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AN INTERCOMPARISON STUDY BETWEEN THE WAVE MODELS MRI AND MRI-II *

—— A COMPILATION OF RESULTS ——

I. Introduction

In 1981, a wave model intercomparison study was carried out by the SEA WAVE MODELLING PROJECT (SWAMP) Group composed of ten groups from USA, Japan and Europe. The main purpose of the intercomparison study was to test our present understanding of the physics of wind generated surface waves from the view point of wave medelling. Fortunately, the author was able to participate in the intercomparison study with a linear wave model called MRI (Meteorological Research Institute) developed for the routine operation of wave prediction (Uji and Isozaki 1972, Isozaki and Uji 1973 and Uji 1975) and it is now in use for the operation at the Japan Meteorological Agency. The study made clear strong points as well as weakness of MRI relative to models based on the parametric representation of the growth of wind waves (The SWAMP Group 1984 (Part 1), 1982 (Part 2) ; MRI gives always reasonable wave height distribution for any complex wind fields but it is inferior in predicting the spectral form for early growth stages of windsea.

A new wave model MRI-II was developed to overcome the weaknesses of MRI (Uji, 1984). MRI-II inherits both the way of numerical representation of wind wave spectrum and the calculation scheme for wave propagation. The intercomparison between MRI and MRI-II, therefore, is effective to made clear how the difference in basic physical assumptions for wave models produces an effect on predicted wave fields and the results can be useful for further wave model development. Furthermore, it is of great inportance to clarify the characteristics of MRI-II for the use of it in practical operation.

For above reasons, numerical experiments for all the SWAMP test cases are carried out using MRI-II and the results are plotted according to the SWAMP format. Here, all diagrams of MRI-II are collected together with those of MRI. For easy reference to the SWAMP reports, a diagram is numbered as Fig. 15-7. 4-1 i.e., the first numeral 15 shows the sequential number in this text, the second one 7.4 corresponds to the number in the SWAMP (Part 1) for the corresponding diagram and the third one 1 is in the SWAMP (Part 2). When there is no corresponding diagram in the SWAMP Part 1 or Part 2, the second or the third

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numeral is written zero. These diagrams will be more instructive if it will be used in conjunction with the SWAMP reports Part 1 and Part 2.

2. Outline of the models

The evolution of a surface wave fields in space x and time t is governed by the energy balance equation

$$\frac{\partial F}{\partial t}+\mathbf{C}g\cdot\nabla F=S_{net}=S_{in}+S_{nl}+S_{ds}, \tag{2.1}$$

where $F(\sigma,\theta;x,t)$ is the two-dimensional (2-D) wave spectrum, dependent on angular frequency σ and propagation direction θ, $\mathbf{Cg}=\mathbf{Cg}(\sigma,\ \theta)$ is the group velocity, ∇ is the gradient operator in the horizontal plane and the net source function S_{net} is represented as the sum of the input S_{in} from the wind, the non-linear transfer S_{nl} and the dissipation S_{ds}.

However we still do not have full understanding about the physics of energy transfer from wind to waves and the energy dissipation of wind waves and also do not have simple way of calculation for S_{nl}. A wave model, therefore, can have its own assumptions on the physics of wind waves, own parametrization of the source functions and own numerical style of representation of wind waves, so that several kinds of wave model were developed according to its usage.

2.1 MRI wave model

MRI contains four energy transfer processes, namely, linear and exponential wave growth, wave breaking leading to an equilibrium state of Pierson & Moskowitz (P-M) spectrum, frictional dissipation for over-saturated waves and decay of waves due to opposing winds. Neither wave-wave interactions nor shallow water effects are considered.

Wave energy is numerically represented by 352 (16 directions times 22 frequencies) spectral components. A special numerical scheme is used to prevent computational spacial deformation of each wave energy component (Uji and Isozaki, 1972). Equally spacing grids on local Cartesian co-ordinates are employed.

Three stages of the sea state are considered, and the source functions are assumed according to the each stage as follows :

$$\begin{aligned}
S_{net}&=(A+BF)\Gamma(\theta-\theta w)\ [1-(F/F_\infty)^2], && |\theta-\theta_w|\leqq 90^\circ, \sqrt{2}F_\infty=F,\\
S_{net}&=-D\cdot f^4F, && |\theta-\theta_w|\leqq 90^\circ, \sqrt{2}F_\infty<F,\\
S_{net}&=-[B\Gamma(\theta-\theta_w)+D\cdot f^4]F, && |\theta-\theta_w|>90^\circ,
\end{aligned} \tag{2.2}$$

where θw is the wind direction, $F_\infty=\Gamma(\theta-\theta_w)\phi_{PM}$ the fully developed 2-D spectrum, ϕ_{PM} the P-M spectrum, $\Gamma(\theta)$ the angular distribution of 2-D spectrum and is assumed to be proportional to $\cos^2\theta$. The numerical values of A and B were given by Inoue (1967) and the constant D is 1/3600 $\sec^3$.

2.2 MRI-II wave model

MRI-II contains five energy transfer processes, namely, the input by the wind, the non-linear transfer among the components of windsea by resonant wave-wave interactions, wave breaking, frictional dissipation and the effect of opposing winds. The non-linear energy transfer is expressed implicitly together with the wind effect by Toba's one-parameter representation of windsea, but neither swell-swell nor swell-windsea resonant interactions are considered.

The bases of the one-parameter representation are Toba's 2/3 power law between wave height and period, Toba's growth equation for the peak frequency of windsea,

$$d\sigma_P{}^{*-2}/dt^* = 1.783\times10^{-3}[1-\mathrm{erf}\ (4.59\times10^{-2}\sigma_P{}^{*-1})], \tag{2.3}$$

and the assumption that the form of the windsea spectrum is similar to that of P-M spectrum. These leads the parametric expression

$$F_P(\sigma;\sigma_P) = (\sigma_P/\sigma_{PM})\,\phi_{PM}(\sigma;\sigma_P)\,\Gamma(\theta-\theta_w)$$

for the 2-D spectrum of windsea, where σ_{PM} is the peak frequency of P-M spectrum .

Hypothetical assumptions are introduced to describe wave breaking effects. The basic idea on the assumptions is that wave breaking is a process in which a water mass at a wave crest with a mass proportional to the square of the wave height loses its wave motion energy. The expression of S_{ds}' thus obtained is

$$S_{ds}' = -Br\cdot F = -\{C_b\cdot Pi\cdot\sigma_P E^2[1+(\sigma/2\sigma_P)^4]/E_n\}\ F,$$

where E is the total energy, Br is the damping ratio, Pi is the probability of breaking determined from data collected by Toba (1979) as

$$Pi = 0.27\log\left(\frac{u^2}{\sigma_P\nu}\right) - 0.78,$$

$E_n = \iint[1+(\sigma/2\sigma_P)^4]F d\sigma d\theta$, $C_b = 1/600\mathrm{m}^{-2}$ and ν is the kinematic viscosity of air.

After all the net source function S_{net} is expressed as

$$S_{net} = [F_P(\sigma_P+\Delta\sigma_P) - F_P(\sigma_P)]/\Delta t,\quad |\theta-\theta_w|\leqq 90^\circ \text{ and } F\leqq F_P(\sigma_P+\Delta\sigma_P)$$

$$S_{net} = 0,\qquad |\theta-\theta_w|\leqq 90^\circ \text{ and } F_P(\sigma_P+\Delta\sigma_P) < F \leqq F_\infty$$

$$S_{net}=[1-(F/F_\infty)^2]Br\cdot F, \qquad |\theta-\theta_w|\leqq 90^\circ \text{ and } F_\infty<F\leqq 1.414\cdot F_\infty$$

$$-Br\cdot F, \qquad |\theta-\theta_w|\leqq 90^\circ \text{ and } F>1.414F_\infty$$

$$S_{net}=-[B\Gamma(\theta-\theta_w)+Df^4+Br]F, \quad |\theta-\theta_w|>90^\circ \tag{2.4}$$

where Δt is the time interval of numerical integration, $\Delta\sigma_P$ is the amount of change σ_P given by Eq. (2.3) for Δt, B is the growth rate of waves by wind and D is the constant, whose numerical values are taken over from MRI. When the energy of swells is preexisting at $t=0$, the effect of it for the growth of windsea is incorporated by the replacement of $\Delta\sigma_P$ by $\Delta\sigma_P'$ which satisfies the relation

$$\Sigma[F_P(\sigma,\theta;\sigma_P+\Delta\sigma_P')-F(\sigma,\theta)]=\Sigma[F_P(\sigma,\theta;\sigma_P+\Delta\sigma_P)-F_P(\sigma,\theta;\sigma_P)],$$
$$([\quad]\text{positive})$$

where ([ ]positive) means to summarize only for the positive bracketed values and $F(\sigma,\theta)$ is the 2-D spectrum at $t=0$ including the swell energy.

MRI-II has the same numerical representation of the wave spectrum and also the same scheme for wave energy propagation as MRI.

2.3 Fundamental differences between MRI and MRI-II

For MRI every spectral component is independently evolved with each other by the action of wind, the effect of wave breaking and the effect of the viscosity of water. On the other hand, for MRI-II a parametrical description of the windsea spectrum and the hypothetical assumptions of wave breaking on which the energy dissipation term is described by the total energy, the peak frequency of windsea and the friction velocity, are introduced. On the consequence of this introduction, spectral components are not independent with each other for MRI-II.

3. Test cases of the intercomparison study

3.1 Introduction

Seven test cases were proposed for the Wave Model Intercomparison Study by SWAMP Group in 1981. This set of seven test cases was so well designed to focus separately on various critical properties of the models that it is also useful to compare MRI-II to MRI and other wave models according to the same procedures as proposed in the Wave Model Intercomparison Study. Description of the test cases are printed in the SWAMP report Part 1 and Part 2. However, for easy reference a short description of notation and model tests is included in this report.

3.2 Test Cases

Seven test cases presented by the SWAMP Group are as follows :

Case I (advection test) is a pure swell propagation experiment. The wave energy of only one component of 2-D spectrum is assumed to be initially, $t=0$, on grid points. The spatial distribution at $t>0$ is calculated by the numerical advection scheme of the wave models.

Case II (fetch and duration limited growth) concerns the growth of a wave field for a uniform, stationary wind blowing orthogonally off a straight shore. The sea state was initially zero. For large fetch the evolution of the wave field with time provides duration limited growth curves, while for large duration the evolution of the wave field with distance off shore yields fetch limited growth curves. The results from this case provides a reference base for discussing this effects of the more complicated wind field geometries considered the remaining case study.

Case III (slanting fetch) represents a generalization of Case II to an off-shore wind blowing at an angle 45° to the coast. The purpose of the experiment is to test the directional response of the models for the simplest case of a uniform wind field in which an asymmetry is introduced by the boundary condition.

Case IV (half-plane wind) is intended to test the propagation of swell away from the side of a laterally bounded wind field into a neighbouring calm region. The case also provides information on the effect of a lateral wind field boundary on the generation of waves within the wind field region.

Case V (diagonal front) concerns the propagation of wind waves across a diagonal front where the wind turned suddenly by 90° from a parallel to a cross-wave direction. The purpose of the experiment is to test the directional response of the models to sudden change in the wind direction. Because of the inhomogeneity of the wave field, however, the experiment actually represents a rather complex superposition of directional response and advection effects. To separate the two, Case VII is added to the set of experiments.

Case VI (stationary and moving hurricane) represents the most complex wind field considered. It is included to test the performance of the models under extreme but nevertheless realistic wind conditions. Most of the critical elements of the models which are investigated separately in the other case studies come into play simultaneously in the examples.

Case VII (90° change in wind direction) represents a simpler analogue to Case V in which the advection effects are removed by considering a non-stationary rather than inhomogeneous wind field. At a given stage in the development of a duration limited windsea, the direction of a uniform wind field is suddenly turned by 90° into the cross wave direction, remaining constant thereafter. Since the wave field remains homogeneous throughout, only one integration variable, the time, enters rather than the two spatial co-ordinates of Case V.

3.3 Symbols

The symbols used in the description and the plots are recapitulated below.

C	Courant number
$\mathbf{C}g$	group velocity
E	total energy (kinematic total wave energy per unit area devided by ρg, where ρ is the density of water)
E_{PM}	total energy of the P-M spectrum
f	frequency
$\bar{f}$	mean frequency
f_P	spectral peak frequency
f_{PM}	peak frequency of P-M spectrum
$F(f)$ or ϕ	one-dimensional (1-D) energy density spectrum
F_{MAX}	maximum value of the energy density spectrum
$F_{PM}(f)$ or ϕ_{PM}	1-D P-M spectrum
$F(f, \theta)$	2-D energy density spectrum
g	acceleration of gravity
H_s	significant wave height
n	number of time steps
S	energy dispersion factor
T (or t)	time variable
$T_{45°}$	time for which mean direction of a given frequency band has turned by 45° (case VII)

Δt	time step
u_*	friction velocity
U_{10}	wind speed at 10 m height
$U_{19.5}$	wind speed at 19.5 m height
X, Y (or x,y)	Cartesian space variables (X is in ease-west direction and Y in north-south)
ΔX, ΔY	grid spacings
α and α_{PM}	Phillips' "constant" and that for P-M spectrum
θ	wave direction
$\bar{\theta}$	mean wave direction
θ_w	local wind direction
σ	angular frequency

3.4 Definitions of quantities

The definisions of dimensional quantities are as follows :

α_{PM} $=0.0081$,

g $=9.806\mathrm{m/s^2}$,

u_* $=0.855\mathrm{m/s}$,

U_{10} $=20\mathrm{m/s}$,

f_{PM} $=0.13g/\mathrm{U}_{10}=0.06374\mathrm{Hz}$,

E_{PM} $=[\alpha_{PM}g^2(2\pi f_{PM})^{-4}]/5=6.0552\mathrm{m}^2$,

H_s $=4E^{1/2}$,

$F_{PM}(f)$ $=\alpha_{PM}g^2(2\pi)^{-4}f^{-5}\exp(-5/4(f_{PM}/f)^4)$ or

ϕ_{PM} $=\alpha_{PM}g^2\sigma^{-5}\exp(-5/4(\sigma_{PM}/\sigma)^4)$,

where $\sigma_{PM}=((4/5)0.74)^{1/4}(g/U_{19.5})$,

$F_{PM}(f_{PM})$ $=\alpha_{PM}g^2(2\pi)^{-4}(f_{PM})^{-5}\exp(-5/4)=136.1\mathrm{m^2/Hz}$,

$F_{PM}(f,\theta)$ $=F_{PM}(f)\frac{2}{\pi}\cos^2(\theta-\theta_w)$, for $|\theta-\theta_w|\leqq\frac{\pi}{2}$,

0, for $|\theta-\theta_w|>\frac{\pi}{2}$,

$F_{PM}(f_{PM},\theta_w)$ $=86.64\mathrm{m^2/Hz\ rad}$,

$\bar{f}$ $=\frac{1}{E}\iint f\ F(f,\theta)\ df\ d\theta$,

$\bar{\theta}$ $=\arg\iint e^{i\theta}\ F(f,\theta)\ df\ d\theta$, with measured clock wise from North,

$E(n)$ $=\sum_{X,Y}E(x,y,n)$,

$$\overline{X}(n) = \sum_{X,Y} x\ E(x,y,n)/E(n),$$

$$\text{or } I(n) = \overline{X}(n)/\Delta X$$

$$\overline{Y}(n) = \sum_{X,Y} y\ E(x,y,n)/E(n),$$

$$\text{or } J(n) = \overline{Y}(n)/\Delta Y$$

$$S_X^2 = \sum_{X,Y} [x-\overline{X}(n)]^2\ E(x,y,n)/E(n),$$

$$S_Y^2 = \sum_{X,Y} [y-\overline{X}(n)]^2\ E(x,y,n)/E(n),$$

$$S^2 = S_X^2 + S_Y^2,$$

$$C = Cg\cdot\Delta t/\Delta x.$$

In Case VI, the Ross hurricane model has been used with a multiplication factor 0.5 for our calculation. The model is defined as follows :

$$F_R(f,\theta) = F_R(f)S_R(\theta),$$

$$S_R(\theta) = \begin{cases} (2/\pi)\cos^2(\theta-\theta_w), & |\theta-\theta_w| \leqq \frac{\pi}{2}, \\ 0, & |\theta-\theta_w| > \frac{\pi}{2}, \end{cases}$$

$$F_R(f) = \frac{\alpha g^2}{(2\pi)^4}\ f^{-5}\ \exp\{-1.25(f/f_P)^{-4} + (\ln\gamma)\ \exp[-\frac{1}{2\delta^2}(\frac{f}{f_P}-1)^2]\},$$

with parameters given by

$$\delta = 0.1,$$

$$f_P = \frac{g}{U_{10}}\cdot 0.97\xi^{-0.21},$$

$$\alpha = 0.035(\frac{U_{10}}{g}\cdot f_P)^{0.82},$$

$$\gamma = 4.7\xi^{-0.13}, \text{ for } \xi \leqq 3\times10^4,$$

and ξ is the dimensionless equivalent fetch

$$\xi = g\cdot r/U^2,$$

where r is the distance to the eye of the hurricane. For $\xi > 3\times10^4$,

set $F_R = 0$.

Non-dimensional variables are as follows :

$$E^* = Eg^2/u_*^4,$$

$$f_P^* = f_P u_*/g,$$

$$T^* = T\cdot g/u_*,$$

$$X^* = X\cdot g/u_*^2,$$

$f_{PM}{}^*$ $=5.5575\times10^{-3}$ and

$E_{PM}{}^*$ $=1.0896\times10^{3}$.

4. Specifications for calculation and plots

There are some differences in the conditions of calculation between SWAMP suggestions and ours. When the SWAMP out put is $X=30$km and ours is $X=40$km, from now on, it will be described as "out put is 40 (S. 30) km".

4.1 Case I——Free Propagation

The purpose of this test is to see how well the models advect energy. We consider a flat earth with an X-Y co-ordinate system. The models have equal grid spacings Δx and Δy of 40km in the 1560km square sea. The wave energy is uni-directional. Two directions were considered in SWAMP. However, our model have three characteristic directions and three directions of propagation are considered : (a) parallel to the Y-axis, (b) a 22.5° angle relative to the Y-axis and (c) a 45° angle relative to the Y-axis. Three different values of the frequency 0.05, 0.1 and 0.2 Hz are considered.

The initial distribution of energy in grid models should be as follows :

.0	.0	.0	.0	.0
.0	.1/16	.1/8	.1/16	.0
.0	.1/8	.1/4	.1/8	.0
.0	.1/16	.1/8	.1/16	.0
.0	.0	.0	.0	.0

The waves should propagate for 3 "simulated" days. The energy distributions every half day are plotted with theoretical location of the center of energy distribution.

S^2 for a wave packet initially at a single grid point is also plotted vs. C and n. For this case, no special plot formats required.

The time step of numerical integration Δt is 1 hour.

4.2 Case II——Fetch and Duration limited growth

With an initially calm sea, a wind of $U_{19.5}$ (S. U_{10}) $=20$m/s is turned on at $T=0$. The wind direction is perpendicular to a boundary, form the west. The western boundary is land, the energy at this boundary remains zero for $T>0$. All other boundaries are perfectly absorbing. Since our model results seem to become stationary by about 36 hours, the test was run for 72 hours to check the stationariness.

Output :

The evolution of the sea with time and fetch along the center of the grid from west to east will be displayed. Suggested output are $X=10$, 20, 30, 50, 100, 150, 200, 300, 400, 500, 750 and 1000 km at $T=1$, 2, 4, 6, 9, 12, 15, 18, 24, 30 and 36 hours, and additional output every 6 hours until stationary condition is attained. However our output are $X=40$, 80, 120 km and nearest grid points to the suggested ones, because our Δx and Δy are 40km. The time step is 1 hour.

Plots :

——E^* and f^* vs. X^* with T^* as the family parameter (plot description #1 and #3, from now on, it will be abbreviated "#1 and #3")

——E^* and f^* vs. T^* with X^* as the family parameter (#2 and #4)

——Contours of E/E_{PM} vs. X^* and T^* (#5)

——Contours of f_P/f_{PM} vs. X^* and T^* (#6)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with X^* as family parameter, stationary state (#7)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with T^* as family parameter, at X=1000km (#7)

——$F(f,\theta)/F_{MAX}$ vs. f^* and θ for $T=6$ and 36 hrs at $X=160$ (S. 150) km, and for $T=6$ and 36 hrs at $X=1000$km (#8).

Total number of suggested plots=12.

4.3 Case III——Slanting fetch

This test starts with the same configuration as Case II, except that the wind now blows diagonally (45°) across the 1000km × 1000km box ocean, and that both southern and western boundaries are land. The remaining boundaries are also land (S. subject to the same conditions as in Case II). The test run 72 hours (S. should be run until the model results are stationary) with Δx and Δy are 40km and Δt is 1 hour.

Output :

The test displays the evolution of the sea with time and asymmetric fetch. Suggested out put points for the spectra are at $(X, Y) = (80,80)$, (320,80), (760,80), (320,320), (760,320), and (760,760) [S. $(X, Y) = (75,75)$, (300,75), (300,300), (750,75), (750,300), and (750,750)] kilometers. Priority output times are $T=6$, 12, 24, 36 hours and stationary.

Plots :

——Contours of E/E_{PM} vs. X^* and Y^*, stationary state (#9)

——Contours of f_P/f_{PM} vs. X^* and Y^*, stationary state (#10)

——Custer diagram of E/E_{PM} and $\bar{\theta}$, stationary state (#11)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with T^* as family parameter, at the co-ordinates $(X, Y) = (80,80)$, (320,320), (760,760) km (#7)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with distance from the origin $\{(X^*)^2+(Y^*)^2\}^{1/2}$ as the family parameter corresponding to the same three coordinates as above. Use priority times (#7).

——$F(f,\theta)/F_{max}$ vs. f^* and θ for the steady state, at the coordinates $(X, Y) = (80,80)$, (320, 80), (760,80), (320,320), (760,320), and (760,760) km (#8).

Total number of suggested plots=17.

4.4 Case IV——Half-plane wind field

A stationary wind of $U_{19.5}$ (S. U_{10}) = 20 m/s is turned on at T=0 over the left half-plane. The right half-plane remains calm. The wind blows offshore to the north, paralled to a north-south front. This front lies grid points, to the left of and as near as possible to $X=500$ km in the 1000 km square sea. All boundaries are land (S.The southern boundary is land. All other boundary condition are as in Case II).

Output :

The test shows the radiation of swell from the windy half-plane into the calm half-plane and the influence of the front on the windsea development in the windy half-plane. Special output co-ordinates are Y=80,320 and 760 (S.75,300,750) km and X equals front location ±20 (S.40) km and 760 (S.750) km. Output only for the steady state.

Plots :

——Contours of E/E_{PM} vs. X^* and Y^* (#9)

——Contours of $\bar{f}/f_{PM}$ vs. X^* and Y^* (#10)

——Custer diagram of E/E_{PM} and $\bar{\theta}$ (#11)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with Y^* as family parameter for each output X^* (#7)

——$F(f,\theta)/F_{max}$ vs. f^* and θ at grid points with the co-ordinates $Y=80,320$ and 760km and X equals front location ±20km and 760km.

Total number of suggested plots=15.

4.5 Case VII——90° change in wind direction

A stationary wind of $U_{19.5}$ (S. U_{10}) = 20m/s is blowing to the north over an infinite ocean. At $T=0$ the wind turns instantaneously from north to west. Consider two cases : an initial state (at $T=0$) equal to a fully developed wind sea as developed by the model for times $T<0$, and an initial state equal to a half developed sea state, defined as the state for which the peak frequency of the wave spectrum f_P equals 2 f_{PM} for $U_{19.5}=20$m/s (S.$f=0.26\ g/U_{10}=2f_{PM}$) and for MRI the state is defined by $E=E_{PM}/8$ for $U_{19.5}=20$m/s. The ocean and wind field should be regarded as completely uniform spatially. This is achieved by bypassing the advection terms in the transport equation. The problem should be one-dimensional, dependent on time only.

Output :

The test displays the directional relaxation characteristics of the sea state under the influence of a turning wind. The problem is strictly one-dimensional, so the output is required at a single grid point only.

Plots :

——E^* vs. T^* for $T^*>0$, both cases(#2)

——$T_{45°}$ vs. f, both cases(#17)

——Custer diagram of $F(f,T)/F_{MAX}$(f) and $\bar{\theta}(f,T)$, both cases(#18)

——$F(f,\theta)/F_{MAX}$ vs. f^* and θ for $T=0$, 1, 2, 4, 6, 9, 12, 15, 18, 24, and 30 hrs, both cases(#8).

Total number of suggested plots=26.

4.6 Case V——Diagonal front

A front is runing diagonally southwest to northeast across a 1000km square grid. All boundaries are land(S. The southernboundary is land and all other boundary conditions are as in Case II) An initial condition is as in Case II. At $T=0$, a wind of $U_{19.5}$(S. U_{10})$=20$m/s, to the north below the front, and to the west above the front, is turned on. For grid points on the diagonal, the wind is to the north, so the front lies between the main diagonal line of grid points and the next diagonal line of points above (to the north of) the main diagonal.

Output :

The test shows the influence of a steady but spatially inhomogeneous wind field on the development of the sea. Special output points are at $(X,Y)=$(240,360),(280,320),(320,280),(360,240),(680,800),(720,760),(760,720) and (800,680) [S.$(X,Y)=$(225,350),(250,325),(325,275),(350,250),(675,800),(700,775),(775,725), and (800,700)] km. These points lie close to orthogonal lines crossing the front 300 and 750km from the southern boundary; the points are about 53 and 88km from the front. Choose your computing grid points to closest the these co-ordinates. Output only for the steady state.

Plots:

——Contours of E/E_{PM} vs. X^* and Y^* (#9)

——Contours of $\bar{f}/f_{PM}$ vs. X^* and Y^* (#10)

——Custer diagram of E/E_{PM} and $\bar{\theta}$ (#11)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with grid point as family parameter for the four points near 300km (#7)

——$F(f)/F_{PM}(f_{PM})$ vs. f^* with grid point as family parameter for the four points near 750km (#7)

——$F(f,\theta)/F_{MAX}$ vs. f^* and θ at or closest to the above mentioned special output points (#8).

Total number of suggested plots=13.

4.7 Case VI——Stationary and moving hurricane

Using idealized hurricane wind fields prepared by Atlantic Oceanographic & Meteorological Labs., run two cases: a stationary storm and a storm translating to the north (Y-direction) at 15 m/s. Consider the storms to be defined on coordinate $0 \leqq X \leqq 1280$ (S. 1300) km, $0 \leqq Y \leqq 1720$ (S. 1700) km. The eye of the stationary storm is at co-ordinates (650, 1400); the eye of the moving storm is at the same co-ordinates after 24 hours. If the computing grid is smaller, its position relative to this co-ordinate system is fixed at the modeller's discretion. Use the hurricane model whose energy is as much as 1/2 of Ross hurricane model (defined before) (S. Use the Ross hurricane model) for initial conditions and for boundary conditions throughout the run. Start the moving storm's eye 1296km south of (650,1400), even if much of the storm is off the computing grid. Run both storms for 24 hours.

Output:

Special output points are at (X,Y) = (640,1400), (600,1440), (600,1360), (680,1440), (680, 1360), (560,1520), (560,1280), (760,1520), (760,1280), (440,1640), (440,1160), (880,1640) and (880, 1160) 〔S. (X,Y) = (650,1400), (600,1450), (600,1350), (700,1450), (700,1350), (550,1500), (550, 1300), (750,1500), (750,1300), (425,1625), (425,1175), (875,1625) and (875,1175) km〕. These points lie at distance 10 (S. 0), 70, 140, and 318km to the northwest, southwest, northeast, and southeast of the eye. Output is required only at T=24 hours.

——Contours of H_s vs. X and Y for each storm (#12)

——Contours of $\bar{f}$ vs. X and Y for each storm (#13)

——Custer diagram of H_s and $\bar{\theta}$ for each storm (#14)

——$F(f)/F_{MAX}$ vs. f with distance from eye as family parameter for each azimuth and for each storm (#15)

——$F(f,\theta)/F_{MAX}$ vs. f and θ for each storm and at or closest to the above mentioned spectral output points (#16).

Note that all hurricane variables are dimensional.

Total number of suggested plots=40.

4.8 Note

It is important that essentially the same resolution and numerical scheme of each individual model is maintained in all tests, wherever possible. Further, it has to be noted that all models are supposed to operate in Cartesian co-oedinates for all exercises of the inter-comparisson study.

5. List of Diagram

Case I

1-0-0 contours of $F(f,\theta)$ vs. X and Y for $f=0.05$ Hz and $\theta=\pi$, every 0.5 day. Numerals on the contours show the interval of them in the unit of 1/1000. The energy is initially at the grid points marked+. The mark × shows the theoretically expected location of the center of the energy packet.

2-0-0 The same as Fig. 1-0-0 except for $\theta=9\pi/8$

3-0-0 The same as Fig. 1-0-0 except for $\theta=10\pi/8$

4-0-0 The same as Fig. 1-0-0 except for $f=0.10$ Hz and $\theta=\pi$

5-0-0 The same as Fig. 1-0-0 except for $f=0.10$ Hz and $\theta=9\pi/8$

6-0-0 The same as Fig. 1-0-0 except for $f=0.10$ Hz and $\theta=10\pi/8$

7-0-0 The same as Fig. 1-0-0 except for $f=0.20$ Hz and $\theta=\pi$

8-0-0 The same as Fig. 1-0-0 except for $f=0.20$ Hz and $\theta=9\pi/8$

9-0-0 The same as Fig. 1-0-0 except for $f=0.20$ Hz and $\theta=10\pi/8$

10-0-0 E(n) vs. n with f and θ as parameters. The energy level falls to zero when the energy travels out of the calculation area.

11-0-0 I(n) and J(n) vs. n with θ as parameter. The end effect appears at around $n=50$, because the maximum grid number in I and J direction is 40.

12-0-0 S^2 vs. n with C as parameter for $\theta=\pi$. The larger the value of C of the wave component, the faster the wave travels out of the calculation area and S^2 is reduced in value.

13-0-0 The same as Fig. 12-0-0 except for $\theta=9\pi/8$

14-0-0 The same as Fig. 12-0-0 except for $\theta=10\pi/8$

Case II

15-7.4-1 E^* vs. X^* with T^* as parameter

16-7.5-3 f_p^* vs. X^* with T^* as parameter

17-7.6-2 E^* vs. T^* with X^* as parameter

18-7.7-4 f_p^* vs. T^* with X^* as parameter

19-7.8-0 rescaled E^* vs. X^* by redefining the drag coefficient to lie the curve E^* vs. X^* as close as possible to the mean curve of the SWAMP results. The ratios Cd'/Cd of modefied drag coefficent Cd' to Cd of 1.83×10^{-3} are 1.05 and 0.87 for MRI and MRI-II respectively.

20-7.9-0 Same as Fig. 19-7.8-0 except rescaled f_p^* vs. X^*

21-7.10-0 Same as Fig. 19-7.8-0 except rescaled E^* vs. T^*

22-7.11-0 Same as Fig. 19-7.8-0 except rescaled f_p^* vs. T^*

23-0-5 contours of E/E_{PM} vs. X^* and T^*

24-0-6 contours of f_p/f_{PM} vs. X^* and T^*

25-7.3-7 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f* with X* as parameter

26-0-8 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f* with T* as parameter

27-0-9 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=6$ hrs, $X=160$km

28-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=36$ hrs, $X=160$km

29-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=6$ hrs, $X=1000$km

30-0-10 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=36$ hrs, $X=1000$km

Case III

31-8.1-0 wind field geometry for Case III and special output points

32-0-11 contours of E/E_{PM} vs. X^* and Y^*

33-8.2-12 contours of f_p/f_{PM} vs. X^* and Y^*

34-8.3-13 custer diagram of E/E_{PM} and $\bar{\theta}$ vs. X^* and Y^*

35-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=6$, 12, 24, 72 and point (80,80)

36-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=6$, 12, 24, 72 and point (320,320)

37-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=6$, 12, 24, 72 and point (760,760)

38-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=6$ hours and points A, B, and D

39-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=12$ hours and points A, B, and D

40-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=24$ hours and points A, B, and D

41-0-14 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=36$ hours and points A, B, and D

42-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ vs. f^* for $T=72$ hours and points A, B, and D

43-0-15 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=72$ hrs and point (80,80)

44-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=72$ hrs and point (320,80)

45-8.4-16 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=72$ hrs and point (760,80)

46-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=72$ hrs and point (320,320)

47-0-17 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=72$ hrs and point (760,320)

48-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T=72$ hrs and point (760,760)

49-8.5-0 location of models in the E_{III}/E_{II} vs. f_{PIII}/f_{PII} parameter plane at point F (MRI is not shown, as the peak wind sea frequency was not well defined for Case II for small fetch), where indices III and II refer to Case III and Case II for the same fetch.

Case IV

50-9.1-0 Wind field geometry for Case IV. A,B and C denote special output points.

51-0-18 countours of E/E_{PM} vs. X^* and Y^*

52-0-19 countours of $\bar{f}/f_{PM}$ vs. X^* and Y^*

53-9.2-20 custer diagram of E/E_{PM} and $\bar{\theta}$ vs. X^* and Y^*

54-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (480,80)

55-0-21 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (480,320)

56-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (480,760)

57-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (520,80)

58-0-22 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (520,320)

59-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (520,760)

60-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (760,80)

61-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (760,320)

62-9.4-23 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for $T = 72$ hrs and point (760,760)

63-0-24 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ for $T= 72$ hrs and point (480,80), (480,320) and (480,760)

64-0-0 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ for $T= 72$ hrs and point (520,80), (520,320) and (520,760)

65-0-25 scaled 1-D spectrum $F(f)/F_{PM}(f_{PM})$ for $T= 72$ hrs and point (760,80), (760,320) and (760,760)

66-9.3-0 model locations in the partameter plane spanned by the values of (E_{IV}/E_{II}) at points A and B

67-9.5-0 model locations in the partameter plane of E_C/E_B vs $\bar{f}_C/\bar{f}_B$, where indices B and C refer to points B and C.

CaseVII-1 ($f_P = 2f_{PM}$)

68-0-55 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 0 hrs

69-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 1 hrs

70-10.1a-56 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 2 hrs

71-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 4 hrs

72-10.1b-57 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 6 hrs

73-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 9 hrs

74-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 12 hrs

75-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 15 hrs

76-0-58 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 18 hrs

77-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 24 hrs

78-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 30 hrs

79-0-0 $T_{45°}$ vs. f

80-0-0 E^* vs. T^*

81-0-0 custer diagram of $F(f)$ and $\bar{\theta}$ vs. T^* and f^*

CaseVII-2 ($f_P = f_{PM}$)

82-0-59 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 0 hrs

83-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 1 hrs

84-0-60 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 2 hrs

85-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 4 hrs

86-0-61 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 6 hrs

87-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 9 hrs

88-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 12 hrs

89-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for 15 hrs

90-0-62 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 18 hrs

91-0-0 scaled 2-D specturm $F(f,\theta)/F(f,\theta)_{MAX}$ for 24 hrs

92-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for 30 hrs

93-0-0 $T_{45°}$ vs. f

94-0-0 E^* vs. T^*

95-0-0 custer diagram of $F(f)$ and $\bar{\theta}$ vs. T^* and f^*

CaseVII-1 and 2

96-10.11-0 peak spectral densities $F_{MAX}(f,\theta)/F_{PM}(f_{PM},\theta_W)$ for windsea and swell vs. time

Case V

97-11.1-0 wind field geometry for the diagonal front Case V

98-0-26 contours of E/E_{PM} vs. X^* and Y^*

99-0-27 contours of $\bar{f}/f_{PM}$ vs. X^* and Y^*

100-0-28 custer diagram of E/E_{PM} and $\bar{\theta}$ vs. X^* and Y^*

101-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (360,240)

102-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (320,280)

103-0-30 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (280,320)

104-0-31 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (240,360)

105-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (800,680)

106-0-29 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (760,720)

107-0-33 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (720,760)

108-0-32 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for T = 72 hrs and point (680,800)

109-0-0 scaled 1-D spectrum $F(f)/F(f_{PM})$ for points (360,240),(320,280),(280,320) and (240, 360)

110-0-34 scaled 1-D spectrum $F(f)/F(f_{PM})$ for points (800,680),(760,720),(720,760) and (680, 800)

111-11.5-0 E along the section S(cf. Fig.97-11.1-0). Note that fetch increase to the right (decreasing X^*)

112-11.6-0 Relaxation of mean wave direction along the section S

CaseVI-1 (Stationary Hurricane)

113-12.1-0 Hurricane wind field and selected output points for spectra

114-0-35 contours of H_s vs. X and Y

115-0-36 contouts of $\bar{f}$ vs. X and Y

116-0-37 custer diagram of H_s and $\bar{\theta}$ vs. X and Y

117-0-47 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400),(680,1440),(760,1520) and (880,1640) (eye and NE direction)

118-0-0 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (600,1440), (560,1520) and (440,1640) (eye and NW direction)

119-0-0 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (600,1360), (560,1280) and (440,1160) (eye and SW direction)

120-0-0 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (680,1360), (760,1280) and (880,1160) (eye and SE direction)

121-0-38 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (640,1400) (eye)

122-12.5-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (680,1440) (NE1)

123-0-39 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (760,1520) (NE2)

124-0-40 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (880,1640) (NE3)

125-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (600,1440) (NW1)

126-0-41 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (560,1520) (NW2)

127-0-42 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (440,1640) (NW3)

128-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (600,1360) (SW1)

129-0-43 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (560,1280) (SW2)

130-0-44 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (440,1160) (SW3)

131-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (680,1360) (SE1)

132-0-45 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (760,1280) (SE2)

133-0-46 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (880,1160) (SE3)

Case VI-2 (moving Hurricane)

134-0-48 contours of H_s vs. X and Y

135-0-49 contours of $\bar{f}$ vs. X and Y

136-0-50 custer diagram of H_s and $\bar{\theta}$ vs. X and Y

137-0-54 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (680,1440), (760,1520) and (880,1640) (eye and NE direction)

138-0-0 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (600,1440), (560,1520) and (440,1640) (eye and NW direction)

139-0-0 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (600,1360), (560,1280) and (440,1160) (eye and SW direction)

140-0-0 scaled 1-D spectrum $F(f)/F(f)_{MAX}$ for points (640,1400), (680,1360), (760,1280) and (880,1160) (eye and SE direction)

141-0-51 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (640,1400) (eye)

142-0-53 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (680,1440) (NE1)

143-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (760,1520) (NE2)

144-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (880,1640) (NE3)

145-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (600,1440) (NW1)

146-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (560,1520) (NW2)

147-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (440,1640) (NW3)

148-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (600,1360) (SW1)

149-0-52 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (560,1280) (SW2)

150-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (440,1160) (SW3)

151-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (680,1360) (SE1)

152-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (760,1280) (SE2)

153-0-0 scaled 2-D spectrum $F(f,\theta)/F(f,\theta)_{MAX}$ for point (880,1160) (SE3)

Case VI-1 and 2

154-12.4-0 Positions of $(H_s)_{MAX}$ for different models. Arrows point in $\bar{\theta}$ and are proportional to $(H_s)_{MAX}$ in length

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