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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Application of Numerical Models

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Deliverable D2.3

Application of Numerical Models

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Summary

This report discusses key aspects of the application of numerical models to marine energy resource assessment. Wave and tidal modelling methodologies are described along with examples of specific models. The modelled processes, model inputs and interpretation of the output data are described and discussed. The role of model validation and calibration is also described.

CONTENTS

1 Introduction

1.1 Role of Numerical Models in Resource Assessment

1.1.1 Scope of this Report

This report is intended to express the authors' experience and knowledge in the field of wave and tidal numerical modelling. In particular it examines the application, calibration and validation of a range of models and model families. This report examines modelled processes, model inputs and interpretation of outputs. While illustrative model results are occasionally presented the generation of new data and quantifiable model comparisons are beyond the scope of this report.

1.1.2 Numerical Models for Resource Assessment

Numerical models potentially play several important roles in the assessment of the marine energy resource. For geographical level *Resource Characterisation* a model may be deployed to provide data over a wide area for a statistically significant period of time. This combination of wide spatial and long temporal coverage is generally not feasible by direct measurement. Point measurement devices (e.g. wave buoys) require multiple deployments to provide useful spatial information and long measurement programmes are not economical. Remote measurement devices (e.g. satellites) provide more detailed spatial information but their temporal coverage tends to be sporadic.

Having identified potentially exploitable sites with the aid of the resource characterisation process a more detailed *Site Assessment* must be conducted. This process aims to provide detailed spatial information sufficient for determining the placement of individual devices along with an understanding of the temporal variations expected over the life of the project.

Many sites of interest to the wave energy community are in relatively shallow water in coastal regions. Models deployed in site assessment, and to a lesser extent resource characterisation, may be used to transform data from a well described deep water region to these shallower regions. The deep water data may be based on physical measurements, a validated global model or a combination of the two. The transformation process is intended to take into account factors such as coastal topography, local bathymetry, wind and current.

Tidal current measurements, as with wave measurements, tend to be limited to point measurements with limited durations. Analysis of the harmonic components allows long term prediction of currents at geographical level. Numerical modelling aims to provide detailed spatial and temporal information accounting for local bathymetry and coastline influences.

In addition to the long term predictions outlined above numerical modelling may also play a role in short term forecasting, particularly in the field of wave energy. The problems associated with the variable nature of the resource (particularly the supply of electricity to the grid) may be mitigated in part if the output can be predicted several days in advance at a particular marine energy site. A calibrated numerical model, likely supported by on-site measurements, may be capable of providing short term forecasts based upon distant data from measurements or a global model.

1.2 Resource Assessment

Marine energy resource assessments may be conducted to various levels of detail depending on the stage of a project or the end user. In particular assessments may be conducted to identify suitable geographic locations for deployment. Once suitable areas have been identified a detailed assessment will be necessary to characterise a particular site. These processes will be referred to as *Resource Characterisation* and *Site Assessment* in the outputs of the EquiMar project.

1.2.1 Resource Characterisation

Resource characterisation is normally carried out to establish suitable geographic locations for deployment, and has the following objectives:

- To ascertain the potential resource for energy production with an explicitly stated degree of uncertainty;
- To identify constraints on resource harvesting.

1.2.2 Site Assessment

Site assessment is normally carried out prior to deployment, to establish the detailed physical environment for a particular marine energy project, with the following objectives:

- To assess the energy production throughout the life of the project;
- To characterise the bathymetry of the site to an explicitly specified and appropriate resolution;
- To ascertain the spatial and temporal variation of the resource with an explicitly stated degree of uncertainty;
- To describe metocean conditions;
- To establish extreme (survivability) conditions with a defined return period;
- To identify potential interference between multiple devices at the site.

2 WAVE RESOURCE MODELLING

2.1 GENERAL

High quality information is required for energy device planning and installation, both for energy resource assessment and for design purposes. Ideally this information should be provided by specific local measurements. There are, however, obstacles to this approach:

1. Measured local data are scarce and rarely available for the long period required for reliable information
2. Measurement programmes are costly and time consuming.
3. Most local measurement programmes (buoys and ADCPs) provide only point measurements.

Therefore a more cost-effective and spatially extensive data source is required.

Data covering the last 10-20 years is available from satellite remote sensing at a reasonably comprehensive level. However, satellites are available only along predetermined ground tracks, and provide information on the significant wave height and possibly period. Synthetic Aperture Radar (SAR) is, in principle, capable of providing full two-dimensional spectra, but their information is not available, rather sparse, and their accuracy is still highly debated.

The most practical solution to the measurement problem is provided by the results of wave models operational at several meteo-oceanographic centres around the world. These provide, and have provided for many years, continuous spectral information on dense regular grids covering the whole world. They are by far the most complete source of wave information presently available. Suitably validated against buoy and altimeter data, the synergy of these three sources provides the most complete and accurate source of wave data presently available. If buoy measured data are not already available in the specific area of interest, wave model data provides the most reliable form of resource assessment.

Data from a calibrated and validated model can also be used to bridge gaps in measured data due to the temporary unavailability of the measurement instrument (due to equipment failure, deployment delays etc.). It is also the case that the measurement instrument may not be capable of supplying all the necessary wave output parameters required for different analyses: for example, some particular types of instrument will only provide unidirectional wave spectral parameters, or only a small subset of wave parameters. In situations like this, if one is interested in directional wave properties, it may be possible to derive them directly from a numerical wave model.

2.2 WAVE MODELLING OVERVIEW

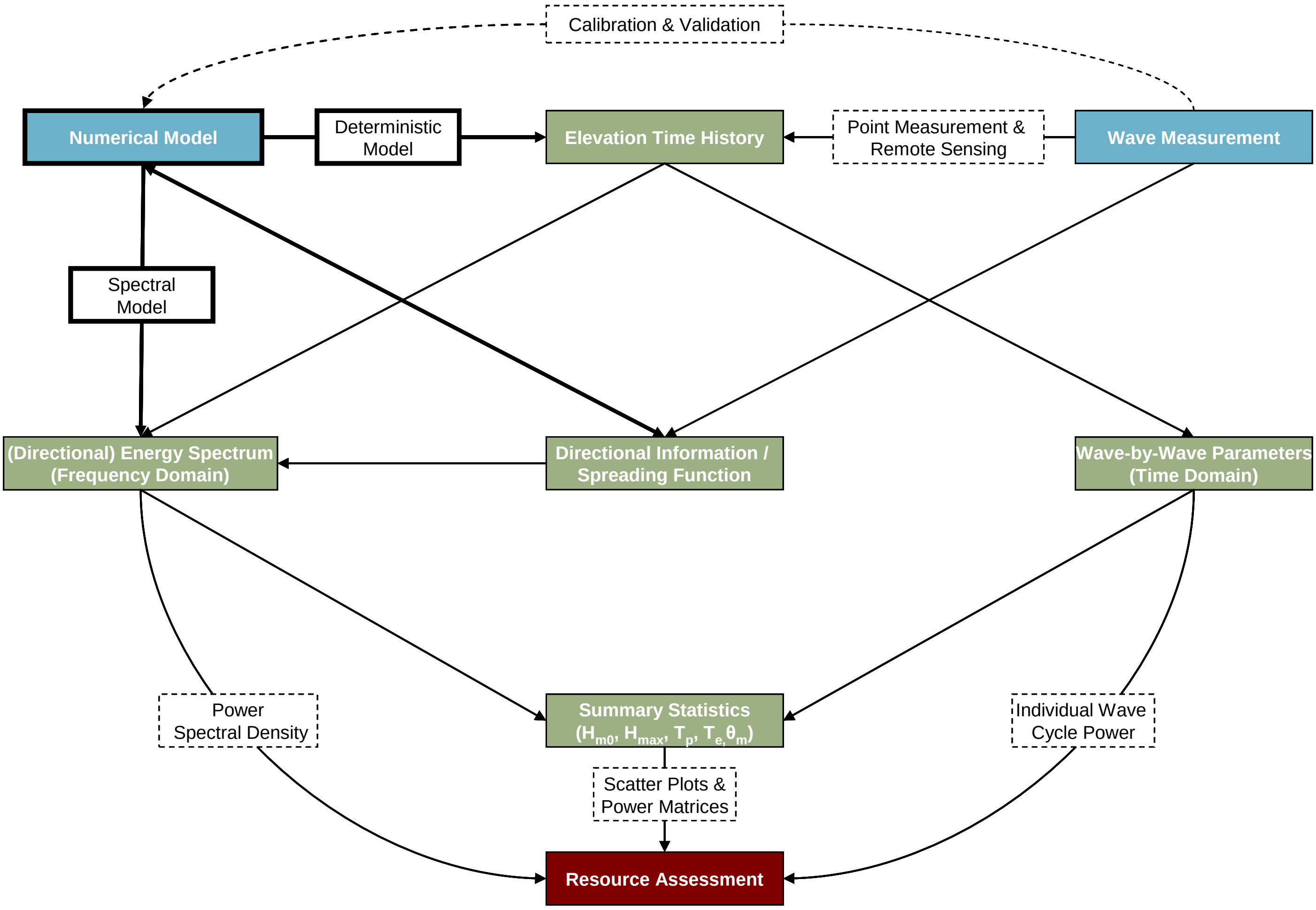

Figure 1 Schematic representation of possible wave Resource Assessment procedures

The sea state at a particular location may be described as a summation of many individual waves with a particular amplitude, propagation direction and frequency. The relationship between a component wave's amplitude and frequency is represented by the wave energy spectrum. The directional characteristics at each frequency may be described through the application of a directional distribution. An alternative representation of the sea state at a particular location is as a time series of the sea surface elevation. The role of numerical models in resource assessment in relation to measurement techniques is illustrated graphically in Figure 1.

Wave propagation models can thus be divided in two major categories:

Deterministic (phase resolving) models are based on a rigorous approximation of the fundamental hydrodynamic equations, and are typically applied in shallow or intermediate water. Their basic characteristic is the capability to translate the elevation time history from one point (the input) to another, providing a continuous high frequency description in space and time of the evolution of the sea surface.

Spectral (phase-averaged) models provide a statistical description of the wave conditions in space and time, typically at the nodes of a grid covering the area of interest. They provide, point by point, the distribution of wave energy in frequency, direction and its evolution in time. Spectral models are commonly divided into three generations:

- **First Generation:** Early models, developed in the 1960s, were designed to model wave energy growth and dissipation. Their major limitation is that they do not account for the nonlinear interactions between the different wave frequencies.
- **Second Generation:** The later generation of models used parameterised approximations to model the nonlinear spectral interactions. Explicit calculation of these interactions is very computationally expensive.
- **Third Generation:** First developed in the late 1980s, these models provide a full description of the physical processes governing wave evolution. This method, while computationally more expensive, requires fewer assumptions on the nature of spectral evolution than the parameterised relationships used in the second-generation models.

The two categories have quite different characteristics summarized in Table 1.

Table 1 Basic characteristics of deterministic (phase resolving) and spectral (phase averaged) models

	Deterministic	**Spectral**
Output	Surface profile	Spectral energy
Equations	Fundamental equations	Integrated equations
Range of application	Typically used in shallow water over limited areas	Global or local applications, deep and shallow water conditions
Modelled Physics	Most wave advection and nonlinear interactions	All the physical processes (but diffraction not explicitly considered and nonlinear interactions handled in an approximate way)
Computational requirements	Computationally expensive	Limited, potentially short
Modelled Area	Very limited in space	Both large and small scales
Usability[1]	Not user friendly	User friendly (at different levels)

In basic terms the deterministic models focus on a specific limited area, with a detailed surface time history at its border. They provide the full time-spatial description of the local sea surface, but are extremely time consuming and generally not user friendly.

Spectral models provide the basic information (significant wave height, direction, peak and mean frequency, plus full spectral energy distribution) required for engineering applications. They are widely available, mostly as open source, and some with a graphical interface allowing use also by non-expert users. They are widely used by both the scientific community and industry. The information produced during the last 20 years is available mostly at meteo-oceanographic centres, and more recently, results from some EU funded projects (e.g. My Ocean and Globewave) are openly available.

It is clear that, except in some specific cases, spectral models and their related databases provide the most suitable tools to study the long term wave conditions in areas of potential interest and are the focus of this report. Deterministic models may be useful to study specific situations over a very limited area, but the requirement for a deterministic, wave by wave, input should be considered.

2.3 WAVE MODELS

2.3.1 Model Summary

Spectral wave models underwent rapid development in the late 1980s and early 1990s, with the introduction of the so-called third-generation models. Unlike previous versions, these models are based uniquely on the physical numerical description of the various processes that occur during the evolution of the sea state. The basic advantage is that, as the physics of wind-waves is the same everywhere, these models can be applied anywhere, with the appropriate bathymetry (grid extension and resolution) and suitable wind data.

The most commonly used spectral wave models are briefly described in Table 2 and further discussed in Annexe 6.1.1.

[1] "User friendly" in this context refers to the level of expert understanding required to implement the model, rather than usability of the actual software interface (e.g. many models do not include a Graphical User Interface but may still be consider user friendly by this definition).

Table 2 Summary of selected wave models

WAM	WAM is in use at many of the world meteo-oceanographic centres and is **openly available**. It is not particularly user friendly, requiring a relatively high degree of user interaction. There is little scope for model calibration but WAM is highly reliable. WAM is used at the European Centre for Medium-Range Weather Forecasts (ECMWF, U.K.) and produces the best results. It works on regular and coastal grids
WAVEWATCH III	WAVEWATCH III is in use at many meteo-oceanographic centres and is **openly available**. The model is reasonably user-friendly. While the default version of the model is reasonably accurate, for best results it requires the adjustment, according to the area of use, of a very large number of parameters. Used at the National Centre for Environmental Prediction (NCEP, U.S.), it works on regular and nested grids.
SWAN	SWAN is probably the most widely applied model, especially by private and industrial users. The software is **openly available** and very user-friendly. Built originally for research, it offers the possibility of different theoretical approaches to the various processes considered. The default version leads to good results. It works on regular and irregular (finite elements or curvilinear) grids.
MIKE 21	MIKE21 is a 3rd generation spectral wind-wave model developed by DHI, Denmark and is **commercially available**. This model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. The model includes wave growth by action of wind, non-linear wave-wave interaction, dissipation by white-capping, dissipation by wave breaking, dissipation due to bottom friction, refraction due to depth variations, and wave-current interaction. Mike21 is a very user friendly software and works on unstructured mesh grids. A structured mesh is characterized by regular connectivity that can be expressed as a two or three dimensional array. This restricts the element choices to quadrilaterals in 2D or hexahedra in 3D. An unstructured mesh is characterized by irregular connectivity is not readily expressed as a two or three dimensional array in computer memory. This allows for any possible element that a solver might be able to use. Compared to structured meshes, the storage requirements for an unstructured mesh can be substantially larger since the neighborhood connectivity must be explicitly stored [CFD online, 2010]. See 2.3.3.2 for more details.
TOMAWAC	TOMAWAC one of the modelling software of the TELEMAC system, a processing line designed to study environmental phenomena in free surface transient flows (now openly available). Main scientific areas covered by Telemac are hydrodynamics, sediments transport and wave modelling. Since all the simulation modules of the TELEMAC system are based on the same framework, the coupling of them is easily achieved. Based on unstructured grids, it is suitable for the computation of spectral wave transformations in coastal complex areas It needs development for operational applications.

2.3.2 Modelled Processes

In general spectral models model the following processes:

a) Wave generation by wind

b) Non-linear interaction

c) White capping (breaking in deep water)

d) Bottom friction.

e) Shallow-water breaking (depth induced)

f) Advection

g) Refraction – shoaling

While non-linear interaction (b) is theoretically well defined, all the other listed processes are critically dependent on the input information to the model. Wave generation (a) depends on the wind speed, fetch and duration. White-capping (c) depends on the input wave spectrum. Processes (d) to (g) depends on the bathymetry and on the quality of the bottom characteristics and composition (mainly its material and grain size).

For resource assessment purposes local wave modelling will be applied to characterise a particular site. The actual domain of the model will, however, extend beyond the boundary of site to a point where suitable input information is available. This input information may take the form of a wave buoy but is more likely obtained from a global wave model. In the following sections we discuss how the accuracy of the results depends on this input information and on modelling of the various processes. The relative importance of these factors is summarised in Table 3.

Table 3 Relative importance of various physical mechanism in different regions of the ocean: 1- negligible; 2- minor importance; 3- significant; 4 – dominant (Battjes, 1994; Young, 1999)

Physical Process	Deep Oceans	Shelf Seas	Shoaling Zone	Harbours
Diffraction	1	1	2	4
Depth refraction/shoaling	1	3	4	3
Current refraction	1	2	3	1
Quad Interactions	4	4	2	1
Triad Interactions	1	2	3	2
Atmospheric Input	4	4	2	1
White-capping	4	4	2	1
Depth Breaking	1	2	4	1
Bottom Friction	1	4	2	1

2.3.2.1 Energy Dissipation

Nearshore spectral wave models account for wave energy dissipation through the processes of whitecapping, bottom friction and wave-induced breaking.

Energy loss through whitecapping is primarily controlled by wave steepness. However, it involves a number of highly nonlinear processes and has not yet been fully theoretically defined. Taking the SWAN model as an example, two options are available to account for whitecapping. The default formulation is derived from Hasselmann's pulse-based model (Hasselmann, 1974), reformulated by the WAMDI group (1988) for applicability in finite depth water. Coefficients within the formulation can be tuned by the user for model calibration, although default values are provided. The alternative is a nonlinear saturation-based model adapted from Alves *et al.* (2003). This formulation is not user-tuneable.

Wave energy is dissipated by a number of seabed mechanisms once waves propagate into regions where they can interact with the seabed (depth < wavelength/2), however bottom friction is dominant in regions with fine sandy bottoms, as is typical for continental shelves, and is the only bottom dissipation mechanism considered in SWAN. Energy loss via bottom friction can be expressed as

$$S_{bf} = -C_b \frac{\sigma^2}{g^2 \sinh^2(kd)} E(\sigma,\theta) \tag{1}$$

where C_b is the bottom friction coefficient, σ the frequency, k the wavenumber, d the water depth, and E the energy density. SWAN provides three possible formulations for C_b, each of which can be tuned by the user. The default formulation is an empirical term derived from the JONSWAP project (Hasselmann et al., 1973), with recommended values of C_b = 0.038m^{2}s^{-3} for swell conditions, and C_b = 0.067m^{2}s^{-3} for wind seas (SWAN User Manual, 2009).

Depth-induced wave breaking is another highly non-linear process, occurring when waves in shallow water become too steep to maintain their shape and collapse, dissipating large amounts of their energy in the process. SWAN models wave breaking based on the formulation of Battjes and Janssen (1978) for a single breaking wave. This process can be tuned by the user.

Further details on all these formulations can be found in the SWAN Technical Documentation (2006).

2.3.2.2 Reflection and Diffraction

Structures can be represented as an obstacle within the model through which a proportion of wave energy can be transmitted or against which waves can be reflected. The obstacle is defined as a sub-grid line which is narrow compared to the grid mesh resolution, and the width of the obstacle should be at least the size of one grid cell. As an example, in SWAN the proportion of wave energy transmitted through the obstacle is set by a user-defined transmission coefficient, which applies a constant energy reduction across the whole spectrum, leaving the spectral shape in the lee of the obstacle unchanged. It is also possible to set a transmission coefficient dependent on the height of the obstacle in addition to the incident wave conditions, which can also apply to submerged obstacles. Reflection is implemented by a coefficient determining the proportion of energy reflected. It can be either specular (angle of reflection equals the angle of incidence), or diffuse, i.e. the incident waves are scattered after reflection. Any such obstacle will also cause diffraction of waves around its ends.

2.3.2.3 Nonlinearity

Nonlinear wave-wave interactions are accounted for via quadruplet (four wave) and triad (three wave) interactions. Quadruplet interactions occur irrespective of water depth, but should be deactivated in the model when no forcing wind is present.. Triad interactions only occur in intermediate or shallow water regions. A description of these nonlinear interaction processes is given in the SWAN Technical Documentation (2006) and MIKE 21 (2008).

2.3.3 Model Setup

2.3.3.1 Computational Boundary Limits

A typical nearshore model will have a combination of ‘water’ and ‘land’ boundaries; water boundaries are boundaries between the model domain and the ocean, across which wave energy can freely propagate, whereas land boundaries occur at the shoreline where the ocean meets the land mass (see Figure 2). In an ideal scenario, accurate wave data would be available to input along all water boundaries. In reality, it is often the case that the only source of available wave data is from a single point measurement such as a wave buoy. Although it might be reasonable to assume that the recorded sea state is constant along the offshore boundary of the model, this will not be the case along boundaries where the water depth is varying as it nears the shoreline. The model can be successfully run with input along only one boundary; however care must be taken in regions close to the boundaries with no input. Wave energy can propagate out of the model along these boundaries, and therefore inaccurate results will be obtained in these regions, as illustrated in Figure 3. If only a single boundary is used for input, it is recommended that the model domain be sufficiently extended to ensure that the area of investigation is well removed from potential areas of disturbance at the lateral boundaries.

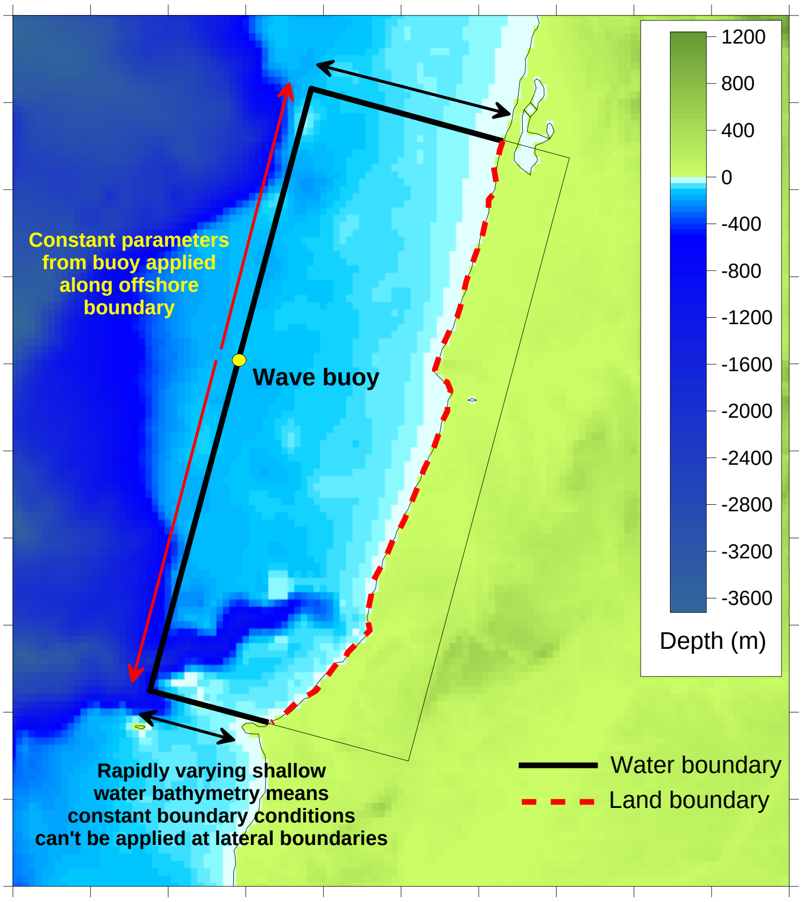

Figure 2 Example model domain illustrating potential issues with boundaries

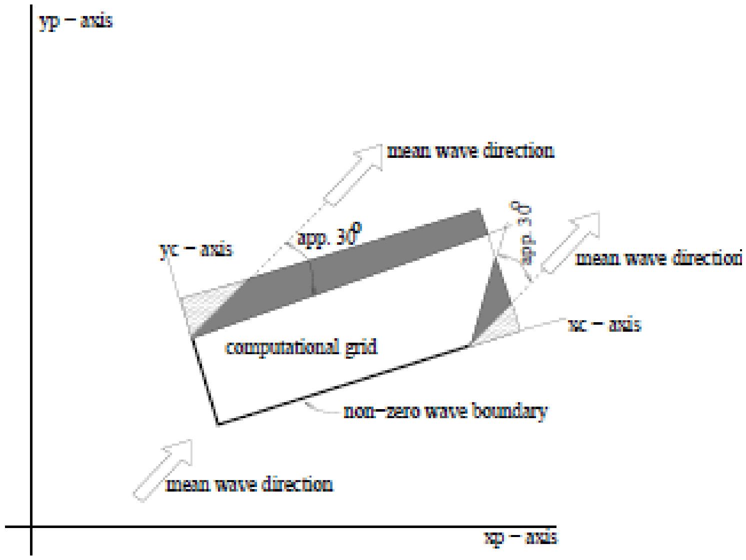

Figure 3: Potential areas of disturbance (shaded) in results due to lack of wave input along partial model boundaries (from SWAN User Manual, 2009).

2.3.3.2 Input grids

The propagation of spectral wave energy density within the model takes place over a user-defined computational grid representing a specific geographical area. Model inputs, such as bathymetry, wind and currents are provided on input grids which may be greater or identical to the computational grid. If the geographical domain of any of the input grids is smaller than the computational grid, it is sometime assumed (SWAN code for example) that the values at the boundary of the input grid will apply to the extended computational area. Two types of grid can be used: structured and unstructured.

Structured grids can be regular, i.e. the cells are rectangular and uniform, or curvilinear,i.e. the cells are quadrilaterals or cuboids. Regular grids have a consistent resolution, nesting must be used to move from coarse to finer scale models. Curvilinear grids provide greater flexibility by allowing variable resolution and grid contours may follow bathymetric lines (if the coastal region is not too complex).

Unstructured grids provide far greater flexibility by allowing variable resolution within a single grid and thus higher resolution in shallower water and around areas of interest where it is most needed. This potentially eliminates the need for nesting. Unstructured grids usually comprise a combination of triangles. An example of an unstructured grid is shown in Figure 4. Complex coastline and protection slopes may be well represented with unstructured grids.

In SWAN, for example, if the computational grid is regular, then all input and output grids must also be, although their domain and resolution may differ. If a curvi-linear computational grid is used, each input grid should be either regular, identical to the computational curvi-linear grid, or staggered with respect to the computational grid. If the computational grid is unstructured, then each input grid must be either identical to the computational grid, or regular and uniform (SWAN User Manual, 2009).

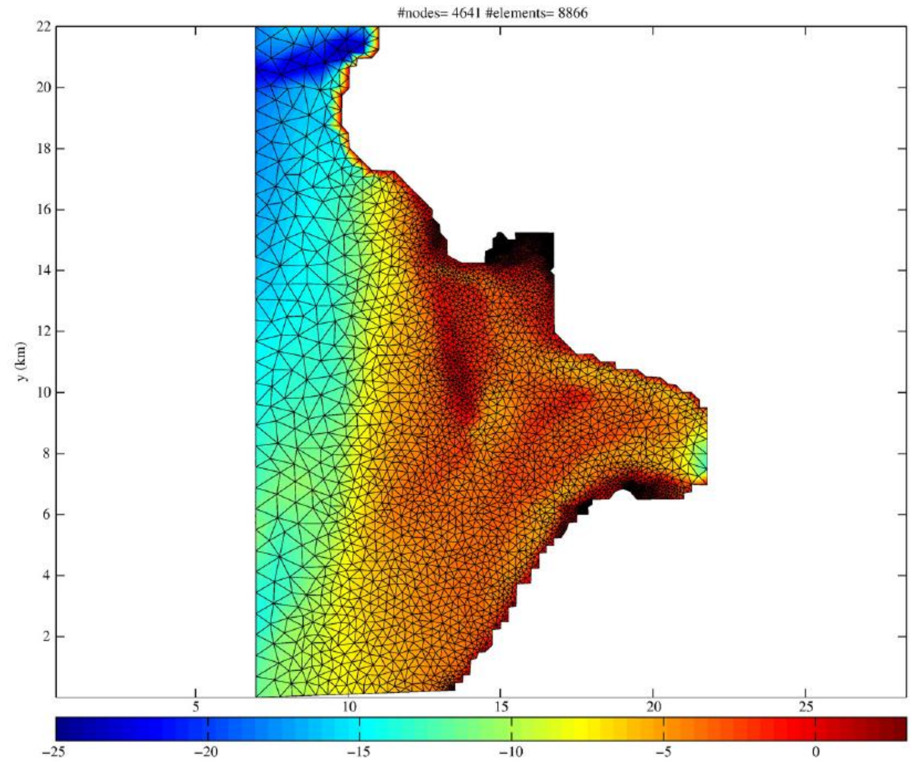

Figure 4: Example of an unstructured mesh grid for Haringvliet estuary (from Zijlema, 2010).

2.3.3.3 Influence of wind

In a given offshore situation (i.e. the input to the local model) the wave conditions are a dynamical equilibrium between the energy input to waves and the dissipation due to white-capping. In the case of low or no wind (i.e. predominately swell) the transfer to the coast results in a simple advection of the outer waves, where the only processes at work are the interactions with the sea bottom ((d) to (g)). If wind is acting on waves, however, neglecting its effect during the transfer to the coast may lead to an appreciable underestimate of the wave height at coastal regions. The reason is that the dissipation by white-capping depends on the spectral shape. Therefore, given the correct input spectrum at the border (e.g. from a buoy or a large scale model), white-capping will be active during the transfer to the coast, leading to underestimated wave heights at the location of interest.

Wind data can be input as either a constant or a variable field across the grid for a given time duration depending on the size of the grid and the data sources available. When a variable wind field is used, it must be presented in the same grid coordinate system as the other inputs such as bathymetry, however the grids need not be identical or of the same resolution.

2.3.3.4 Bathymetry Requirements

Consideration of processes (d) to (g) (§2.3.2) becomes important once the depth becomes low enough for the waves to feel the bottom (shallow water conditions are commonly defined as depth < half the wavelength). Hence the bottom effects will vary with spectral frequency (a long swell will feel it well before the shorter wind sea). The question is how detailed and accurate the bathymetry needs to be. Although high resolution bathymetry (e.g. 50m or better) might be available, it would not always be appropriate to use it at this resolution because of the level of computation required. Given that the maximum level of detail is limited by the resolution of the grid, the practical rule is not to neglect details that can lead to appreciable effects on the waves, e.g. bottom ridges or canyons that can lead to concentration or dissipation of energy in certain area. Clearly this is important for energy harvesting.

If a particular location is identified by its geographical coordinates and depth (e.g. a wave buoy used for validation purposes), it is necessary to verify if this depth agrees with the bathymetry data. If not, it is advisable to change the nominal position slightly in the model so as to have the correct depth.

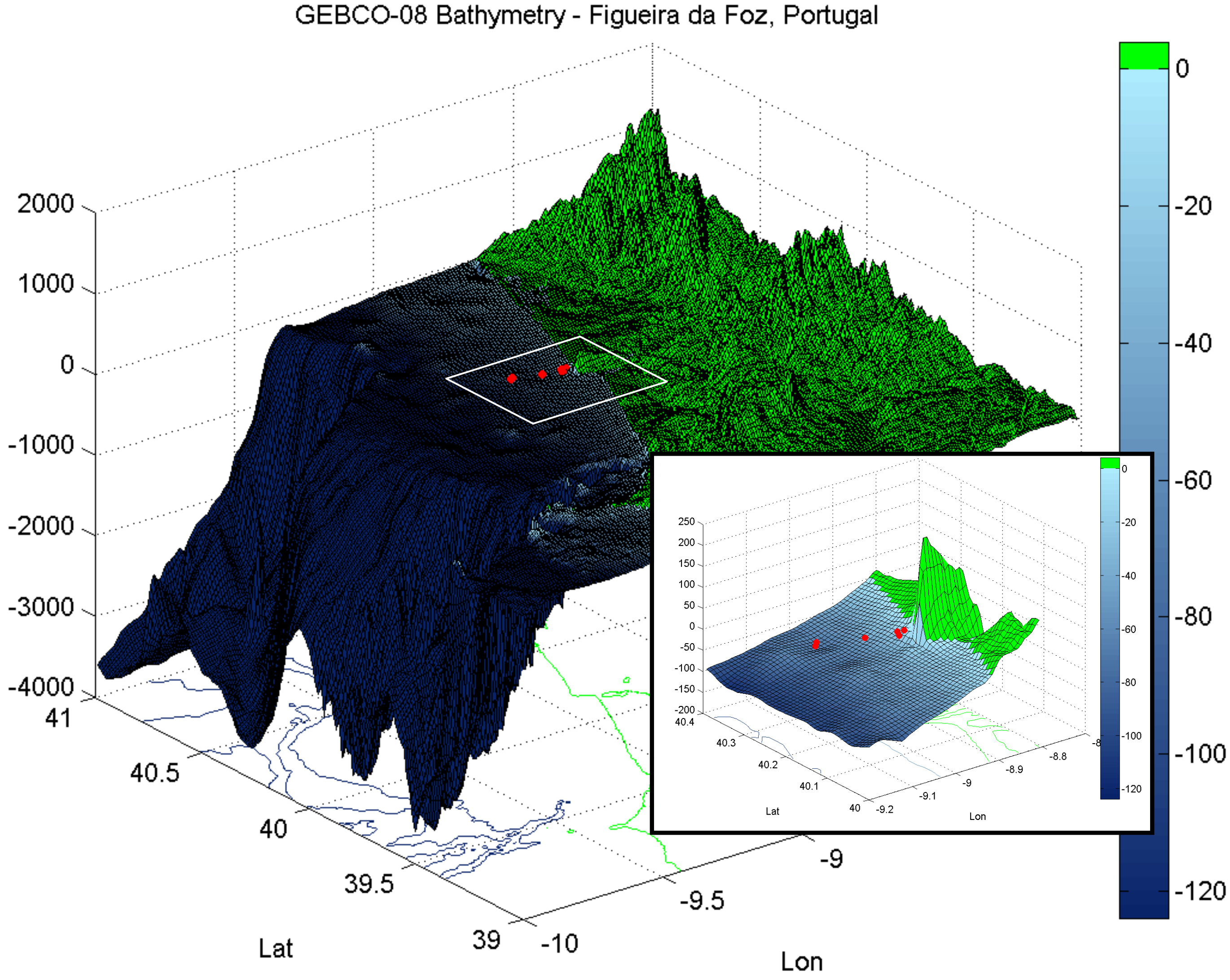

Figure 5 GEBCO_08 30 arc-second resolution bathymetry for Figueira da Foz, Portugal. Red markers indicate previous wave buoy deployments. Scale indicated depth in metres.

Land boundaries in the model will absorb all incident wave energy in the way that a gently sloping beach would. In some cases however, e.g. where waves are incident on a steep cliff or a harbour wall, this is not representative of what would actually occur; although some wave energy will be absorbed, there will also be reflection. In SWAN, the only mechanism by which wave reflection can be represented is by the use of a partially transmitting barrier in the model. This can represent any type of structure, and will absorb and/or reflect a user-defined proportion of the incident wave energy.

Obtaining detailed bathymetry and topographical information is potentially costly, particularly if a survey must be conducted. There are, however, a number of open source datasets available. The most notable of these are the National Oceanic and Atmospheric Administration's (NOAA, USA) ETOPO1 global grid and the GEBCO_08 (GEneral Bathymetric Chart of the Oceans) dataset available from the British Oceanographic Data Centre (BODC). These datasets are both available for free download (for use within the terms and conditions of the respective institutes). The resolution is 30 arc-second and 1 arc-minute for the GEBCO_08 and ETOPO1 grids respectively. An example of the available bathymetry (GEBCO) is illustrated in Figure 5 for Figuira da Foz, Portugal, site of the WAVEMOD wave buoy deployment in 1993-1994. Whether this level of detail (i.e. 30 arc-second resolution) is sufficient will depend on the purpose of the modelling. In the case of a high level, geographical scale, resource assessment the resolution is likely to be sufficient. When the locations of the buoy deployments are examined in more detail (~30km x 30km grid) it is noted that some detail is lost in shallow water, particularly when examining the coastline.

It is important to check the bathymetric data against any depth point measurements. In the case of a resource assessment this is likely to be the measured depth at the measurement device location. While this error may only be of the order of a few metres this can be significant in shallower waters. It is also important to note that the bathymetric data may be less accurate in shallow water due to a greater reliance on interpolation between the tracks of the survey vessels (and/or the coastline and other data sources).

A comparison of the GEBCO and ETOPO1 datasets at the Figueira da Foz site (Figure 6) shows differences between the datasets which, although small in magnitude, are significant. This is especially true in the shallowest water. Comparing the depths with the measured depth at the wave buoys showed an average disagreement in the order of 3-5 metres.

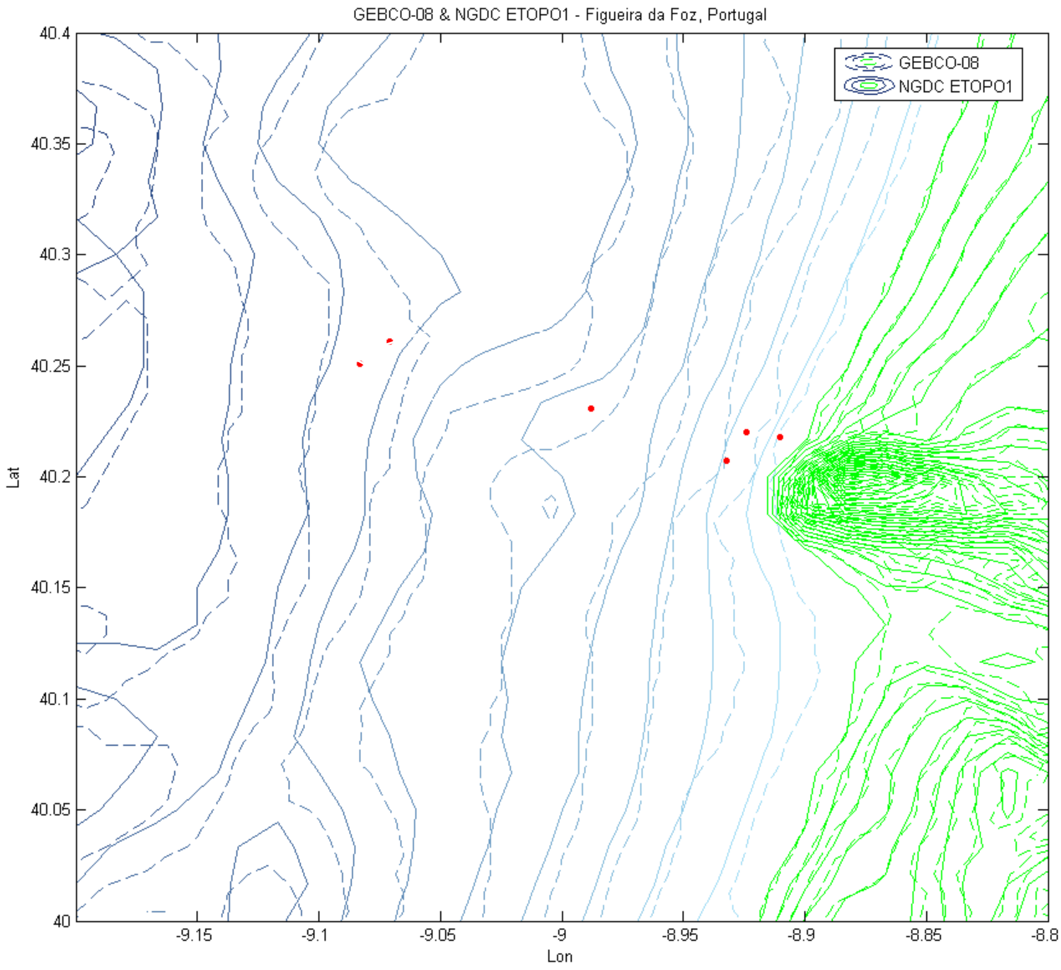

Figure 6 Comparison of GEBCO_08 and NOAA ETOPO1 bathymetry at Figueira da Foz, Portugal. Contours at 8m intervals.

2.3.3.5 Sea Floor Composition

When interacting with the sea bottom, waves stir the bottom material. Depending on its characteristics and, if sandy or stony, size, this material will dampen waves with bottom interaction processes, the dominant one being commonly bottom friction. As this process can dampen waves at a substantial degree, knowledge of bottom material is relevant.

2.3.3.6 Influence of Water Level,Tides and Currents

Tides can affect waves via two different actions. If the tidal excursion is appreciable (approximately >5%) of the local depth, the bottom interaction processes will be affected as well due to the change in relative water depth. Indeed it is common to see tidal modulation in coastal wave records. To account for this effect a local tide time history should be incorporated into the depth when running the model. In areas with a large tidal range the water depth can change by more than 6m over every tidal cycle. In shallow water areas, this will have a significant impact on wave propagation due to varying levels of refraction and bottom friction, and potentially influence processes such as wave-induced breaking. In inter-tidal areas, it might make the difference between the model treating a grid point as wet or dry, and therefore including it in calculations. To account for this change in water level, a grid of water depths relative to the depths provided in the bathymetry input file can be provided.

Even if tidal range information is available, this may not be easy because not all models are equipped to incorporate this information. A practical solution can be to run the model with the extreme (highest and lowest) depths so as to have an estimate of the possible effects.

A more difficult effect to consider derives from the influence of currents. These may be tidal, oceanic, local wind-generated, wave generated or river currents. Currents may affect local wave heights to a substantial degree, with a tidal period modulation. The related information is not easily available, as it implies modelling the tidal stream over the model domain. If the modelled site is in an area where currents are relevant, care is required when using global model input data at the boundary. If the data is available a grid of currents may be input to the model to represent the variation over the model domain. It should be ascertained if the tidal information has already been taken into account in this large scale modelling. Usually this is not the case. For tidal current modelling reference is made to the parallel section in this report.

2.3.4 Model Input

2.3.4.1 Input Parameters

A spectral model needs full two-dimensional (frequency and direction) spectral information as input at the offshore model boundaries. If 2D spectra are available from a large scale wave model, they simply need to be interpolated at the (presumably higher density) grid points of the local grid. Within the accuracy of the large scale model this is the most complete and detailed possible input. If only global parameters (H_{m0}, θ_m, T_p, T_m) or 1D frequency spectra are available, the full 2D spectra must be derived, but only under a number of hypotheses.

Where only global parameters such as H_{m0} and T_m (or T_p) are required, a frequency spectrum must be derived based upon a parametric formulation. Bretschneider and Pierson-Moskowitz spectra, still used on occasion, should be considered unrealistic. These spectra are based on fully developed seas which are rarely, if ever, truly realistic. A JONSWAP spectrum is a more realistic solution, although in case of dominant swell (e.g. $T_m > 6 \sqrt{H_{m0}}$) a more peaked spectrum (in frequency and direction) should be used.

In regions such as Western Europe where sea states comprise a mix of ocean swells and locally generated seas, bi-modal or multi-peaked spectra are common. The only way these can be realistically represented in a model is through the input of either a one- or two-dimensional spectrum. Parametric spectra (e.g. JONSWAP) based upon simple summary statistics (e.g. H_{m0} and T_p) are unable to convey multi-modality. This is particularly important if one of the aims of the study is a resource assessment to identify, for example, the peak periods of the sea states for the purpose of device tuning.

The directional distribution of energy in each frequency is also critical. In the absence of any other information, a common solution is to assume a $\cos^n \theta$ distribution centred on the local wave direction if available, and otherwise on the wind direction. While $n=2$ with $-90° < \theta < 90°$ is a common solution, n should be increased up to 10-20 as long-period swell increasingly dominates the sea state. Note that the integral between -90° and 90° must be normalized to produce the correct integral. Another standard formula for directional spread is denoted by $\cos^{2s}(\theta-\theta_m)$, where θ_m is the mean direction and '*s'* is the spread factor. The value of $s = 12$ is commonly used as an estimate for practical purposes (Tucker & Pitt, 2001).

Directional buoy information, if available, should be treated with care. Except from rare sophisticated approaches, the directional distribution of energy is considerably smoothed, and this may appreciably affect the results at the modelled site. A more promising recent approach is to derive the global parameters (H_{m0}, T_m, θ_m) of the different wave systems (e.g. wind sea from one direction and one or more swells from different distant storms) that compose the full spectrum. If this is the case, the overall 2D spectrum results from the non-linear addition of the various spectra associated with the single wave systems.

2.3.4.2 Input Data Sources

There are two sources of potential wave input data at the model boundaries: measured data and output from other models. Measured data, from sources such as wave buoys, acoustic Doppler profilers (ADP), satellite or radar, provide the most accurate representation of the sea state. However, for nearshore modelling applications, with the exception of remote sensing systems, data usually comprises point measurements, leading to the problems with boundaries described previously.

Although potentially lacking the accuracy of recorded data, the use of output from other models as input for a nearshore model can often be a better option because of its spatial distribution. Output from other models can be treated in the same way as point measurements, and used to provide input at intervals along the model boundaries – the model will then interpolate between the input points. A second option, depending on the models being used, is nesting. Nesting involves running a larger-scale, coarser resolution model to generate boundary conditions for a finer grid, and can be repeated on decreasing scales until the required scale is attained.

SWAN, for example, is designed so that it can be nested in WAM and WaveWatch III, allowing global outputs to feed into nearshore models.

2.3.4.3 Spectral Description

The frequency domain of the model defines the minimum and maximum spectral frequencies and their resolution, or spacing. Within this range, the spectral energy density can develop freely. Below the low frequency cut-off, the energy density is set to zero. Above the high frequency cut-off, an f^m tail is imposed to enable calculation of nonlinear interactions and integrated wave parameters. The value of m can be 4 or 5 depending on the wind generation formulation used.

In SWAN, a logarithmic frequency resolution is used, where $\Delta f = 0.1 f$, and the recommended range of frequencies is 0.04 – 1.0 Hz (SWAN manual, 2009).

In MIKE 21 the logarithmic distribution of frequencies is recommended by

$$f_n = f_0 c^n, \qquad n = 1,2,\ldots$$

where f_n = n^{th} *frequency*, f_0 = *minimum frequency* and c = *frequency factor* which is taken as 1.1.

The frequency range should cover realistic wave frequencies that would occur in the ocean. For typical wave energy applications the range 0.04 – 0.25 Hz may be used, thus covering wave periods in the range 4 to 25 seconds.

2.3.4.4 Directional Description

The directional range covers a full 360° unless the user specifies otherwise, e.g. for reasons of computational economy. The directional space of the model is discretised by the user to a specific resolution, $\Delta\theta$, influenced by the prevalent sea conditions. The recommended directional resolution for wind seas with larger directional spread is $\Delta\theta$ = 10°-15°, whereas for swell conditions with a much lower spread, a higher resolution of $\Delta\theta$ =2°-5° is suggested (SWAN User Manual, 2009). In MIKE 21 a resolution of 2°-10° (2^o for coastal area and 10^o for offshore region) is recommended for swell conditions. For wind waves, $\Delta\theta$ < 10°-30° is suggested.

2.3.5 Model Output and Interpretation

2.3.5.1 Output Parameters

Models offer the option of output either in spectral files or as specific parameters (i.e. summary statistics). Spectral output might be of interest if spectra were used as input to the model, otherwise the spectrum will be based on the selected parametric spectral shape. For high level resource assessment studies for ocean energy developments, a set of parameters including significant wave height, energy period and direction will usually be sufficient, and will allow additional parameters such as the wave power to be calculated.

2.3.5.2 Data Archiving and Presentation

A range of options are available for presenting model output. If the purpose of the model is to investigate specific locations, results for the requested parameters can be written into a table for easy access. A more visual presentation can be produced by outputting results across a grid which can then be imported into appropriate plotting software. Consideration should be given to the electronic storage of results to allow for easy import into other analysis software. Data can also be produced as one or two-dimensional spectral files to enable more detailed analysis when spectral data has been available as input.

2.3.5.3 Quantification of Error and Uncertainty

In order to quantify errors in the results, measured data must be available for a location within the model domain. Statistical comparisons between the modelled and recorded data can be performed using the methods described in §4.2. This process should ideally be performed during the model calibration stage.

A detailed overview of sources of error in spectral wave models is provided by Cavaleri *et al.* (2007).

3 TIDAL RESOURCE MODELLING

3.1 INTRODUCTION

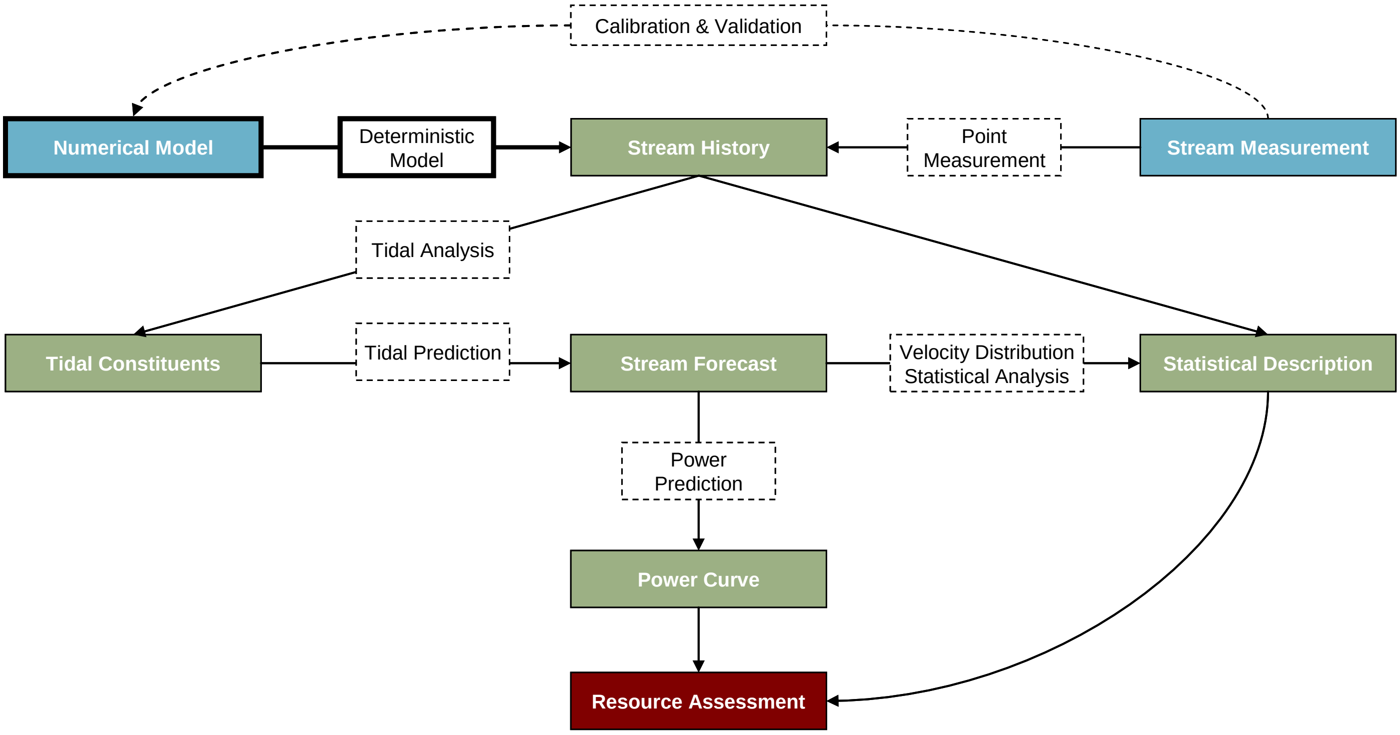

Figure 7 Schematic representation of possible tidal Resource Assessment procedures

The forces driving tidal motions are astronomic in nature and mainly governed by the relative positions of the Earth, Sun and Moon. The Newtonian theory of tides enables determination of the tide-generating forces on the ocean waters and is capable of explaining the existence of tides, including the harmonic periods governing the temporal variations in tidal behaviour. However, it cannot explain the local variations in amplitude caused by geographic effects. The presence of coastlines and depth variations modify the response of the oceanic waters to the astronomic tide-generating forces and the flow speed varies in both space and time.

Measurements may provide good information on water levels and currents but, when available, the information is usually based upon a limited point measurement (at one position and for a limited duration). Modelling provides an effective means of completing this information in time and space given knowledge of the local bathymetry.

The role of numerical models in resource assessment in relation to measurement techniques is illustrated graphically in Figure 7.

3.2 TIDAL MODELLING OVERVIEW

3.2.1 Governing equations

To compute sea level and currents, coastal hydrodynamic models solve the Navier-Stokes equations. Most of the time (for example for the models MARS3D, ROMS, MIKE) these equations are simplified using the following assumptions:

- Hydrostaticity: vertical motion is much smaller than horizontal motion
- Boussinesq approximation: the variation in density is neglected everywhere except in the buoyancy term

In 3 dimensions, these equations have to be completed by thermodynamic equations to model:

- The advection-diffusion of tracers particularly Temperature and Salinity
- The solar radiation flux and the surface ocean-atmosphere heat flux

When integrating along the vertical, the primitive equations can be simplified in a 2 dimension horizontal system called “Saint-Venant” system. This 2D model is most of the time an efficient mean to represent coastal propagation of tide and to estimate tidal level ζ and barotropic currents (u,v) in shallow water.

<u>Equation of motion:</u>

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=F_x+\frac{\tau_{wind\_x}-\tau_{bottom\_x}}{\rho H}-\left(\frac{1}{\rho}\frac{\partial Pa}{\partial x}+g\frac{\partial \zeta}{\partial x}\right)-\frac{\partial V_M}{\partial x}$$

$$\underbrace{\frac{\partial v}{\partial t}}_{time}+\underbrace{u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}}_{advection}+\underbrace{fu}_{Coriolis}=\underbrace{F_y+\frac{\tau_{wind\_y}-\tau_{bottom\_y}}{\rho H}}_{friction\ stress}-\underbrace{\left(\frac{1}{\rho}\frac{\partial Pa}{\partial y}+g\frac{\partial \zeta}{\partial y}\right)}_{pressure}-\underbrace{\frac{\partial V_M}{\partial y}}_{tidal\ potential} \quad (2)$$

Continuity Equation:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (Hv)}{\partial y}=0 \quad (3)$$

With:

- *u* the zonal and v the meridional components of barotropic currents,

- ζ the sea surface elevation and *H* the total height of the water column.

A first difference between the different 2D models is the physical parameterisation of the different terms involved in these equations:

- the possibility to take into account a constant or variable Coriolis force *f*,
- the possibility to take into account the tidal potential $V_{M,}$
- the possibility to take into account atmospheric (Pa, wind) forcing and the way wind stress τ_{wind} is modelled,
- the way to model bottom friction τ_{bottom} ,
- the way to model inner frictions forces (*Fx, Fy*) due to viscosity and mainly to turbulence.

Other sources and sinks can be taken into consideration in the hydrodynamic equations. For example:

- the effect of waves on the currents
- river discharges

As 3D models, some 2D models (TELEMAC 2D for example) give the possibility to use a 2 dimensional system without assuming hydrostatics hypothesis. This is the Boussinesq formulation, an extension of the Saint Venant equations taking partly into account the vertical velocity.

3.2.2 Numerical resolution and Computational Grids

Another major difference between the hydrodynamic models is the computational mesh and the numerical schemes used to solve the Partial Differential Equations system (2D or 3D).

Three mathematical properties characterise the quality of a numerical scheme:

- the accuracy of the scheme : when the integration steps (temporal and spatial) tend toward zero the numerical scheme should tend to the continuous differential equation.

- the convergence of the scheme: the numerical solution should tend toward the exact solution when the integration steps (temporal and spatial) tend toward zero.

- the stability of the scheme: the solution should not diverge.

Another important point is the monotony and the order of the scheme. The implemented scheme should be a compromise between accuracy with risk of oscillation and guaranty of monotony but too much diffusivity. Finally, a numerical scheme should be conservative (mass, motion, heat conservation).

Most often used resolution methods are:

- finite differences methods
- finite volumes methods
- finite elements methods
- spectral methods

The main advantage of finite elements methods and finite volumes methods is that they can be used on unstructured meshes which facilitate the numerical modelling for complex geometries of coastal regions. Further information on the different numerical methods is given in Annexe 6.2.

3.3 TIDAL MODELS

Various tidal models exist and a summary is given in

Table 4. For tidal studies, 2D models are generally sufficient, therefore two freely available 2D models are presented more deeply here:

- MARS 2D model, developed by IFREMER, DYNECO department (Lazure & Dumas, 2008)
- TELEMAC-2D model, developed by EDF-DRD (Hervouet, 2003)

After having described the models and their distinguished strengths and weaknesses the two models quality are compared.

3.3.1 Mars 2D

3.3.1.1 Computational Grid

MARS 2D solves Saint-Venant system on an ARAKAWA C rectangular grid of constant longitude and latitude step. As shown on Figure 8, ζ is computed at the middle of the cell grid and u and v components on each side of the cell. The model uses an "Alternate Direction Implicit" numerical scheme. This consists in dividing the time step in two half time steps and to use alternatively an implicit (centred or quick) method in each direction: first along line then along row to compute ζ , u and v.

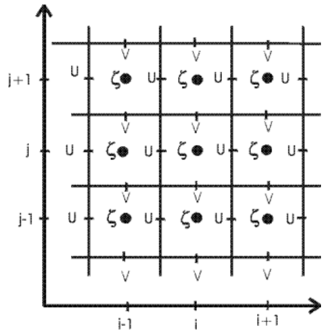

Figure 8: ARAKAWA C grid

As the horizontal resolution is constant, in order to improve the resolution of the final results, it is necessary to implement a set of nested models, as illustrated in the example in Figure 9. Each model provides open boundaries conditions to the smaller and higher resolution model. These nested models can be coupled offline or online (via Adaptive Grid Refinement In Fortran package from LMC-IMAG) on 2-ways or one-way.

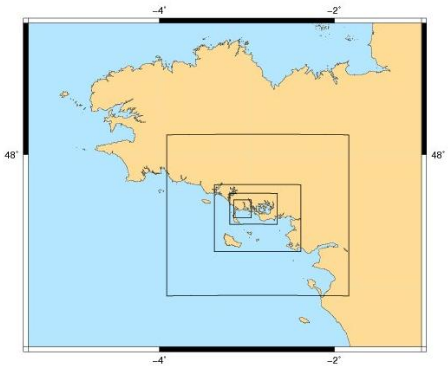

Figure 9 : Example of nested models

In coastal regions, MARS take into account wet and dry cells with adequate parameters to avoid overestimation of the velocity or negative sea level during the drying of a cell.

3.3.1.2 Modelled Processes

- The Coriolis force is taken into account and the Coriolis coefficient is variable in space by default. This coefficient can be considered as a constant and the Coriolis force can also be deactivated by the user.
- Tidal potential is not taken into account.

- Wind driven circulation: Wind stress at the surface is computed with the 10m high wind $\vec{W}_{10}\begin{pmatrix} U_{10} \\ V_{10} \end{pmatrix}$

$$\begin{cases} \tau_{wind\_x} = C_D \rho_a U_{10} \left\| \vec{W}_{10} \right\| \\ \tau_{wind\_y} = C_D \rho_a V_{10} \left\| \vec{W}_{10} \right\| \end{cases} \qquad (4)$$

C_D can be a constant coefficient (default) or a wind dependant coefficient (Large and Pond (1981), Smith and Banke (1975), Geernaert et al. (1986), Charnock s relation (1955))

- Bottom friction dependency with barotropic velocity is modeled using a Strikler coefficient k (20<k<50) :

$$\begin{cases} \tau_{bottom\_x} = \rho g \dfrac{u\left\|\vec{u}\right\|}{k^2 H^{1/3}} \\ \tau_{bottom\_y} = \rho g \dfrac{v\left\|\vec{u}\right\|}{k^2 H^{1/3}} \end{cases} \qquad (5)$$

The Strikler coefficient is by default homogenous but if necessary it can be defined spatially.

- In the MARS 2D version, internal frictions due to turbulence are represented as molecular viscosity. Thus a turbulent viscosity coefficient is defined:

$\varepsilon = 0.01 f_{visc} dx^{1.15}$ ($1<f_{visc}<17$) (6)

3.3.1.3 Input Data

The quality of the tidal model highly depends on the quality of the bathymetry and of its boundary conditions.

- At the open boundaries the sea surface elevations ζ must be specified. It can come either from a grower model (in case of nested models) or (for the largest model) from a harmonic composition using tidal constituents from a global dataset (possibility to use FES2004, FES99 or Schwiderski datasets). Currents can also be prescribed (using Dirichlet or the characteristics method). Otherwise, currents are computed to assure zero velocity gradients at the open boundaries.
- MARS 2D can take into account homogeneous and stationary wind and pressure imposed by the user or realistic meteorological forcing from a netCDF file.

3.3.2 TELEMAC-2D

3.3.2.1 Computational Grid

TELEMAC-2D solves the Saint-Venant equations using the finite-element or finite-volume method. Finite element method is the default and the most often used. Equations are solved in two stages. Convection terms are solved first, followed by propagation and diffusion terms. Telemac offers different numerical schemes to solve the convection terms, the characteristics method is the default one. Propagation and convection are solved using the finite element method (various solvers for the linear system).

The finite element computation mesh of triangular elements enables to adapt the horizontal step at the study area: large mesh grid near the border, refined mesh grid at the coast and particularly near the areas of interest (see Figure 10). One should choose the spatial resolution of the computational grid such that relevant spatial details in the bathymetry are properly resolved. The grid can be either in spherical coordinates (for large domains) or projected (in meters, for small domains like coastal regions or harbors).

In the nearshore region, Telemac takes into account wet and dry cells.

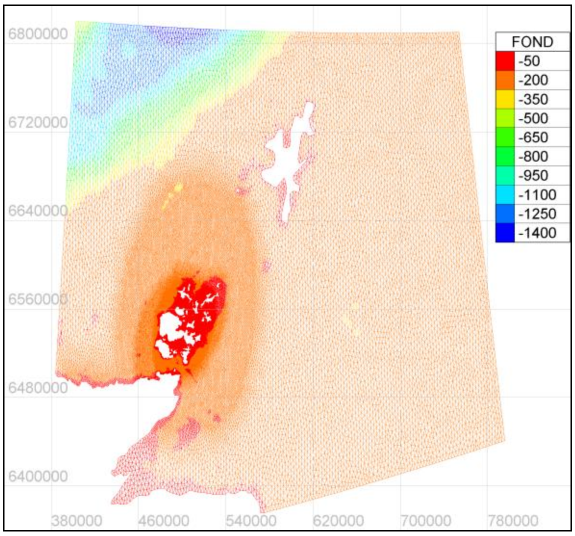

Figure 10 : Example of mesh grid

3.3.2.2 Modelled Processes

- The Coriolis force is taken into account by default but can be deactivated by the user. If the model grid is in spherical coordinates, the Coriolis coefficient (f = 2 ω sin (lat) , with ω = 7.292 x 10-5 rd/s) is variable and calculated by the software. Otherwise, the coefficient is a constant (which is satisfying enough for small domains) and should be prescribed by the user.
- Tidal potential can be taken into account.
- Wind stress at the surface depends on the 10m high wind $\vec{W}_{10}\begin{pmatrix} U_{10} \\ V_{10} \end{pmatrix}$

$$\begin{cases} F_{wind\_x} = \dfrac{\tau_{wind\_x}}{\rho H} = \dfrac{1}{H}\dfrac{\rho_a}{\rho} a_{wind} U_{10} \left\| \vec{W}_{10} \right\| \\ F_{wind\_y} = \dfrac{\tau_{wind\_y}}{\rho H} = \dfrac{1}{H}\dfrac{\rho_a}{\rho} a_{wind} V_{10} \left\| \vec{W}_{10} \right\| \end{cases} \quad (7)$$

$\dfrac{\rho_a}{\rho} a_{wind}$ being a constant coefficient given by the user.

- Bottom Friction dependency with barotropic velocity can be modeled using different laws:
  - No friction
  - Haaland Law
  - Chezy Law
  - Strikler Law
  - Manning Law
  - Nikurades Law

Bottom friction can be expressed as $$\begin{cases} F_{bottom\_x} = \dfrac{\tau_{bottom\_x}}{\rho H} = \dfrac{g}{C^2 H} u \left\| \vec{u} \right\| \\ F_{bottom\_y} = \dfrac{\tau_{bottom\_y}}{\rho H} = \dfrac{g}{C^2 H} v \left\| \vec{u} \right\| \end{cases} \quad (8)$$

Where the Chézy law is applied C is constant.

When $C = KH^{1/6}$, K is a Strickler coefficient

When $C = \dfrac{H^{1/6}}{m}$, m=1/K is a Manning coefficient

Strikler, Chézy or Manning coefficient are given by the user. They can be a constant (default) or they can be variable in space or time (user defined).

- The effect of turbulence can be represented by four different ways:
  - Similarly to molecular viscosity by defining a global viscosity coefficient.
  - With an Elder model
  - With a k-ε model
  - With a Smagorinsky model

3.3.2.3 Input Data

- At the open boundaries sea surface elevation and currents (or flows) must be specified. If only sea levels are available, the Thomson method will use the characteristics method to appraise the value of currents along the boundaries.
- Telemac-2D takes into account wind and pressure influence. The integration of a meteorological forcing variable in time and space is possible but has to be done by the user.
- Telemac can compute wave induced currents by coupling with a sea state model (preferably TOMAWAC, the spectral wave model developed in the Telemac system).

3.3.3 Comparison Summary

The main advantage of TELEMAC-2D against Mars 2D is its finite element adaptable mesh. This enables it to cover an entire area with a single model with refined areas of interest. On the contrary, the implementation of the nested models of MARS 2D requires more time and caution in order to assure a good transfer of the information between each models (bathymetry concordance, domain definition) and it can lead to difficulties in some rugged coastal areas (island).

However, contrary to MARS-2D, TELEMAC-2D is not dedicated to operational forecasting or long time realist runs. Therefore one can say that TELEMAC is more appropriate for engineering studies and test case and MARS-2D for operational forecasting and long time runs.

Concerning physical parameterisation, if focusing on tidal prediction, bottom friction model is probably the major difference. Indeed, the bottom friction coefficient is often used to adjust the sea level model prediction to the measurements or to harmonic analysis prediction. It seems that the Chézy law coded in TELEMAC-2D enables more variability than the Strikler law in MARS so that the model results are more flexible.

Finally, TELEMAC-2D can take into account wave induced currents. Since all the simulation modules of the TELEMAC system are based on the same framework, the coupling of them is easily achieved. Wave-current interactions may be easily studied by coupling TELEMAC-2D and the spectral wave model TOMAWAC.

The basic properties of TELEMAC-2D and Mars 2D, along with a selection of other commonly used tidal models are summarised in Table 4.

Table 4 Basic properties of selected tidal models

Models	Equations	Qualities	Drawback	Operational forecasting	Developer and access
MARS 2D **MARS 3D**	Saint Venant (Primitive equations)	Computation time Drying cells Meteorological forcing	Nested models	Yes	IFREMER (France) http://wwz.ifremer.fr/ezprod/index.php/dyneco_en/layout/set/print/moyens_outils/logiciels/mars FREE ACCESS
TELEMAC2D **TELEMAC3D**	Saint Venant + Boussinesq Navier Stockes equations	Bathymetry mesh creation Finite elements Drying cells Meteorological forcing Wave induced currents Hydrostaticity or not Integrated in a complete water modelling system	Input & output files format	No	EDFR&D (France) http://www.telemacsystem.com/index.php?lang=en FREE ACCES (summer 2010)
ROMS	Primitive equations	Pre and post processing tools Netcdf input and output files AGRIF nested models Meteorological forcing	No atmospheric pressure forcing	Yes	IRD version: ROMS AGRIF on http://roms.mpl.ird.fr/ American version on http://www.myroms.org/ (without AGRIF procedure) FREE ACCESS

HYCOM	Primitive equations	Existing global model that can provide boundary conditions Hybrid vertical coordinates Meteorological forcing		Yes	National Ocean Partnership Program (multi-institutional US) http://www.hycom.org/hycom/overview FREE ACCES
NCOM 3D	Primitive equations	Existing global model that can provide boundary conditions Meteorological forcing		Yes	Naval Research Laboratory (US) http://www.ccsm.ucar.edu/models/ocn-ncom/
OPA-NEMO		Existing global model that can provide boundary conditions Pre and post processing tools AGRIF nested models Meteorological forcing	Main application are not coastal	Yes	Nucleus for European Modelling of the Ocean (multi-institutional European) http://www.nemo-ocean.eu/ PUBLIC LICENSE
MIKE 21 **MIKE3**	Saint Venant + Boussinesq Primitive equations	Meteorological forcing Wave induced currents Unstructured mesh technique Finite volume method Wet-dry capability Integrated in a complete water modelling system	No information about nesting procedure Commercial application	Yes	DHI http://mikebydhi.com/
POM	Primitive equations	Drying cells Meteorological forcing		Yes	Princeton Ocean Model http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/
MOHID	Primitive equations	Finite volume method Meteorological forcing Integrated in a complete water modelling system		Yes	MARETEC & Instituto Superior Tecnico of Lisbon http://www.mohid.com/
SYMPHONIE	Navier Stokes equations	Meteorological forcing Hydrostaticity or not		Yes	http://sirocco.omp.obs-mip.fr/outils/Symphonie/Sources/SymphonieSource.htm

4 CALIBRATION AND VALIDATION OF NUMERICAL MODELS

4.1 PURPOSE OF CALIBRATION AND VALIDATION

Wave and tidal models will have a number of model-dependant parameters to allow “tuning” for different sites and scenarios. Some of these values may be chosen based on published literature and guidance while others may require comparison to real world measurements. The processes of the calibration and validation are intrinsically linked.

4.2 WAVE MODELS

4.2.1 Data Sources for Calibration and Validation

Where possible data from measurement device (e.g. wave buoy) deployments should be used to calibrate and validate the model. For detailed site specific assessment this will likely require a dedicated measurement programme. Geographical level resource assessments may be able to rely on a number of historical and ongoing measurement deployments. Some of these datasets are openly available. Figure 11 illustrates a number of measurements which have been utilised in the course of the EquiMar project.

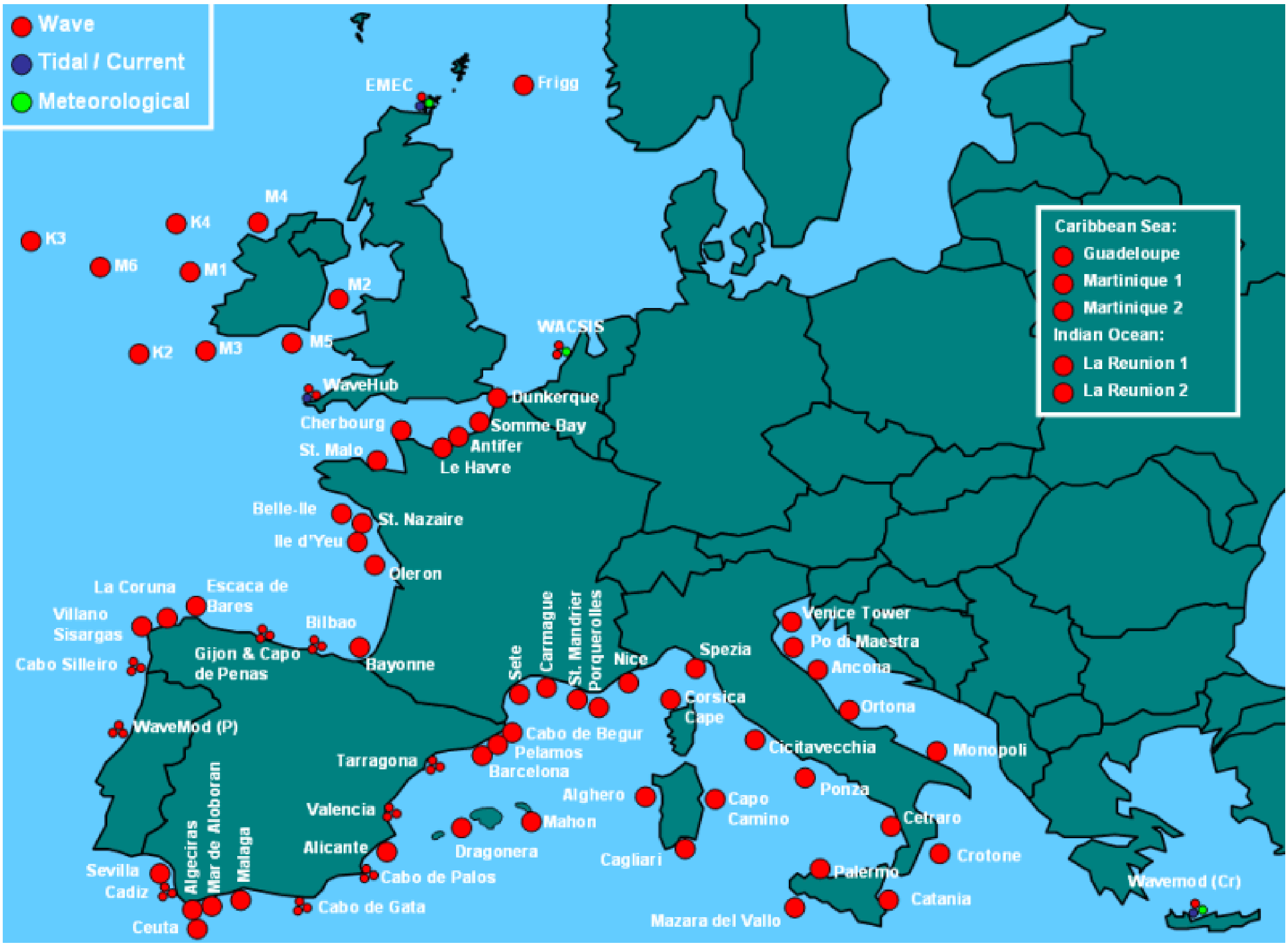

Figure 11 Examples of European wave and tidal measurement device deployments

Sources of wave data include

- The French coastal buoy network (Candhis - National Center for Archiving Swell Measurements)
- Spanish REDCOS and REDEXT buoys (Puertos del Estado)
- Italian R.O.N. buoy network
- UK WaveNet (Cefas)

4.2.2 Validation of Model Data

Comparison of the wave model forecasts/hindcasts with measurements is very important for characterising model performance and to identify any deficiencies for improvement. In-situ observations obtained from buoys, ships, oil platforms and satellites can be used for this purpose. The following simple statistical parameters [Ris et al.,(1999)] can be calculated to validate data

(i) Bias:

$$bias = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i) \tag{9}$$

Where x_i and y_i are the measured and model (or computed) wave parameters

(ii) Root mean square error:

$$rms_{error} = \left[\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2\right]^{1/2} \tag{10}$$

(iii) Scatter Index, SI

$$SI = \frac{rms_{error}}{\overline{x}} \tag{11}$$

where, $\overline{x}$ is the measured values

(iv) Model Performance Index (MPI):

$$MPI = 1 - \frac{rms_{error}}{rms_{changes}}$$

where $rms_{changes}$ is identical to rms_{error}, except that computed y_i values are replaced by the measured values x_i. For a perfect model $rms_{error} = 0$, hence MPI = 1.

(iv) Operational Performance Index, OPI (rms error normalized with the incident observed value x_i):

$$OPI = \frac{rms_{error}}{x_i} \tag{12}$$

4.3 TIDAL MODELS

4.3.1 Data Requirements

4.3.1.1 Input Data

The quality of the tidal model highly depends on the quality of the bathymetry and its boundary conditions.

The propagation of the tidal wave to the shore is highly dependent on the bathymetry. Reliable bathymetry data with a resolution consistent with the desired resolution is the first essential element to build a tidal model. This is particularly true when focusing on some rugged coastal area where currents are highly variable and where fine resolution meshes are required.

The influence of open boundary conditions is particularly significant if boundaries are close to the area of interest and located in shallow water area. On the contrary, if situated beyond a continental shelf, results will be less dependent on open boundary conditions.

It is therefore necessary to build a large enough approach model to propagate the tidal wave to the coast where the mesh can be refined (either using nested models or the same mesh) to get accurate currents depending on the available bathymetry resolution.

4.3.1.2 Validation Data

Validation data may be obtained from in-situ sea level and current measurements. It must be noted that such measurements not only include tide but also other phenomena such as meteorological (wind or pressure) effects which may be less significant depending on the situation of the area.

Tide gauge networks can be useful sources of in-situ measurements. They provide long term records of tidal elevation in harbour locations. In France, for example, measurements are carried out and controlled by the SHOM (Service Hydrographique et Océanographique de la Marine, see Figure 12) through the RONIM network. In the UK they are controlled by the British Oceanographic Data Centre (BODC).

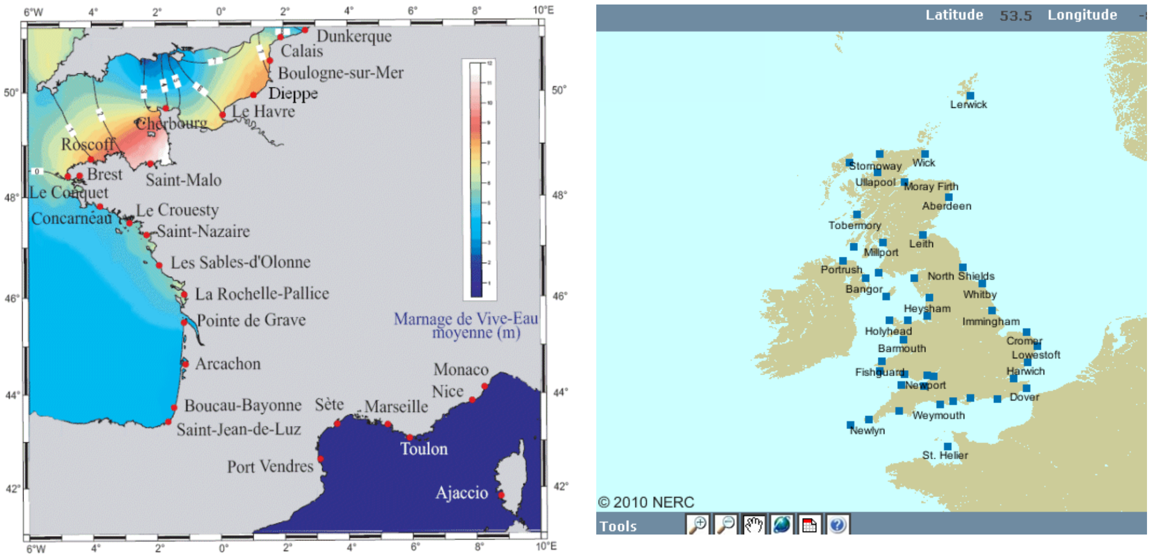

Figure 12 : French (source SHOM) and UK (source BODC) National Tide Gauge Networks

More generally various international programmes aim at gathering quality sea level data from the different countries' networks, for example:

- The European Sea-Level Service (ESEAS: http://www.eseas.org/)
- The Global Sea Level Observing System (GLOSS: http://www.gloss-sealevel.org/)

To separate tide from surge levels (or currents) it is possible to do a harmonic analysis (if the data record is long enough) to find the tidal constituents. Another solution is to use a filter (e.g. Demerliac filter) to remove the tidal signal. Figure 13 gives the example of the surge obtained from Brest tide gauge record during the December 1999 storms.

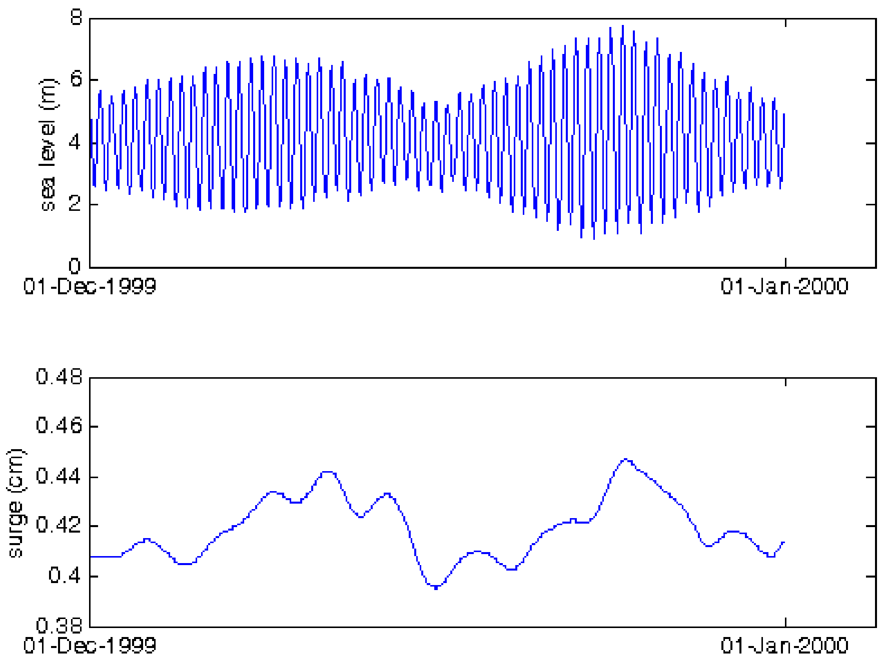

Figure 13 : Sea level and filtered surged at Brest from 01/12/1999 to 01/01/2000

The harmonic components of tidal level in a harbour may be calculated by tidal analysis of long term tide-gauge measurements. They can be used to predict tidal level for comparison purposes. Depending on the tide-gauge situation (inside a protected area or near a river outlet), it is possible that the model is not precise enough to represent the tide propagation, thus leading to differences between prediction and model results.

Current data from atlas and navigation maps can also been used. For example, on navigation maps the French hydrography service (SHOM) give values of mean spring tide and mean neap tide currents (tidal coefficients 95 and 45 respectively) derived from historical measurements. For these two coefficients, tidal currents direction and intensity are given every hour from HT-6h to HT+6h relatively to the closest reference harbour.

Current measurements may also be made with Acoustic Doppler Current Profilers (ADCPs) and radar (measuring surface currents, see Figure 14). This second solution enables to cover a larger area and time period.

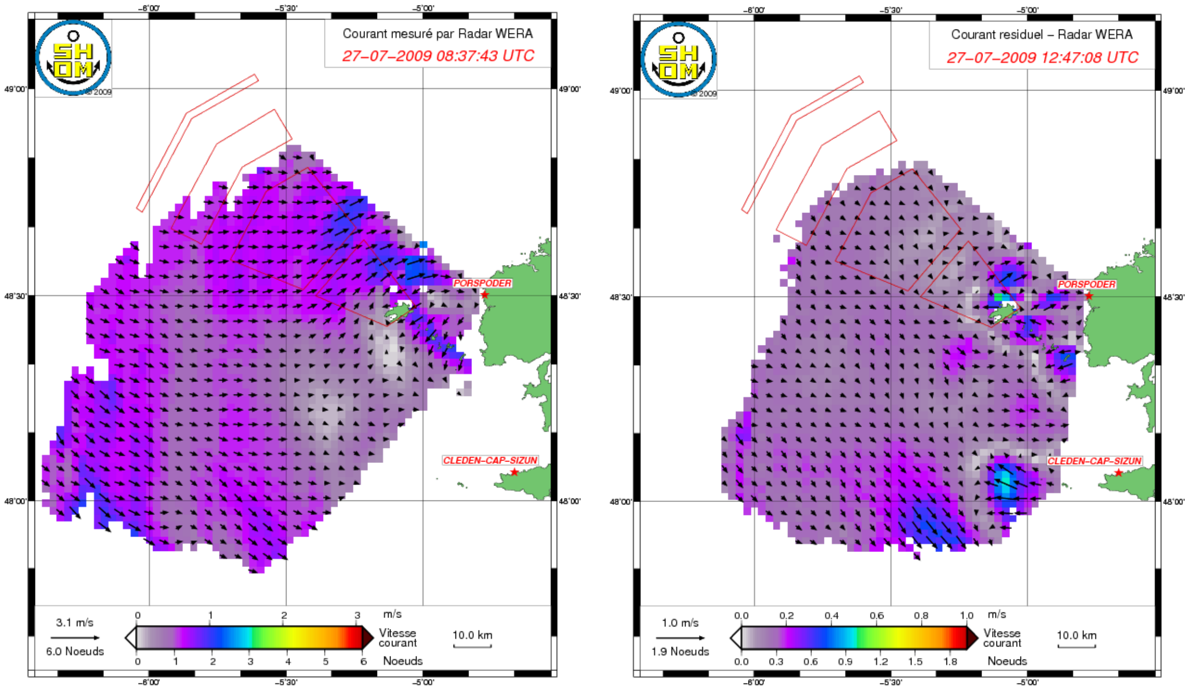

Figure 14 : Example of instantaneous and residual surface currents in the Iroise Sea from radar HF measurements (http://www.shom.fr/)

4.3.2 Calibration and Validation

4.3.2.1 Model Validation

Figure 15 and Figure 16 show example of graphical comparison between model results and validation data. Figure 15 focuses on realistic tidal level from tidal model and from harmonic analysis components at Port Haliguen. Figure 16 gives the example of a neap tide current cycle (HT-6, HT+6) from tidal model and SHOM navigation maps.

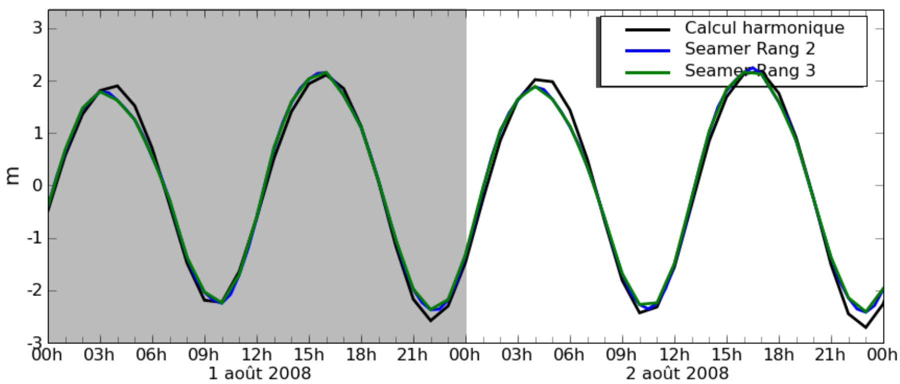

Figure 15 : Sea level at Port Haliguen

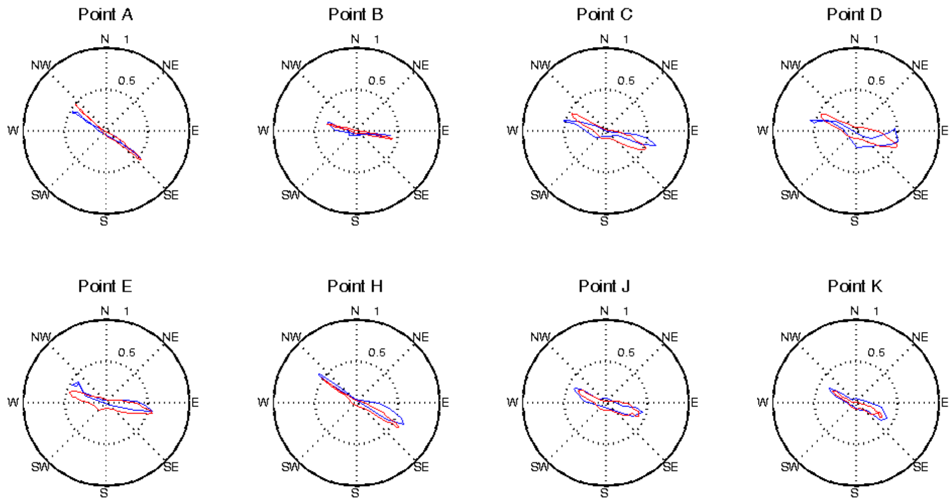

Figure 16 : Comparison of currents from hydrodynamic model and from SHOM for a mean neap tide in the Bay of Seine

A simple way to assess the quality of a model's results is to compare it instantaneously to measurements. In addition to classical statistical tools (RMS error for example), the difference of phase (DPhi) and the difference of tidal amplitude (DA) between the two signals (level or currents) during a given period can be estimated, as illustrated by the example in Figure 17.

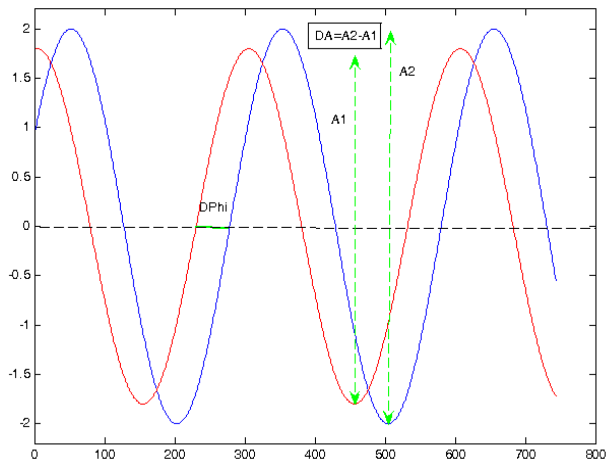

Figure 17 : Evaluation of model results

Another solution is to carry out the tidal analysis of both model results and measurements and compare each tidal constituent (amplitude and phase) separately. This method avoids the consideration of meteorological effects. It does, however, require a long measurement and model simulation period (preferably around 1 year). Figure 18 give the example of a tidal spectrum obtained with Matlab "t_tide" tool (Pawlowicz *et al.*, 2002).

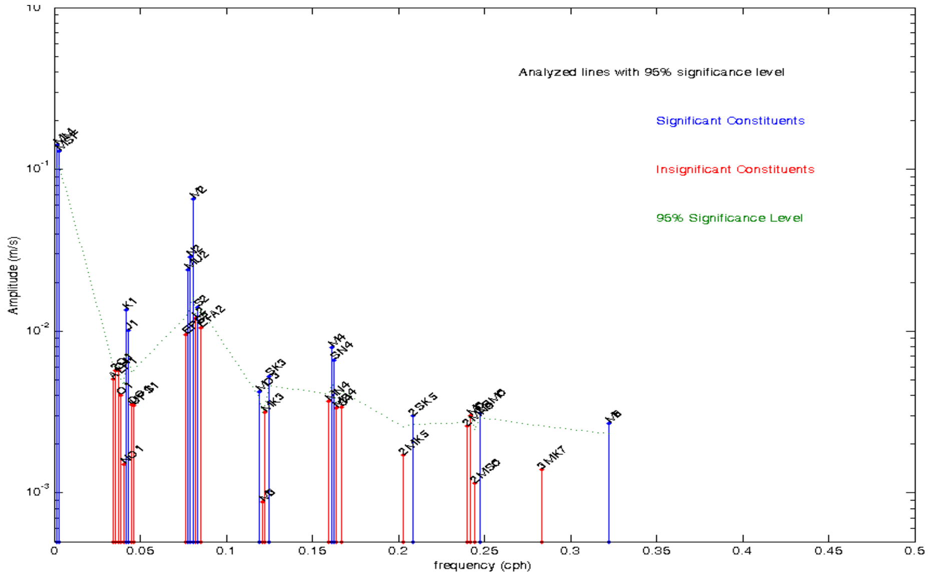

Figure 18: Tidal spectra from t_tide

4.3.2.2 Model Calibration

As the major sources of error are the model mesh grid and the associated open boundary conditions and bathymetry, if the model results are too far from measurements the first stage should be:

- to verify that the model domain is large enough to represent the involved phenomena and to enable a good propagation of the open boundaries conditions
- to verify that the position of the open boundaries are in agreement with the area's main currents and the chosen model prescription.
- to verify that the model mesh resolution is fine enough in the coastal area of interest
- to verify if the model bathymetry is fine and accurate enough and if necessary to try to get other bathymetric data
- to try other open boundary data source if available

Then, the leading parameter when trying to adjust tidal level and barotropic current model results is the bottom friction coefficient. This acts on tidal propagation and have an influence both on amplitude and phase. It could be appropriate to spatialized this coefficient but then its calibration is more difficult. This could be done using an assimilation method but only if enough measurement points are available.

4.3.2.3 Tidal Model Limitations

2-dimensional models which represent the barotrope propagation of the tidal wave is often sufficient to reproduce tidal levels and currents and consequently to evaluate tidal resource.

However, even in strong tidal areas, other phenomena can interfere with tide propagation and modify currents or sea level. For example particularly strong atmospheric forcing conditions can generate significant storm surge or currents. These events may be episodic and of limited importance to resource assessment. However, for design criteria or for daily prediction, their intensity and occurrence should be evaluated and if they are significant they should be taken into consideration. Using a 2D model it is useful to carry out a wind (and wave) influence analysis in typical weather conditions. However, one must consider that a 2D model provides barotrope currents which can not be perfectly representative of surface or bottom currents. Depending on the application and on the area, their results should be used with caution.

In other areas, tidal currents can be partly affected by 3-dimensional phenomena such as river outlet in estuaries or thermal stratifications. In such areas, a 2D tidal model is not capable of modelling the current complex distribution. Before implementing the model it is therefore necessary to estimate the relative influence of tide and other phenomena (using harmonic analysis of measurements and focussing on vertical distribution of currents for example). If a 3D circulation model has to be implemented, the existence of thermal or salinity influences must be identified in order to be properly taken into consideration in the model:

- river discharge
- seasonal stratification
- fronts

This should be done using in-situ or satellite surface measurements of salinity and temperature. It can also be useful to analyse existing 3D model results.

5 ANNEXE: REFERENCES

5.1 WAVE MODELLING REFERENCES

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6 ANNEXE: ADDITIONAL MODELLING INFORMATION

6.1 WAVE MODELLING

6.1.1 Model Summaries

A brief description of the wave models that are commonly considered for use in wave resources estimation worldwide are given below.

6.1.1.1 WAM:

The WAM-model is a third generation wave model (Gunther et al. 1992) which solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. The model runs for any given regional or global grid with a prescribed topographic dataset. The grid resolution can be arbitrary in space and time. The propagation can be done on a latitudinal – longitudinal or on a carthesian grid. The model outputs the significant wave height, mean wave direction and frequency, the swell wave height and mean direction, wind stress fields corrected by including the wave induced stress and the drag coefficient at each grid point at chosen output times, and also the 2D wave spectrum at chosen grid points and output times. The model runs for deep and shallow water and includes depth and current refraction.

The equation solved in the code reads in Cartesian coordinates as (Monbaliu et al 2000, The spectral wave model, WAM, adopted for applications with high spatial resolution, Coastal Engineering, 41, pp 41-62):

$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial x}(c_x F)+\frac{\partial}{\partial y}(c_y F)+\sigma\frac{\partial}{\partial \sigma}\left(c_\sigma \frac{F}{\sigma}\right)+\frac{\partial}{\partial \theta}(c_\theta F)=S_{tot} \qquad (13)$$

Where,

$F(t,x,y,\sigma,\theta)$ is the wave energy spectrum, t is the time, σ is the intrinsic angular frequency, θ is the wave direction measured clockwise from the true north, c_x and c_y are the propagation velocities in geographical space, c_σ and c_θ are the propagation velocities in frequency and directional space (spectral space).

The local rate of change of wave energy density, propagation in geographical space and shifting of frequency and refraction due to spatial variation of depth and current is represented by the expression on the left hand of the equation. All effects of wave generation and dissipation including wind input S_{in}, white capping $S_{ds,}$ non-linear quadruplet wave-wave interactions S_{nl} and bottom friction S_{bf} are of the waves are represented by the right side expression.

Further details can be found in

(i) Gunther, H., Hasselmann, S., Janssen, P.A.E.M, 1992. The WAM model Cycle 4. Report No.4. Hamburgh.

(ii) Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M., 1994. Dynamics and Modelling of Ocean Waves. Cambridge Univ. Press, Cambridge.

6.1.1.2 WAVEWATCH III

This model operational at NOAA (National Oceanic and Atmospheric Administration) is a third generation wind-wave model.

The present version of the model WAVEWATCH III is denoted by NWW3. NWW3 predicts the wave evolution in two dimensional physical space $\mathbf{x}$ and time t of the wave action density spectrum. This is expressed as a function of wave number k and wave direction θ. The governing balance equation for the spectrum $N(k,\theta;\mathbf{x},t)$ is given by

$$\frac{\partial N}{\partial t}+\nabla_x\cdot\dot{\mathbf{x}}N+\frac{\partial}{\partial k}\dot{k}N+\frac{\partial}{\partial\theta}\dot{\theta}N=\frac{S}{\sigma}$$

$$\dot{\mathbf{x}}=\mathbf{c}_g+\mathbf{U} \qquad (14)$$

$$\dot{k}=-\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial s}-\mathbf{k}\cdot\frac{\partial\mathbf{U}}{\partial s}$$

$$\dot{\theta}=-\frac{1}{k}\left[\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial m}-\mathbf{k}\cdot\frac{\partial\mathbf{U}}{\partial m}\right]$$

Where $\mathbf{c}_g$ calculated from c_g and θ, s = coordinate in the direction of θ, m = coordinate perpendicular to s. The equation (1) is valid for a Cartesian grid. For large scale applications, this equation is transferred to a spherical grid defined by longitude and latitude. The left hand derivative terms in equation (1) represents the local change and effects of wave propagation. The right hand function S represents the net source term for wave growth and decay, by wind action, exchange of action between components of the spectrum due to nonlinear effects, whitcapping loss and shallow water processes.

In deep water, the net source term S is consists of three parts: a wind-wave interaction terms S_{in}, a noblinear wave-wave interactions term S_{nl} and a dissipation (whicapping) term S_{ds}. For model initiation and to provide more realistic initial wave growth a linear input term S_{ln} is also considered. In shallow water additional terms for wave-bottom interactions S_{bot} is included. In extremely shallow water, depth induced breaking term S_{db} and triad wave-wave interactions term S_{tr} are included. The scattering of waves by bottom features is governed by the source term S_{sc} is also important. In addition a general purpose slot for user defined source term S_{xx} is also included in WAVEWATCH III. Thus all the source terms are written as

$$S = S_{ln} + S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{db} + S_{tr} + S_{sc} + S_{xx} \tag{15}$$

Further details can be found in Tolman, H.L., (2009). 'User manual and system documentation of WAVEWATCH III TM version 3.14', Technical Note, MMAB Contribution No. 276 , U. S. Department of Commerce National Oceanic and Atmospheric Administration, National Weather Service, National Centers for Environmental Prediction.

6.1.1.3 SWAN

SWAN (Simulating WAves Nearshore) has been developed by Delft University of Technology in the Netherlands. It is a third-generation, phase-averaged spectral wave model designed to compute wave propagation in nearshore, shallow-water and coastal regions (Booij *et al*., 1999; Ris, 1997). SWAN is able to represent the following wave generation, propagation and dissipation processes (SWAN Technical Documentation, 2006):

- Wave generation by wind
- Propagation through geographic space
- Refraction due to seabed and current variations
- Shoaling due to seabed and current variations
- Diffraction
- Blocking and reflection by opposing currents
- Blocking, transmission and reflection by obstacles
- Non-linear interactions
- Dissipation by whitecapping
- Dissipation by bottom friction
- Dissipation by depth-induced breaking

SWAN calculates the evolution of the spectrum based on the action balance equation (Booij *e.t al.*, 1999)

$$\begin{aligned}&\frac{\partial}{\partial t}N(\sigma,\theta)+\frac{\partial}{\partial x}c_x N(\sigma,\theta)+\frac{\partial}{\partial y}c_y N(\sigma,\theta)\\&\qquad+\frac{\partial}{\partial\sigma}c_\sigma N(\sigma,\theta)+\frac{\partial}{\partial\theta}c_\theta N(\sigma,\theta)=\frac{S(\sigma,\theta)}{\sigma}\end{aligned} \tag{16}$$

The action density, $N(\sigma,\theta)$, equals the energy density, $E(\sigma,\theta)$, divided by σ, the angular frequency relative to any currents present, used because action density is conserved in the presence of currents whereas energy density is not. The rate of change of $N(\sigma,\theta)$ in time is given by the first term of the equation, with the second and third terms representing the two-dimensional spatial propagation of $N(\sigma,\theta)$ with velocity components c_x and c_y. The fourth term represents changes in the relative frequency due to variations in depth and currents, and the final term on the left-hand side is the directional propagation of $N(\sigma,\theta)$ due to refraction. The term $S(\sigma,\theta)$ on the right-hand side is the source term of the equation, representing the generation and dissipation of energy density. It can be written as

$$S(\sigma,\theta) = S_{in}(\sigma,\theta) + S_{ds}(\sigma,\theta) + S_{nl}(\sigma,\theta) \tag{17}$$

where S_{in} represents the energy input into SWAN from wind, S_{ds} represents the energy dissipated by the mechanisms of bottom friction, whitecapping and depth-induced breaking, and S_{nl} represents energy redistribution across the spectrum caused by the nonlinear triad and quadruplet interactions.

References:

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6.1.1.4 MIKE21

In this section a short description of this wave model is given. The spectral wind-wave model simulates the growth, decay and transformation of wind-generated sea and swells. This model includes two methods of wave simulation namely, (i) directional decoupled parametric formulation and (ii) a fully spectral formulation. This model accounts the physical phenomena of; (i) wave growth by the action of wind (ii) non-linear wave-wave interaction, (iii) dissipation of energy by white capping, bottom friction and depth induced wave breaking, (iv) refraction and shoaling, (v) wave-current interaction and (vi) the effect of time varying water depth, flooding and drying. A cell-centered finite volume method is used in the discretization of the governing equations and a multi-sequence explicit method is used for the wave propagation with the time integration carried out using a fractional step approach. This model produces phase averaged wave parameters as output for the computational area. Further details can be found in [1].

The wind waves are expressed by the wave action density spectrum $N(\sigma,\theta)$, where σ is the relative (intrinsic) angular frequency and θ is the direction of wave propagation. The relative angular frequency can be related to the absolute angular frequency (ω) by the linear dispersion relationship as

$$\sigma = \sqrt{gk\tanh(kd)} = \omega - \bar{k}\cdot\bar{U} \tag{18}$$

where, g = gravity constant,

k = wave number,

d = water depth,

$\bar{U}$ = current velocity vector and

$\bar{k}$ = wave number vector with magnitude k and direction θ

The action density $N(\sigma,\theta)$ can be related to the energy density $E(\sigma,\theta)$ by

$$N = \frac{E}{\sigma} \tag{19}$$

(i) Directional Coupled Parametric Formulation:

This formulation is based on a parameterisation of the wave action conservation equation. The following coupled equations explains the parametererisation

$$\begin{aligned}\frac{\partial(m_o)}{\partial t} + \frac{\partial(c_x m_o)}{\partial x} + \frac{\partial(c_y m_o)}{\partial y} + \frac{\partial(c_\theta m_o)}{\partial \theta} &= T_o \\ \frac{\partial(m_1)}{\partial t} + \frac{\partial(c_x m_1)}{\partial x} + \frac{\partial(c_y m_1)}{\partial y} + \frac{\partial(c_\theta m_1)}{\partial \theta} &= T_1\end{aligned} \tag{20}$$

In the above equations, $m_o(x,y,\theta)$ and $m_1(x,y,\theta)$ respectively are the zeroth and first moment of the action spectrum $N(x,y,\sigma,\theta)$. The terms $T_o(x,y,\theta)$ and $T_1(x,y,\theta)$ are source functions based on the action spectrum. The source functions T_o and T_1 accounts for the effect of local wind generation (only for stationary solution mode) and energy dissipation due to bottom friction and wave breaking. The *n*th order spectral moment is given by

$$m_n(x,y,\theta) = \int_0^\infty \omega^n N(x,y,\omega,\theta)\, d\omega \tag{21}$$

The local wind generation source functions are derived from empirical growth relations [Johnson , 1998].

(ii) Fully spectral Formulation:

In this mode, the wave action balance equation is formulated in either Cartesian or spherical co-ordinates. The conservation equations for wave action in Cartesian co-ordinates is given by

$$\frac{\partial N}{\partial t} + \nabla \cdot (\bar{v} N) = \frac{S}{\sigma} \tag{22}$$

Where, $N(\bar{x}, \sigma, \theta, t)$ = the action density,

t = time,

$\bar{x}$ = the Cartesian coordinates (x,y),

$\bar{v} = (c_x, c_y, c_{\sigma,} c_\theta)$ the propagation velocity of a wave group in the four dimensional phase space, $\bar{x}, \sigma$ *and* θ,

S = source term for energy balance equation,

∇ = the four dimensional differential operator in the $\bar{x}, \sigma$ *and* θ space.

The source function term S is given by

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf} \tag{23}$$

Where, S_{in} = the momentum transfer of wind energy to the wave generation

S_{nl} = the energy transfer due to non-linear wave –wave interaction

S_{ds} = the energy dissipation of wave energy due to white-capping

S_{bots} = the energy dissipation due to bottom friction

S_{surf} = the energy dissipation due to depth-induced breaking

The source functions S_{in}, S_{nl} and S_{ds} are similar to WAM cycle-4 model.

References:

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Johnson, H.K., 1998. On modelling wind-waves in shallow and fetch limited areas using the method of Holthuijsen, Booij and Herbers. J. Coastal Research, 14, 3, 917-932.

6.1.1.5 TOMAWAC

TOMAWAC equations are equivalent to SWAN, WAM and WW3 except that the energy balance equation is solved in its transport form :

$$\frac{\partial(BF)}{\partial t} + \dot{x}\frac{\partial(BF)}{\partial x} + \dot{y}\frac{\partial(BF)}{\partial y} + \dot{\theta}\frac{\partial(BF)}{\partial \theta} + \dot{f}_a\frac{\partial(BF)}{\partial f_a} = BQ(x, y, \theta, f_a, t)$$
$$B = \frac{C_g}{\sigma k} = \frac{CC_g}{\sigma^2} \tag{24}$$

B and Q are the source terms

TOMAWAC includes the following processes:

Interaction waves – sea floor. TOMAWAC models the transformation of surface waves under the combined effects of refraction and shoaling, and includes the wave amplitude damping due to dissipation phenomena such as bottom friction (represented by a conventional quadratic friction law to represent bottom shear stress) and depth induced wave breaking. Non-linear triads interactions which may significantly transform the spectral shape in shallow water areas can be activated in TOMAWAC.

Interaction waves – atmosphere. Strong relations exist between the atmosphere limit layer and the wave field. The energy supply to the wave field is governed by a retroaction mechanism which depends on the quantity present in the wave field. The interaction between waves and atmosphere is responsible for the energy transfers from wind to water waves, but also participates in energy dissipation processes (white capping) and in the non-linear energy transfers between wave components (quadruplets interactions). The interaction waves - atmosphere is modelled in TOMAWAC through three source terms added on the right hand term of the energy balance equation.

Interaction waves – currents. The currents may affect the wave field in a significant way, depending on their intensity. They modify the wave direction by refraction (for a spatially non-homogeneous current) and the wave amplitude by shoaling. Refraction, shoaling and wave blocking (effect of strong opposite currents) are considered in the software.

Interaction waves – tide. The temporal variation of currents and water depth affects the wave field in coastal areas. These effects may be considered in the “third generation mode” of TOMAWAC.

6.2 TIDAL MODELLING

6.2.1 Phenomenon description of tides and currents

The tide generating force

The astronomical origin of the tidal phenomenon is well known and results directly from the Newton gravitational law: with $\vec{F}(A)$ the **gravitational force** acting on each particle of fluid A and $\vec{F}(T)$ the resultant force acting on the Earth, in a terrestrial reference frame each particle of unit mass is subjected to the resultant tide generating force:

$$\vec{F}_M(A) = \vec{F}(A) - \vec{F}(T) = \frac{GM}{\Delta^2}\vec{u}_{AM} - \frac{GM}{r^2}\vec{u}_{TM} \qquad (25)$$

Where:

- G in the gravitational constant
- M is the celestial body mass
- R and Δ are respectively the distance between the celestial body and the earth centre and the distance between the celestial body and the particle A (see Figure 19).

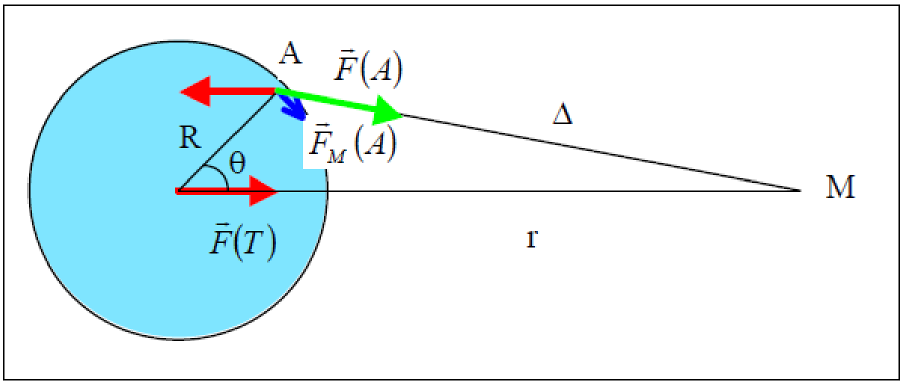

Figure 19 : Force composition scheme for a given celestial body (M)

In theory, the tide generating force results from the action of every celestial body. But actually, the sun and the moon have a prevailing influence, the first one because of its mass and the second one because of its closeness.

General circulation

Excepting the tide generating force, the main phenomena acting on global ocean circulation are due to solar energy (combined action of wind and buoyancy) and the earth rotation (via the Coriolis force).

- <u>Wind effects</u>

Differences of radiative flux induce winds in the atmosphere. At the ocean-atmosphere interface, winds transfer energy to the ocean surface via a friction stress generating ocean currents:

$$\tau = C_D \rho u^2 \qquad (26)$$

C_D being a drag coefficient, increasing with wind speed (wave effects).

As visible on Figure 20, surface general circulation is clearly linked to prevailing winds but their influence is limited to the surface layer.

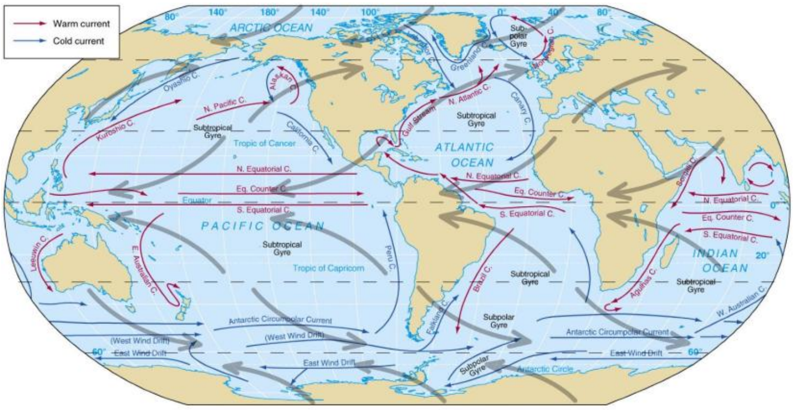

Figure 20 : Prevailing winds and surface global circulation

However, wind driven currents are modified by interaction with other effects, the Coriolis force responsible for Ekman derive (sea below) and the existence of the continents: sea-surface slopes caused by prevailing winds pushing water to the coast generate a horizontal pressure gradient responsible for slope currents.

- <u>Thermohaline circulation</u>

The global thermohaline circulation or deep circulation is a very slow flow of dense water (generated in winter in polar region: the Norvegian Sea and the Labrador Sea in the North Atlantic Ocean and around the continent of Antarctica particularly in the Weddell Sea) getting of to the bottom and then spreading in the oceanic basins (see Stommel circulation model on Figure 21) toward the equator. This must produce a surface current in the opposite direction.

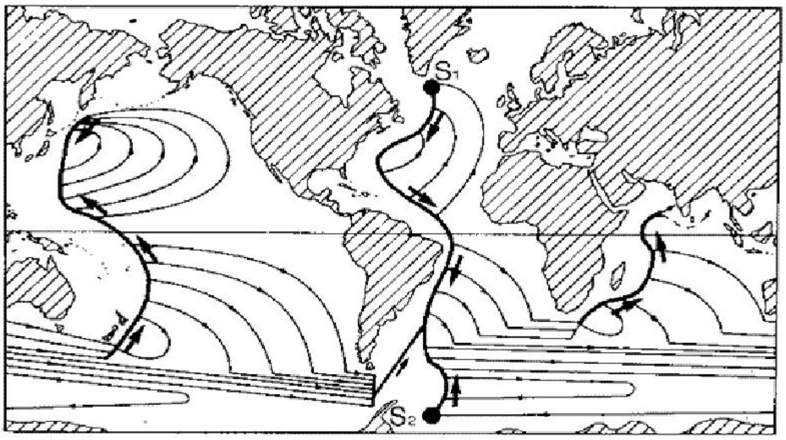

Figure 21 : Stommel thermohaline circulation model

- <u>Coriolis force</u>

Due to the earth rotation, the Coriolis force acts on moving systems and tends to deviate it to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. For example, the interaction between the Coriolis force and the wind stress explains the well known Ekman spiral (Figure 22).

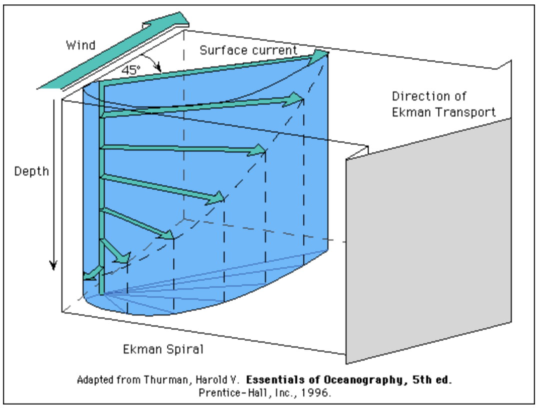

Figure 22 : Ekman spiral

Coastal circulation

The phenomena acting on coastal areas are the same that in global ocean. Their relative importance highly depends on the area.

- *Tide*

Tidal level can be decomposed into a sum of tidal wave components (Lagrange theory):

$$H = h_0 + \sum_k A_k \cos(2\pi f_k t - \varphi) \quad (27)$$

Major components are:

- semi diurnal components (M2, S2, N2, K2)
- diurnal components (K1,01,P1)
- long term components (monthly, annual)

But in shallow water, the compound tide waves generated by nonlinear interactions of primary constituents can become important.

Amplitude and phase of each component highly depends on the geography. Figure 23 shows estimation (FES 2004) of the global repartition of amplitude and phase for the moon semi-diurnal M2 constituent. In closed sea, tidal range is very weak (Mediterranean Sea, Black Sea) but it can locally increase in some particular bay (Figure 24) or gulf due to resonance effects (for example in the gulf of Gabes in the Mediterranean Sea). In deep oceans it is also weak but it increases when it get closer to the coast where it can reach high values depending on the propagation on the continental shelf. The greatest tidal range is observed in the Fundy Bay (Canadian Atlantic coast) with 13 meters for mean spring tide.

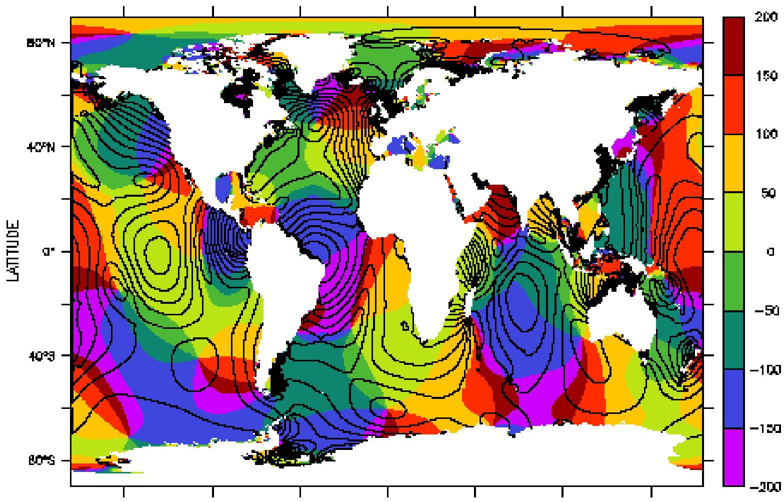

Figure 23 : Amplitude and phase of M2 component (source: FES 2004)

Similarly, if tidal currents are very weak in global ocean (only a few decimetres per second) they can reach several meters per second in coastal areas. Generally, between two tides, the velocity vector associated with each component of the tidal current describes an ellipse called tidal ellipse. However, close to the coast, these ellipses tend to flatten to become line (parallel to the coast). In such a case, current orientation is nearly invariant and its direction change after half a tide.

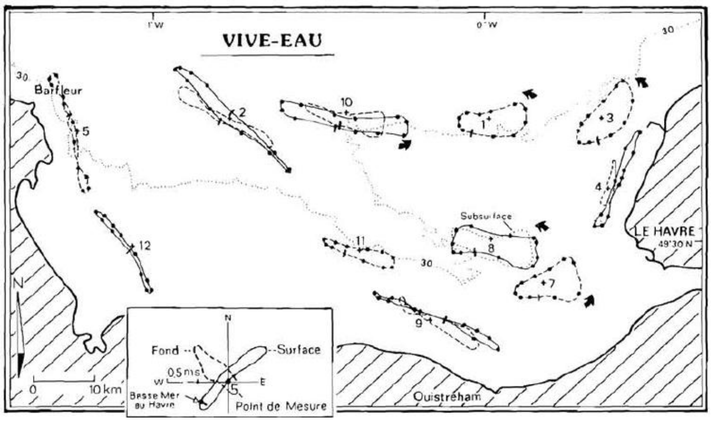

Figure 24 : Example of tidal current in Bay of Seine during spring tide (source: Ifremer)

Contrary to the other phenomena acting on coastal circulation, tide is highly predictable and reproducible as currents and level variations depend only of the position of the sun and the moon and of the particularity of the chosen area. That is why they represent a reliable resource all the more so as in some coastal areas they can reach high values.

- Atmospheric forcing

The effects of the atmospheric pressure can be evaluated through the inverse barometer approximation:

$$\Delta\zeta = \frac{1}{\rho g}\left(P_{ref} - P\right) \tag{28}$$

That estimates that a 1mbar depression generates a 1 cm rise of the sea level. But in shallow water, dynamics effects neglected by this approximation can generate larger variations.

In coastal areas, winds can significantly modify the circulation. If considering a wind blowing in the ox direction and neglecting all the other forces action (tidal potential, bottom friction, pressure gradient), the equilibrium barotrope equation integrated on the water column depth H is:

$$\begin{cases} u = \frac{1}{H}\int_{-H}^{0} u(z)\,dz = 0 \\ V = \frac{1}{H}\int_{-H}^{0} v(z)\,dz = -\frac{\tau_x}{f\rho H} \end{cases} \tag{29}$$

With

- τ_x is the wind stress proportional to the square of the wind velocity

- f is the Coriolis force

- ρ is the water density considered as a constant

Thus the average current is directed at right angles to the wind direction according to Ekman law. In fact, bottom frictions are significant and the real deviation is lower than 45°.

- Density gradient

Coastal sea water temperature depends on heat flux at the ocean-atmosphere interface and salinity depends on fresh water intake (river discharge) and evaporation. These phenomena can generate vertical stratification of the sea water column, for example:

- The propagation of a river plume of weak density (lower salinity and higher temperature due to turbidity) on the surface of higher density water mass.
- The summer surface warming inside a bay.

These situations are all the more so stable as the vertical density gradient is strong but the stratification can be destroyed by turbulence effect of currents (wind induced currents for the upper part of the water column, bottom friction for the lower part). If currents are strong enough to mix the different masses of water, the water column become homogenous. If there is no wind and tidal currents are weak, the vertical stratification of the water column remains.

As the stratification makes difficult the exchange between the two layers which behave (more or less) as two independent systems, it is no longer possible to consider the total water column from a barotrope point of view. The effects of tide or atmospheric forcing have to be considered in 3 dimensions. This is particularly true in some specific areas where the density gradient together with other external forcing generate particular 3D circulations, for example:

- *Coastal upwellings* (Figure 25) : when the wind blows along a coast, the surface warm water under the influence of the wind derives perpendicularly to the wind (according to Ekman derive law), giving birth to vertical currents of cold water rising to the coast.

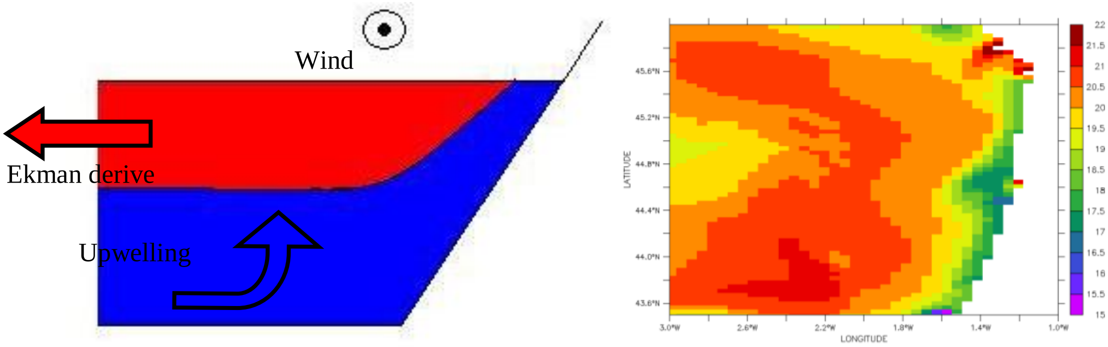

Figure 25 : Upwelling scheme and example of model results

Internal waves: they are generated by a perturbation at the interface of a stratified system, they propagate at the interface between the two density systems and their amplitude decreases from the interface to the surface and to the bottom (Figure 26). Internal waves can have various origins. An example is the generation of tidal internal waves due to the propagation of barotrope tide on the continental slope when the column water is stratified.

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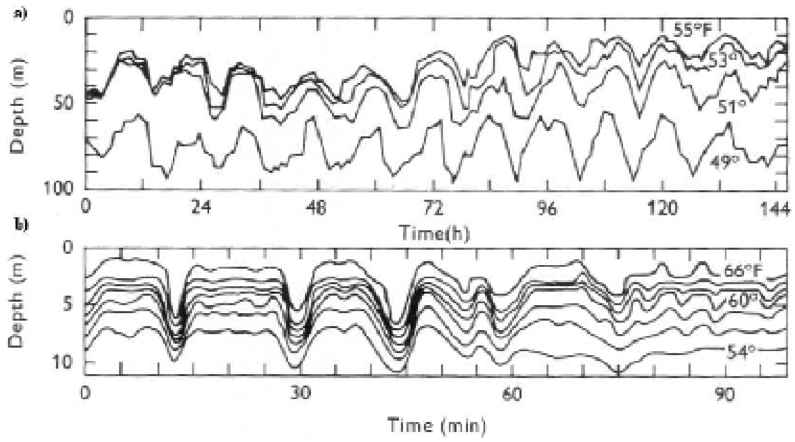

Figure 26 : Isotherms representing the internal wave motion

Another example of density gradient is thermal or salinity fronts. Figure 27 shows the example the Ushant thermal front with a coldest surface wedge of homogeneous water generated by turbulent mixing due to tidal currents in the Iroise Sea.

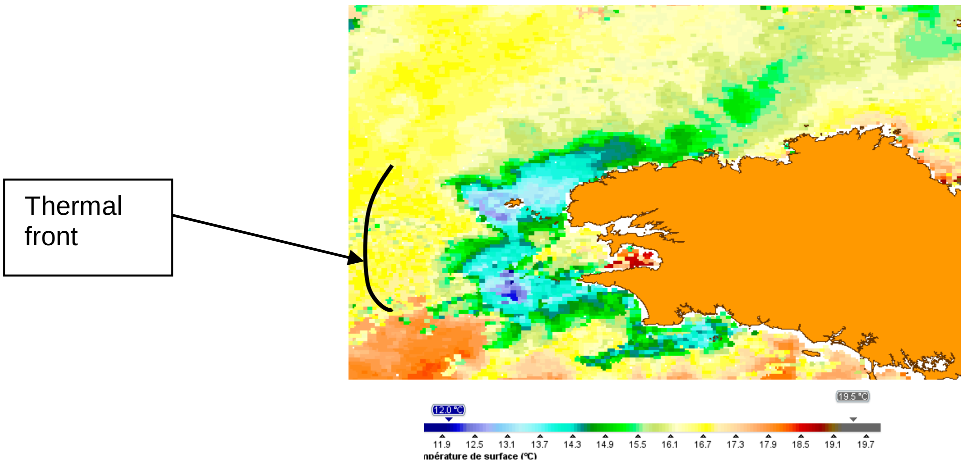

Figure 27 : Satellite observation of Sea surface Temperature 21/07/2008
(Source Ifremer/MarCoast, NAR/NOAA18, ref. 4)

This coexistence of stratified and homogenous thermal situations generates particular dynamics and instabilities illustrated on Figure 28.

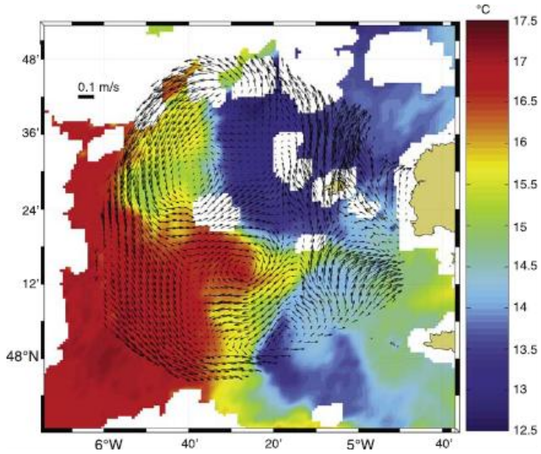

Figure 28: Lagrangian residual currents from HF radar and satellite SST (°C) on 28/09/2007 (from ref. 5)

- General circulation

Last, coastal areas can also be affected by global currents. For example in the Mediterranean Sea, the Liguro-Provençal density current originated from the Gulf of Genes, goes along Italian, French and Spanish coast. It intensifies in winter (50cm/s) and generates many meanders and eddies reaching the coast. Another example is the equatorial upwelling in the Guinea Gulf induced by the trade winds blowing in the equatorial Atlantic Ocean.

6.2.2 Numerical methods in computational modelling

The *finite differences method* computes the solution at each node of a uniform structured mesh. It approximates the derivative expressions (in space or time) with differences using the Taylor series expansion.

The numerical scheme used to rely the solution at the new time step t_{n+1} to the its values at the previous time steps can be either implicit or explicit.

The scheme is explicit when it is possible to estimate the value of the solution at each mesh node regardless of the other points (Figure 29). At each point, the solution can be simply expressed as a function of oldest (previous time steps) values.

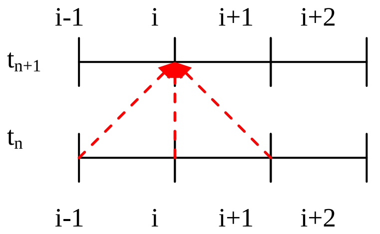

Figure 29: Example of centred explicit scheme

This is a simple and quick method but it is stable only for small values of time step. Thus, stability implies that the Courant number defined as $u\frac{\Delta t}{\Delta x}$ is lower than 1. This is the Courant Friedrichs–Lewy condition (CFL condition). Otherwise, the scheme is called implicit (Figure 30) and the problem should be solved simultaneously at the different points through a linear equation system (matrix resolution)

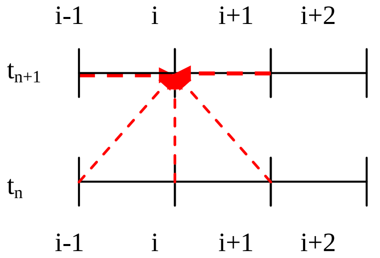

Figure 30 : Example of implicit scheme

Given the matrix resolution implicit scheme implementation is heavier in terms of calculus and time but they are generally unconditionally stable and the limitation of Δt only comes from the truncation error.

In the *finite volumes method*, unknowns are this time the mean value of the solution on each "finite volume" cell of the compute mesh and equations are then integrated on this cell "finite volume" before solving. Then, the derivative expressions are approximated with differences such as in the finite differences method. The main advantage of this method is to deals with flux which assure good properties of mass and motion conservation (the flux leaving one cell enters in the adjacent one). Another advantage of the finite volumes method is that it can be used on an unstructured mesh. However, its drawbacks come from the evaluation of source terms such as bottom friction. It implies suplementary calculations (mostly through an intermediate time step).

In the *finite element method* the unknown function u is approximated by its projection u_h on a finite space of dimensions N described by a basis of functions φ_i :

$$u_h(x,y) = \sum_{i=1}^{n} u_i \varphi_i(x,y) \text{ (2D problem)} \tag{30}$$

The values of $u_i\varphi_i(x,y)$ are the exact values of u at n given points of the domain called interpolation node. There are many way to define the basis of functions φ_i . If using a Fourier series, it leads to the spectral method. Generally, for the finite element method φ_i is a basis of piecewise linear functions such as φ_i is 1 in node i and 0 in the other nodes (Figure 31).

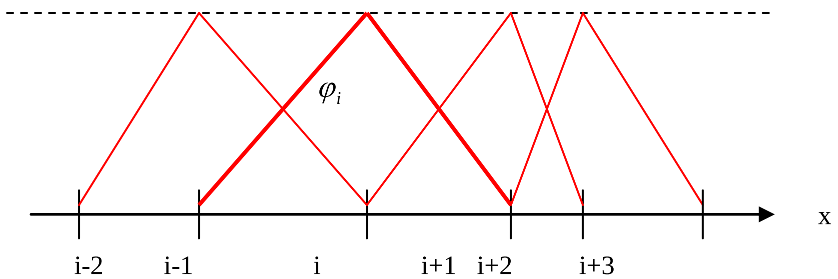

Figure 31 : Example of 1D linear basis

To solve the EDP system, the finite element method then relies on the variational formulation of the equation to solve, E(u)=0:

$$\int_{\Omega} E(u)\Psi d\Omega = 0 \text{ for any function } \Psi \tag{31}$$

This is particularly true for a given basis of test functions Ψi.

A classical method (Galerkin method) for finite element consists in taking: Ψi= φ_i such leading to a linear system whose unknown are u_i.