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Wave simulation using SWAN in nested and unnested mode applications

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MOTIVATION

- **Original SWAN implementation of WAM Cycle-4 (WAM4) in version 40.31 and earlier versions was in error leading to underprediction of H_s when compared with that from SWAN using the default option WAM Cycle-3 (WAM3). The error was corrected and the modified code provided to the SWAN Centre was included in version 40.72**

- **The goal is to run both versions 40.31 and 40.72 to determine whether the coastal model SWAN is required to get reliable results or whether the ocean model WAM Cycle-4.5 (WAM4.5) is capable enough to provide wave data of sufficient and acceptable accuracy and quality when applied in deep and intermediate-shallow water depths in an operational environment.**

METHODOLOGY-1

- **WAM Cycle-4.5 (WAM4.5) and SWAN versions 40.72 and 40.31 are used in wave simulations for two case studies:**
  - ***the northwest Atlantic storm storm case of 20-22 January 2000***
  - ***Lake Erie case for the period 12 November – 4 December 2003***

- **In the January storm case, simulations are done on two grids:**
  - ***a coarse grid* with a resolution of 0.5^o covering the area 25^{o}N - 70^{o}N and 82^{o}W - 0^{o}W**
  - ***a fine grid with a resolution of 0.1^o nested within the coarse grid and covering the area 40^{o}N - 52^{o}N and 74.5^{o}W - 46^{o}W.***
  - **WAM4.5 runs on the coarse grid while SWAN and a nested version of WAM4.5 run on the fine grid**

- **In Lake Erie case the two models run in parallel on the same computational grid with a spatial resolution of 0.05^o**

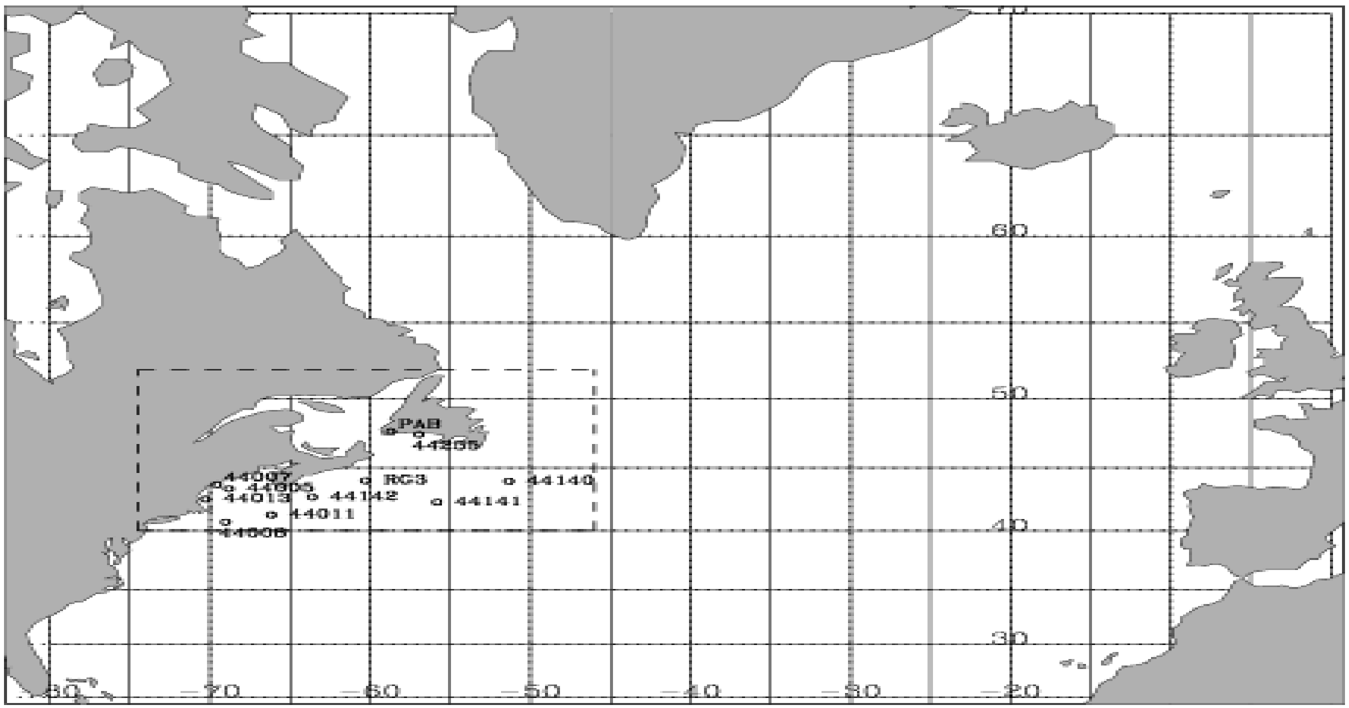
- **The two models are driven by 10 m level surface winds obtained from the CMC GEM regional weather prediction model**

- **Assessment of the performances of the two models in the two cases**

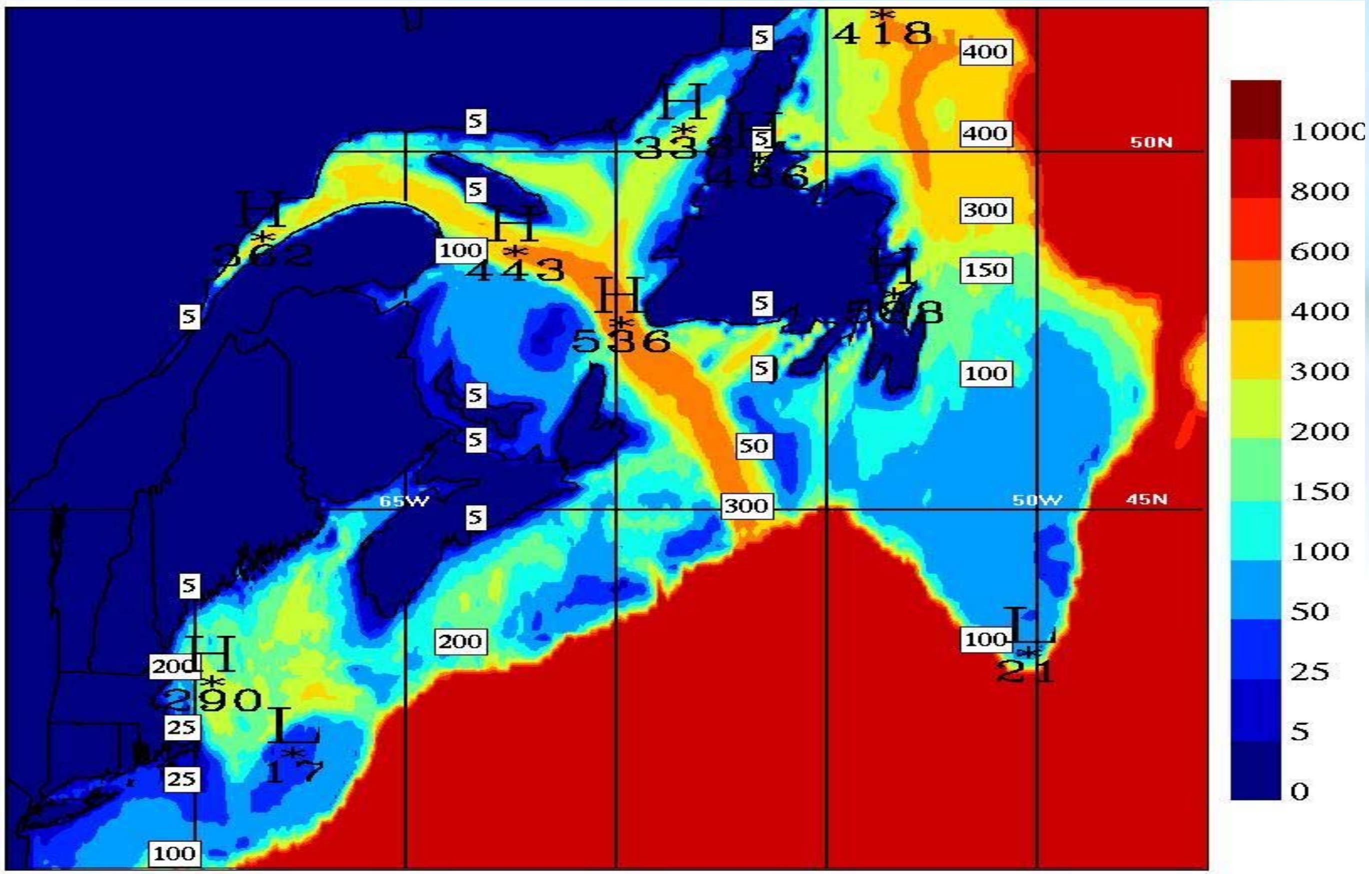
Methodology-2: Wave model coarse and nested fine grids

Verification buoy locations and identification numbers

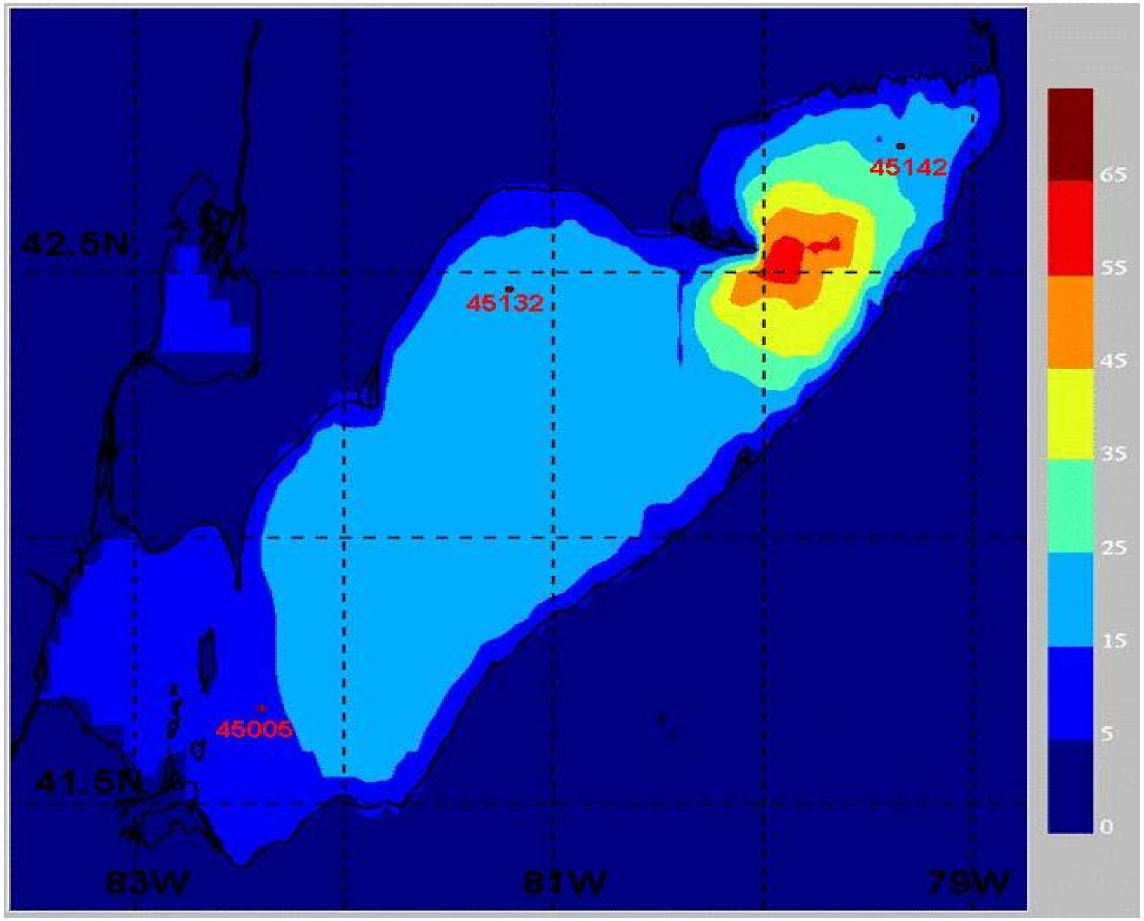
RG3: Rowan Gorilla III   PAB: Port-aux-Basques



Methodology-3
NESTED FINE GRID OCEAN BATHYMETRY



Methodology-4
Lake Erie Computational Grid Area and Bathymetry (m)



SUMMARY of CONCLUSIONS

- **Study indicates:**
  - **Correction of the original implementation of SWAN WAM4 causes a slight enhancement of the normalized growth rate and results in better agreement with the observed wave heights and when compared with those from SWAN default WAM3 and WAM4.5 for both January 2000 storm and Lake Erie case studies.**
  - **For the January 2000 storm case in which SWAN and WAM4.5 are nested inside a coarse grid WAM4.5:**
    - **Differences between the WAM4.5 coarse and fine grid runs are minimal, suggesting that for open and intermediate water depths the coarse grid WAM4.5 with a grid resolution of 0.5º can be used in operational applications to simulate extreme waves associated with storm event such as the January 2000 storm and that a fine grid WAM4.5 with a grid resolution of 0.1º may not be necessary except for nearshore applications given that submerged bathymetric features and small islands are adequately resolved by the coarse grid resolution.**
    - **The agreement between the peak wave height from the corrected SWAN WAM4 run and that from the WAM4.5 fine grid is reasonably good at buoy locations where the sea is locally windsea dominated and not so good where the sea state is swell dominated.**

SUMMARY of CONCLUSIONS (cont'd)

- For the Lake Erie case where SWAN is not nested inside the WAM4.5 as is done in the January 2000 storm case:
  - the performances of the two models indicate that WAM4.5 seems to be a reasonable choice for use in an operational environment instead of the coastal wave model SWAN in an application in intermediate-shallow water depths in an enclosed water basin such as Lake Erie.

Description of WAM4.5 and SWAN Cycle-III Versions 40.72/ 40.31

The conservation equation for the action density *N* in flux form in spherical coordinates and in frequency-direction space is given in the form:

$$\frac{\partial N}{\partial t} + (\cos\phi)^{-1}\frac{\partial}{\partial \phi}(c_\phi \cos\phi N) + \frac{\partial}{\partial \lambda}(c_\lambda N)$$

$$+ \frac{\partial}{\partial \sigma}(c_\sigma N) + \frac{\partial}{\partial \theta}(c_\theta N) = \frac{S}{\sigma} \quad (1)$$

where

$$S = S_{phil} + S_{in} + S_{nl4} + S_{nl3} + S_{ds} + S_{bf} + S_{br} \quad (2)$$

Source Terms

- **Wind generation**
  - S_{phil} (linear wave growth)
  - S_{in} (exponential wave growth)
- **Nonlinear wave-wave interactions**
  - S_{nl4} (quadruplet)
  - S_{nl3} (triad)
- **Dissipation**
  - S_{ds} (whitecapping)
  - S_{bf} (bottom friction)
  - S_{br} (depth-induced wave breaking)

Depth and Current Assumption

- **Depth is time-independent and current is zero**
  - **$c_\sigma = 0$ and the action density equation (1) reduces to the energy balance equation**
  - **Depth refraction depends only on depth gradient**
- **Both WAM4.5 and SWAN solve the energy balance equation**

In Eq. (2) the exponential wave growth term

$$S_{in} = \gamma_{in} F(f,\theta) \quad (3)$$

where $\gamma_{in} = \gamma_{inJ}$ is the growth rate based on the WAM4 formulation taken from Janssen et al. (1991), that is,

$$\gamma_{inJ} = \frac{1.2}{\kappa^2}\varepsilon\lambda \ln^4 \lambda x^2 \sigma \quad \text{for } \lambda \le 1$$
$$= 0 \quad \text{for } \lambda > 1 \quad (4)$$

where ε is the air-water density ratio and

$$x = \max[0., (\frac{u_*}{c} + z_\alpha)\cos(\theta - \theta_{wnd}); \quad \lambda = \frac{gz_0}{c^2}\exp(\frac{\kappa}{x}) \quad (5)$$

$Z_\alpha = 0.011$ is the shift growth parameter

- Omitted in original SWAN implementation of WAM4 in 40.31 and earlier versions

SWAN: Default is WAM3 (WAMDI Group, 1988, Komen et al., 1984)

WAM4.5 uses the limiter of Hersbach and Janssen (1999) expressed in f-θ space is

$$|\Delta F(f,\theta)|_{max} = 3.0 \times 10^{-7} g \hat{u}_* f^{-4} f_c \Delta t \qquad (6)$$

in which f_c **is the model prognostic cut-off frequency and** Δt ***the*** **source term integration time step. Here** $\hat{u}_* = max(u_*, gf^*_{PM}/f)$ ***and*** $f^*_{PM} = 5.6 \times 10^{-3}$ **is the dimensionless Pierson-Moskowitz frequency.**

SWAN uses the limiter described in Ris (1997) given by

$$|\Delta N(\sigma,\theta)|_{max} = (0.1\alpha_{PM})/(2\sigma k^3 c_g) \qquad (7)$$

where α_{PM} = *0.0081* is the Phillips constant for a Pierson-Moscowitz (1964) spectrum. Expressed in σ-θ space and in terms of action density the HJ99 limiter Eq. (6) becomes

$$|\Delta N(\sigma,\theta)|_{max} = (2\pi)^2 \times 3.0 \times 10^{-7}\, g\hat{u}_* \sigma_c \Delta t/(\sigma^3 k) \qquad (8)$$

This limiter is added as an option and is used when the modified WAM4 option is chosen in SWAN.

Source Term Options

Source term	Reference	WAM4.5	SWAN
S_{phil}	Cavaleri and Malanotte-Rizzoli (1981)	x	x
S_{in}	Komen et al. (1984); WAMDI (1988) Janssen (1989, 1991)	 x	x x^* x^+
S_{nl4}	Hasselmann et al. (1985)	x	x
S_{nl3}	Eldeberky (1996)		Not activated
S_{ds}	Janssen (1989, 1991) Hurdle and van Vleddar (2004)	x	 x
S_{bf} Dissip const. (m^2s^{-3})	Hasselmann et al. (1973)	x 0.038	x 0.038
S_{br}	Battjes and Janssen (1978)	NA	NA
Growth limiter	Hersbach and Janssen (1999) Ris (1997)	x	x x
Depth refr. – Erie - Storm		x NA	x NA

NA = Not Activated

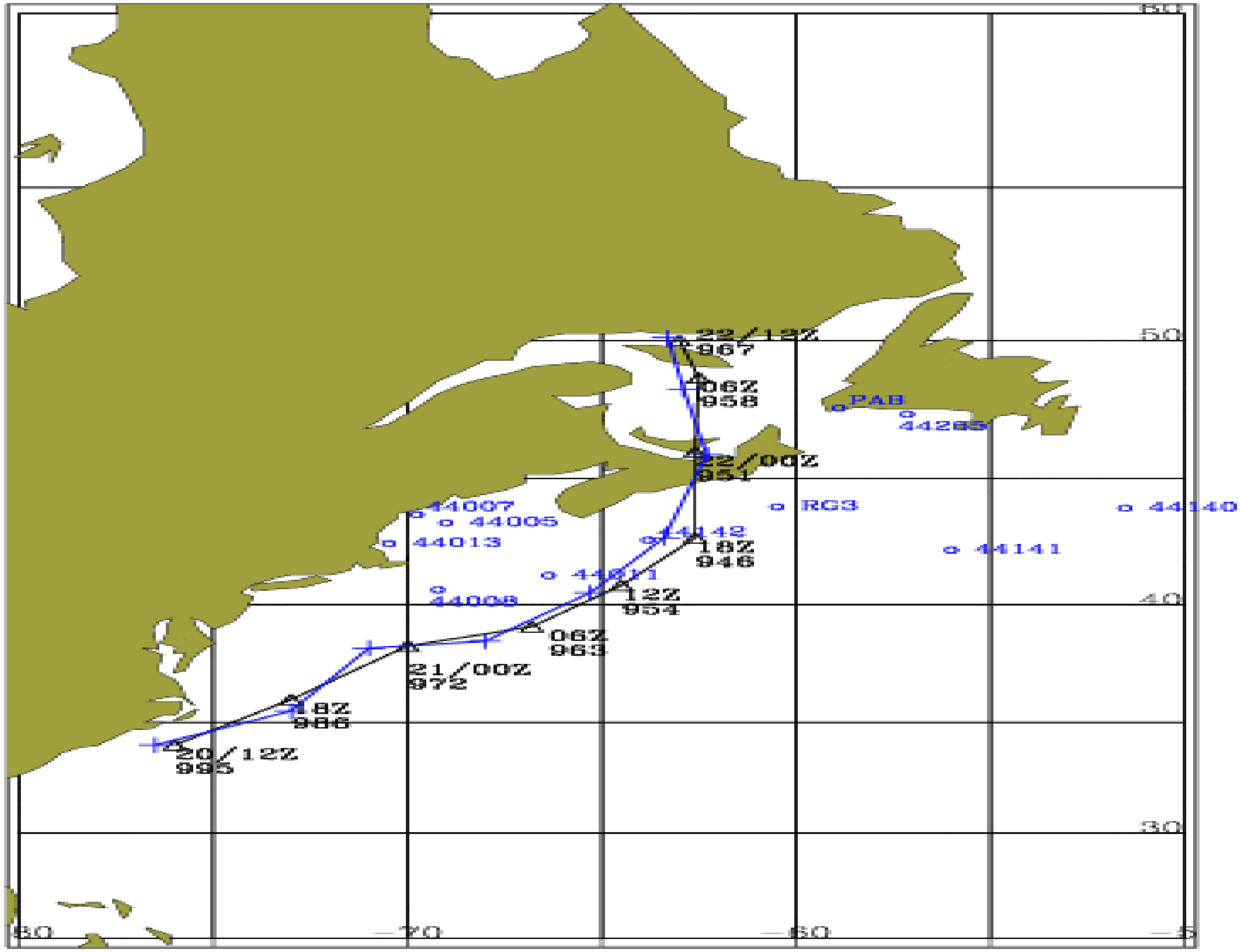
x^* = Original SWAN implementation of WAM4; x^+ = Modified SWAN WAM4

WAVE MODEL RUN IDENTIFICATIONS

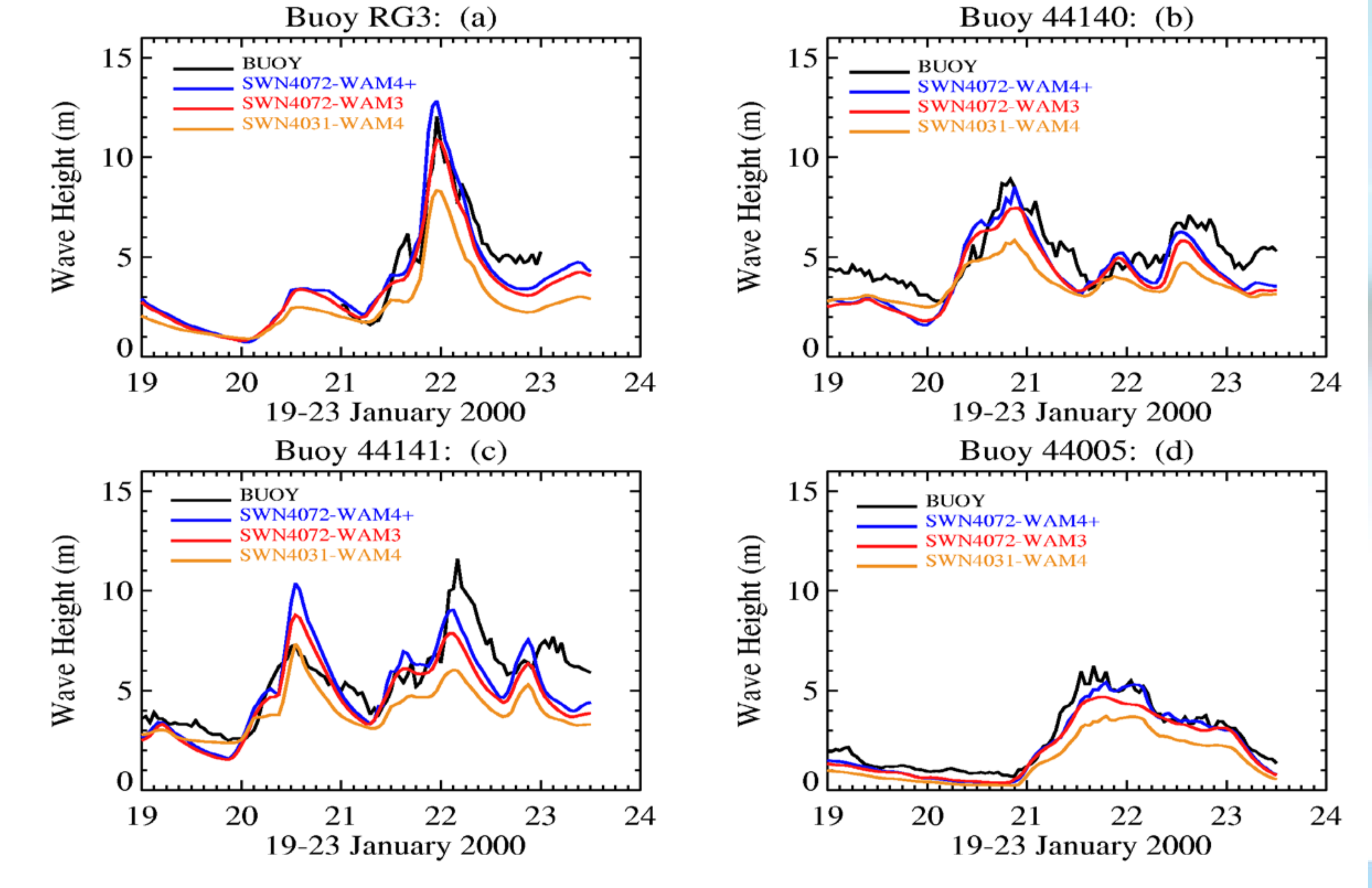
- WAM45-CG for the WAM4.5 coarse grid run (January storm case)
- WAM45-FG for the WAM4.5 fine grid run (January storm case)
- WAM4.5 for the WAM4.5 (Lake Erie case)
- SWN4072-WAM3 for the run based on version 40.72 and using SWAN WAM3 physics
- SWN4072-WAM4+ for the run based on version 40.72 and using the modified implementation of SWAN WAM4 physics.
- SWN4031-WAM4+ for the run based on version 40.31 and using the modified implementation of SWAN WAM4 physics (lake Erie case).
- SWN4031-WAM4 for the run based on version 40.31 and using the original implementation of SWAN WAM4 physics

6-HOURLY STORM TRACK FOR THE PERIOD 20-22 JANUARY 2000

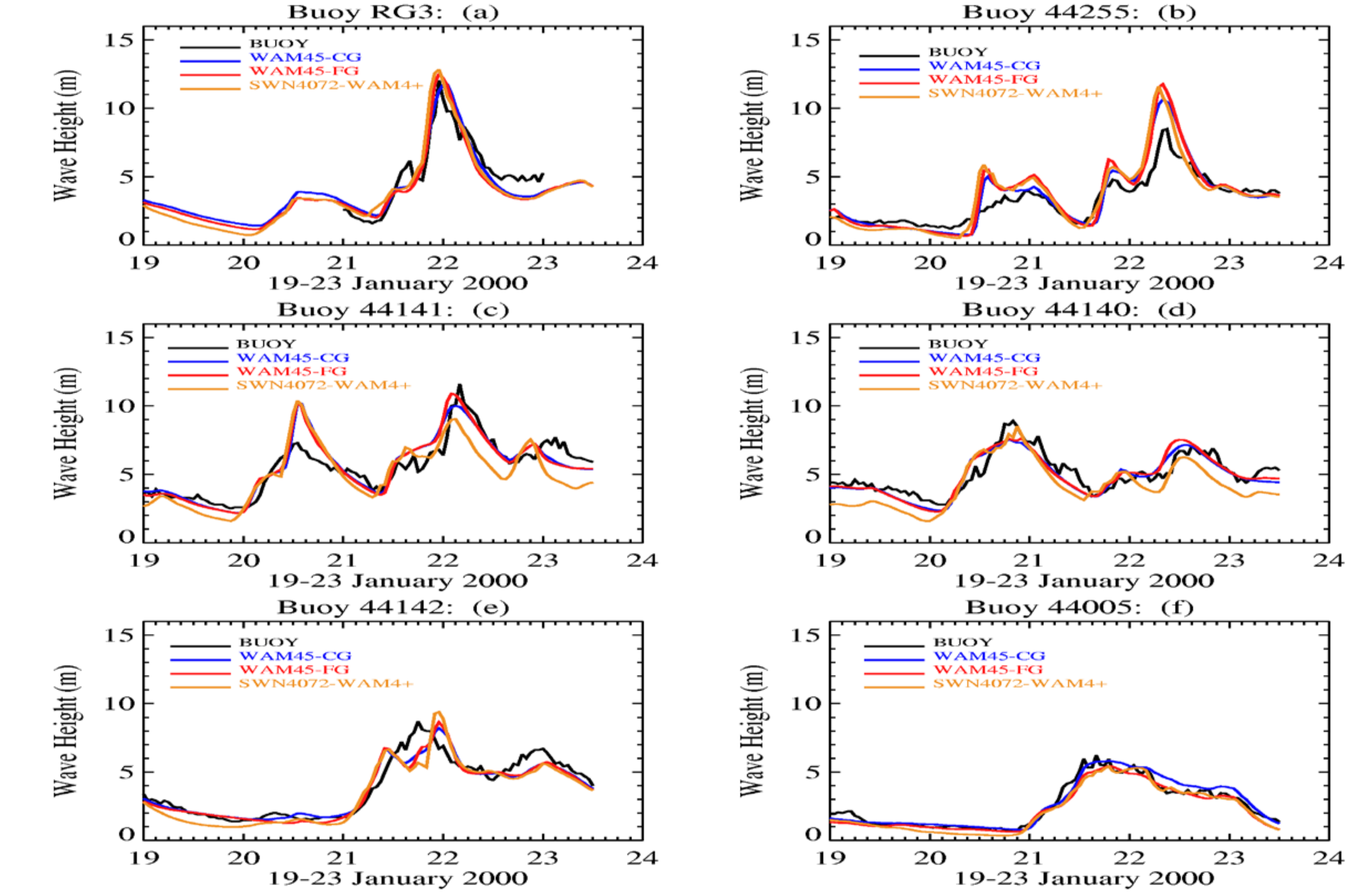
Blue line: CMC GEM model track **Black *line: Observed track***



SWAN RUNS: TIME SERIES OF WAVE HEIGHTS



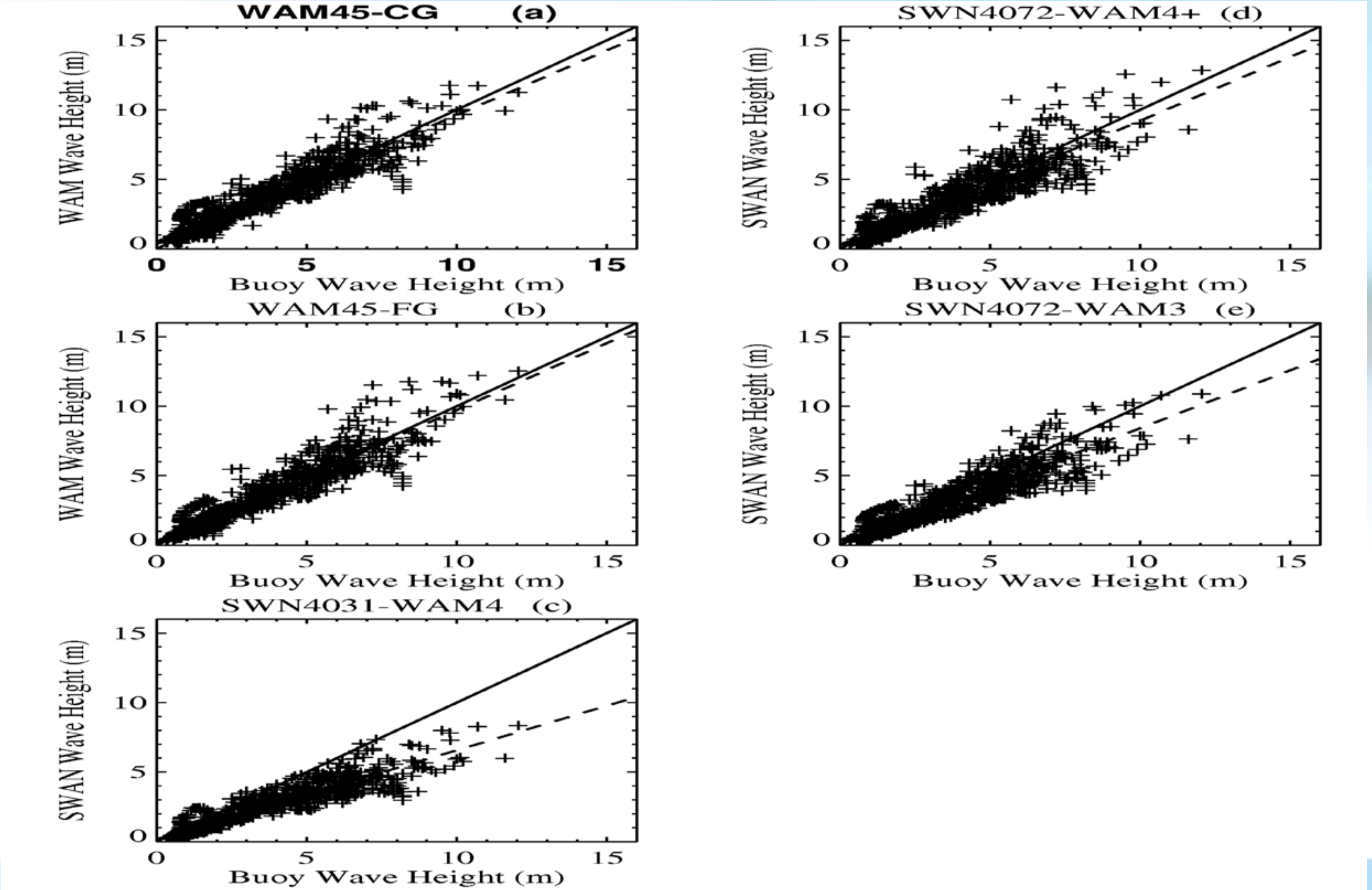
TIME SERIES OF WAVE HEIGHTS



Scatter Plots of Model vs. Observed SWH

Broken black line: Line with symmetric slope s

Solid black line: Perfect fit line



VALIDATION STATISTICS (January 2000 Storm)

ac = anomaly correlation; rv = reduction of variance
b = slope and a = y-intercept of linear regression line

WAVE HEIGHT STATISTICS (m)

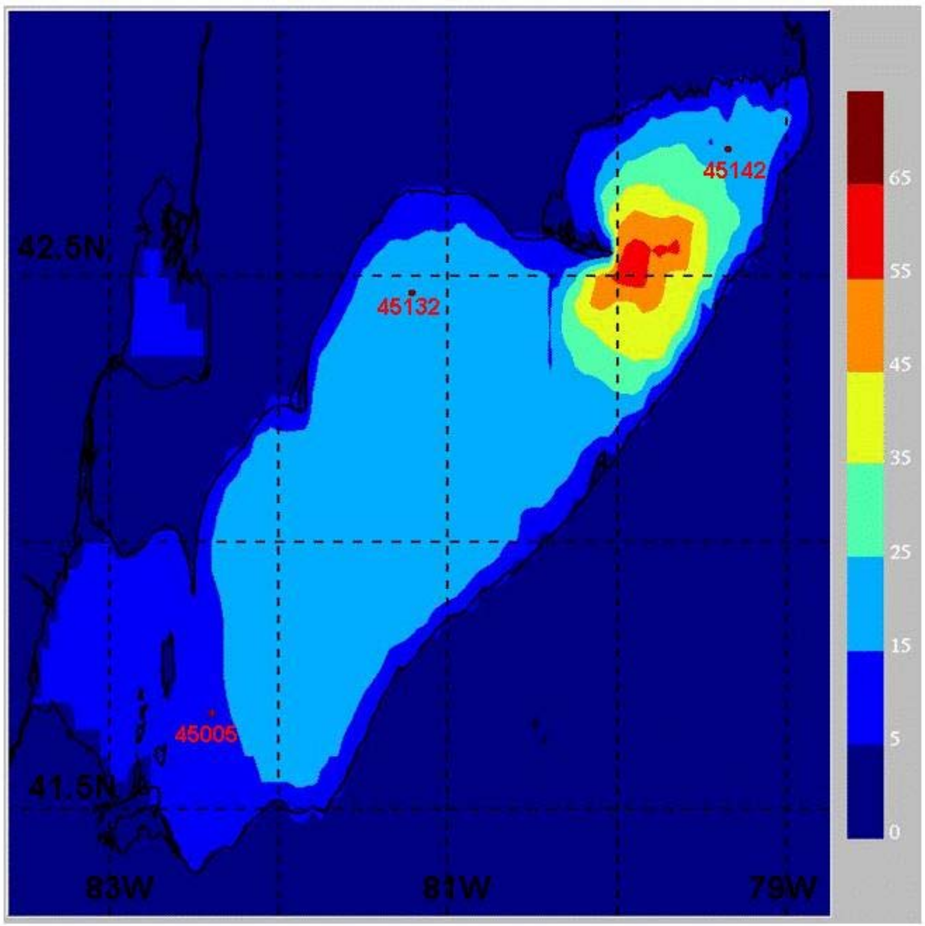
	WAM45-CG	WAM45-FG	SWN4031-WAM4	SWN4072-WAM4+	SWN4072-WAM3
Buoy mean	3.408	3.408	3.408	3.408	3.408
Model mean	3.497	3.379	2.352	3.154	2.923
Bias	0.090	-0.029	-1.056	-0.254	-0.485
Rmse	0.802	0.799	1.462	0.981	0.992
SI	0.235	0.234	0.429	0.288	0.291
r	0.939	0.941	0.928	0.915	0.926
ac	0.939	0.942	0.772	0.910	0.902
rv	0.877	0.878	0.591	0.816	0.812
a	0.328	0.099	0.170	0.022	0.082
b	0.930	0.963	0.640	0.919	0.833
N (no. of obs.)	990	990	990	990	990

WAVE SIMULATION IN LAKE ERIE

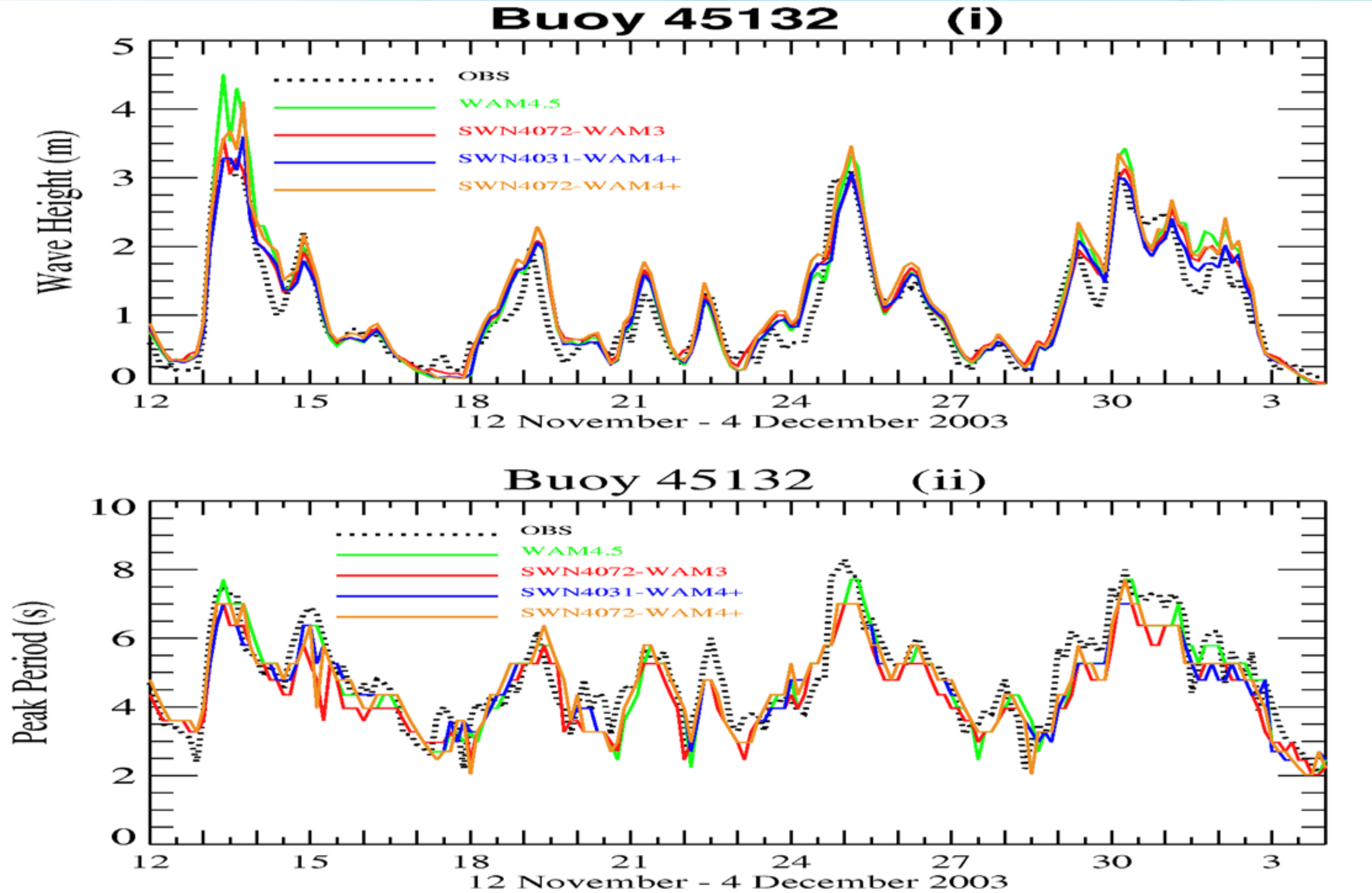
- *Simulation Period*
  - 10 November - 4 December 2003
  - Period chosen because it includes a remarkable storm event that generated high wind speeds and SWH
- *Wind Forcing*
  - CMC GEM model quasi-hindcast 10 m level winds at 3-hourly intervals on 24-km grid interpolated onto the wave model grid with resolution of 0.05º (~ 4-5 km)
- Both WAM4.5 and SWAN run in parallel using the same wind input

Lake Erie Bathymetry (m)

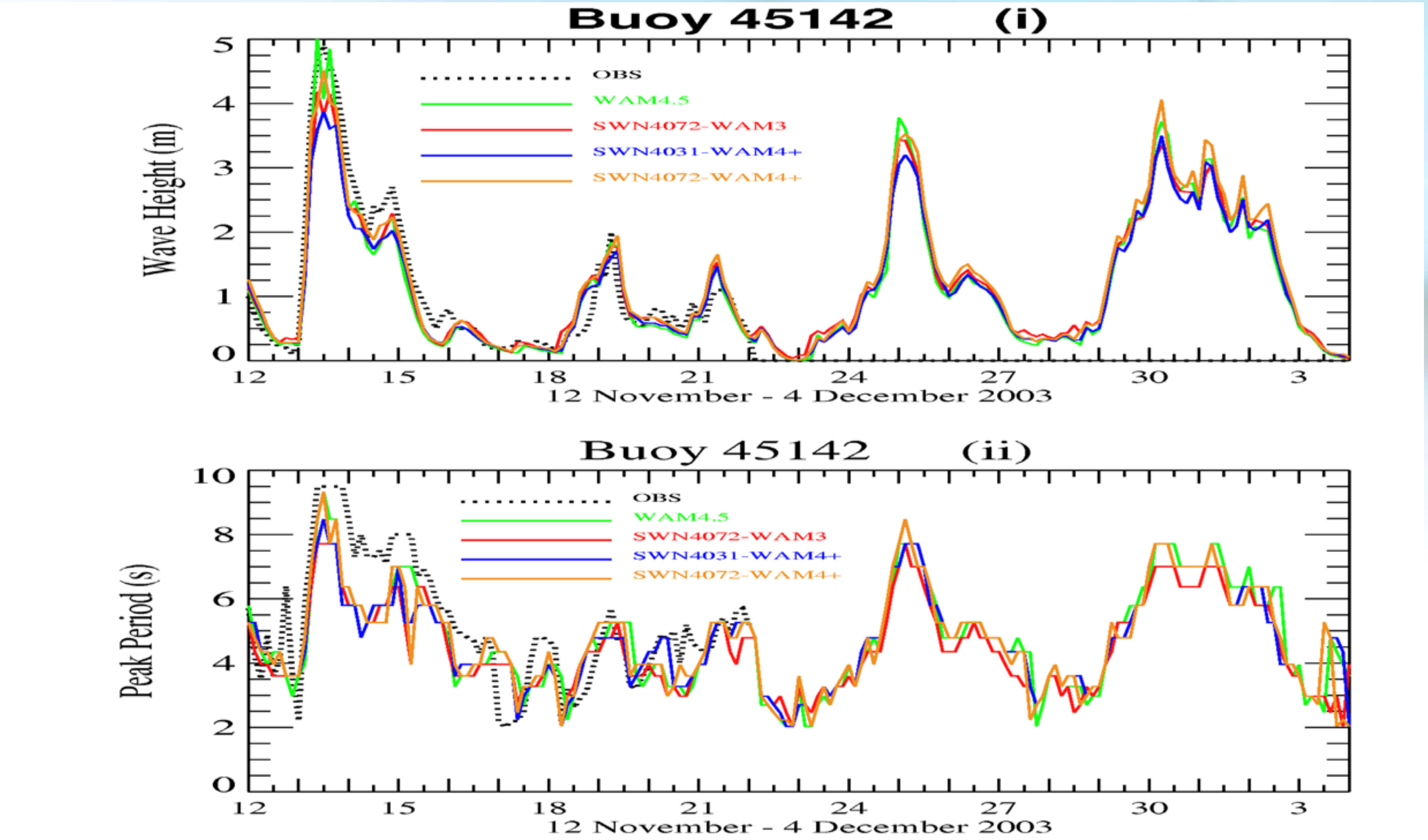
Obs. Buoys: 44005 (d=14 m); 44132 (d=22 m); 44142 (d=27 m)



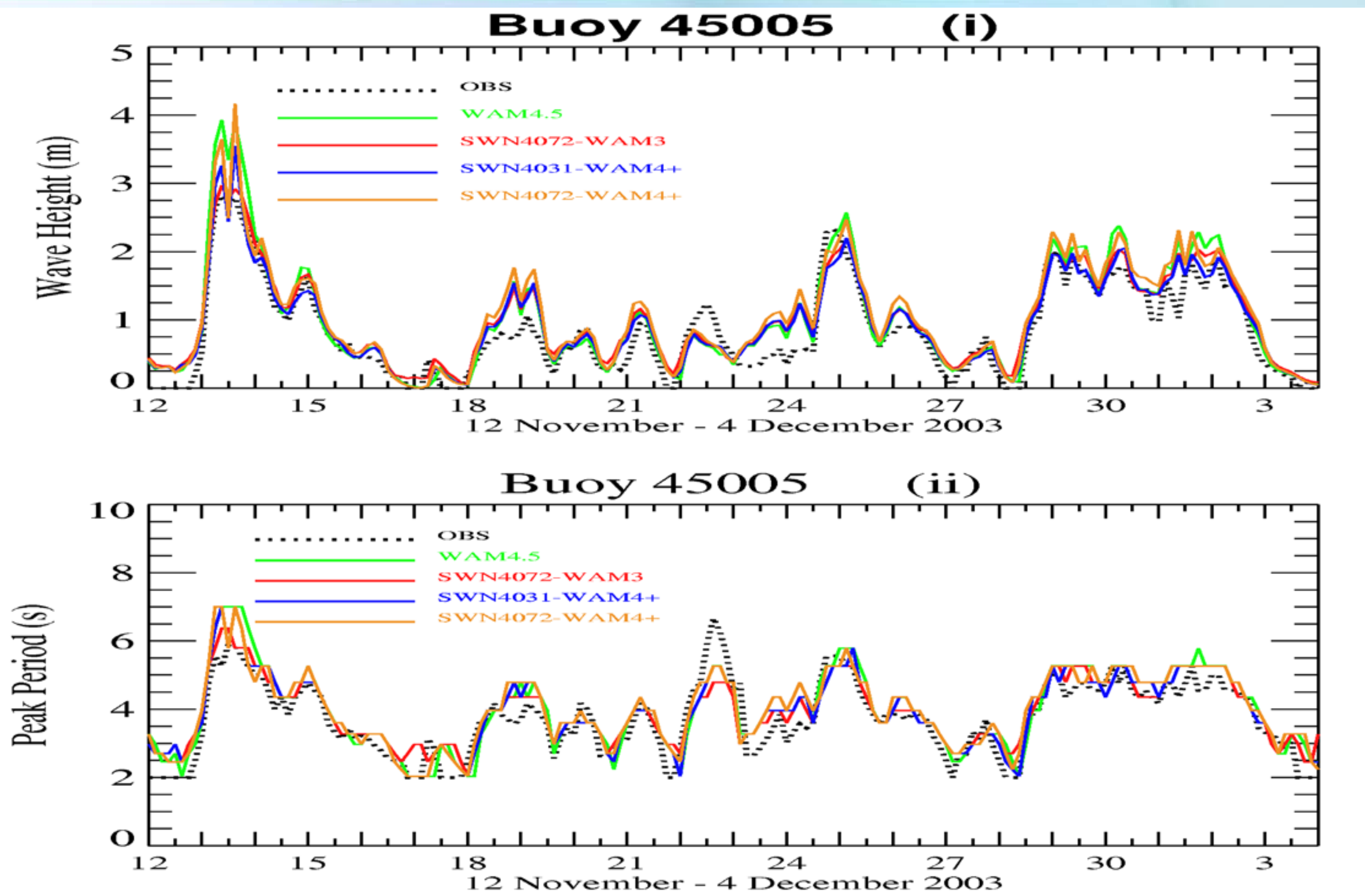
Model vs. Observed SWH and Peak Period at Buoy 45132 (d = 22 m)



Model vs. Observed SWH and Peak Period at Buoy 45142 (d = 27 m)

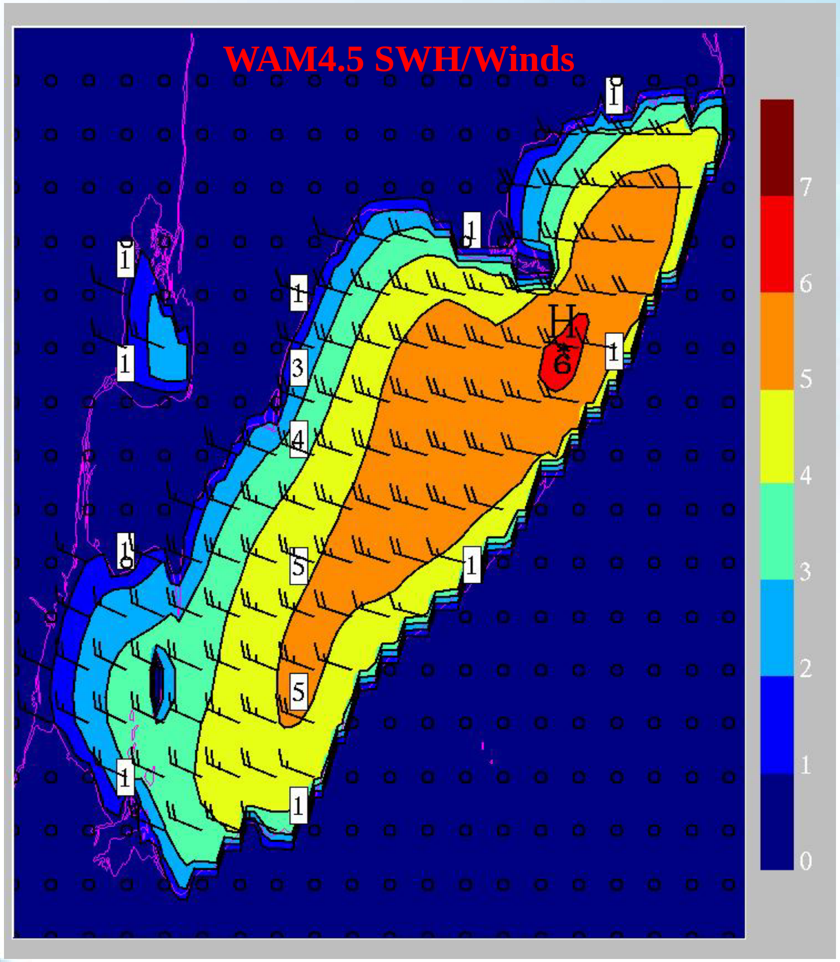


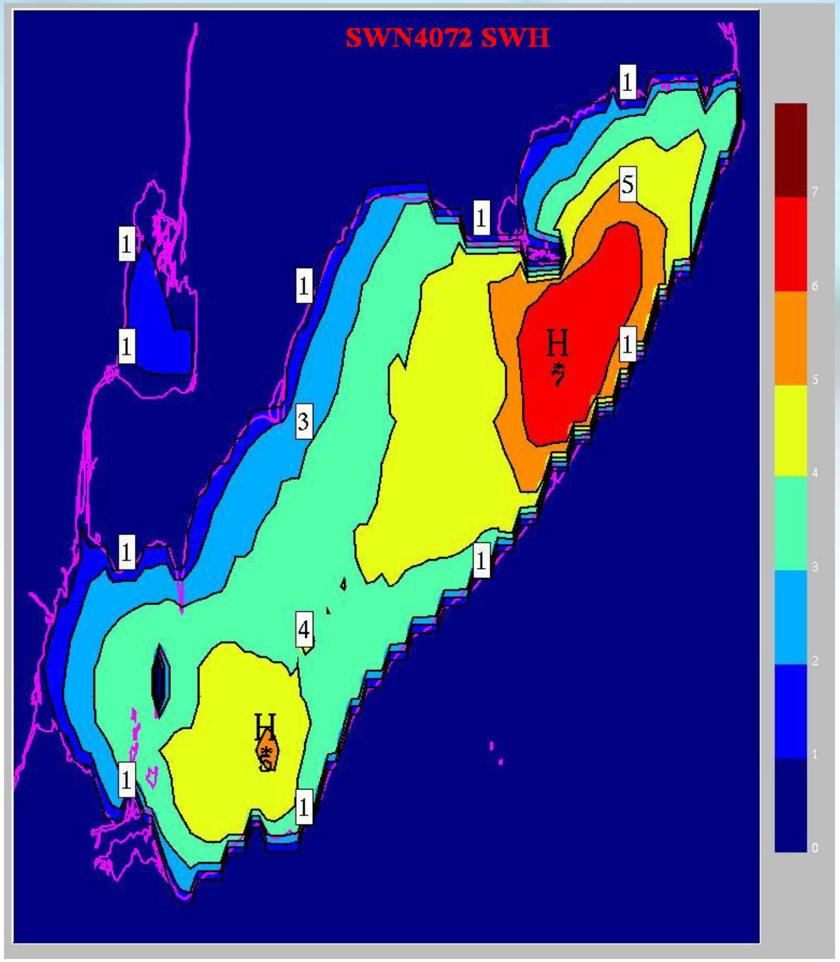
Model vs. Observed SWH and Peak Period at Buoy 45005 (d = 14 m)



Snapshots of SWH/WINDS valid 1500 UTC 13 November 2003

Full wind barb = 10 m/s; half barb = 5 m/s

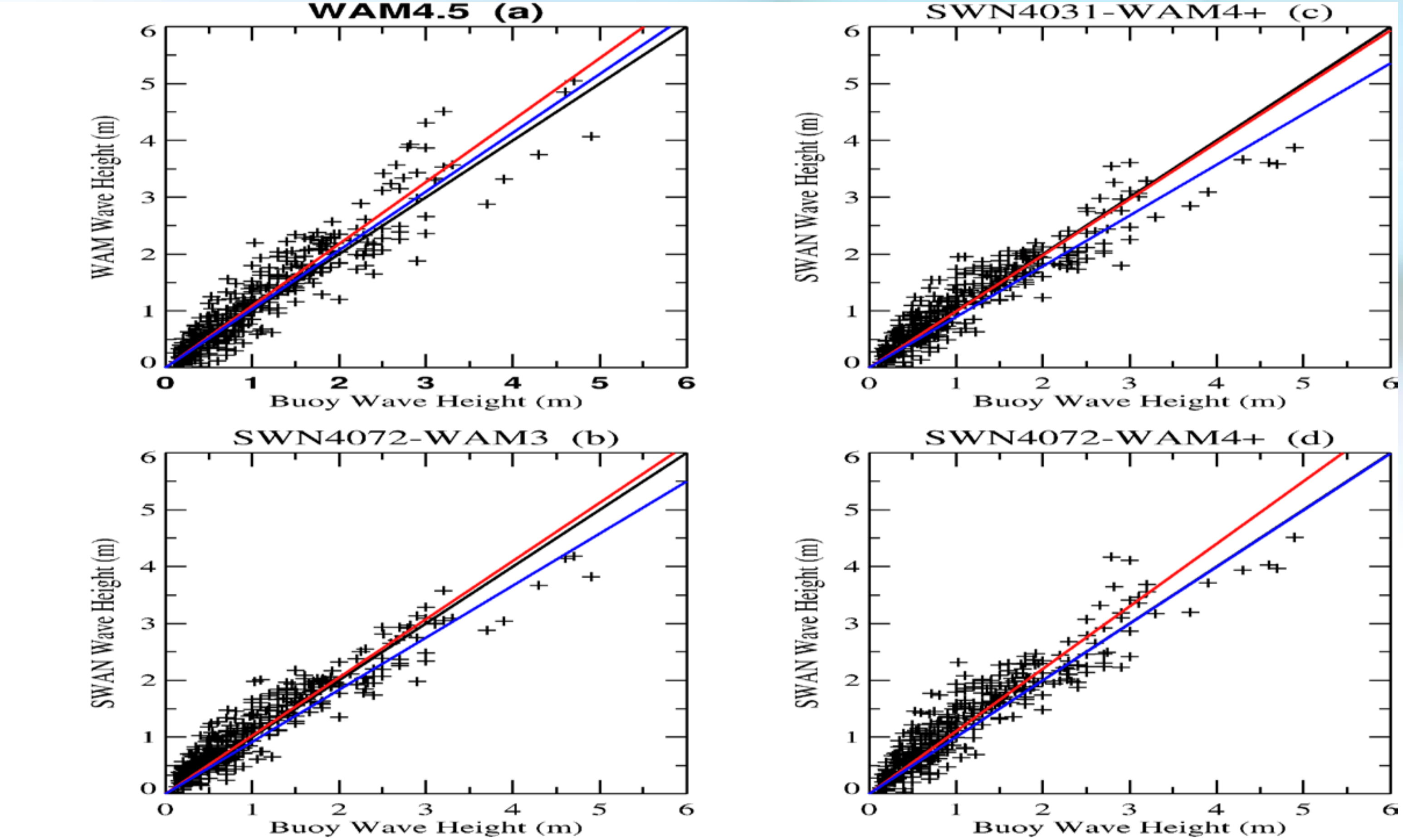




Lake Erie: Scatter Plots of Model vs. Observed SWH

Red line: Line with symmetric slope s; *Blue line: Best fit linear regression line*

Black line: Perfect fit line



Lake Erie: VALIDATION STATISTICS

ac = anomaly correlation; rv = reduction of variance; s = symmetric slope
b = slope and a = y-intercept of linear regression line

WAVE HEIGHT STATISTICS (m)

	WAM4.5	SWN4072-WAM3	SWN4031-WAM4+	SWN4072-WAM4+
Buoy mean	1.043	1.043	1.043	1.043
Model mean	1.136	1.128	1.076	1.191
Bias	0.093	0.085	0.033	0.148
Rmse	0.332	0.283	0.292	0.338
SI	0.318	0.271	0.280	0.324
r	0.938	0.947	0.938	0.937
ac	0.927	0.934	0.934	0.915
rv	0.844	0.887	0.879	0.839
s	1.089	1.025	0.989	1.100
a	0.070	0.209	0.175	0.181
b	1.022	0.881	0.864	0.968
N (no. of obs.)	412	412	412	412

SWN 4072: Lake Erie: VALIDATION STATISTICS

ac = anomaly correlation; rv = reduction of variance; s = symmetric slope
b = slope and a = y-intercept of linear regression line

PEAK PERIOD STATISTICS (s)

	WAM4.5	SWN4072-WAM3	SWN4031-WAM4+	SWN4072-WAM4+
Buoy mean	4.591	4.591	4.591	4.591
Model mean	4.479	4.302	4.441	4.500
Bias	-0.112	-0.290	-0.150	-0.091
Rmse	0.786	0.839	0.787	0.794
SI	0.171	0.183	0.171	0.173
r	0.846	0.846	0.850	0.841
ac	0.834	0.837	0.839	0.827
rv	0.717	0.677	0.716	0.710
s	0.967	0.922	0.952	0.967
a	1.064	1.361	1.356	1.327
b	0.744	0.641	0.672	0.691
N (no. of obs.)	411	411	411	411

SUMMARY of CONCLUSIONS

- **Study indicates:**
  - **Correction of the original implementation of SWAN WAM4 causes a slight enhancement of the normalized growth rate and results in better agreement with the observed wave heights and when compared with those from SWAN default WAM3 and WAM4.5 for both January 2000 storm and Lake Erie case studies.**
  - **For the January 2000 storm case in which SWAN and WAM4.5 are nested inside a coarse grid WAM4.5:**
    - **Differences between the WAM4.5 coarse and fine grid runs are minimal, suggesting that for open and intermediate water depths the coarse grid WAM4.5 with a grid resolution of 0.5^{o} can be used in operational applications to simulate extreme waves associated with storm event such as the January 2000 storm and that a fine grid WAM4.5 with a grid resolution of 0.1^{o} may not be necessary except for nearshore applications given that submerged bathymetric features and small islands are adequately resolved by the coarse grid resolution.**
    - **The agreement between the peak wave height from the corrected SWAN WAM4 run and that from the WAM4.5 fine grid is reasonably good at buoy locations where the sea is locally windsea dominated and not so good where the sea state is swell dominated.**

SUMMARY of CONCLUSIONS (cont'd)

– For the Lake Erie case where SWAN is not nested inside the WAM4.5 as is done in the January 2000 storm case:

  • the performances of the two models indicate that WAM4.5 seems to be a reasonable choice for use in an operational environment instead of the coastal wave model SWAN in an application in shallow-intermediate water depths in an enclosed water basin such as Lake Erie.

References pertaining to this study

- **Lalbeharry, Roop, Ralph Bigio, Bridget Thomas and Laurence Wilson, 2009a: Numerical simulation of extreme waves during the storm of 20-22 January 2000 using CMC weather prediction model generated winds. *Atmosphere-Ocean 47 (1), 99-122, doi:10.3137/OC292.2009*.**

- **Lalbeharry, Roop, Arno Behrens, Heinz Guenther and Laurence Wilson, 2009b: Matching of coastal and open ocean wave models in a mesoscale application over Lake Erie. Atmosphere-Ocean 47 (3), 184-203, doi:10.3137/OC305.2009.**

Thank you!