The impact of ocean bottom morphology on the modelling of the long gravity waves, from tides and tsunami to climate

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Abstract

Ocean basin morphology is a major controlling parameter of the ocean dynamics. We address here its impact on long gravity waves: tsunamis, storm surges and tides. The deterministic character of the tides allows one to easily illustrate how modelling of long gravity wave in the ocean is dependant upon the knowledge of the shape and depth of the ocean basins, and on the slope of seamounts, mid ocean ridges and continental shelf breaks. A few examples are given. The first one is the impact of inaccuracies in the bathymetry on wave propagation at basin scale (the North Atlantic). The second one shows the global dependency of the solutions (the remote effect of the resolution of the tides under the Weddel Sea permanent ice shelf). The third one illustrates the trapping of energy by the continental slopes above the critical latitudes (the diurnal tides over the Yermak plateau). Particular focus is given on the importance of the energy transfer from barotropic tides to baroclinic internal waves. This transfer is taking place over seamounts, mid ocean ridges and at the shelf breaks, closely dependent upon the slope of the bathymetry. This energy transfer to internal wave could play a role on the deep ocean mixing, contributing to the maintenance of the thermohaline circulation, and hence impacting the climate of the earth.

Introduction

The morphology of the ocean basins is a major controlling parameter of the ocean dynamics. This is particularly true for the ocean long wavelength gravity waves (tides, storm surges and tsunamis). Their characteristics are closely related to the size and the shape of the ocean basins, and on their bathymetry. One key element of the physics of the long gravity waves is indeed that their propagation speed and their wavelength are dependent on the square root of the local depth. It is thus extremely important that correct bathymetry can be introduced in ocean models aiming at their simulation, for the scientific understanding of their characteristics, and for improving their prediction. Ocean tide modelling is typically a domain where numerical simulations have reached a stage where the inaccuracies in the available bathymetric databases represent a clear limiting factor for new progress. The aim of this paper is to illustrate on a few examples the major role of bathymetry in controlling the physics of the response of the ocean to high frequency forcing, at the local or global scale. This ocean response corresponds to tsunamis, storm surges, and tides. In the following, tides will be used as basic examples because their deterministic character allows to more easily demonstrate the impact of ocean bottom morphology and bathymetry on key processes: wave propagation, energy trapping and energy dissipation. The reason why the title ended by “climate” is related to the role that the tidally induced ocean vertical mixing is now considered to play in the maintenance and control of the global thermohaline circulation, hence on the long-term impact of the ocean on the climate.

State of the art in global ocean tide numerical modelling and ocean morphology

Global ocean tide numerical modelling started thirty years ago with the pioneering works of Bogdanof and Magarik (1969) and Pekeris and Accad (1969). Numerical models are based on the Laplace Tidal Equations, completed by dissipation. In the seventies, a very significant improvement in numerical tidal models resulted from the introduction in the equations of the effects of earth tides, ocean tide loading, and self-attraction: see Zahel (1977), Accad and Pekeris (1978), Gotlib and Kagan (1981). However these solutions only qualitatively agreed with *in situ* observations: their accuracy was not at the level required for new geophysical applications. Hence the need to compensate for the deficiencies of these unconstrained models by additionally forcing the solutions to fit observed data. This was the way Parke and Hendershott (1980) and Schwiderski (1980, 1983) got their solutions. Indeed, Schwiderski's solutions have been considered as the best available through more than one decade, in the eighties. With a resolution of 1º x 1º, they cover the world ocean, except for some semi-enclosed basins like the Mediterranean Sea. But the accuracy of these solutions was dependent on the quality of the observations used, and suffered from the same weakness as the purely hydrodynamic models over the areas where data were not available.

In order to improve the purely hydrodynamic models it was of evidence necessary to reproduce details of the tidal motions over the shelf areas and the marginal seas, by reducing the resolution down to a few tens of kilometres. Models have been developed with grids of variable size: 4º over the deep ocean, 1º over some continental shelves, and 0.5º in particular shallow seas (Krohn, 1984). A new approach was developped in the beginning of the nineties. It was based on finite element (FE) method, and allowed to improve the modelling of rapid changes in ocean depth, the refinement of the grid in shallow waters, and the description of the irregularities of the coastlines (Kuo, 1991; Le Provost and Vincent, 1991). The global FE tidal model (FES) developed by Le Provost et al (1994) allowed to use a mesh size of the order of 200 km over the deep oceans reducing to 10 km near the coasts. Compared to observations, this FE solution was in many areas closer to reality than the Schwiderski's one. However, many discrepancies remained. At that time it became easy to identify where these errors were located, thanks to the new solutions issued from the analysis of the altimeter data produced by the NASA-CNES TOPEX / POSEIDON (T/P) mission (Shum et al, 1997; Le Provost, 2002). One reason of these discrepancies was clearly linked to the uncertainties in the bathymetry, as will be illustrated in the following. But the major reason was a more basic default of the hydrodynamic model formulation: the lack of one key sink of energy corresponding to the transfer of energy from the barotropic ocean tides to their baroclinic component, until now neglected. This finding represents a major new step in the understanding of the way tidal energy is dissipated in the ocean. But it also more basically re-opens the “old” idea on the possible role of the tides in ocean bottom mixing and its impact on the thermohaline ocean circulation, as proposed by Munk (1966). We will extend on this in the following, and point out how important is the knowledge of the slopes of the ocean topography. But before let us finish the presentation of the state of art in term of ocean tide description.

A way to compensate the weaknesses of the numerical models is to make a compromise best fitting the assumed dynamic equations and all the available data of good quality, treated as an inverse problem. This approach is known as 'data assimilation'. Following this approach, the assimilation of T/P data allowed to reach a level of accuracy never obtained before: Egbert et al (1994), Kantha et al (1995), Le Provost et al (1994). The more recent tidal solutions (Ray, GOT2000) and (Le Provost et al, FES 2002) are now within a few centimetre differences for all the major tidal components, at least over the deep ocean. Indeed, differences of a ten of centimetres remain over the shallow water areas.

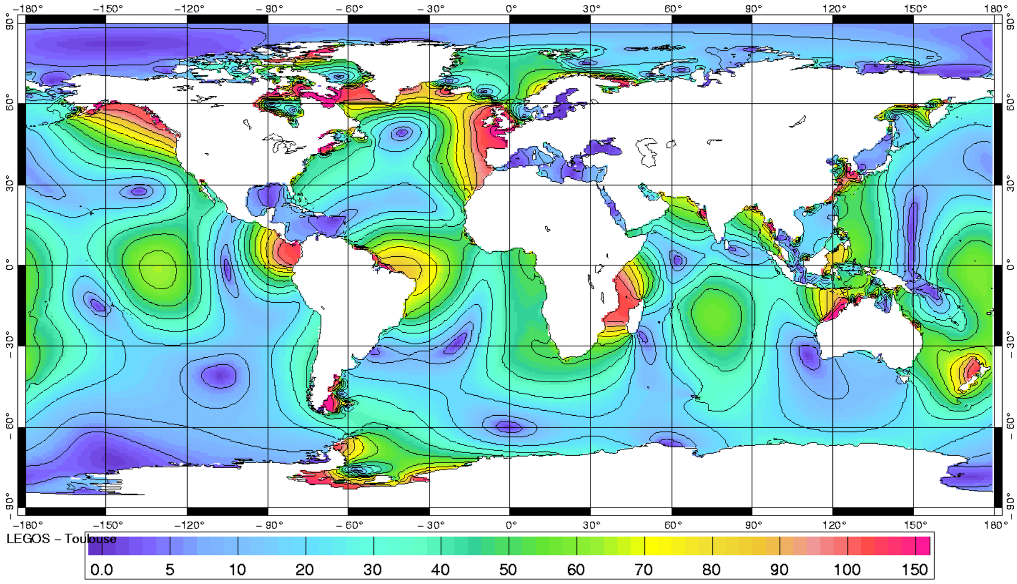

Figure 1: Amplitude of the M2 lunar component of the tides (FES 2002). The scale is in centimetres

Some sensitivity studies of ocean tide simulations to bathymetry

The inaccuracies now observed in the hydrodynamic models are partly due to uncertainties in the bathymetry. The physics of ocean tide gravity waves is indeed dependent upon the depth through several processes. As said before, the propagation speed of these waves is directly related to the square root of the depth. Their velocity fields and dissipation are partly controlled by the local water depths. It is possible to find in the literature sensitivity studies giving some insights on the order of magnitude of the changes in tidal solutions induced by changes in the bathymetry. Some examples follow.

Lyard and Genco (1994) addressed this problem within their investigations on how to approximate bottom topography. Their tests were carried on the North Atlantic. They compared solutions computed with the same model and the same conditions (forcing, open boundary conditions, parameterisation of dissipation). The only difference was the description of bathymetry over each FE triangle of the domain: either a linear interpolation computed from the ocean depth issued from ETOPO5 data bank, or a more sophisticated interpolation which they called 'optimal'. The statistical differences between the two tested bathymetries were the following:

(i) the global mean depth integrated over the domain was the same for the two cases,

(ii) the extreme differences were -275 m and +300 m, and the RMS difference was 33 m, with typical wavelength of these differences of the order of the size of the triangulation of the domain, i.e. 800 km. The tests were done on the simulation of the major tidal component: M2.

Solutions for this wave in the North Atlantic typically look like an amphidromy, with a nodal point in the centre of the basin and amplitudes increasing up to 1 to 2 m over the different continental margins around (see figure 1). Lyard and Genco observed that the differences between their two simulations were coherently distributed over the basin. These differences were ranging from a few centimetres in the deep ocean to a mean range of 4 to 7 cm over significant areas: the entrance of the English Channel, the Labrador Sea, the east coast of Florida. They were increasing up to ten centimetres (or even more) in specific places: the Amazon plateau, the entrance of the Hudson Bay. These differences are important, if we consider the level of accuracy of the global ocean tide solutions now available.

Another instructive example is the one reported by Le Provost (1993) showing how changes in ocean depths can influence computed tides over large distances. This sensitivity exercise was also carried with the finite element model developed by Le Provost et al (1994). When investigating tides over the South Atlantic Ocean, it appears the dissipative processes taking place in the Weddel Sea under the permanent Ice Shelf were important for the global quality of the simulated solutions over this sub-basin. However, finding a good bathymetry and correct permanent ice shelf thickness is not easy. This resulted in the realization of two experiments: one with an incorrect guessed difference between the bottom of the Weddel Sea and the base of the ice shelf (of 100 m), and the other with the “correct” value (varying around 300 m). Considerable changes were observed over the Weddel Sea between the two responses. But more spectacular was a change of more than 10 cm in the Gulf of Guinea, about 8000 km away from the area where bathymetry was modified

These two examples are related to global ocean tide modelling, with uncertainties on the bathymetry of the order of a hundred meters. Numerous examples are available in the literature of sensitivity tests for regional coastal models with changes in the bathymetry of only a few to ten meters for water depths of the order of a hundred meters: here also solutions can be very sensitive to such changes. Davies and Aldridge (1993), for example, found that a modification of the order of 8% in the depth of their 3D model of the Irish Sea was necessary to fit their simulations to observed data (sea surface elevations and currents

Bathymetry and topographically trapped tidal waves

Diurnal tidal waves are particularly sensitive to bottom topography. The existence of topographically trapped tidal waves has been demonstrated analytically by several authors in the sixties: Mysak (1967), Buchwald and Adams (1968), Saint Guily (1968), Longuet-Higgins (1968), Rhines (1969). Since then, these waves have been observed over shelves and at the shelf break in many places of the global ocean. Their characteristics are dependent upon the slope of the shelves along which they are trapped and propagate. Such features appear as local structures of rather short wavelengths, of the order of some hundred of kilometres. As they are quasi-non-divergent, their presence is mainly observable through the local intensification of the currents that they induce

The area of the Yermak plateau, north of Iceland, is a typical area where intense diurnal oscillations have been observed, and several modelling studies have allowed explanation of the main processes taking place there (Kovalik and Proshutinsky, 1993; Le Provost and Genco, 1994; Lyard, 1997). The Fram strait, between Greenland and Iceland, is a key area for the world ocean circulation, because it is the place where sea ice coming from the Arctic Ocean enters the Atlantic Ocean. When observing this ice drift by following the position of ARGOS beacons released on the ice pack, Gascard et al (1991) noted a trapping of their 'floats' which were turning around with a period of one day over the edge of the Yermak plateau. The FES model has been applied to the simulation of the diurnal tides over this area (Le Provost and Genco, 1994). A regional model extending from 75ºN to 85ºN, and from 40ºE to 32ºW allowed refinement of the computation mesh down to 4 km resolution over the Yermak Plateau. Open boundary conditions were supplied from a larger model (see figure 2) embedded in the global model of Le Provost et al (1996). Bottom topography was deduced from a local bathymetry supplied by Gascard et al (1991). Solutions were computed for two diurnal tidal components: K1, of period 23.93 h, and 01, of period 25.82 h. These solutions confirmed the existence of topographically trapped quasi-non-divergent waves. But they revealed also the extreme sensitivity of the ocean response to frequency and thus to the shape of the bottom slopes, if we refer to their frequency - wave number dependency on bathymetry and its slopes.

The K1 wave is amplified under a typical double Kelvin wave expending along the whole western edge of the Yermak Plateau. The sea surface oscillation is only weakly intensified, rising up to 10-15 cm along the shelf break (see Figure 2). But the main signature is on the velocity field (see figure 3). The solution is dominated along the western side of the Yermak Plateau by a system of cyclonic and anticyclonic eddies propagating northward. The top of the plateau is on their right. Velocities are locally reaching up to 30 cm/s. The energy fluxes associated with this local system clearly show that the trapped energy propagates anticyclonically southward along the tip and northward along the foot of the shelf edge. The characteristics of these features in term of phase speed and wavelength fit relatively well with the theory of shelf waves, for which the shape of the shelf break is a key parameter.

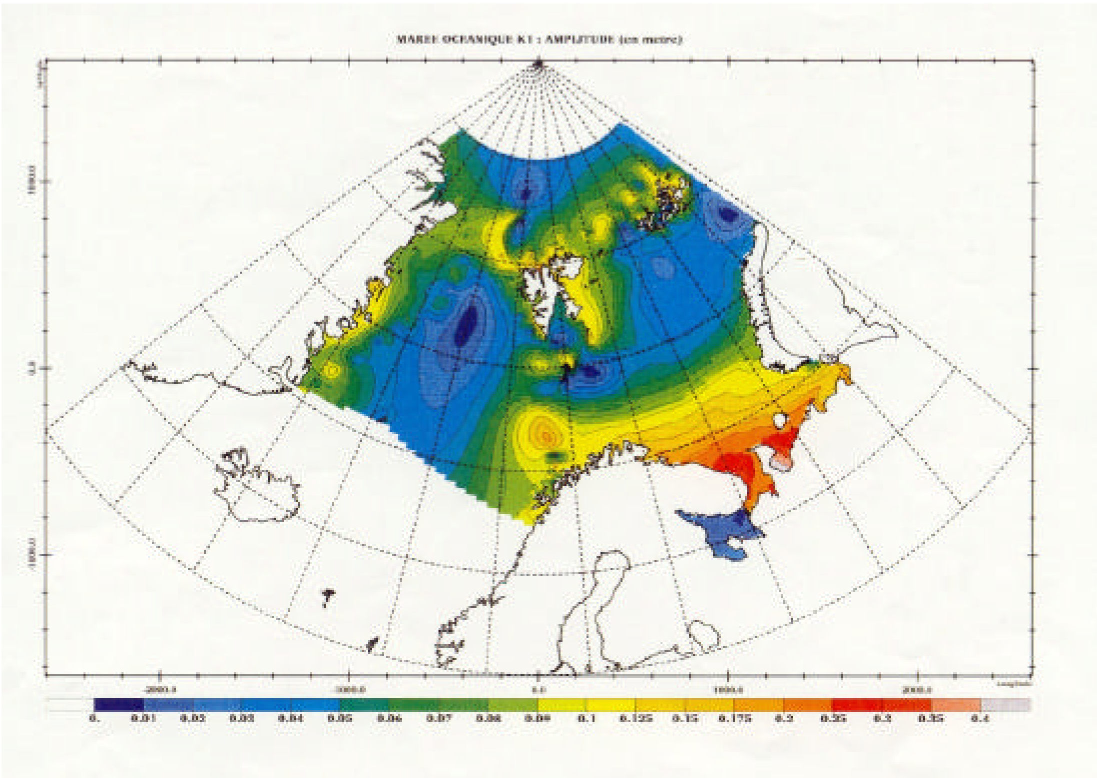

Figure 2: Amplitude of the K1 main diurnal constituent of the tides over the Northern part of the North Atlantic Ocean. The scale is in metres. This map shows the amplification of this wave over the Yermak Plateau. Other remarkable features are noticeable along the Greenland and the Barentz Sea Shelf break.

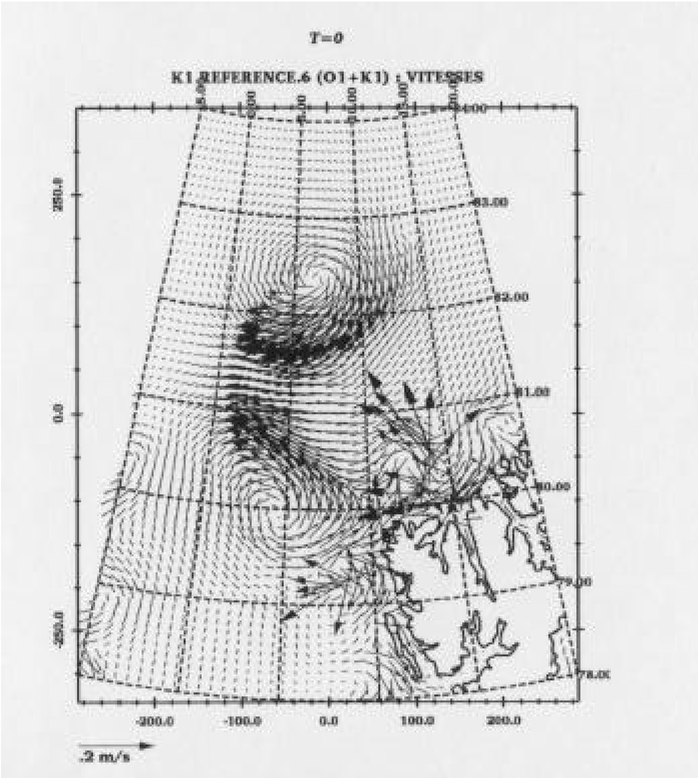

Figure 3: Instantaneous distribution of the velocity field of the K1 main diurnal constituent of the tides over the Yermak Plateau. The remarkable features are the presence of three eddies (two anti cyclonic and one cyclonic) with their center located on the western slope of the Yermak Plateau. These eddies propagate Northward, leaving the top of the plateau on their rigth, as said by the theory of quasi non divergent waves trapped by shelf slopes.

By contrast, the O1 response looks locally very different. The numerical simulation reveals a localized area of intense trapping, at the northern end of the Plateau. The sea surface elevation is there also amplified up to 12-14 cm although the O1 astronomical forcing is weaker than for K1. But it is in the velocity fields and energy fluxes that the local resonance clearly appears. The eddy structure already observed in the K1 solution here reduces to a couple of cyclonic-anticyclonic eddy systems reaching their maximum of intensity when sitting on top of the steepest part of the shelf break. The ocean response to the diurnal tidal forcing appears thus over this area critically dependent on the shape of the bathymetry. This is a clear illustration of why modellers need to get the more accurate bathymetry especially when addressing the simulation of such specific features

Ocean tides dissipation and relation to bathymetry

Tidal energy is dissipated through bottom friction and internal tide breaking. These mechanisms are linked to bathymetry: bottom dissipation is related to the intensity of the flows, hence to the depth of the water column, and generation of internal tidal waves is due to the interaction of the barotropic tides with bottom hills, middle ridges and continental shelf edges. The knowledge of the bottom topography morphology over the areas of dissipation and internal wave generation is a key for accurate ocean tides modelling.

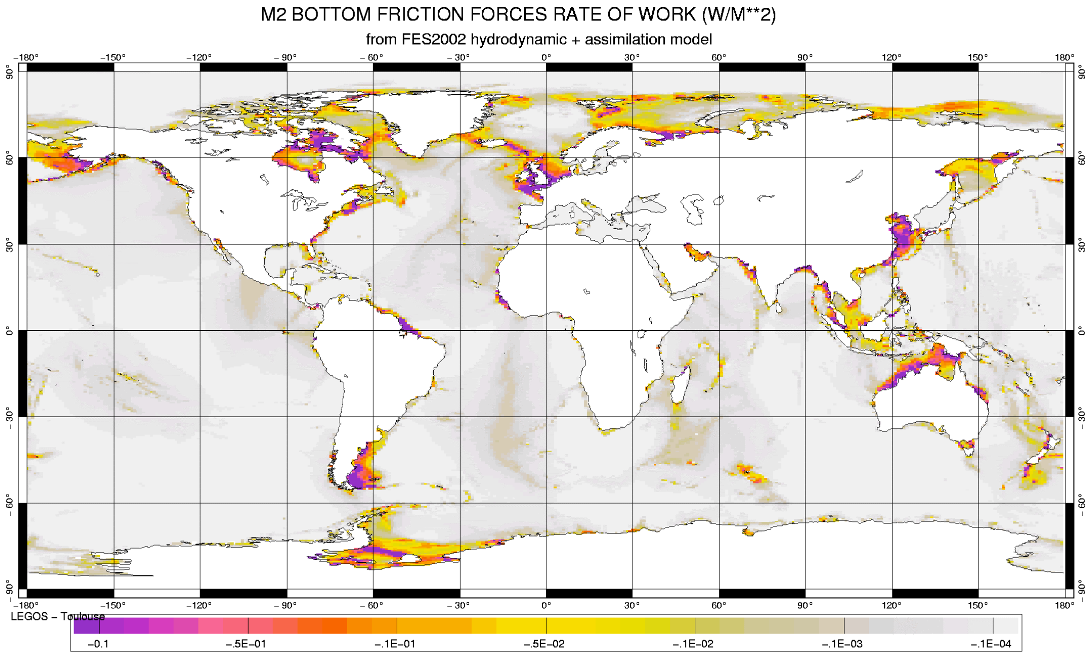

Figure 4: Global scale distribution of M_2 energy dissipation by bottom friction. The scale is in W/m^2.

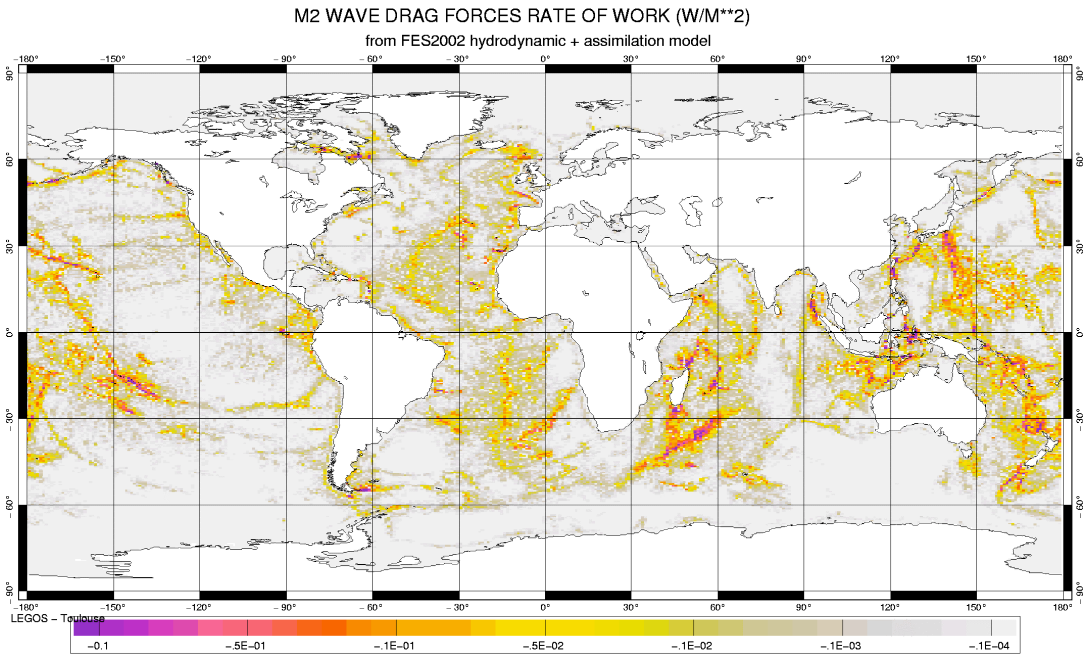

Figure 5: Global scale distribution of M_2 energy transfer from barotropic tide to baroclinic internal waves. The scale is in W/m^2.

The developments in ocean tide numerical modelling, combined with assimilation of altimeter data issued from TOPEX/POSEIDON, as above reported, have led to revised estimates of global tidal energy budgets (Egbert, 1997; Le Provost and Lyard, 1997; Lyard and Le Provost, 1997; Egbert and Ray, 2000). Global and regional budgets have been established, telling on one hand where the energy input by astronomical forcing (2.45 TW) takes place, and on the other hand how and where this energy is dissipated.

Until very recently, it was considered that this energy was mainly dissipated by bottom friction over the main continental shelves. However, Le Provost and Lyard (1997) noted in the energy budget of the FES94 hydrodynamic tide solution including only bottom friction dissipation that this sink of energy was not sufficient to balance the energy input by the astronomical forcing. Following the Egbert and Ray (2000) idea that internal wave could play a significant role in the tidal energy dissipation, an additional sink of energy has been introduced in the FES model. The parameterisation of this extra mechanism consist in the introduction in the momentum equation of a wave drag dependant on the local density stratification of the ocean, the local topography gradient, and the barotropic tidal velocity. The introduction of this new sink of energy dramatically improved the accuracy of the FES model. The amplitude of the M2 solution, which was biased too high without this internal wave drag parameterisation, adjusted globally to within 1 cm bias, and its RMS difference to a standard set of 100 in situ data reduced from 13 cm too less than 6 cm. Of course, this hydrodynamic solution is still not at the level of accuracy (1.7 cm) of the more recent tidal solutions GOT2000 and FES2002. The former is issued from the analysis of the T/P and ERS data and in the later a large set of tide gauge data and T/P and ERS data have been assimilated. But it is certainly the first time that a purely hydrodynamic model produces a solution so close to reality. A large part of the remaining inaccuracies can certainly be attributed to the inaccuracies in the representation of bottom topography (depth and slopes).

Figure 4 and 5 show the spatial distribution of tidal energy dissipation derived from the FES2002 solution. These maps are very similar to the ones produced by Egbert and Ray (2000, 2001). A quantitative comparison has not done, but the total amounts of energy dissipation corresponding to these solutions are close enough to let think of the robustness of the results:

- dissipation over the deep ocean, mainly through internal waves:

GOT 99 (Ray): 0.73 TW, TPXO (Egbert): 0.83 TW, FES2002: 0.82 TW

- dissipation over shallow waters, through bottom friction

GOT 99 (Ray): 1.71 TW, TPXO (Egbert): 1.60 TW, FES2002: 1.47 TW

These maps are designing the areas where the bathymetry of the ocean floor and its morphology need to be known with high accuracy. Figure 4 shows where energy dissipation through bottom friction occurs. The main areas are the Hudson Bay, the Yellow sea, the Amazon shelf, the European shelf, the Patagonian shelf. Besides, energy transfer from barotropic tides to internal tides is taking place over many of the ocean ridges, but not all (Figure 5). This energy transfer is indeed depending upon the slope of the topographies, the intensity and direction of the tidal currents, and the density stratification of the ocean.

From Tsunamis, storm surges and tides to Climate

A tsunami is an ocean gravity wave generated by dislocation of the ocean bottom, due to seismic faulting, volcanic eruption, or submarine landslide. The typical time scale of tsunamis is much smaller than tides. Their wavelength are of the order of only several tens to hundreds of kilometres in the deep ocean, and once the tsunami approaches a shore, the shoaling of the seabed causes their wavelength to decrease and their amplitude to increase, often dramatically. Their propagation and evolution are strongly affected by the bottom bathymetry and its morphology. And the violence of this kind of phenomenon is such that they run up beyond the shorelines sometimes far inland the continent. Thus, unlike tides, tsunami analyses and modelling require extended bathymetric information not only of the entire ocean basins but also of the coastal topography up to 30 m above sea level or up to 5 km inland from the shoreline (Yeh, 1998).

Storm surges are forced by high frequency atmospheric wind and pressure variations acting over the whole ocean. Their effect is amplified over the continental shelves, due to shoaling. They result from combination of local and remote forcing, including wave propagation trapped along shore by the topography and the coasts. The impact of bathymetry on storm surges is the same as illustrated above on tidal examples, in term of propagation, energy trapping by the topography and the coastlines, damping, and non linear deformation (not illustrated here). As storm surge modelling is particularly focusing on continental shelves and on shallow water areas, up to the shores, accurate and high resolution bathymetric data are required. Indeed, two major ingredients controlling the quality of storm surge predictions are detailed and accurate ocean bathymetry and atmospheric forcing fields.

Why in this paper including the term climate when the whole above presentation focused on high frequency events ranging from tsunamis to storm surges and tides? The paradox is that these high frequency oceanic motions can impact the deep water mixing in the open ocean, then partly controlling the thermohaline circulation and thus the climate. This mechanism was suggested by Munk (1966) but neglected until recently, when the progress in our knowledge on ocean tides, as reported above, led to the conclusion that a significant part of the tidal energy is dissipated through internal tides. It is now considered that about half of the energy required to maintain the global abyssal density distribution against the estimated 30 Sverdrups of deep water formation could be due to tides, the rest being supplied by the wind. This would occur when deep ocean tidal currents hit sea mounts and mid ocean ridges, creating turbulent internal waves that stir and lift cold bottom water to mix with the warmer waters from above (Munk and Wunsch, 1998). Hence the link between tides and climate, and coming back to our purpose to the need for a better knowledge of the ocean floor morphology and its rugged bottom topography.

Conclusions

The characteristics of the ocean bottom topography plays an important role in the physics of ocean gravity waves, by controlling their propagation, their possible resonance within each ocean basin, and the trapping of their energy over topographic slopes. The knowledge of the ocean bathymetry is particularly important over the continental shelves, where the amplitude of the waves is amplified by the shoaling of the bottom topography. Besides, the damping through bottom friction in coastal areas is proportional to the square of the velocity: it is thus very sensitive to the bathymetry and its detailed morphology. Modelling of ocean long gravity wave ranging from tsunamis to storm surges and tides has made important progress over the last few years, with the constant increase in computing capacities, and moreover, for tides, with the huge set of information coming from satellite altimetry. Models are now at the stage where uncertainties in bathymetry appear as a clear limiting factor for new progress in our understanding of the physics of these gravity waves, at global to regional and local scales, and our capacity for producing accurate predictions. For our purpose, following the recent Score WG 107 report (2001), specifications for accuracy and resolution needed in term of ocean bathymetry could be as follows:

- over the deep ocean, 10 m accuracy with 5 km resolution,
- with an improved resolution down to one km over the continental slopes,
- and a few meter accuracy on the continental shelf with a hundred meters resolution in coastal areas.

This is needed over the whole ocean, because of the global dependency of these phenomena upon bathymetry. Priorities must be put over the continental shelves and along the coasts where accurate predictions of tsunamis, storm surges, and tides are required. The new theory on the role of these gravity wave (mainly tides) contributing through bottom tidal mixing to the maintenance of the thermohaline circulation, and to the control of our climate, leads to another priority over the sea mounts, ocean ridges and shelf breaks where these internal waves are generated.

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