SAND2018-1502C

High Resolution Wave modeling for Characterizing Wave Energy Resources along the U.S East Coast

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Motivation

- The global need to diversify energy portfolios, expand energy supplies and reduce carbon emissions
- Renewable energy supplied by ocean waves and swells can be converted to electricity using an assortment of technologies known as wave energy converters (WEC)
- The potential wave energy resource for the United States is about ten-percent of the global resource
- Resource characterization and assessment is an important first step to develop this wave energy resource potential and it supports a broad range of regional planning, project development and WEC design activities

Annual average wave power density along the East, Gulf, and West Coasts (EPRI 2011)

Objectives

- Preparing a long-term modeling database for waves along the East Coast based on a high spatial resolution computational mesh that is sufficient for high accuracy wave resource characterization

- Thorough calibration and verification of the model based on the 6 IEC parameters calculated at the location of coastal and offshore buoys and consistent with the test bed study along the Oregon Coast

- Presenting desired quantities including 6 IEC parameters and partitioned spectra at different locations and along the shoreline

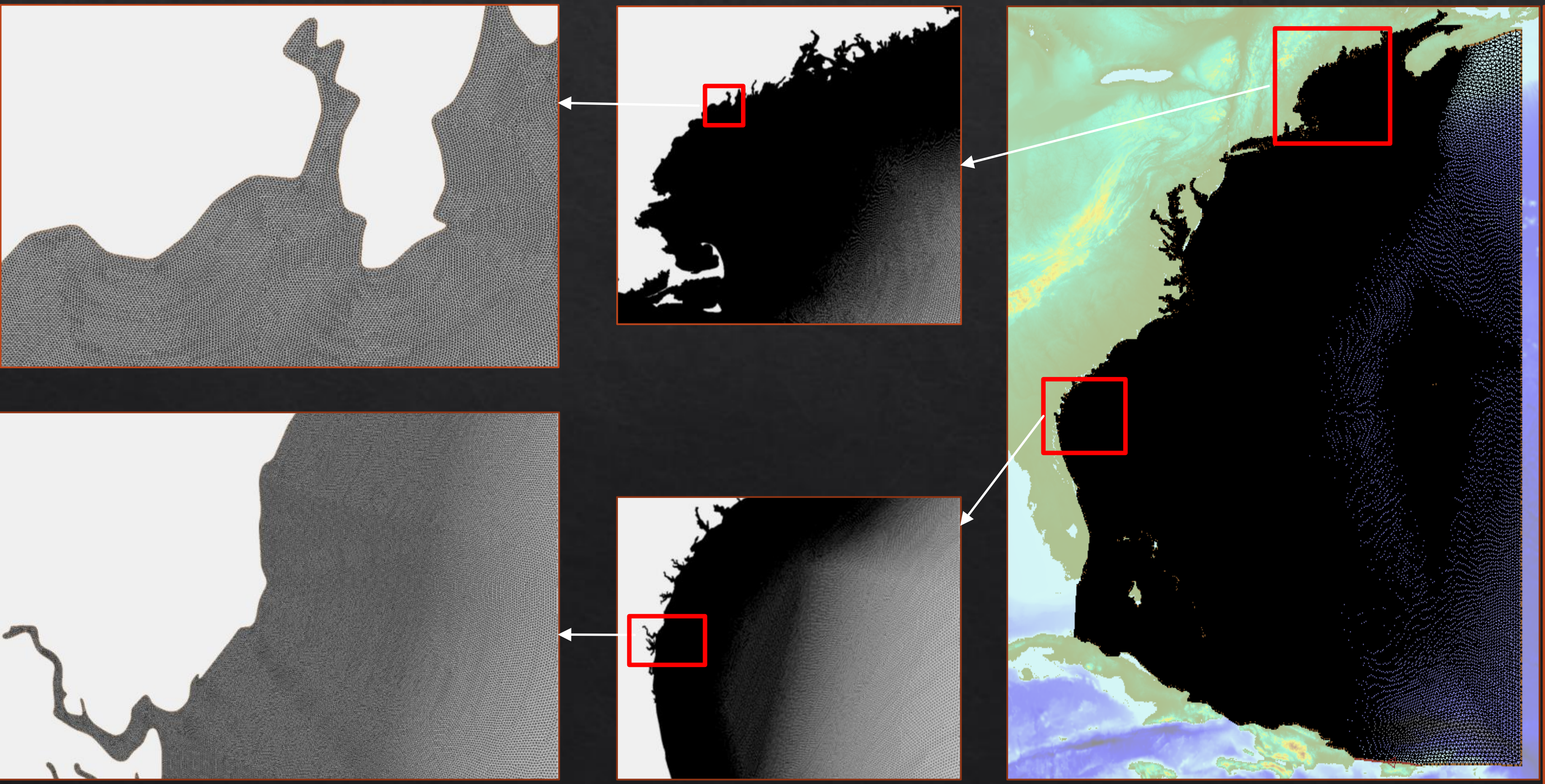
Buoy data

- 18 NDBC buoys
- Both coastal and offshore
- All measured wave parameters including H_s, T_p, and T_{02}
- Only 7 of them measure directional spectra

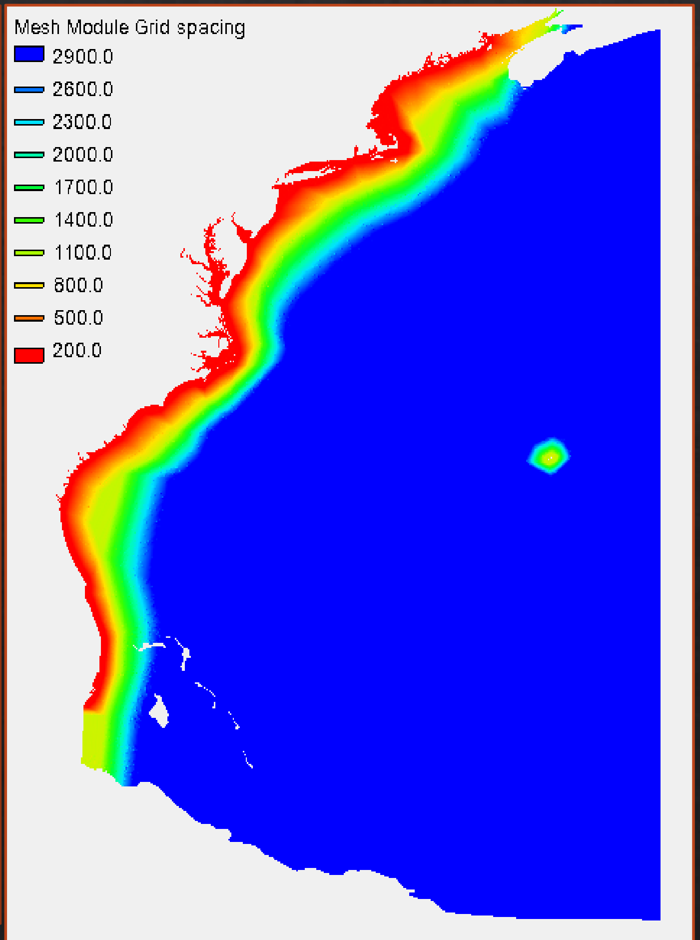
Buoy	Depth(m)	Description	Longitude	Latitude
41002	3980	SOUTH HATTERAS - 225 NM South of Cape Hatteras	-74.840	31.76
41004	38.4	EDISTO - 41 NM Southeast of Charleston, SC	-79.099	32.501
41008	18.288	GRAYS REEF - 40 NM Southeast of Savannah, GA	-80.868	31.4
41010	888	CANAVERAL EAST - 120NM East of Cape Canaveral	-78.45	28.884
41013	23.5	Frying Pan Shoals, NC	-77.743	33.436
41025	68.3	Diamond Shoals, NC	-75.402	35.006
41047	5283	NE BAHAMAS - 350 NM ENE of Nassau, Bahamas	-71.479	27.485
41048	5340	WEST BERMUDA - 240 NM West of Bermuda	-69.590	31.86
44005	180.7	GULF OF MAINE - 78 NM East of Portsmouth, NH	-69.128	43.201
44007	26.5	PORTLAND 12 NM Southeast of Portland, ME	-70.141	43.525
44008	74.7	NANTUCKET 54NM Southeast of Nantucket	-69.248	40.504
44009	43	DELAWARE BAY 26 NM Southeast of Cape May, NJ	-74.703	38.461
44011	82.9	GEORGES BANK 170 NM East of Hyannis, MA	-66.619	41.098
44013	64.5	BOSTON 16 NM East of Boston, MA	-70.651	42.346
44017	52.4	MONTAUK POINT - 23 NM SSW of Montauk Point, NY	-72.048	40.694
44018	217.3	CAPE COD - 24 NM East of Provincetown, MA	-69.7	42.119
44025	40.8	LONG ISLAND - 30 NM South of Islip, NY	-73.164	40.251
44027	178.6	Jonesport, ME - 20 NM SE of Jonesport, ME	-67.307	44.287

Computational mesh

- Unstructured SWAN
- coastal resolution (within 20 km distance from the shoreline) : 200 meters
- Resolution along the offshore boundaries 10-15 km
- over 4,300,000 grid points

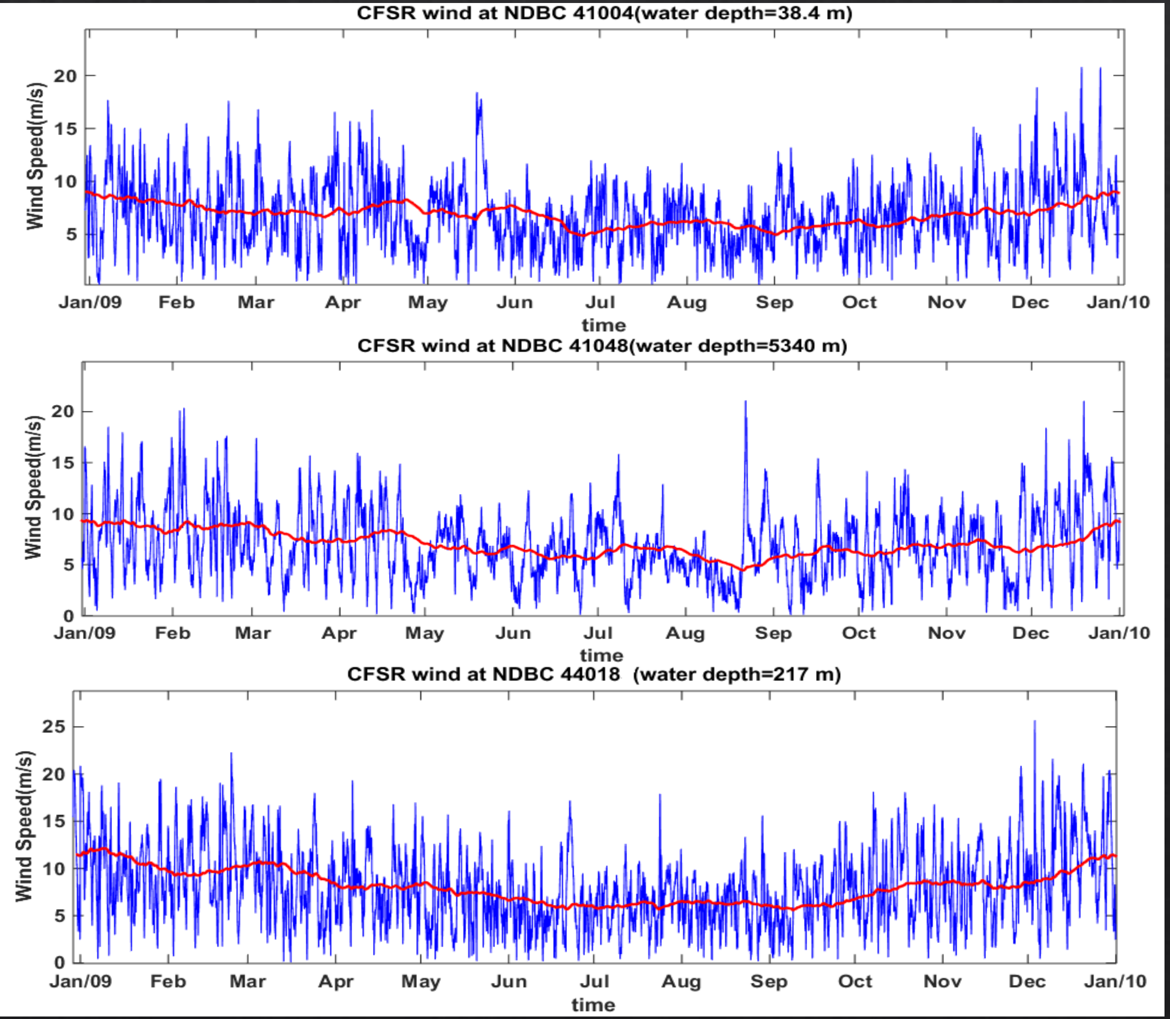


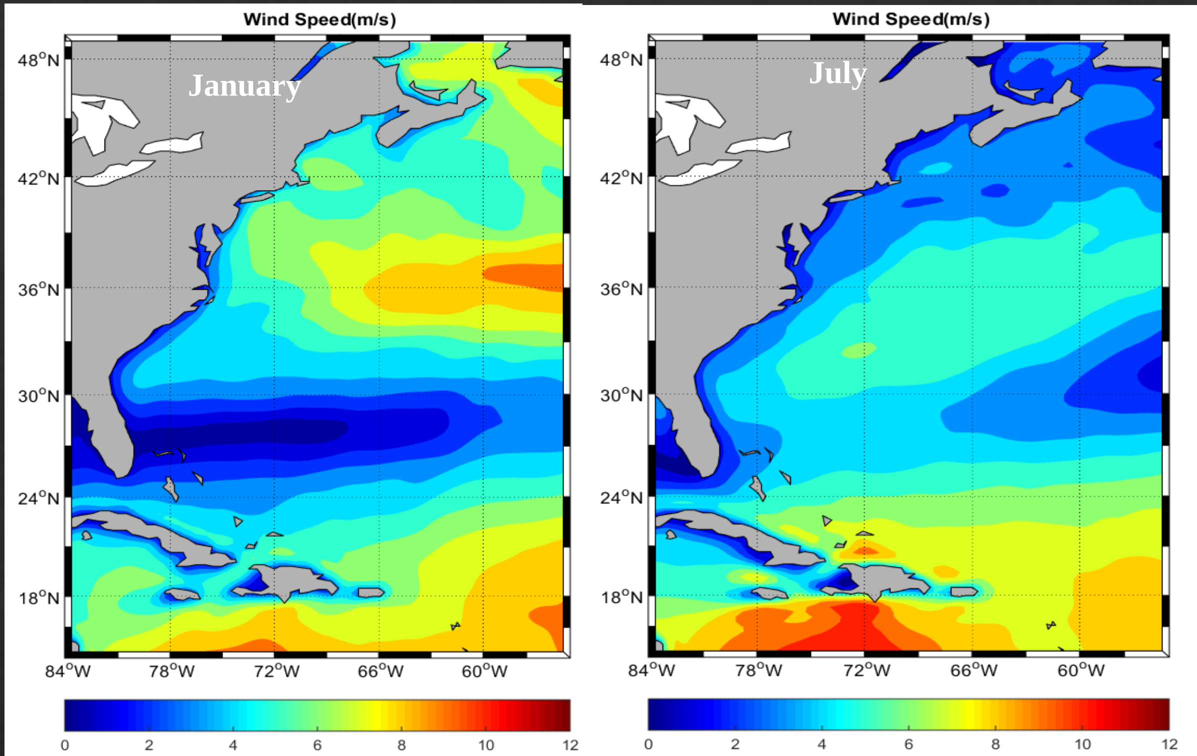
Map of spatial resolution

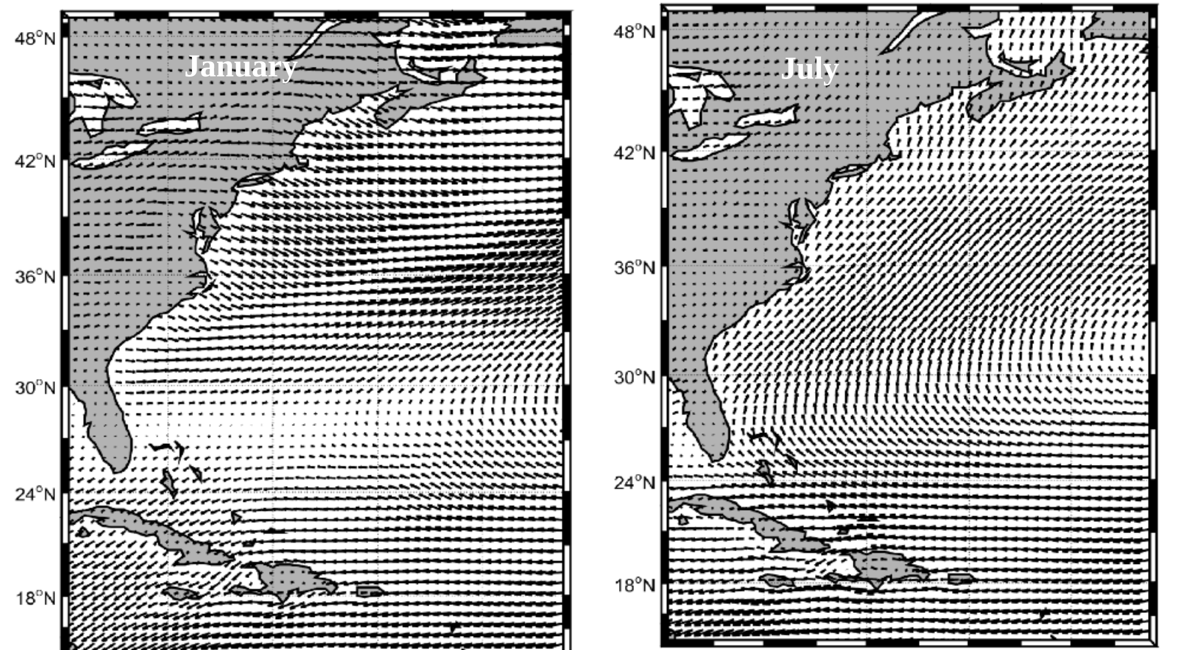


Wind Field

- Climate Forecast System Reanalysis (CFSR)
- Spatial resolution: 0.312 °
- Temporal resolution: 1 hour
- Seasonality

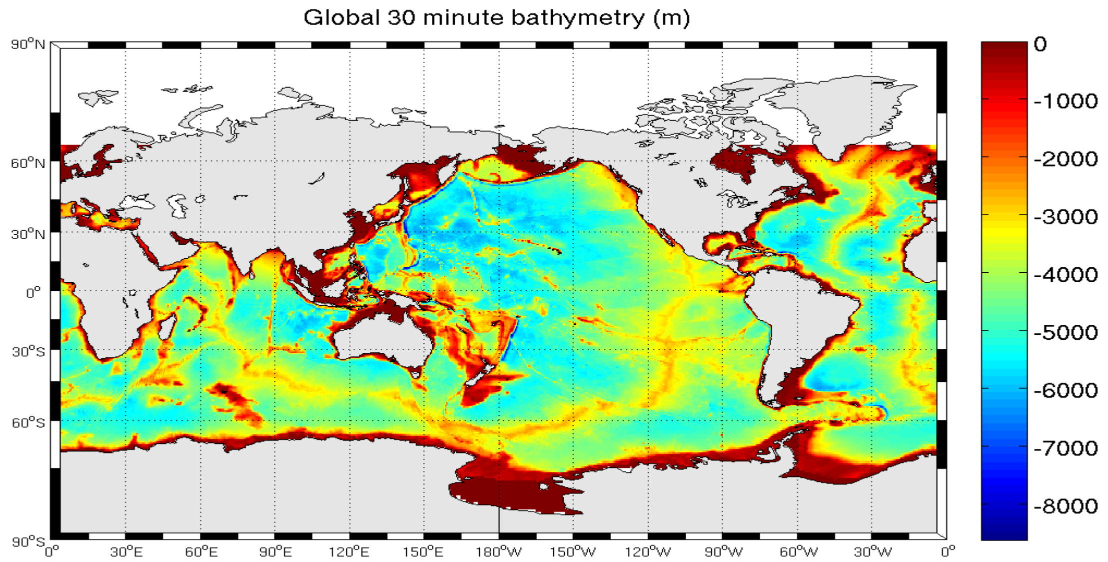


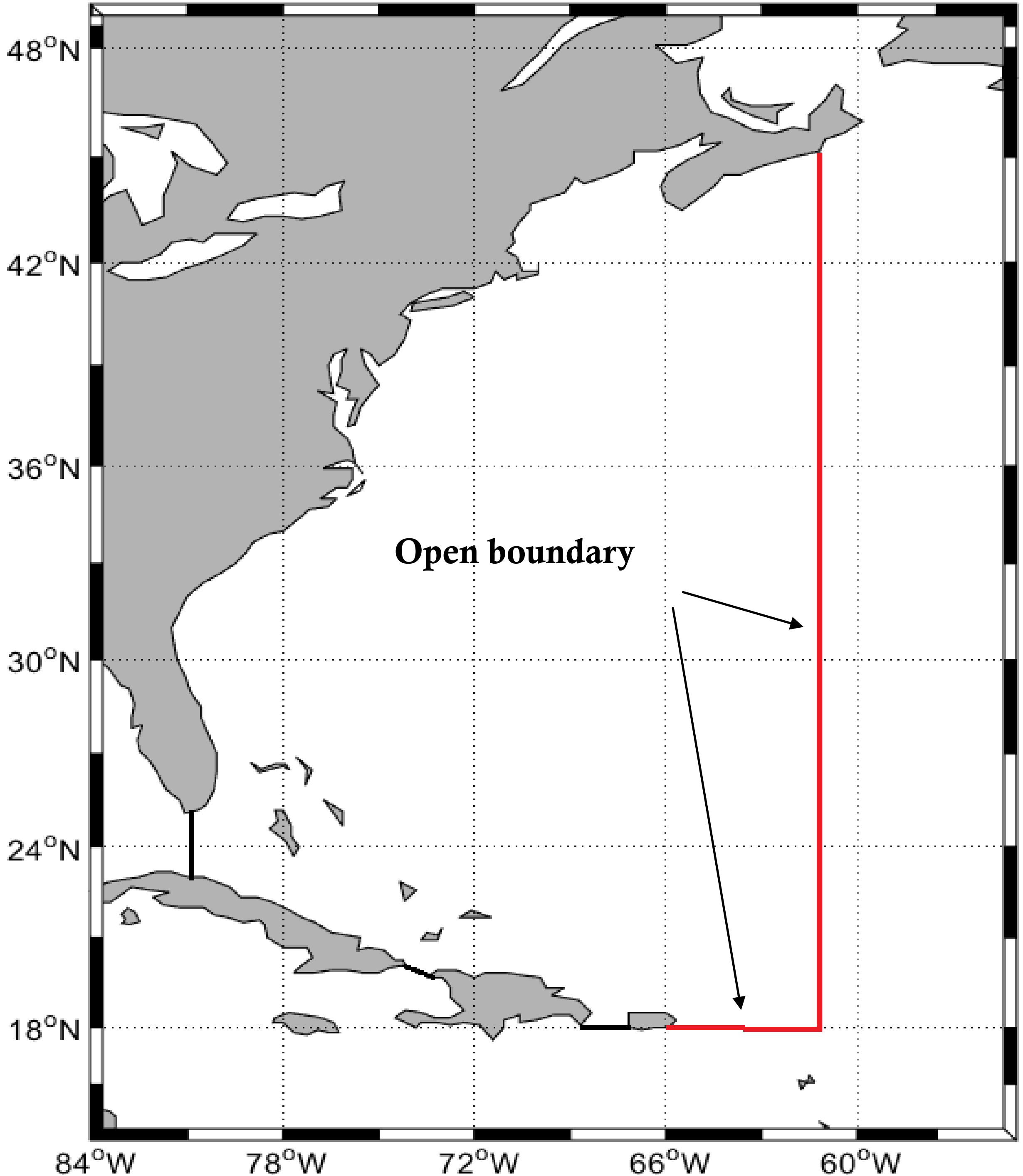




Boundary Conditions

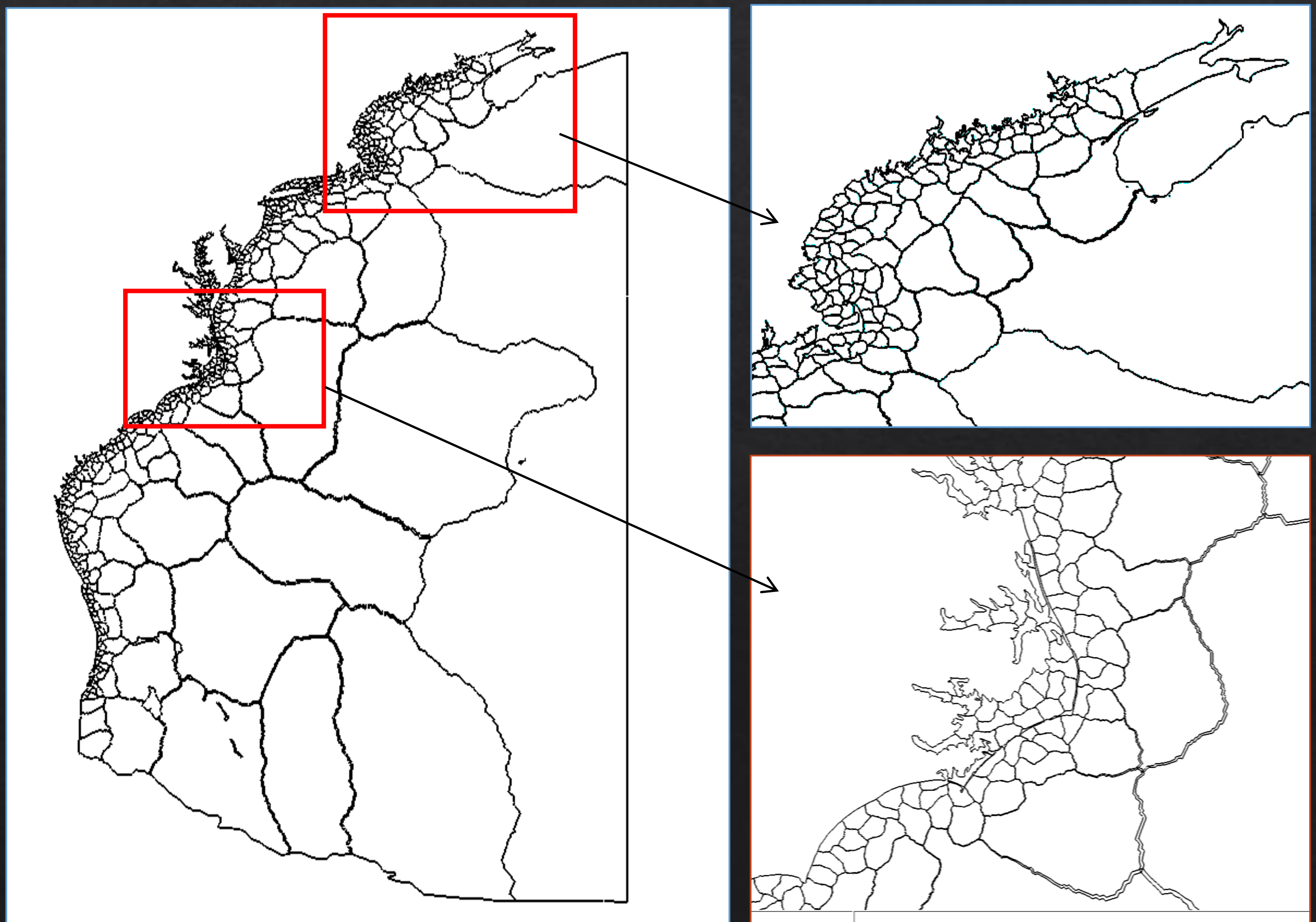
- Global WWIII model implemented by NOAA (http://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php)
- Spatial resolution: 0.5 °
- Temporal resolution: 3 hours
- Physics package : ST4
- Wave parameters including height, peak period, and direction were prescribed along open boundaries





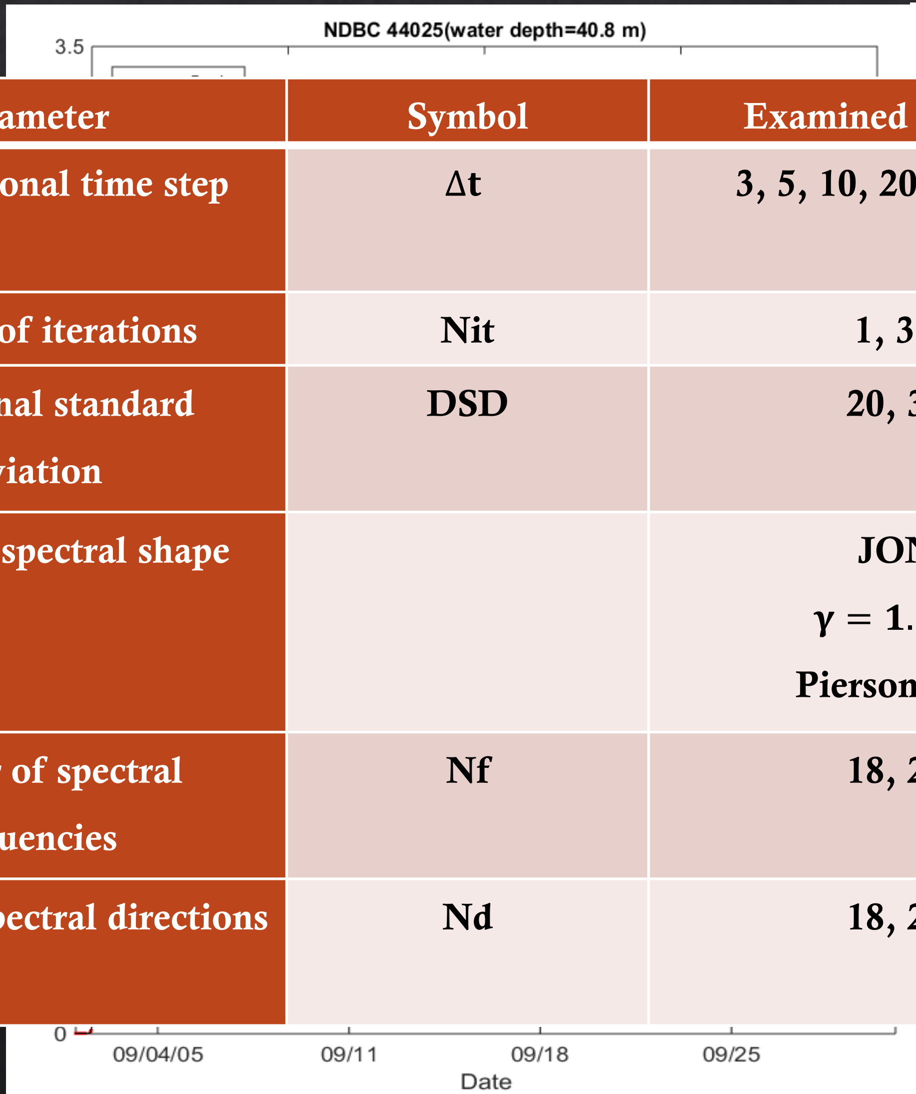
Model run

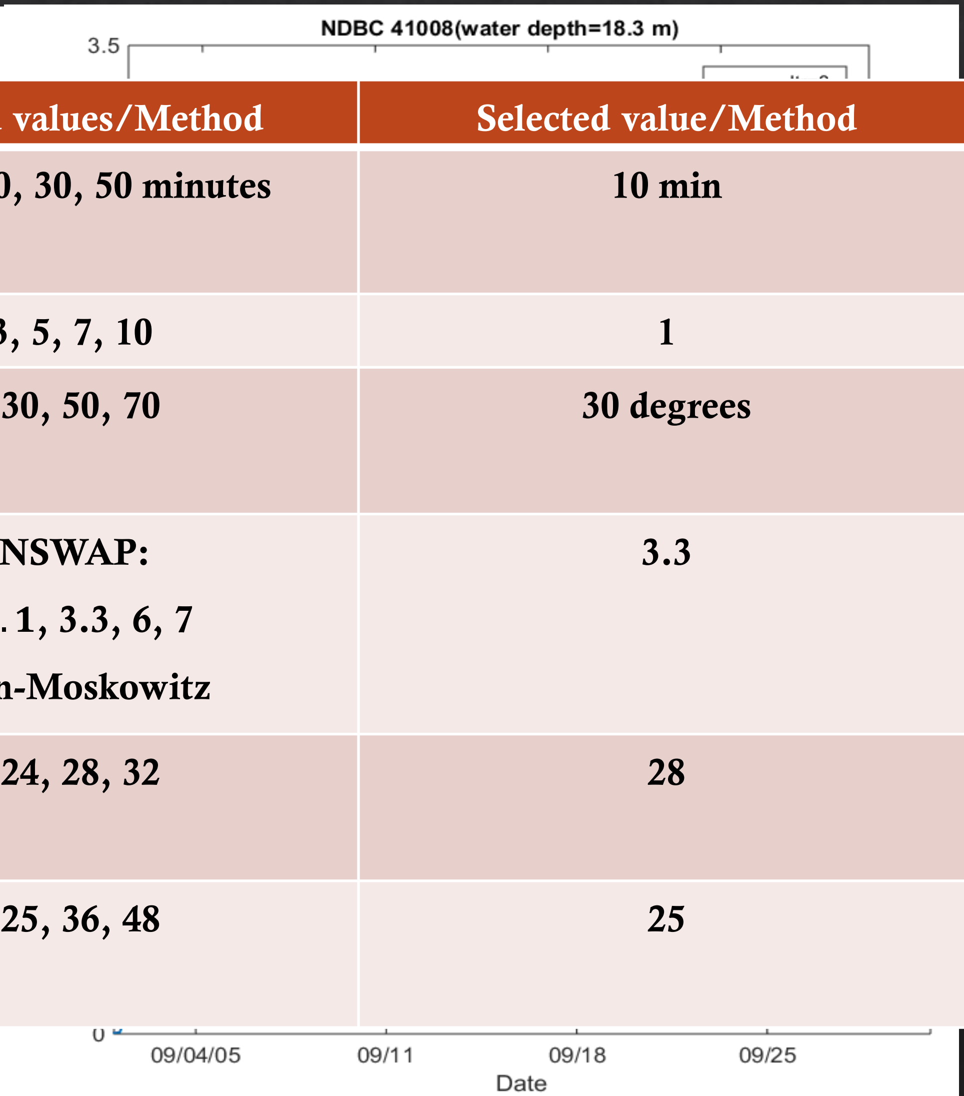
- 4,396,138 grid points
- 496 cores on the Sandia SkyBridge cluster~ 8700 node for each core
- Each month of simulation took about 6 hours



Model Sensitivity analysis

- Several model parameters are site or scale specific
- Regional wind and wave climate may be important





Parameter	Symbol	Examined values/Method	Selected value/Method
Computational time step	Δt	3, 5, 10, 20, 30, 50 minutes	10 min
Number of iterations	Nit	1, 3, 5, 7, 10	1
Directional standard deviation	DSD	20, 30, 50, 70	30 degrees
Frequency spectral shape		JONSWAP: $\gamma = 1.1, 3.3, 6, 7$ Pierson-Moskowitz	3.3
Number of spectral frequencies	Nf	18, 24, 28, 32	28
Number of spectral directions	Nd	18, 25, 36, 48	25

Model Calibration

Whitecapping dissipation and the associated parameters were used

Komen-type approaches (mean spectral parameters)
Komen(1984) and Janssen(1991)

$$S_{ds,w}(\sigma,\theta) = -\Gamma\tilde{\sigma}\,\frac{k}{\tilde{k}}E(\sigma,\theta)$$

$$\Gamma = C_{ds}\left((1-\delta)+\delta\frac{k}{\tilde{k}}\right)\left(\frac{\tilde{S}}{\tilde{S}_{PM}}\right)^{p}$$

$$\tilde{S}_{PM} = (3.02\times10^{-3})^{1/2}$$

$$\tilde{S} = \tilde{k}\sqrt{E_{tot}}$$

Saturated-based approach
Van der Westhuysen(2007)

$$S_{ds,break}(\sigma,\theta) = -C_{ds}\left[\frac{B(k)}{B_r}\right]^{p/2}\,[\tanh(kd)]^{\frac{2-p_0}{4}}\,g^{\frac{1}{2}}\,k\,\frac{1}{2}\,E(\sigma,\theta)$$

$$S_{ds,w}(\sigma,\theta) = f_{br}(\sigma)S_{ds,break} + [1-f_{br}(\sigma)]S_{ds,non-break}$$

$S_{ds,non-break}$

accounts for dissipation by turbulence and short-wave-long-wave interaction

Three 1-month time periods were used for model calibration / measured waves at 18 NDBC buoys
different whitecapping formulations and different sets of parameters were examined

Janssen(1991) C_{ds}=2.7 δ=0.9

Model verification

Model performance metrics

$$R = \frac{\sum_{i=1}^{N}(M_i-\bar{M})(P_i-\bar{P})}{\sqrt{(\sum_{i=1}^{N}(M_i-\bar{M})^2)(\sum_{i=1}^{N}(P_i-\bar{P})^2)}}$$

$$bias(P) = \frac{\sum_{i=1}^{N}(P_i-M_i)}{N}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i-M_i)^2}{N}}$$

$$SI = \frac{RMSE}{\bar{M}}$$

M: measurement P: model prediction

IEC parameters

Significant wave height H_s

Energy period T_e

Omnidirectiona wave power $J = \rho g \sum_{i,j} c_{g,i}\ S_{ij}\Delta f_i \Delta\theta_j$ $[\frac{kW}{m}]$

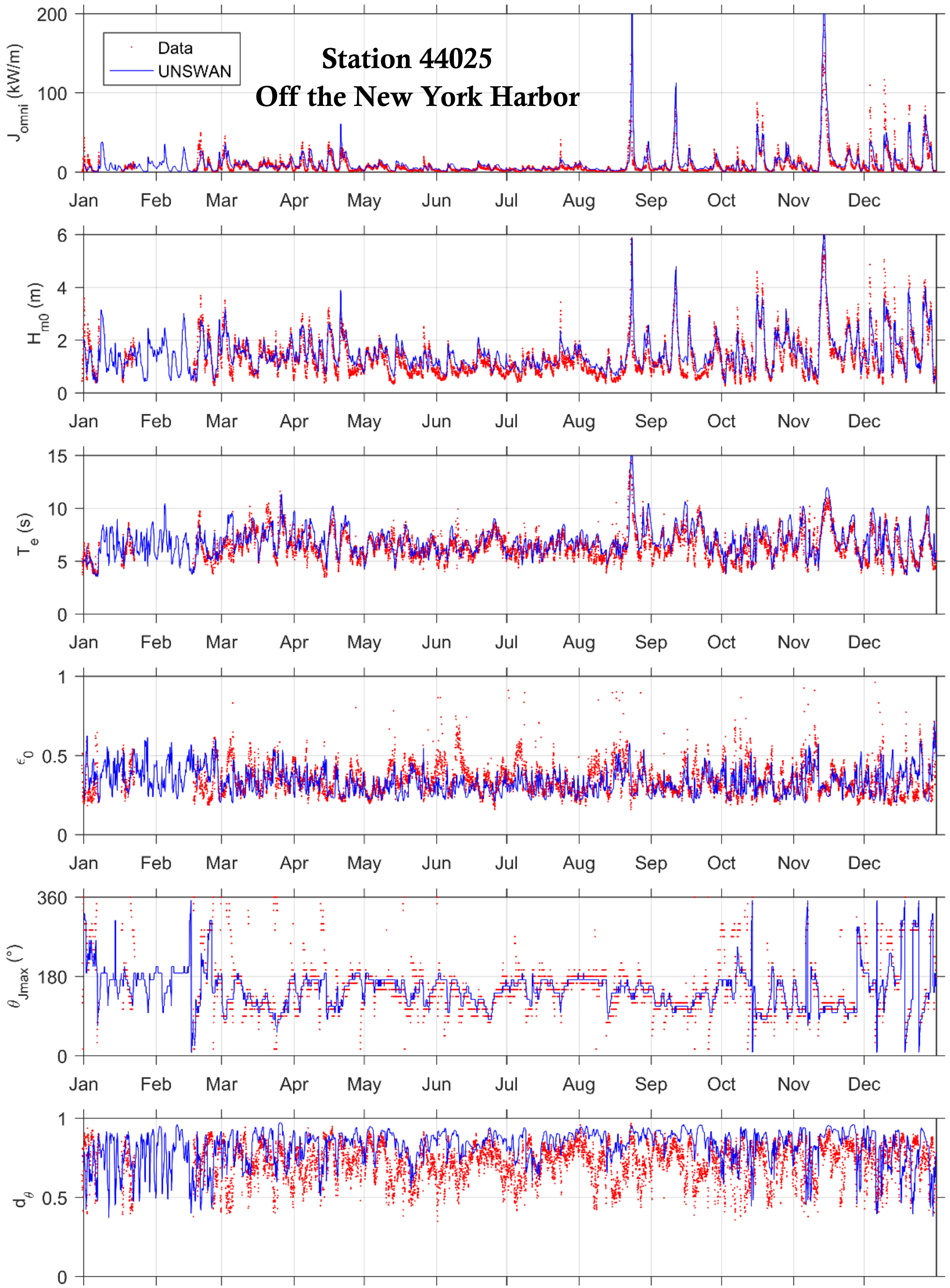
Directional resolved wave power $J_\theta = \rho g \sum_{i,j} c_{g,i}\ S_{ij}\Delta f_i \Delta\theta_j\ \cos(\theta-\theta_l)\,\delta$ $[\frac{kW}{m}]$

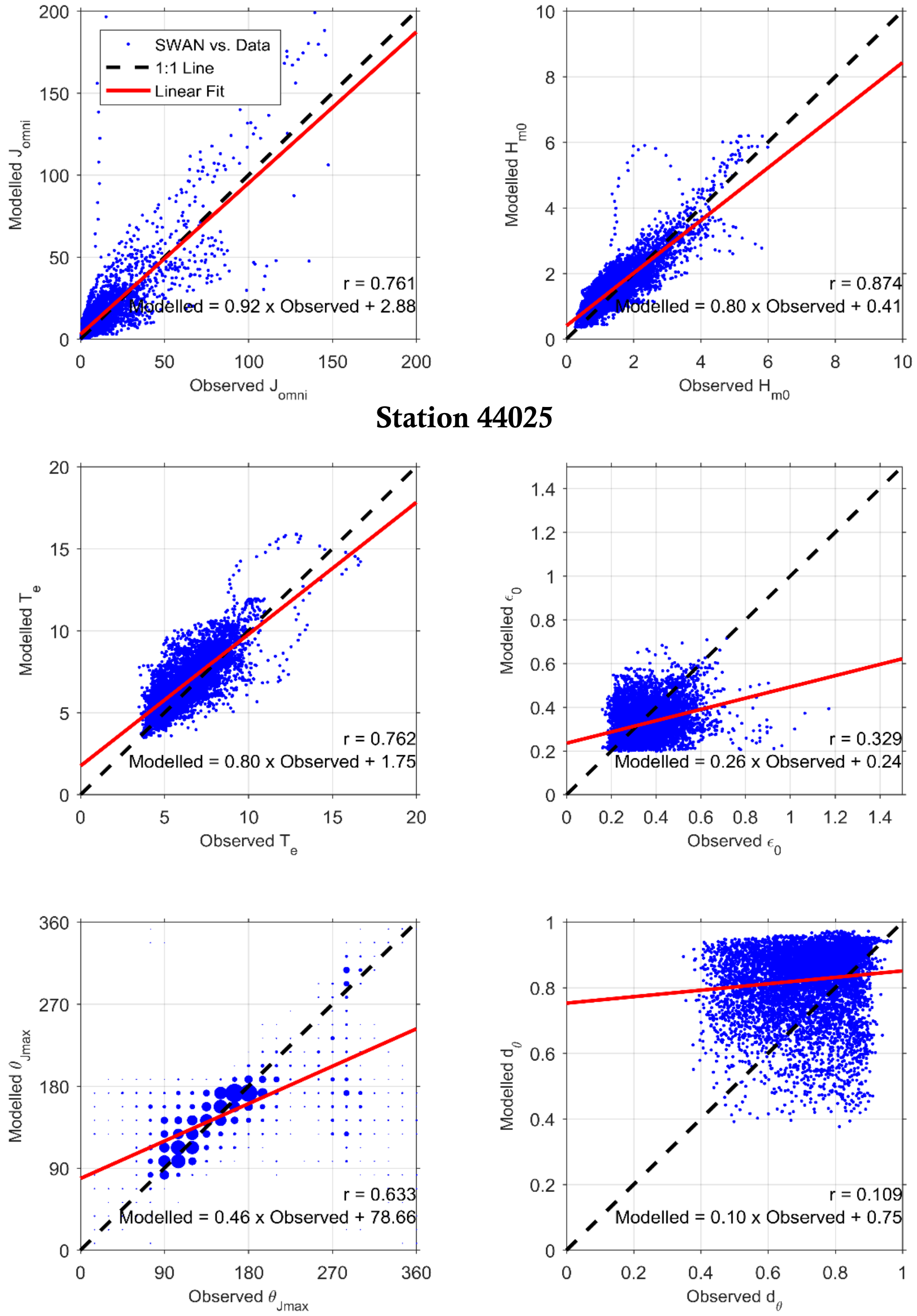
Direction of max power θ_{Jmax}

Directionally coefficient $d = \frac{J_{\theta_{Jmax}}}{J}$

i,j : number of spectral frequencies and directions, respectively

3-year verification from 2007 to 2009


Station 44025
Off the New York Harbor
Data
UNSWAN
J_{omni} (kW/m)
H_{m0} (m)
T_e (s)
ϵ_0
θ_{Jmax} (°)
d_θ
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


SWAN vs. Data
1:1 Line
Linear Fit
Station 44025
Modelled J_{omni}
Observed J_{omni}
r = 0.761
Modelled = 0.92 x Observed + 2.88
Modelled H_{m0}
Observed H_{m0}
r = 0.874
Modelled = 0.80 x Observed + 0.41
Modelled T_e
Observed T_e
r = 0.762
Modelled = 0.80 x Observed + 1.75
Modelled ϵ_0
Observed ϵ_0
r = 0.329
Modelled = 0.26 x Observed + 0.24
Modelled θ_{Jmax}
Observed θ_{Jmax}
r = 0.633
Modelled = 0.46 x Observed + 78.66
Modelled d_θ
Observed d_θ
r = 0.109
Modelled = 0.10 x Observed + 0.75

Model performance metrics at selected stations

Buoy	Parameter	RMSE	SI	Bias	R
41013					
	Hs(m)	0.31	0.24	0.13	0.91
	Te(s)	0.92	0.15	0.45	0.79
	ϵ_0(-)	6.44	0.82	2.12	0.90
	J(kw/m)	0.07	0.20	-0.01	0.59
	$\theta_{\mathrm{Jmax(degrees)}}$	39.50	N/A	2.77	0.68
	d_θ (-)	0.14	0.19	0.07	0.37
41048	Hs(m)	0.38	0.20	0.14	0.93
	Te(s)	0.78	0.11	0.35	0.87
	ϵ_0(-)	14.94	0.85	3.53	0.88
	J(kw/m)	0.05	0.17	-0.02	0.65
	θ_{Jmax}(degrees)	39.63	N/A	0.92	0.70
	d_θ (-)	0.09	0.13	0.02	0.77
44018	Hs(m)	0.46	0.31	0.01	0.86
	Te(s)	1.13	0.17	-0.32	0.68
	ϵ_0(-)	11.07	0.98	-1.10	0.80
	J(kw/m)	0.09	0.27	0.03	0.45
	$\theta_{\mathrm{Jmax(degrees)}}$	47.57	N/A	-3.20	0.55
	d_θ (-)	0.17	0.25	0.10	0.27
44025	Hs(m)	0.40	0.30	0.15	0.87
	Te(s)	1.12	0.17	0.42	0.73
	ϵ_0(-)	10.11	1.25	2.15	0.77
	J(kw/m)	0.10	0.28	-0.03	0.44
	$\theta_{\mathrm{Jmax(degrees)}}$	43.81	N/A	-0.29	0.58
	d_θ (-)	0.19	0.26	0.11	0.11

Summary of metrics for all 18 stations

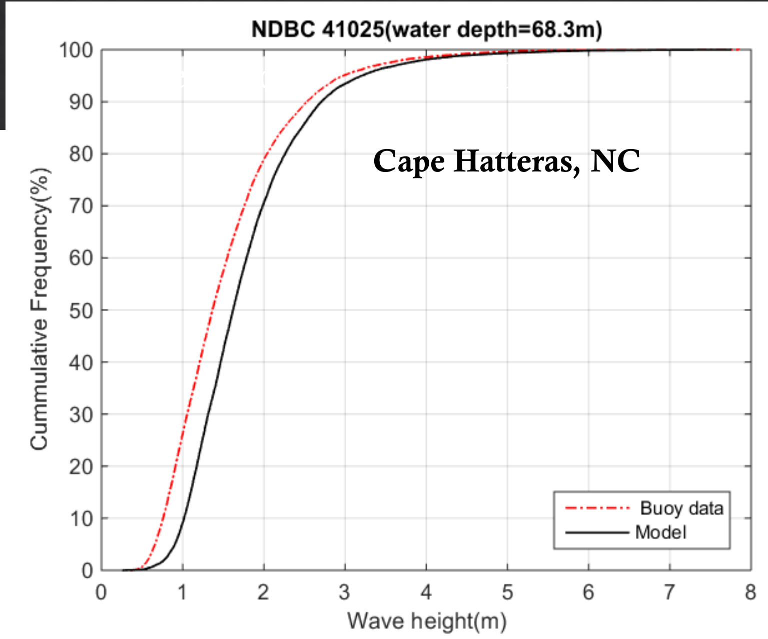
Parameter	Type of statistics	RMSE	SI	Bias	R
Hs(m)					
	Mean	0.39	0.28	0.11	0.88
	Max	0.51	0.44	0.24	0.95
	Min	0.29	0.19	0.01	0.78
Te(s)					
	Mean	1.15	0.18	0.58	0.75
	Max	1.61	0.26	0.98	0.88
	Min	0.75	0.10	0.30	0.59
J(kw/m)					
	Mean	10.51	1.05	2.06	0.83
	Max	17.71	1.75	4.54	0.93
	Min	4.70	0.68	0.04	0.73
ϵ_0(-)					
	Mean	0.08	0.25	0.02	0.47
	Max	0.13	0.36	0.03	0.65
	Min	0.05	0.17	0.00	0.22
$\theta_{\mathrm{Jmax(degrees)}}$					
	Mean	42.36	N/A	4.37	0.59
	Max	47.57	N/A	10.55	0.70
	Min	39.50	N/A	0.29	0.33
d_θ (-)					
	Mean	0.16	0.22	0.10	0.32
	Max	0.22	0.30	0.19	0.77
	Min	0.09	0.12	0.02	0.04

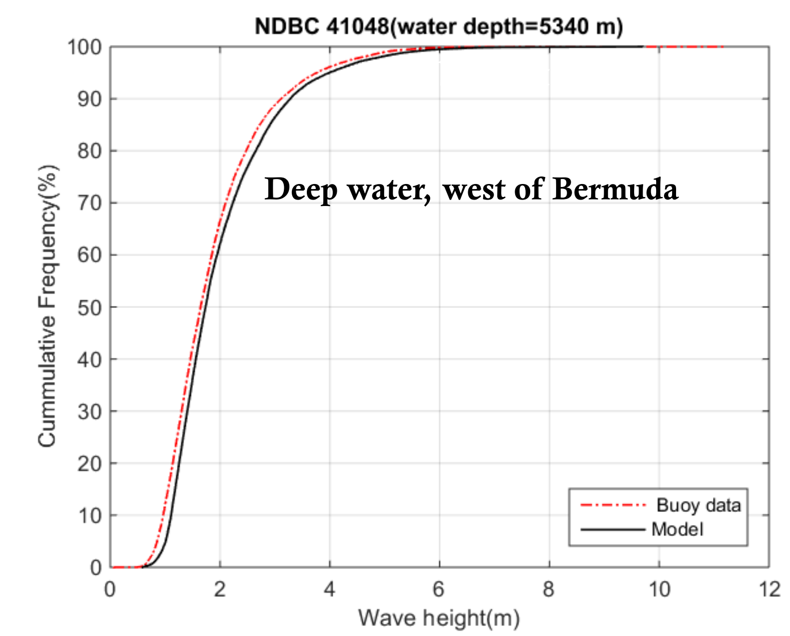
NDBC 41013- NC coastal

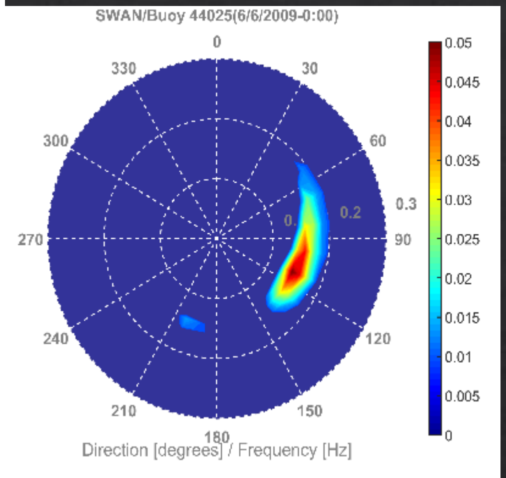
NDBC 44025- Off the NY Harbor

Model

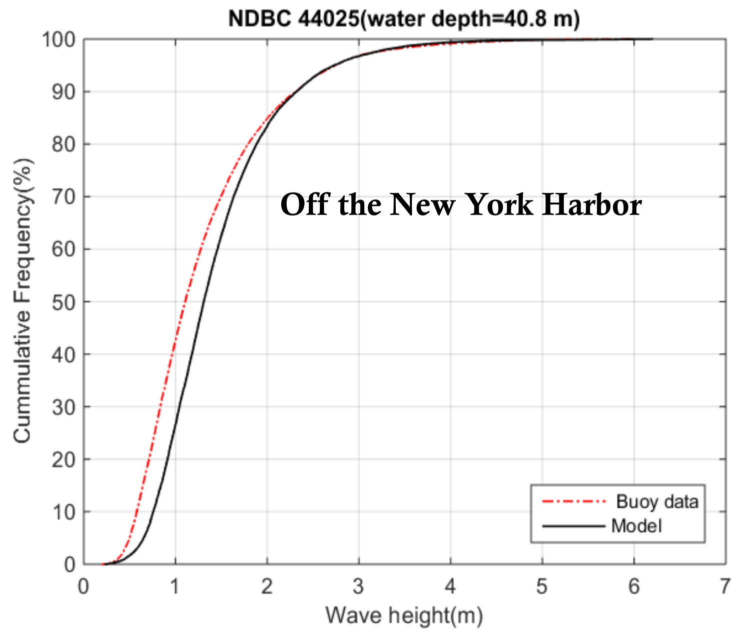
Summer

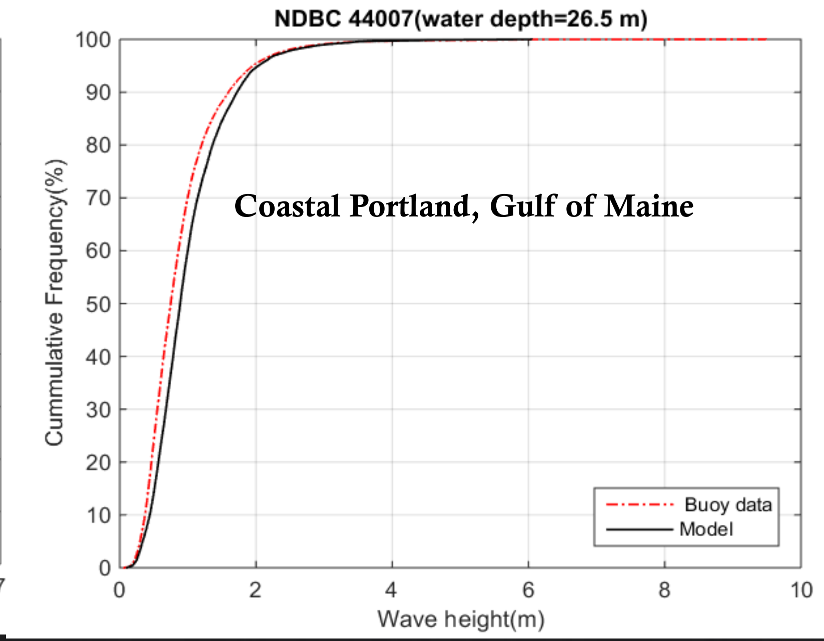


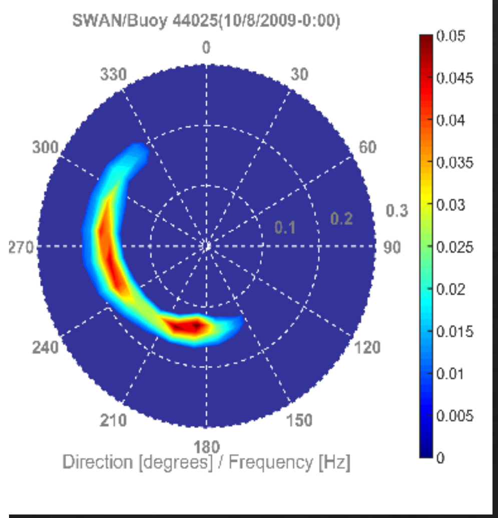




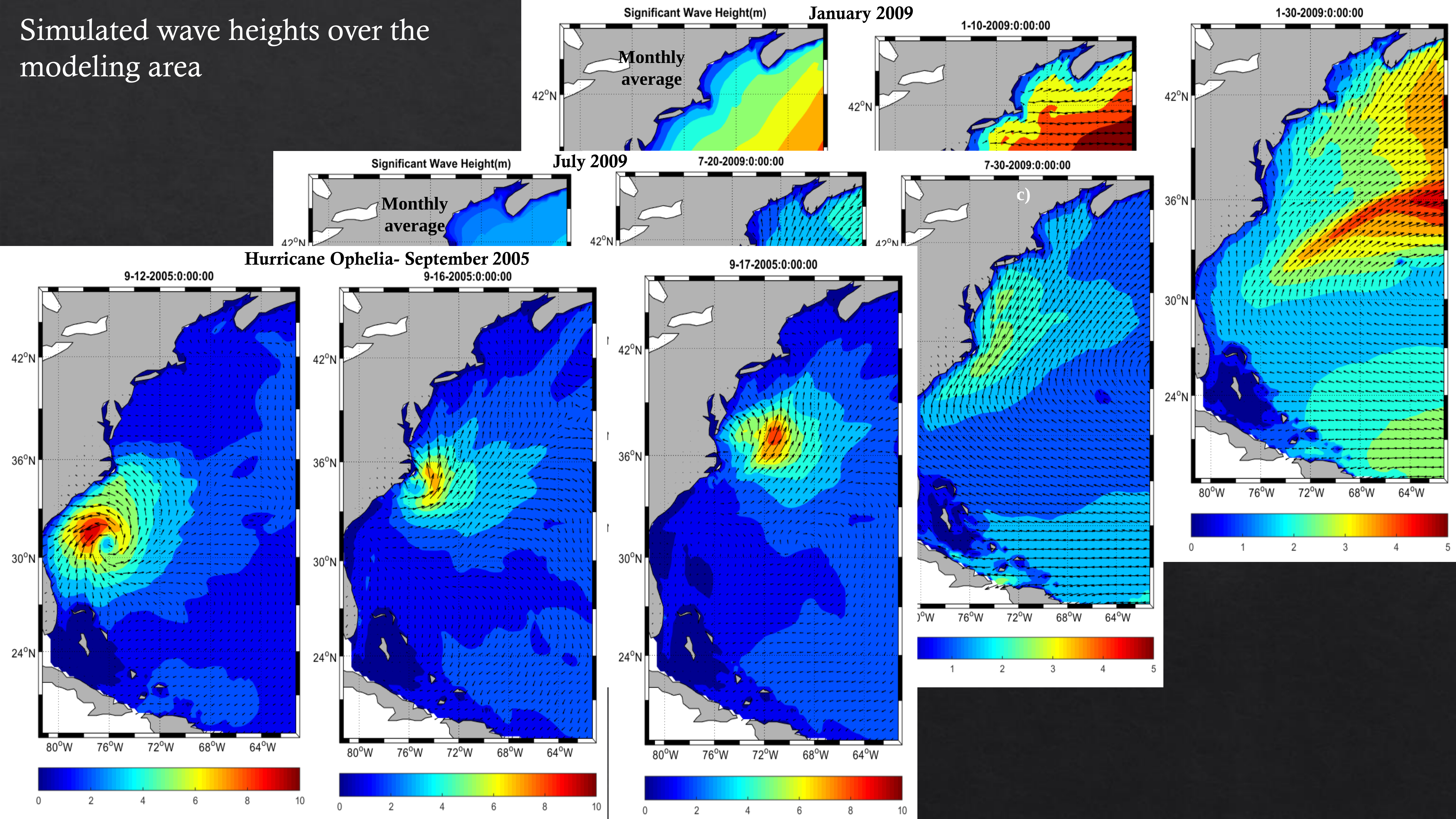
Non-Summer



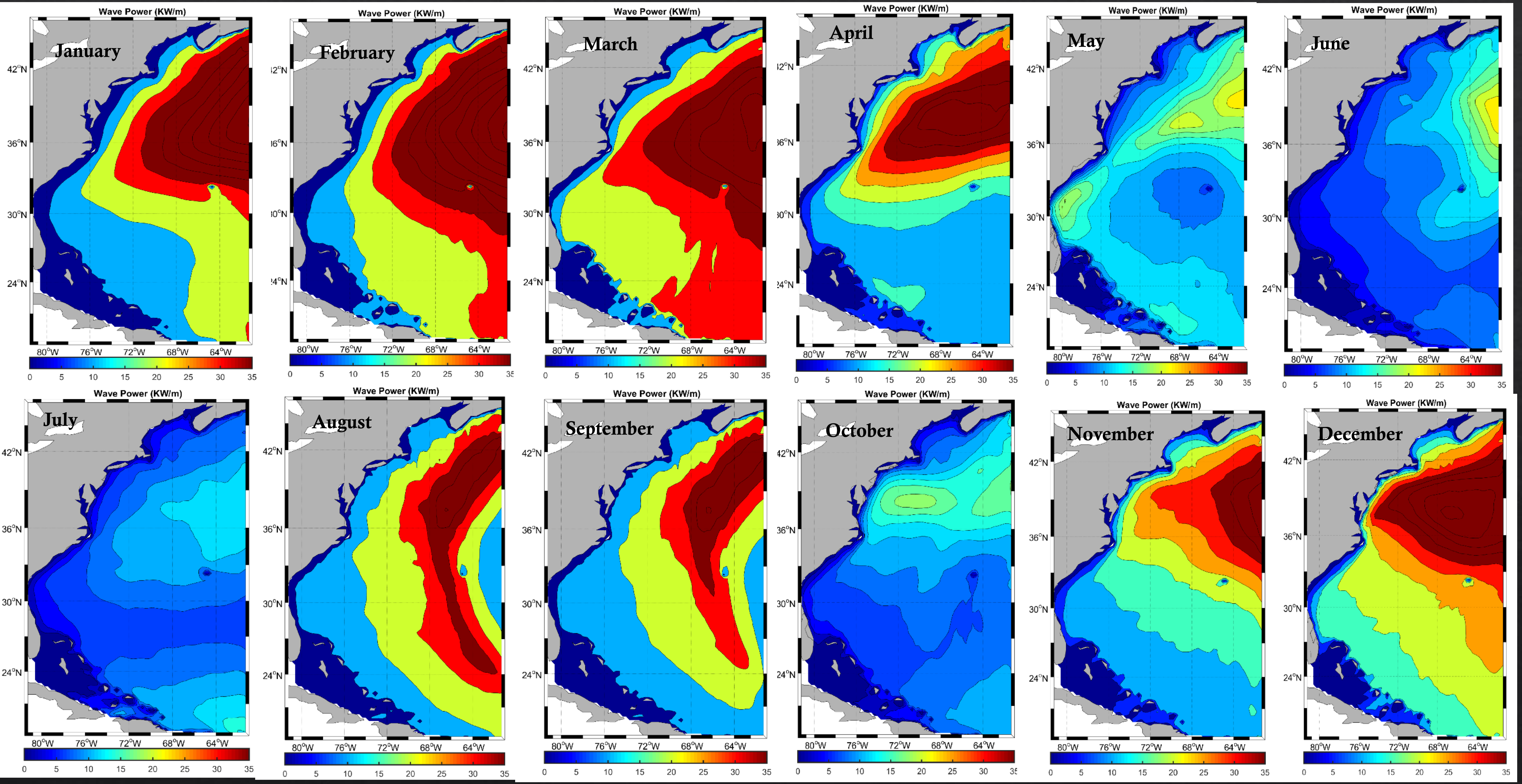




Simulated wave heights over the modeling area



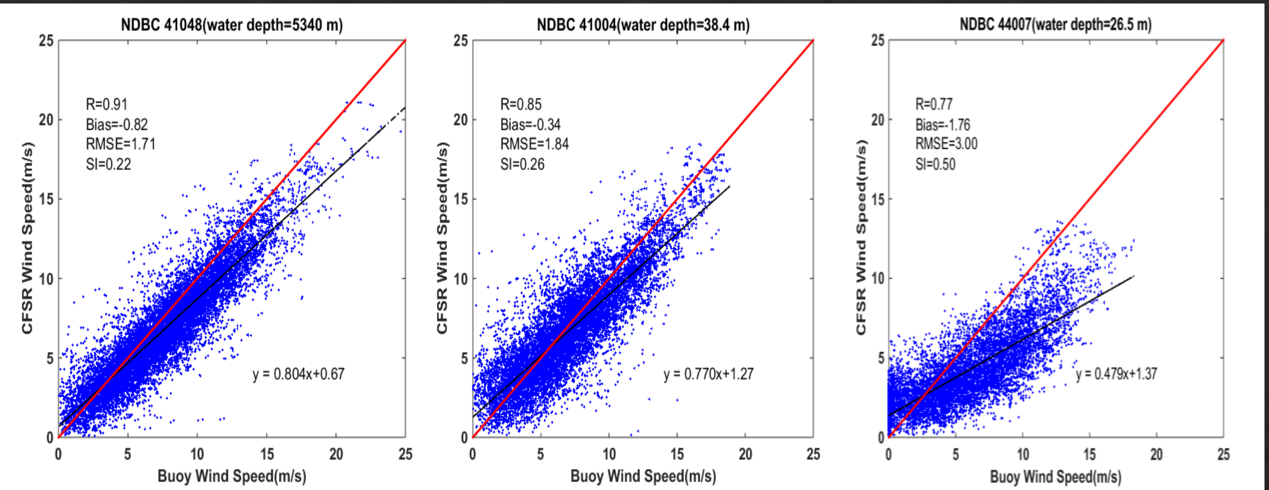
Monthly mean wave power for 2009

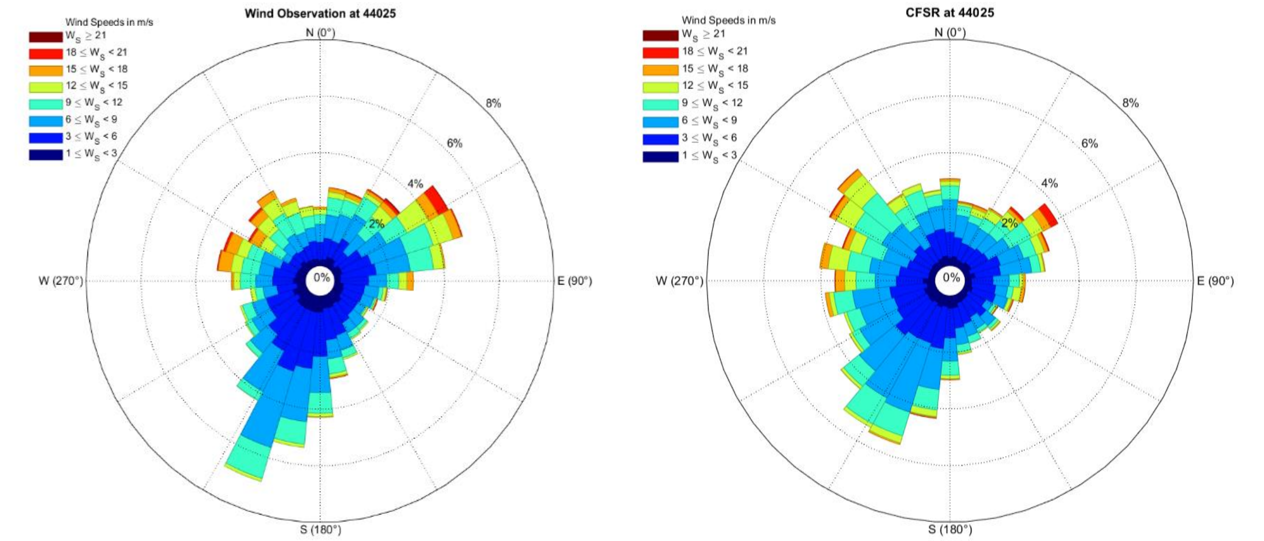


Discrepancy sources

Wind field

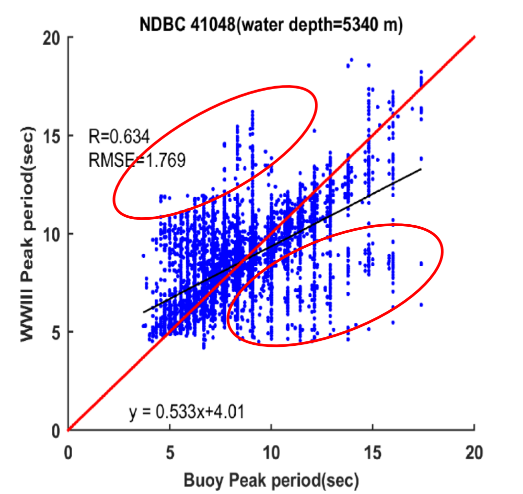
- Higher accuracy at southern buoys
- Decreasing accuracy when approaching the land
- Differences in the prevailing wind direction : 10-25° for southern and offshore buoys and more for northern coastal buoys

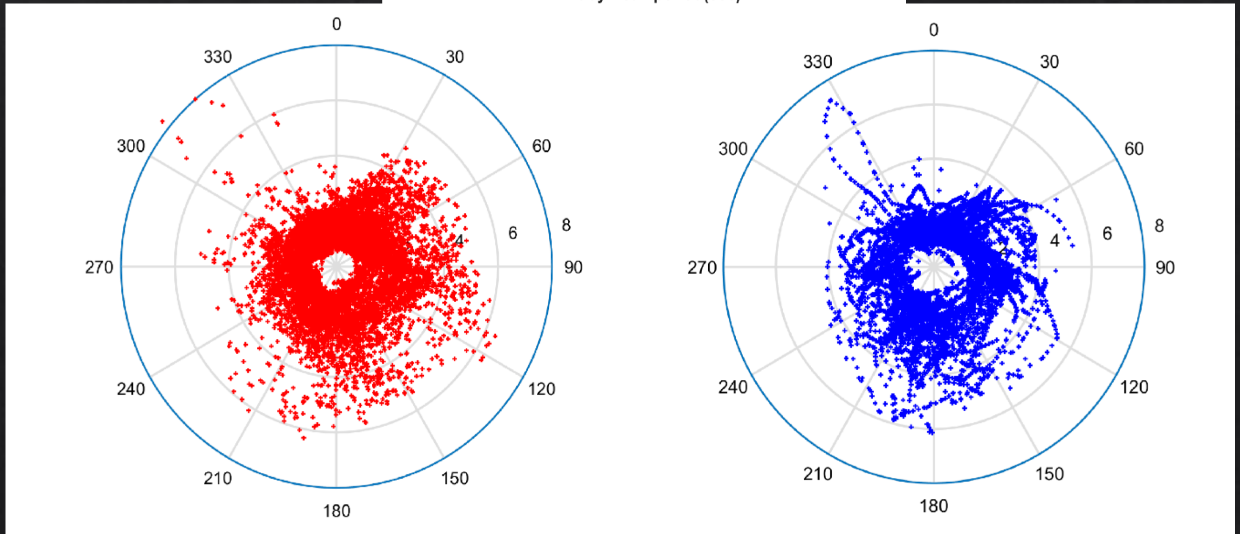




Boundary condition data

- Significant underestimations and overestimations for the peak period
- Good agreements for wave height and direction





Summary and conclusions

- An ultra high-resolution wave climate model with coastal resolution of 200 meters was setup and verified
- Unstructured SWAN using a mesh with triangular elements was used
- CFSR wind field(spatial resolution of 0.312 ° and temporal resolution of 1 hour) along with WWIII-ST4(spatial resolution of 0.5 ° and temporal resolution of 3 hours) as the boundary condition were used to force the model.
- Seasonality of wind with generally higher wind speeds in winter
- Model was calibrated and verified for whitecapping dissipation
- Six IEC parameters were used for model verification
- based on model calibration and verification results at the location of 18 NDBC buoys, Janssen(1991) with C_{ds}=2.7 δ=0.9 was selected for whitecapping dissipation. The 3-year verification results(2007-2009) were comparable with the test bed study along the West Coast
- Seasonality in wind caused seasonality in the simulated wave power with largest amounts of coastal wave power in winter and early spring and the lowest power in summer.

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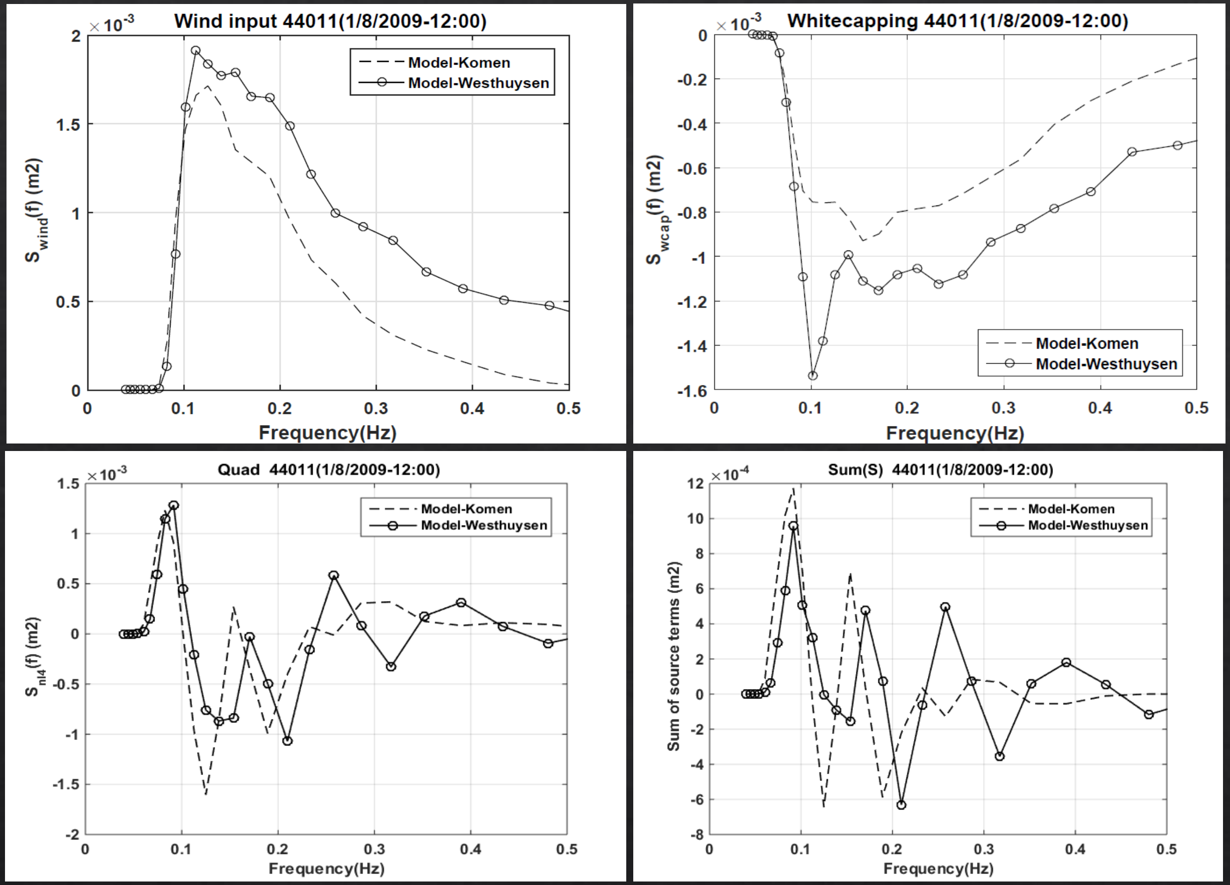
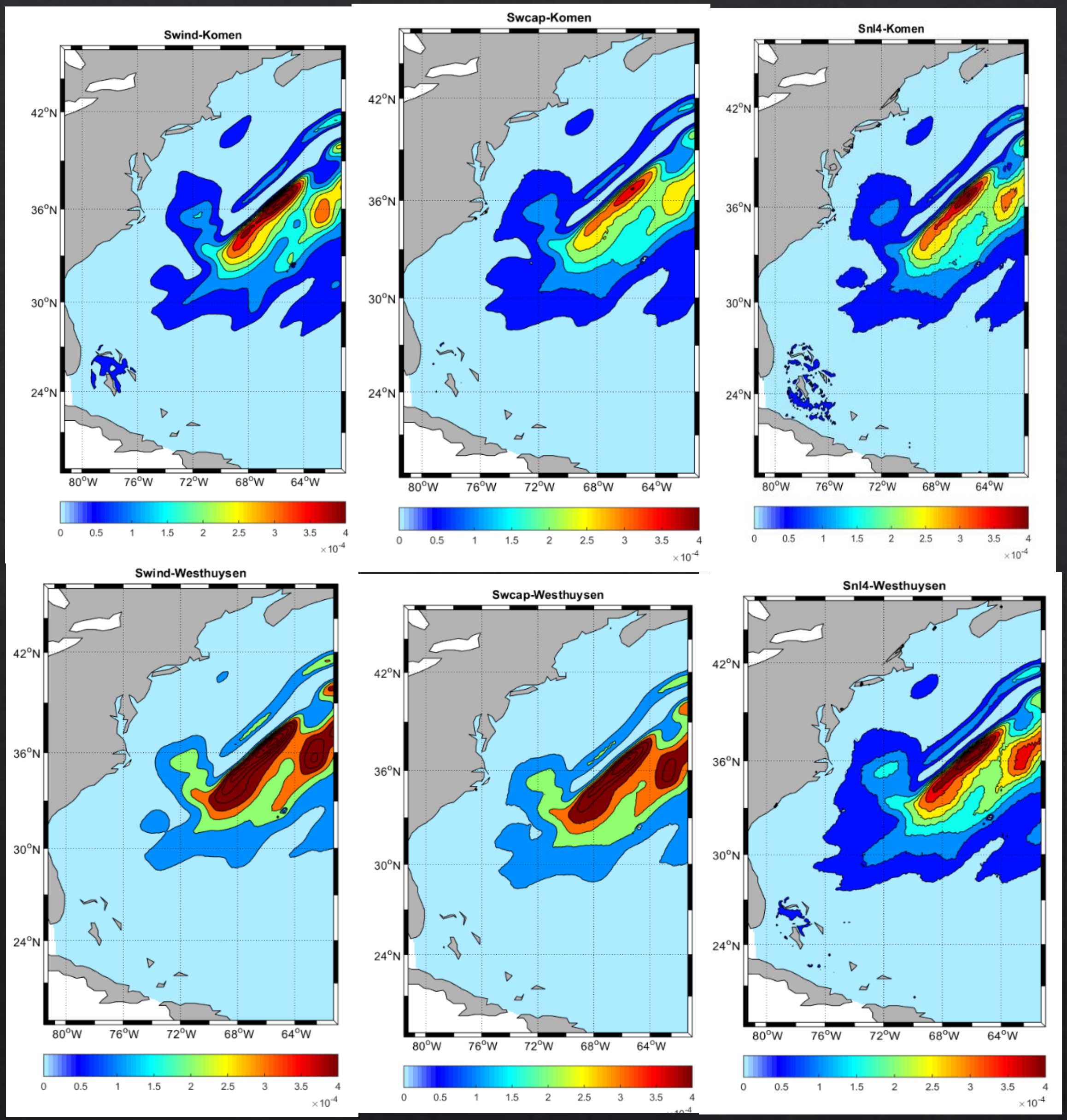
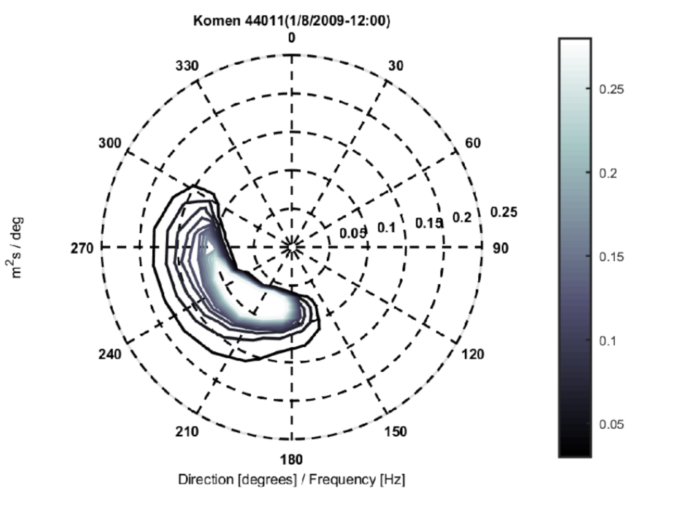
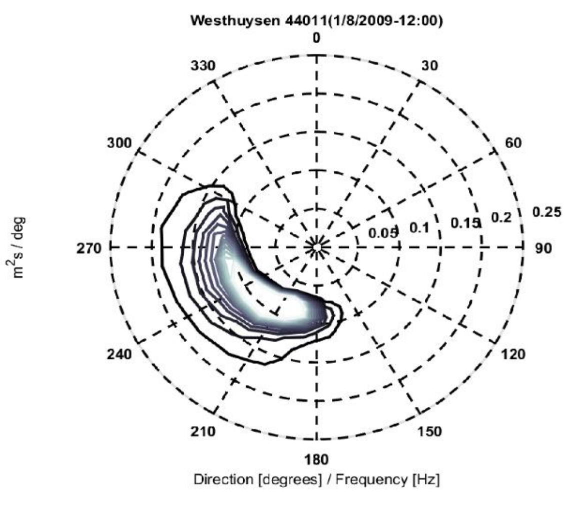
Thank you

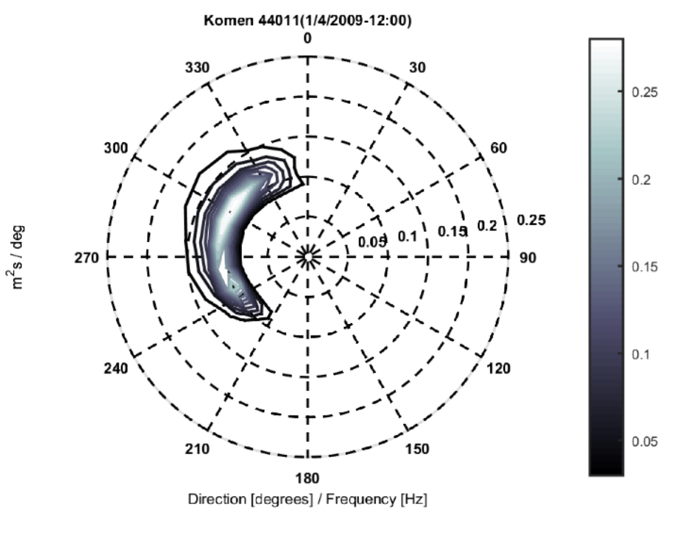
Questions?

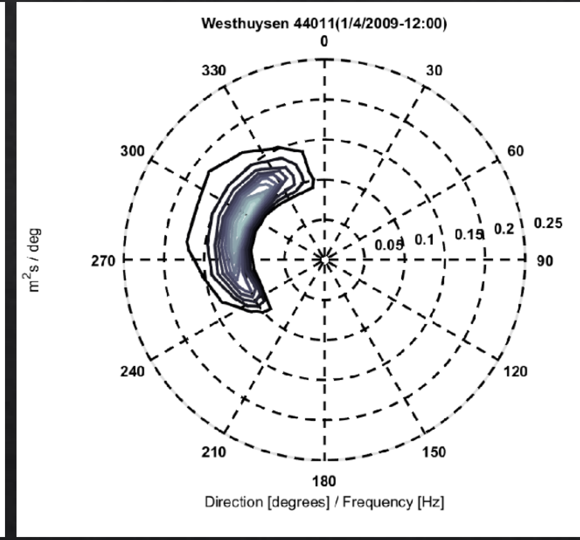

Wind input 44011(1/8/2009-12:00)
Model-Komen
Model-Westhuysen
S_wind(f) (m2)
Frequency(Hz)
Whitecapping 44011(1/8/2009-12:00)
Model-Komen
Model-Westhuysen
S_wcap(f) (m2)
Frequency(Hz)
Quad 44011(1/8/2009-12:00)
Model-Komen
Model-Westhuysen
S_nl4(f) (m2)
Frequency(Hz)
Sum(S) 44011(1/8/2009-12:00)
Model-Komen
Model-Westhuysen
Sum of source terms (m2)
Frequency(Hz)

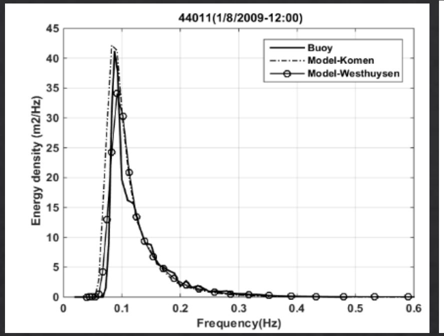

Swind-Komen
Swcap-Komen
Snl4-Komen
Swind-Westhuysen
Swcap-Westhuysen
Snl4-Westhuysen

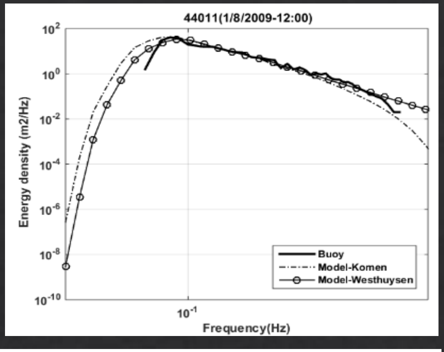

Komen 44011(1/8/2009-12:00)
m²s / deg
Direction [degrees] / Frequency [Hz]

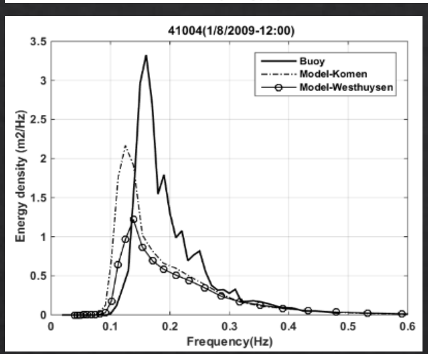

Westhuysen 44011(1/8/2009-12:00)
m²s / deg
Direction [degrees] / Frequency [Hz]

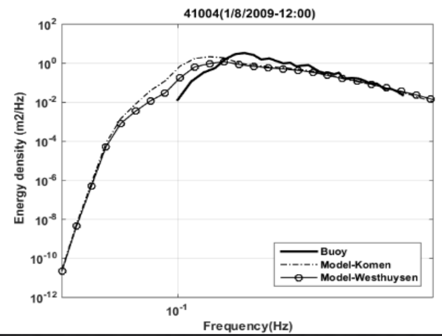

Komen 44011(1/4/2009-12:00)
m²s / deg
Direction [degrees] / Frequency [Hz]

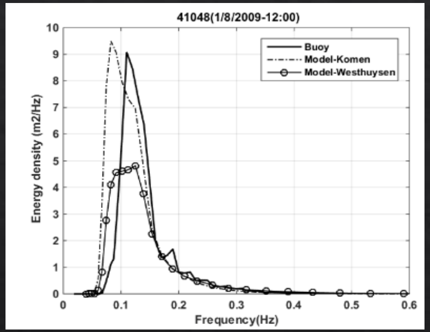

Westhuysen 44011(1/4/2009-12:00)
m²s / deg
Direction [degrees] / Frequency [Hz]

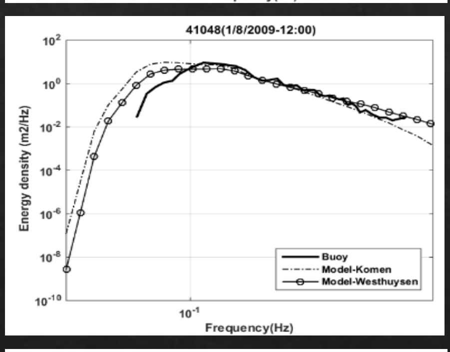

44011(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)


44011(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)


41004(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)


41004(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)


41048(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)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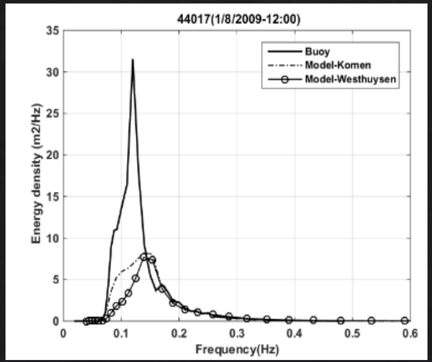
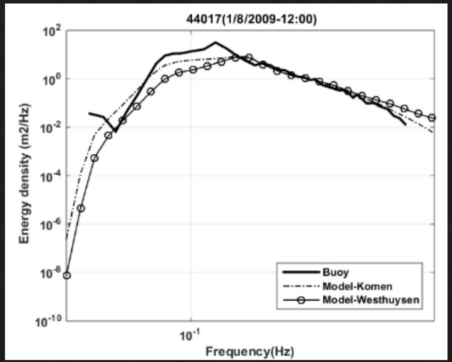
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)


44017(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)


44017(1/8/2009-12:00)
Buoy
Model-Komen
Model-Westhuysen
Energy density (m2/Hz)
Frequency(Hz)