A Multiple-Model Ensemble Examination of the Probabilistic Prediction of Hurricanes Sandy (2012) and Edouard (2014)

Christopher Melhauser and Fuqing Zhang
Penn State University

In collaboration with: Yi Jin (NRL), Hao Jin (NRL), Allen Zhao (NRL), and Yonghui Weng (PSU)

Sponsored by ONR, NOAA, and NASA

Given pseudo-operational configurations of three TC-tuned regional models …

1) How do the mean and spread of an ensemble with the same initial perturbations evolve using “multiple-models”?

2) Are single-core ensembles sufficient for representing model uncertainties in TC prediction or do we need multi-core ensembles?

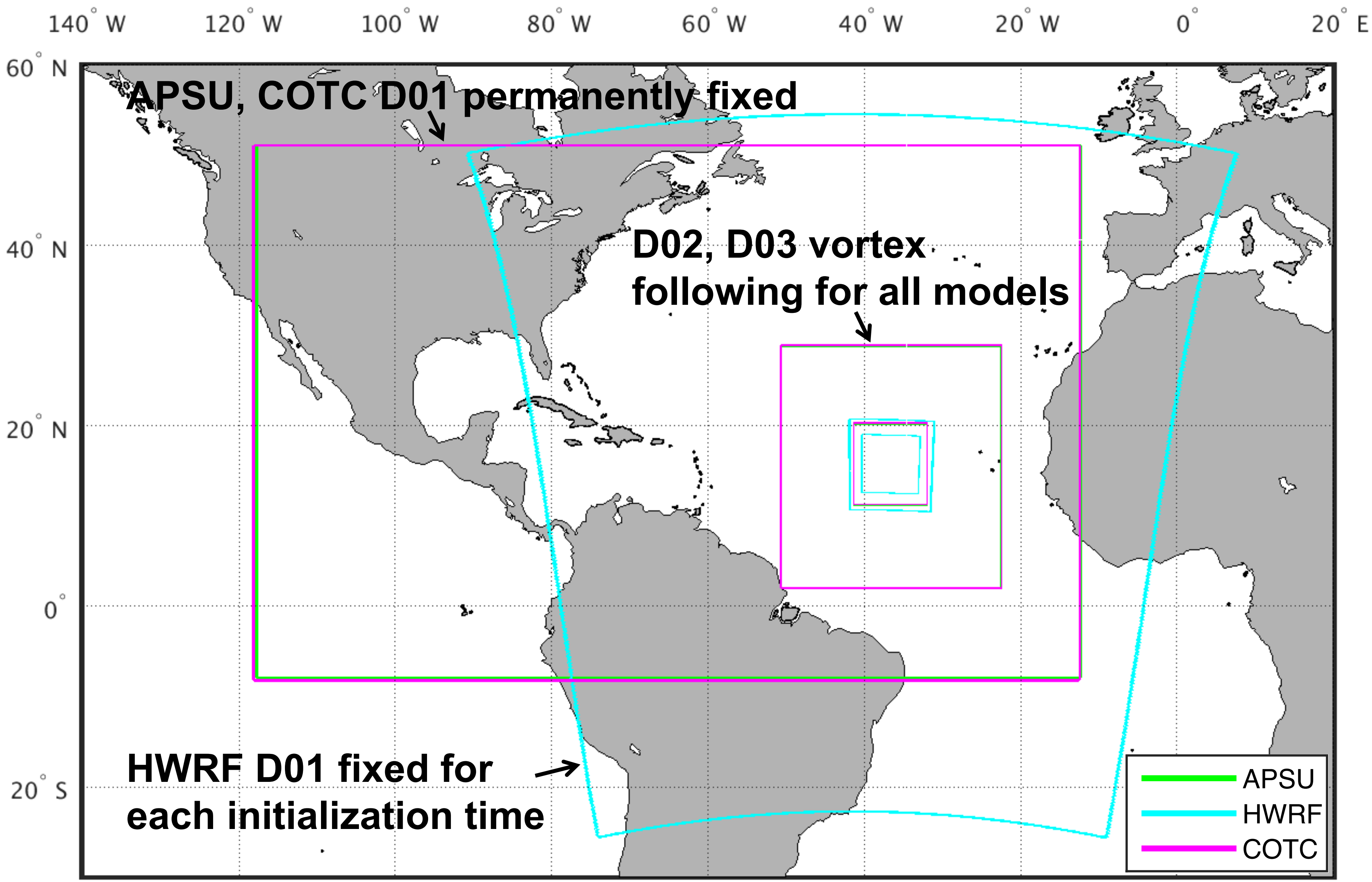
- **Pseudo-operational configurations of TC tuned regional models**
  - Same initial conditions for all models
  - Fixed SST from operational GFS
  - Atmospheric component only

- **Model Versions**
  - WRF-ARW v3.6
  - HWRF v3.5b
  - COAMPS-TC v1.0 (Feb 2015)

- **Model Configurations**

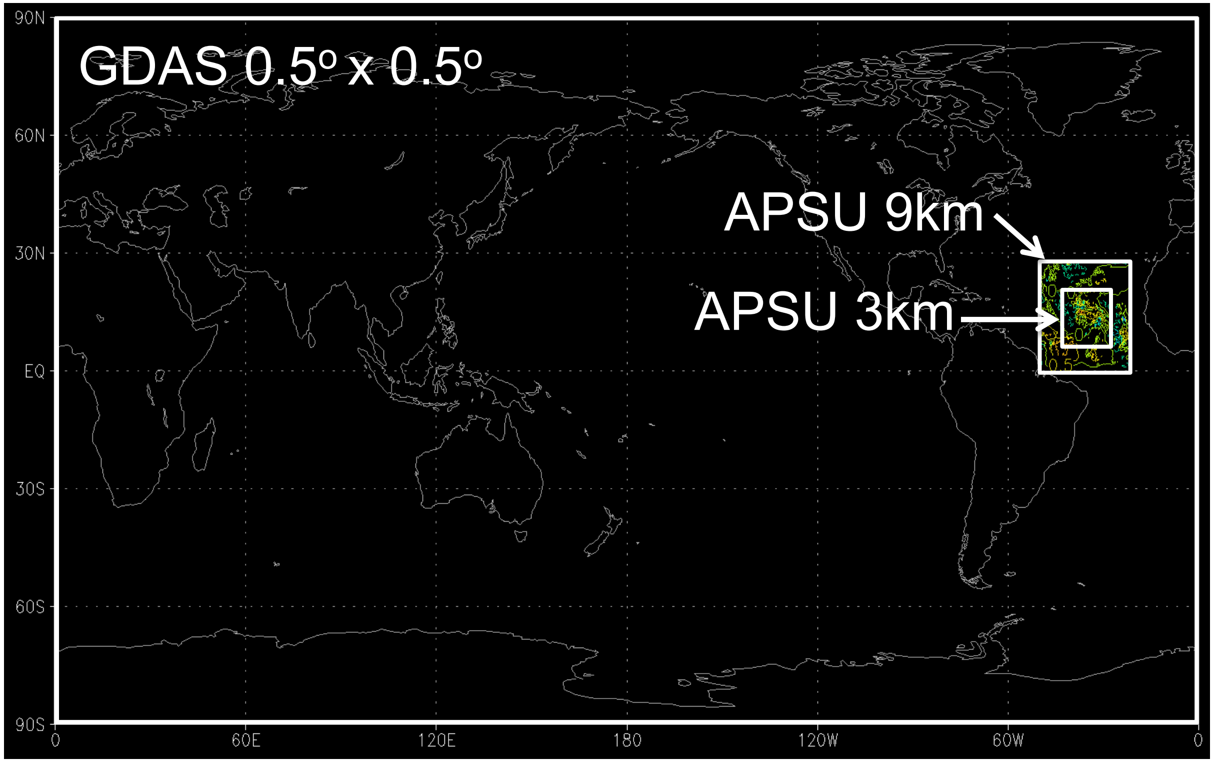
APSU	PSU WRF-ARW w/ 2014 real-time configuration
HWRF	HWRF w/ 2013 HWRF configuration, but no ocean
COTC	COAMPS-TC w/ 2014 HFIP configuration

Domain Setup



Initial and Boundary Conditions

- Initial Conditions:
  – PSU WRF-EnKF (APSU) real-time 60-member ensemble analysis and perturbations
  – Operational GDAS analysis
  – APSU + GDAS interpolated and merged onto $0.1^o \times 0.1^o$ grid on standard pressure levels

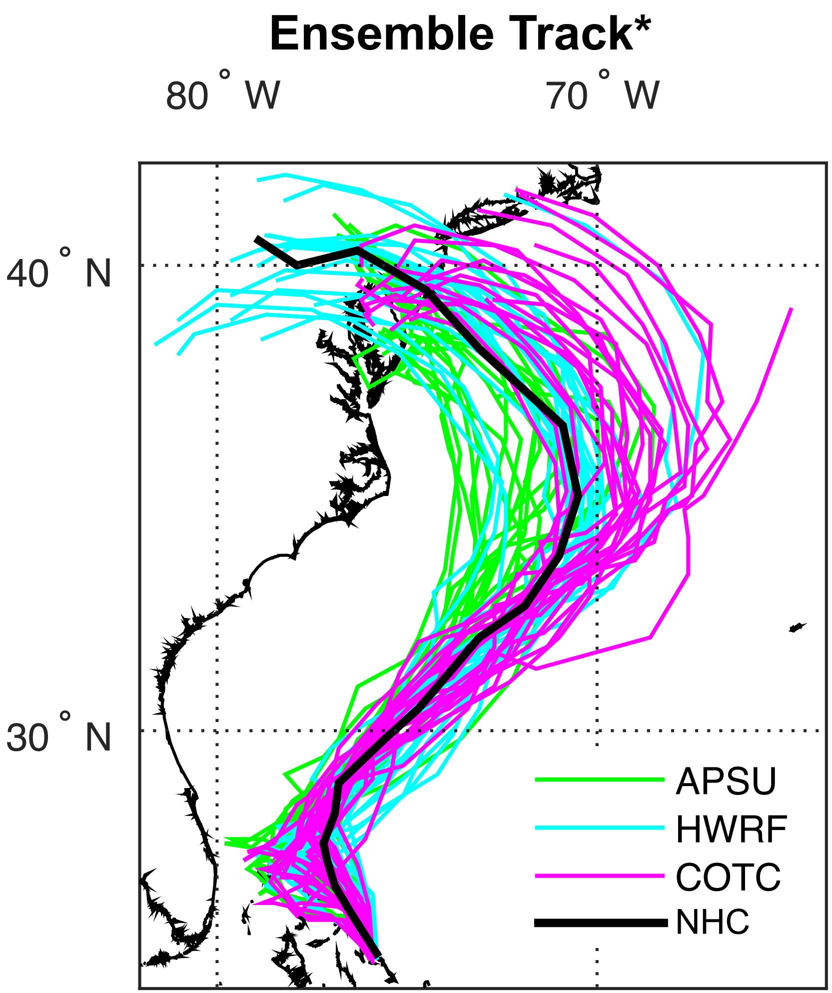


- Boundary Conditions: GFS forecast 6-120 hr (not perturbed)

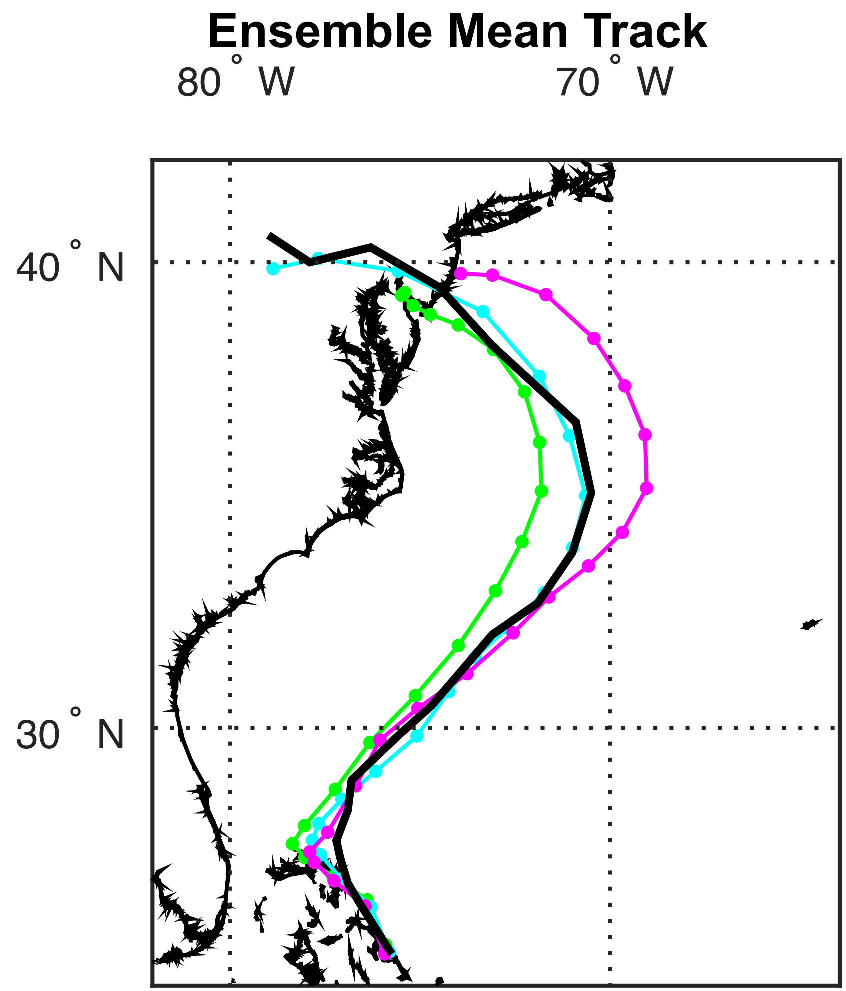
Hurricane Sandy (2012) Ensemble Track

5 day forecast initialized 2012-10-26 00 UTC

- Ensemble track mean and spread reproduced by each model-core
  - Systematic mean difference at longer lead times



*20 of 60 members shown



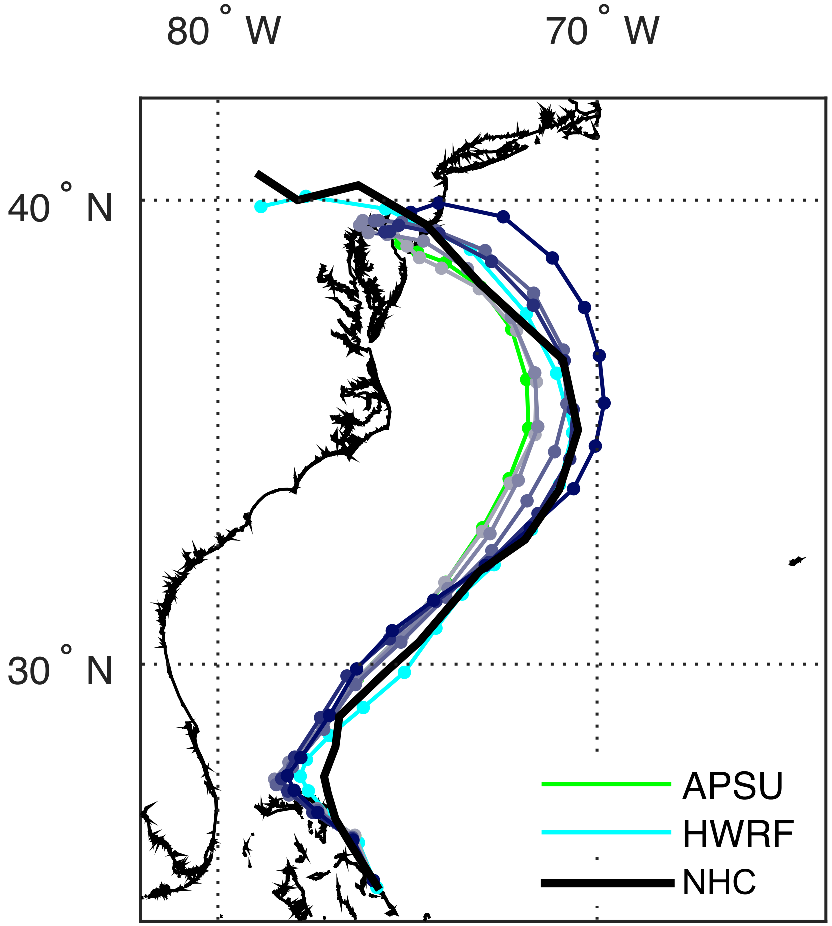
Hurricane Sandy (2012) Multiple Physics Ensembles

“APSU-Like” Physics

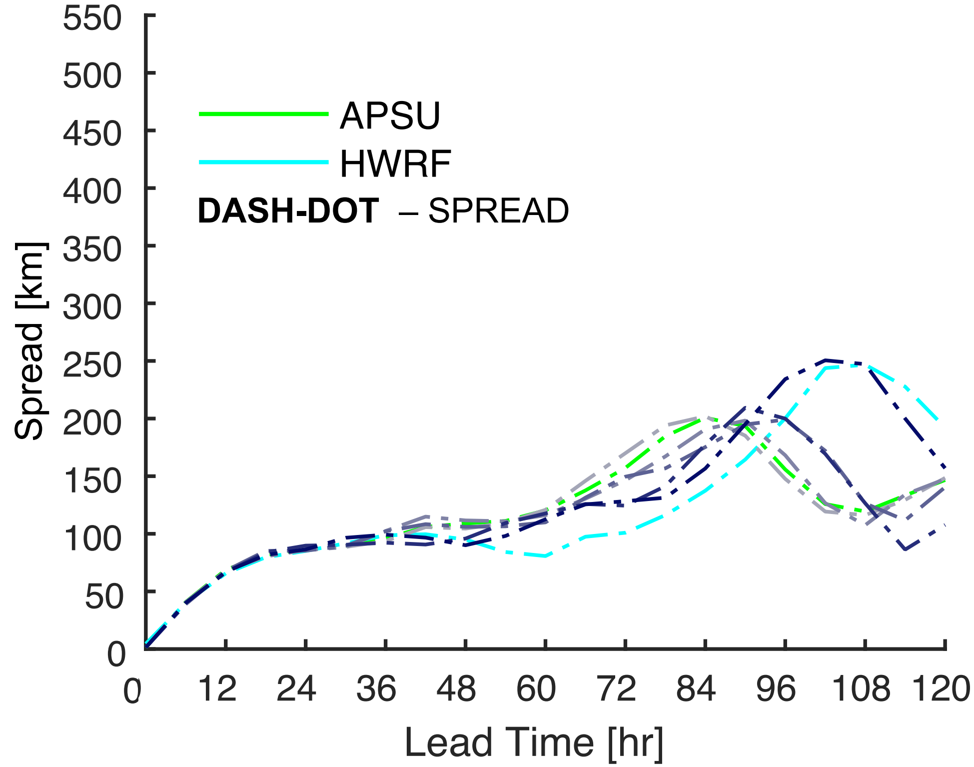
Modify microphysics, radiation, PBL, surface drag, cumulus

“HWRF-Like” Physics

Ensemble Mean Track

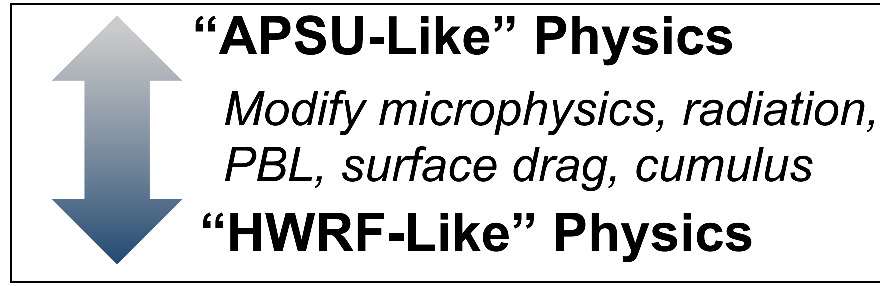


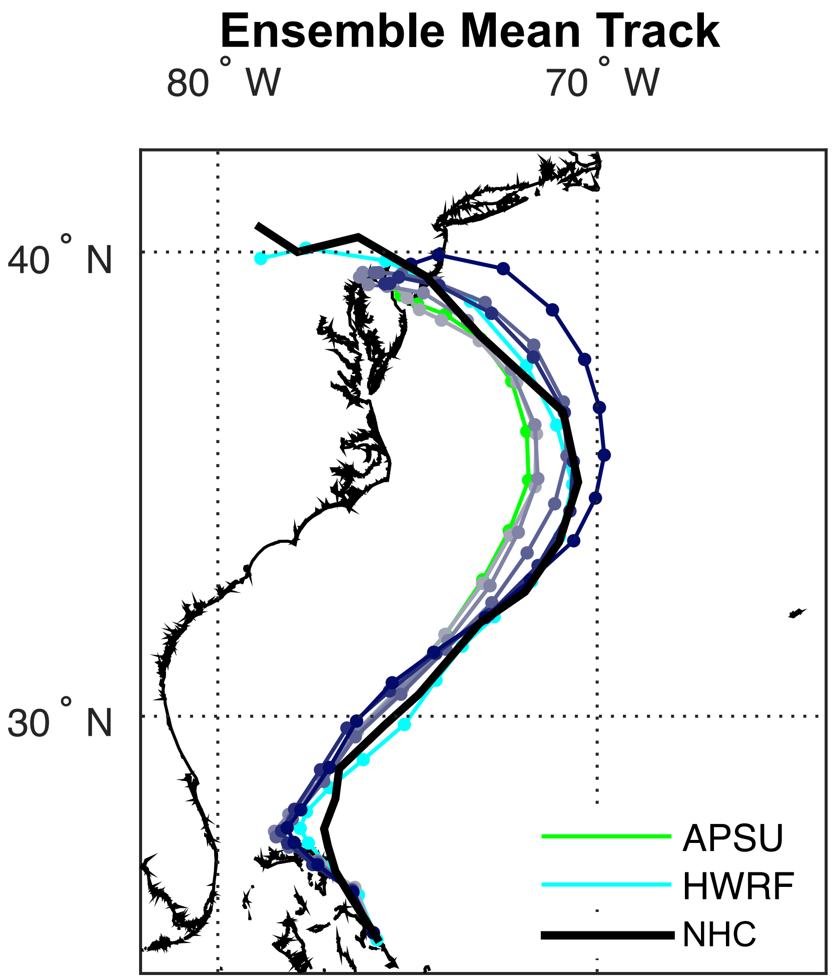
Track Spread*

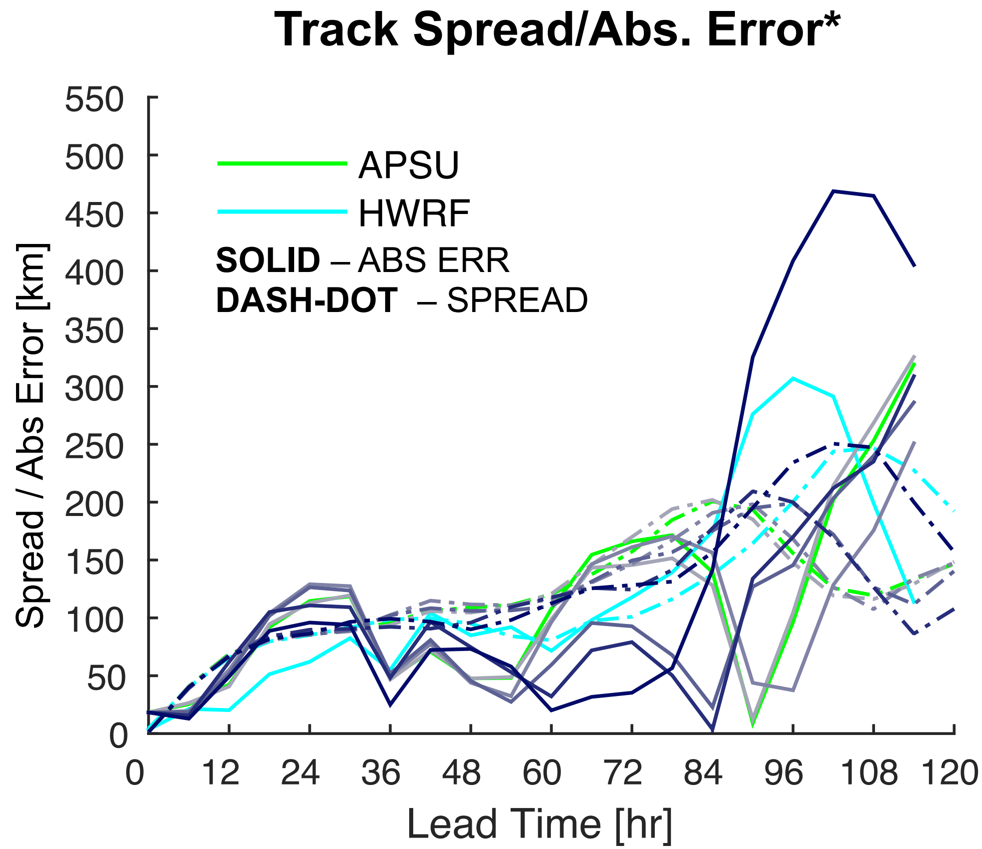


**NHC best track data as verification*

Hurricane Sandy (2012) Multiple Physics Ensembles





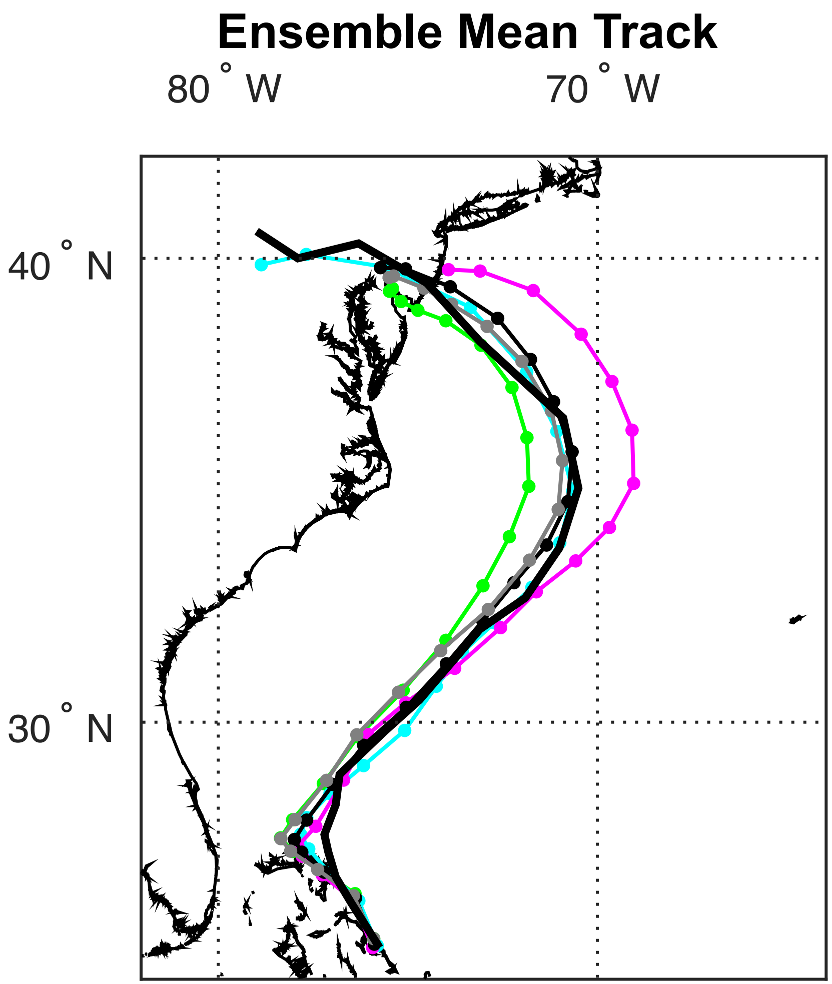


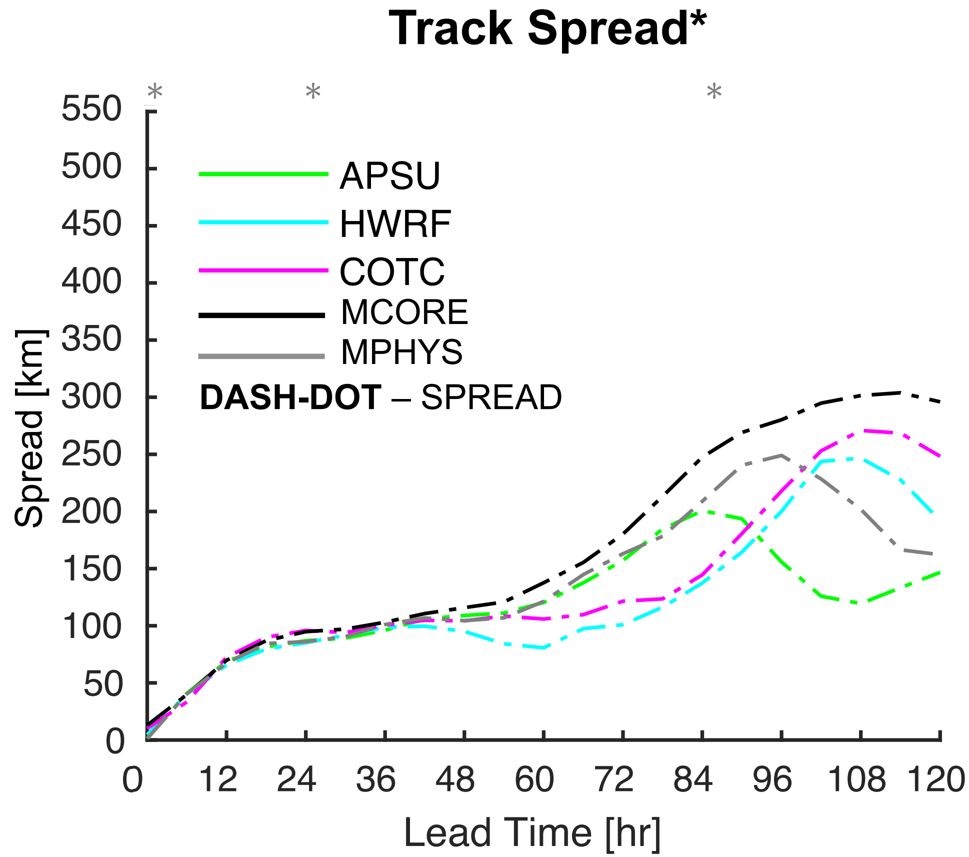
**NHC best track data as verification*

Hurricane Sandy (2012) Multi-Model Ensembles

Multi-core and multi-physics ensemble track error distributions cannot be proven statistically different**

Increased track spread at longer lead times for multi-core or multi-physics





**NHC best track data as verification*

*** Bootstrapped Kolmogorov–Smirnov test (10,000 samples; α=0.05)*

Hurricane Sandy (2012) Multi-Model Ensembles

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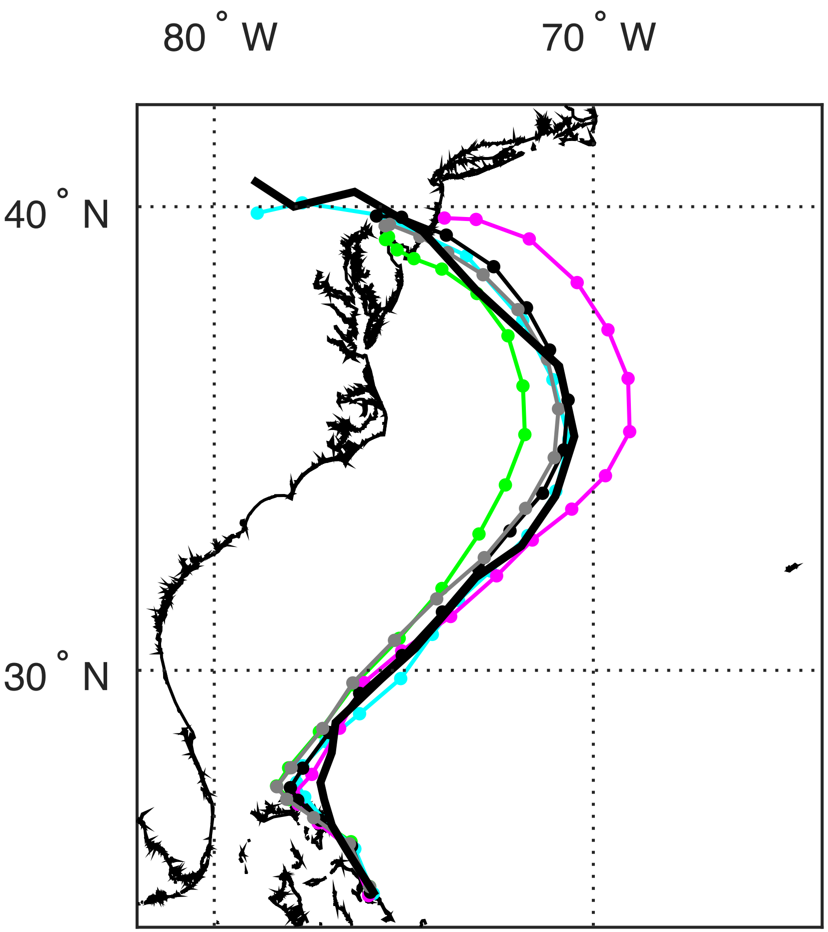
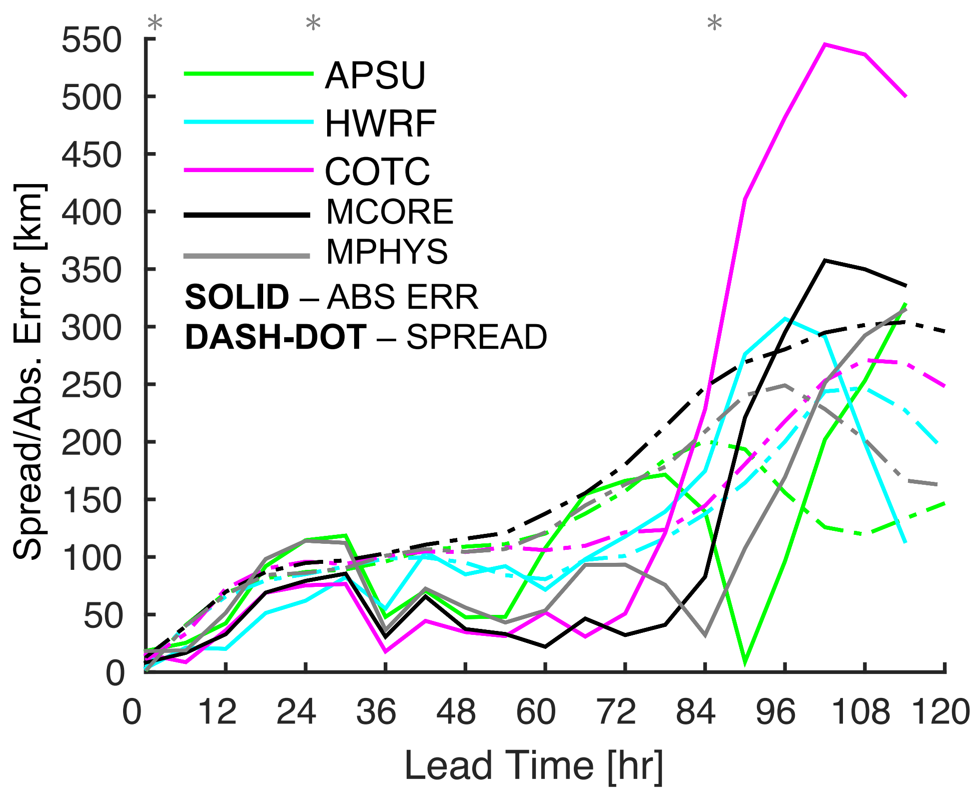
Ensemble Mean Track



Track Spread/Abs. Error*



**NHC best track data as verification*

*** Bootstrapped Kolmogorov–Smirnov test (10,000 samples; α=0.05)*

Hurricane Edouard (2014) Ensemble Track and Intensity

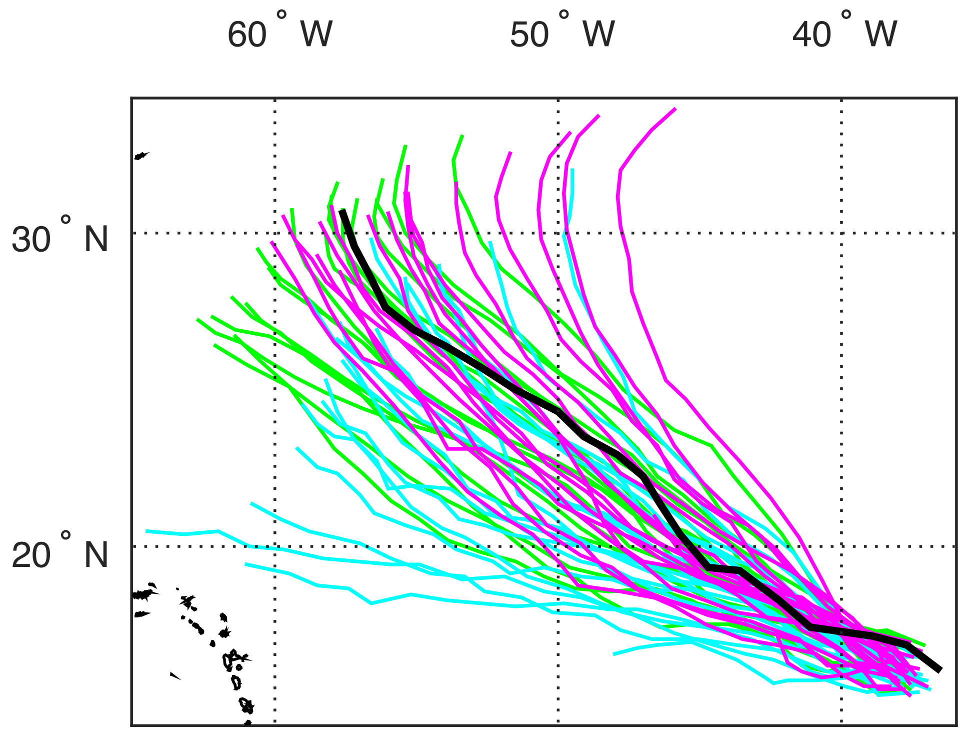
5 day forecast initialized
2014-09-11 12 UTC

Multi-core ensemble spread larger than any individual single-core

Spread:

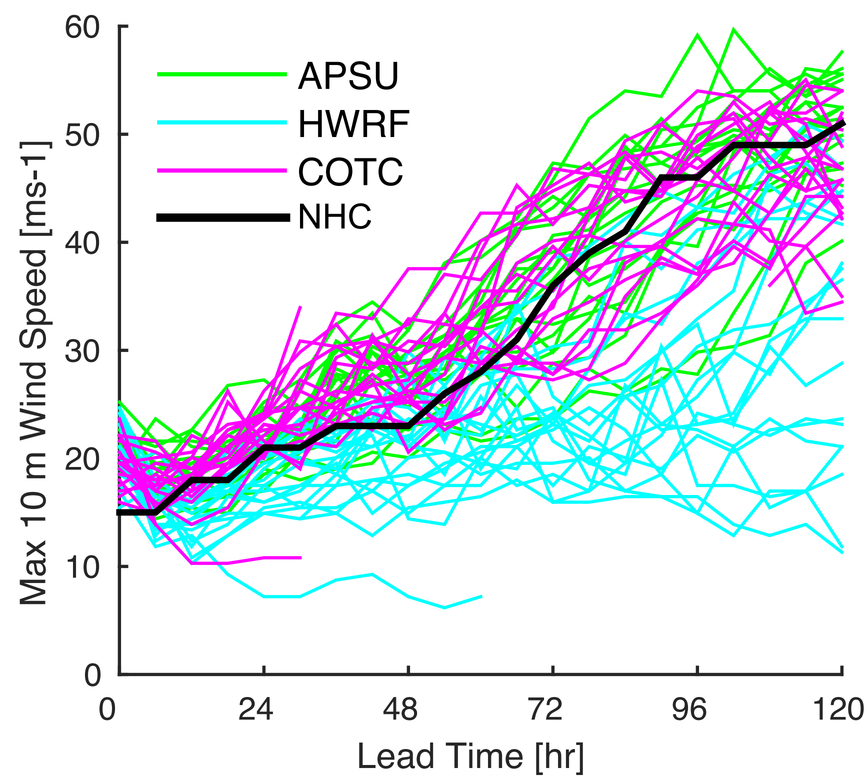
APSU ~ COTC !~ HWRF

Ensemble Track*

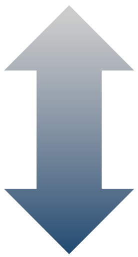


**20 of 60 members shown*

Ensemble Intensity*



Hurricane Edouard (2014)
Ensemble Mean - Physics



“APSU-Like” Physics

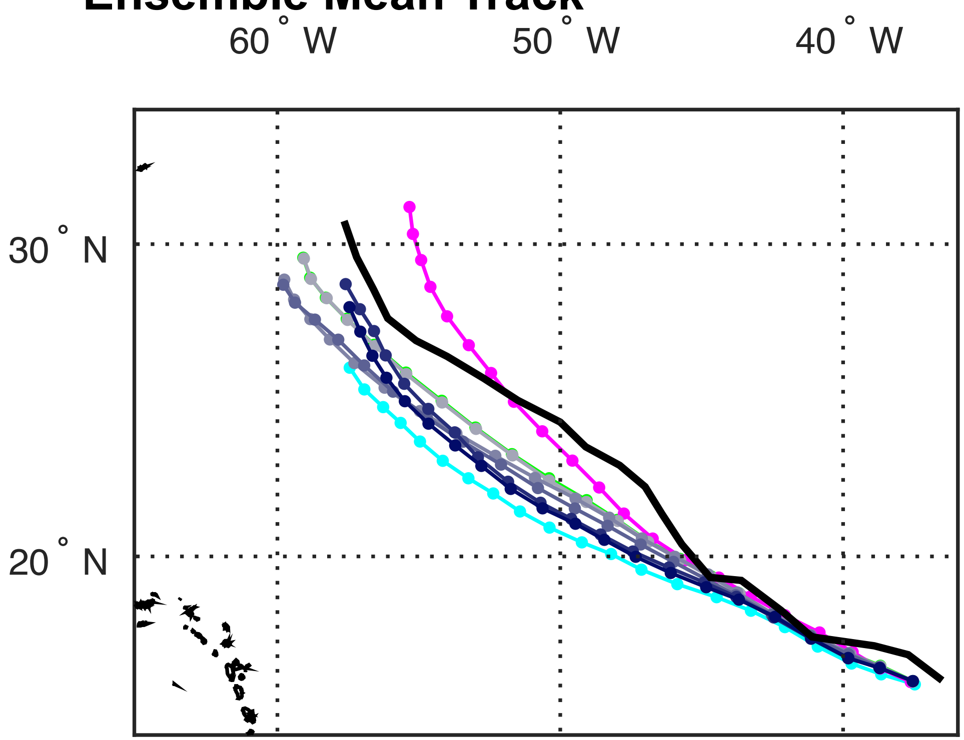
Modify microphysics, radiation, PBL, surface drag, cumulus

“HWRF-Like” Physics

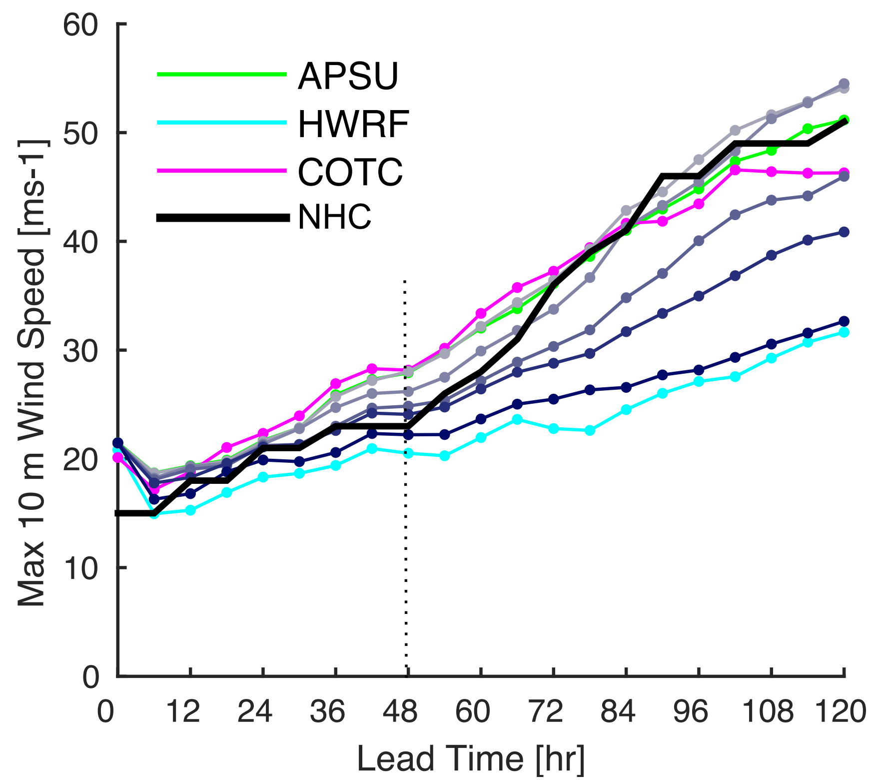
Shift single-core mean to behave similarly to a different model-core

- Physics configuration has a leading influence
- More evident in intensity

Ensemble Mean Track



Ensemble Mean Intensity



Hurricane Edouard (2014) Track Verification

“APSU-Like” Physics

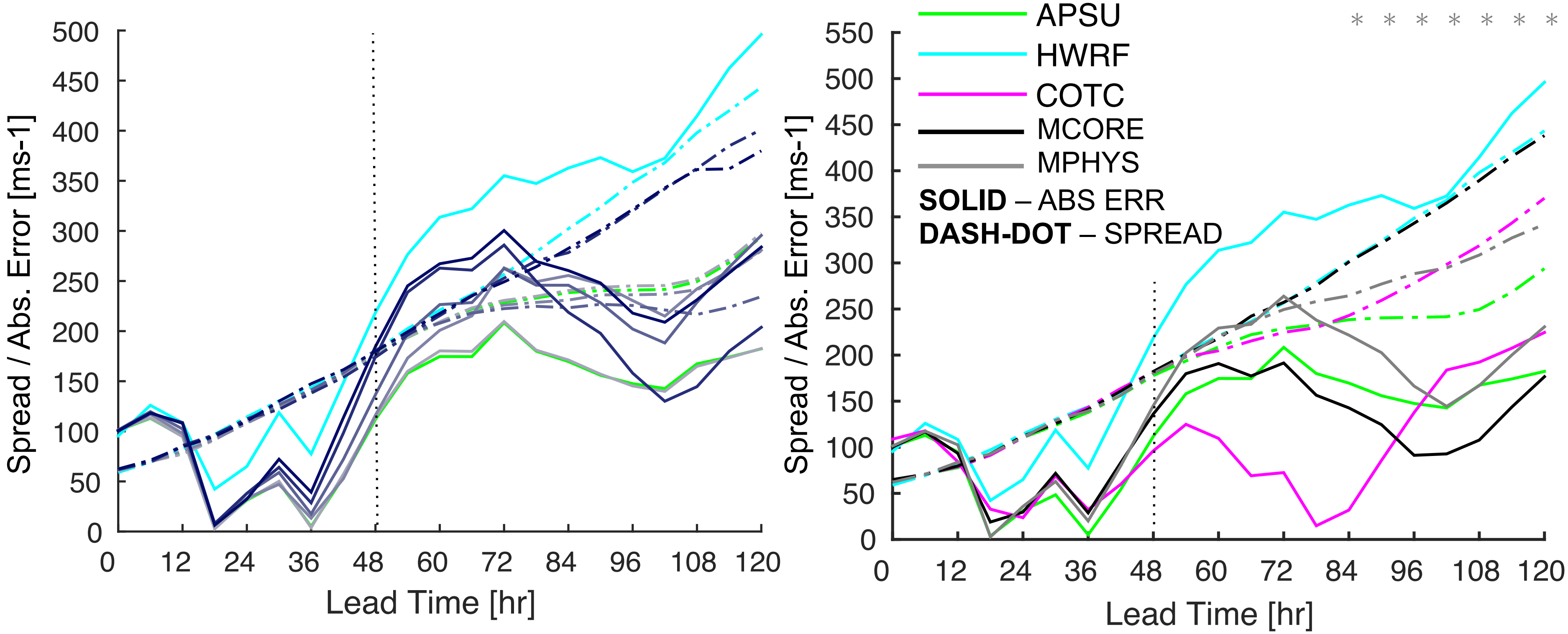
Modify microphysics, radiation, PBL, surface drag, cumulus

“HWRF-Like” Physics

Missing solutions similar to COTC (further east track displacement) in multi-physics ensemble

Lacking broad set of physics combinations

Intensity Spread/Abs. Error of Mean*



**NHC best track data as verification ** Bootstrapped K-S test (10,000 samples; α=0.05)*

Hurricane Edouard (2014) Intensity Verification

“APSU-Like” Physics

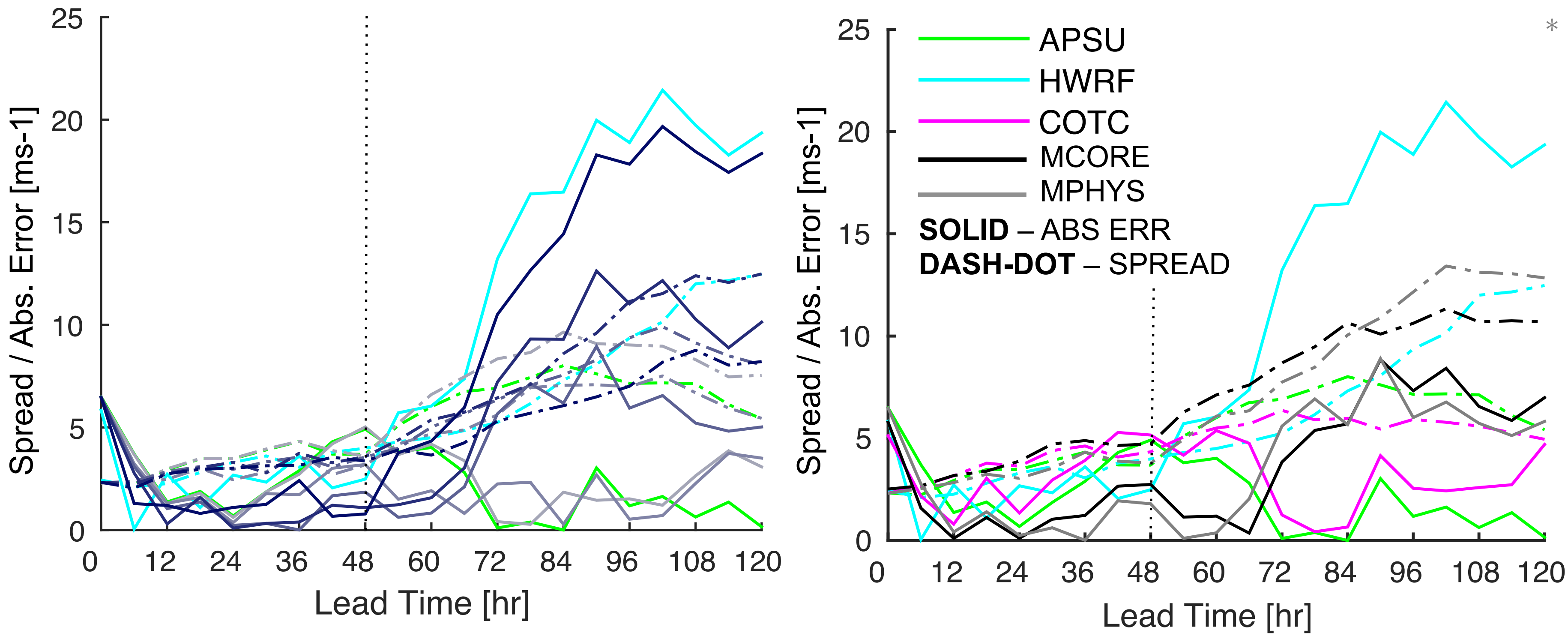
Modify microphysics, radiation, PBL, surface drag, cumulus

“HWRF-Like” Physics

Similar spread evolution for multi-core and multi-physics ensembles

Both multi-core and multi-physics improve mean error within 3 days, but detriment after RI

Intensity Spread/Abs. Error of Mean*



**NHC best track data as verification ** Bootstrapped K-S test (10,000 samples; α=0.05)*

Hurricane Edouard (2014) Ensemble Mean – Stochastic Physics

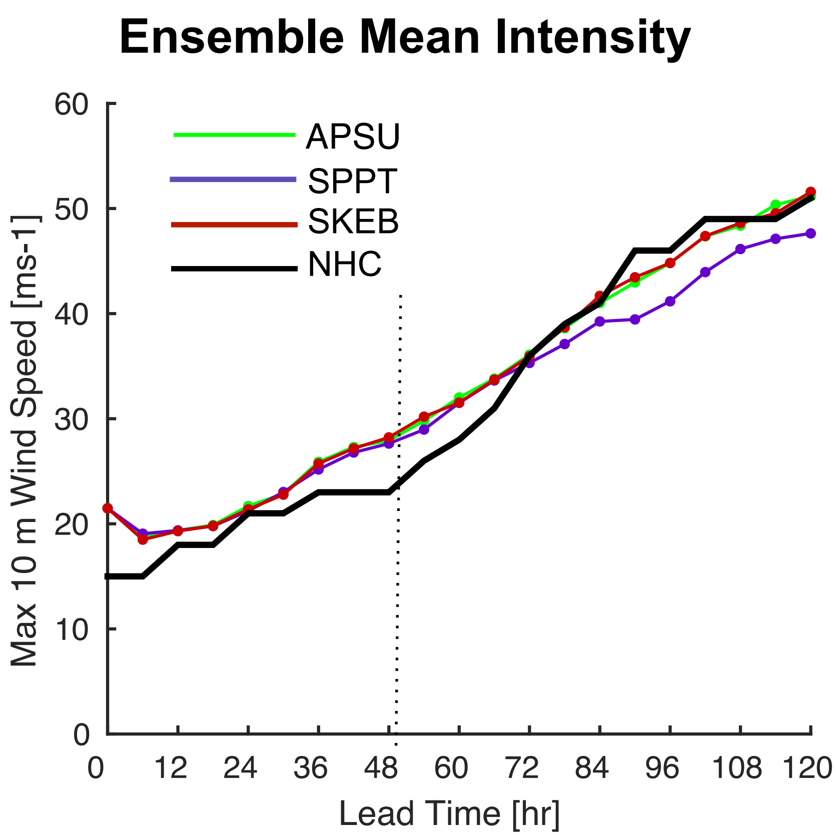
- Stochastic Kinetic Energy Backscatter Scheme (SKEBS; Shutts (2005), Berner et al. 2009)
  - Simulate upscale-propagating errors to account for shortcomings in un-resolved subgrid-scale processes
  - Perturb rotational u- and v-wind components and potential temperature (additive)
  - Spatially and temporally correlated perturbations

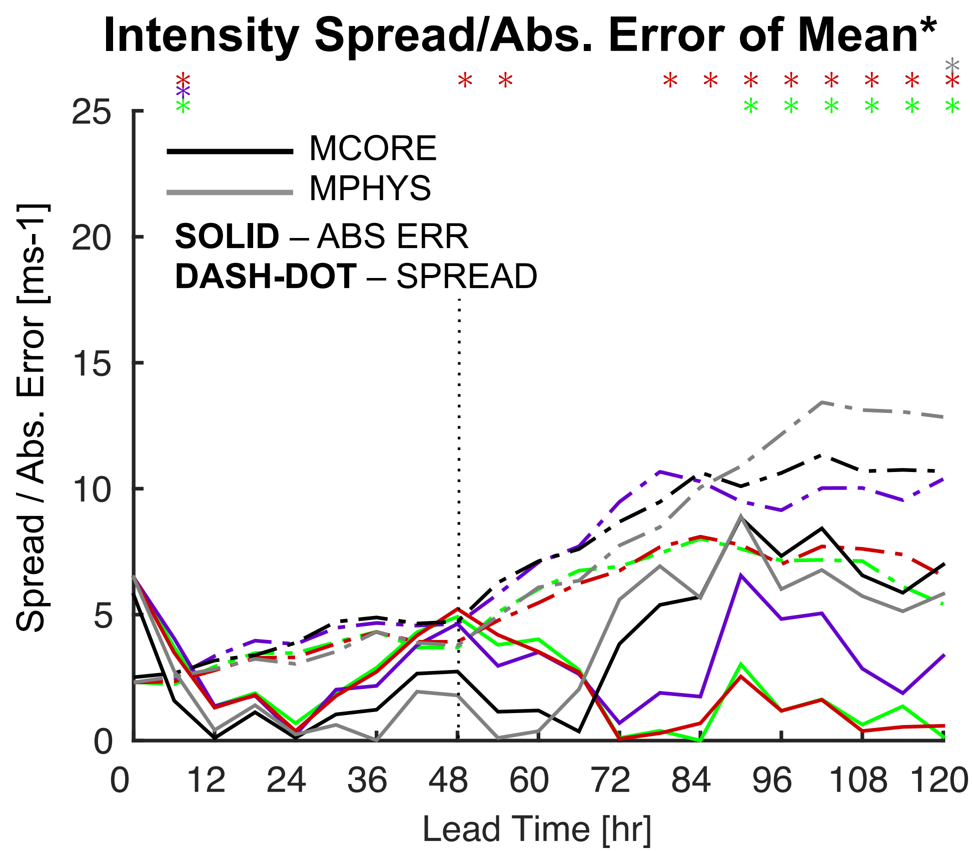
- Stochastically Perturbed Parameterization Tendencies (SPPT; Palmer et al. 2009, Berner et al. 2015)
  - Account for uncertainties in existing parameterization schemes
  - Perturb parameterization tendencies (multiplicative)
  - Similar spatial and temporally correlated perturbations to SKEBS

Hurricane Edouard (2014) Ensemble Mean – Stochastic Physics

SKEBS minimally impacts ensemble mean intensity and intensity spread.

SPPT increases spread, but degrades mean at longer lead times relative to control.





*** Bootstrapped K-S test (10,000 samples; α=0.05)*

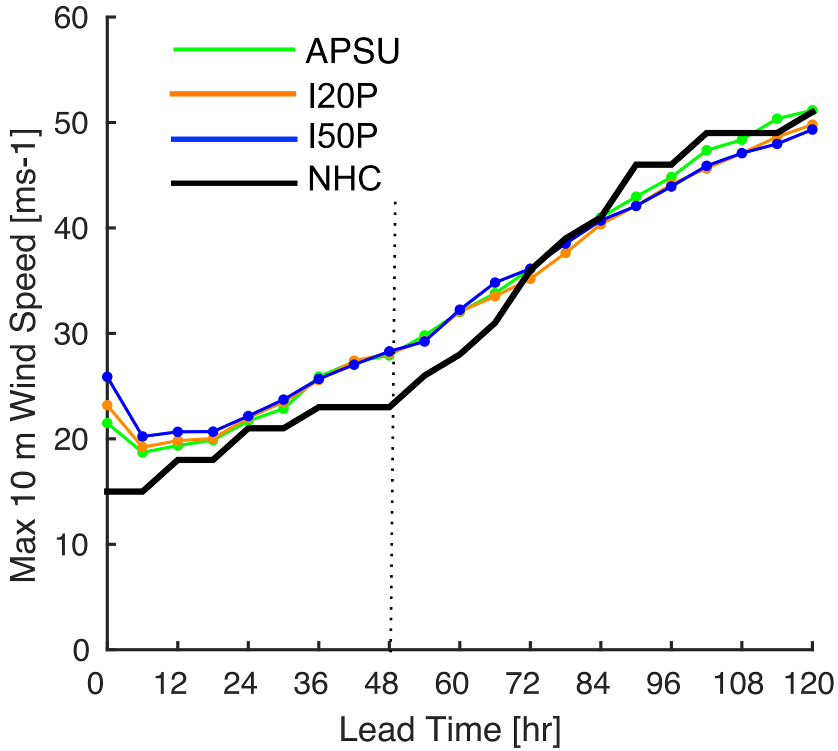
Hurricane Edouard (2014) Ensemble Mean – Increased Initial Perturbations

I20P: 20% inflation

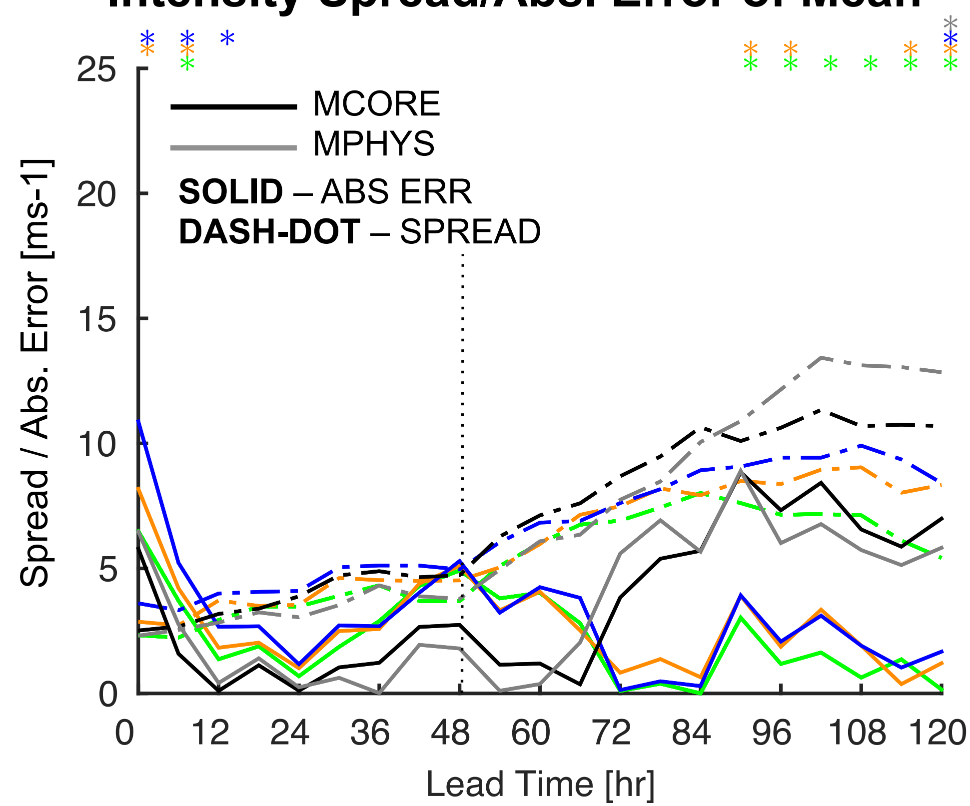
I50P: 50% inflation

Inflating initial perturbations can cover the intensity spread of multi-core and multi-physics ensemble while providing lower error and longer lead times

Ensemble Mean Intensity



Intensity Spread/Abs. Error of Mean*



*** Bootstrapped K-S test (10,000 samples; α=0.05)*

Discussion

→ Recall: initializing three state-of-the-art regional TC-tuned models with the same global resolution IC/BC

- Ensemble track mean and spread generally reproduced by each model-core track and intensity solutions using identical initial perturbations
  - Systematic differences in mean track and intensity evident between model-cores

- Modifying single-core physics can alter mean and spread. Track and intensity error distributions for single-core multi-physics ensemble generally cannot be statistically proven different from multi-core ensemble
  - Stochastic physics and inflating initial perturbations can have similar effect

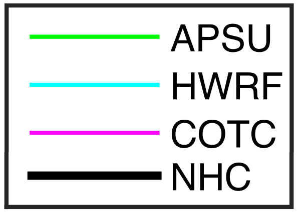
→ Single-core multi-physics may be sufficient for TC prediction

→ How much spread is sufficient?? Extremely hard to determine!

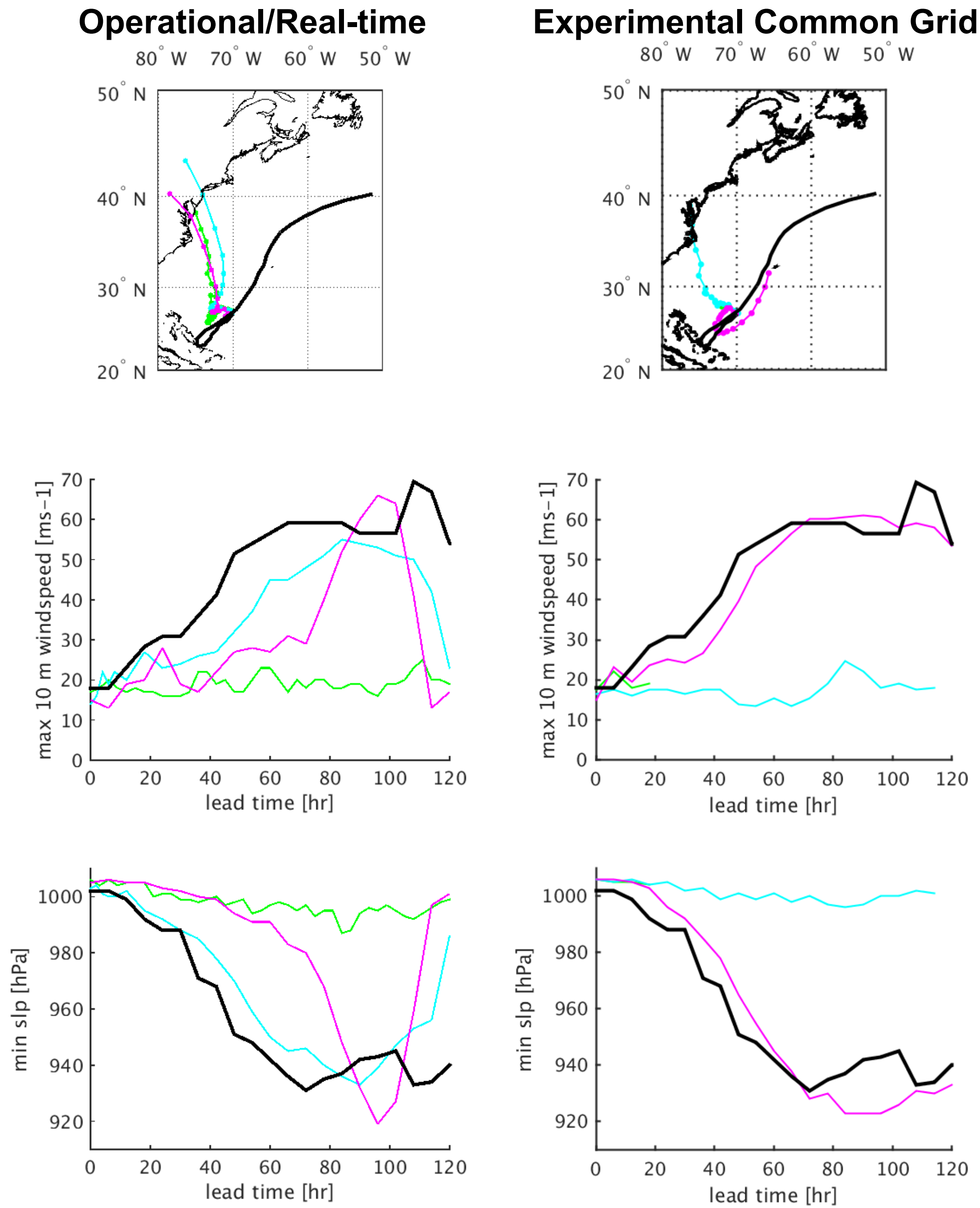
SUPPLEMENTARY MATERIAL

HU JOAQUIN (2015)

Initialized: 09-29 00 UTC

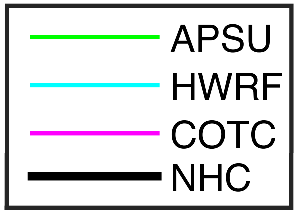


*APSU could not be tracked in experimental grid

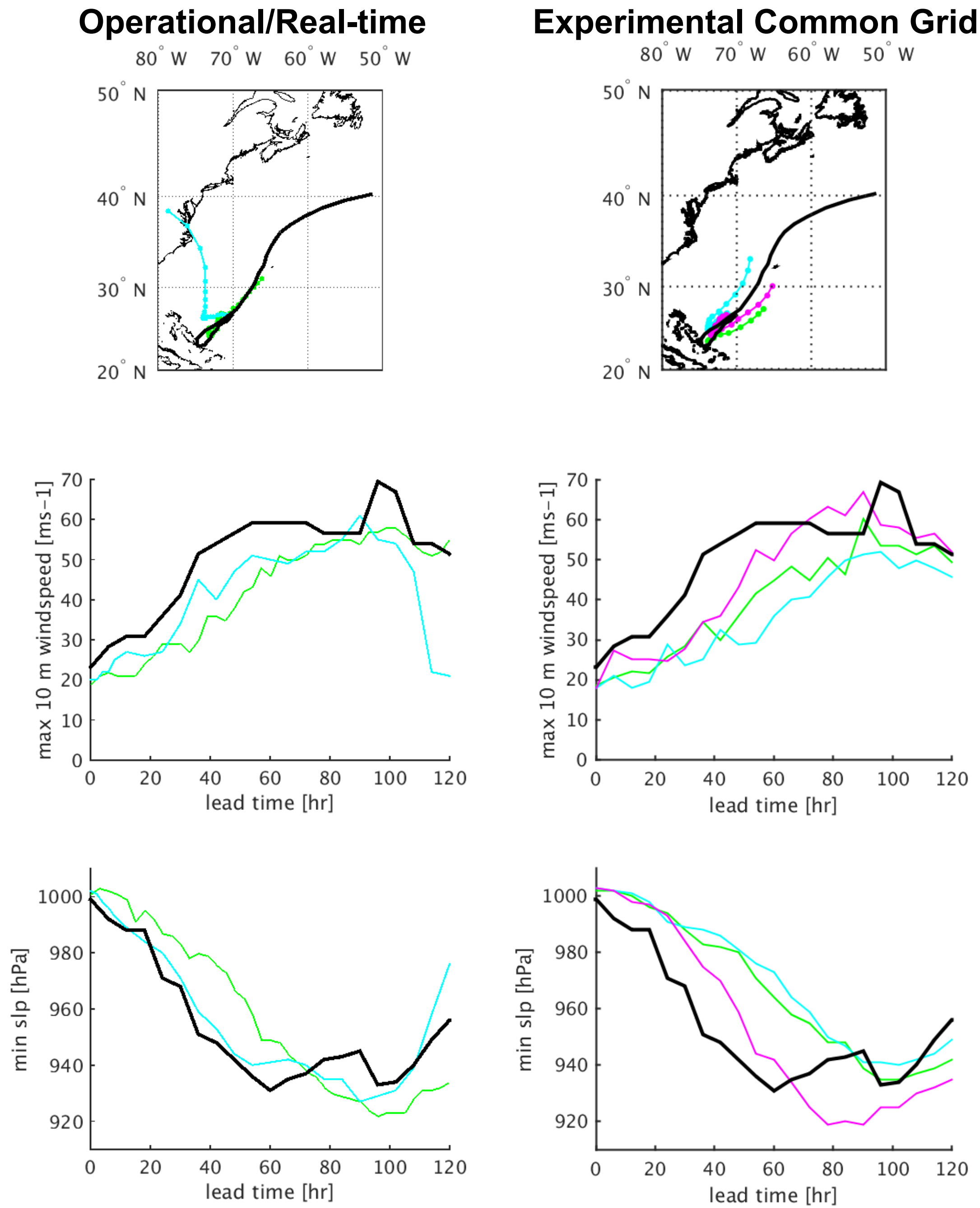


HU JOAQUIN (2015)

Initialized: 09-29 12 UTC

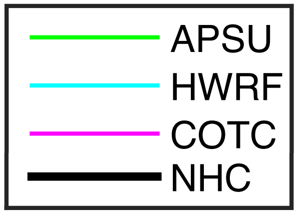


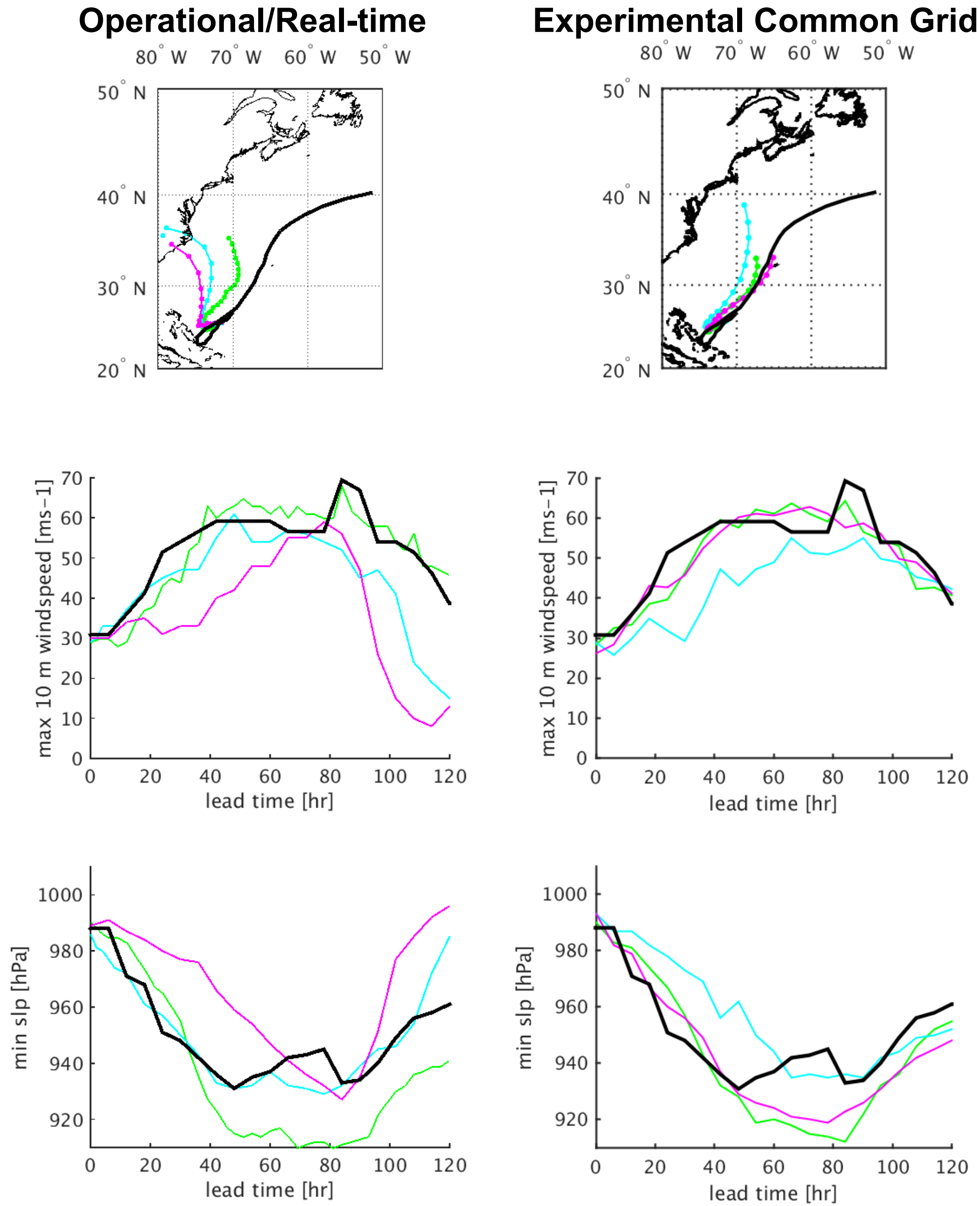
*COTC not in adeck file



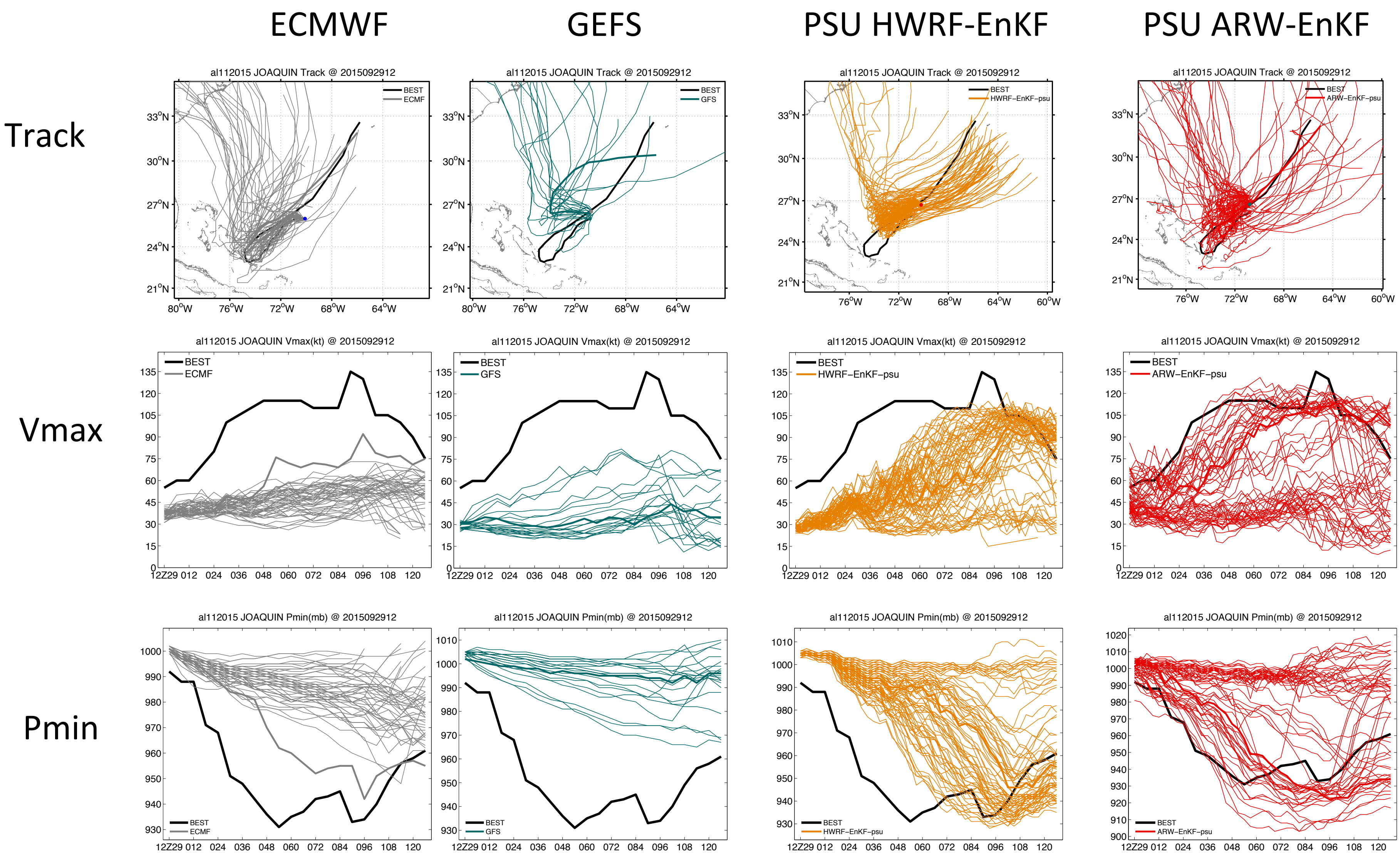
HU JOAQUIN (2015)

Initialized: 09-30 00 UTC





PSU-EnKF real-time systems for Joaquin (2015): Ensemble at 12Z/29



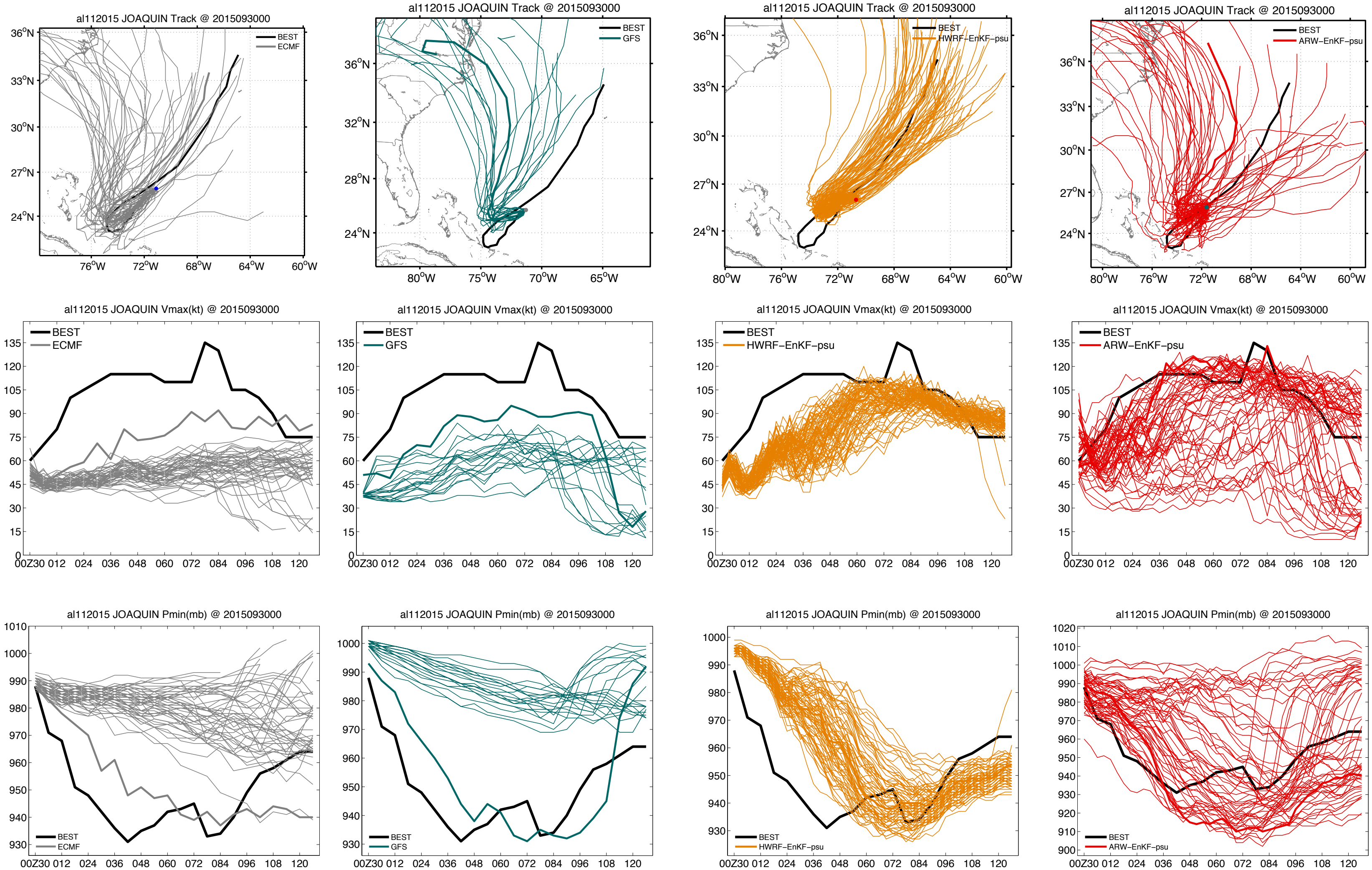
PSU-EnKF real-time systems for Joaquin (2015): Ensemble at 00Z/30

ECMWF | GEFS | PSU HWRF-EnKF | PSU ARW-EnKF

Track

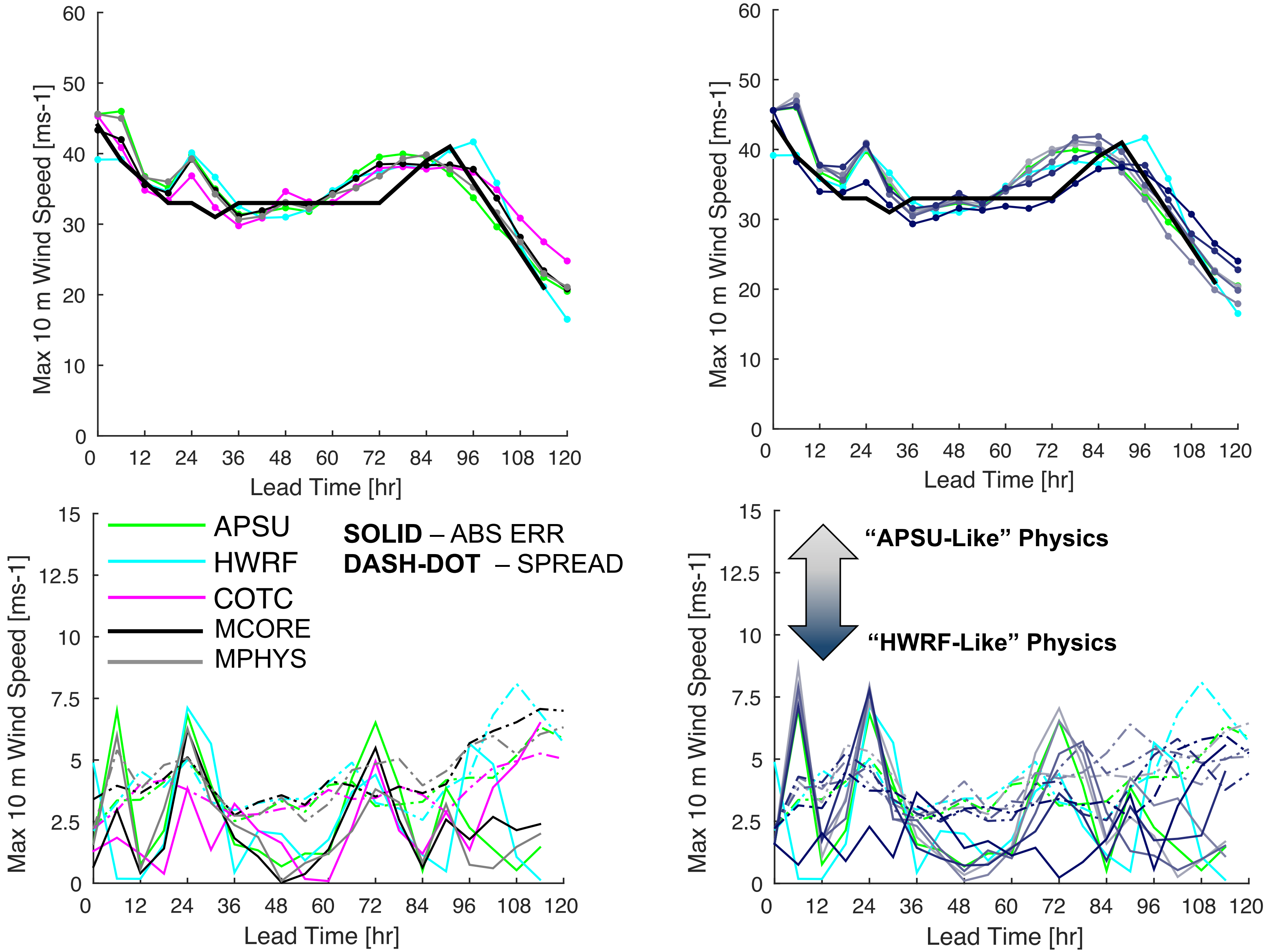
Vmax

Pmin



Hurricane Sandy (2012)

*NHC best track data as verification

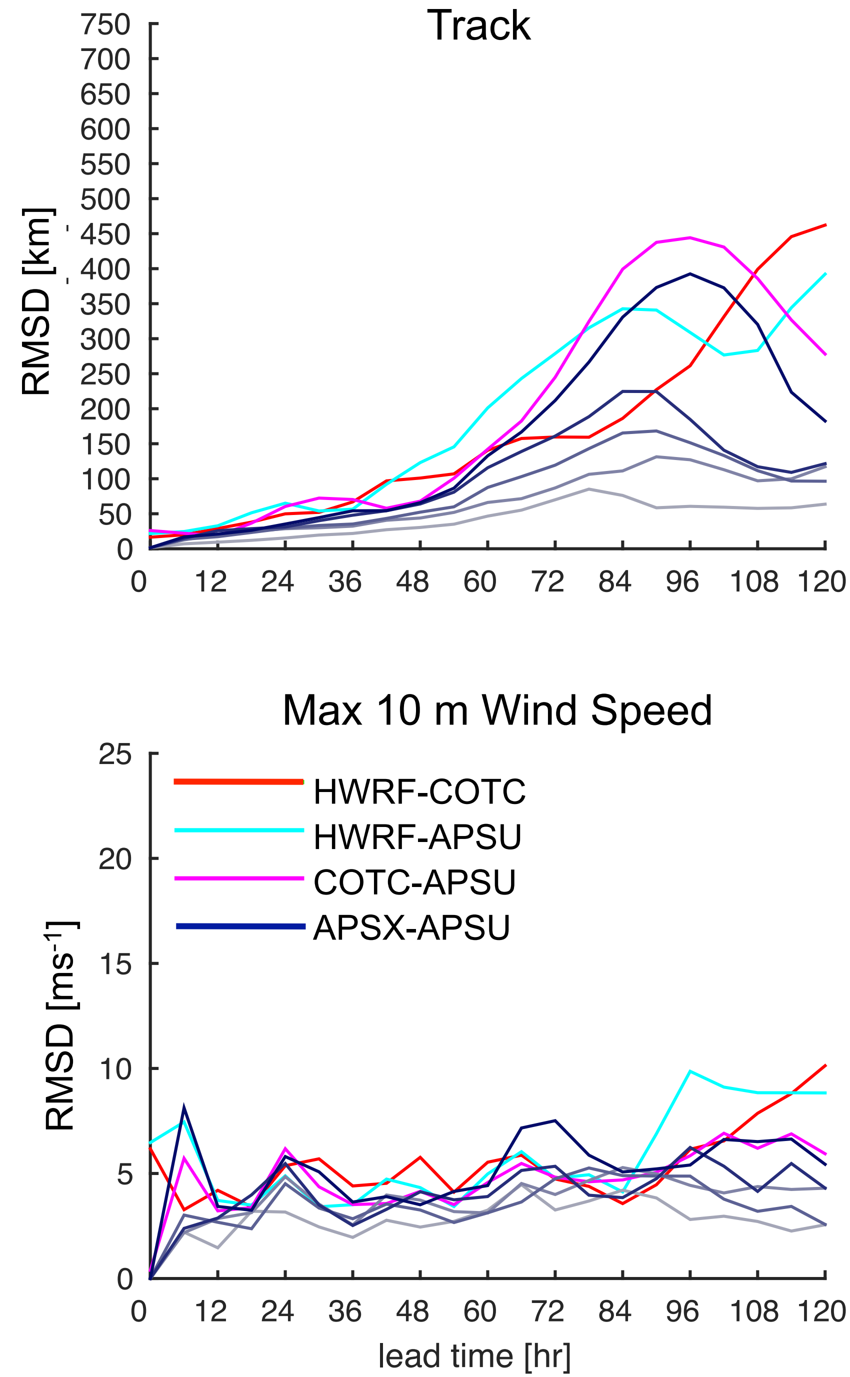


Hurricane Sandy (2012) Model Error Growth

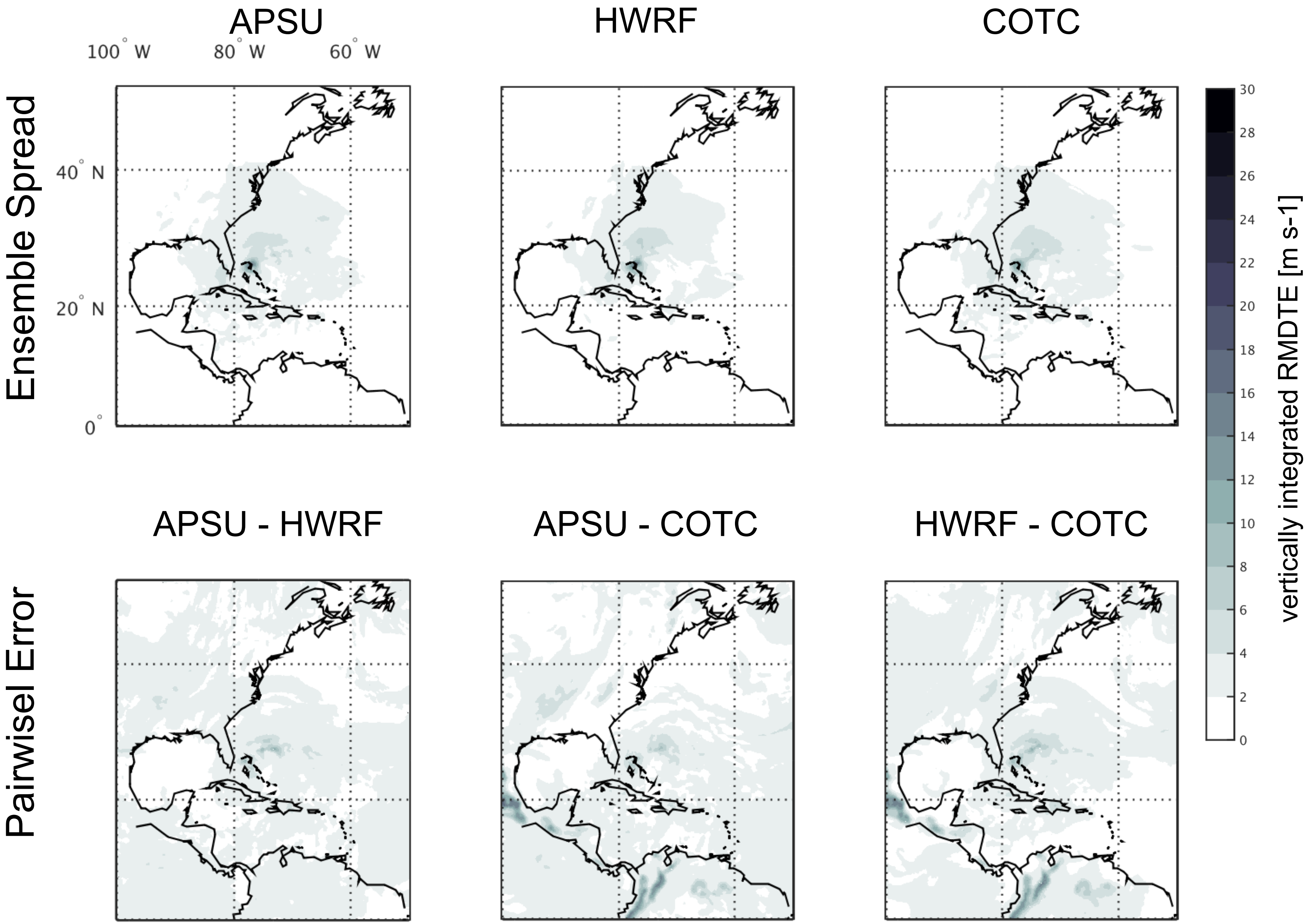
"APSU-Like" Physics

Modify microphysics, radiation, PBL, surface drag, cumulus

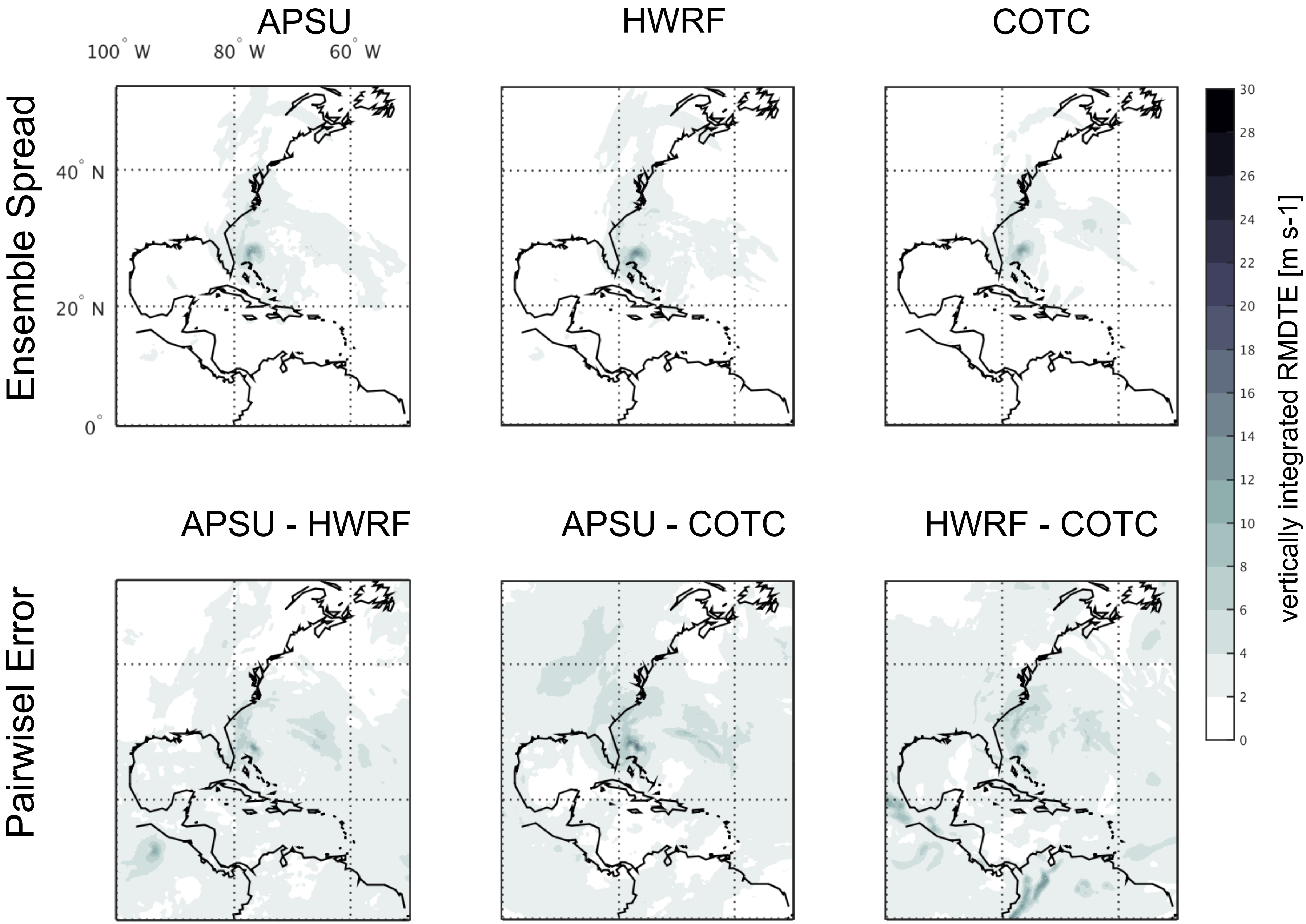
"HWRF-Like" Physics



Hurricane Sandy (2012) Dom. Int. DTE (FHR 012)

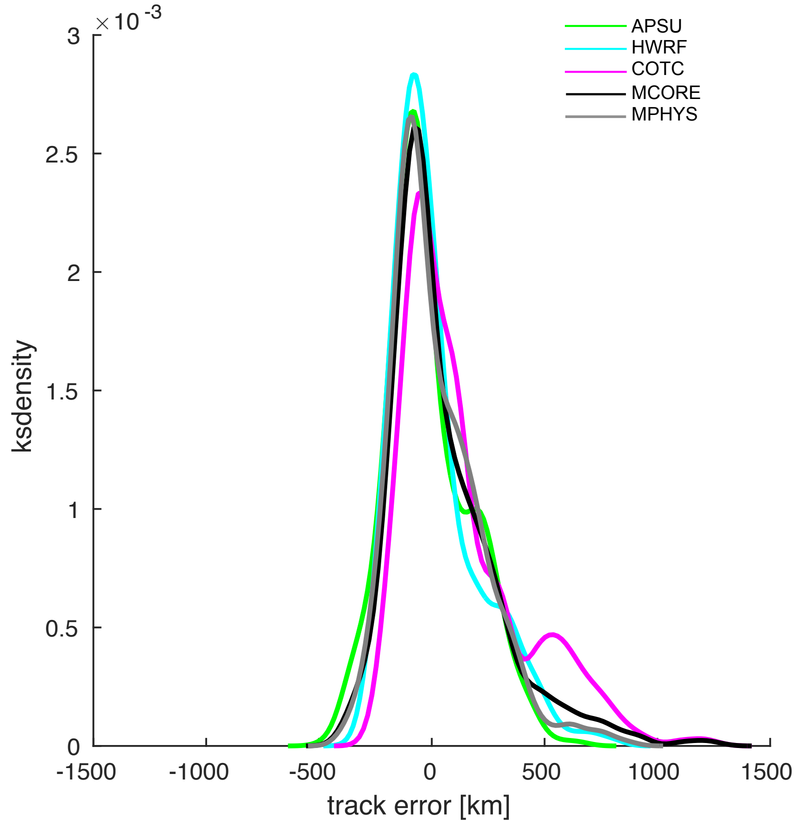


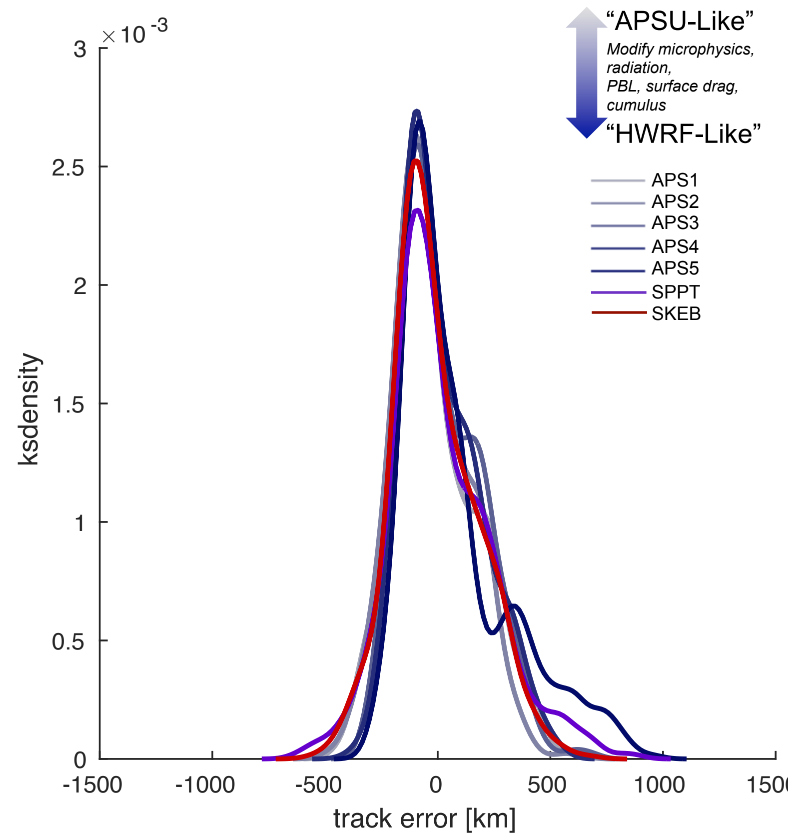
Hurricane Sandy (2012) Dom. Int. DTE (FHR 036)



Track Error kernel smoothed density distribution (HU Sandy)

Including all 6-hrly forecasts (0 to 120 h) and ensemble members

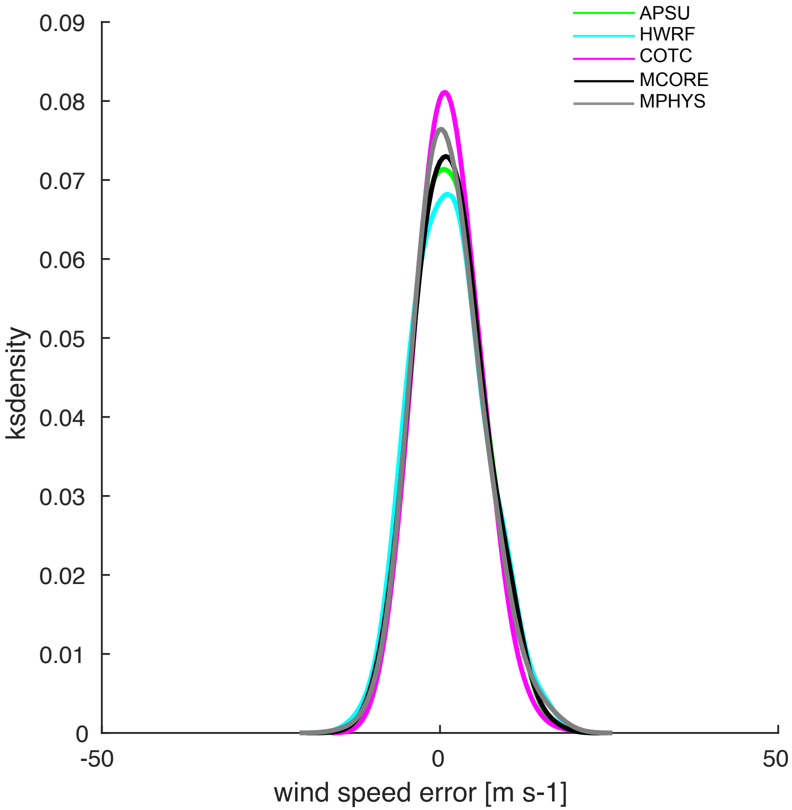


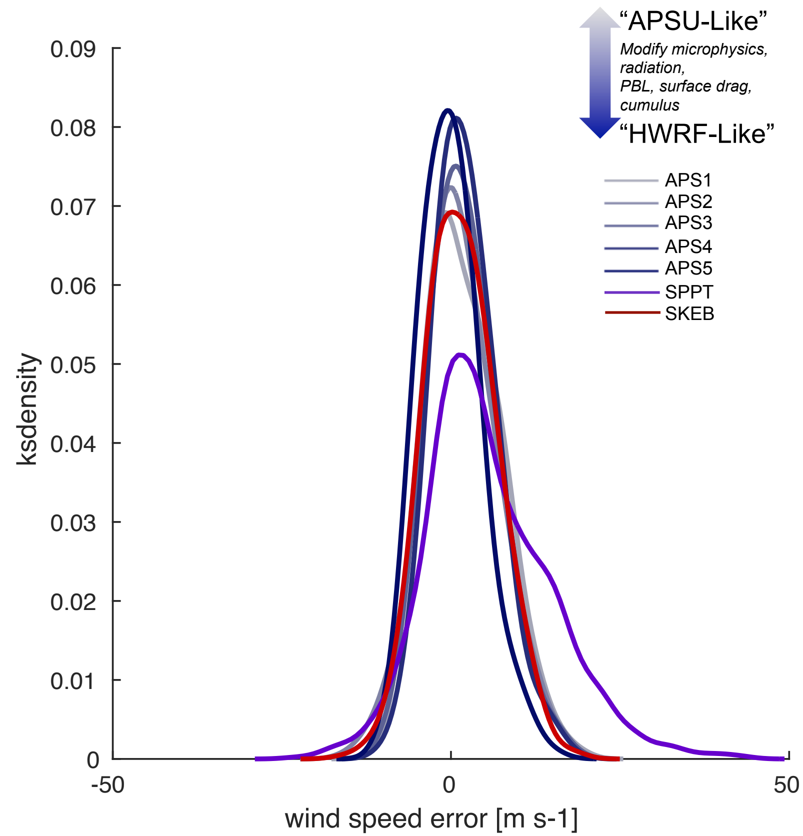


- …

WSP error kernel smoothed density distribution (HU Sandy)

Including all 6-hrly forecasts (0 to 120 h) and ensemble members

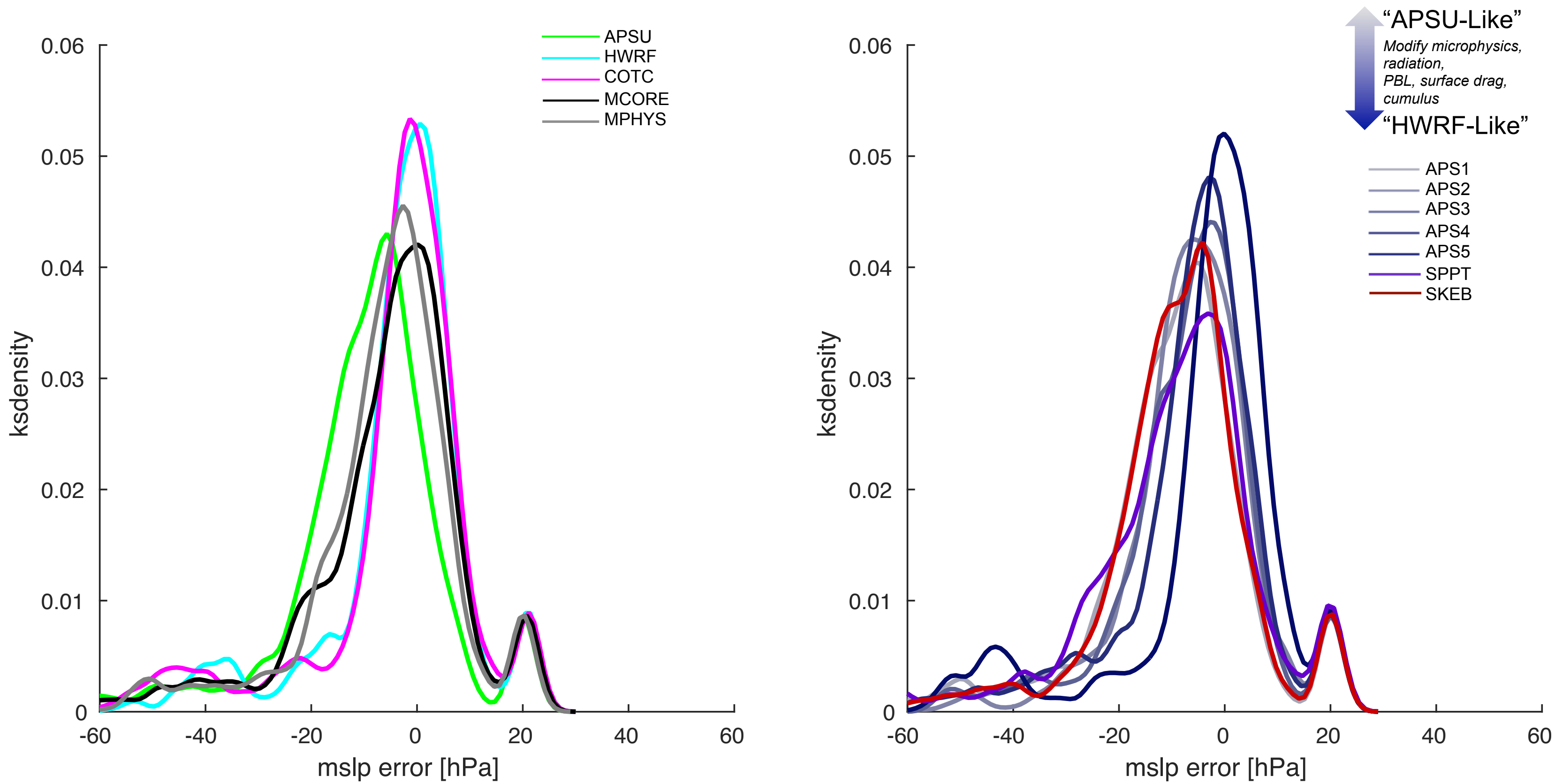




- …

MSLP error kernel smoothed density distribution (HU Sandy)

Including all 6-hrly forecasts (0 to 120 h) and ensemble members



- …

Kolmogorov–Smirnov non-parametric @ alpha=0.05 (HU Sandy)

TRACK ERROR

	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
APS1 - HWRF	🔴	🟢	🟢	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
APS2 - HWRF	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
APS3 - HWRF	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	
APS4 - HWRF	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
APS5 - HWRF	🔴	🔴	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	
SPPT - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	
SKEB - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	
MPHYS-MCOMB	🔴	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	

WSP ERROR

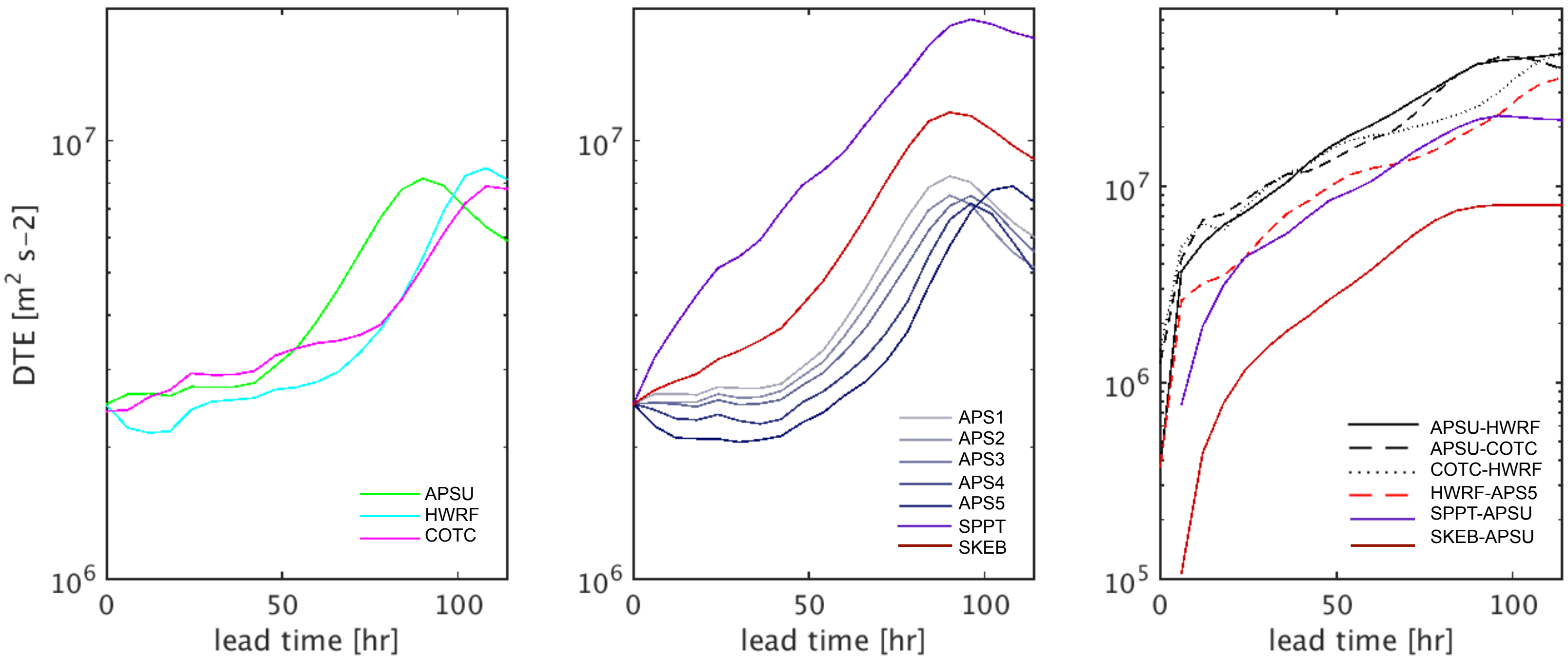
	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
APS1 - HWRF	🔴	🔴	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	
APS2 - HWRF	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🟢	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	
APS3 - HWRF	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🔴	🔴	🔴	🟢	
APS4 - HWRF	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	
APS5 - HWRF	🔴	🟢	🔴	🟢	🔴	🔴	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	
SPPT - APSU	🟢	🟢	🟢	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
SKEB - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	
MPHYS-MCOMB	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	

MSLP ERROR

	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
APS1 - HWRF	🔴	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	
APS2 - HWRF	🔴	🟢	🟢	🟢	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
APS3 - HWRF	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	
APS4 - HWRF	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟢	
APS5 - HWRF	🔴	🟢	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	
SPPT - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	
SKEB - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	
MPHYS-MCOMB	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	

Domain integrated DTE (HU Sandy)

6-hrly forecasts initialized at 2012-10-26 00 UTC

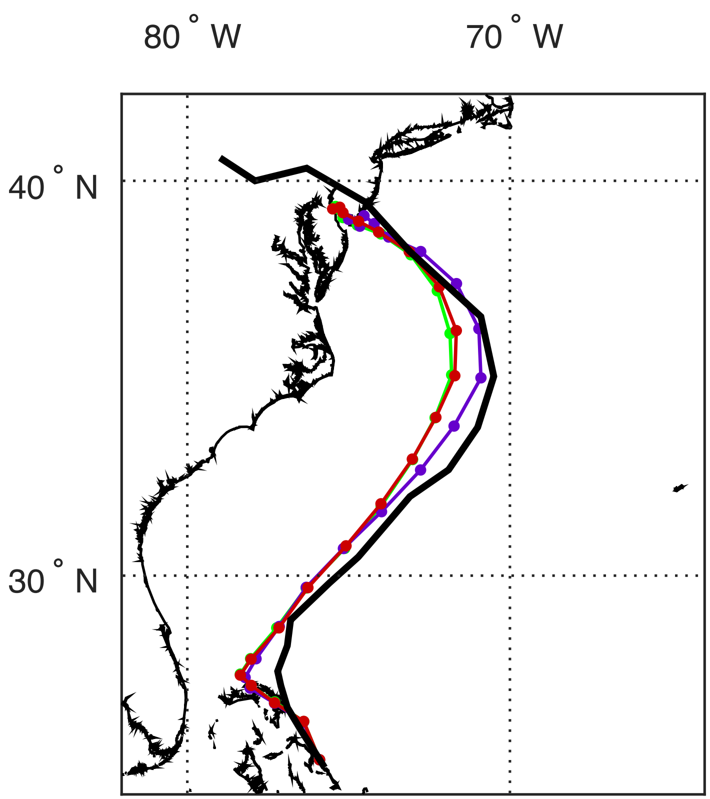


Hurricane Sandy (2012) Ensemble Mean – Stochastic Physics

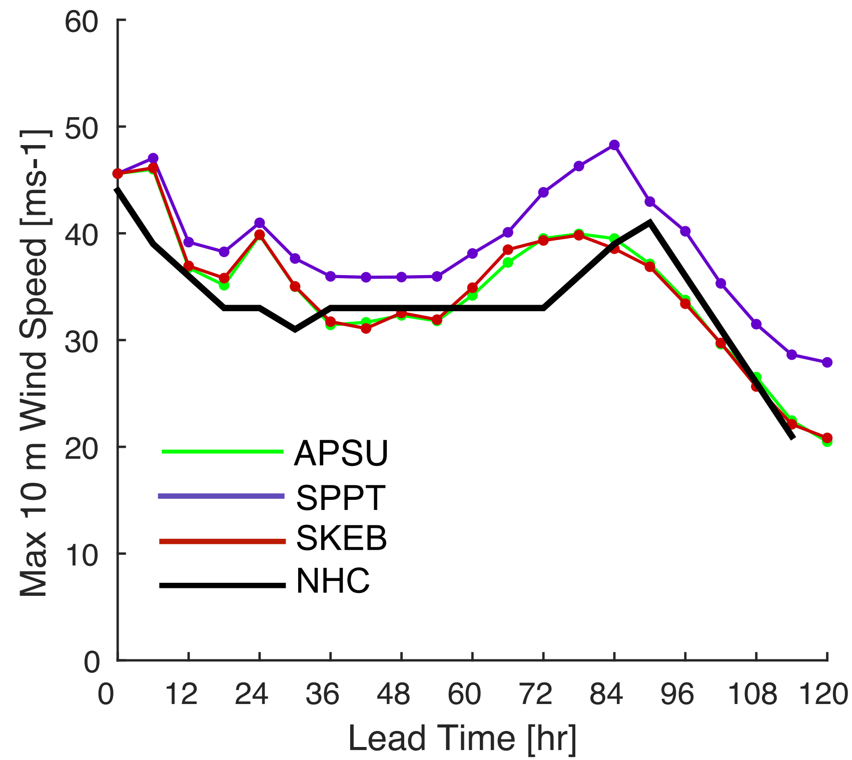
SPPT shifts both the ensemble mean, improving track but degrading intensity

SKEBS minimally impacts mean

Ensemble Mean Track

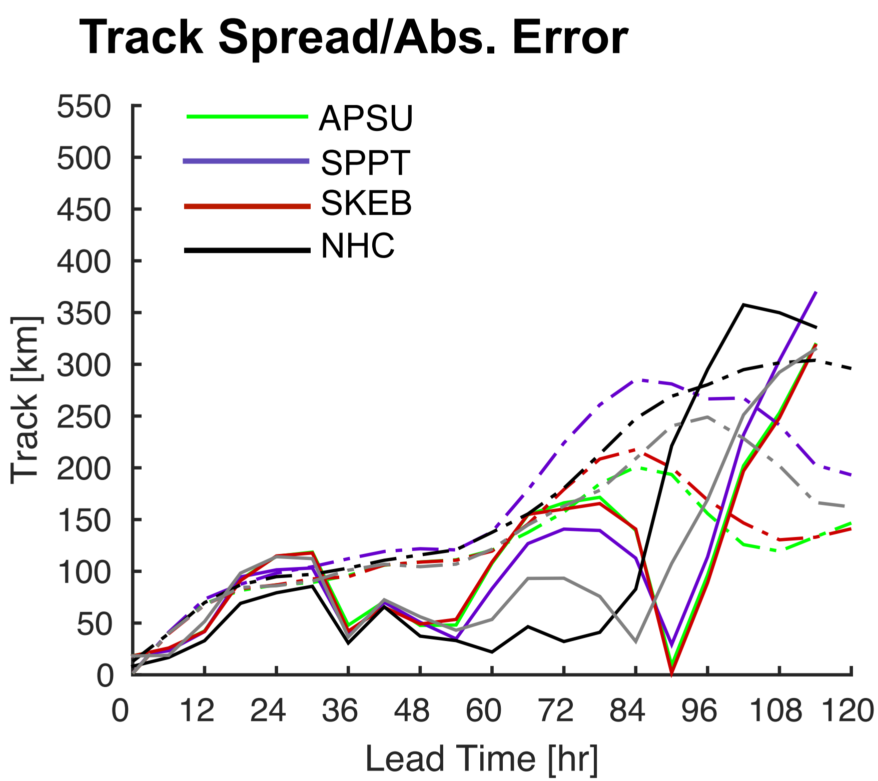


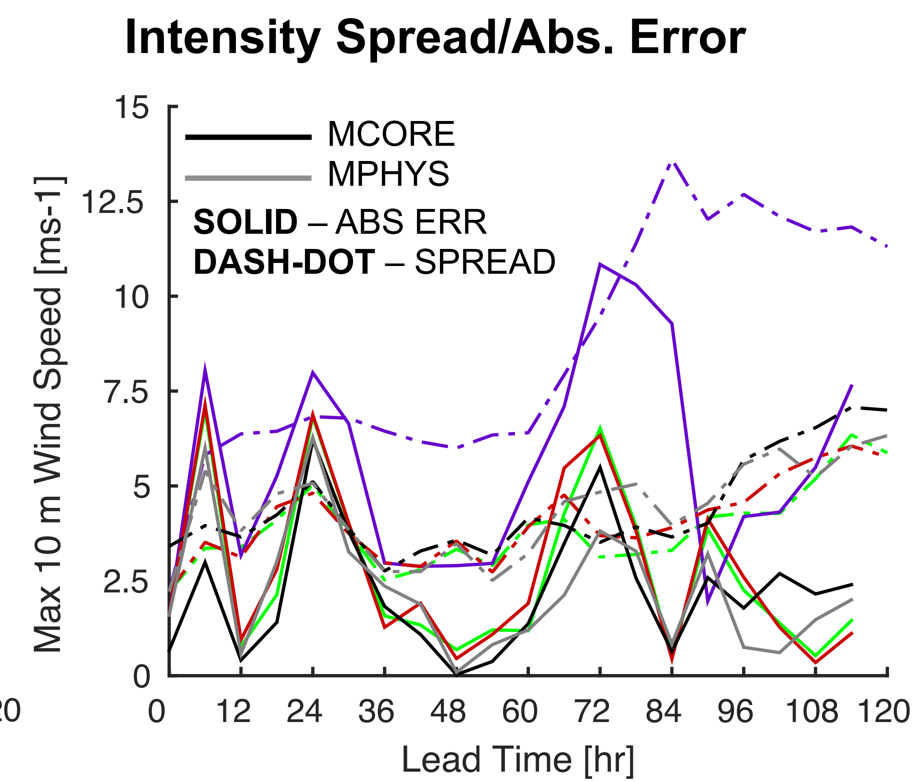
Ensemble Mean Intensity



Hurricane Sandy (2012) Absolute Error and Spread – Stochastic Physics

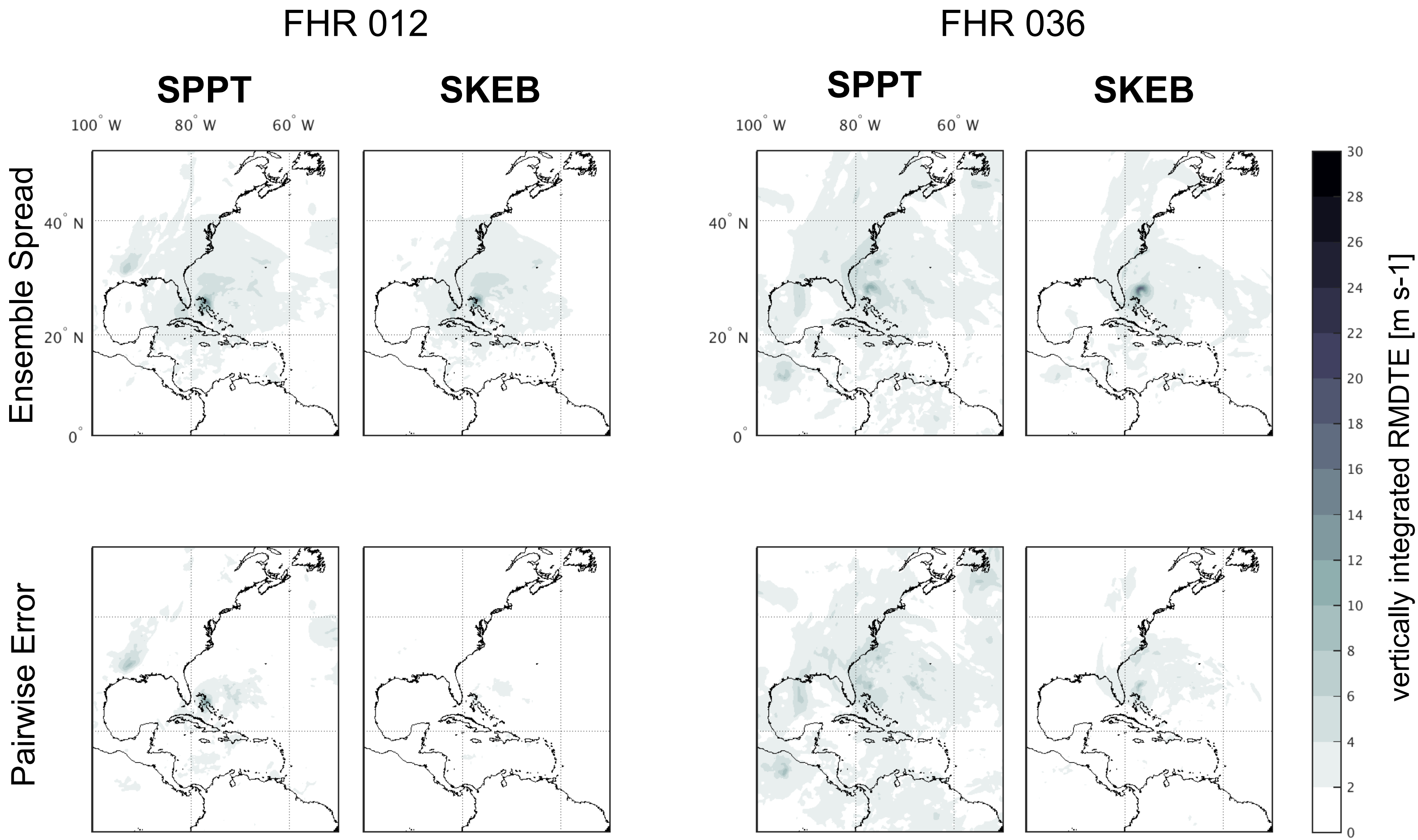
…





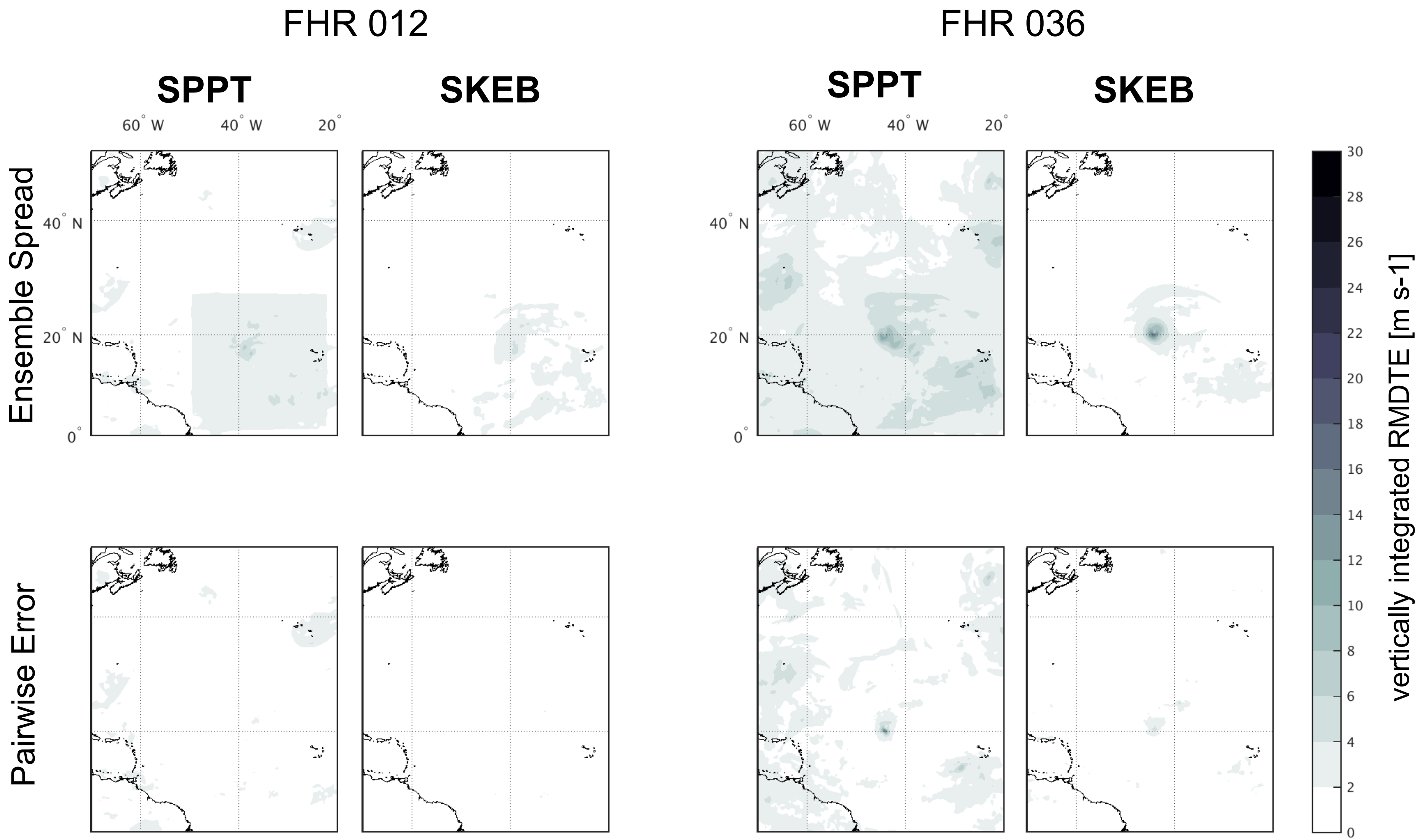
Horizontal RMDTE (HU Sandy) – Stochastic

Initialized at 2012-10-26 00 UTC



Horizontal RMDTE (HU Edouard) – Stochastic

Initialized at 2012-10-26 00 UTC



Hurricane Edouard (2014) Model Error Growth

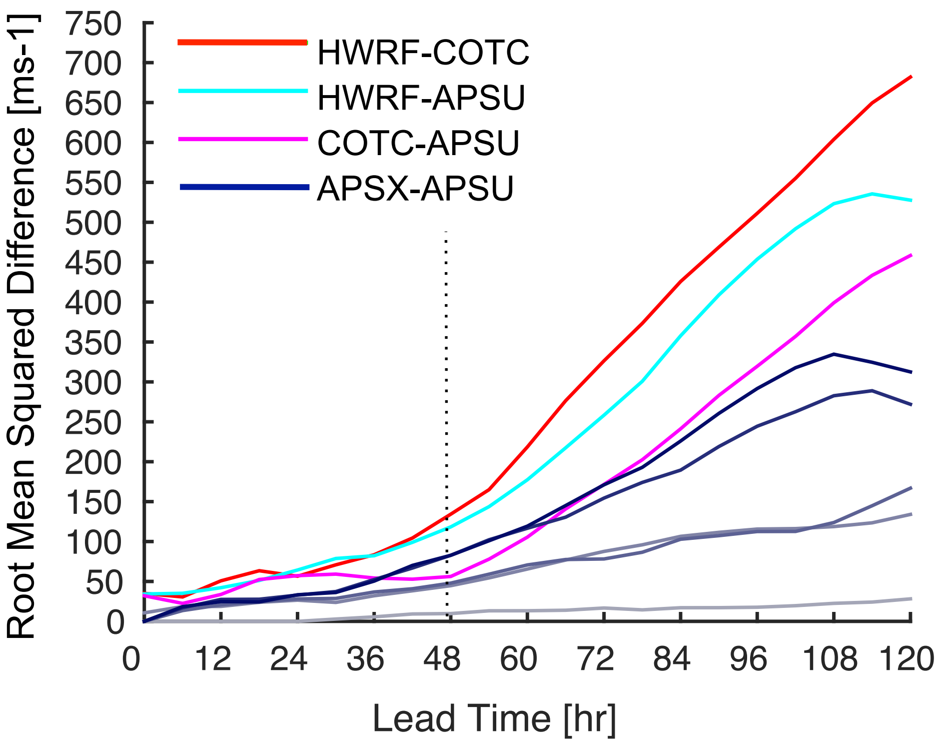
"APSU-Like" Physics

Modify microphysics, radiation, PBL, surface drag, cumulus

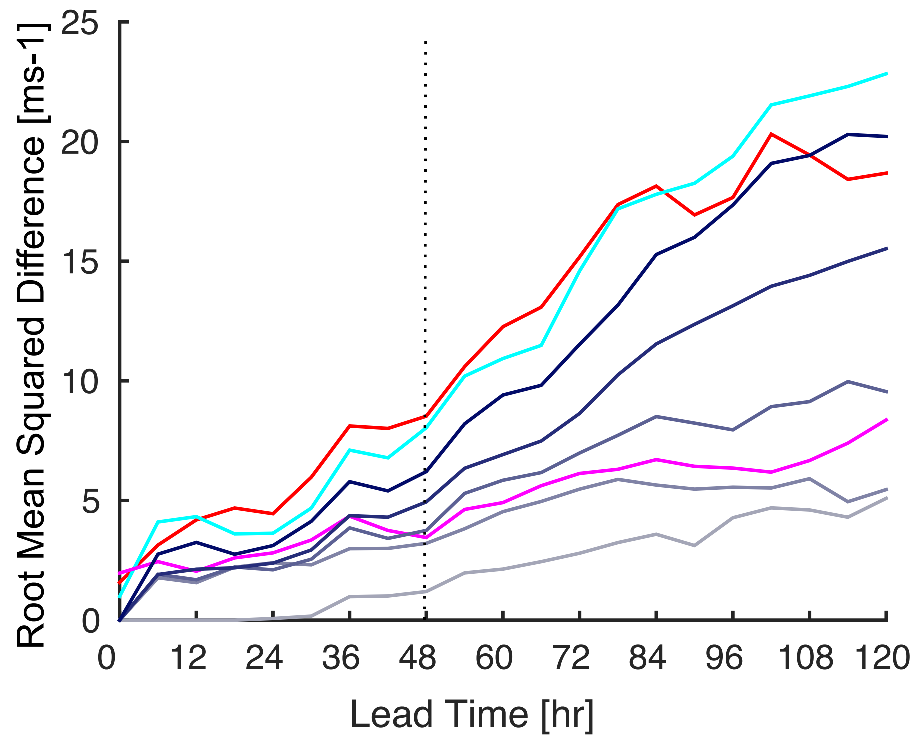
"HWRF-Like" Physics

Error growth between models for the same ensemble member is highly dependent on model and/or physics configuration

Pairwise Track RMS Difference



Pairwise Intensity RMS Difference

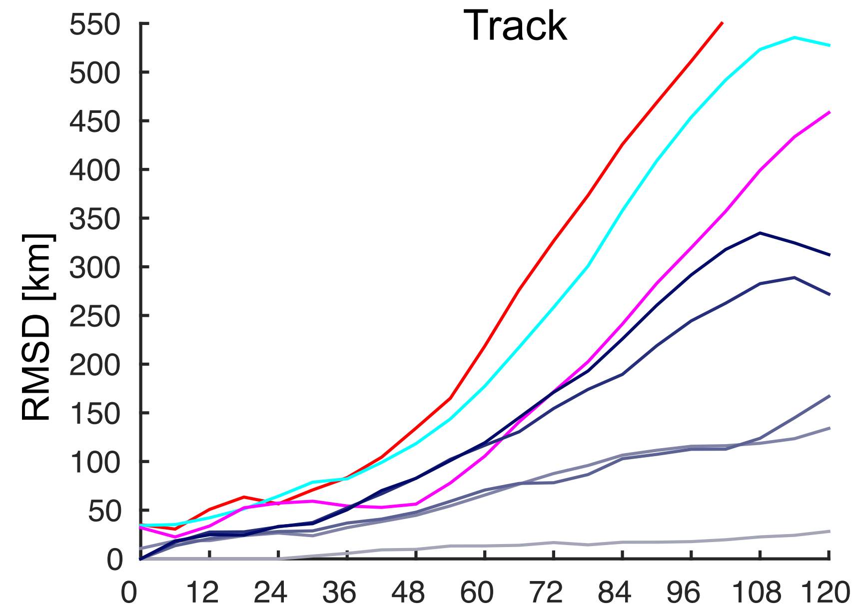


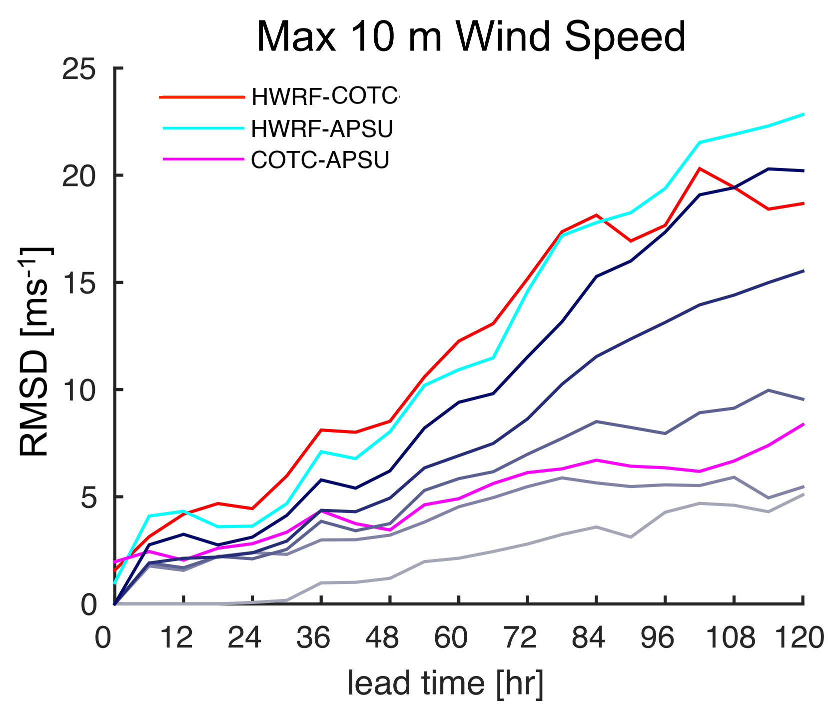
Hurricane Edouard (2014) Model Error Growth

"APSU-Like" Physics

Modify microphysics, radiation, PBL, surface drag, cumulus

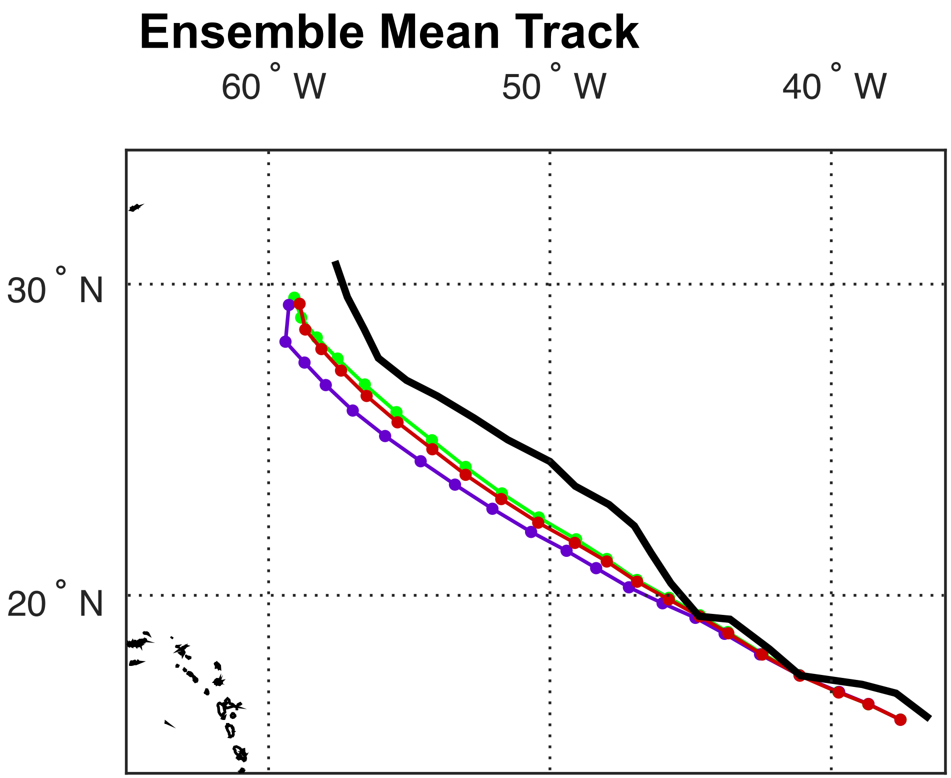
"HWRF-Like" Physics

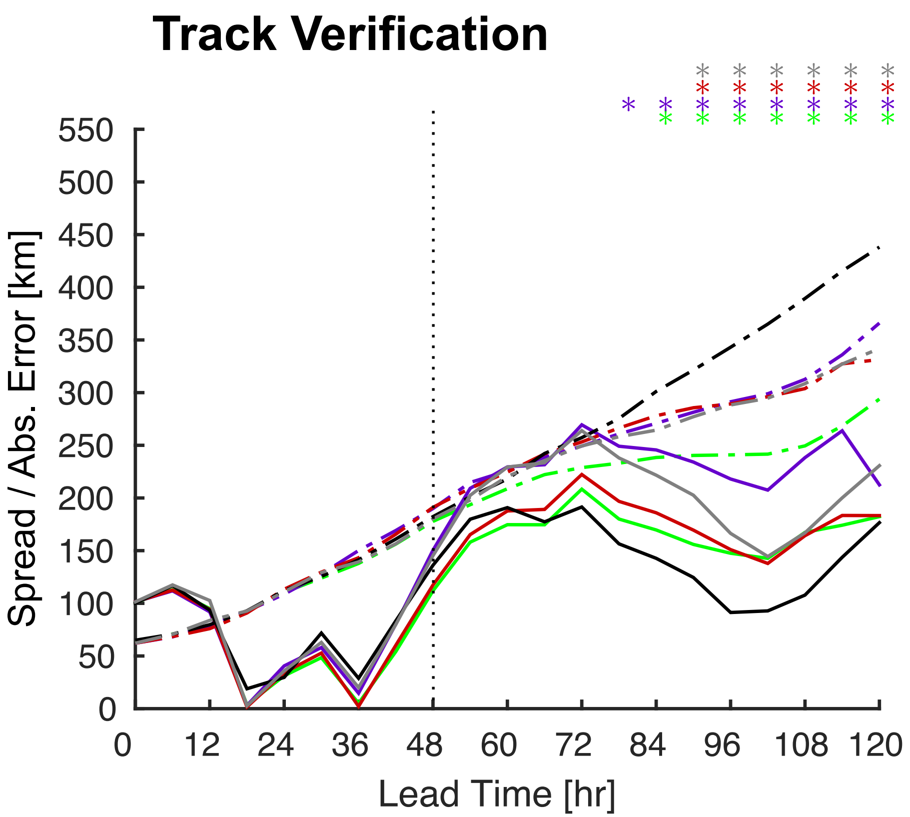




Hurricane Edouard (2014) Absolute Error and Spread – Stochastic Physics

…





Hurricane Edouard (2014) Absolute Error and Spread – Initial Perturbations

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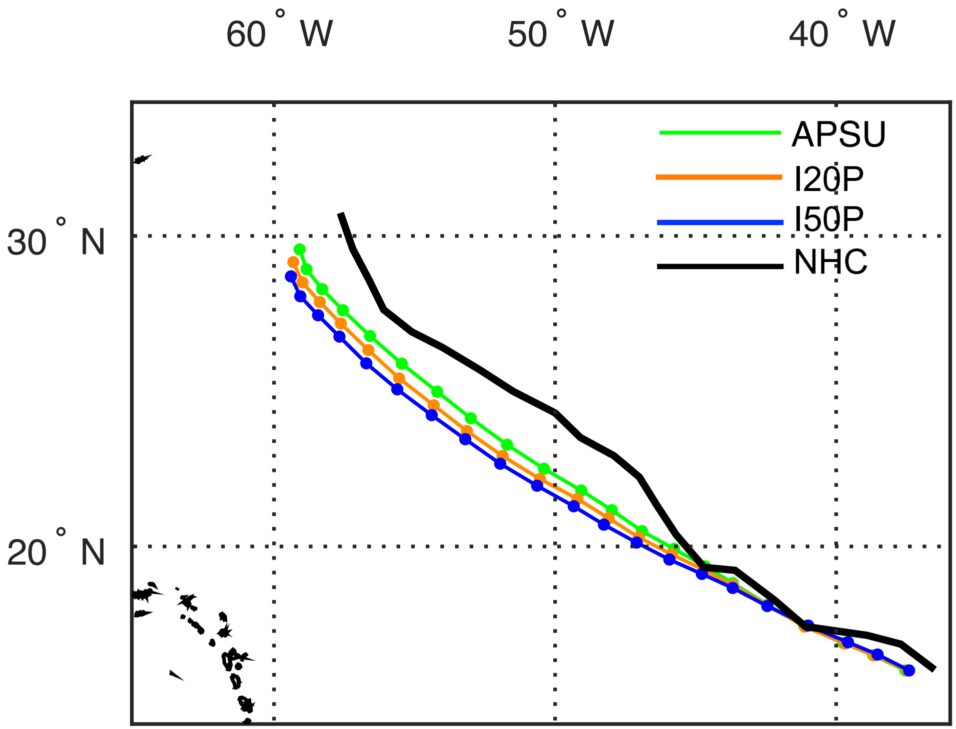
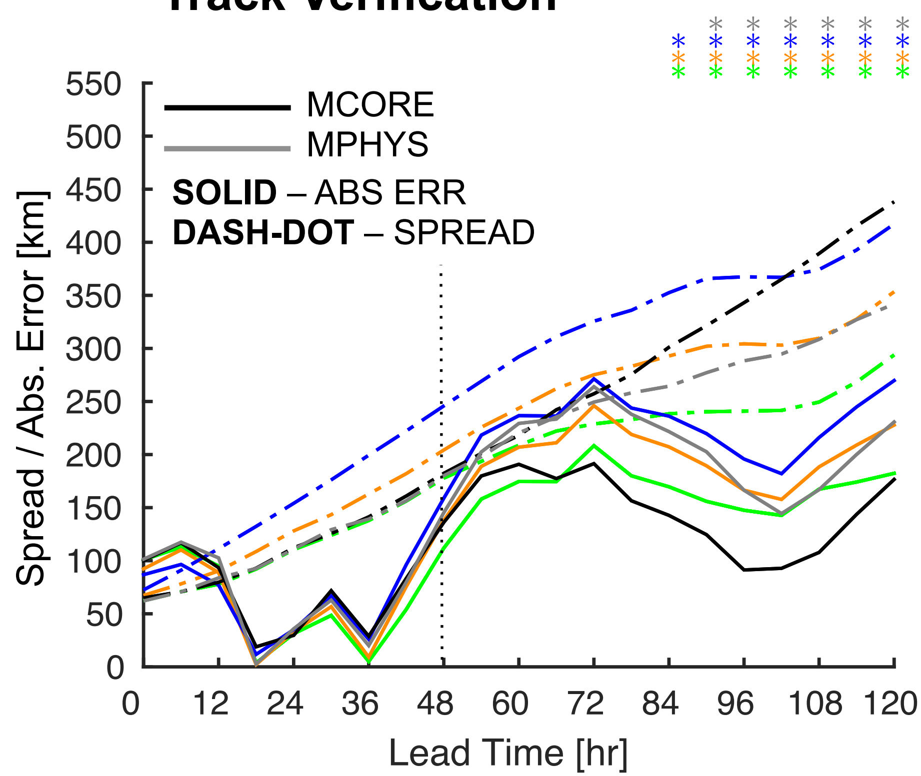
I20P: 20% inflation

I50P: 50% inflation

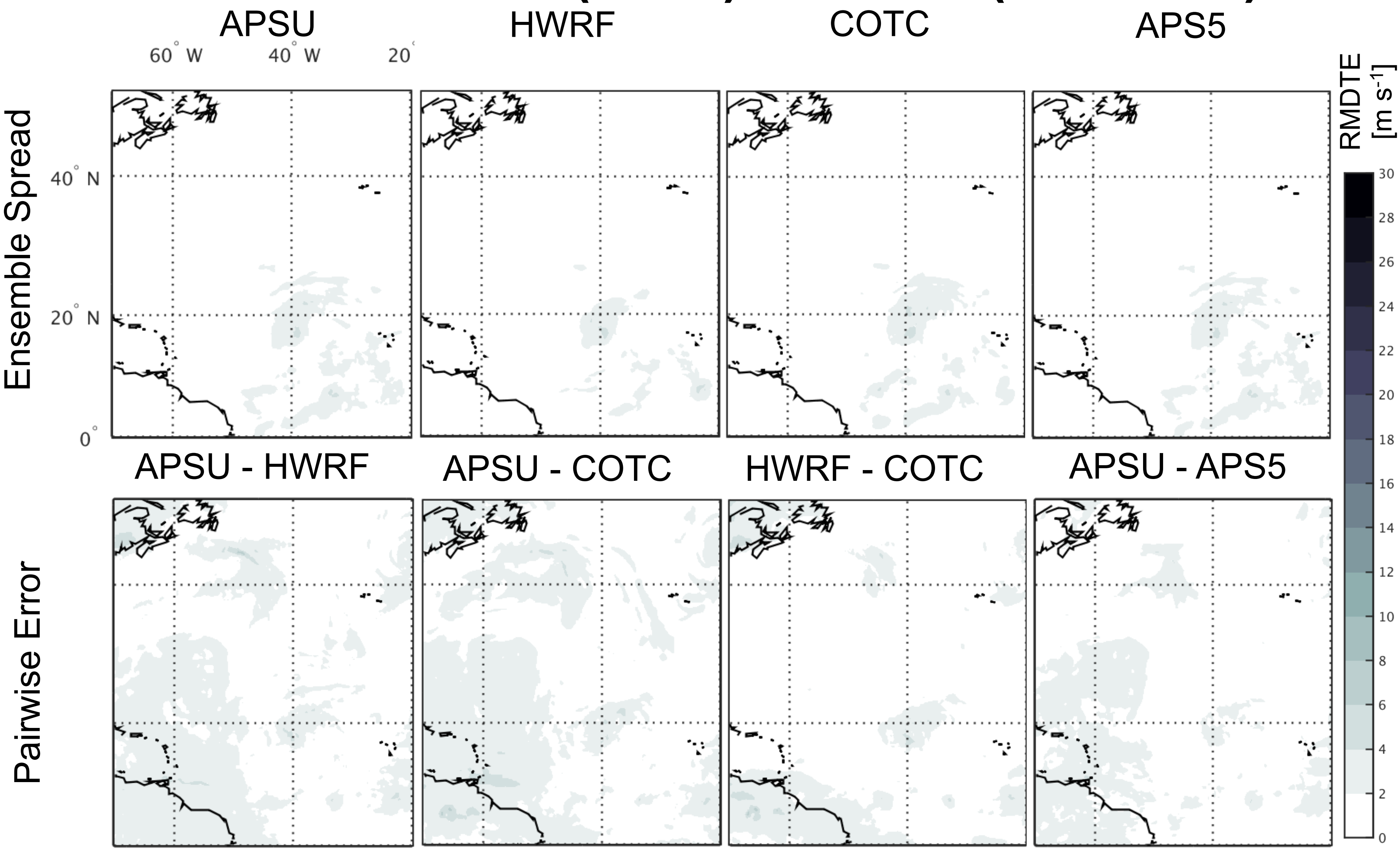
Ensemble Mean Track



Track Verification



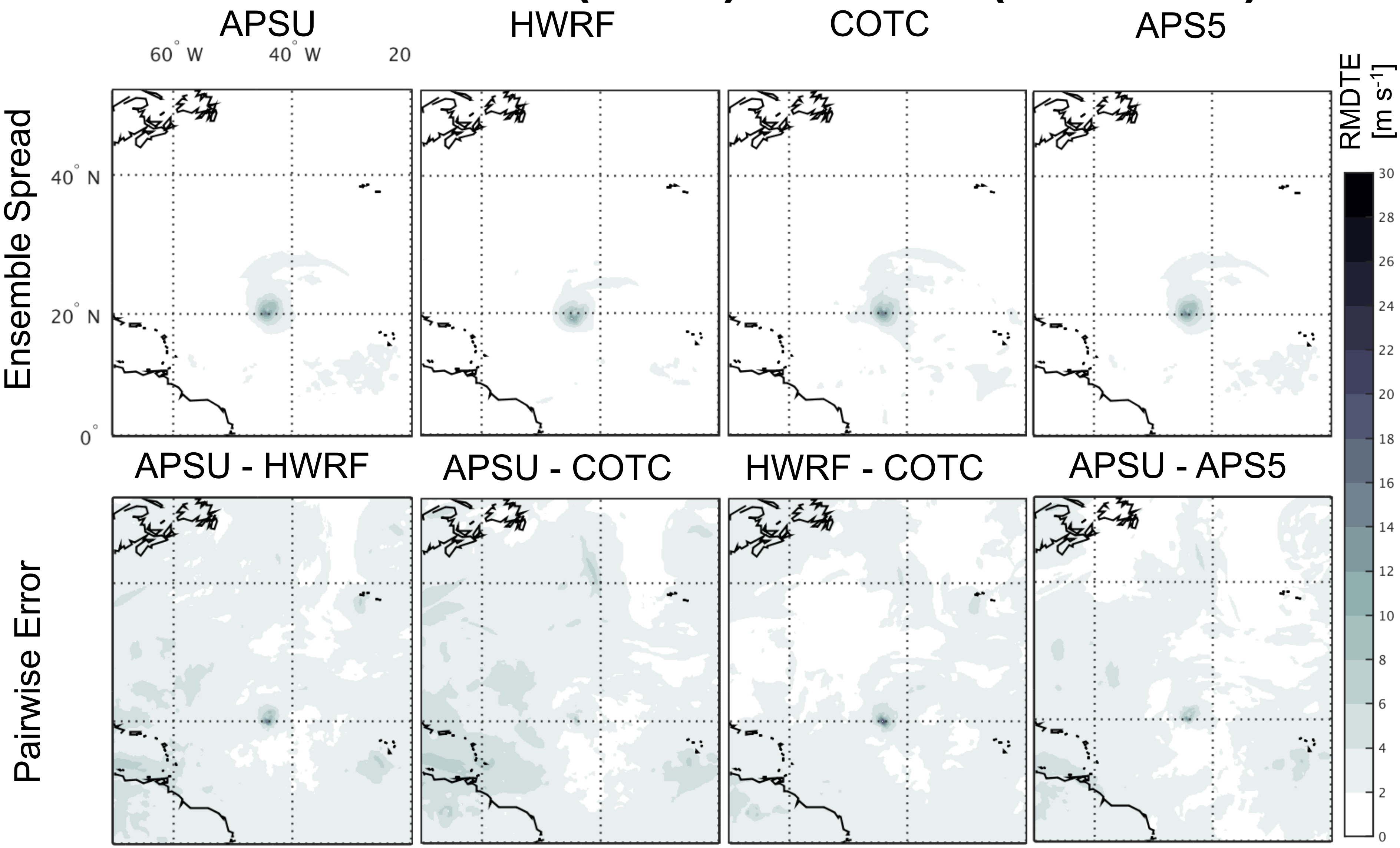
Hurricane Edouard (2014) RMDTE (FHR 012)



$$RMDTE_{i,j} = \sqrt{\frac{1}{k}\sum_{k}\frac{1}{n}\sum_{n} U'^{2}_{i,j,k,n} + V'^{2}_{i,j,k,n} + \kappa T'^{2}_{i,j,k,n}}$$

where ‘ indicates difference between experiments and $\kappa = \frac{c_p}{T_0}$

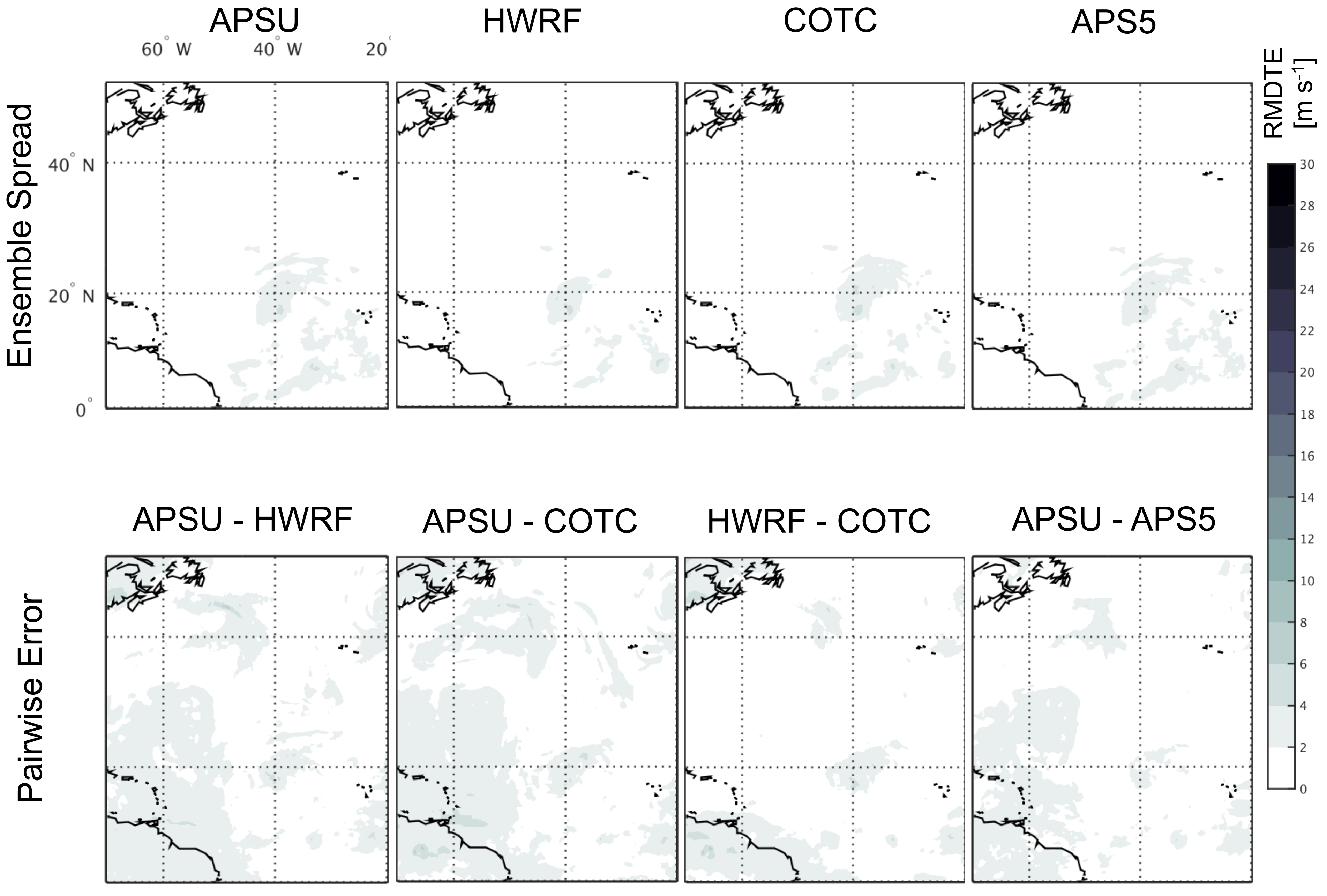
Hurricane Edouard (2014) RMDTE (FHR 036)



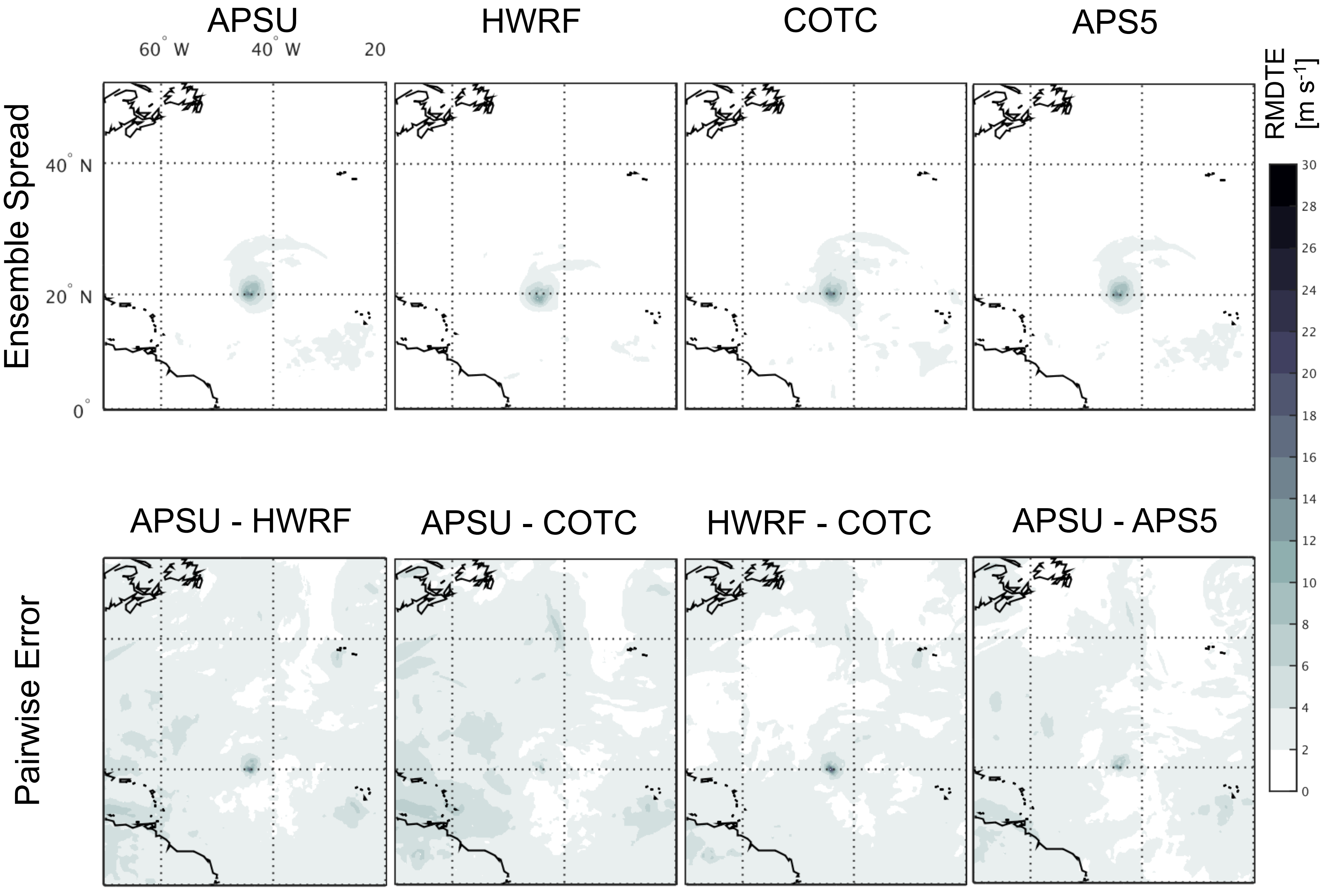
$$RMDTE_{i,j} = \sqrt{\frac{1}{k}\sum_{k}\frac{1}{n}\sum_{n} U'^2_{i,j,k,n} + V'^2_{i,j,k,n} + \kappa T'^2_{i,j,k,n}}$$

where ‘ indicates difference between experiments and $\kappa = \frac{c_p}{T_0}$

Hurricane Edouard (2014) RMDTE (FHR 012)

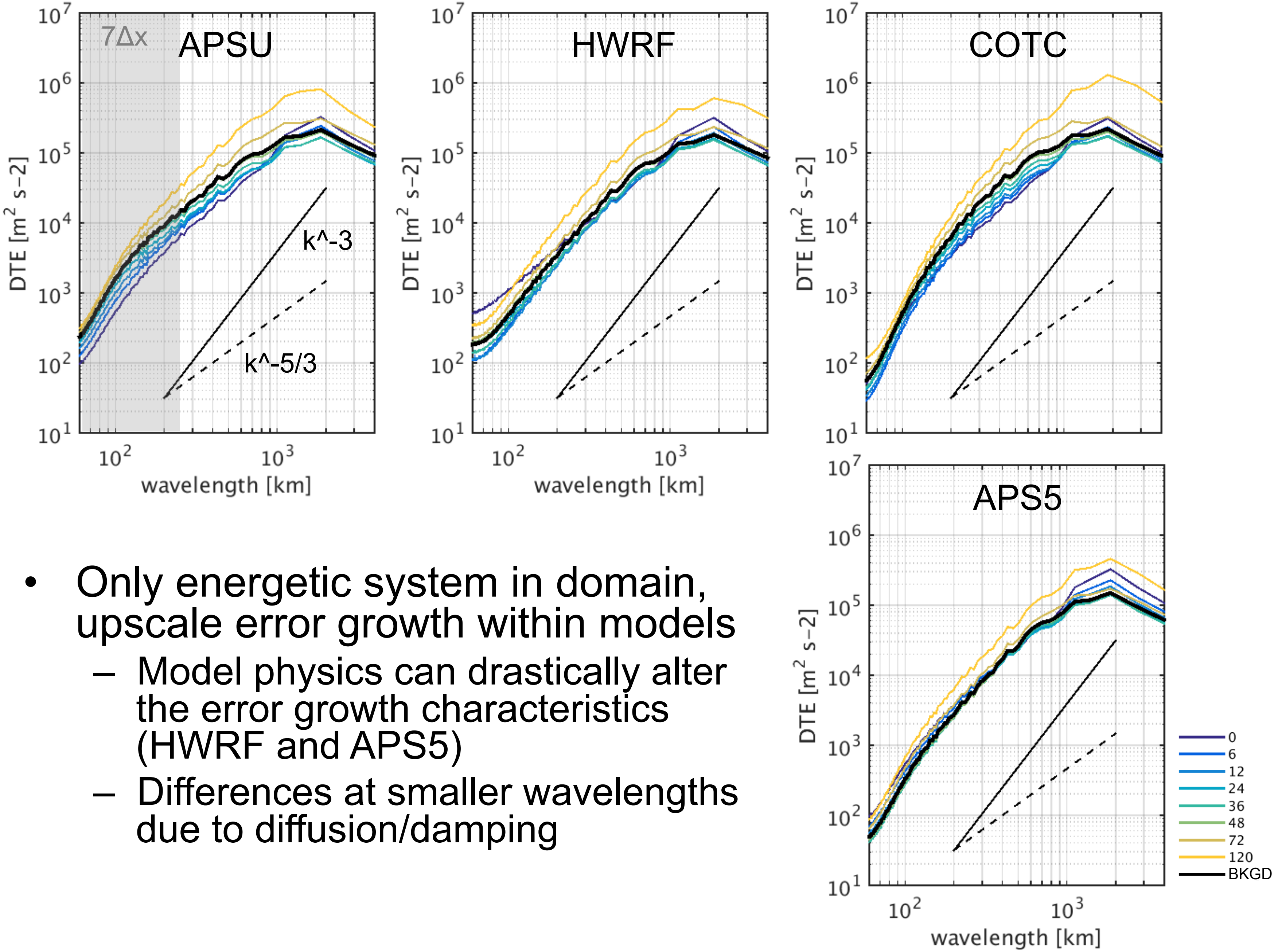


Hurricane Edouard (2014) RMDTE (FHR 036)



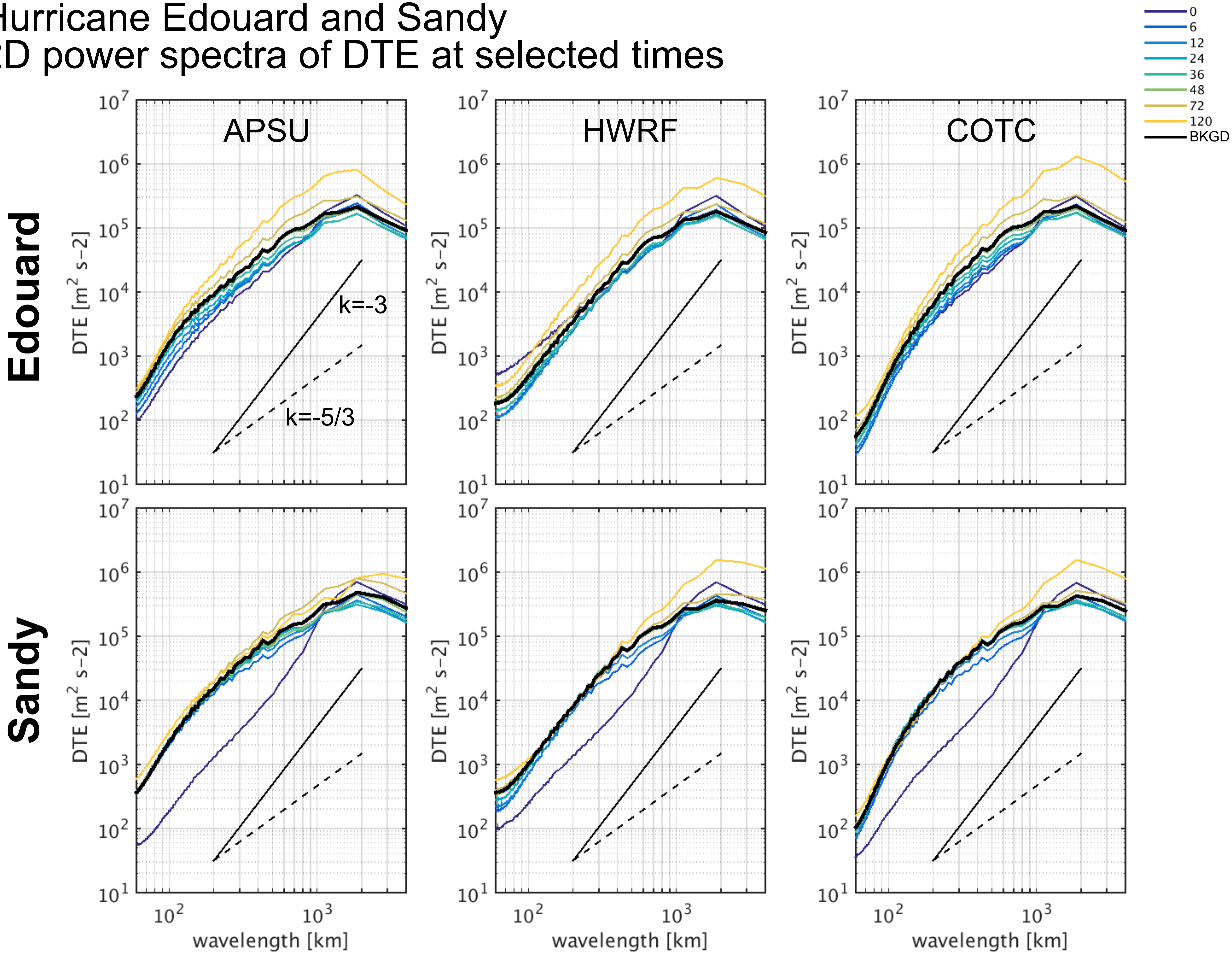
Hurricane Edouard

2D power spectra of DTE at selected times

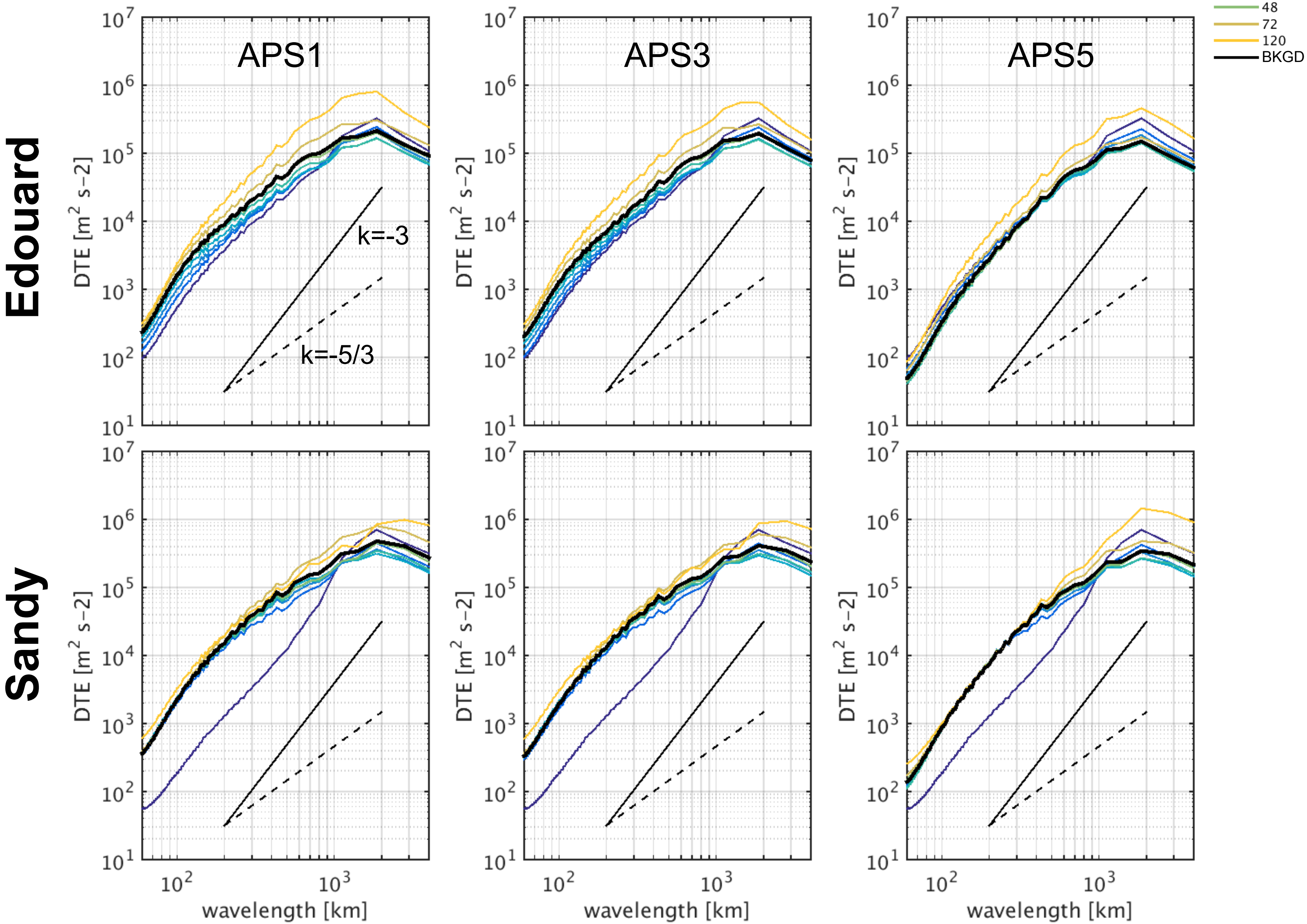


- Only energetic system in domain, upscale error growth within models
  - Model physics can drastically alter the error growth characteristics (HWRF and APS5)
  - Differences at smaller wavelengths due to diffusion/damping

Hurricane Edouard and Sandy
2D power spectra of DTE at selected times

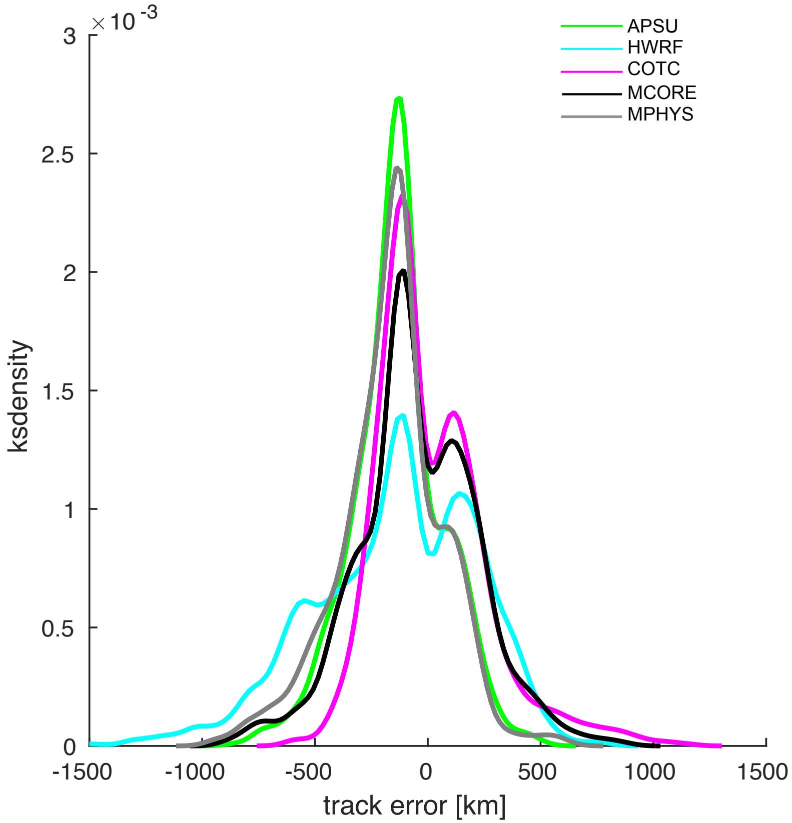


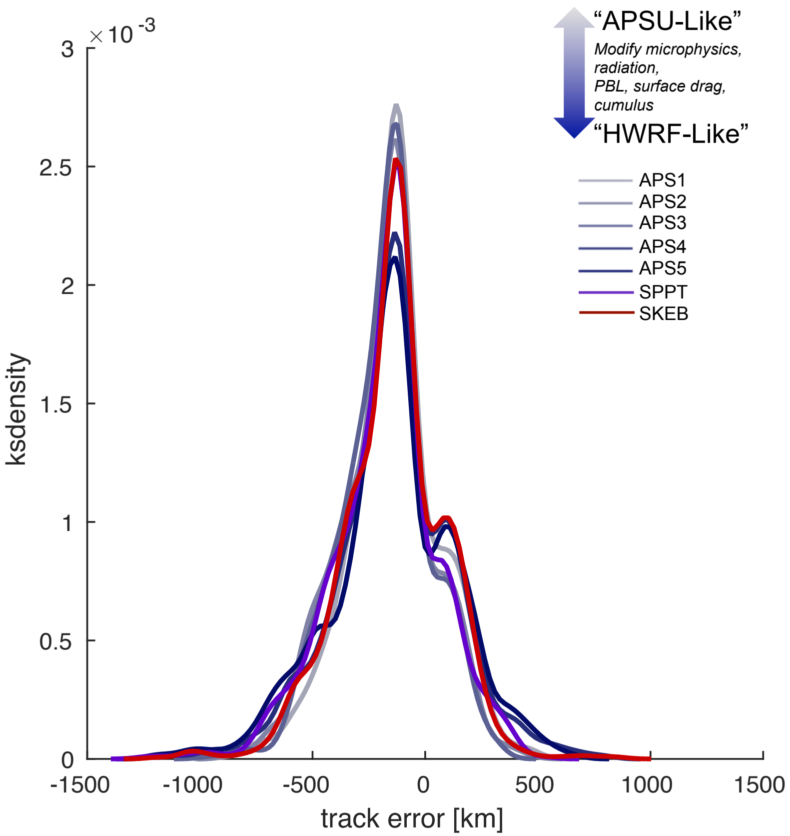
Hurricane Edouard and Sandy
2D power spectra of DTE at selected times



Track Error kernel smoothed density distribution (HU Edouard)

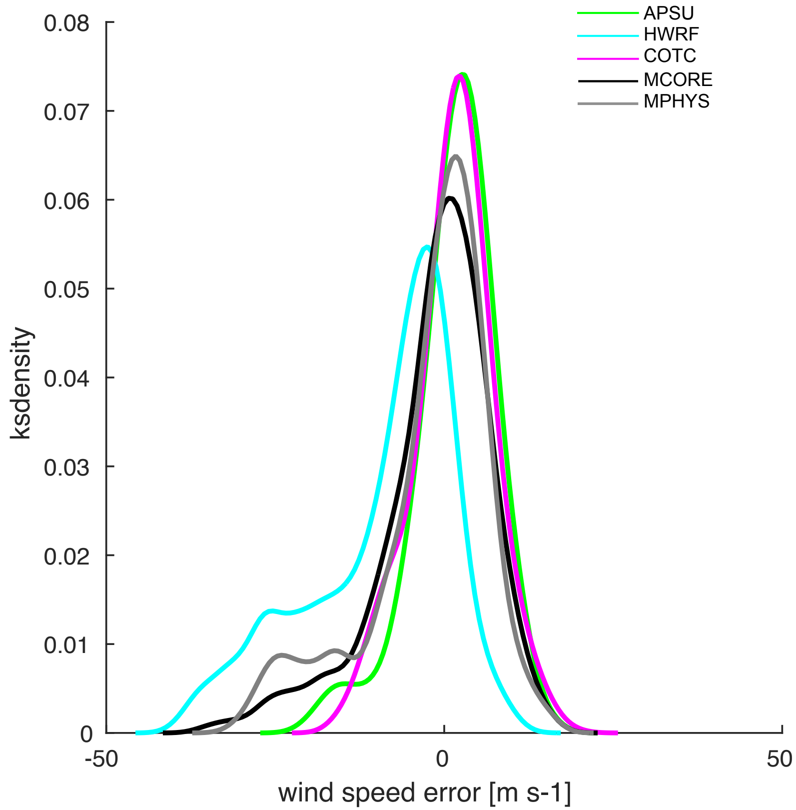
Including all 6-hrly forecasts (0 to 120 h) and ensemble members

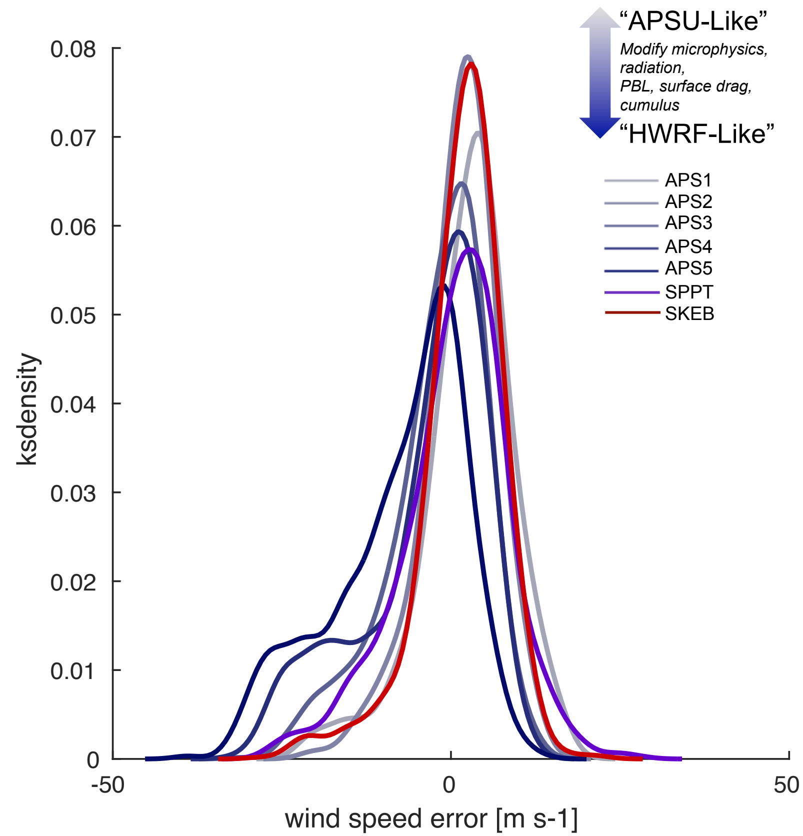




WSP error kernel smoothed density distribution (HU Edouard)

Including all 6-hrly forecasts (0 to 120 h) and ensemble members

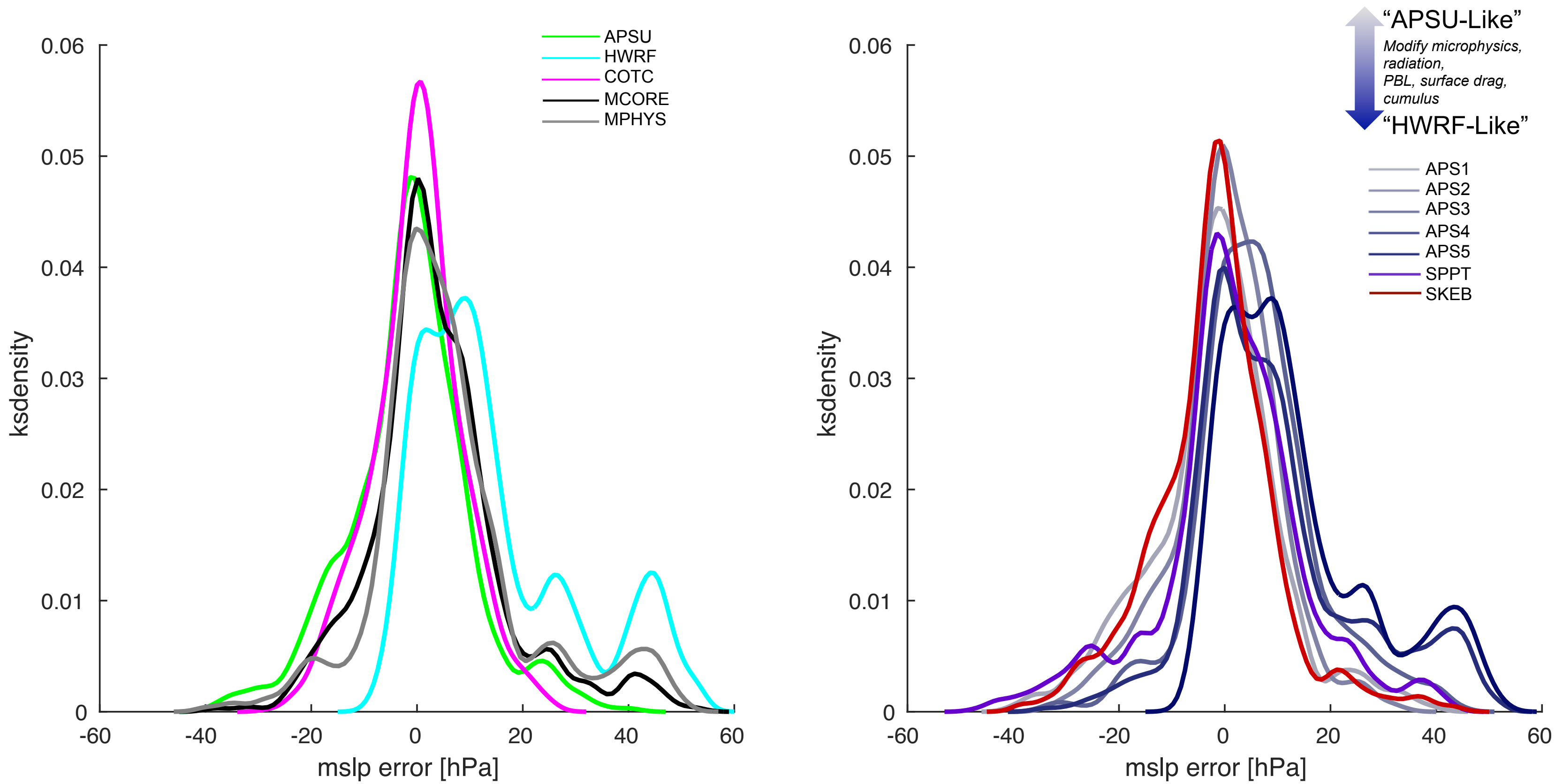




- …

MSLP error kernel smoothed density distribution (HU Edouard)

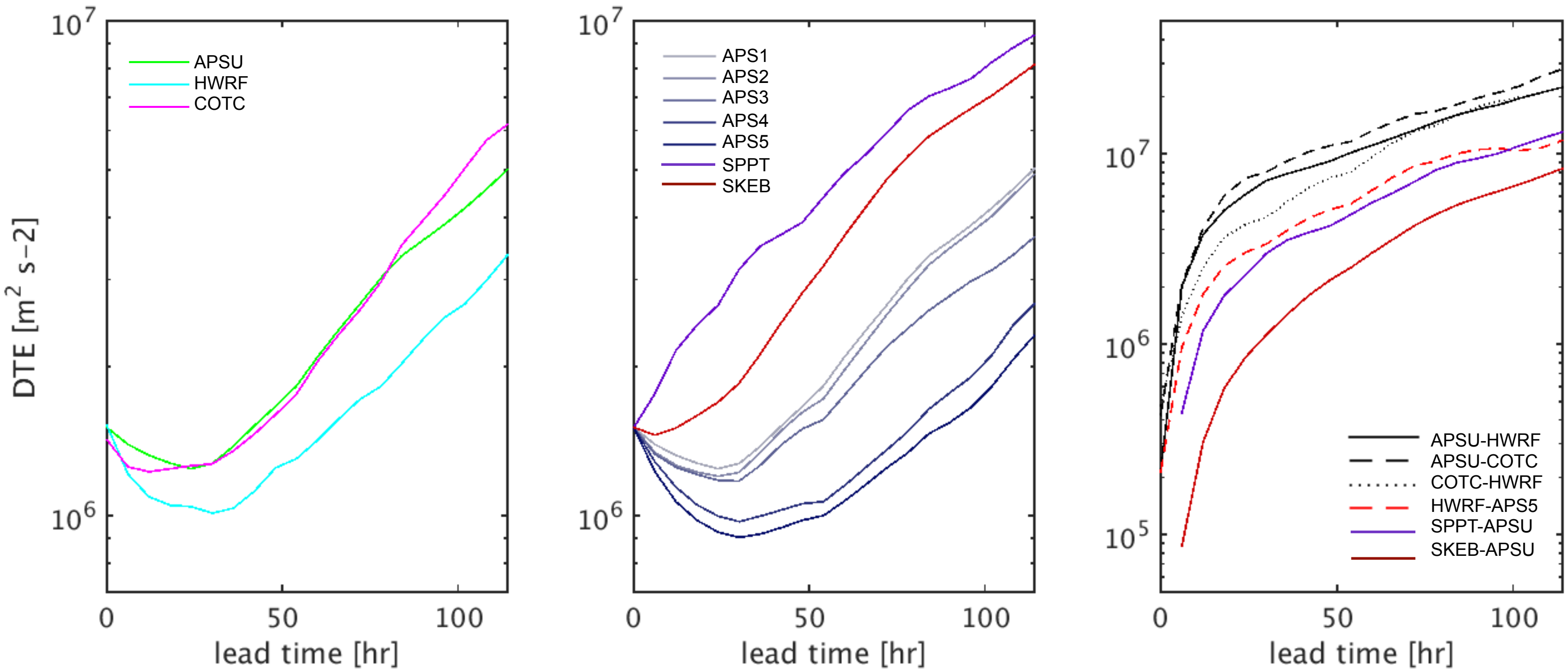
Including all 6-hrly forecasts (0 to 120 h) and ensemble members



- ...

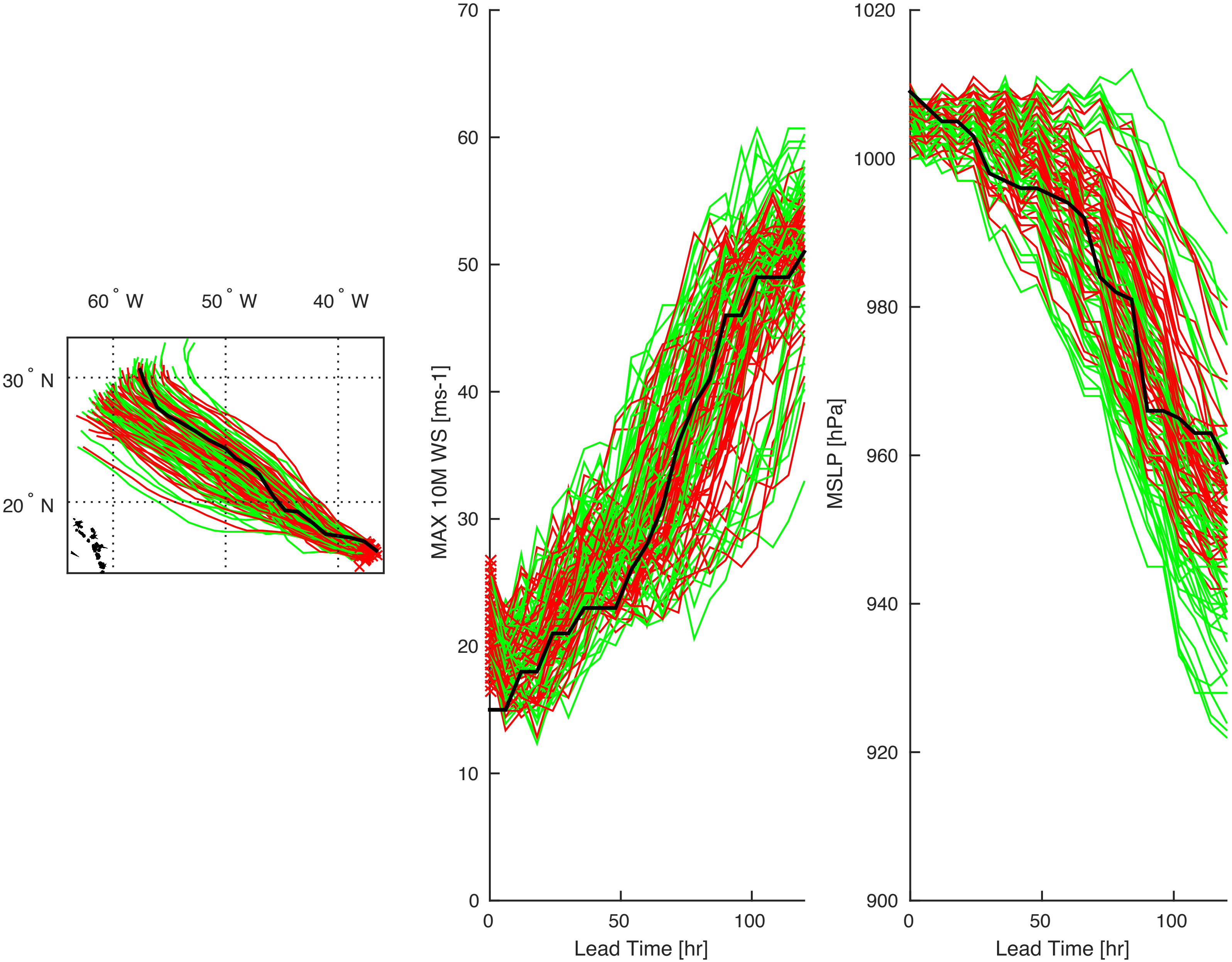
Domain integrated DTE (HU Edouard)

6-hrly forecasts initialized at 2014-09-11 12 UTC



Altering APSU dynamics (HU Edouard)

Including 60 ensemble member 6-hrly forecasts (0 to 120 h)



Kolmogorov–Smirnov non-parametric @ alpha=0.05 (HU Edouard)

TRACK ERROR

	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
APS1 - HWRF	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS2 - HWRF	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS3 - HWRF	🟢	🟢	🟢	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS4 - HWRF	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS5 - HWRF	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴
SPPT - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
SKEB - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
MPHYS-MCOMB	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴

WSP ERROR

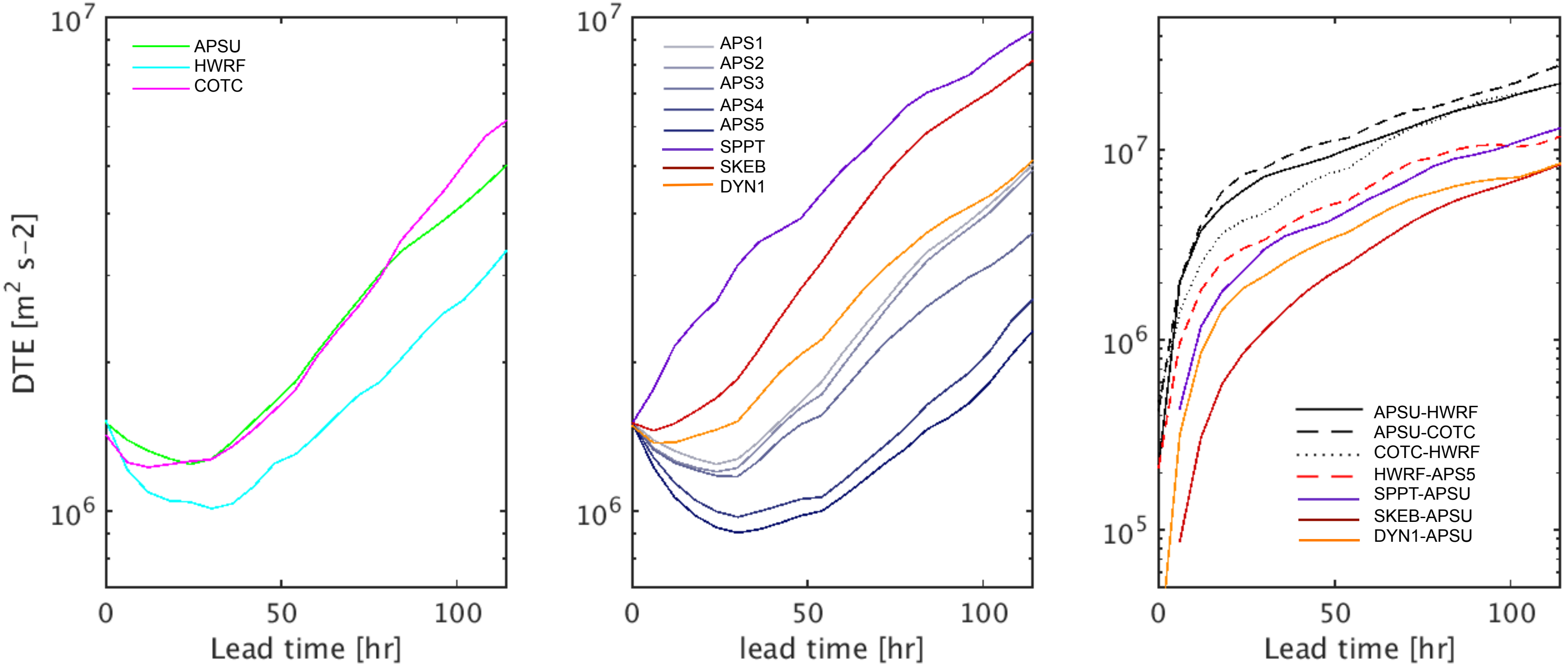
	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
APS1 - HWRF	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS2 - HWRF	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS3 - HWRF	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS4 - HWRF	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS5 - HWRF	🟢	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🔴	🔴	🔴
SPPT - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🔴	🔴	🔴
SKEB - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
MPHYS-MCOMB	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴

MSLP ERROR

	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120
APS1 - HWRF	🟢	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS2 - HWRF	🟢	🟢	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS3 - HWRF	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS4 - HWRF	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
APS5 - HWRF	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
SPPT - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🔴	🔴	🔴
SKEB - APSU	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
MPHYS-MCOMB	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢

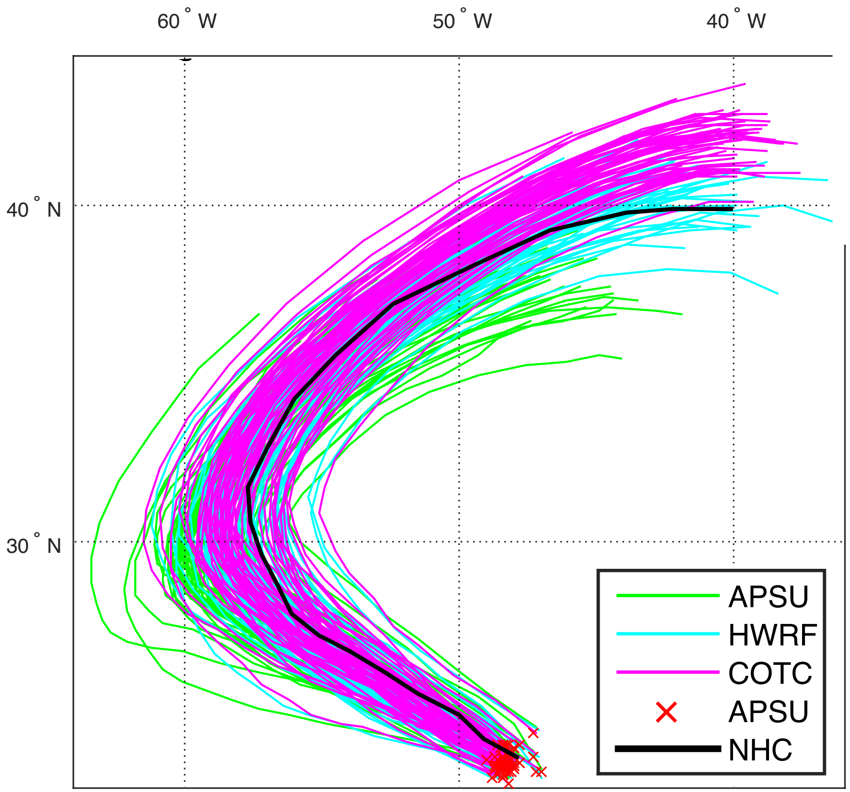
Domain integrated DTE (HU Edouard)

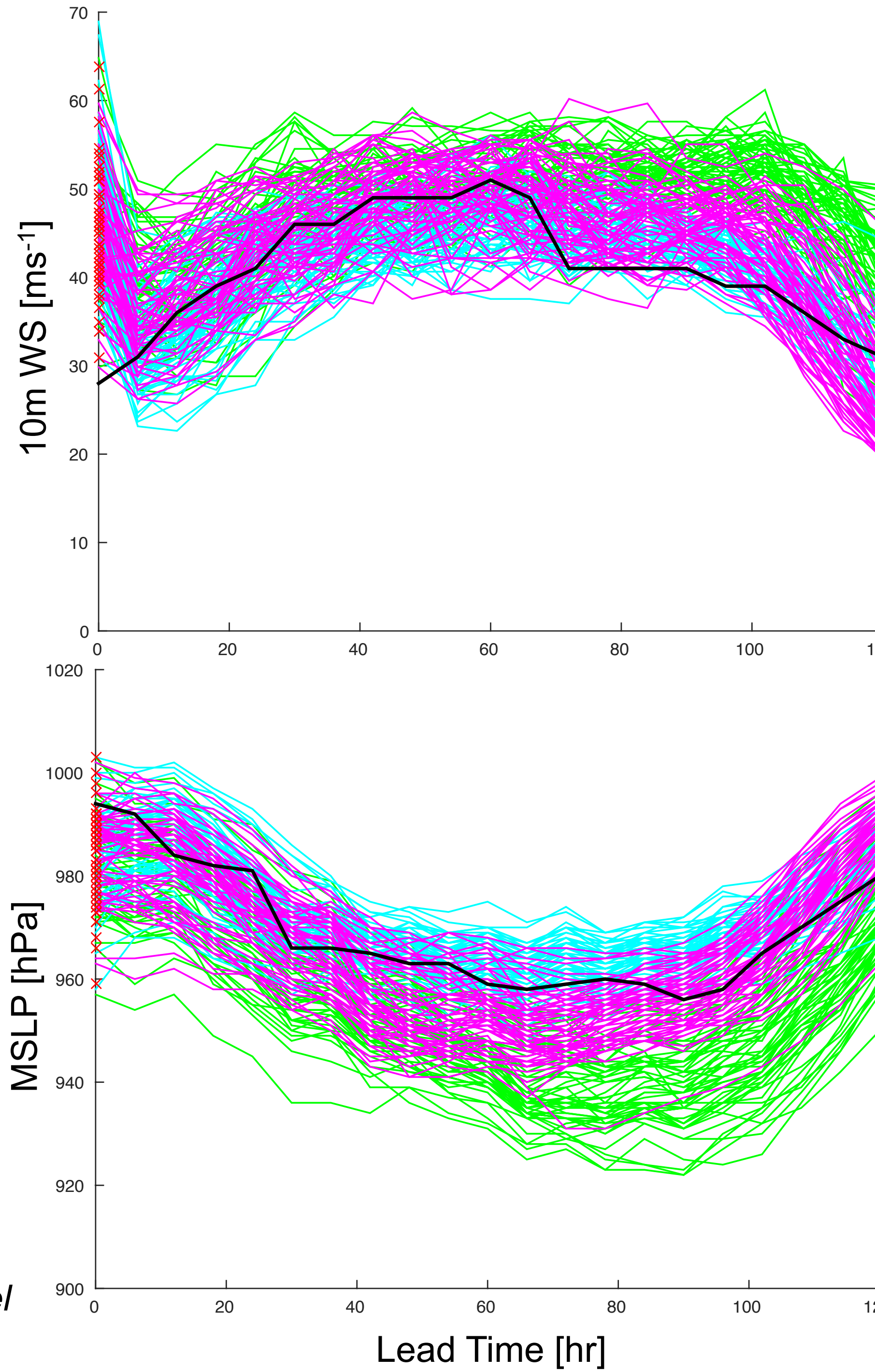
6-hrly forecasts initialized at 2014-09-11 12 UTC



Hurricane Edouard (2014) Ensemble Simulations

- APSU 2014 IC; GFS BC
- Initialized 2014-09-14 00 UTC
- 5 day forecast





**APSG: original high resolution GRIB IC before model initialization*

Hurricane Edouard (2014)
Ensemble Mean Simulations

- Initialized
  2014-09-14 00UTC

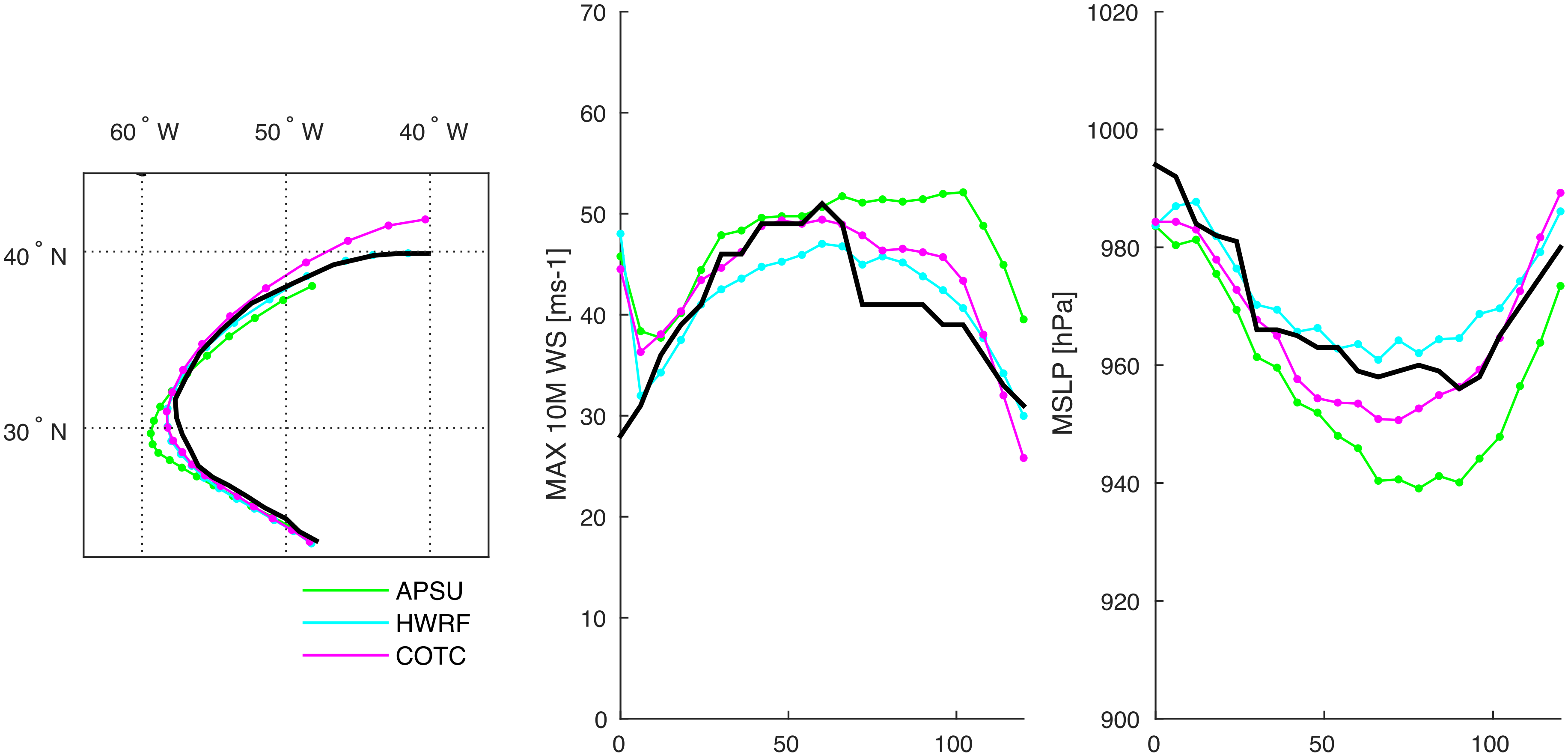


Table 1

Model	DOMAIN	CP	MP	PBL	RAD	SFC
APSU (2014) (WRF-ARW)	D01: 27km (379x244) D02: 9km (304x304) D03: 3km (304x304) Vertical Levels: 43 Model Top: 10 hPa	D01 ONLY Grell-Freitas (Grell et al. 2013)	WSM-6 (Hong and Lim 1996)	YSU (Hong et al. 2006)	Dudhia shortwave (Dudhia 1989) RRTM longwave (Mlawer et al. 1997)	- Modified MM5 similarity (WRF option 91) - PSU formulation surface TC flux (Green and Zhang, 2013) - 5-layer thermal diffusion land surface
HWRF (2013) (modified WRF-NMM)	D01: 0.18 deg (216x432) D02: 0.06 deg (88x170) D03: 0.02 deg (180x324) Vertical Levels: 43 Model Top: 50 hPa	D01 & D02 New SAS (HWRF) (Han and Pan 2011)	Tropical Ferrier (Ferrier 2005)	Modified GFS (Hong and Pan(1996); e.g. Gopalakrishnan et al. (2013); Zhang et al. (2013))	GFDL shortwave and longwave (Fels and Schwarzkopf 1981)	- HWRF surface physics - GFDL hurricane slab model land surface (Bob Tuleya 2011)
COTC (2015) (COAMPS-TC)	D01: 27km (379x244) D02: 9km (304x304) D03: 3km (304x304) Vertical Levels: 40 Model Top: ~ 12 hPa	D01 ONLY Kain-Fritsch scheme (Kain and Fritsch, 1983)	COAMPS v2 single-bulk (Rutledge and Hobbs, 1983) w/ drizzle	Mellor-Yamada 2.5 scheme (Mellor and Yamada 1982) w/ prognostic TKE	NOGAPS SW/LW (Harshvardhan et al., 1987)	COAMPS surface physics (Louis, 1979)

Table 2

Model	Time Discretization	Spatial Discretization	Prognostic Variables	Advection	Diffusion
APSU (2014) (WRF-ARW) (see Skamarock et al. 2008 and references therein)	Runge-Kutta 3rd order predictor-corrector scheme (Wicker and Skamarock (2002)) with short time step time-splitting for high frequency acoustic modes	Horizontal: Arakawa C-grid Vertical: mass + U,V and vertical velocity staggering	U, V, W, perturbation potential temperature, perturbation geopotential, perturbation surface pressure of dry air, TKE, Q_v , Q_r, Q_s , Q_g , Q_i , Q_c	6th order accurate for momentum, scalars and geopotential	6th order accurate
HWRF (2013) (modified WRF-NMM) (see Janjic et al. (2010), Tallapragada et al. (2013, and references therein)	Forward-backward scheme with an implicit scheme for high frequency vertically propagating modes	Horizontal: Arakawa E-grid Vertical: Lorenz staggering (mass + U,V on consistent levels)	U, V, T, non-hydrostatic pressure, hydrostatic surface pressure, Q_v , Q_r, Q_i , Q_{ci} , Q_c	Horizontal: modified Adams-Bashforth, for horizontal advection of u,v, and T, and Coriolis terms, Vertical: Crank Nicholson for vertical advection of u,v, and T, Scalars: upstream Lagrangian forward time differencing	2nd order accurate
COTC (2015) (COAMPS-TC) (see Hack (1996), Chen et al. (2003), and references therein)	Centered-in-time (i.e. leap frog) 2nd order scheme with short time step time-splitting for high frequency acoustic modes	Horizontal: Arakawa C-grid Vertical: mass + U,V and vertical velocity staggering	U, V, W, θ, π, TKE, Q_v , Q_r, Q_i , Q_g , Q_s, Q_c	2nd order accurate upstream, forward-in-time advection	4th order accurate

Table 3

Experiment Name	CP	MP	PBL	RAD	SFC
ALT1 APSU w/mod TC SFC flux	D01 ONLY Grell-Freitas	WSM-6	YSU	Dudhia shortwave RRTM longwave	Same to APSU w/ WRF TC surface flux (Garratt formulation)
ALT2 APSU w/mod TC SFC flux, MP	D01 ONLY Grell-Freitas	Eta (Ferrier)	YSU	Dudhia shortwave RRTM longwave	Same as ALT2
ALT3 APSU w/mod TC SFC flux, MP, RAD	D01 ONLY Grell-Freitas	Eta (Ferrier)	YSU	GFDL shortwave/ longwave	Same as ALT2
ALT4 APSU w/mod TC SFC flux, MP, RAD, CP	D01 & D02 New SAS (HWRF)	Eta (Ferrier)	YSU	GFDL shortwave/ longwave	Same as ALT2
ALT5 “HWRF-LIKE”	D01 & D02 New SAS (HWRF) (Han and Pan 2011)	Eta (Ferrier) (Rogers, Black, Ferrier, Lin, Parrish and DiMego 2001)	GFS (Hong and Pan 1996)	GFDL shortwave/ longwave (Fels and Schwarzkopf 1981)	Same as ALT2