

# Tutorial: Using WAVEWATCH III and SYMPHONIE

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In order to correctly reproduce the circulation in the nearshore and the surf zone, the processes linked to waves have to be considered. To take into account impact of waves into the 3D circulation model SYMPHONIE (Marsaleix et al., 2008, 2009a), we have followed the simplified equations of Bennis et al. (2011) which use glm2z-RANS theory (Ardhuin et al., 2008). These adiabatic equations are completed by additional parameterizations of wave breaking, bottom friction and wave-enhanced vertical mixing, making the forcing valid from the surf zone through to the open ocean. The wave forcing is performed by wave generation and propagation model WAVEWATCH III (Tolman, 2008, 2009; Ardhuin et al., 2010).

The first time we have attempted to introduce the wave forcing in a realistic configuration was in the Têt innershelf. The aim was to accurately reproduce phenomena induced by waves and current, covering scales from the whole Western Mediterranean Sea to the Têt mouth. A first numerical solution was to use nested grids. Yet, this has generated spurious flows at the boundary of the finest grid. The second solution was to use an unstructured grid or a grid with a variable resolution that covers the entire Têt inner-shelf, with a fine resolution at the Têt mouth which is gradually reduced to a coarser resolution in offshore zones. Using such grids ensures a smooth transition between offshore and nearshore zones.

For the study of nearshore circulation, we advice to use unstructured grids. In fact, the advantages of using such grids are to avoid boundary effects, to gain numerical calculations (because we will use 1 grid covering the entire domain instead of 3 for example)... This tutorial will explain how to use Symphonie with the wave forcing. The test case will be the Rhône's prodelta.

## I. Running the wave model

### 1. General principles

WAVEWATCH III™ (Tolman 2008, 2009) is a third generation wave model developed at NOAA/NCEP and IFREMER in the spirit of the WAM model (WAMDIG 1988, Komen *et al.* 1994). More information can be found on this website :

<http://polar.ncep.noaa.gov/waves/wavewatch/>

The phase-averaged spectral wave models represent the local sea state - at any point at the surface of the ocean and any point in time - by a discretized spectrum - say  $N$  - which has 2 dimensions:  $N(k, \theta)$ . Here  $k$  and  $\theta$  are the wavenumber ( $k=2\pi/L$  where  $L$  is the wavelength) and the direction of propagation (beware of wave direction conventions). The spectrum gives the distribution of the energy or some closely related quantities across the different components. Because the variance of any wave-induced disturbance can be related to the variance of the sea surface elevation, the spectrum can thus be used to compute many statistical parameters (bottom agitation, surface slopes ...).

The tasks performed by the model are:

- the propagation of the wave energy as a function of the wavenumber  $k$ , direction  $\theta$  and medium properties (water depth  $D$ , current profile ...)
- the integration of the sources and sinks of energy for each spectral component.

The model produces information about the sea state that are all estimated from the directional wave spectrum , these include a wide range of parameters ...

We will present today the unstructured version of WWIII, corresponding to the version 4 of the code. This version is under development for now, but will be released by NCEP within the next 6 months. The manual of this version can be found in the directory ~/session\_WW3model\_student/manual\_ww3/manual/

The main differences between the “officially released” version 3.14 of WWIII (that can be downloaded on the NOAA website) and this version are:

- WWIII on triangle-based grids : interface with and inclusion of Aron Roland's (TUD) propagation schemes on triangle-based meshes
- an updated wave breaking term as part of the ST4 switch option (which is now tested to also be able to deal with depth-induced breaking: this is Jean François Filipot's thesis work)
- extra output parameters (surface mean square slope, energy fluxes ...)
- direct output to NetCDF files with a ww3\_ounf program that can be used instead of ww3\_outf and ww3\_ounp program that can be used instead of ww3\_outp
- possibility to use an iceberg mask on top of the usual ice mask
- coastal reflection
- movable bed bottom friction
- infragravity wave modelling

## 2. Construction of the Symphonie grid and the mesh for WWIII

The first step is to generate a notebook\_grid for SYMPHONIE and notebook\_grid\_ww3 for WWIII. More details about the notebook\_grid can be found here: <http://sirocco.omp.obs-mip.fr/outils/Symphonie/Documentation/SymphonieDocNotebook.htm#grid>

Go in the directory ~/session\_WW3model\_student/generate\_mesh/ and modify the notebook\_grid and notebook\_grid\_ww3. You can view the grids with Xscan. by clicking on Symphonie tools in the Menu and loading the notebook\_grid. To launch Xscan use the command:

```
alias xscan='xscan'  
xscan -s ~/siroccoTP_Xscan.startup &
```

then click on:

**Menu**

**Symphonie tools**

On the right panel, load the notebook\_grid you want to use.

### a. WWIII mesh

For generating the mesh file, there are some steps:

- we need to interpolate the Ifremer bathymetry in our grid. Go in the directory: ~/session\_WW3model\_student /generate\_mesh/symtools/ then type:  

```
~/softs/src/tools-2.1.0/objects/symtools -zmin 0.1 -inv -b ../lion-2010-03-v1.grd -n  
../notebook_grid_ww3 -p ../contour_gdl
```

lion-2010-03-v1.grd is the bathymetry file and contour\_gdl.plg is the coastline in a polygone format. A bathymetry file in netcdf is generated: symphonie.chk.spherical.nc that you can view with Ncview. The grid is a rectangular mesh.

- We need to cut every cell of the mesh in two to form a triangular mesh. Go in the directory symmic:

```
cd ../symmic
```

and type:

```
~/softs/src/tools-2.1.0/objects /symmic -source symtools -d F-GRID -g
../symtools/symphonie.chk.spherical.nc ../symtools/symphonie.chk.spherical.nc
```

A symmic-regular.nei is then generated.

- Then we need to define the open boundary. For this, in Xscan, click on :

**Menu**

**Element Edition**

**File**

**open**

Open the file "symmic-regular.nei". Check that the « trigrd » option is activated. Then click on:

**Menu**

**T-UGO tools**

On the right panel, click on:

**Build Boundary conditions**

**Init boundary code**

**Set boundary code**

Click on the first node on the left side of the exterior frontier and on the last element on the right side of the exterior frontier. Type 5 for the boundary code. Then click on:

**save \*.bel file**

And call your file "symmic-regular.bel"

- Now you can convert the mesh in the gmsh format, from "symmic-regular.nei" to "symmic-regular.msh ":

```
~/softs/src/tools-2.1.0/objects/mesh-format -i symmic-regular.nei -o symmic-regular.msh -b
symmic-regular.bel --format="input=nei output=gmsh_ww"
```

GMSH is a format for unstructured grids that can contain comments and additional information ("tags") for the nodes and elements. WW3 developers strongly encourage users to include all the following in their GMSH grids:

- Node list (mandatory)
- Element list (mandatory), including : boundary point elements (type 15): not mandatory but very useful to define the open boundary
- list of triangle elements (mandatory)

## b. Symphonie grid

At the same time, we will generate the grid for Symphonie. Type:

```
cd ~/session_WW3model_student /generate_mesh/bathy_symphonie/ then type:
```

```
~/softs/src/tools-2.1.0/objects/symtools -zmin 0.1 -format " %6.2f" -b ../lion-2010-03-v1.grd -n
../notebook_grid -p ../contour_gdl
```

This generates the bathymetry: “symphonie.bathycote\_in.dat” Check if the boundaries are closed and correct them.

### 3. Running WWIII

#### a. First run with only the wind forcing

##### *First test with the GDL structured grid:*

Go in the directory ~/session\_WW3model\_student /WW3/gdl/test1/

Assuming that WWIII is installed and compiled, you will need to:

- generate a configuration: this is done with the input file “ww3\_grid.inp”. Check and fill in the “ww3\_grid.inp” and run it with the command: `./ww3_grid`  
All the input files are described in the manual of WW3.  
When it runs, ww3\_grid prints a lot of information to the screen. It is a good habit to store this in a file, like this: `./ww3_grid > ww3_grid.out` because then you can go back to check on namelists and other things. This operation generates 2 files: “mod\_def.ww3” : this is a binary file containing all the configuration information and “mask.ww3” : this is the land / sea mask in ASCII.
- Now we have to define the initial conditions in the file “ww3\_strt.inp”. Launch `./ww3_strt`
- We need then to define and pre-process the different forcing fields (going from ASCII / NetCDF to the binaries used at runtime): This is done in ww3\_prep.inp (wind or current or sea levels for example). In this test, we just take into account the wind fields. Run `./ww3_prep`
- Run the model: modify the ww3\_shel.inp file and run `./ww3_shel ...` but this can take some time. So we have to launch the calculations in parallel mode. This is done with the command:  
`mpirun -np 4 ./ww3_shel`  
Have a look to the file “log.ww3”

Now you have the results in two binary files:

- out\_pnt.ww3 : spectra at selected points
- out\_grd.ww3 : gridded output

In order to look at the results, you can post-process them with different methods:

- `./ww3_outp` to have results at some points that you have defined in ww3\_shel.inp. This operation turns results from binary runtime files to something usable, that can be compared with buoy data.
- if you have loaded the proper libraries of Netcdf, you can run `./ww3_ounf` (if you don't, you can launch `./ww3_outf` which makes grids in ascii). It will give results on the grid in NetCDF files that you can view with Ncview or Xscan.

##### *Second test with the Prodelta unstructured grid:*

Go in the directory ~/session\_WW3model\_student /WW3/prodelta/test1/

In this case, you will also need to:

- generate a configuration: this is done with the input file “ww3\_grid.inp”. Copy the mesh file you have generated before in the directory prodelta:  
`cp ../../generate_mesh/symmic/symmic-regular.msh ../`

Check the “ww3\_grid.inp” and run it with the command: `./ww3_grid > ww3_grid.out`

This operation generates 2 files: “mod\_def.ww3” : this is a binary file containing all the configuration information and “mask.ww3” : this is the land / sea mask in ASCII.

Be careful in the msh file, the sea depth must be negative. If they are positive, put a -1 factor at the requested line.

- Now we have to define the initial conditions in the file “ww3\_strt.inp”. Launch `./ww3_strt`
- We need then to define and pre-process the different forcing fields (going from ASCII / NetCDF to the binaries used at runtime): This is done in `ww3_prep.inp` (wind or current or sea levels for example). In the first test, we just take into account the wind fields. Run `./ww3_prep`
- Run the model: `mpirun -np 4 ./ww3_shel`  
Have a look to the file “log.ww3”

In order to look at the results, you can post-process them with different methods:

- `./ww3_outp` to have results at some points that you have defined in `ww3_shel.inp`. This operation turns results from binary runtime files to something usable, that can be compared with buoy data.
- if you have loaded the proper libraries of Netcdf, you can run `./ww3_ounf` (if you don't, you can launch `./ww3_outf` which makes grids in ascii). It will give results on the grid in NetCDF files. `ncview` won't be any useful because it is not rectangular, but `Xscan` will. In the “Menu”, choose “Unstructured netcdf”, then open your file.

### b. Second test with a wave forcing at the boundaries

For studying the sea state in the Rhône prodelta, we have actually used 3 nested grids. Their dimensions and coverages are defined in table 1 and figure 1. The MED and GDL grids are structured and the PRODELTA is unstructured.

Table 1: Computational grids used in this study for WWIII

Grids	Resolution	Latitude	Longitude	N $\lambda$	N $\theta$	$\delta t$ (s)
MED	0.1°	31°N to 45°N	-5.6°E to 16.3°E	141	220	400
GDL	0.02°	41.28 to 44.45°N	2.02°E to 11.86°E	117	213	300
Grid	Max. Reso	Min. Reso	Latitude	Longitude	No Nodes	$\delta t$ (s)
PRODELTA	103 m	250 m	43.0158°N to 43.5326°N	4.20345°E to 5.31655°E	28295	5

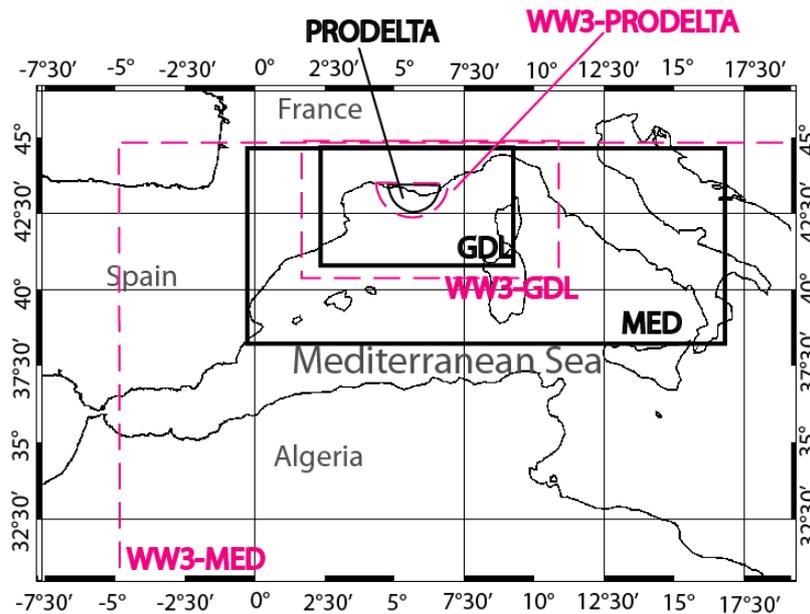


Figure 1: The three embedded domains used in Symphonie (black frame) and WWIII (pink frame)

We need to run WWIII for the MED grid and then the GDL grid. The following paragraph will explain how to make the imbrications of these grids.

### Structured grid (MED) -> structured grid (GDL)

We have to modify the two configurations

In the MED configuration:

In the med directory (~/session\_WW3model\_student/WW3/med/), for imposing the boundary conditions at the GDL grid, we have to define in the ww3\_grid.inp the points at the frontiers of the GDL grid where we want to generate an output file.

In our case, we add in the ww3\_grid.inp:

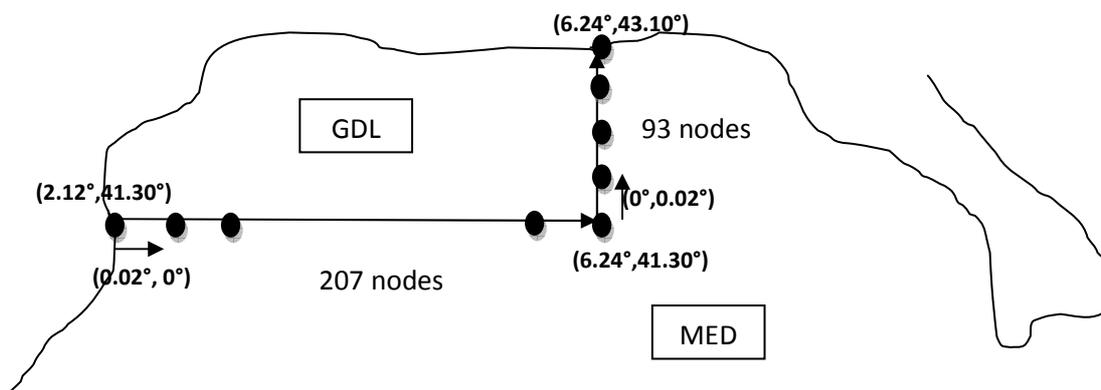
```

$ Output boundary points ----- $
  2.12  41.30  0.02  0.  207
  6.24  41.30  0.  0.02  91
  
```

Two frontiers at sea border the GDL grid. For the South boundary:

2.12 41.30: are the coordinates in degree of the point (2,2) of the GDL grid. In fact, the first and last lines and columns are numerically considered as land point in WWIII. So we have to take the interior points.

0.02 0. : are the increments in degree to define all the frontiers. Take the same discretization than the GDL grid.



Then in the ww3\_shel.inp, we have to define the period of the outputs. (in this case every 3 hours)

```
$ Type 5 : Boundary data (no additional data required).
$           The data file is nestN.ww3, see
$           w3iobp.ftn for additional doc.
$
20071101 000000 10800 20081115 210000
```

A nest1.ww3 file will be generated when running the model.

#### In the GDL configuration:

We take the file nest1.ww3 generated by the MED simulation and rename it nest.ww3 in the directory ~/session\_WW3model\_student/WW3/gdl/test2/.

Then we modify the ww3\_grid.inp :

```
$ Input boundary points ----- $
$ An unlimited number of lines identifying points at which input boundary conditions are to be
$ defined. If the actual input data is not defined in the actual wave model run, the initial conditions
$ will be applied as constant boundary conditions. Each line contains:
$ Discrete grid counters (IX,IY) of the active point and a connect flag. If this flag is true, and the $ present
and previous point are on a grid line or diagonal, all intermediate points are also defined $ as boundary
points.
  6 2 F
 212 2 T
$
 212 2 F
 212 92 T
$ Close list by defining point (0,0) (mandatory)
  0 0 T
```

We define the first and last point of the frontiers. The south frontier is thus:

```
  6 2 F
 212 2 T
```

When running ww3\_grid, the active points of the external boundaries are set to 2.

#### **Structured grid (GDL) -> unstructured grid (PRODELTA)**

In the ww3\_grid.inp of the gdl/ configuration, we have to define the boundary points of the prodelta mesh. These points can be obtained by running: `./getopenboundaryMSH symmic-regular.msh 0 0 > liste` in the directory ~/session\_WW3model\_student/WW3/prodelta/find\_boundary/

The getopenboundaryMSH program gets the open boundary information from the symmic-regular.msh file

In the file « liste », the first list of points must be written in the ww3\_grid.inp of the PRODELTA configuration (in the directory test2/), in the « Input boundary points » part. The second list of points must be written in the ww3\_grid.inp of the GDL configuration in the « Output boundary points » part. When

running `./ww3_shel` in the GDL configuration, a file `nest1.ww3` will be created. It has to be copied in the PRODELTA configuration and renamed `nest.ww3`.

## 4. Summary

To launch WW3, you have to fill in the input files (\*.inp) and then run:

```
./ww3_grid
```

```
./ww3_strt
```

```
./ww3_prep
```

```
./ww3_shel or mpirun -np 4 ./ww3_shel
```

```
./ww3_ounf
```

## II. From WWII to SYMPHONIE

The `ww3_ounf.inp` will generate all the files necessary to run the circulation model. But these files are unstructured. For converting them on the structured grid, we type in the same directory:

```
In -s ~/softs/src/tools-2.1.0/objects/ww3-U2S
```

```
for i in `ls ww3*.nc`; do ./ww3-U2S -r $i -n ../.././generate_mesh/notebook_grid_ww3 ; done
```

Then we prepare some lists for all the necessary files:

```
ls ~/session_WW3model_student/WW3/prodelta/test2/SG_ww3.*_hs.nc > file_list_hs
```

## III. Running the circulation model: SYMPHONIE

### 1. General principles of Symphonie

Hydrodynamic modelling is performed using the SYMPHONIE model (S). S is a Boussinesq hydrostatic ocean circulation model. Momentums and tracers are computed on an Arakawa curvilinear C-grid using an energy conserving finite difference method described in Marsaleix et al. (2008). The time stepping method consists of a Leap Frog scheme combined to a Laplacian filter (Marsaleix et al, 2012). A generalized terrain following coordinate preserves the vertical resolution within the bottom boundary layer and ensures the continuity of the fields near the bottom boundary. On the other hand, the well known "sigma coordinate errors" reported in Auclair et al (2000a) have been reduced through the use of a suitable pressure gradient scheme (Marsaleix et al, 2009, 2011). Radiative conditions are applied at the lateral open boundaries (Marsaleix et al, 2006). The large scale forcing terms, included in the radiation conditions formulation, are generally provided by the daily outputs of the MERCATOR system. The relevant questions related to the nested models are discussed in Estournel et al, 2009 and Auclair et al, 2006, 2000b. The high frequency barotropic forcing is provided by the TUGO tidal model (Pairaud et al, 2008). Besides, the astronomical tide potential has been implemented in the momentum equations according to Pairaud et al (2008). The air/sea fluxes are computed by the bulk formulae detailed in Estournel et al 2009. The river discharge is introduced through a lateral volume and salt conserving condition (Reffray et al, 2004). The turbulence closure, based on a TKE prognostic equation and two diagnostic turbulent length scales, covers

a wide range of applications including convective processes (Bougeault and Lacarrère, 1989, Gaspar et al, 1990).

This model has been widely used to understand the Mediterranean Sea circulation at different spatial and time scales, leading to a series of processus oriented papers generally including a validation section based on in situ data. Among these processes, we may cite the river plume dynamics (Reffray et al, 2004), the dense water formation over the continental shelves (Estournel et al, 2005, Herrmann et al, 2008), the dense water cascading (Ulses et al, 2008), the eddy formation (Rubio et al, 2009, Hu et al 2009), the northern current (Bouffard et al, 2008). Most of the other applications concern the Bay of Biscay. This region is notably known for the strength of the tidal currents (Pairaud et al 2008) and the related internal waves exited at the continental shelf break (Pairaud et al, 2010). The general circulation along the slope (Herbert et al, 2011) is eventually dominated by the Navidad current. Errors developed by the model in relation with the uncertainties surrounding the wind field have been studied by Le Hénaff et al (2009).

Numerical method	C-grid, s coordinate, energy conserving	Marsaleix et al., 2008 <a href="http://dx.doi.org/10.1016/j.ocemod.2007.07.005">http://dx.doi.org/10.1016/j.ocemod.2007.07.005</a>
<b>Time Stepping</b>	Leap-Frog+Laplacian Filter	Marsaleix et al., 2012 <a href="http://dx.doi.org/10.1016/j.ocemod.2011.11.002">http://dx.doi.org/10.1016/j.ocemod.2011.11.002</a>
<b>Pressure Gradient</b>	Pressure Jacobian	Marsaleix et al., 2009 <a href="http://dx.doi.org/10.1016/j.ocemod.2009.06.011">http://dx.doi.org/10.1016/j.ocemod.2009.06.011</a>
<b>Equation of state</b>	McDougall 2003	Marsaleix et al., 2011 <a href="http://dx.doi.org/10.1016/j.ocemod.2011.07.004">http://dx.doi.org/10.1016/j.ocemod.2011.07.004</a>
<b>Open boundary conditions</b>	Radiation conditions	Marsaleix et al., 2006 <a href="http://dx.doi.org/10.1175/JTECH1930.1">http://dx.doi.org/10.1175/JTECH1930.1</a>
<b>Sea surface conditions</b>	Bulk formulae, Craig & Banner TKE boundary conditions	Estournel et al, 2009 Ocean Science, 5, 73-90
<b>Turbulence closure</b>	Gaspar (JGR 1990)	
<b>Tides</b>	Tide potential & TUGO nesting	Pairaud et al, 2008 <a href="http://dx.doi.org/10.1016/j.csr.2008.03.004">http://dx.doi.org/10.1016/j.csr.2008.03.004</a>
<b>T,S advection</b>	QUICK	
<b>River input</b>	Lateral condition	Estournel et al, 2001 <a href="http://dx.doi.org/10.1006/ecss.2000.0685">http://dx.doi.org/10.1006/ecss.2000.0685</a>

## 2. How to run Symphonie ?

You have to fill in all the notebook files in the directory ~/session\_Smodel/PRODELTA/

Then go in the directory ~/session\_Smodel/S2010.25/UDIR/PRODELTA/

For taking into account the wave forcing, don't forget to activate the Istokes option at the compilation (in the makefile file). Compile the model with `make ifortpar=on`

Then go in ~/session\_Smodel/S2010.25/RDIR/PRODELTA/. Write in notebook\_list which notebook files you want to use. Run the model with the command: `mpirun -np 4 ./S25.exe`

For this simulation, we will use nested grids, whom coverages and characteristics are described in table 2.

Table 2: Computational grids used for Symphonie

Grids	Resolution	Latitude	Longitude	imax	jmax	levels
MED	2500 m	38.39°N to 44.44°N	-0.39°E to 11.65°E	402	270	40
GDL	800 m	41.98 to 43.57°N	3.03°E to 5.75°E	278	222	36
PRODELTA	From to 103m to 247 m	43.0285°N to 43.5267°N	4.22095°E to 5.29905°E	278	134	20

## IV. Appendix – Description of the wave forcing in Symphonie

### 1. General equations

The momentum equations of the coastal circulation model are rewritten in order to take into account the wave forcing. It gives the equations (18)-(21) of Bennis et al. (2011) which govern the evolution of the quasi-Eulerian velocities  $(\hat{u}, \hat{v}, \hat{w})$  which are equal to:

$$(\hat{u}, \hat{v}, \hat{w}) = (u, v, w) - (U_s, V_s, W_s)$$

$(u, v, w)$  are the mean Lagrangian velocities and  $(U_s, V_s, W_s)$  the Stokes drift in the horizontal  $(x, y)$  and vertical  $(z)$  directions. They are valid from the bottom  $z=-h$  to the local phase-averaged free surface  $z=\hat{\eta}$ .

$$\begin{aligned} \frac{\partial \hat{u}}{\partial t} + \hat{u} \frac{\partial \hat{u}}{\partial x} + \hat{v} \frac{\partial \hat{u}}{\partial y} + \hat{w} \frac{\partial \hat{u}}{\partial z} - f \hat{v} + \frac{1}{\rho} \frac{\partial p^H}{\partial x} \\ = [f + (\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y})] V_s - W_s \frac{\partial \hat{u}}{\partial z} - \frac{\partial J}{\partial x} + F_{m,x} + F_{d,x} \end{aligned}$$

$$\begin{aligned} \frac{\partial \hat{v}}{\partial t} + \hat{u} \frac{\partial \hat{v}}{\partial x} + \hat{v} \frac{\partial \hat{v}}{\partial y} + \hat{w} \frac{\partial \hat{v}}{\partial z} + f \hat{u} + \frac{1}{\rho} \frac{\partial p^H}{\partial y} \\ = - [f + (\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y})] U_s - W_s \frac{\partial \hat{v}}{\partial z} - \frac{\partial J}{\partial y} + F_{m,y} + F_{d,y} \end{aligned}$$

With  $p^H$  the hydrostatic pressure,  $f$  the Coriolis parameter,  $\rho$  the mean density and  $t$  the time.

The forces added by the wave forcing in the momentum equation are the following:

- the vortex force:  $(+\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y})V_s - W_s \frac{\partial \hat{u}}{\partial z}$  ,  $-(\frac{\partial \hat{v}}{\partial x} - \frac{\partial \hat{u}}{\partial y})U_s - W_s \frac{\partial \hat{v}}{\partial z}$ )
- the Stokes-Coriolis force:  $(fV_s, -fU_s)$
- the force linked to the wave-induced mean pressure J called the Bernouilli's head:  $(-\frac{\partial J}{\partial x}, -\frac{\partial J}{\partial y})$
- the mixing force where some parameterization of the wave-enhanced mixing are taking into account:  $(F_{m,x}, F_{m,y})$
- the force of dissipation by breaking, bottom dissipation and wave-turbulence interaction:  $(F_{d,x}, F_{d,y})$

The evolution of  $C$  the concentration of a passive tracer is then governed by :

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} + \frac{\partial wC}{\partial z} = 0$$

And the mass conservation becomes:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

These steady previous equations were implemented in MARS 3D (Lazure and Dumas, 2008). We transform them to a discrete form by using the flux-divergence form of the advection terms which can be found in most coastal hydrodynamic models (e.g. Marsaleix et al., 2008; Blumberg and Mellor, 1987; Shchepetkin and McWilliams, 2004). They become then:

$$\begin{aligned} \frac{\partial \hat{u}}{\partial t} + \frac{\partial u\hat{u}}{\partial x} + \frac{\partial v\hat{u}}{\partial y} + \frac{\partial w\hat{u}}{\partial z} - f\hat{v} + \frac{1}{\rho} \frac{\partial p^H}{\partial x} \\ = fV_s + \frac{\partial \hat{u}}{\partial x} U_s + \frac{\partial \hat{v}}{\partial x} V_s - \frac{\partial S^J}{\partial x} - \frac{\partial S^{shear}}{\partial x} + F_{m,x} + F_{d,x} \end{aligned}$$

$$\begin{aligned} \frac{\partial \hat{v}}{\partial t} + \frac{\partial u\hat{v}}{\partial x} + \frac{\partial v\hat{v}}{\partial y} + \frac{\partial w\hat{v}}{\partial z} + f\hat{u} + \frac{1}{\rho} \frac{\partial p^H}{\partial y} \\ = -fU_s + \frac{\partial \hat{u}}{\partial y} U_s + \frac{\partial \hat{v}}{\partial y} V_s - \frac{\partial S^J}{\partial y} - \frac{\partial S^{shear}}{\partial y} + F_{m,y} \\ + F_{d,y} \end{aligned}$$

This choice allows a global calculation of the term  $w = \hat{w} + W_s$  and the calculation of the value  $W_s$  is not needed anymore. In the new set of equations, the vortex force does not appear clearly and is replaced by a new force equal to  $(\frac{\partial \hat{u}}{\partial x} U_s + \frac{\partial \hat{v}}{\partial x} V_s, \frac{\partial \hat{u}}{\partial y} U_s + \frac{\partial \hat{v}}{\partial y} V_s)$  . But if we want to properly represent the wave forcing, then we have to take also into account the force present in the advection terms:  $(\frac{\partial U_s \hat{u}}{\partial x} + \frac{\partial V_s \hat{u}}{\partial y} + \frac{\partial W_s \hat{u}}{\partial z}, \frac{\partial U_s \hat{v}}{\partial x} + \frac{\partial V_s \hat{v}}{\partial y} + \frac{\partial W_s \hat{v}}{\partial z})$ , so we find again the vortex force.

The wave-induced mean pressure J term in Bennis et al. (2011) is replaced by a wave-induced and a shear-induced pressure terms  $S^J$  and  $S^{shear}$  .

The depth-uniform wave-induced term,  $S^J$  is equal to:

$$S^J = g \frac{kE}{\sinh(2kD)}$$

With  $D = \hat{\eta} + h$  the water depth,  $g$  the acceleration due to gravity,  $E$  the wave energy,  $k$  the wave number. Actually in realistic configurations, this term is summing over the spectrum of the wave model and is an output of the wave model.

The shear-induced term is given in Arduin et al. (2008b, Eq40) using a wave spectrum integrated form. Here it has been replaced by a spectrum-averaged expression around the principal frequency, that is:

$$S^{shear} = S_1^{shear} + S_2^{shear}$$

with

$$S_1^{shear} = -\frac{h_s^2}{16} \left\{ \frac{\sigma}{k} \tanh(kD) \left( k_x \left( \frac{\partial \hat{u}}{\partial z} \right)^{z=\zeta} + k_y \left( \frac{\partial \hat{v}}{\partial z} \right)^{z=\zeta} \right) + \frac{1}{2} \left( k_x \left( \frac{\partial \hat{u}}{\partial z} \right)^{z=\zeta} + k_y \left( \frac{\partial \hat{v}}{\partial z} \right)^{z=\zeta} \right)^2 \right\}$$

and

$$S_2^{shear} = \int_z^\zeta \left( w_s \left( \frac{\partial u_s}{\partial x} + \frac{\partial v_s}{\partial y} \right) - u_s \frac{\partial}{\partial z} (\hat{u} + u_s) - v_s \frac{\partial}{\partial z} (\hat{v} + v_s) \right) dz'$$

The 3D stokes velocity being non-divergent (Uchiyama et al, 2010), we have (Bennis et al, 2011, Eq18):

$$\frac{\partial u_s}{\partial x} + \frac{\partial v_s}{\partial y} = -\frac{\partial w_s}{\partial z}$$

This leads to:

$$S_2^{shear} = -\int_z^\zeta \left( \frac{1}{2} \frac{\partial}{\partial z} (u_s^2 + v_s^2 + w_s^2) + u_s \frac{\partial \hat{u}}{\partial z} + v_s \frac{\partial \hat{v}}{\partial z} \right) dz'$$

Assuming that  $w_s^2 \ll u_s^2 + v_s^2$ , the vertical velocity dependent terms are consequently omitted in our calculus. Last, we arbitrarily defined a pseudo equilibrium surface height with the depth-uniform terms, that is

$$\zeta_s = -\frac{S^J + S_1^{shear}}{g}$$

$\zeta_s$  is added to the other contributions of the low frequency variations of the sea surface height (atmospheric pressure, sea surface height field of the OGCM) to build the sea surface height of reference appearing at the right hand side of the barotropic open boundary conditions described in Marsaleix et al (2006, 2009).

Stokes velocities ( $U_s, V_s$ ) are:

$$(U_s, V_s) = \sigma k (\cos\theta, \sin\theta) E \frac{\cosh(2k(z+h))}{\sinh^2(kD)}$$

With  $\sigma$  the relative frequency and  $\theta$  the angle of wave propagation.

Actually in realistic configurations where we use the Wavewatch wave model, the Stokes drift is summing over the spectrum of the wave model:

$$(U_s, V_s) = \sum_{k_n} [U_{sf}(k_n), V_{sf}(k_n)] P(k_n)$$

With  $k_n$  the wave numbers associated to the different frequencies of the spectrum,  $(U_{sf}(k_n), V_{sf}(k_n)) = w_n k_n E$  are the surface Stokes velocities discretized in the frequency spectrum and provided by WW3.  $w_n$  is calculated by  $w_n = \sqrt{g k_n \tanh(k_n D)}$  and  $P(k_n)$  the vertical profiles associated to the different frequencies defined by:  $P(k_n) = \frac{\cosh(2k_n(z+h))}{\sinh^2(k_n D)}$ .

Stokes drift is strongly sheared at the surface so a high resolution near the surface is required.

In these equations, the wave-induced dissipation force as defined by Bennis et al. (2011) is split in two forces: the one associated to wave breaking dissipation (bathymetric breaking and whitecapping), and the one induced by the bottom dissipation. In absence of a known vertical profile, these two forces find themselves in the boundary conditions respectively at the surface and at the bottom as a surface and bottom stresses. One can impose an empirical vertical profile for the two forces (Bennis et al., 2011; Uchiyama et al., 2010), but this parameterization is smooth out with the choice of the vertical mixing parameterization.

## 2. Boundary conditions

Boundary conditions becomes then:

*At the surface:*

$$K_z \frac{\partial \hat{u}}{\partial z} \Big|_{z=\hat{\eta}} = \tau_{a,x} - \tau_{aw,x} + \tau_{wo,x} \quad \text{and} \quad K_z \frac{\partial \hat{v}}{\partial z} \Big|_{z=\hat{\eta}} = \tau_{a,y} - \tau_{aw,y} + \tau_{wo,y}$$

with  $K_z$  the vertical eddy viscosity calculated by a turbulent closure scheme representing the energy cascade toward small scales (Mellor and Yamada, 1982).  $\vec{\tau}_a = (\tau_{a,x}, \tau_{a,y})$  is the wind stress,  $\vec{\tau}_{aw} = (\tau_{aw,x}, \tau_{aw,y})$  the momentum flux from atmosphere to wave, and  $\vec{\tau}_{wo} = (\tau_{wo,x}, \tau_{wo,y})$  the momentum flux from wave to ocean linked to wave breaking (bathymetric breaking, or whitecapping), wave-turbulence interaction and viscous effects. In fact, waves influence the flux transfers from atmosphere to ocean. A part of the atmosphere momentum flux goes directly in the ocean via  $\vec{\tau}_a$ . Another part  $\vec{\tau}_{aw}$  goes in the wave field. Then this field is subjected to dissipation and releases  $\vec{\tau}_{wo}$ . Only a little part of  $\vec{\tau}_{aw}$  (5%) is radiated in the wave field (Ardhuin et al., 2004).

For a simulation at a bigger extent than the surf zone, these two terms are necessary. WW3 provides directly them. In the surf zone, the term  $\vec{\tau}_{wo}$  is predominant, and we can neglect  $\vec{\tau}_{aw}$ . One can link  $\vec{\tau}_{wo}$  to the wave dissipation due to wave breaking ratio  $\epsilon^b$  used by Uchiyama et al. (2010), by:

$$\vec{\tau}_{wo} = \frac{\epsilon^b \vec{k}}{\sigma}$$

In fact, this ratio is often used in the literature, and given at a  $\frac{1}{\rho g}$  factor by the SWAN wave model.

### At the bottom:

To add the momentum lost by waves due to bottom friction, we add the wave bottom stress vector  $\overrightarrow{\tau_{wob}}$  in the bottom boundary condition of the momentum equation:

$$K_z \frac{\partial \hat{u}}{\partial z} \Big|_{z=-h} = \tau_{bot,x} + \tau_{wob,x}$$

$$K_z \frac{\partial \hat{v}}{\partial z} \Big|_{z=-h} = \tau_{bot,y} + \tau_{wob,y}$$

Soulsby et al. (1995) have established a drag law function of the bottom stresses linked to waves, and to currents:

$$\overrightarrow{\tau_{bot}} = \overrightarrow{\tau_c} \left[ 1 + 1.2 \left( \frac{|\tau_w|}{|\tau_w| + |\tau_c|} \right)^{3.2} \right]$$

With  $\overrightarrow{\tau_c} = \rho_0 C_d \|\overrightarrow{V_b}\| \overrightarrow{V_b}$  the bottom stress due to current calculated ( $C_d$  is the bottom drag coefficient and  $\overrightarrow{V_b}$  the bottom velocity) and  $|\tau_w| = 0.5 f_w |\overrightarrow{u_{orb}}|^2$  the bottom stress linked to waves. With this parameterization, the bottom stress is increased since it is comprise between:  $\tau_c < \tau_{bot} < 2.2\tau_c$ .

$\overrightarrow{\tau_{wob}} = - \frac{\epsilon^{wd} \vec{k}}{\sigma}$  with  $\epsilon^{wd}$  is the wave bottom drag calculated using the parameterization of Reniers et al. (2004):  $\epsilon^{wd} = \frac{1}{2\sqrt{\pi}} \rho_0 f_w |\overrightarrow{u_{orb}}|^3$ ,  $\overrightarrow{u_{orb}}$  is the bottom wave orbital velocity:  $|\overrightarrow{u_{orb}}| = \frac{\sigma H_s}{\sqrt{8} \sinh(kD)}$  and  $f_w$  is the wave friction factor that can be calculated according to Myrhaug et al. (2001).

### Lateral boundary:

At the open boundaries, radiation conditions from Flather (1976) are applied as Uchiyama et al. (2009). Technically, we follow the equations (14) of Marsaleix et al. (2006). Thus, for the sea surface elevation external variable,

$$\eta = \eta_F \pm \sqrt{\frac{D}{g}} (\hat{u}^N - u_F^N)$$

Where  $\hat{u}^N$  is the velocity normal to the boundary, and F refers to the external forcing terms. If waves are the only external forcing,

$$\begin{cases} \eta_F = -\frac{\zeta_S}{g} \\ u_F^N = -U_S^N \end{cases}$$

Non linear terms and J are negligible offshore, and equation (2) is dominated by the Coriolis force, so a steady solution suggests the previous equation. Yet, it is less justified in shallow waters.

## 3. Wave-induced vertical mixing

The eddy viscosity  $K_M$  and the eddy diffusivity  $K_H$  respectively used in the momentum and tracer equations are given by:  $K_M = \sqrt{2E_k} l_{SM}$ ,  $K_H = \sqrt{2E_k} l_{SH}$ . The turbulent length  $l$  is related to  $E_k$  the turbulence kinetic energy (TKE) and to  $\epsilon$  the dissipation rate of TKE according to:  $l = c_0^3 k^{1.5} \epsilon^{-1}$

$S_M$  and  $S_H$ , the quasi-equilibrium stability functions of Kantha and Clayson (1994), depend on  $E_k, \varepsilon$  and the Brunt-Väisälä frequency. The equations for  $E_k$  and  $\varepsilon$  (Burchard and Bolding, 2001) are:

$$\begin{cases} \frac{dE_k}{dt} = \frac{\partial}{\partial z} (K_M \frac{\partial E_k}{\partial z}) + P + B - \varepsilon \\ \frac{d\varepsilon}{dt} = \frac{\partial}{\partial z} \left( \frac{K_M}{\sigma_k} \frac{\partial E_k}{\partial z} \right) + \frac{\varepsilon}{E_k} (c_1 P + c_3 B - c_2 \varepsilon) \end{cases}$$

Where  $P = K_M \left[ \left( \frac{\partial \bar{u}}{\partial z} \right)^2 + \left( \frac{\partial \bar{v}}{\partial z} \right)^2 \right]$  is the production term and  $B = \frac{g}{\rho_0} K_H \frac{\partial \rho}{\partial z}$  is the buoyancy term. Parameters values (Warner et al, 2005) are given in table 3.

**Table 3**

$\sigma = 1.3$	$c_0 = 0.5544$	$c_1 = 1.44$	$c_2 = 1.92$	$c_3 = 1 \quad B \geq 0$ $c_3 = -0.52 \quad B < 0$
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Bottom boundary conditions for  $E_k$ :

The  $E_k$  bottom boundary condition is based on the assumption of the equilibrium of the production and dissipation terms ( $P = \varepsilon$ ):

$$E_{k(z=-h)} = \frac{\|\vec{\tau}_{bot}\|}{\rho_0 \sqrt{2^{0.5} c_0^3 S_M}}$$

A surface boundary conditions for  $E_k$  based on  $P = \varepsilon$ :

The  $E_k$  surface boundary conditions can be obtained from a similar reasoning. Using the surface momentum boundary conditions:  $K_M \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right)_{z=\hat{\eta}} = \frac{(\tau_x, \tau_y)}{\rho_0}$  where  $\tau = \|\vec{\tau}_a - \vec{\tau}_{aw} + \vec{\tau}_{wo}\|$  is the surface stress, we obtain  $E_{k(z=\hat{\eta})} = \frac{\|\vec{\tau}_a - \vec{\tau}_{aw} + \vec{\tau}_{wo}\|}{\rho_0 \sqrt{2^{0.5} c_0^3 S_M}}$

A surface “flux” boundary conditions for  $E_k$  :

Alternatively, the boundary conditions can be specified as surface flux conditions, namely:  $K_M \frac{\partial E_k}{\partial z} = F$

Where the surface flux can be computed according to Craig and Banner (1994) ( $F = 100 \left( \frac{\tau}{\rho_0} \right)^{1.5}$ ) or directly prescribed from the “wave to ocean” turbulence flux computed by a wave model when available ( $\phi_{oc}$  term in WWIII). The surface flux condition is believed to produce more realistic results than the  $P = \varepsilon$  condition (Estournel et al, 2001).

Bottom and surface boundary conditions for  $\varepsilon$  :

The  $\varepsilon$  surface and bottom conditions are computed on the first level under the surface and above the bottom boundaries. Let  $z_0$  denotes the distance between this level and the considered boundary. Boundary conditions for  $\varepsilon$  are obtained from  $E_k$  and (2), using the latter with some appropriate hypothesis for  $l_B$  a boundary length scale value. A simple formulation (Warner et al, 2005) is eventually given by  $l_B = 0.4(z_1 + z_0)$ , where  $z_0$  is a length scale representing the roughness of the boundary. It corresponds to the depth of the wave breaking responsible of the increase of the turbulent mixing. Terray et al. (1996, 2000) by using

dissipation data, have linked this term to the significant wave height:  $z_0 = 1.6H_s$ . We therefore have tested  $0.8 H_s < z_0 < 2.4 H_s$  which are consistent values found in the literature (Raschle et al., 2006). Actually, we should not use the significant wave height, but the significant wave height of the wind-sea only. In fact, given that the swells have a small surface slope and consequently do not break, it is more appropriate to use the wave height of the wind sea only ( $H_{sw}$ ) to calculate the roughness length instead of the significant wave height  $H_s$  (Raschle et al., 2008). That value is calculated according to Raschle et al. (2008), and is now available in WWIII.

Unfortunately, this formulation  $l_B = 0.4(z_1 + z_0)$  potentially leads to unrealistic high values, especially when the grid resolution is low. It must indeed be realized that coastal ocean models generally have to deal with strong variations of bathymetry. For sigma coordinate models, this unavoidably results in a loss of resolution in the deepest areas of the numerical domain. A more complete formulation is thus used in our case. Following Estournel and Guedalia (1987), the stratification and the shear effects are taken into account through the use of the Richardson number:

$$\begin{aligned}
 l_B &= 0.4(z_1 + z_0) & Ri < 0 \\
 l_B &= 0.4(z_1 + z_0)(1 - 5Ri) & 0 \leq Ri \leq 0.16 \\
 l_B &= 0.4(z_1 + z_0)(1 + 41Ri)^{-0.8} & Ri > 0.16
 \end{aligned} \tag{10}$$

Minimum values :

$E_k$  and  $\varepsilon$  can not be lower than the minimum values given by  $E_{kmin} = 10^{-8}$  and  $\varepsilon_{min} = 10^{-12}$ . Moreover the length scale limitation suggested by Galperin (1988) is transposed to the dissipation rate of TKE, that is:

$$\varepsilon \geq k \frac{c_0^3}{0.53\sqrt{2}} \sqrt{\frac{-g}{\rho_0} \frac{\partial \rho}{\partial z}}$$

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