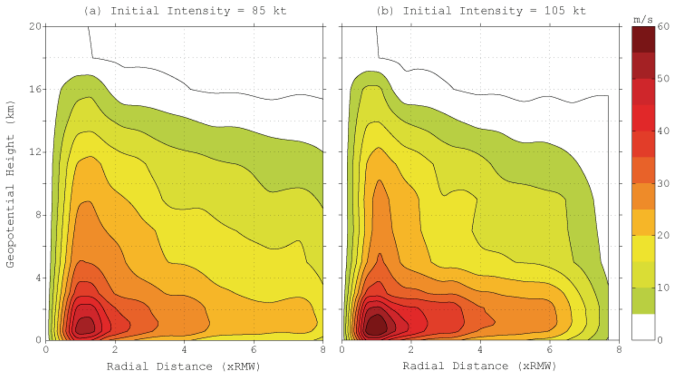
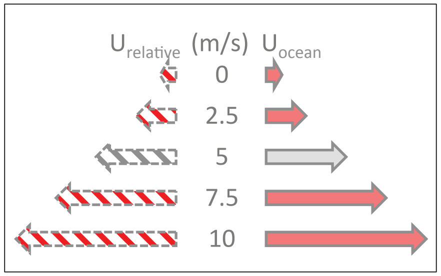
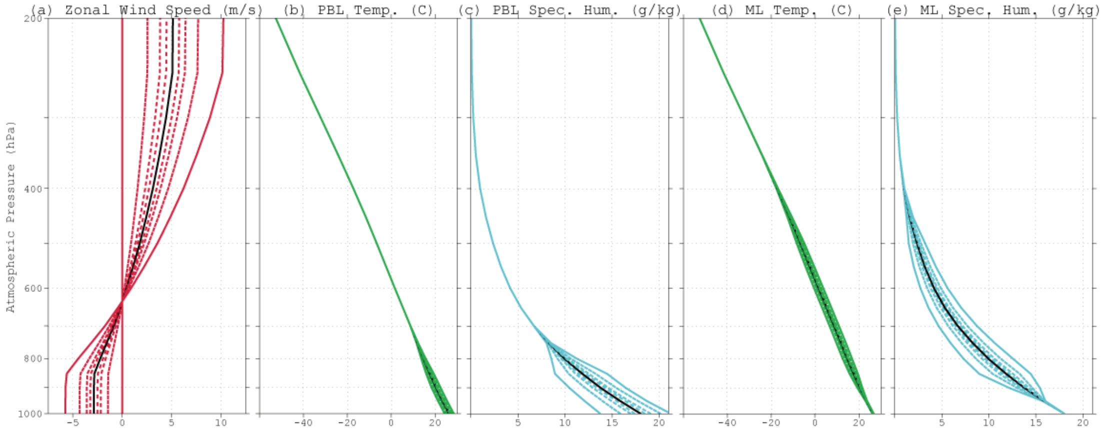
Introduction: Perturbations

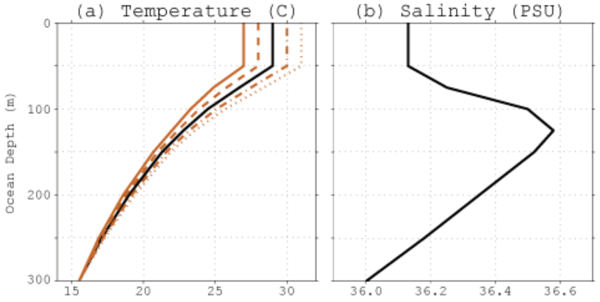
Environment, Initial Vortex, and Model Parameters

		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



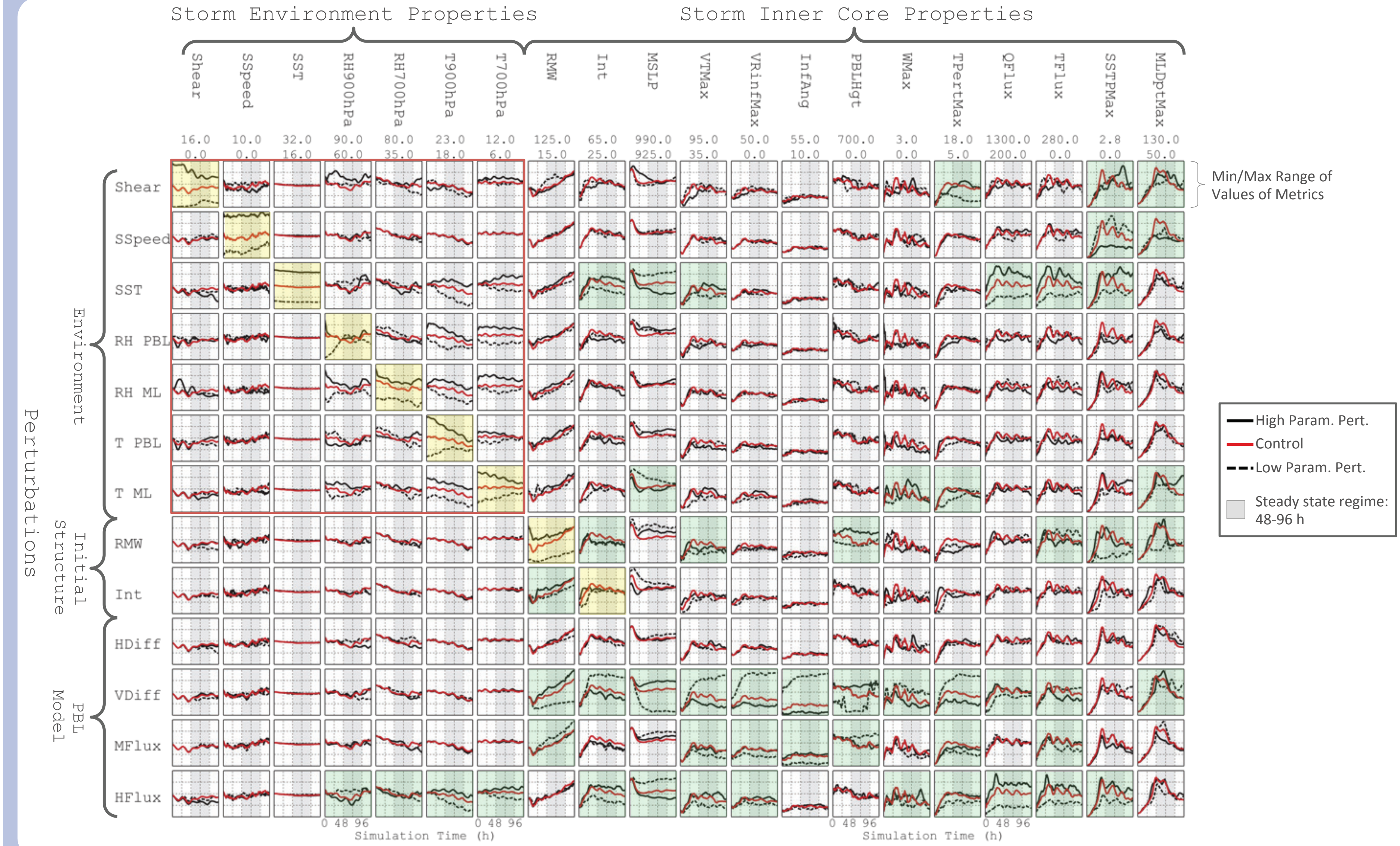






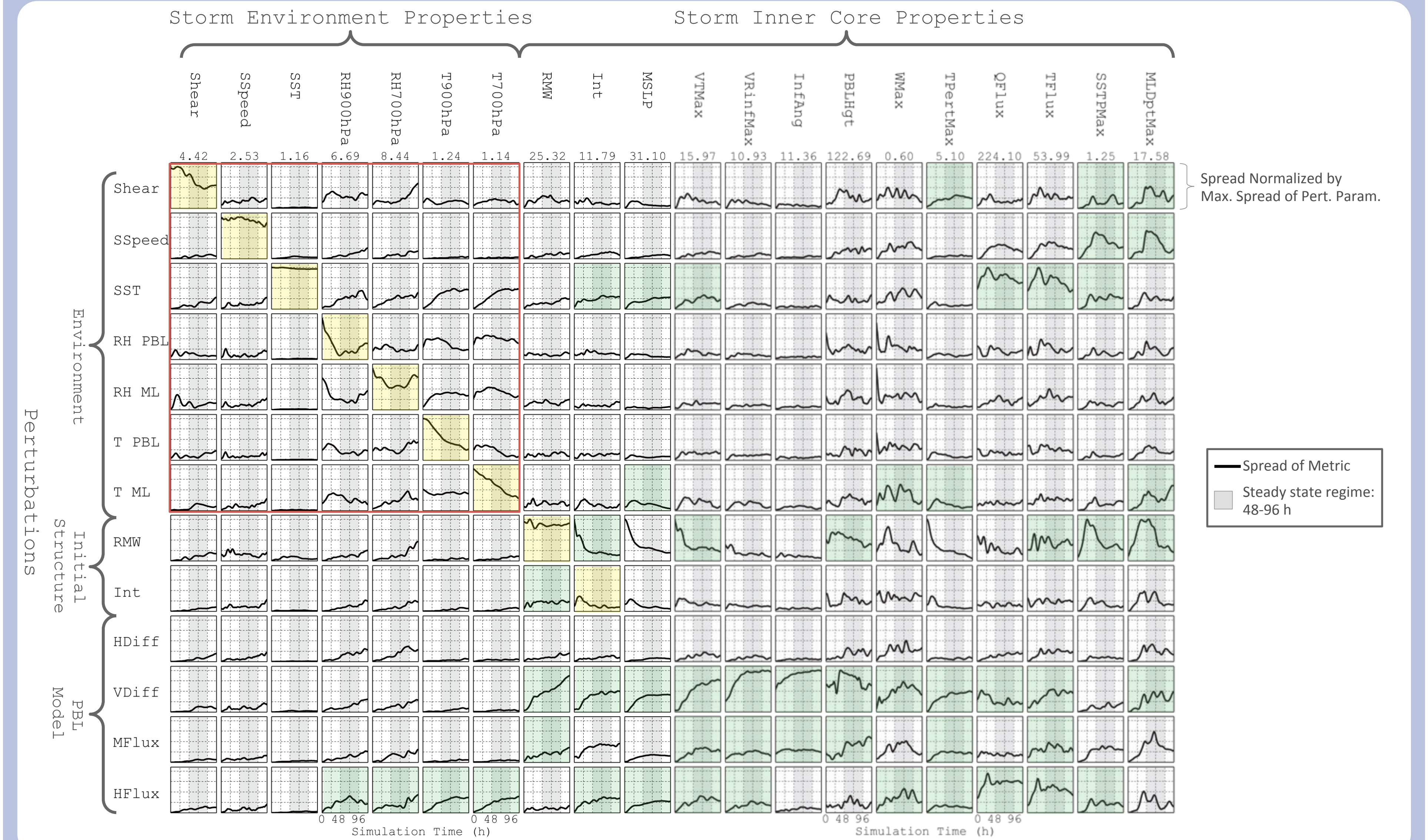
Parameter Sensitivity

Response to Parameter Extremes



Parameter Sensitivity

Spread as a Measure of Variability



Spread Normalized by Max. Spread of Pert. Param.

- Spread of Metric
- ▨ Steady state regime: 48-96 h

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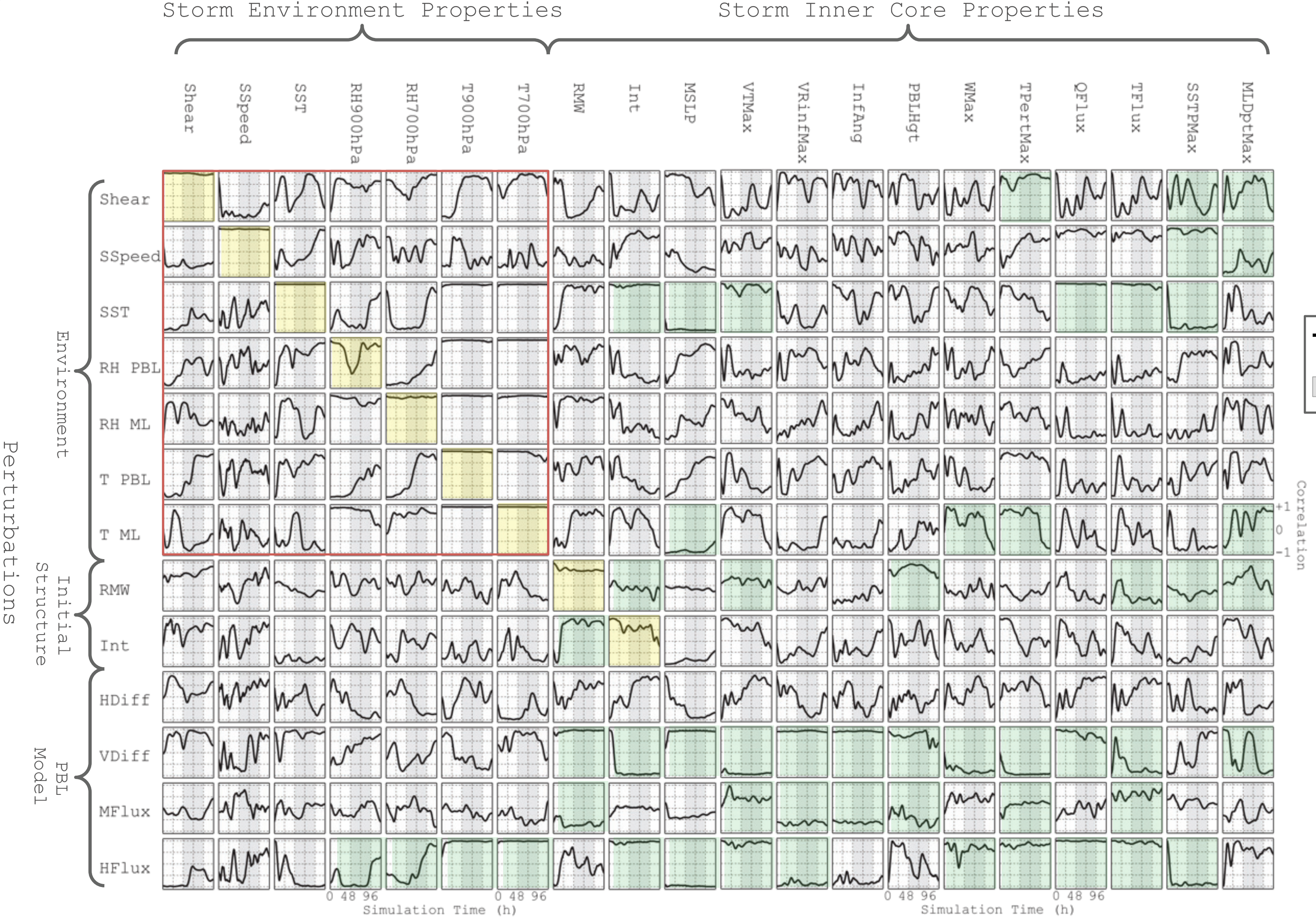
Parameter Sensitivity

Parameter-Simulation Correlations



Parameter-Metric Correlation

Steady state regime: 48-96 h

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Measure of Sensitivity: First Alternative

Cumulative Correlation Coefficient

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

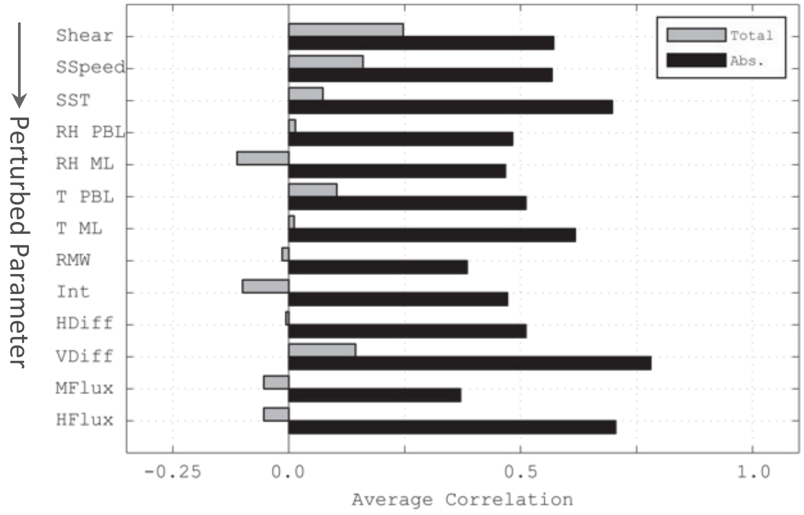
- Correlation coefficient averaged over 48-96 h and multiple metrics for cumulative impact:

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

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

Measure of Sensitivity: Second Alternative

Average Normalized Spread

SPREAD (STANDARD DEVIATION)

- Works for a given metric and parameter combination
  (example: metric = intensity, parameter = shear)
- Measures the variability in a metric as a result of the parameter perturbation across all available samples (control and all parameter perturbations)

$$\sigma^{t}_{M,p} = \left(\frac{1}{(N_r - 1)} \sum_{r=1}^{N_r} \left(M^t_r - \overline{M}^{t} \right)^2 \right)^{1/2}$$

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

- We then apply time averaging to measure “persistent” variability.
- However, spread itself cannot be compared across metrics, unless some normalization is applied. Here, time-averaged spread is normalized by the maximum spread from any of the parameters, then averaged over all metrics for a given parameter:

$$\tilde{\sigma}_{M,p} = \frac{\frac{1}{N_t} \sum_{t=1}^{N_t} \sigma^{t}_{M,p}}{\overline{\sigma}^{\max}_{M}}$$

$$\tilde{\sigma}_{p} = \frac{1}{N_m} \sum_{M=1}^{N_m} \tilde{\sigma}_{M,p}$$

Metrics Included in Calculation		
Environment	**Structure**	
Shear magnitude	Intensity	Max. Core T Pert.
Shear direction	MSLP	RMW
Storm speed	Max. Vt	Latent heat flux
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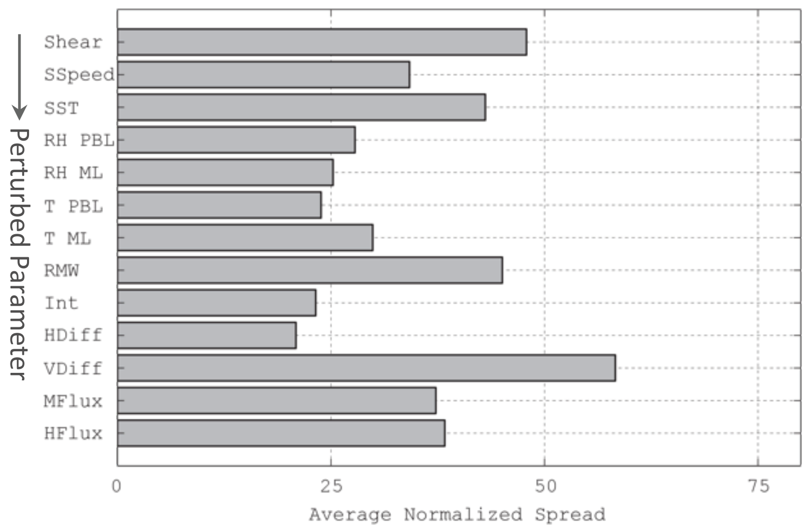
SST	Inflow Angle	Max. SST Pert.
	PBL height	Max. Mixed Layer Depth
	Max. W	

Average Normalized Spread



Strongest Normalized Spread	
VDiff	SST
Shear	HFlux
RMW	MFlux

Measure of Sensitivity: Second Alternative

Cumulative 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:

Metrics Included in Calculation		
Environment	**Structure**	
Shear magnitude	Intensity	Max. Core T Pert.
Shear direction	MSLP	RMW
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	PBL height	Max. Mixed Layer Depth
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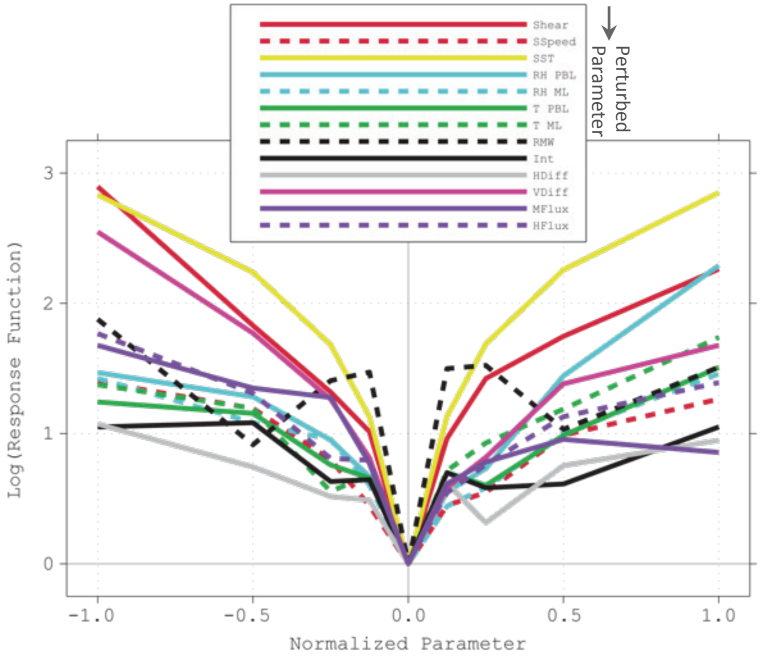
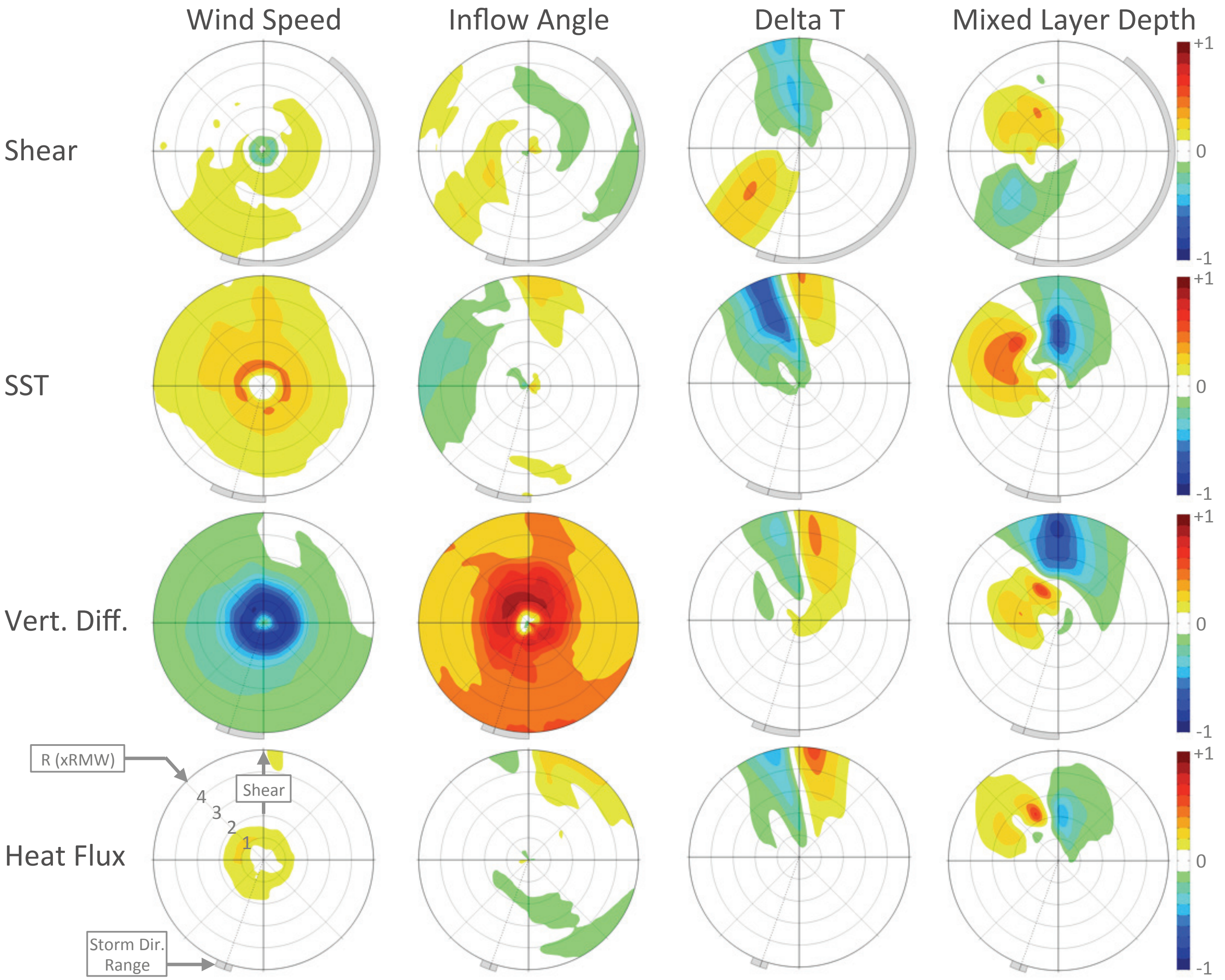
Cumulative Response Function



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

Correlation Structures from Impactful Parameters

Surface Features



Correlations Normalized by Maximum Spread of Shown Fields to Focus on Areas with Most Variability of Underlying Field

Radii Normalized by RMW
Each Line = 1xRMW

Plots Are Relative to Shear
Shear Direction Points Up

Variability of Storm Direction
Shown in Gray Band
at 5xRMW Circle

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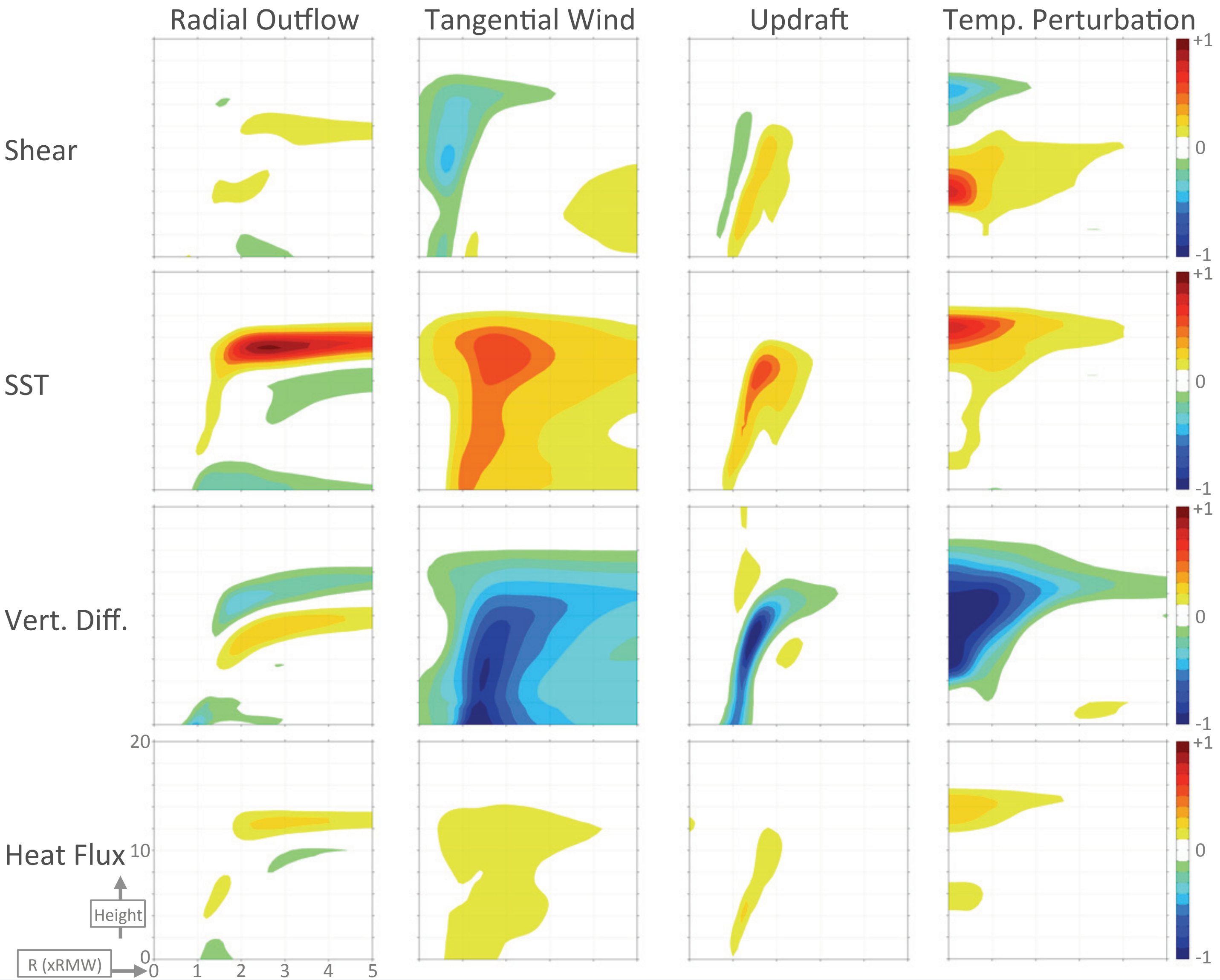
Correlation Structures from Impactful Parameters

Vertical, Azimuthally Averaged Features



Correlations Normalized by Maximum Spread of Shown Fields to Focus on Areas with Most Variability of Underlying Field

Radii Normalized by RMW

Each Line = 1xRMW

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Calibrated Perturbations

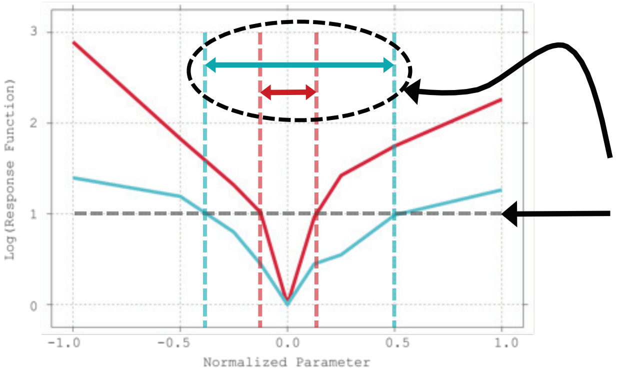
Use of Response Function to Calibrate Ensemble Spread

- Even after normalization, Average Normalized Spread is not a fair comparison of spreads, because:

  Maximum spread itself is 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):

  Consider an example with two perturbed parameters, and their response functions as follows:



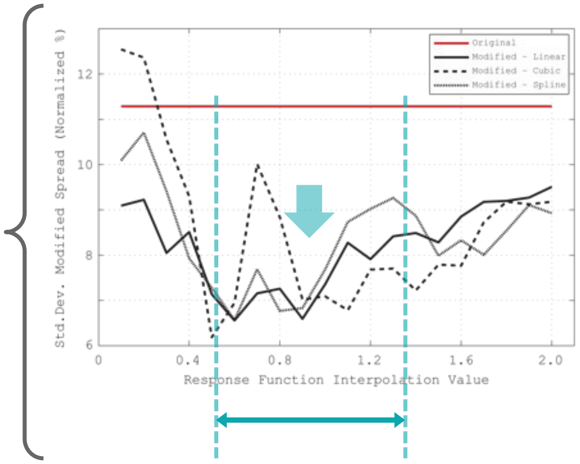
For a specified *response function threshold*, what is the inferred scaling for the parameter range?

Interpolate specified *response function threshold* to normalized parameter to obtain relative scaling

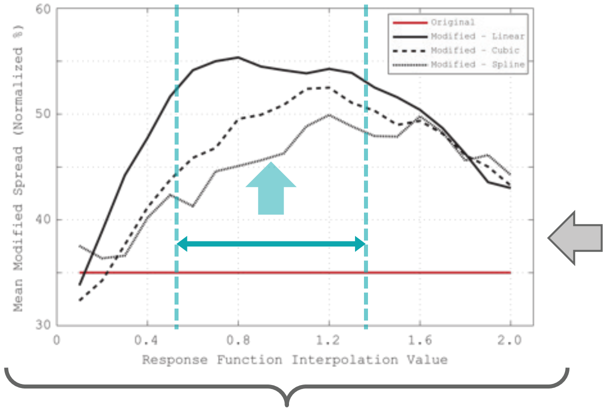
$$\sigma^{\mathrm{mod}}_{M,p} = p^{\mathrm{thresh}}_{M} \cdot \sigma_{M,p}$$

(Here, the scaling factor *p* is metric specific and depends on the *response function threshold* applied)

The overall goal is to achieve better spread calibration: Normalized spread of parameters should become more similar!



Indeed, the standard deviation of normalized spread across parameters is reduced by half for within the highlighted threshold range

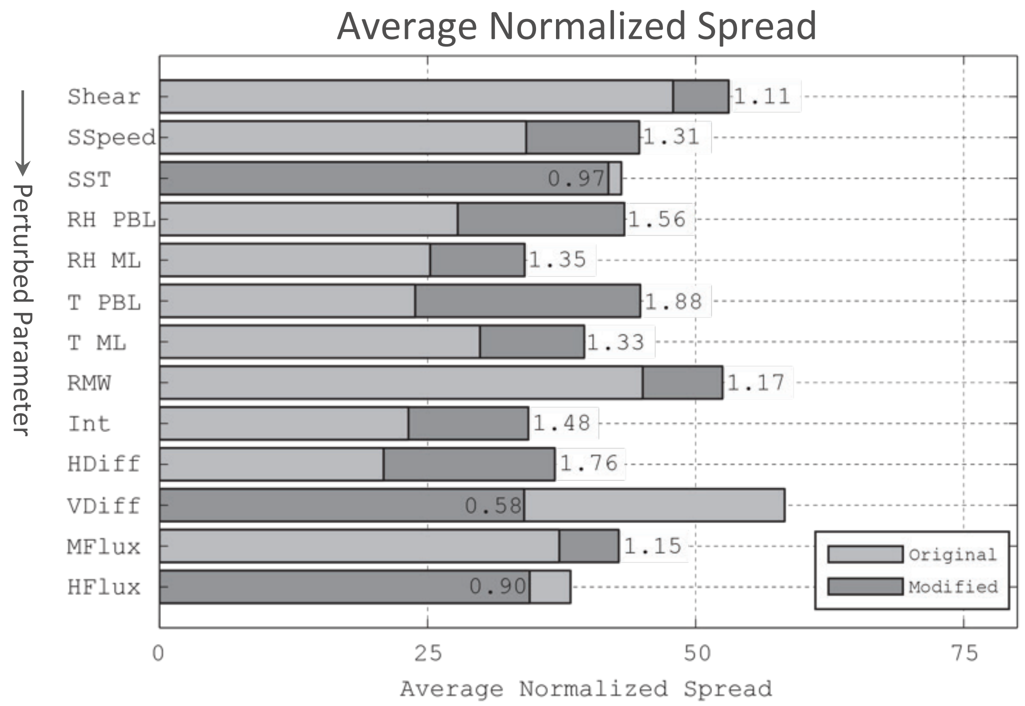


Also, the mean normalized spread across parameters is increased, which is always good for a healthy ensemble!

Calibration Based on Response Function

Impact on Normalized Spread

- We choose a response function threshold value of 0.6 with linear interpolation that seem to:
  - Maximize the reduction in the standard deviation of normalized spread (make normalized spreads the most similar across parameters)
  - Maximize the increase in the average normalized spread
- And recalculate Average Normalized Spread:



Light Gray bars denote normalized spread **before calibration**

Dark Gray bars denote normalized spread **after calibration**

Numbers next to bars denote **average scaling factors**

⇩

Modified spread shows much smaller variability across perturbed parameters, an indication of better-calibrated overall spread.

✚

Modified spread is greater for most parameters, an indication of the possibility of improved ensemble variability.

Summary

1 Idealized (but realistic) hurricane simulations reveal significant model sensitivity to all types of perturbations including storm environment, initial structure, and model physics.

2 Sensitivity manifests itself in various ways, including, but not necessarily limited to, spread in various metrics, correlations with perturbed parameters, and response function.

3 Overall, perturbations in shear and SST (storm environment), RMW (initial structure), as well as vertical diffusivity, and momentum and enthalpy exchange coefficients (PBL physics) all appear to have a large impact on model solutions.

4 Further investigation of the structure of correlations also reveals significant differences in how various parameters impact the structure of a hurricane. This suggests that the perturbations from various sources are (mostly) orthogonal.

5 Response function is shown as a tool to calibrate for spread from various error sources. Assuming a linear response, optimization leads to a reduction in the variability of spread from various sources by almost half.