Future Wave Climate Projection for the Northwestern Atlantic

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Motivation for studying future wave climate

Issues and background:

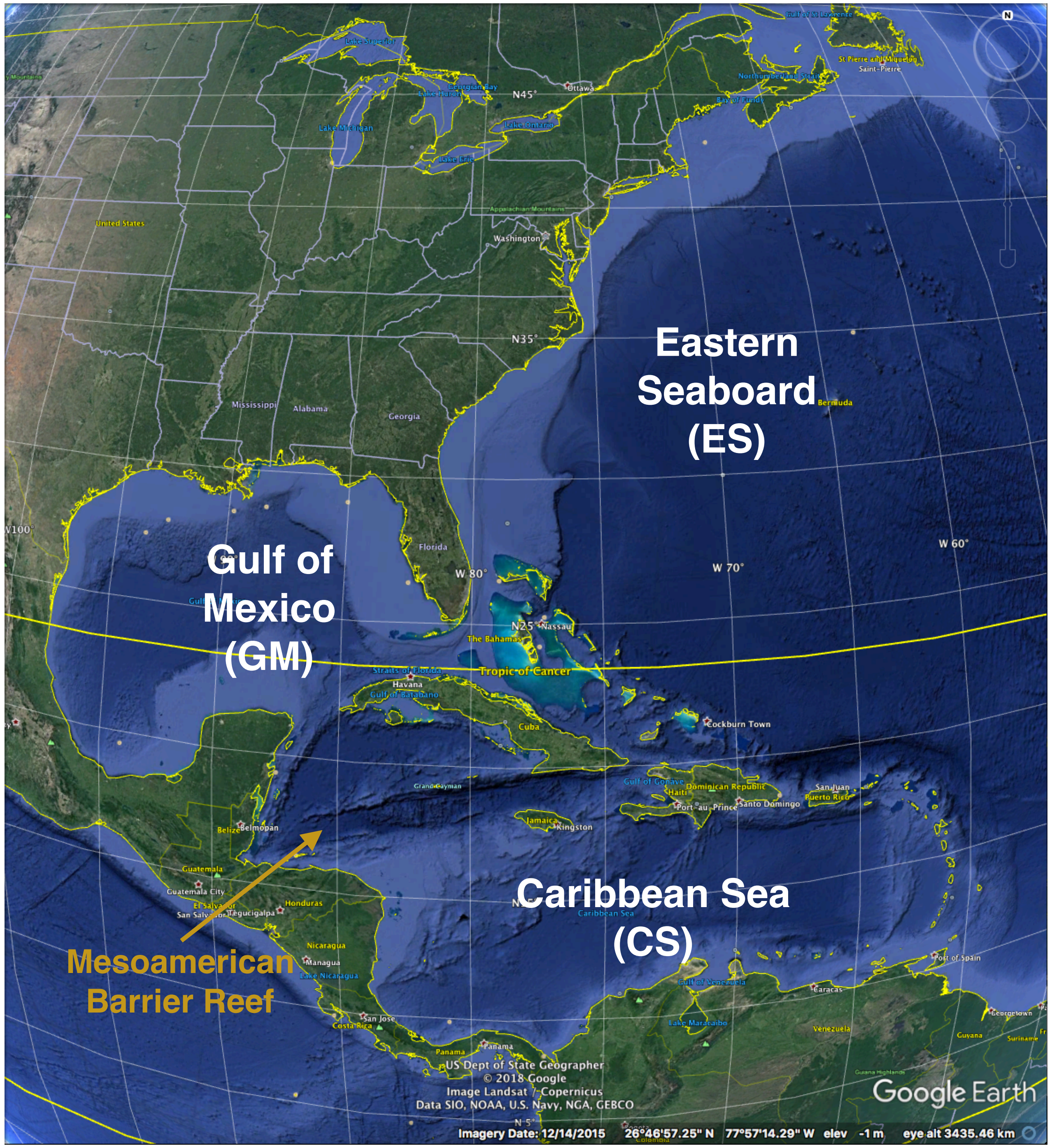
- **Coastal systems will increasingly experience adverse impacts such as submergence, flooding, and coastal erosion due to relative sea level rise (IPCC AR5, WGII, Ch. 5)**
- **Higher waves and surges increase the probability that coastal sand barriers and dunes will be overwashed or breached**
- **More energetic and/or frequent storms exacerbate all these effects**

Nearshore / Offshore Impacts

Figure: Surfers Paradise, Queensland's Gold Coast, May 2013 (Web: The Conversation)

Overview of study

End-of-century regional wave climate projection for the Northwest Atlantic covering the US Eastern Seaboard, Gulf of Mexico, and Caribbean Sea



Wave modeling approach:

- **Dynamical model (vs statistical)**
- **High-resolution AGCM (vs GCM / fully-coupled)**

2 x 25-year simulations:

- **Historical: 1979—2003**
- **Future: 2075—2099**

Motivation for study:

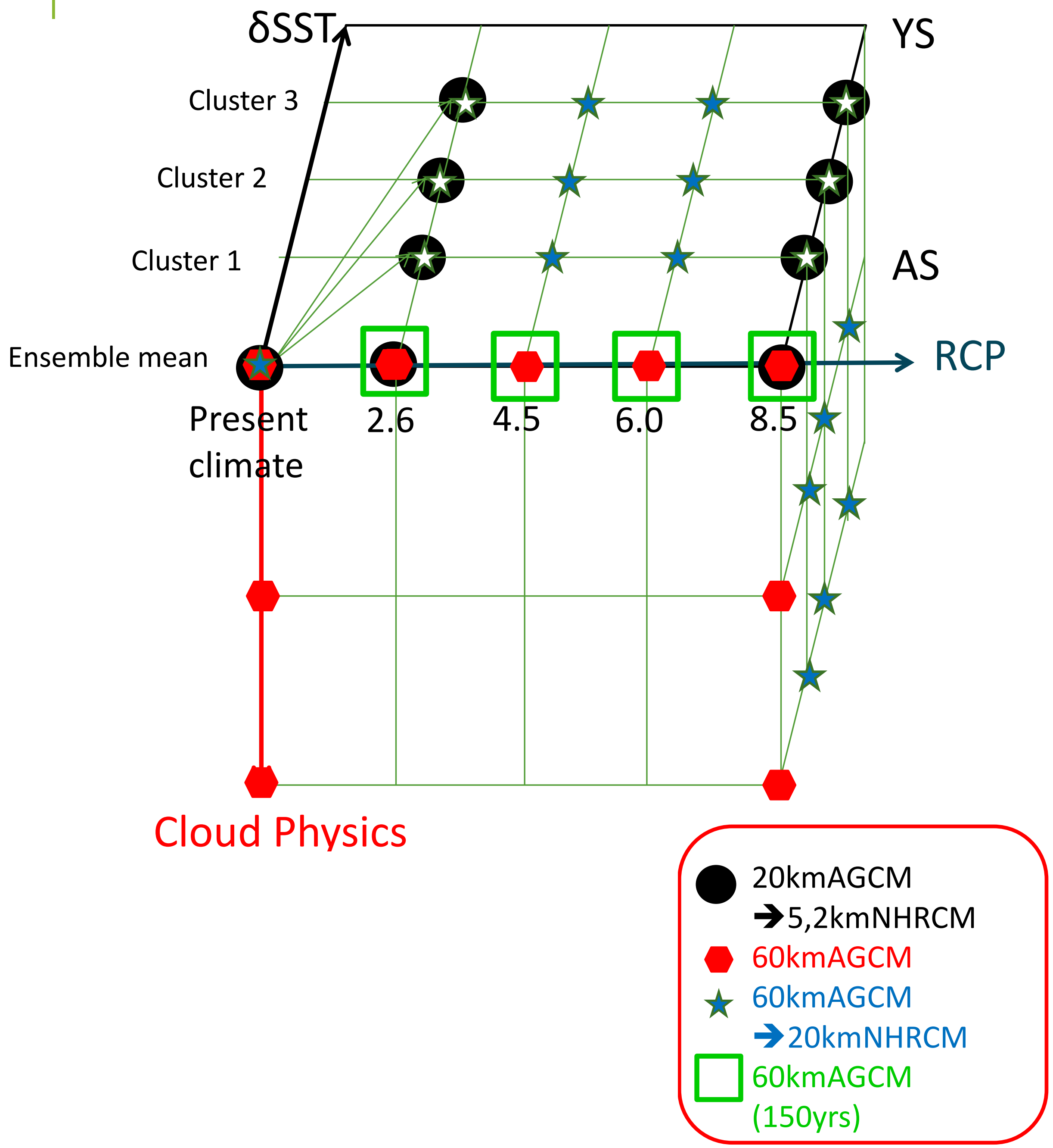
- **Limited regional studies**
- **Task 2 of COWCLIP**

Climate modeling approach: High resolution AGCM forcing

MRI-AGCM forcing details

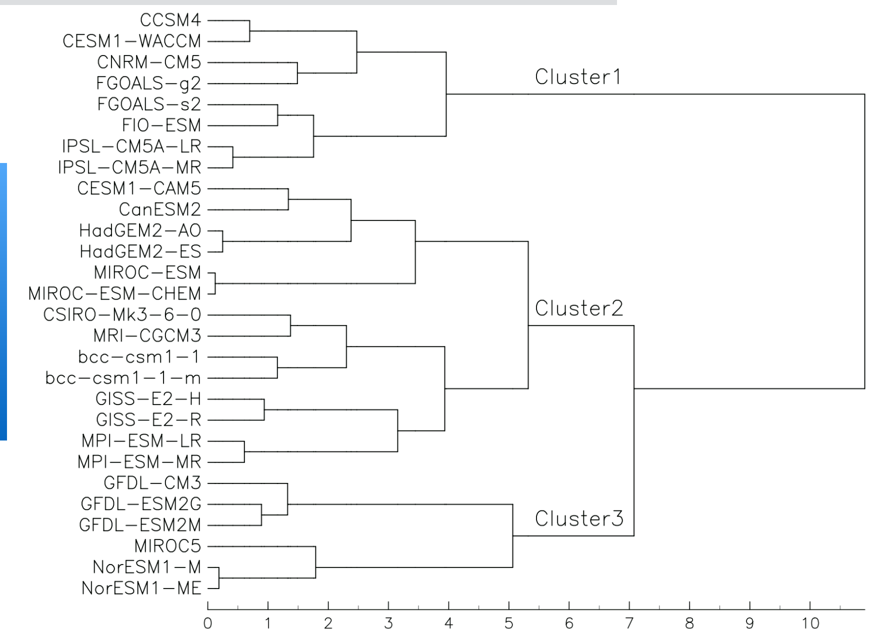
Mori, 2018

Scenario run 2017
MRI-AGCM 3.2X series

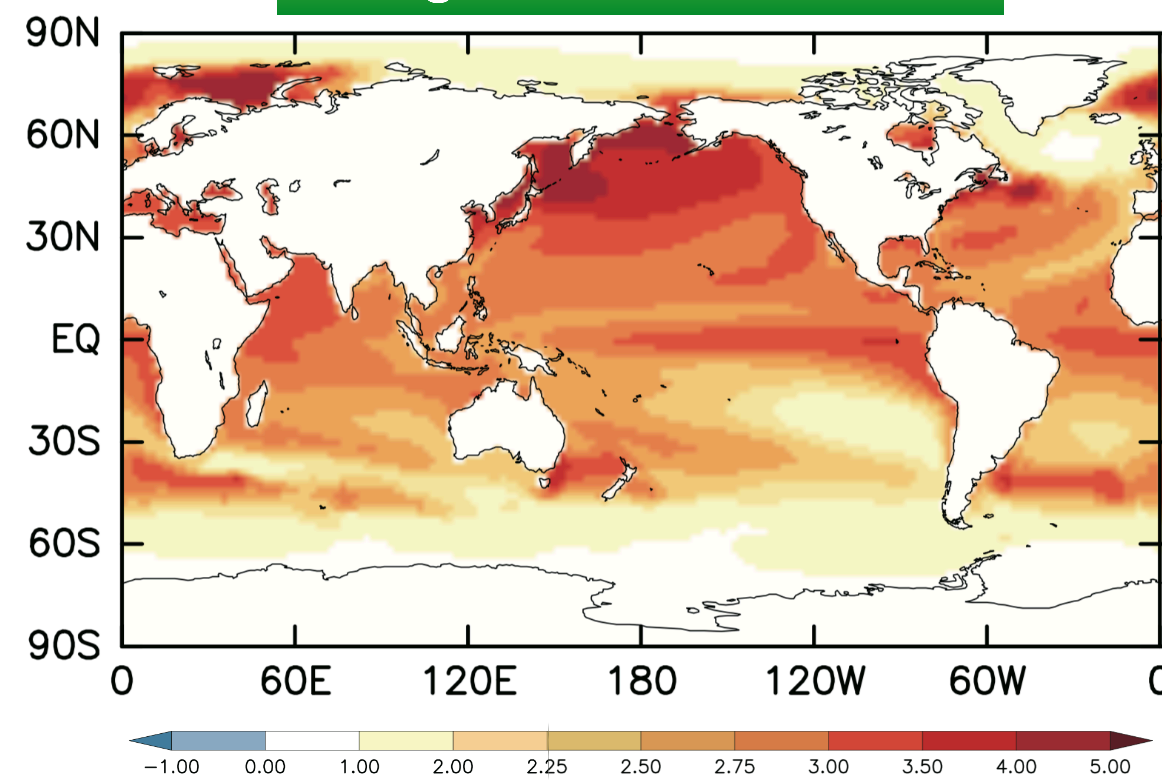


Mizuta et al. (SOLA, 2014)

CMIP5 SST Experiments (28 members)



Changes in ensemble mean

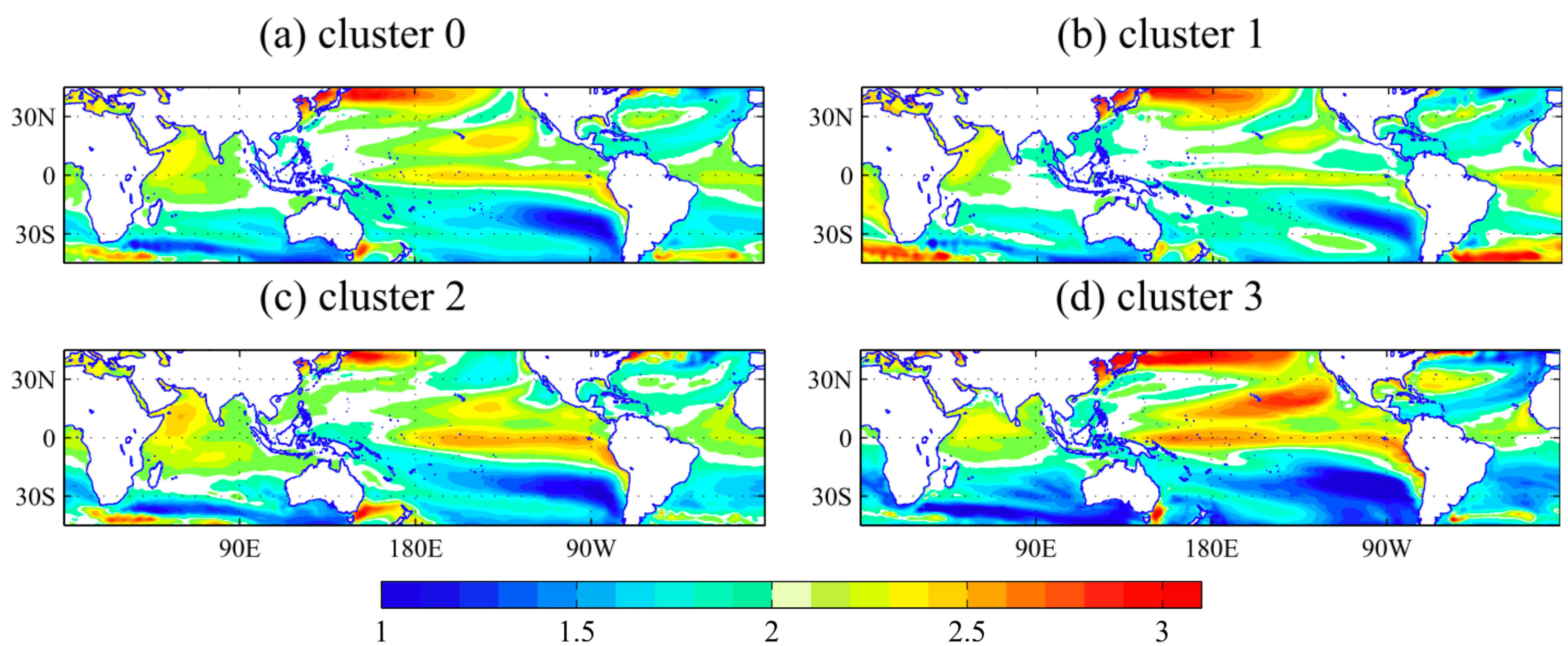


Previous analysis of SST impacts on wave climate changes

Shimura, Mori, & Mase (AMS 2015)

CMIP3 SST Experiments (18 members)

A1B scenario



60 km winds

U10: Future annual changes (m/s)

SWH: Future annual changes (m)

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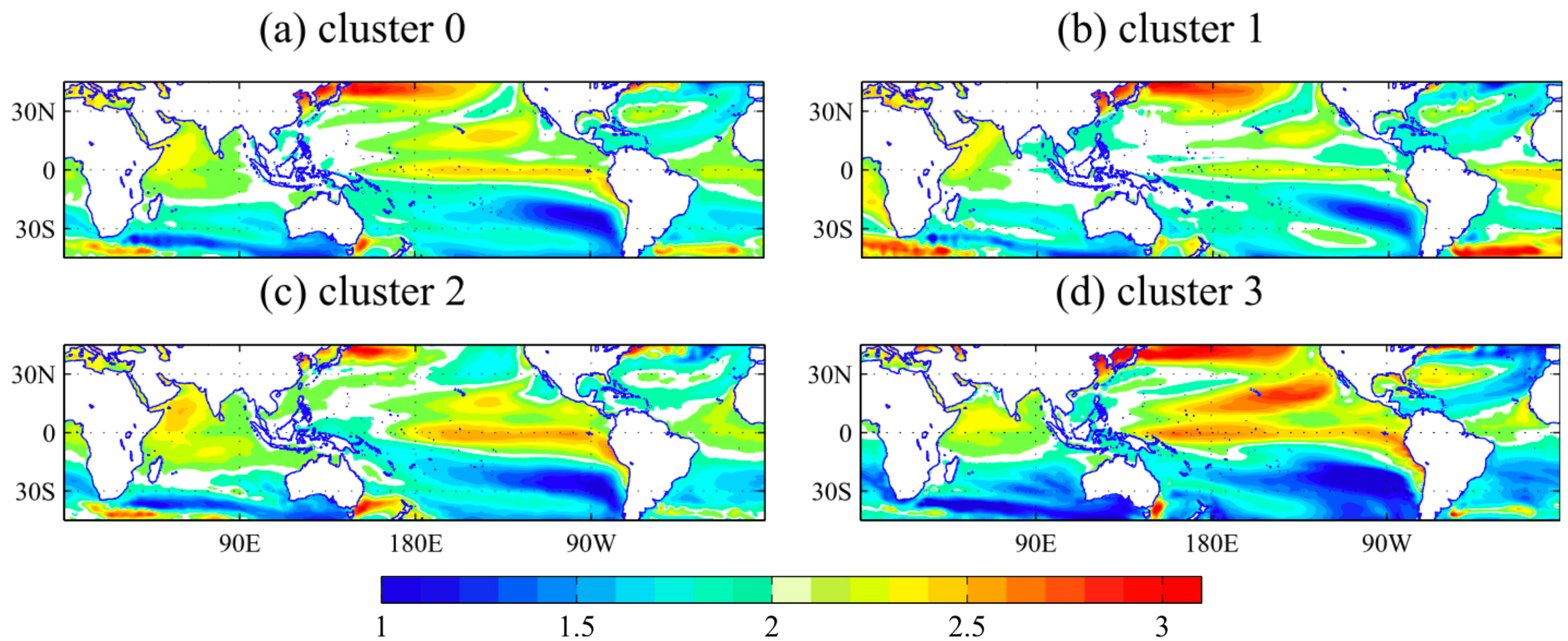
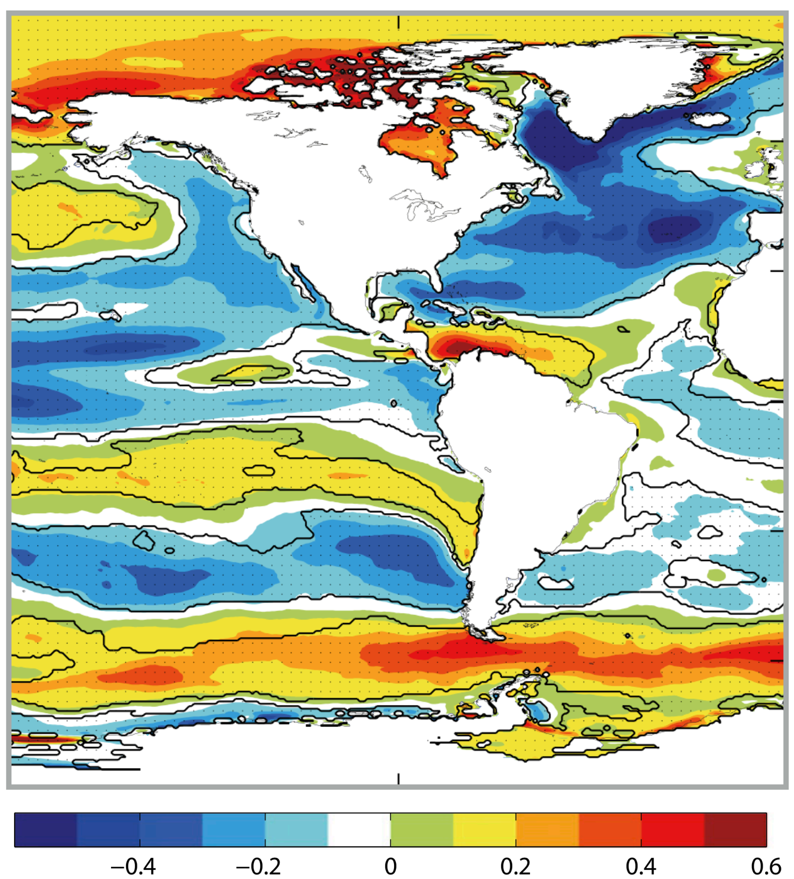
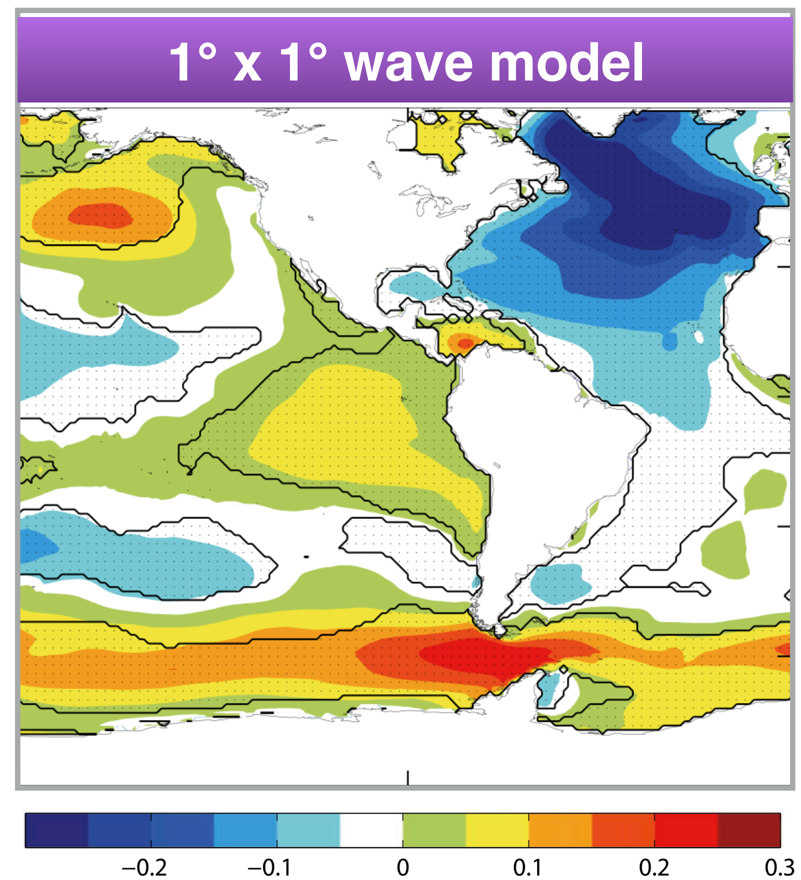


60 km winds

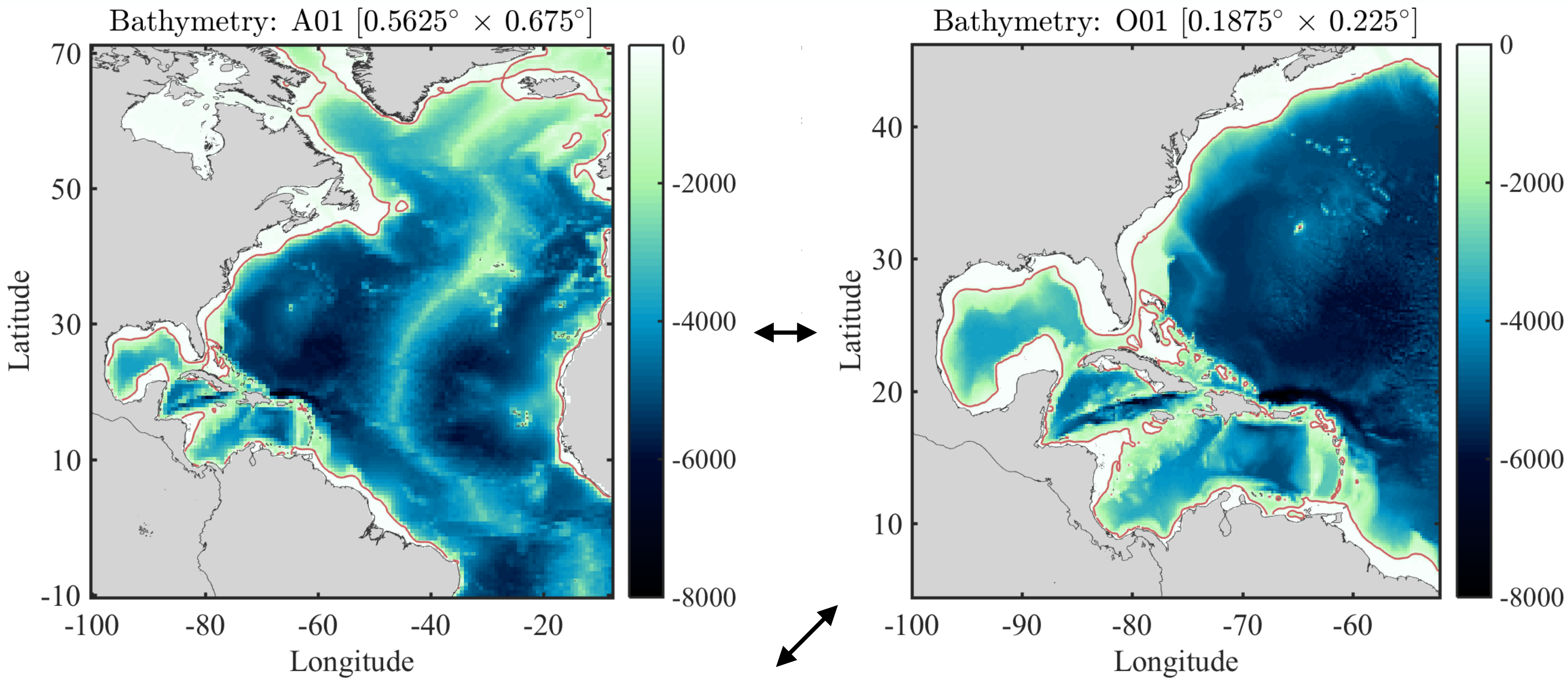
U10: Future annual changes (m/s)





SWH: Future annual changes (m)

Model domain and nested setup



NWA-n1:

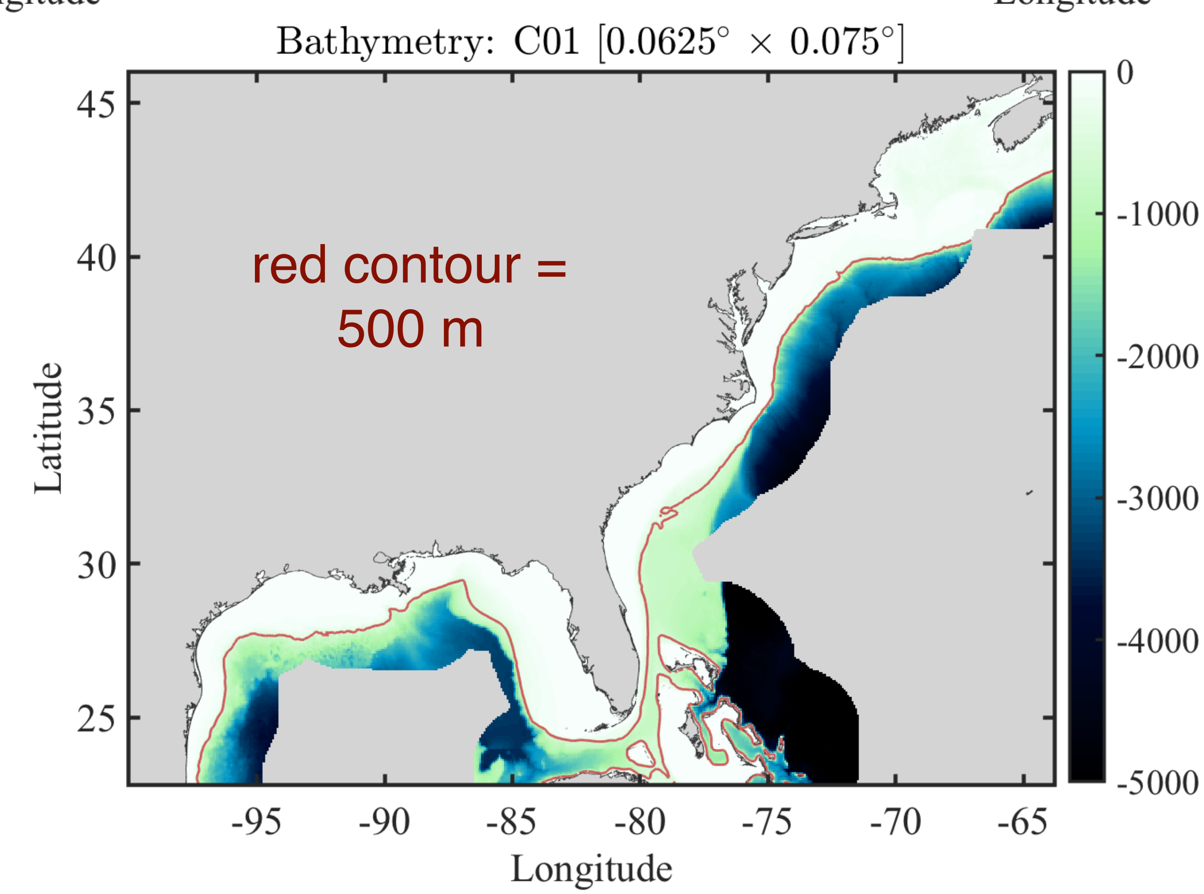
- **dy = 62.4066 km**
- **median(dx) = 64.8563 km**

NWA-n2:

- **dy = 20.8022 km**
- **median(dx) = 22.3228 km**

NWA-n3:

- **dy = 6.9341 km**
- **median(dx) = 6.8806 km**

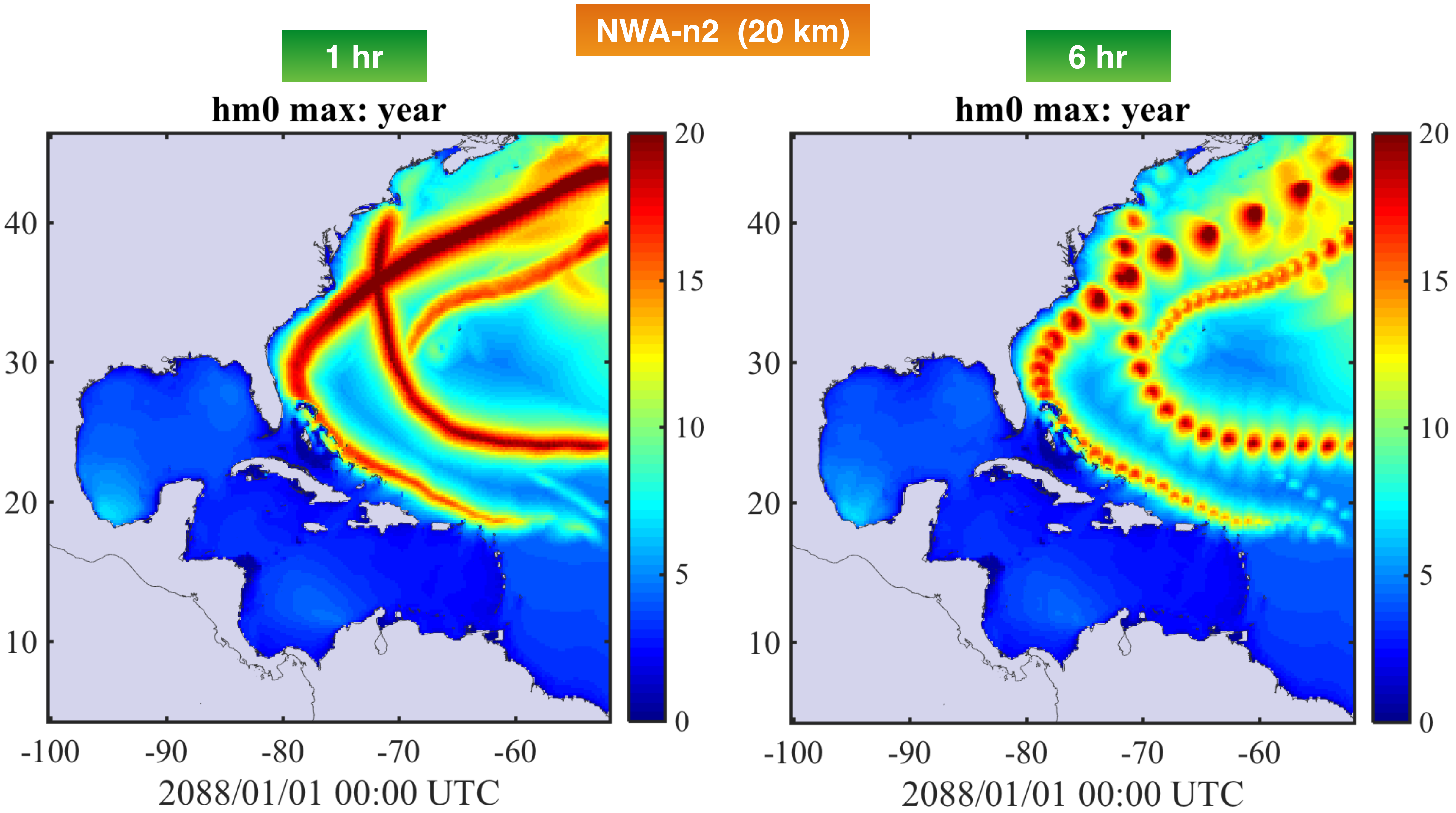


Alves (Ocean Modelling, 2006)

Spectral wave model details

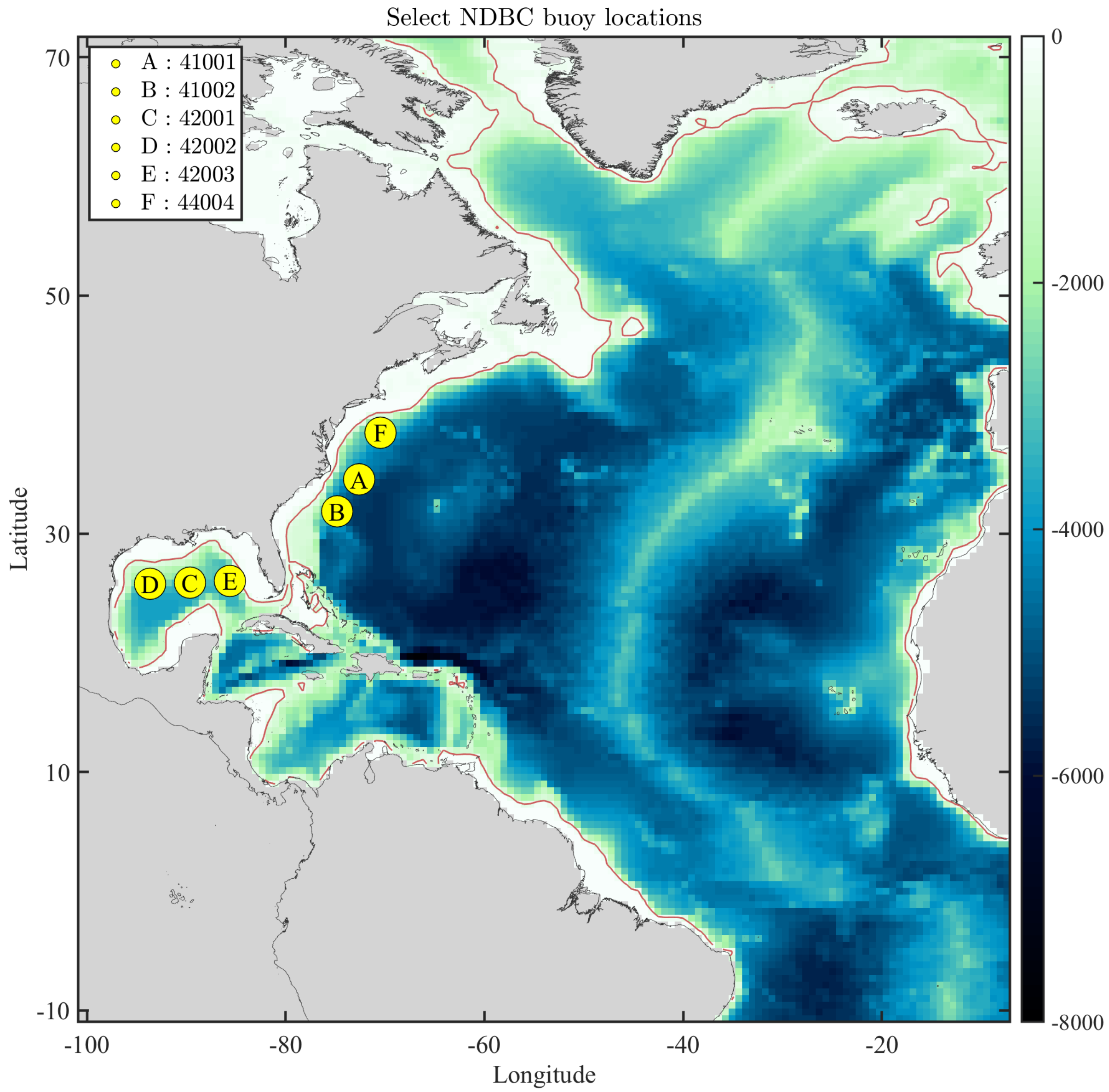
Details	Nested Layers: North Atlantic, Gulf of Mexico, US East
Base Model	NOAA WAVEWATCH III (version 4.18)
Spatial Resolution	0.5625° (62.4 km) → 0.1875° (20.8 km) → 0.0625° (6.93 km)
Spectral Resolution	35 frequency and 36 directional bins
Bathymetry	ETOPO1 (1/60°)
Shoreline	GSHHS version 2.3.4/5
Projection Type	RCP8.5, Yoshimura scheme
Forcings: Wind	MRI-AGCM 3.2S: 1 hour (TL959; 20 km)
Forcings: Ice	MRI-AGCM 3.2S: 1 month (TL959; 20 km)
Forcings: Current	None
Output Frequency	1 hour
Model Physics	ST4 (Ardhuin et. al); IC0
Simulation Period	1979—2003 (25 years) / 2075—2099 (25 years)

Extreme SWH for 2088 with different temporal frequencies



Inter-model hindcast comparison with NDBC buoys: Nest 1

WW3 model	Res. [km/lat]	Output freq.	Wind product	Res. [km/lat]	Output freq.	Source
NWA-n1	62.4	1 hr	MRI-AGCM 3.2S	20.8	1 hr	KyotoU
JRA-55	62.4	1 hr	JRA-55	62.4	6 hr	KyotoU
CFSR-n1	55.5	3 hr	CFSR	34.6	1 hr	NCEP
ERA-I	83.2	6 hr	ERA-Interim	**	**	ECMWF



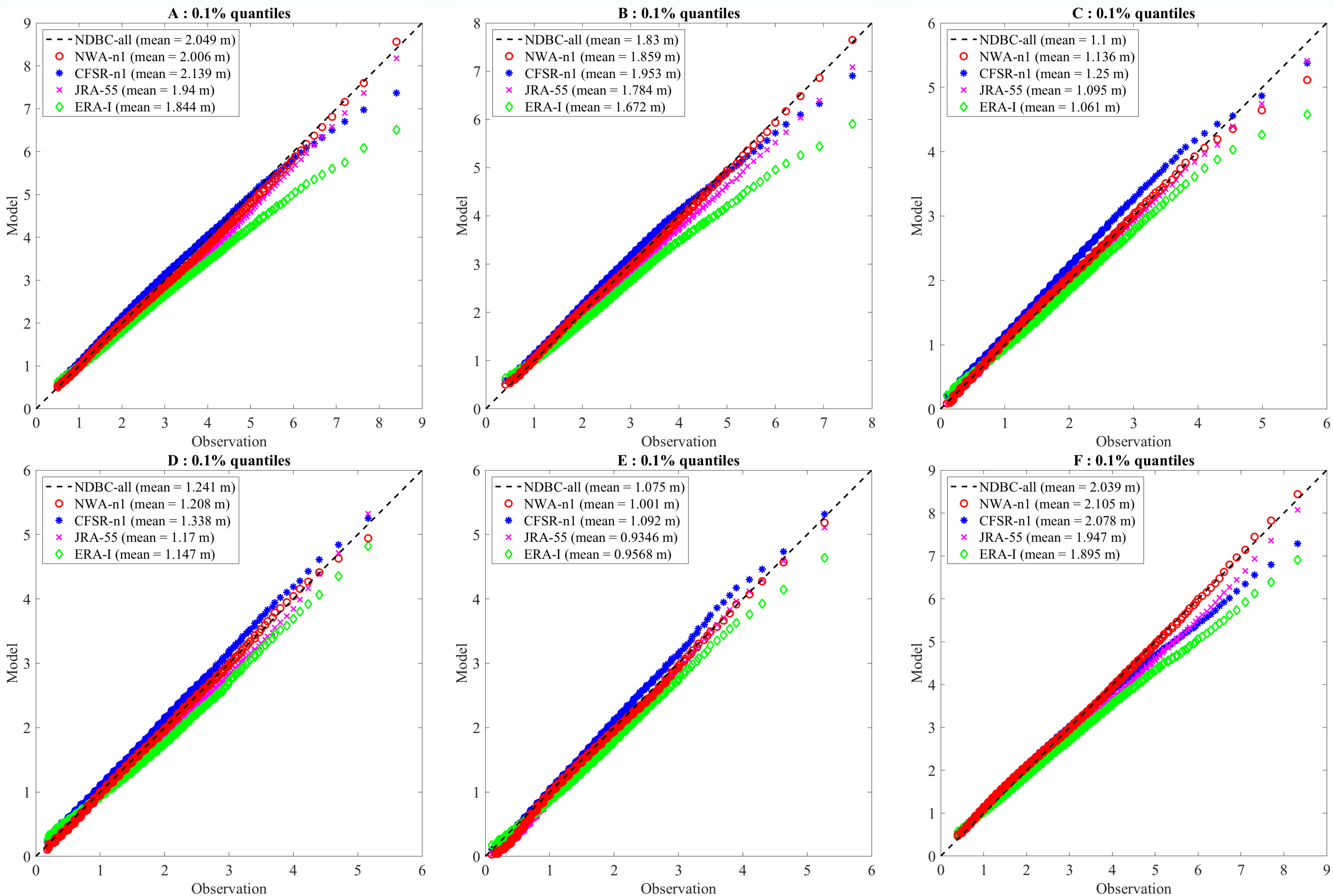
Model:

- All : 1979/01—2003/12

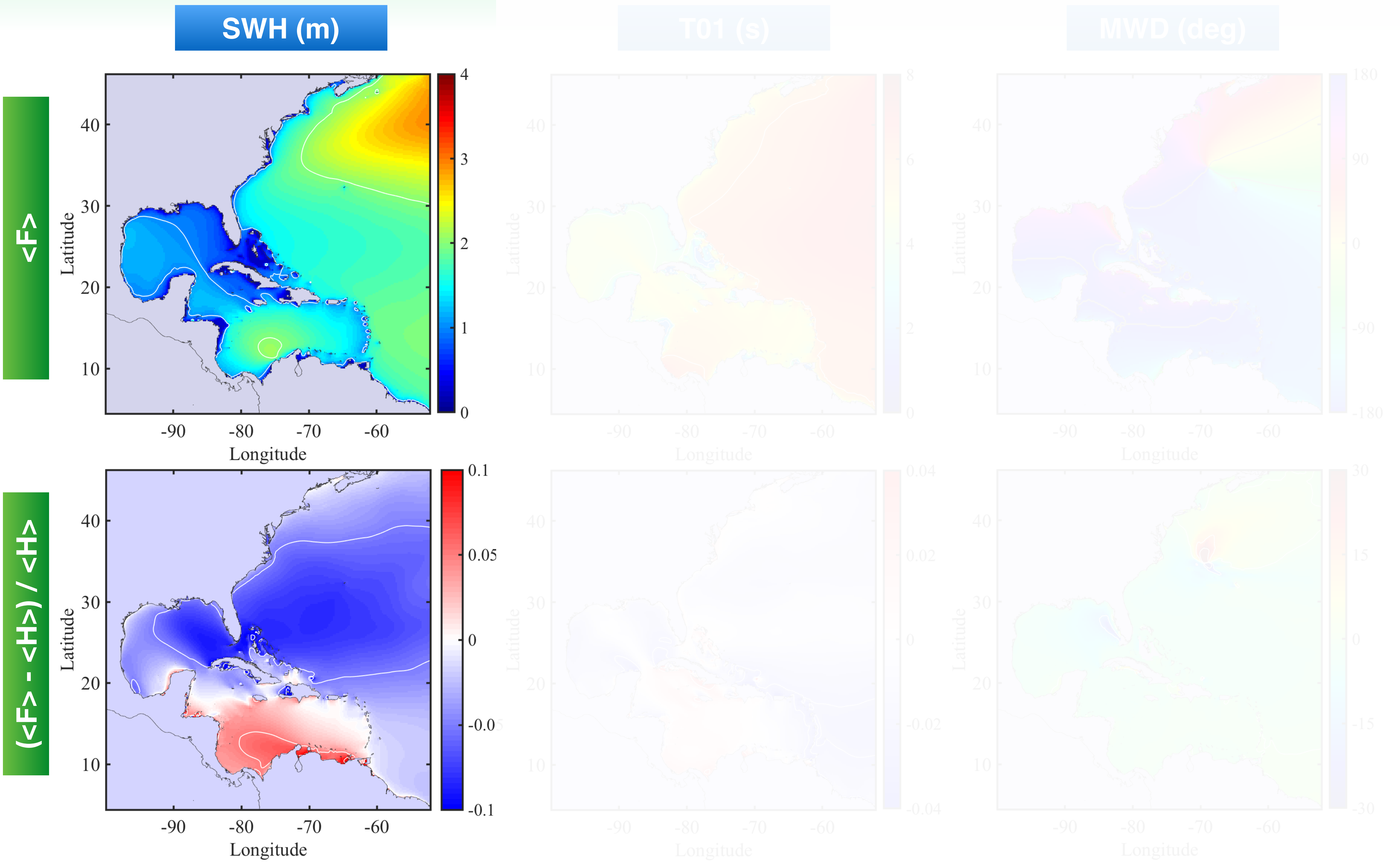
Observation:

- A : 1976/06—2013/05
- B : 1975/06—2013/12
- C : 1976/01—2013/12
- D : 1976/10—2013/12
- E : 1977/07—2013/12
- F : 1977/10—2008/03

Observation (all) and model quantile comparison: Nest 1



Projected climatology and relative difference

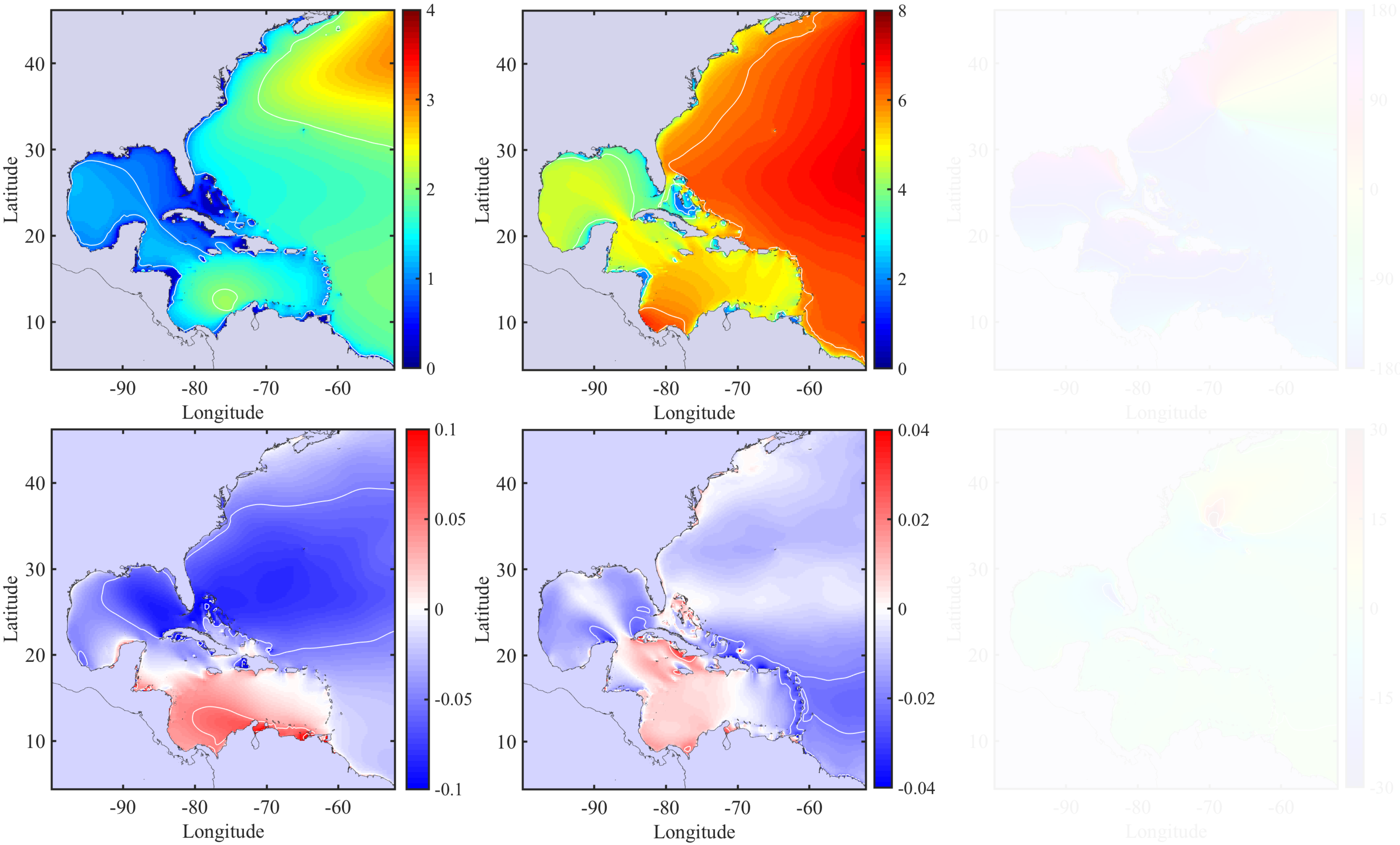


Projected climatology and relative difference

SWH (m) | **T01 (s)** | **MWD (deg)**

<F>

(<F> - <H>) / <H>



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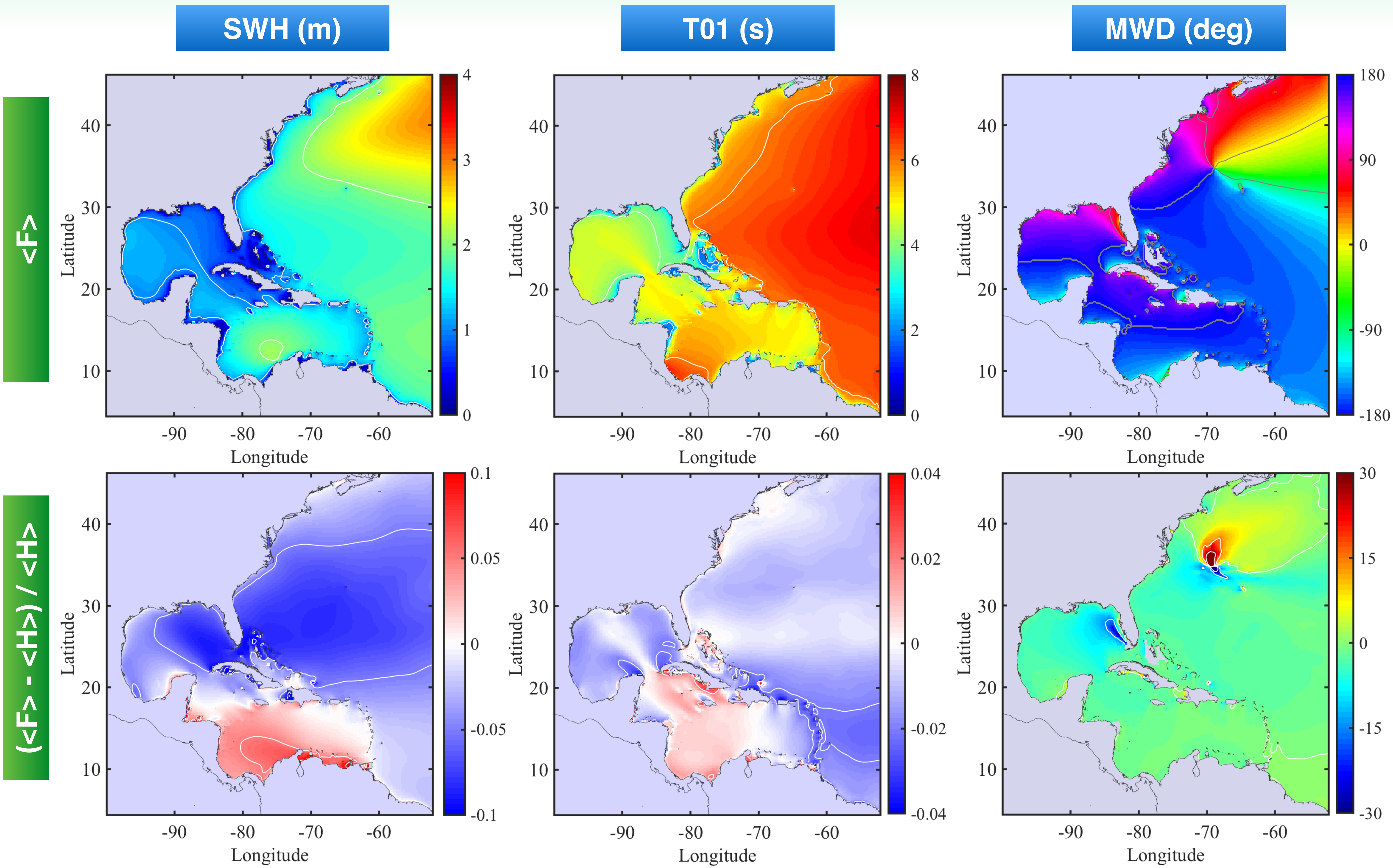

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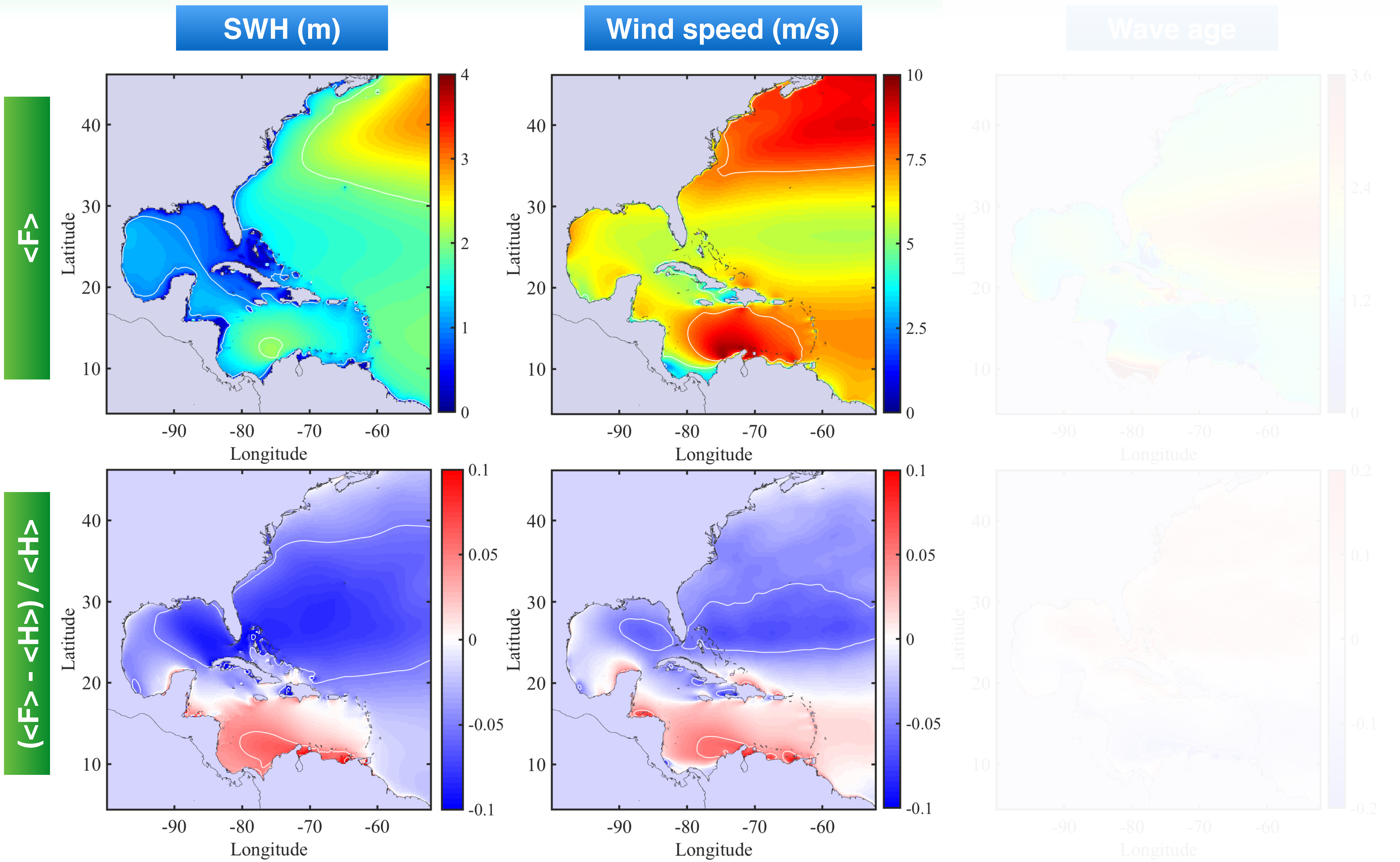

$$\text{wave age} = c_p/u_{10}, \;\; \text{fetch-limited} \leq 1.2$$

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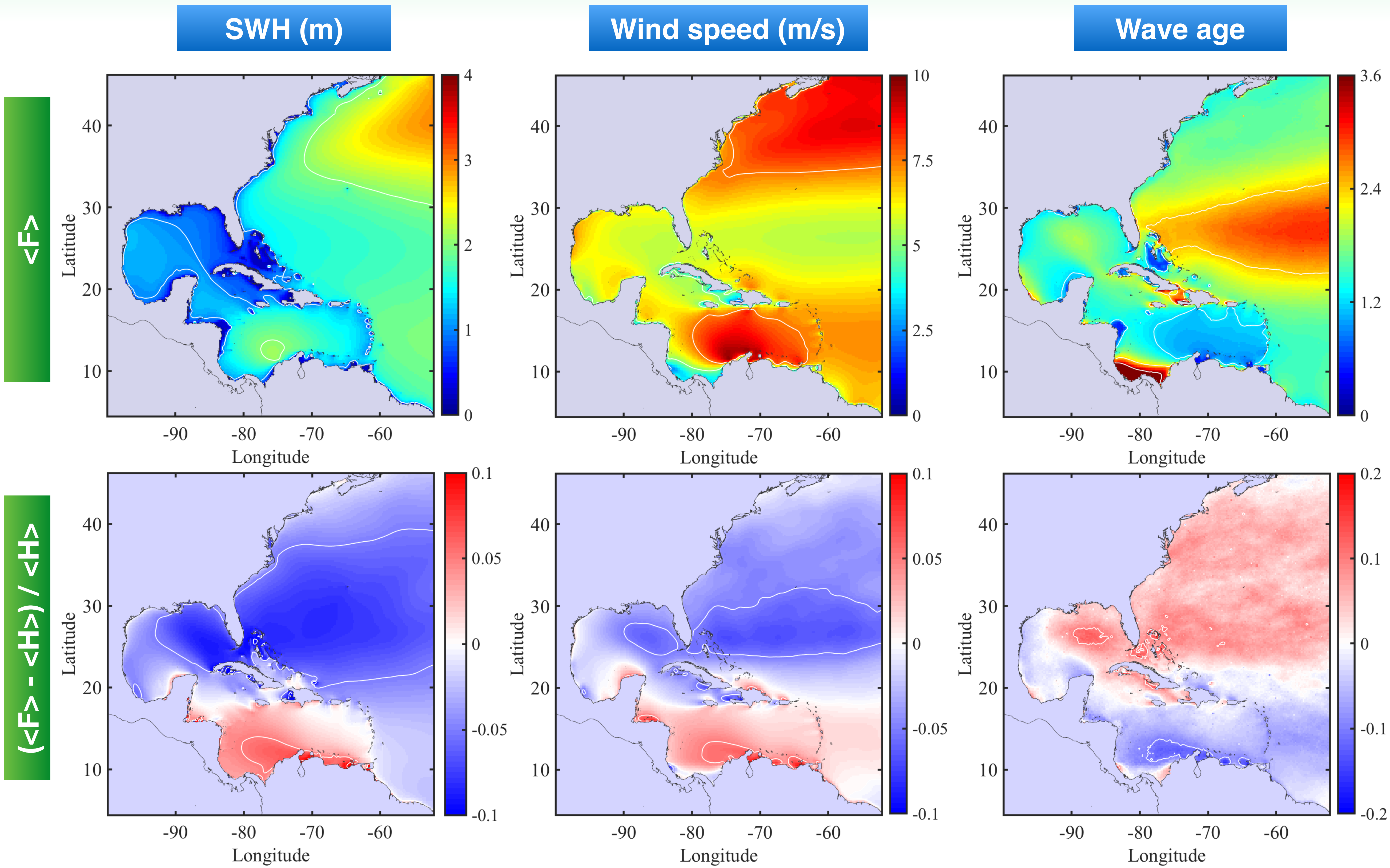

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Regional means and relative differences

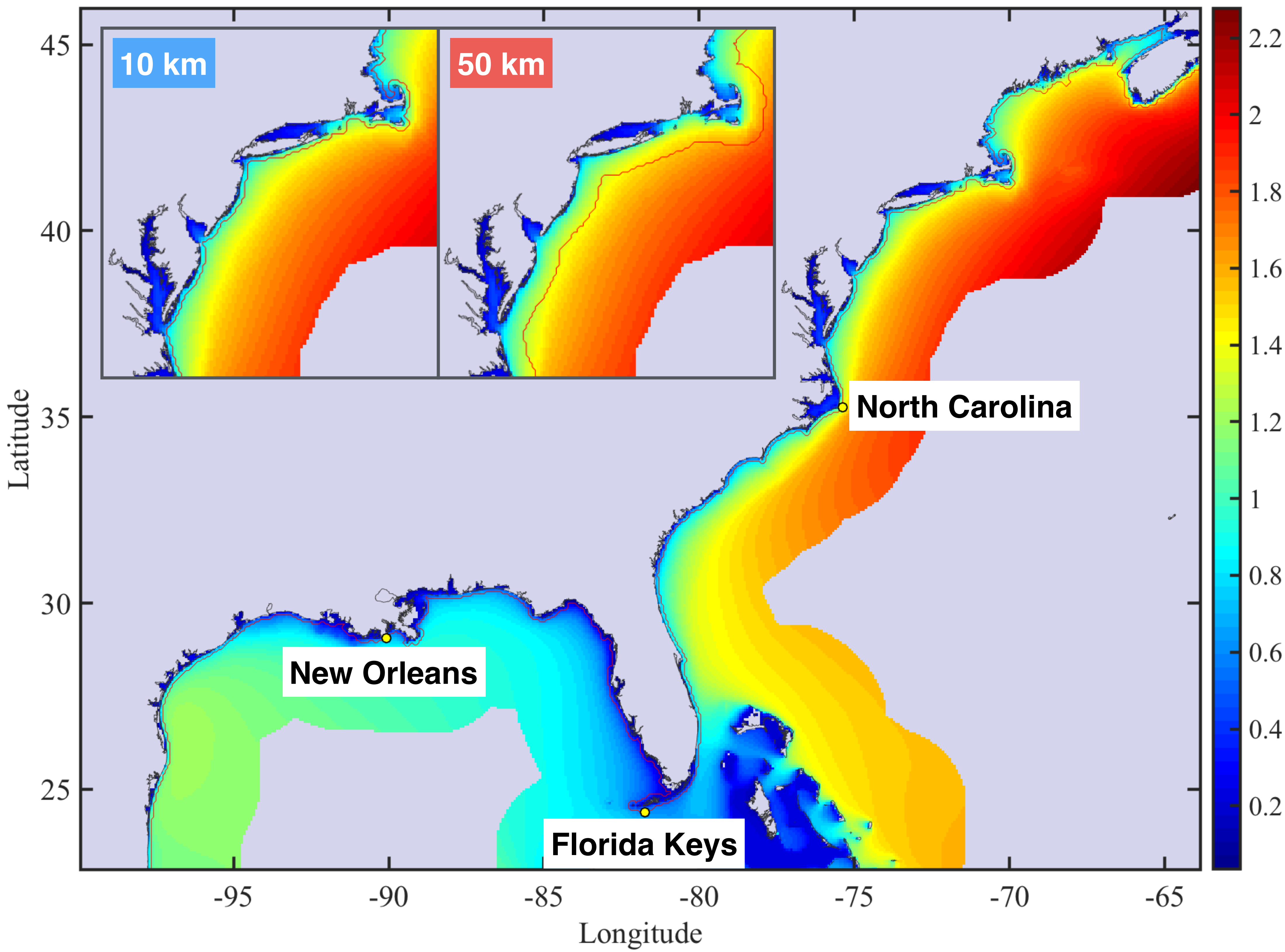
Regional means

	NWA-n2 (all)					Northwest Atlantic					Gulf of Mexico					Caribbean Sea				
	AN	WI	SP	SU	FA	AN	WI	SP	SU	FA	AN	WI	SP	SU	FA	AN	WI	SP	SU	FA
SWH (m)	1.46	1.84	1.58	1.10	1.32	1.73	2.22	1.82	1.20	1.69	0.97	1.25	1.14	0.62	0.85	1.38	1.62	1.52	1.43	0.96
T01 (s)	5.37	5.65	5.37	5.00	5.48	6.04	6.32	5.92	5.51	6.41	4.30	4.57	4.45	4.01	4.17	4.99	5.19	5.06	4.93	4.77
Wind (m/s)	6.56	7.64	7.08	5.64	5.90	6.75	8.03	7.19	5.53	6.29	5.90	6.87	6.56	4.70	5.47	7.10	7.83	7.63	7.39	5.55
MWD (deg)	-177	-149	-176	152	-163	-172	-106	-157	135	-161	168	-168	162	143	-166	-170	-165	-173	-174	-166

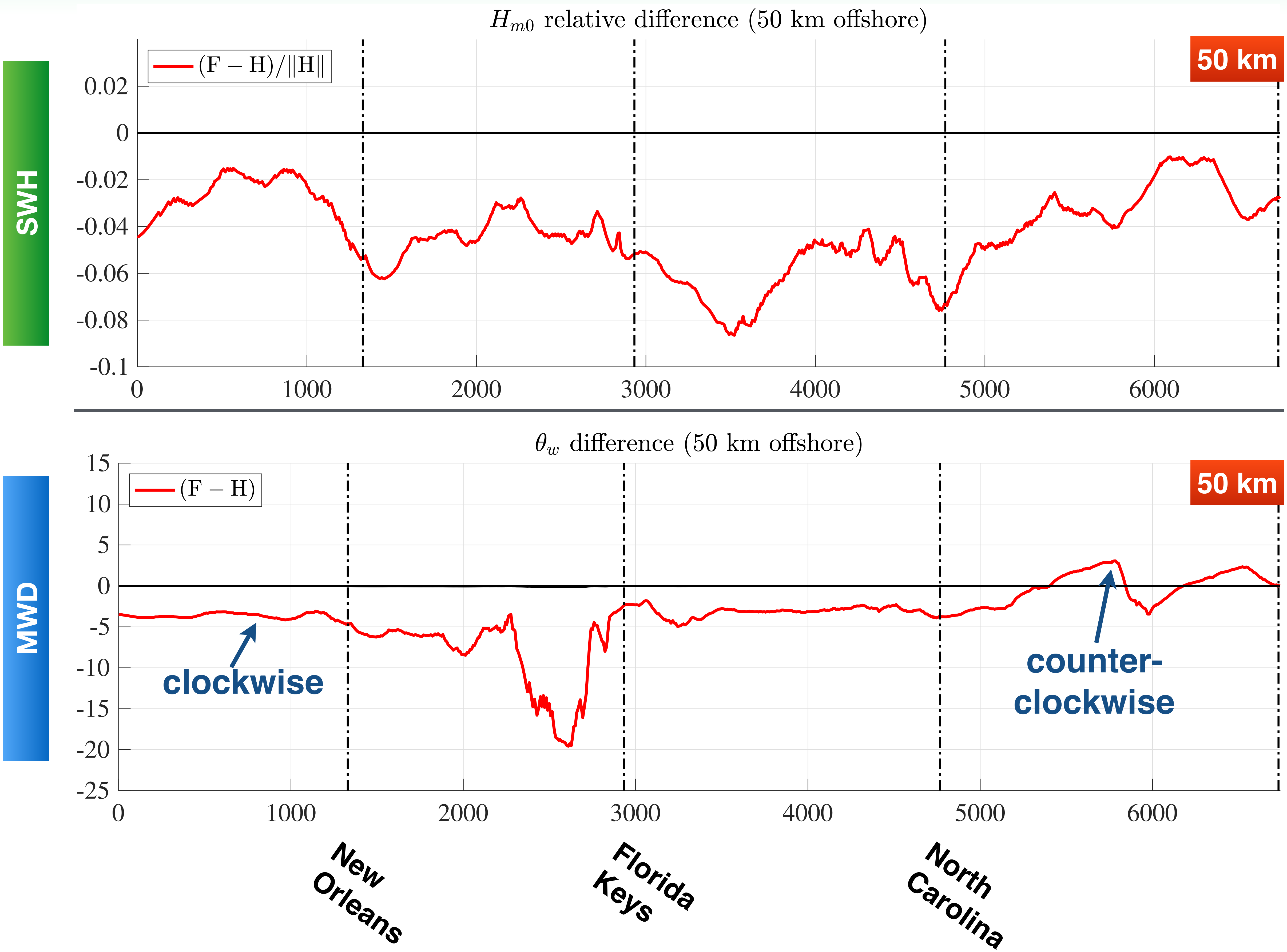
Regional absolute and relative differences

	NWA-n2 (all)					Northwest Atlantic					Gulf of Mexico					Caribbean Sea				
	AN	WI	SP	SU	FA	AN	WI	SP	SU	FA	AN	WI	SP	SU	FA	AN	WI	SP	SU	FA
SWH (%)	-3.7	-3.7	-1.8	-1.9	-7.7	-5.7	-4.7	-4.3	-6.3	-7.6	-4.7	-4.2	-1.2	-1.6	-12.2	2.4	-0.4	3.8	7.4	-2.1
T01 (%)	-0.7	-1.7	-0.7	-0.3	-0.2	-0.7	-1.9	-1.6	-1.0	1.7	-0.9	-1.6	0.1	0.5	-2.4	-0.1	-0.9	0.6	0.4	-0.6
Wind (%)	-2.0	-1.8	-0.6	-0.1	-5.7	-3.9	-2.7	-2.0	-3.4	-7.6	-2.5	-2.1	-0.9	0.1	-7.2	2.6	0.7	3.1	6.6	-0.4
MWD (deg)	3.4	4.0	3.0	5.1	7.9	3.4	3.8	4.1	5.7	14.4	5.0	6.1	2.9	7.1	2.2	1.4	2.2	1.5	1.4	2.9

Along-shore analysis:10 & 50 km tracks



Along-track analysis: SWH and MWD change at 50 km



Along-track analysis: Incident shoreline energy change at 50 km

Incident shoreline energy

$$\propto \quad H_{m0}^2 \, T_e \, cos(\theta_i); \quad \theta_i = \text{incident angle}$$

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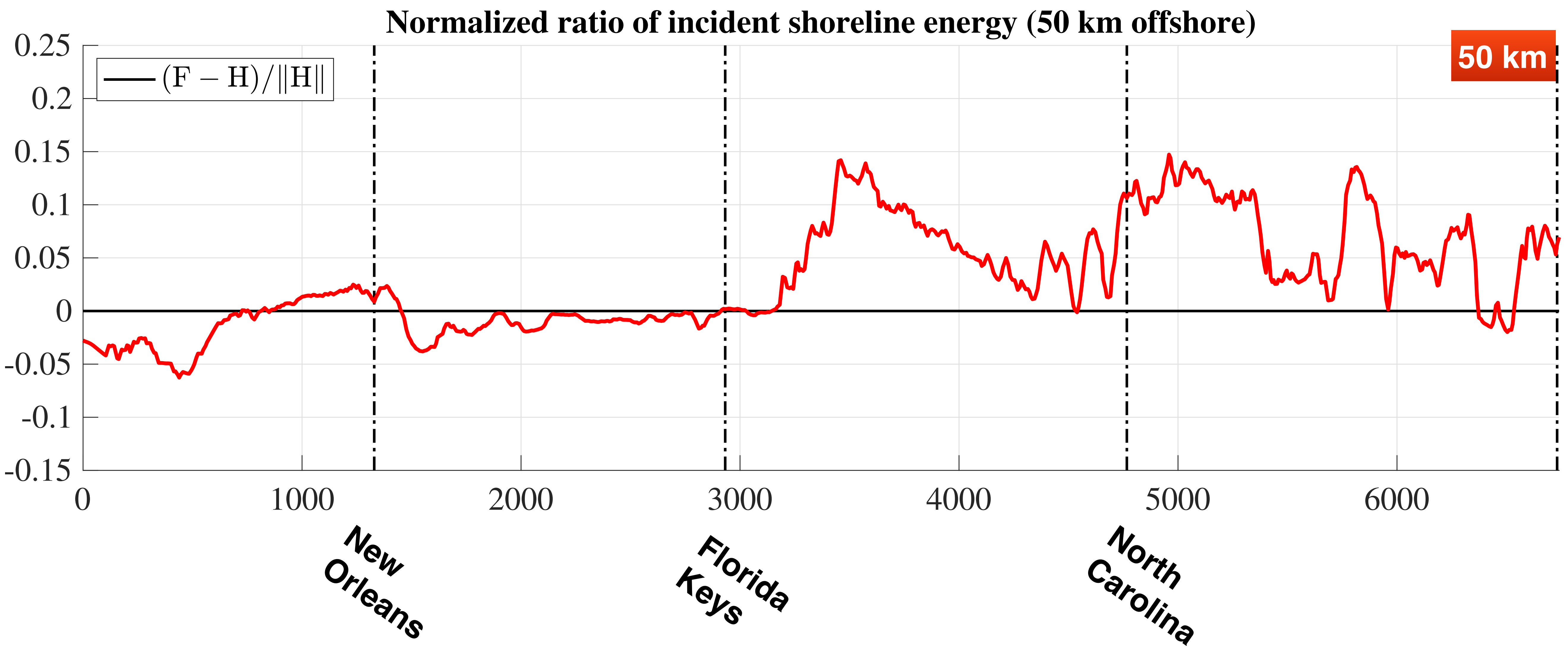
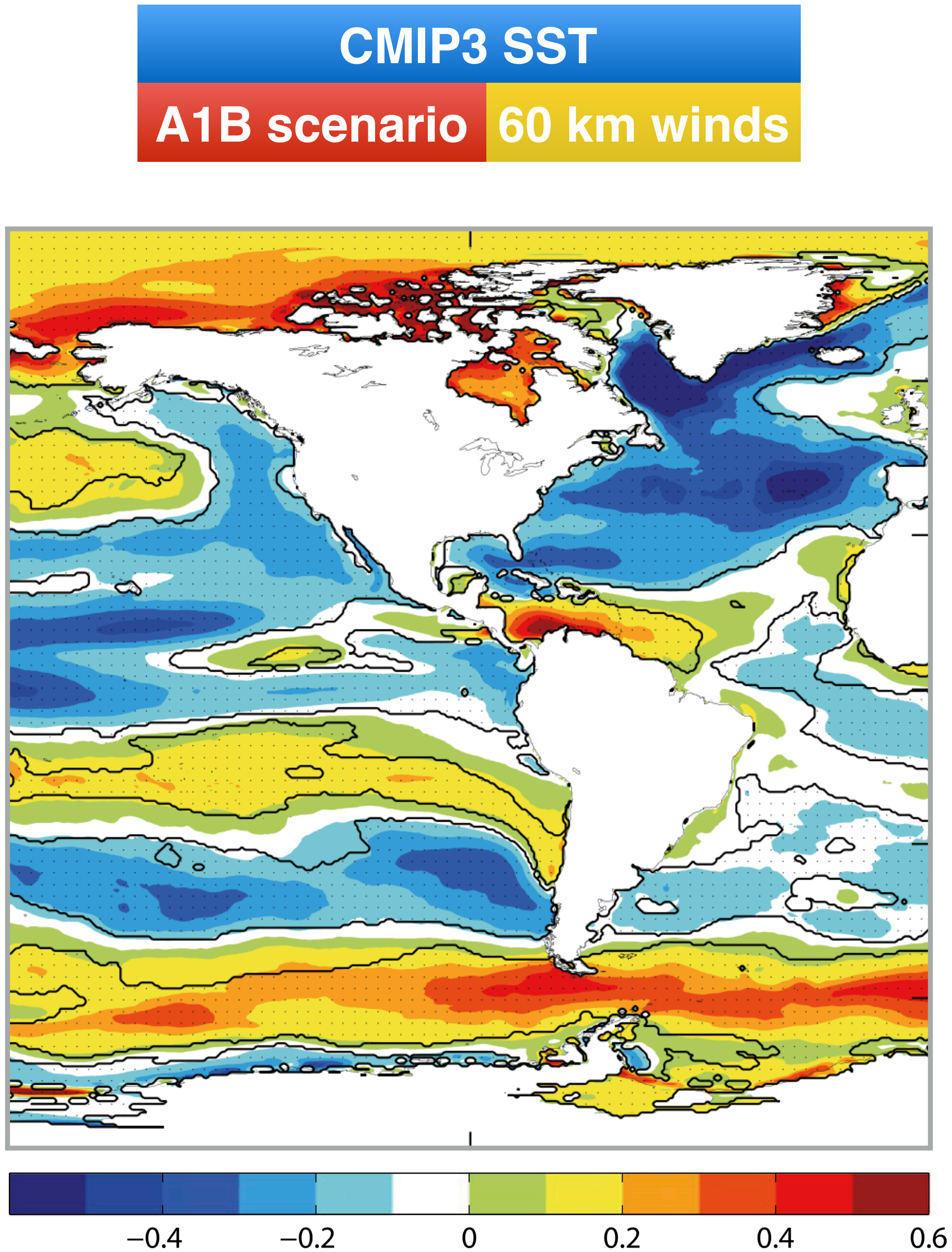
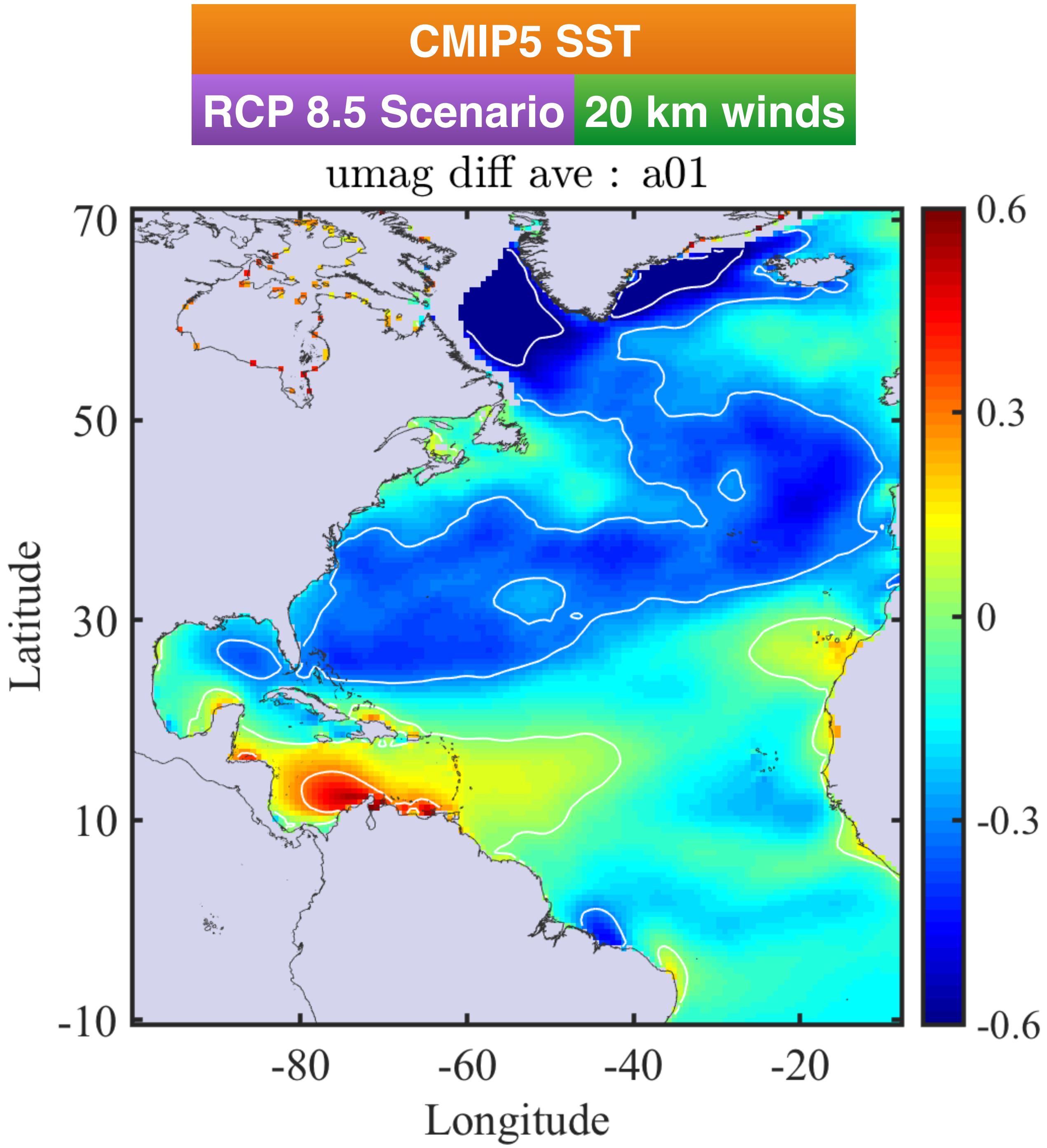


CMIP comparison of projected changes in surface winds

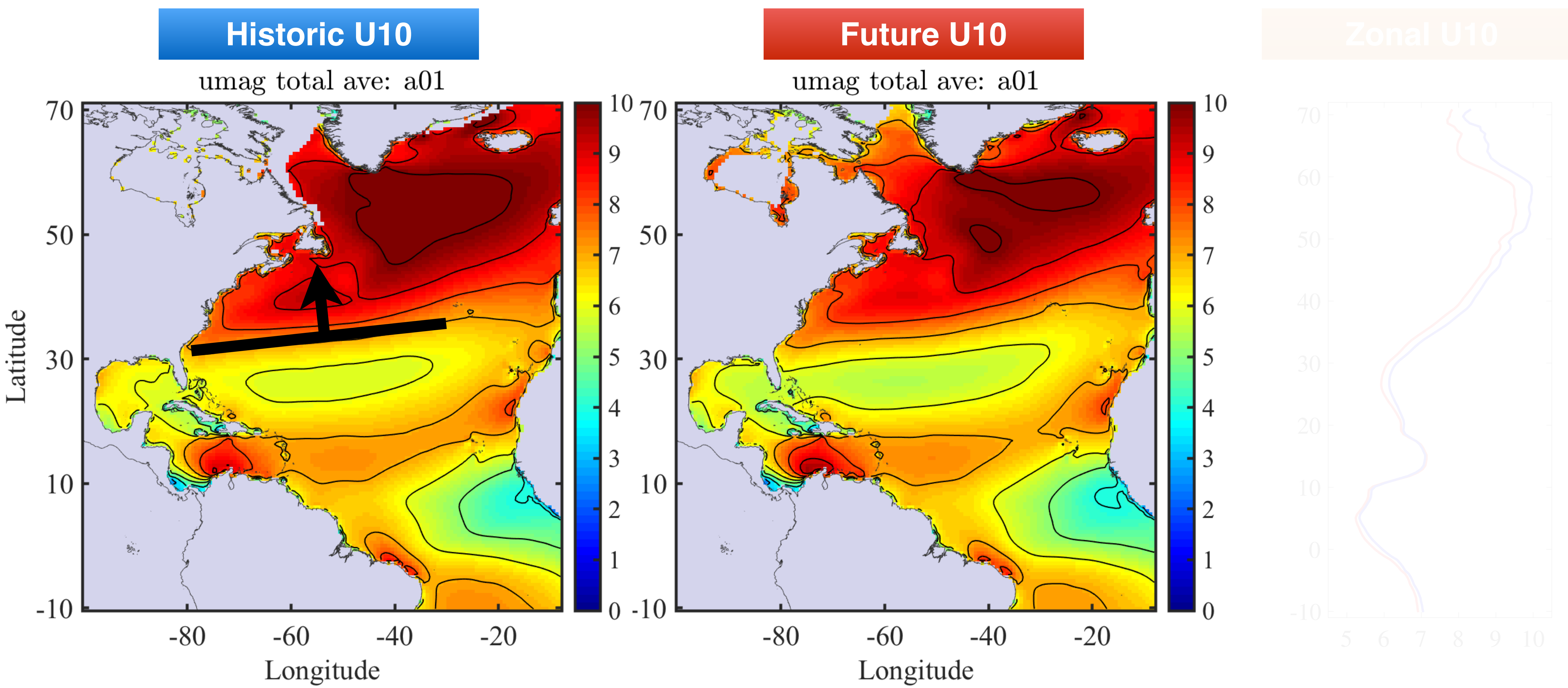




Comparison of projected changes in surface winds

SROC / IPCC AR5:

- **Mean SLP is projected to decrease in high latitudes and increase in mid-latitudes**
- **Medium confidence that mid-latitude jets will move ~1 degree poleward by end of the 21st century under RCP8.5 in the Northern Hemisphere**



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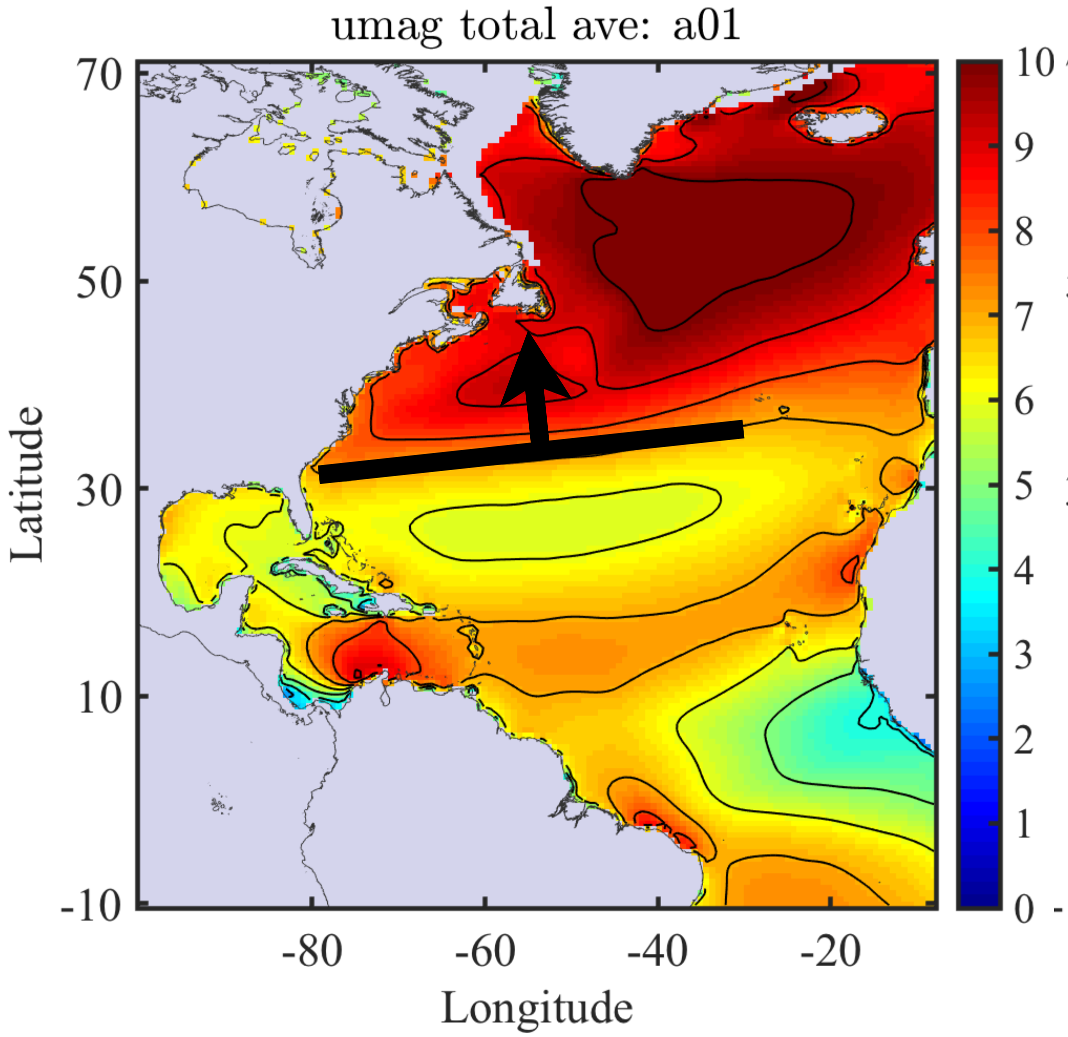
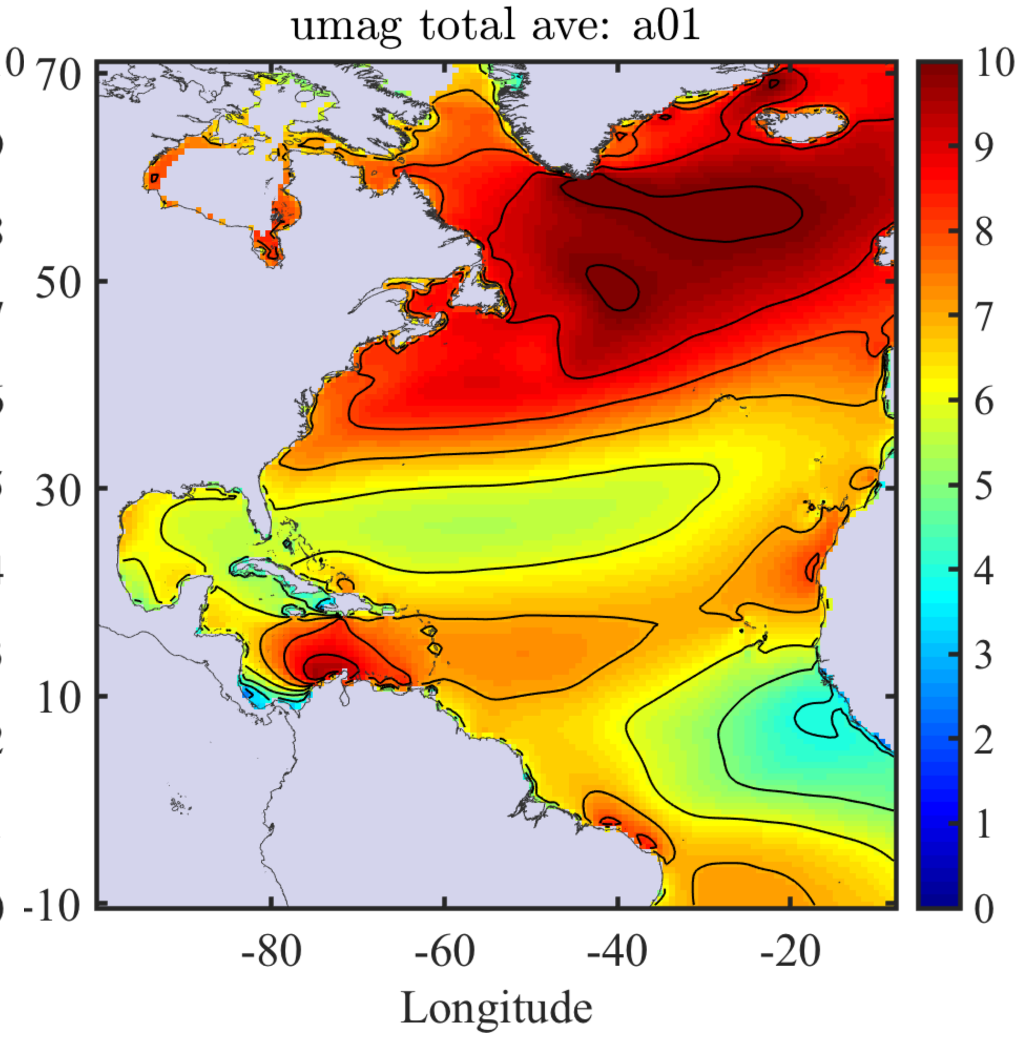
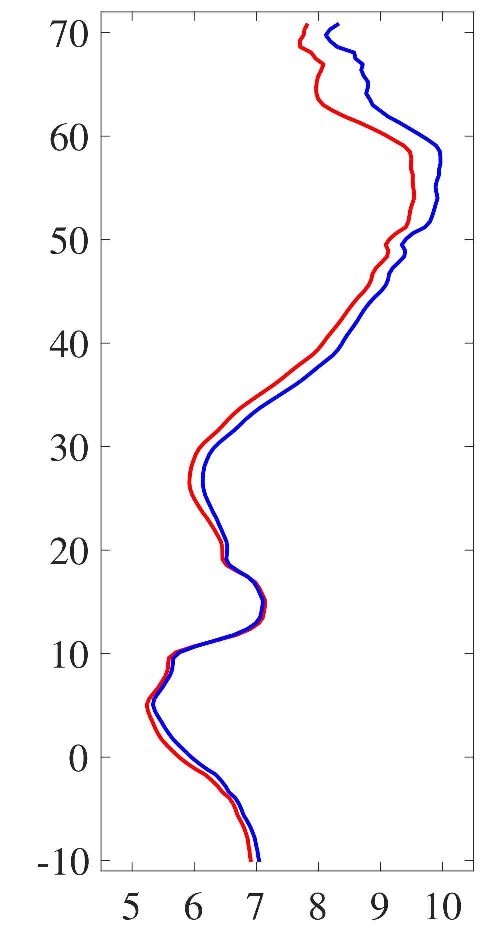
Historic U10



Future U10



Zonal U10



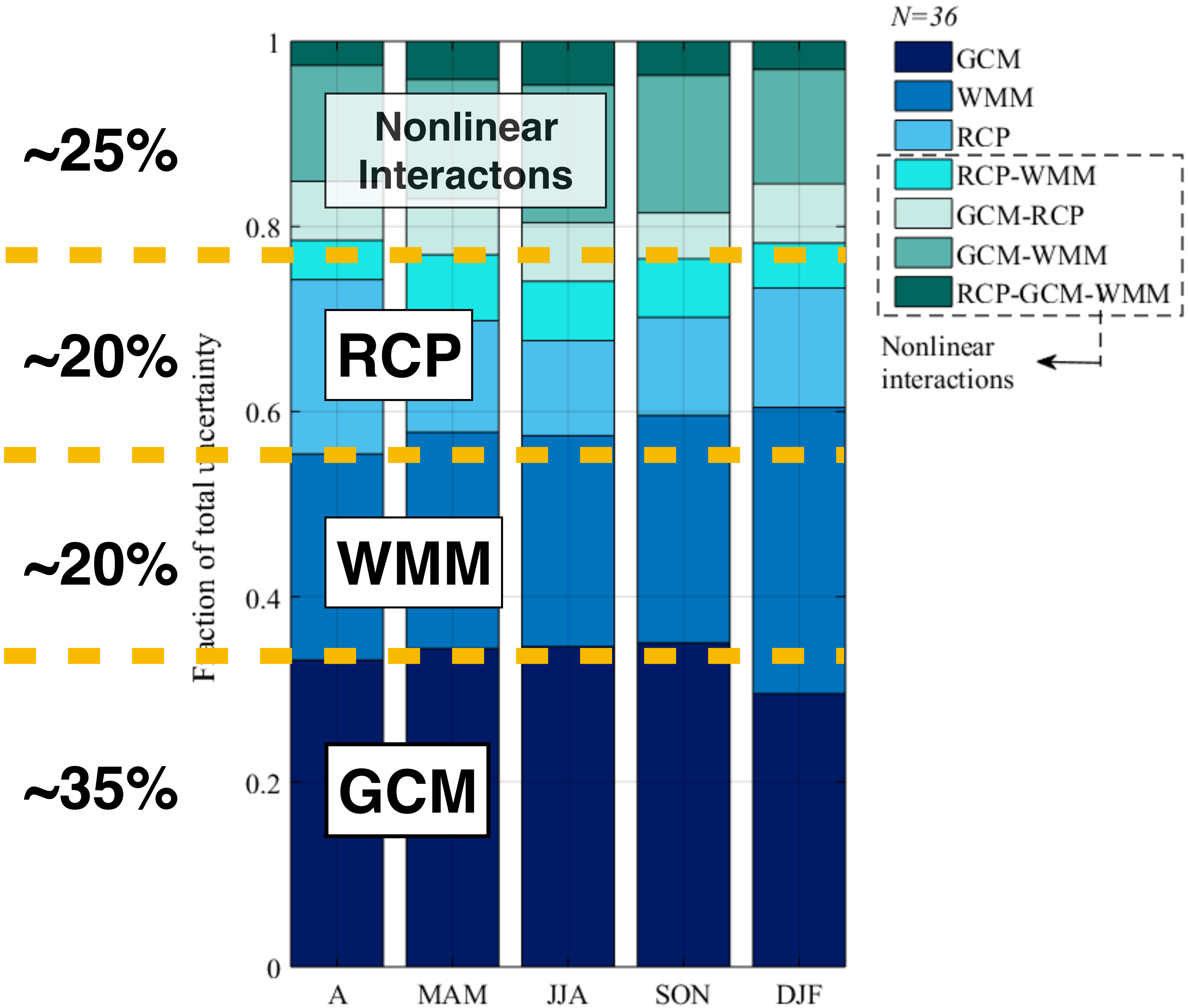
Relative contribution of different sources of uncertainty

Morim, et al., 2019 - Robustness and uncertainties in global multivariate wind (Nature Climate Change)

GCM (6):
ACCESS1.0, BCC-CSM1.1, CNRM-CM5, INM-CM4, MIROC5, MRI-CGCM3

Wave Modeling Method (WMM; 3):
CSIRO (dynamical), IHC (statistical), ECCC (statistical)

Representative Concentration Pathways (2) :
RCP4.5, RCP8.5



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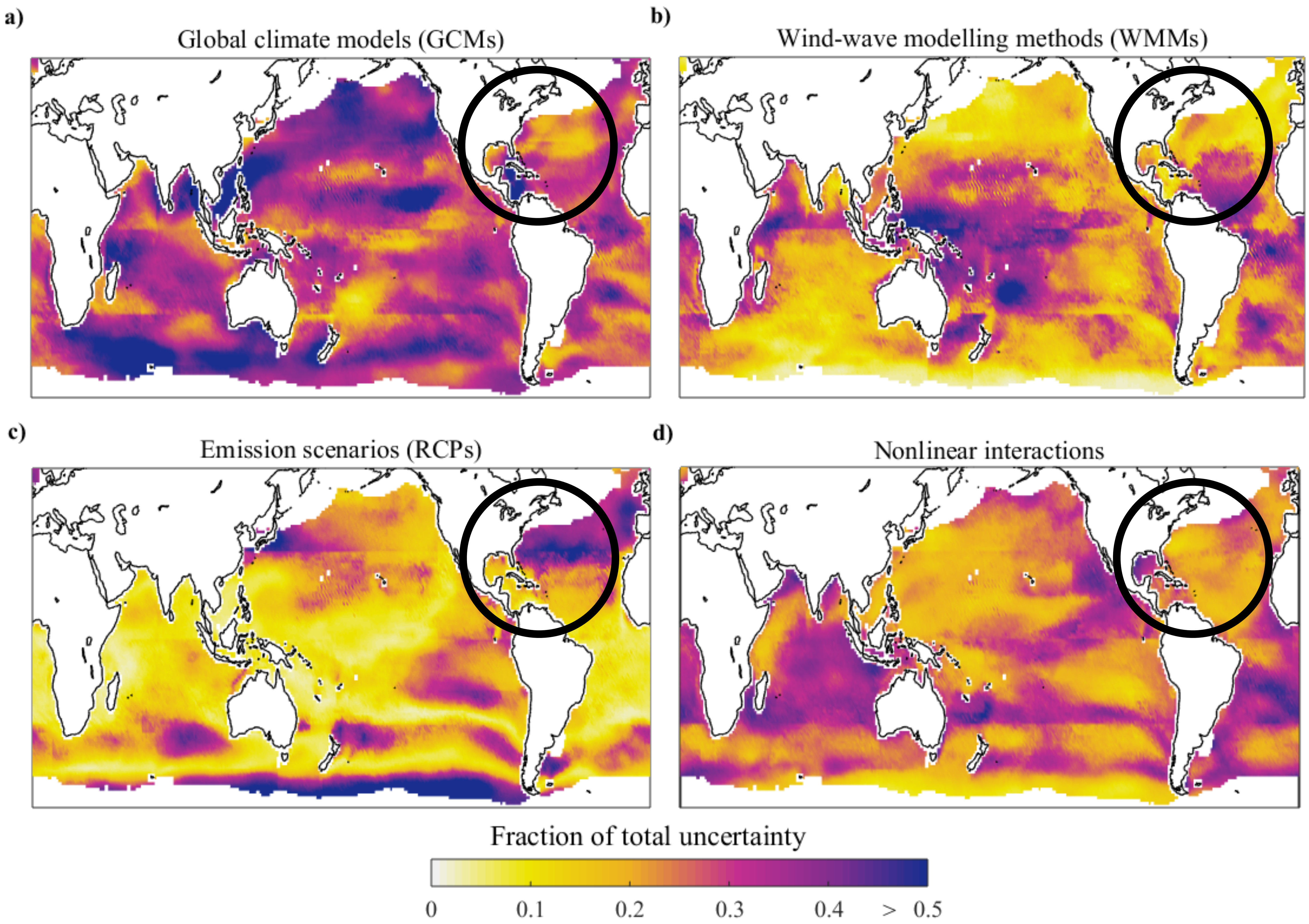
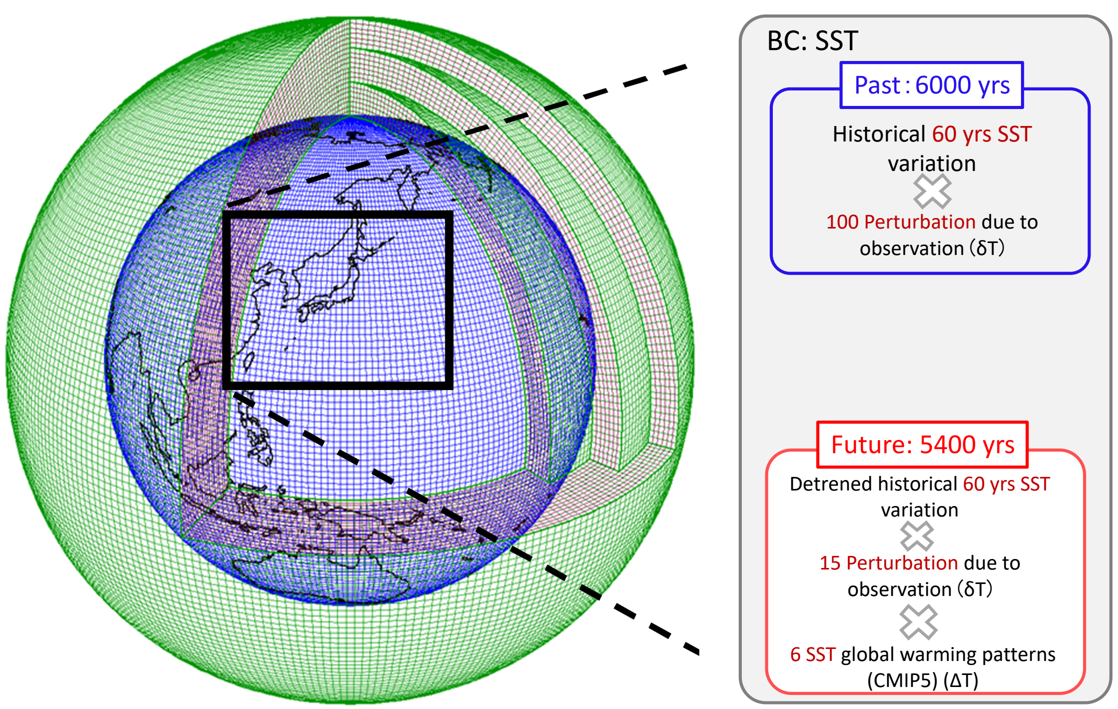


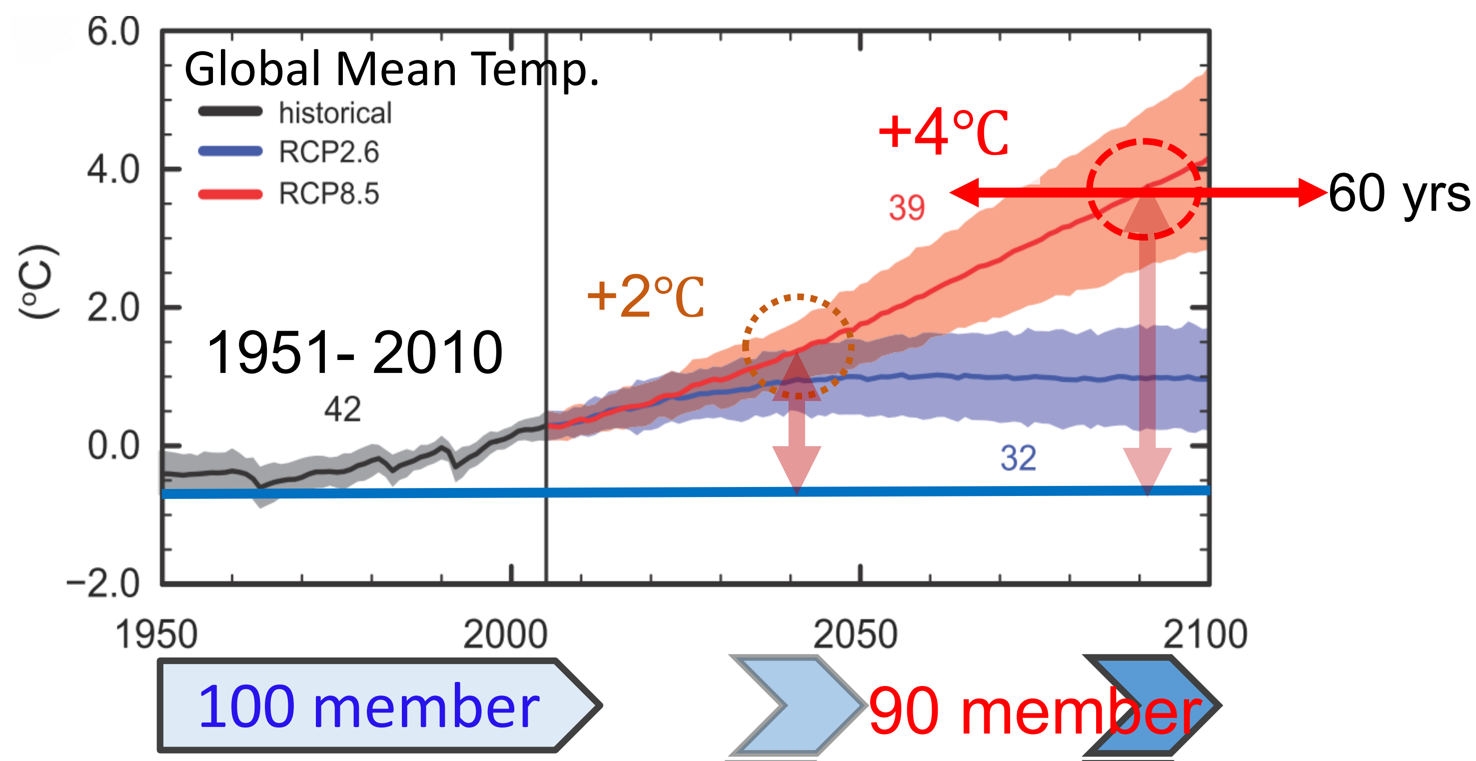
d4PDF Dataset

Database for Policy Decision-Making for Future Climate Change

Reference: Mizuta et al. (2017) BAMS

- **Extremely large ensemble of climate simulations**
- **Enables assessment of probabilistic change in low-frequency hazardous events**





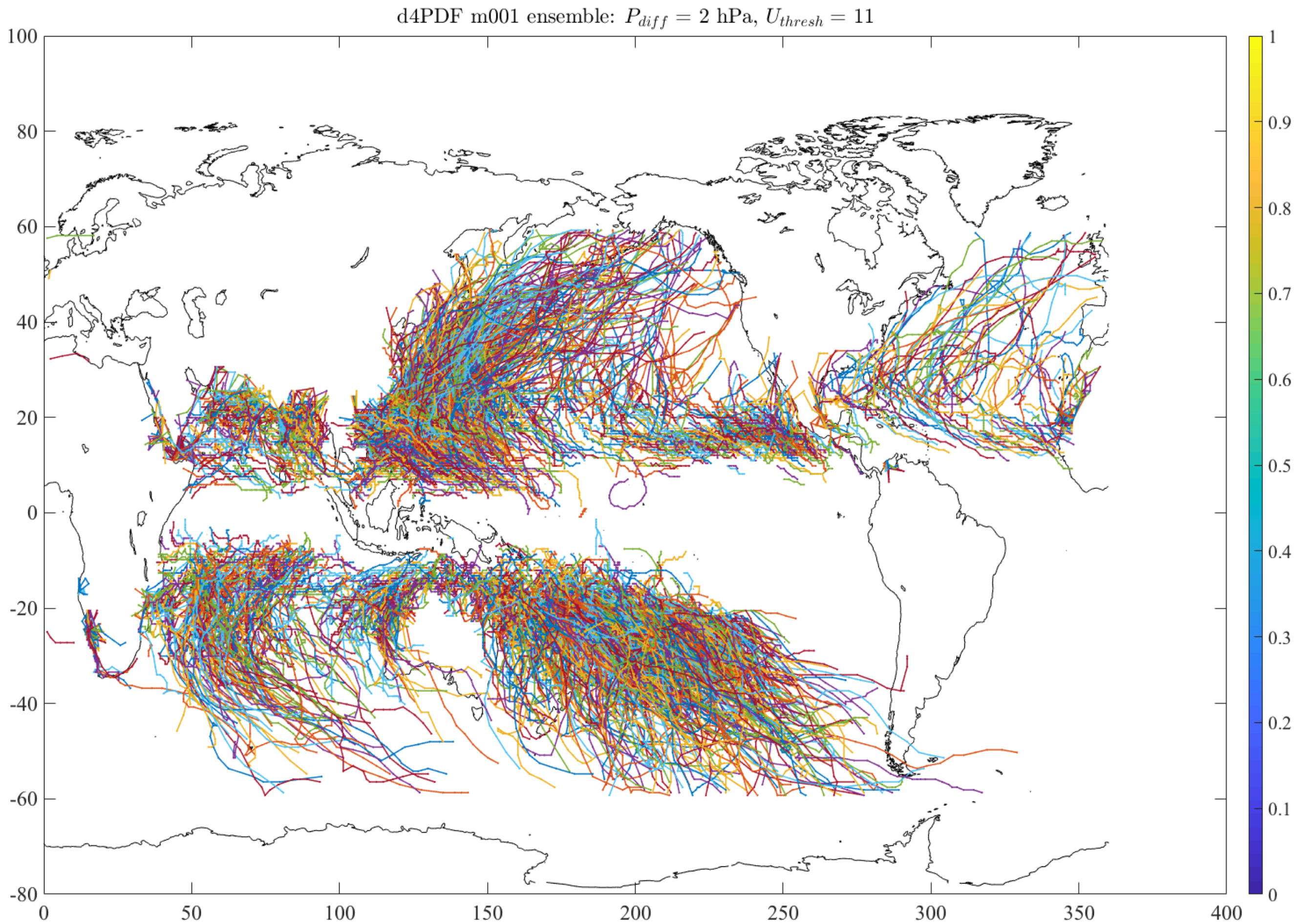
Atmospheric general circulation model: MRI-AGCM3.2 (60 km)

JAMSTEC Earth Simulator 3 (ES3) NEC SX-ACE

Uses of the d4PDF tropical cyclone track data

- **TC tracks are useful for modeling hazardous events such as extreme rainfall, storm surge, etc.**
- **d4PDF can be used to estimate 100 year or longer return values**

detected d4PDF TC tracks: Past (1 ensemble)



With 6000+5400 years of data, not limited to historic events to estimate low frequency events

Summary

Regional projection:

- **Decreases (~5%) in SWH in Northwest Atlantic and Gulf of Mexico**
- **Increases (~2.5%) in SWH in Caribbean Sea**
- **Little changes in wave period for entire region**
- **Large increases (over 10%) in incident shoreline energy along US Eastern Seaboard**
- **Largest contribution of uncertainty in Northwest Atlantic comes from RCP scenario, followed by GCM**

Mega-ensemble climate dataset:

- **The d4PDF dataset is available for modeling low-frequency hazardous events**
- **Tropical cyclones have been identified for a +4K warming scenario (11,400 years)**

Thank You!

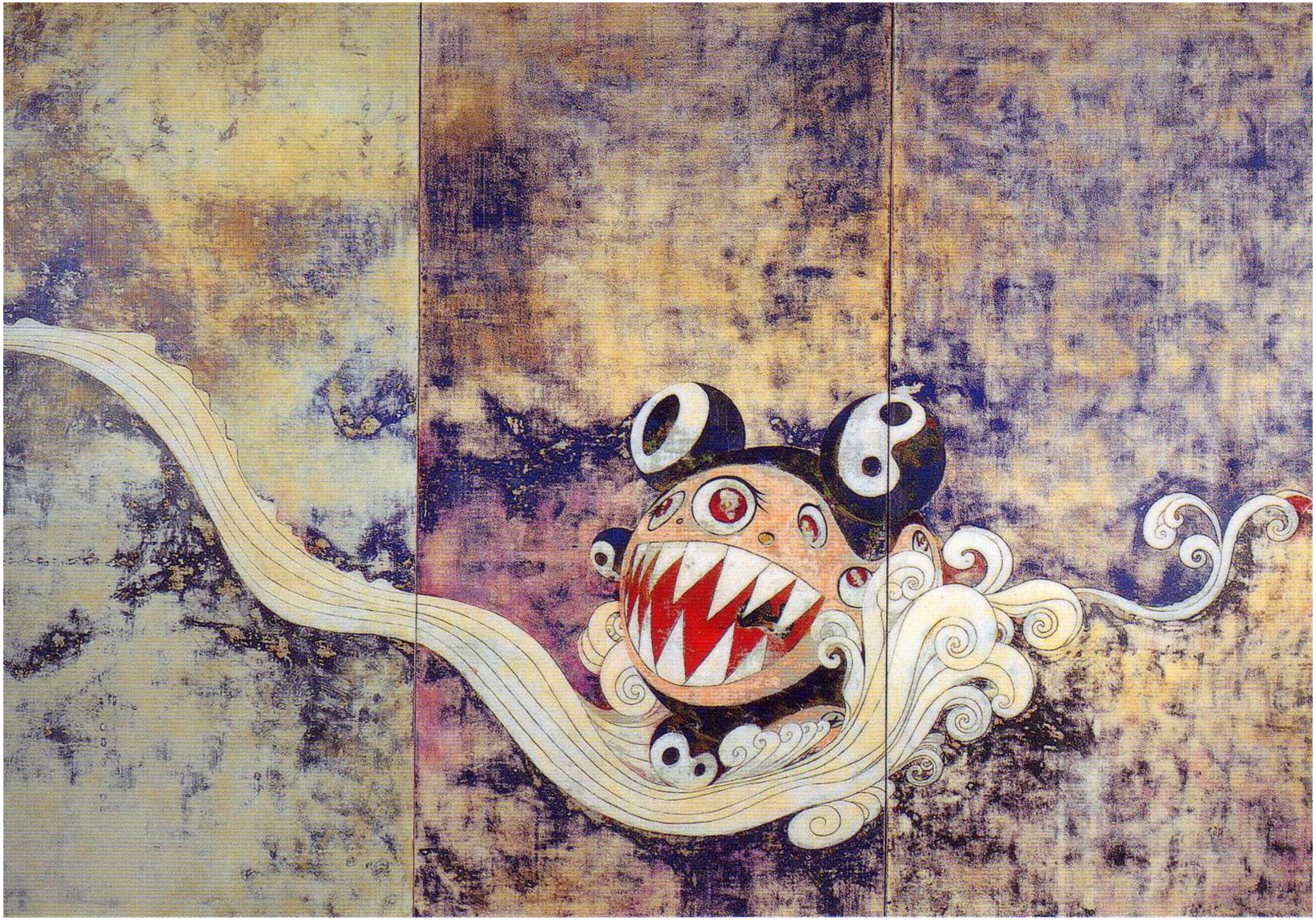


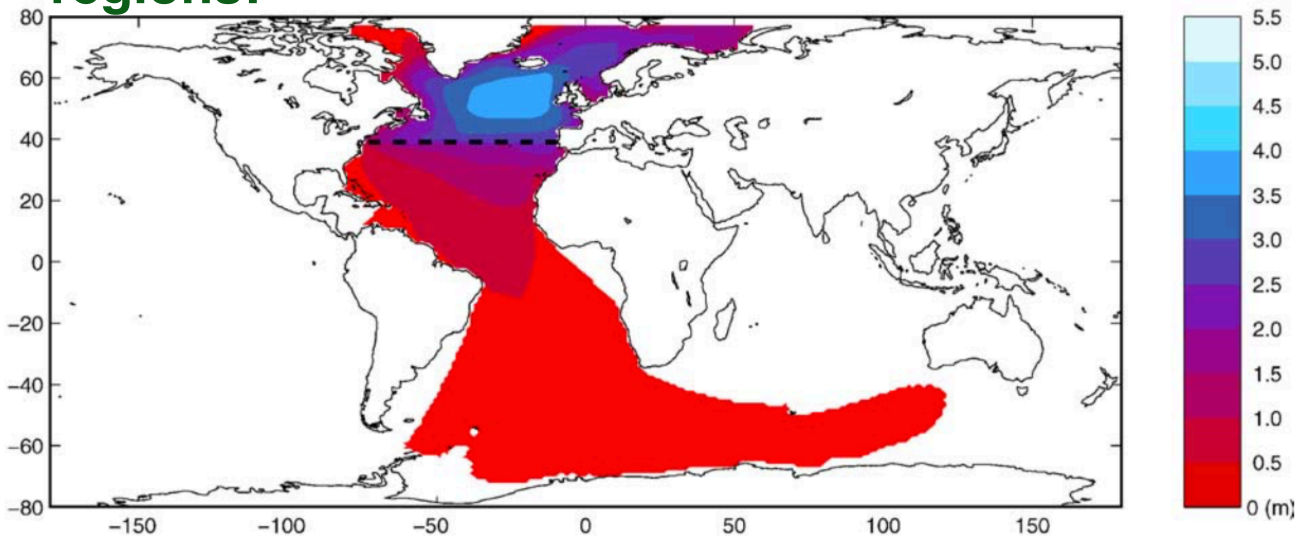
Figure: A modern reinterpretation of Hokusai's "The Great Wave" (Murakami, "727").

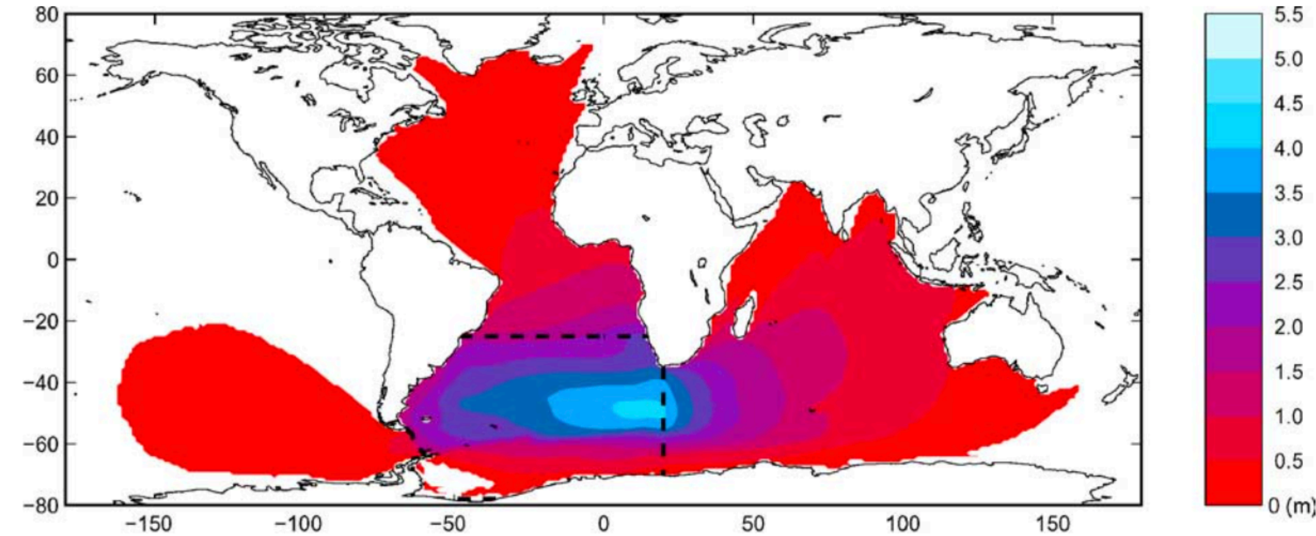
Role of swell in Tropical North Atlantic Ocean

Alves, 2006 - *Numerical modeling of ocean swell contributions to the global wind-wave climate (Ocean Modelling)*

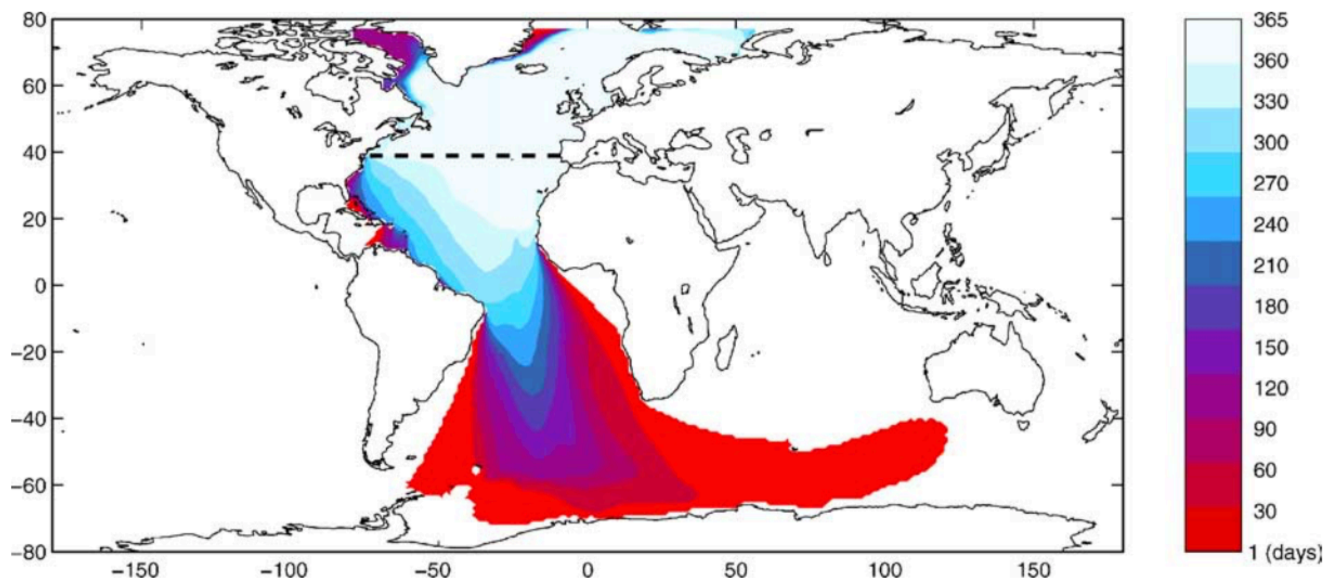
- Analyzes swell contribution to global wind-wave climate using numerical wave model

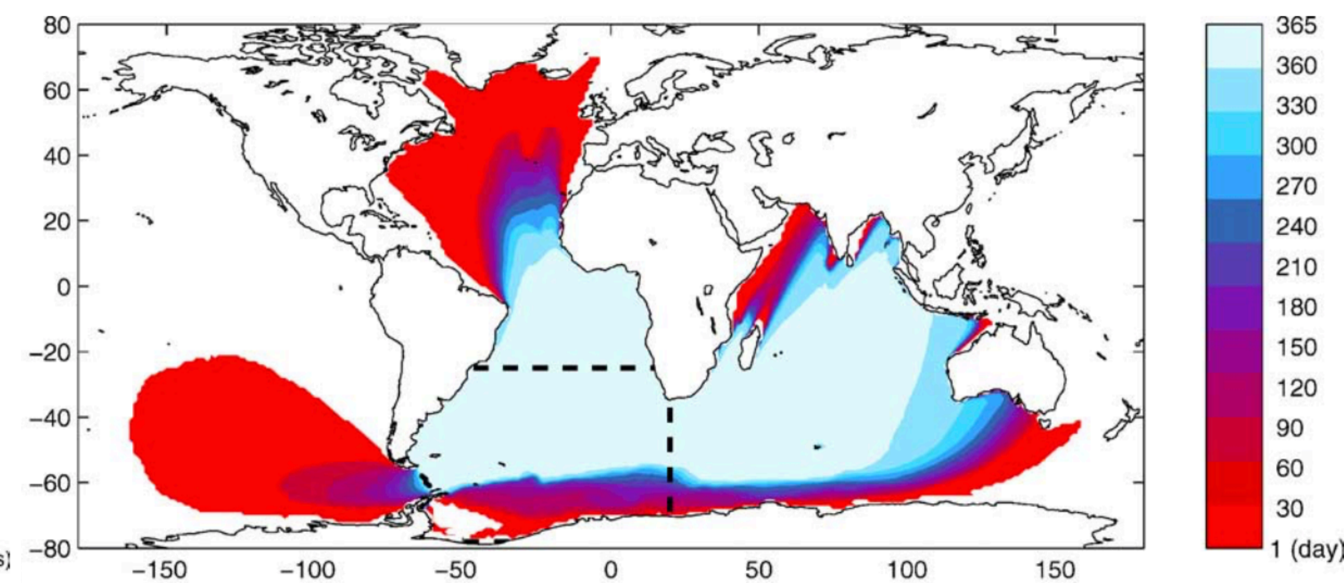
Global fields of annual mean Hs (year 2000) originating from selected regions:





Global fields of persistence of waves originating from selected regions:



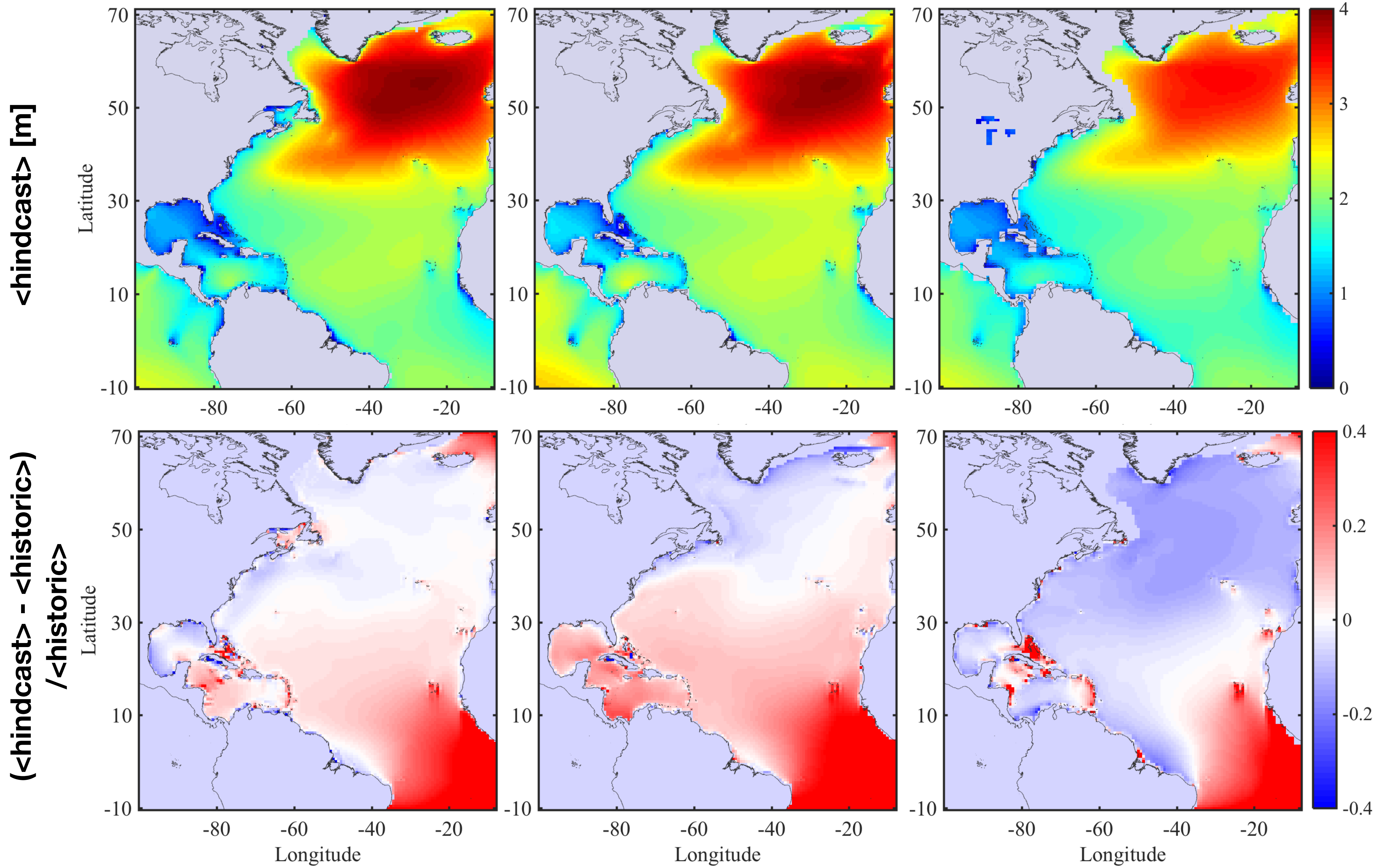


Inter-model comparison

Wave model	Resolution [km/lat]	Output frequency	Wind product	Resolution [km/lat]	Output frequency	Source
NWA-n1	62.4	1 hr	MRI-AGCM 3.2S	20.8	1 hr	KyotoU
NWA-n2	20.8	1 hr	MRI-AGCM 3.2S	20.8	1 hr	KyotoU
NWA-n3	6.9	1 hr	MRI-AGCM 3.2S	20.8	1 hr	KyotoU
JRA-55	62.4	1 hr	JRA-55	62.4	6 hr	KyotoU
CFSR-n1	55.5	3 hr	CFSR	34.6	1 hr	NCEP
CFSR-n2	18.5	3 hr	CFSR	34.6	1 hr	NCEP
CFSR-n3	7.4	3 hr	CFSR	34.6	1 hr	NCEP
ERA-I	83.2	6 hr	ERA-Interim	**	**	ECMWF

Inter-model comparison : SWH climatology (25 years)

JRA-55 (62.4 km) | **CFSR-n1 (55.5 km)** | **ERA-I (83.2 km)**



Inter-model comparison : SWH total annual mean