An evaluation of ocean wave model performances with linear and nonlinear dissipation source terms in Lake Erie

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MSC/MRB/ARMN

OUTLINE

1. Introduction

2. Wave Models

3. Model configuration and simulation period

4. Results and discussion

5. Conclusions

6. Current and future work

INTRODUCTION

- **Collaborative project between MSC and GKSS**
- **Dr. Heinz Guenther provided the WAM Cycle-4.5 (WAM4.5) and the K-MODEL codes**
- **Dr. Arno Behrens parallelized the WAM4.5 in both MPI and OpenMp versions and assisted in the installation of both models on the IBM and LINUX platforms**
- **SWAN Cycle-III version 40.31 was made available in the public domain**

- ***Objective***
  - ***Assess the performances of these 3 state-of-the-art ocean wave models in an enclosed water body mainly dominated by locally generated wind waves in shallow water mode with depth refraction and without tidal influences***

WAVE MODELS

- **WAM Cycle-4.5 (WAM4.5)**
  - **Update of WAM Cycle-4 (WAM4)**
  - **describes the evolution of the spectral energy density E(s,q) in frequency-direction space**
  - **uses upwind propagation and fully implicit source integration schemes**

K-MODEL

  - **developed in the technical frame of WAM4**
  - **describes the evolution of the spectral action density N(k,q) in wavenumber-direction space**
  - **uses WAM3 wind input source term modified to include the effect of wind gustiness**
  - **includes a nonlinear whitecapping dissipation source term but no quadruplet nonlinear wave-wave interaction source term**
  - **uses upwind propagation and fully implicit source integration schemes**

- **SWAN Cycle-III Version 40.31**
  - **describes the evolution of the spectral action density N(s,q) in frequency-direction space**
  - **uses fully implicit propagation and source integration schemes**

Wave spectral action density balance equation in a moving spherical coordinate system in frequency-direction space

$$\frac{\partial}{\partial t}N + (\cos\phi)^{-1}\frac{\partial}{\partial \phi}(c_\phi \cos\phi\, N) + \frac{\partial}{\partial \lambda}(c_\lambda N) + \frac{\partial}{\partial \sigma}(c_\sigma N) + \frac{\partial}{\partial \theta}(c_\theta N) = \frac{S}{\sigma}$$

where

$N = N(\sigma, \theta, \phi, \lambda, t) = E(\sigma, \theta, \phi, \lambda, t)/\sigma$ = wave action density spectrum

$E(\sigma, \theta, \phi, \lambda, t)$ = energy density spectrum

ϕ = latitude

λ = longitude

σ = relative angular frequency

= $[gk\tanh(kh)]^{1/2}$

θ = wave direction (measured clockwise relative to true north)

c_ϕ, c_λ = propagation speeds in geographic space

c_σ, c_θ = propagation speeds in spectral space

Model Physics:

Net energy source term S in s - q space

S	=	**S(**s, q, f**,** l, **t)**
	=	$S_{phil} + S_{in} + S_{nl4} + S_{ds} + S_{bf}$

where

S_{phil}	=	**linear wind growth**
		Cavaleri and Malanotte-Rizzoli (1981) modified by Tolman (1992)
S_{in}	=	**exponential wind growth**
		Komen et al. (1984); Janssen (1991)
S_{nl4}	=	**quadruplet nonlinear wave-wave interaction**
		Hasselmann et al. (1985)
S_{ds}	=	**dissipation due to whitecapping**
		Komen et al. (1984); Janssen (1991)
S_{bf}	=	**dissipation due to bottom friction**
		Hasselmann et al. (1973)

SWAN WAM4/WAM3

- **Actual implementation of SWAN WAM4**
  - **Shift growth parameter z_a = 0.011 in S_{in} omitted**
  - **Uses Ris (1997) wave growth limiter**
- ***Modification of SWAN WAM4 implementation***
  - **Inclusion of z_a**
  - **Inclusion of Hersbach and Janssen (1999) wave growth limiter**
- ***SWAN WAM3***
  - **Komen et al. (1984) physics of S_{in} and S_{ds}**

WAVE GROWTH LIMITERS

In terms of action density and s for deep water:

WAM4.5 Limiter (Hersbach and Janssen, 1999)

$$|DN(s,q)|_{\mathbf{max}} = (2p)^2 \ \mathbf{x}\ 3\ \mathbf{x}\ 10^{-7} \mathbf{g u_*} s_{\mathbf{c}} D\mathbf{t} / (s^3 \mathbf{k})$$

SWAN Limiter (Ris, 1997)

$$|DN(s,q)|_{\mathbf{max}} = (0.1\, a_{\mathbf{PM}}) / (2 s\, \mathbf{k^3 c_g})$$

$a_{\mathbf{PM}}$ **= 0.0081 is the Phillip's constant**

SWAN run IDs

	Run ID		
Source term	*SJ1*	*SJ2*	*SK1*
S_{in}	**WAM4**$^{+}$	**WAM4**$^{++}$	**WAM3**
S_{ds}	**WAM4**	**WAM4**	**WAM3**
Limiter	**R97**	**HJ99**	**R97**

\+ *SWAN implementation of WAM4*

++ *SWAN implementation of the modified WAM4*

K-MODEL S_{in}

$$S_{in} = \beta \sigma G N(k, \theta)$$

Gustiness Parameter:

$$G = \frac{1}{\sqrt{2\pi}} \frac{\sigma_{u_*}}{c_*} \exp\left[-\frac{(c_* - u_*)^2}{2\sigma^2}\right] + \frac{1}{2}\left[\frac{u_*}{c_*} - 1\right]\left[1 - \Phi\left(\frac{c_* - u_*}{\sigma_{u_*}}\right)\right]$$

with

$$c_* = \frac{\sigma}{28k \cos(\theta - \theta_w)}$$

$$\Phi(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-\frac{t^2}{2}} dt$$

$$G = 0 \text{ for } \cos(\theta - \theta_w) < 0$$

$$\beta = \text{constant}; \quad \frac{\sigma_{u_*}}{u_*} = 0.4; \quad 28u_* = 1.2u_{10}$$

σ_{u_*} = ***standard deviation of the assumed normal distribution for the friction velocity***

K-MODEL NONLINEAR S_{ds}

$$S_{ds} = -g\, gk^5 \left[\coth(2kh) + \frac{kh}{\sinh^2(kh)}\right] N^2(k,q)$$

$$g(N) = g_o \frac{p_1 \left(p_2 \frac{k}{\langle k \rangle}\right)^q + 1}{\left(p_2 \frac{k}{\langle k \rangle}\right)^q + 1}$$

K-Model tunable parameters and run IDs

		Run ID	
Source term	***Parameter***	***KM1***	***KM2***
S_{in}	b	**0.0009**	**0.0006**
S_{ds}	g_o	**0.09485**	**0.06775**
	p_1	**10**	**4**
	p_2	**1.6**	**1.2**
	q	**6**	**8**
S_{bf}	G(m^2s^{-3})	**0.038**	**0.01**

MODEL DOMAIN AND CONFIGURATION

Domain	**Lake Erie: 41.30ºN - 43.00ºN/83.60ºW - 78.60ºW**
Coord System	**Spherical**
Spatial Resolution	**0.05º x 0.05º (4 x 4 km)**
Spectral Resolution	**25 frequencies: f_1 = 0.05 Hz, f_{i+1}/f_i = 1.1** **25 wavenumbers: k_1 = 0.01 m^{-1}, k_{i+1}/k_i = 1.21** **24 directions: Dq = 15º; 1st direction = 7.5º**
Refraction	**Depth refraction only. Water depth is time-independent.** **No current refraction as currents set to zero.**
Grid Size	**98 x 35**
Land + Sea Points	**3430**
Sea Points	**1172**
Time steps (s)	**WAM4.5: Dt_p = 120, Dt_s = 720** **K-Model: Dt_p = 180, Dt_s = 720** **SWAN : Dt_p = Dt_s = 1200** **Dt_p = propagation time step** **Dt_s = source term integration time step**

MODEL SOURCE TERMS

Source Term	WAM4.5	K-MODEL	SWAN
S_{phil}	*X*	X^{+}	*X*
S_{in}	*WAM4*	$WAM3^{*}$	*WAM3/WAM4*
S_{nl4}	*X*		*X*
S_{ds}	*WAM4*	*Nonlinear*	*WAM3/WAM4*
S_{bf}	*X*	*X*	*X*

\+ *Additional filter applied*

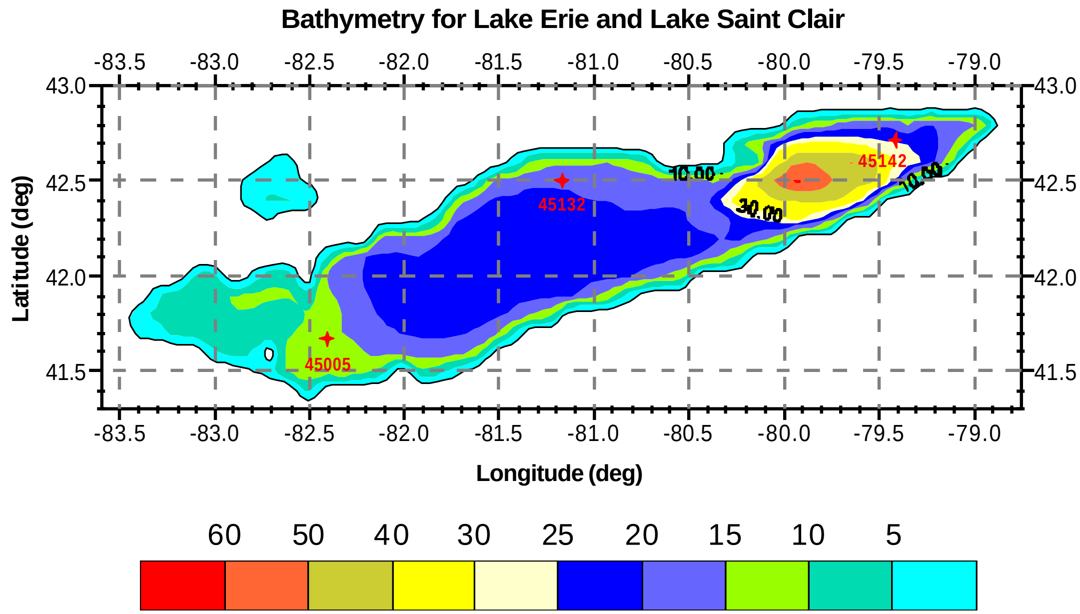
* *Modified to include the effect of wind gustiness*

SIMULATION PERIOD AND WIND FORCING

- ***Simulation Period***
  - **10 November - 4 December 2002**

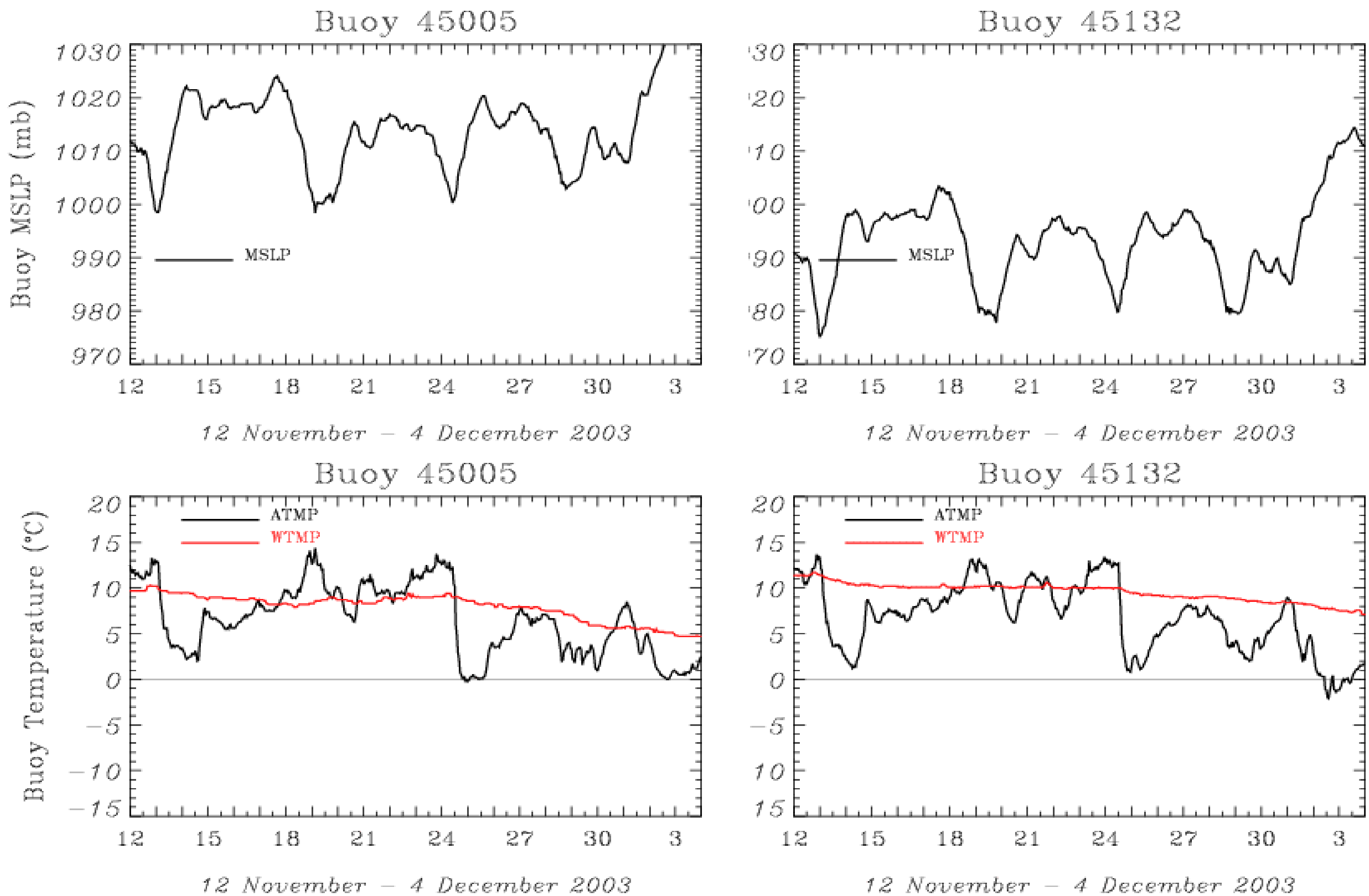
- ***Wind Forcing***
  - **CMC GEM model quasi -hindcast 10 m level winds at 3-hourly intervals on 24-km grid interpolated onto the wave model grid with resolution close to 4 km**

Bathymetry and observation buoys



Buoys	*Water depth (m)*
45005	*14.5*
45132	*22.0*
45142	*27.0*

Time series of pressure, air and sea temperatures



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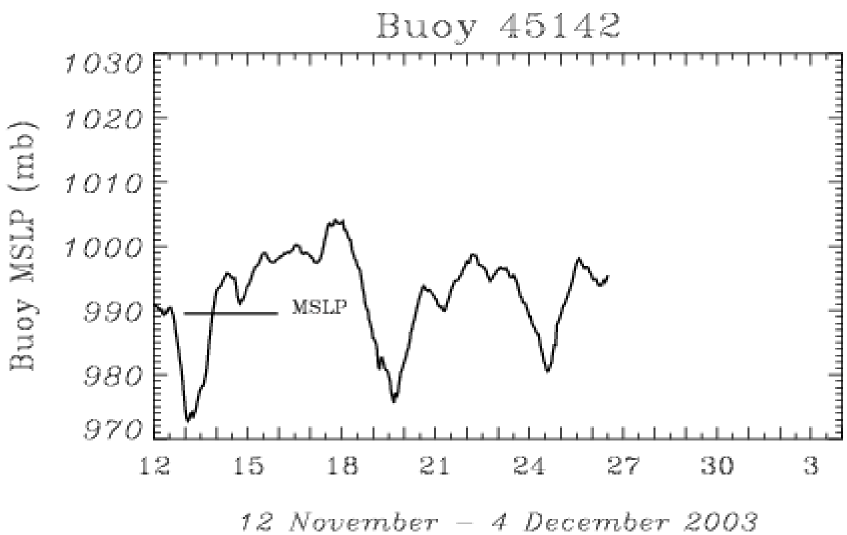
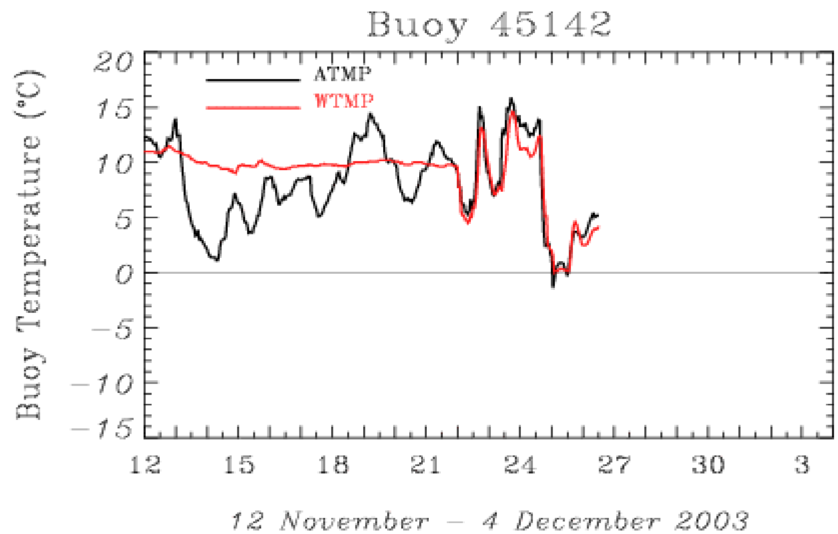
Time series of pressure, air and sea temperatures





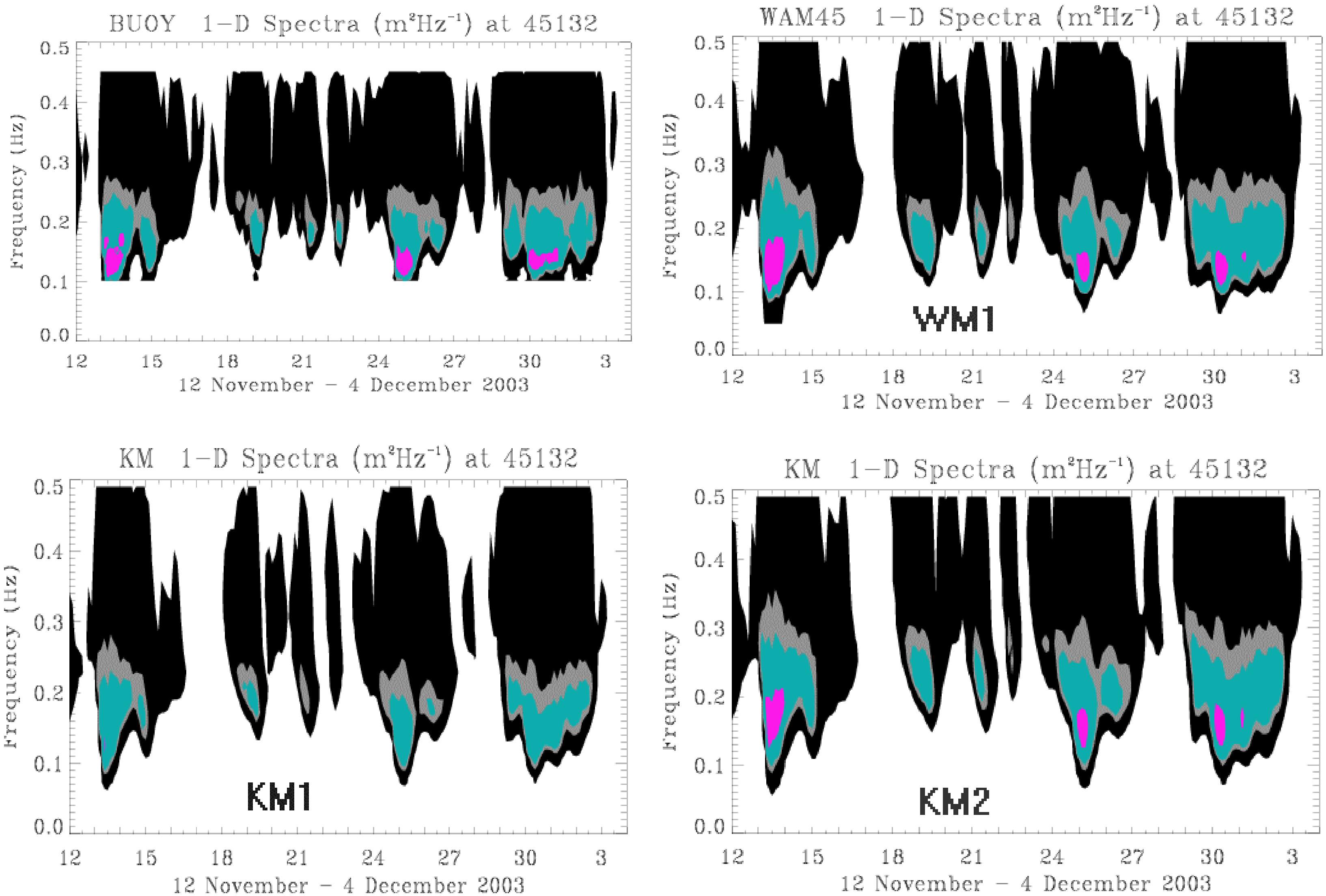
MODEL RUN IDs

MODEL	*RUN ID*	*RUN TYPE*
WAM4.5	**WM1**	**WAM4 Run 1 using Janssen's physics**
K-MODEL	**KM1**	**K-Model Run 1 using 1st set of tunable parameters**
	KM2	**K-Model Run 2 using 2nd set of tunable parameters**
SWAN	**SJ1**	**SWAN using Janssen's WAM4 physics as implemented in SWAN - Run 1**
	SJ2	**SWAN using Janssen's WAM4 physics but as modified - Run 2**
	SK1	**SWAN using Komen's WAM3 physics - Run 1**

Buoy vs. Model 1-d spectra at buoy location 44132:

Buoy (upper left); Run WM1 (upper right); Run KM1 (lower left); Run KM2 (lower right)

Color scale (m^2Hz^{-1}): black (0.025-0.5); gray (0.5-1.0): torquoise (1.0-10.0): rose (10.0-20)



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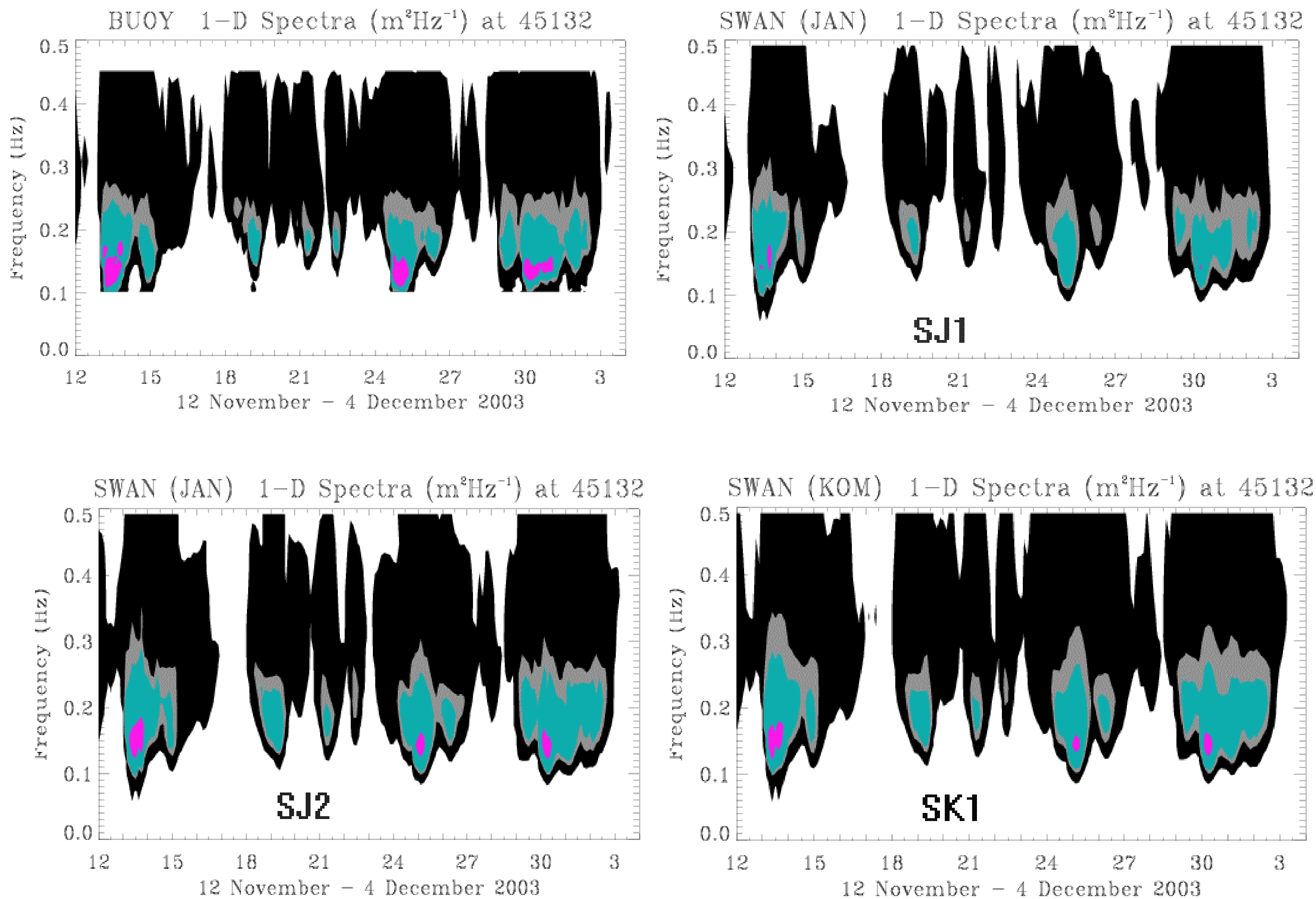
Buoy vs. Model 1-d spectra at buoy location 44132 (cont'd):

Buoy (upper left); Run SJ1 (upper right); Run SJ2 (lower left); Run SK2 (lower right)



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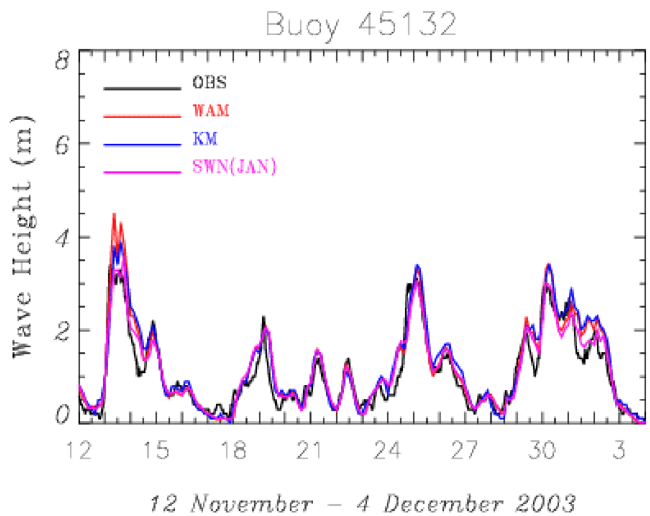
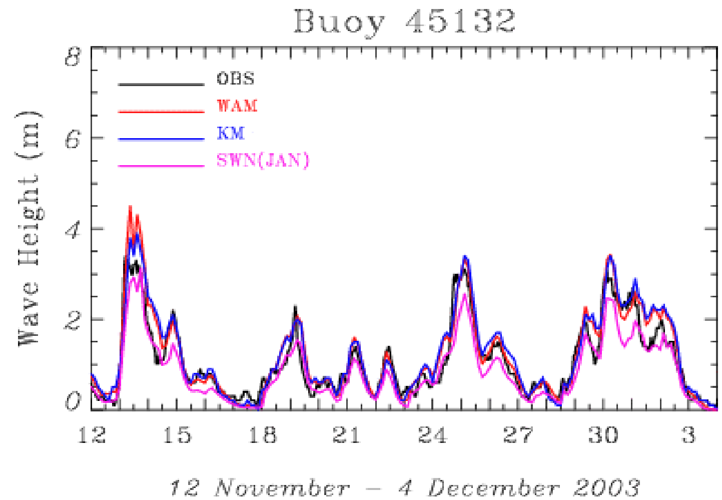
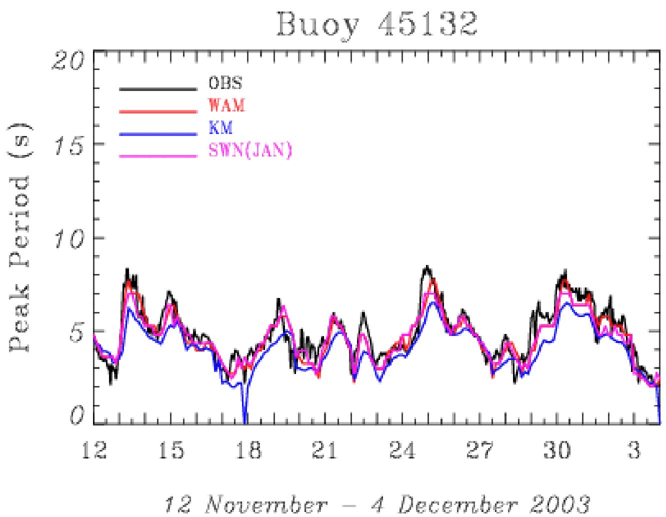
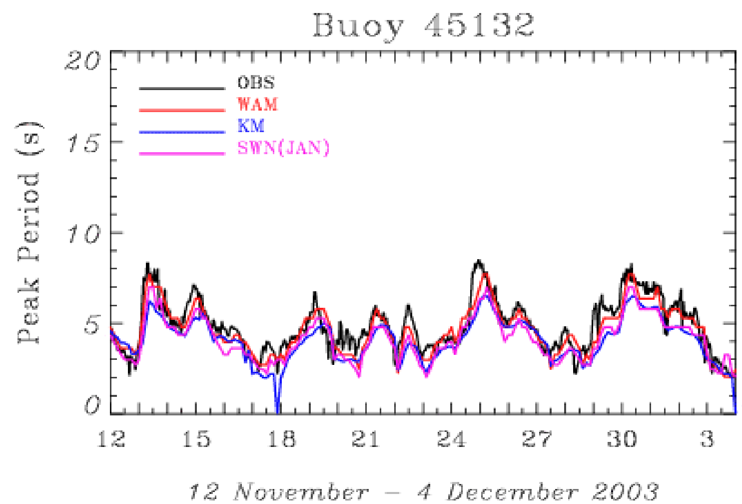
Time series of SWH and Peak Period at buoy 45132

Left panels (Runs WM1, KM2 and SJ2); Right panels (Runs WM1, KM2 and SJ1)









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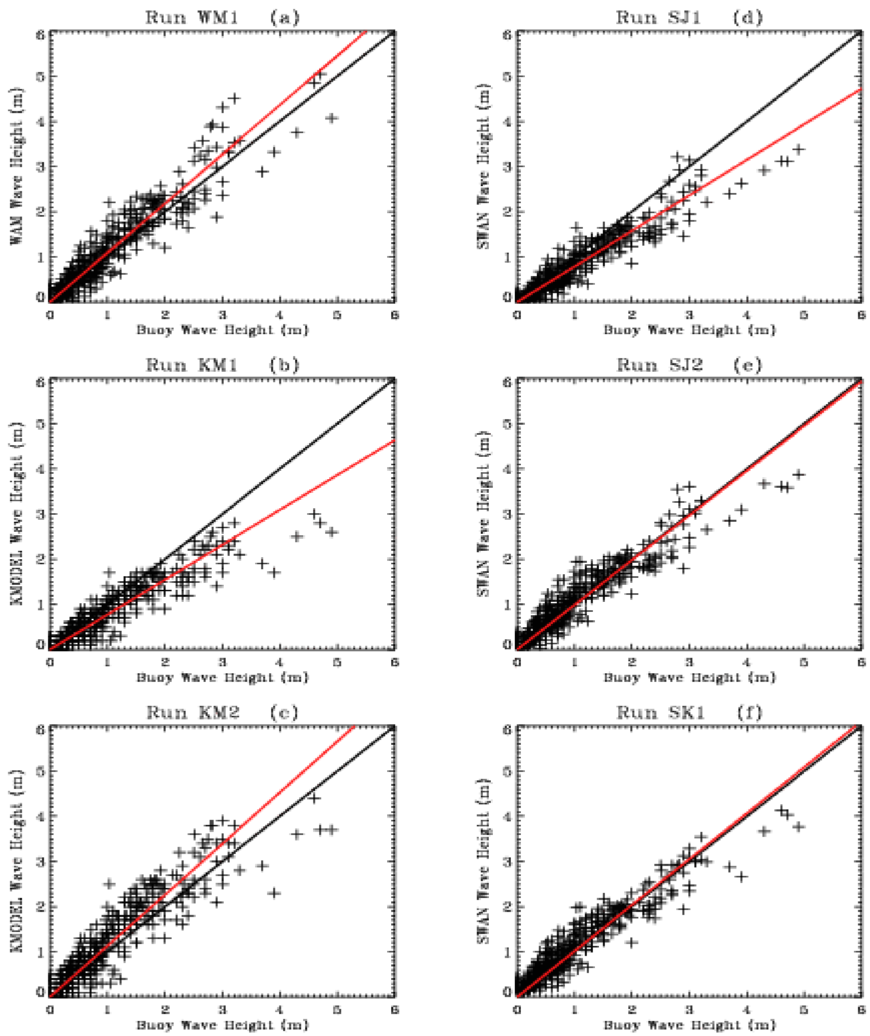
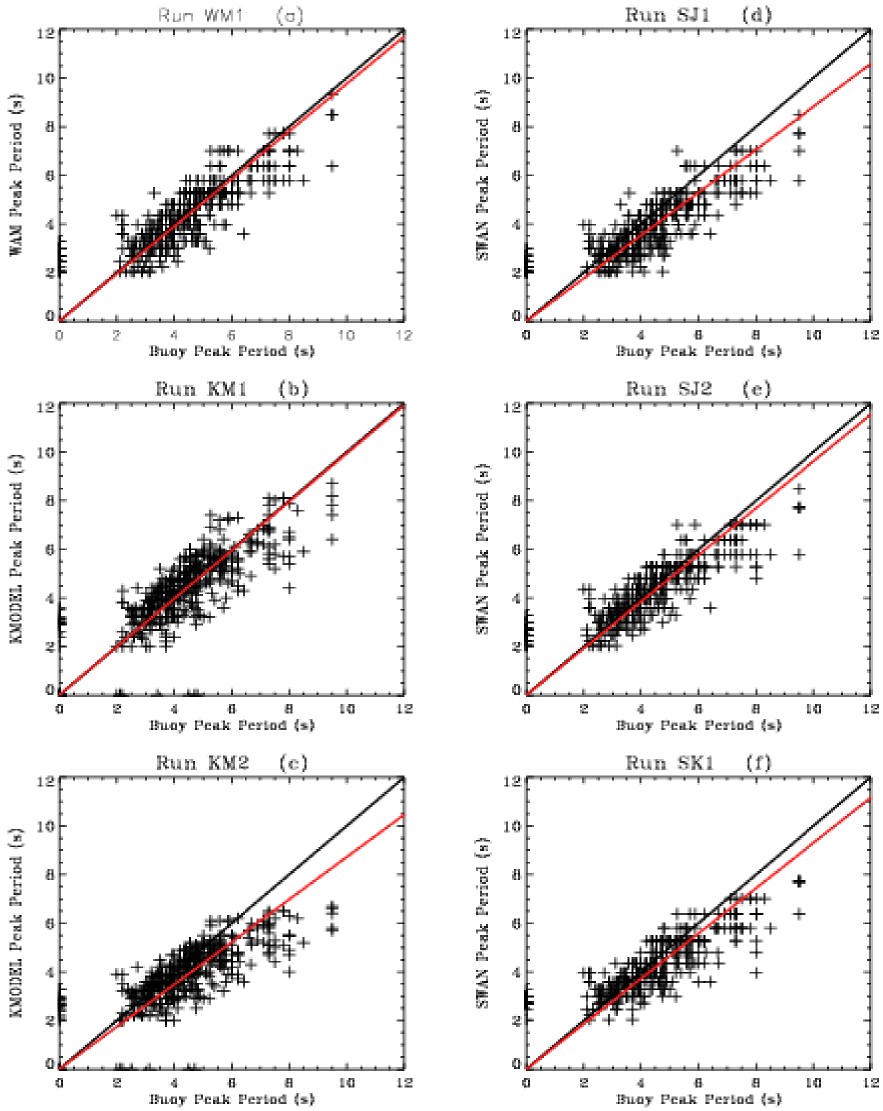
SCATTER PLOTS OF MODEL vs. OBSERVED WAVE HEIGHTS

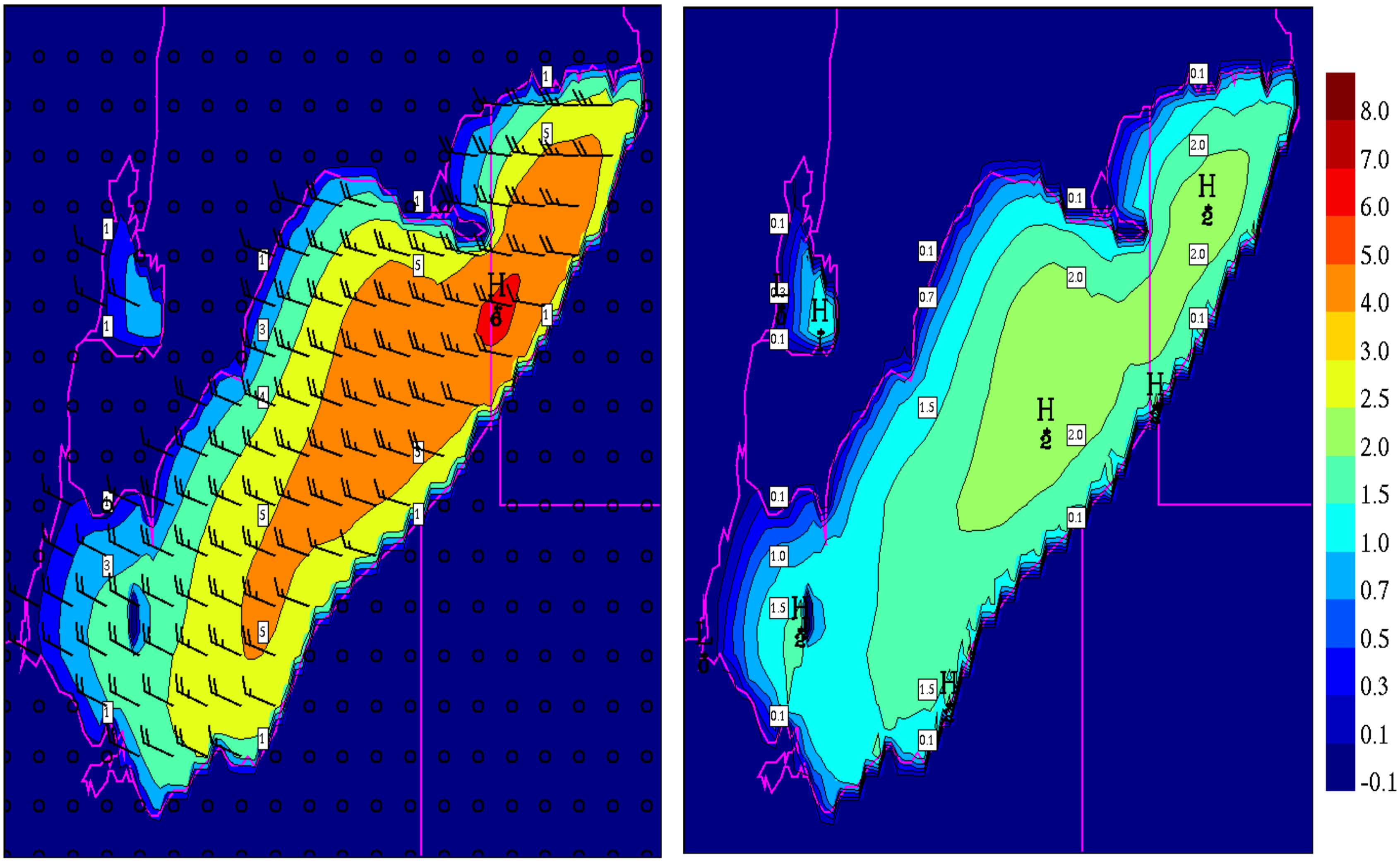


SCATTER PLOTS OF MODEL vs. OBSERVED PEAK PERIODS



Snapshots of: SWH and winds (left panel) and WM1 SWH - KM1 SWH (right panel) valid 1500 UTC 13 November 2003

Wind barb units: m^2s^{-1}



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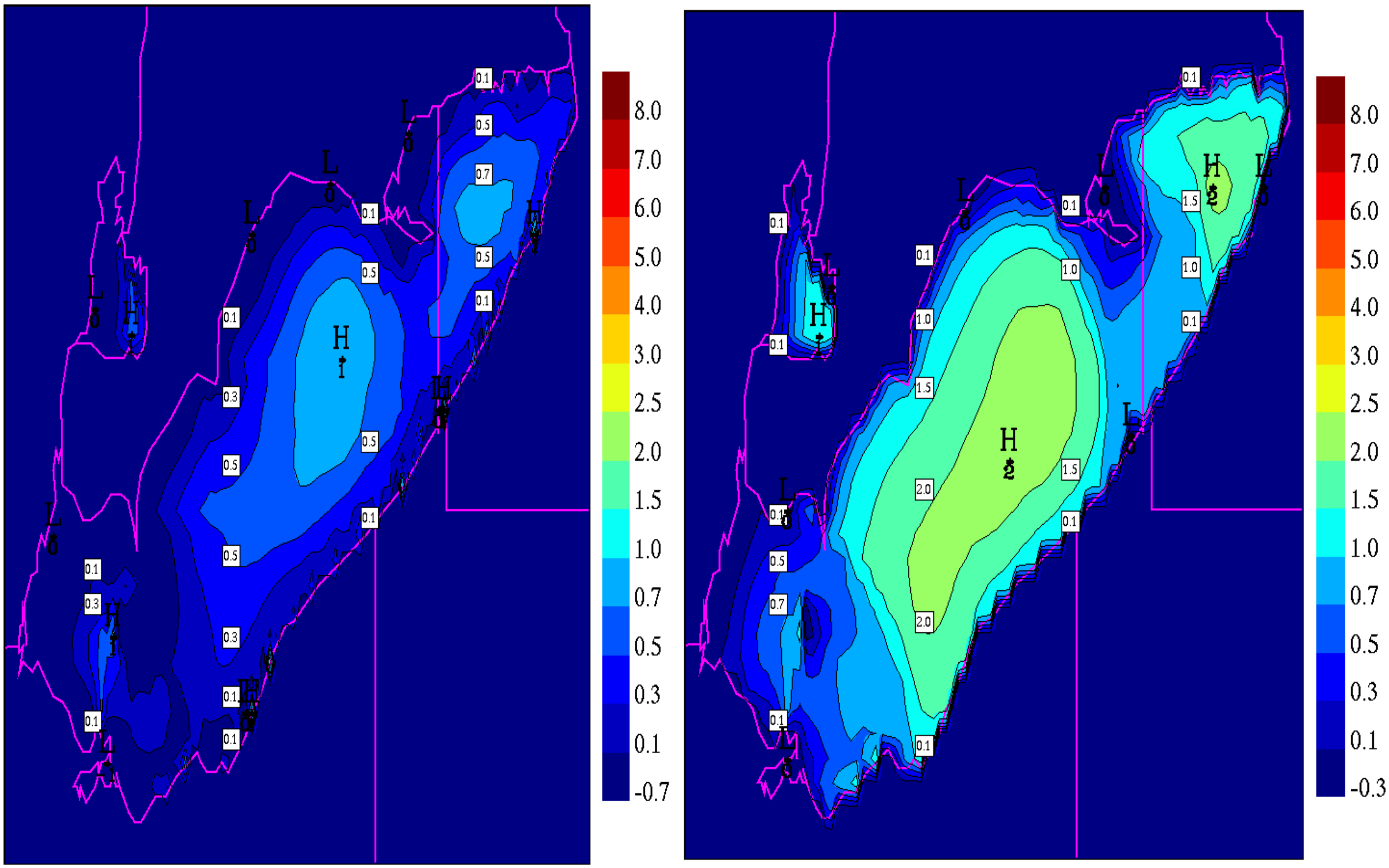
Snapshots of: ***WM1 SWH - KM2 SWH (left panel) and WM1 SWH - SJ1 SWH (right panel) valid 1500 UTC 13 November 2003***



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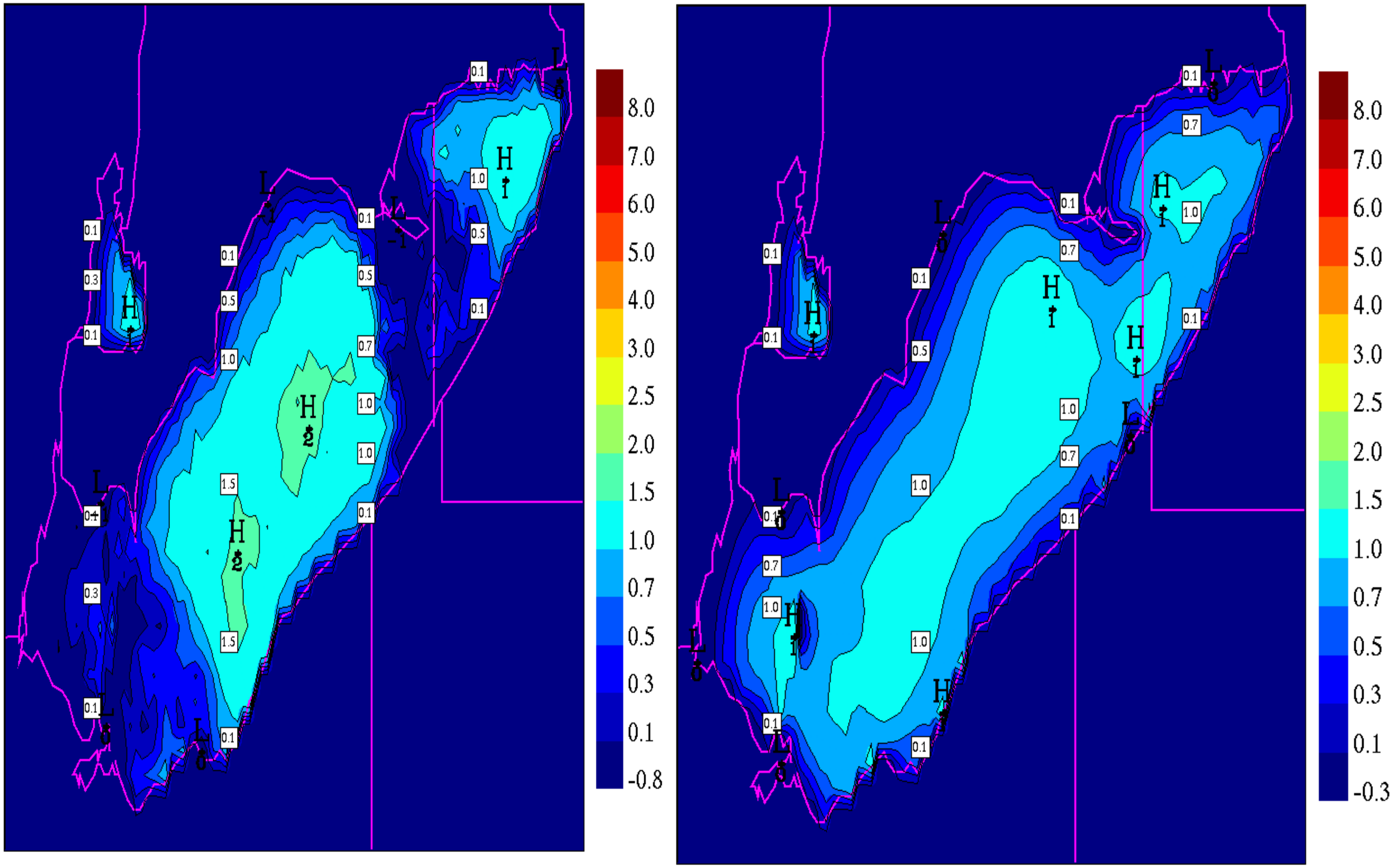
Snapshots of: WM1 SWH - SJ2 SWH (left panel) and WM1 SWH - SK1 SWH (right panel) valid 1500 UTC 13 November 2003



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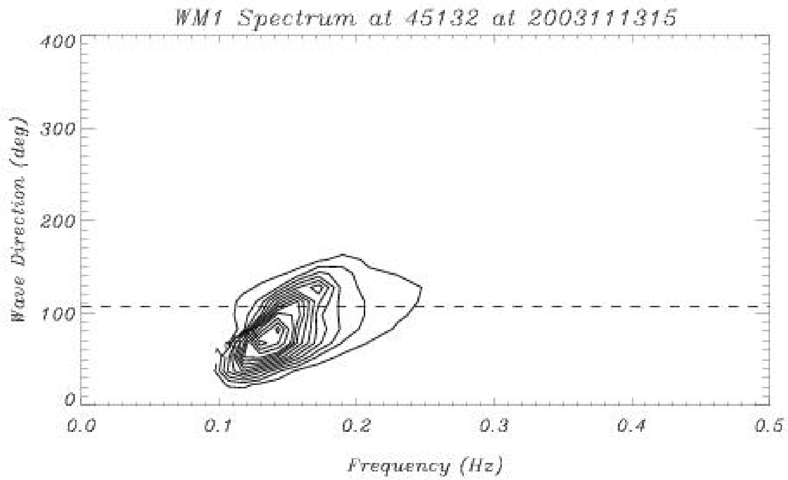
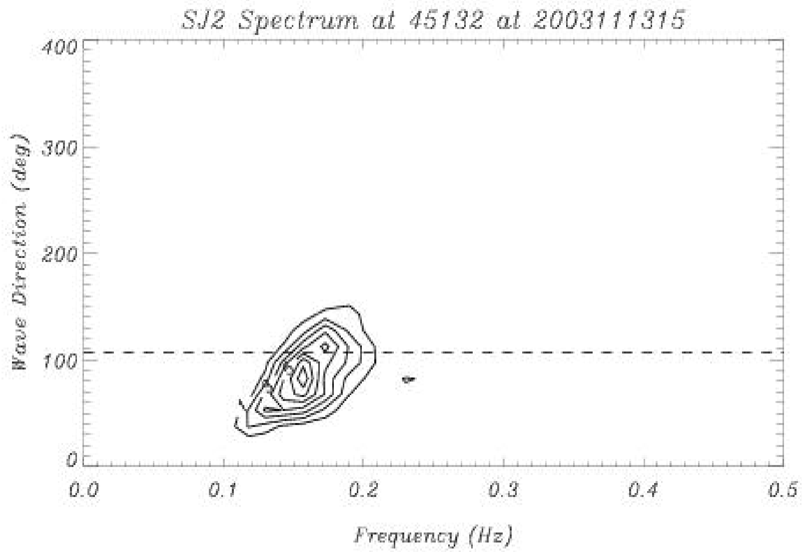
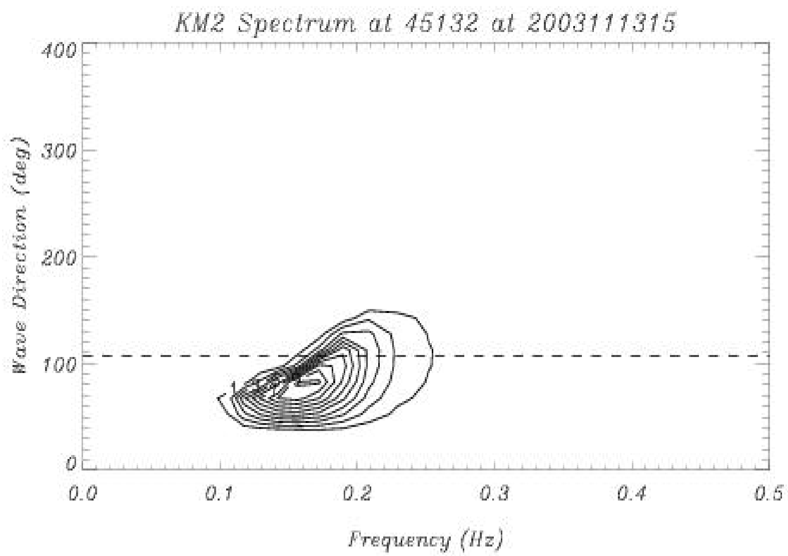
Model 2-D Spectra ($m^2/(Hz.rad)$) valid 1500 UTC 13 November 2003

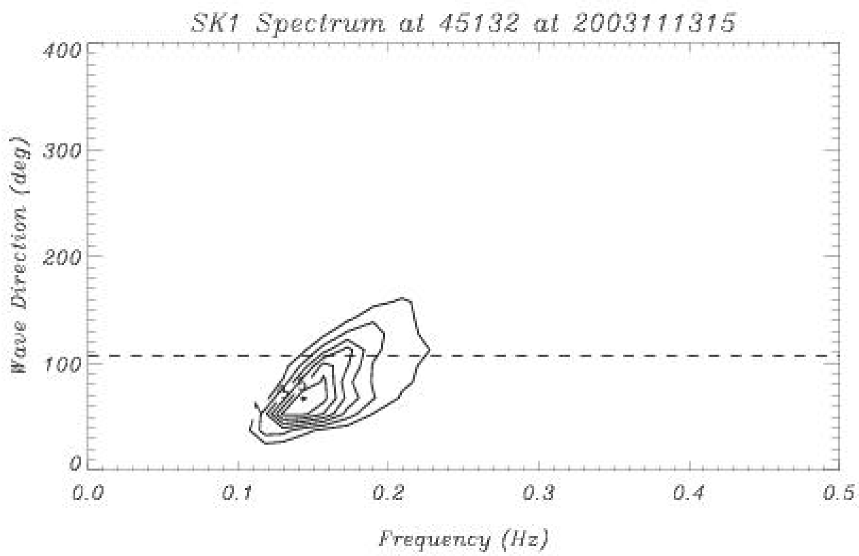
Dashed line: Direction to which wind is blowing

Contour intervals ($m^2Hz^{-1}rad^{-1}$): 1 unit for 1st 10 units and 2 units thereafter









Model Statistics

bias = S(model - buoy)

SI (scatter index) = Stddev/(buoy mean); r = linear correlation coefficent

ac = anomaly correlation; rv = reduction of variance; s = symmetric slope

WAVE HEIGHT STATISTICS (m)

	WAM	KMODEL	KMODEL	SWAN	SWAN	SWAN
Run ID	WM1	KM1	KM2	SJ1	SJ2	SK1
Buoy mean	1.043	1.043	1.043	1.043	1.043	1.043
Model mean	1.136	0.819	1.204	0.815	1.076	1.119
Bias	0.093	-0.224	0.161	-0.228	0.033	0.076
Stddev	0.319	0.360	0.376	0.310	0.291	0.277
SI	0.305	0.345	0.361	0.297	0.279	0.265
r	0.938	0.919	0.912	0.941	0.938	0.945
ac	0.927	0.887	0.890	0.910	0.934	0.933
rv	0.844	0.746	0.764	0.791	0.879	0.884
s	1.089	0.772	1.131	0.787	0.989	1.016
N (no. of obs.)	412	412	412	412	412	412

PEAK PERIOD STATISTICS (s)

	WAM	KMODEL	KMODEL	SWAN	SWAN	SWAN
Run ID	WM1	KM1	KM2	SJ1	SJ2	SK1
Buoy mean	4.591	4.591	4.591	4.591	4.591	4.591
Model mean	4.479	4.542	4.008	4.046	4.441	4.294
Bias	-0.112	-0.050	-0.583	-0.545	-0.150	-0.298
Stddev	0.778	0.974	0.973	0.794	0.773	0.810
SI	0.169	0.212	0.212	0.173	0.168	0.176
r	0.846	0.768	0.745	0.840	0.850	0.836
ac	0.834	0.754	0.704	0.803	0.839	0.826
rv	0.717	0.563	0.409	0.574	0.716	0.658
s	0.967	0.987	0.864	0.874	0.952	0.919
N (no. of obs.)	411	411	411	411	411	411

CONCLUSIONS

- ***Intensities of 1-d spectral peaks of 3 main wave episodes are well captured by the 3 models when compared with the buoy 1-d observations.***

- ***Given the right choice of tunable parameters the K-model with nonlinear S_{ds} and no S_{nl4} produced results in close agreement with those of the other 2 models and with the buoy observations.***
- ***The modified SWAN implementaton of WAM4 produced results in closer agreement with observations and with WAM4.5 than those of WAM4 as actually implemented by SWAN.***

- ***The timings of the peak SWH coincided well with the observed timings in all 3 models***
- ***The statistics indicate that the 3 models show minimal differences and relatively good skill suggesting that the WAM4.5 can be used to produce wave forecasts in an enclosed body of water such as Lake Erie.***

CURRENT and FUTURE WORK

- ***CURRENT***
  - **Operational implementation of:**
    - **WAM4.5 on the Great Lakes**
    - **WAM4.5 with grid resolution of 0.5º over the northwest Atlantic and northwest Pacific**

- ***FUTURE***
  - Nesting of the K-model with the WAM4.5. The nested version is to be tested in the Gulf of St. Lawrence with and without currents