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Wave modelling in coastal and inner seas

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ABSTRACT

In the long term development of the research on wind waves and their modelling, in particular of the inner and coastal seas, the present situation is framed with a short look at the past, a critical analysis of the present capabilities and a foresight of where the field is likely to go. After a short introduction, Chapter 2 deals with the basic processes at work and their modelling aspects. Chapter 3 highlights the interaction with wind and currents. Chapter 4 stresses the need for a more complete, spectral, approach in data assimilation. Chapter 5 summarizes the situation with a discussion on the present status in wave modelling and a look at what we can expect in the future.

1. Wave challenges in coastal and inner seas

a review of the present know-how, results, problems and expectations in this not large environment, but with a lot of connections to it

It is amply acknowledged that surface wind wave modelling has now achieved a high degree of reliability. Global modelling of the best operational centres regularly provide analyses and forecasts with an accuracy of a few percents; see, among others, http://www.ecmwf.int/en/forecasts/charts/obstat/?facets = Category,Satellite%20Data%3BParameter,Surface%20wind%20speed (wind speed) and http://www.ecmwf.int/en/forecasts/charts/obstat/?facets = Parameter,Wave%20Height (wave height) for the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, U.K.) and http://polar.ncep.noaa.gov/waves/validation/ for the National Center for Environmental Prediction (NCEP, Maryland, USA). Also in the medium range, forecasts are generally (but not always) reliable till one week in advance. This is due to the substantial improvements progressively achieved in meteorological modelling and, particularly in the middle range, to recent refinements in the physics of generation and dissipation of wind waves. Problems still exist and require attention, particularly in view of the growing acknowledgement of the role of wind waves in modulating all the exchanges at the air-sea interface (Cavaleri et al., 2012), and therefore having a basic role in determining the Earth climate. However, from the point of view of traditional wave applications, the general user can be quite satisfied.

This is not always the case in restricted (coastal and semi-enclosed) seas. The obvious affecting factors are the presence of land and associated orography, and, on purely marine terms, the presence of often extended areas of shallow waters. Land and orography substantially affect the wind fields, with immediate consequences on the evolution of the local wave fields. The presence of shallow waters, with different kinds of bottom, either rocky or sandy, and possibly covered with vegetation, mud or, in the Arctic Ocean, ice, complicates or changes which are the dominant processes at work, hence the relevance of the accuracy of the background information. In very shallow water

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($kh < 0.5$) the details of the bottom effects may become the dominant factors, especially with small grids with a high spatial resolution. On the application side, in limited depth areas the wave conditions may become the relevant information for, e.g., the local biological conditions, sea productivity and the corresponding proper management. At the larger end of the limited basins the so-called Arctic ocean should be included as well, its present dimensions when free of ice being comparable to some of the enclosed areas we regularly deal with, e.g., the Great Lakes of North America. The extra factor to be considered is obviously the waves-ice interactions.

An often emerging difference with respect to deep open waters is the relevance of currents. In the oceans, with the exception of well determined areas, most of the time and in most of the places the surface currents do not reach velocities as to substantially affect wave conditions (for the time being we purposely ignore the wave induced currents). Therefore also the frequent lack of accuracy in the details that characterizes most of the large scale circulation models is not likely to appreciably affect the local wave results, at least for waves of a certain dimensions, hence of general interest for most of the users. This is not the case close to the coast. Here quite often the currents (barotropic and baroclinic) are geographically enhanced reaching values that, if not considered, can lead to substantial errors in wave model results. This is more frequently the case in semi-enclosed seas, where the limited dimensions imply in general shorter wave periods than in the oceans, more sensitive to the influence of currents.

The interactions between waves and current act in both the directions, sometimes with a positive feed-back effect, forcing us on one hand to consider these interactions in their various facets, and on the other hand to pay much more attention to current modelling to achieve, as far as possible, the accuracy required for the one desired for wave model results. It is rather intuitive that, given the smaller time and spatial scales in the inner seas, the relevance of “smaller” (high resolution) details is high, and it implies a shortening of the reliable range of forecast. There are two reasons for this. On very general terms the smaller is an important detail, the more likely a forecast is to be affected by errors, because of the inaccuracies of the initial conditions and the imperfections of the model. More specifically for the coastal areas and semi-enclosed seas, the local conditions are much more sensitive than in the open sea to, e.g., a slight shift of the forcing meteorological pattern, either in space or time, with respect to the local geometry. When looking at the coastal meteorological surge, the phasing relative to astronomical tide becomes crucial, a simple time shift, of, e.g., three hours of the meteorological event possibly leading to completely different overall conditions on the coast. This implies a shortening of the useful range of forecast because the error is growing with range faster than in the open sea.

On the other hand, there is a steady growth of the already intense interest in the wave conditions in coastal areas, both at local and a more extended scale. Increasing maritime traffic, recreational activities, urban development, ecosystem restoration, renewable energy industry, offshore management, all push in this direction. The purpose of this paper is to frame the present situation in wave modelling in coastal waters and in the enclosed seas. We do not aim at a review of the existing literature (a daunting task), but rather to touch the main subjects of relevance in coastal and semi-enclosed sea wave modelling, citing sufficient examples of the relevant literature. The emphasis will be on the problems that still affect this topic. We stress the physics involved, and in turn this will imply to touch, but not to dig in, the field of meteorological and circulation modelling because of the tight coupling in a spatially limited environment. Similarly we stress the importance of wave-bottom interactions, but we do not go into details as this would open the door to sediment transport, a subject that would easily require another extensive paper to frame the related situation. All this will be complemented with an extensive range of applications, both to frame the possible accuracy and to call the attention, via the use of different models for the same event, to the differences and difficulties we still find in practical applications.

Based on this approach the paper is structured as follows.

In Chapter 2 we deal with the basic processes at work, analysing the various modelling aspects that lead to, and condition, the final results.

In particular Section 2.1 analyses the reasons why the wind model input information are likely to be less correct than in the open ocean. We also stress the higher variability and that very high wave conditions are possible also in enclosed seas.

Section 2.2 deals with the basic aspects of wave modelling in this relatively restricted environment. It explains the reasons for the greater difficulty to obtain good results compared to the open sea.

Section 2.3 focuses more on this aspect, detailing the physics involved.

In Section 2.4 we leave physics (partially) aside to discuss the crucial aspect of any numerical model, its numerics, i.e. how the various equations are integrated in space and time. Although the models are (partially) built with some self-control mechanism, we stress that every user should be aware of the approximations involved, and of the consequent likely accuracy of the final results.

Section 2.5 focuses on a crucial aspect of the validation of our model results, i.e. the accuracy of the measured data we use to compare with. While we touch most of the main instruments at use in the world, we devote quite a bit of attention to buoys. These have been for decades the almost official reference for the calibration of other instruments, especially from satellites. For this reason we devote quite a bit of space to this analysis, just to make the unaware wave modeller aware of the implied approximations.

Section 2.6 deals with applications. We have chosen a number of examples from quite different environments to highlight the various problems we (may) face in practical use and the accuracy we can expect in the various conditions.

In Chapter 3 we abandon the view of modelling waves as an isolated process, and we deal with the interaction with the two media waves involve when moving.

Section 3.1 deals with the interaction with sea currents, and how wave and currents interact with mutual and feed-back effects. We show this in a number of examples in quite different environments.

In Section 3.2 we extend this mutual interaction also to the atmosphere. This interaction can be particularly intense in coastal waters due to the enhanced effects associated to orography and limited coastal depths. The extensive citation of the existing literature is a clear proof of the complexity of these three-component interactions, exemplified in a number of cases.

Chapter 4 discusses data assimilation in enclosed seas. While the described principles are quite general, we highlight the related problems in this specific environment. In particular we stress that long term used approaches, as e.g. Optimal Interpolation, are generally not suitable for the constrained geometry of the enclosed seas. Therefore we focus our attention on a spectral approach that two examples show to be more suitable, especially for a complicated geometry.

In Chapter 5 we make an extensive summary of the situation. We discuss the quality of the present approaches, the reliability of the results, and what we must be aware of when modelling waves in enclosed seas. We also make an outlook into the future discussing the expected or likely developments, which problems are technical, hence with a foreseeable development, and which are physical, when knowledge and theory are not necessarily moving at a regular pace.

The bibliography is quite comprehensive, each Chapter and Section requiring its own share of know-how and historical and modern developments. Here below we provide a list of the most common and repetitively used acronyms with their meaning.

Being the product of multiple contributions, there is not a unique