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Tidal downscaling from the open ocean to the coast: a new approach applied to the Bay of Biscay

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ABSTRACT

Downscaling physical processes from a large scale to a regional scale 3D model is a recurrent issue in coastal processes studies. The choice of boundary conditions will often greatly influence the solution within the 3D circulation model. In some regions, tides play a key role in coastal dynamics and must be accurately represented.

The Bay of Biscay is one of these regions, with highly energetic tides influencing coastal circulation and river plume dynamics. In this study, three strategies are tested to force with barotropic tides a 3D circulation model with a variable horizontal resolution. The tidal forcings, as well as the tidal elevations and currents resulting from the 3D simulations, are compared to tidal harmonics extracted from satellite altimetry and tidal gauges, and tidal currents harmonics obtained from ADCP data.

The results show a strong improvement of the M2 solution within the 3D model with a ”tailored” tidal forcing generated on the same grid and bathymetry as the 3D configuration, compared to a global tidal atlas forcing. Tidal harmonics obtained from satellite altimetry data are particularly valuable to assess the performance of each simulation. Comparisons between sea surface height time series, a sea surface salinity database, and daily averaged 2D currents also show a better agreement with this tailored forcing.

1. Introduction

Increasing efforts are made to improve the accuracy of global circulation models at regional scales, by improving the grid resolution, by taking into account more physical processes or through data assimilation techniques (e.g. Holt et al., 2017). In spite of significant progresses in the recent years, the global or basin simulations performance generally remains insufficient to accurately study coastal phenomena, and regional models are still the best option, thanks to their higher resolution, tuned parameterizations or parameters, and to the consideration of comprehensive coastal processes such as tides, surface waves, estuarine processes, etc. Since regional physical processes are partly driven by large scale processes (Zheng and Weisberg, 2012), with this limited-area approach comes the issue of downscaling and managing open boundary conditions. As first stated by Oliger and Sundström (1978), open boundary conditions can never be considered as perfect. Several strategies have been developed to deal with this issue, as discussed for instance by Blayo and Debreu (2005) and Herzfeld (2009). More particularly, the nesting of several grids within each other are often used to gradually increase the resolution near the coast. However, the interpolation necessary due to resolution differences and bathymetry inconsistencies may induce errors at the open boundaries.

Modelling the 3D ocean circulation in coastal areas and shelf seas requires an accurate representation of the tidal dynamics, especially near the coast. The tidal solution in a regional circulation model results from the introduction of the astronomical tidal potential in the primitive equations, and from open boundary conditions in sea surface elevation (hereafter SSH) and currents. The accuracy of the tidal forcing at the open boundaries is critical for the representation of tides of course, but also for the simulation of mixing and circulation through different mechanisms: non-linear interactions between tidal currents and the general circulation, mixing induced by internal tides, bottom friction modulation by tidal currents, mixing enhancing by vertical tidal currents shear (Carter and Merrifield, 2007; Herzfeld, 2009; Guarnieri et al., 2013). Guarnieri et al. (2013) show the impact of tides on the Adriatic Sea circulation, with a 3D model. They find that tides influence the circulation by modifying the horizontal advection, especially during periods of weak wind stress. They also assess the impact of tides on mixing, this time for strong wind stress periods. Residual tidal flows due to non-linear interactions with the topography (‘topographic rectification’) can also be generated (González-Pola et al., 2012; Wang et al.,

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2013). Holt et al. (2017) show that the inclusion of tides in circulation models allows a better representation of seasonal stratification cycles than high resolution models without tides.

In principle, the tidal forcing at the open-boundaries is given either as a set of tidal constituents or as time-varying fields of sea surface elevation and horizontal currents. The latter option is for instance tempting when the coastal model is also forced at the open-boundaries by a large-scale circulation model that simulates both the tidal and non-tidal circulation. However, such an option requires the availability of the large-scale forcing at very high-frequency (a few minutes) which is, in practice, never (or very rarely) possible. That is why in most cases, the open-boundary conditions for tides and for the non-tidal circulation are prescribed as distinct sources. We have adopted such an approach in the present study.

Downscaling tides in a coastal (child) model is not a trivial issue: as for the general problem of open-boundary conditions, the difficulties come from the numerical scheme or from the prescribed fields (at least for incoming conditions or 'active boundaries') stemming from the parent model. Another difficulty is introduced if the model is also forced at the open boundaries (hereafter OB) by low frequency motions. For instance, Herzfeld and Gillibrand (2015) discuss the problem of dealing with multiple timescales in a scheme based on local adjustment of the flux at the OB; they propose an approach based on dual relaxation timescales for their scheme. In general, the use of prescribed tidal fields lead to inconsistencies with the interior solution, mainly due to differences in bathymetry between the forcing and forced models. As an example, Wang et al. (2013) note that an adjustment of the prescribed tidal barotropic velocity at the OB is necessary to ensure consistency of the depth integrated barotropic transport with the interior solution. In the case of baroclinic tides, other complications come from possible inconsistencies between the child and parent stratification as well as from the non-stationary part of the internal wave fields that requires the availability of the parent outputs at very high-frequency. For these reasons, in cases of offline downscaling problems such as the one addressed in this paper, only the barotropic tides are taken into account.

To prescribe barotropic tides at the OB, two strategies are usually adopted. The most common one is based on the use of tidal atlases that provide tidal harmonics (amplitude and phase) of sea surface elevation and, in most case, of barotropic velocities for a given tidal spectrum. Several global atlases exist and are regularly updated (for a review see Stammer et al., 2014): some of them are built from empirical adjustment mostly from satellite altimetry to a prior model, such as the GOT (Ray, 1999), or TPXO (Egbert and Erofeeva, 2002) models. Other atlases are solutions of barotropic hydrodynamical models constrained by satellite and/or in situ observations via data assimilation. Among the latter, FES2012 is the last distributed product from a long series of solutions obtained with the T-UGOm hydrodynamical model (Lyard et al., 2006) described in Section 2.2. (At the time when we write this paper, the FES2014 atlas is under construction). Several examples of regional or coastal circulation models that prescribe tidal harmonics from global atlases at their open-boundaries are found in the recent literature: Dong et al. (2011) and Wang et al. (2013) use the TPXO.6 solution for their regional models in the Southern California Bight and Prince William Sound respectively; Katavouta and Thompson (2016) use FES2004 over the Nova Scotia Shelf. In coastal/estuarine applications, one or several levels of nesting are often necessary and the open-boundary conditions may be obtained from a larger scale model, as done in Toublanc et al. (2016).

Another strategy consists in running the regional or coastal model in a 2D mode without any other forcing than tidal harmonics in sea surface elevation at the OB (the latter provided by an atlas). The solution of this barotropic simulation gives tidal constituents that are then used to force the model in 3D mode. The tidal spectrum that can be estimated from the 2D run depends mainly on the length of the simulation. Such an approach has been used in the North-East Atlantic by Maraldi et al. (2013).

In this paper, we therefore address the issue of downscaling barotropic tides in a circulation model, where an accurate representation of tides is required either for the tidal signal itself (both barotropic tides and internal tides) or for its impact on the circulation and hydrology. There is a wide literature on open-boundary conditions (hereafter OBC) in regional models, and many variants of the Dirichlet, Flather, radiation and relaxation conditions are developed, based on different implementations on the model grid and different strategies regarding sponge layers. A thorough work with the SYMPHONIE model has been made to implement relevant OBC for coastal applications in presence of strong or weak tides and consideration to fundamental properties (such as conservation of mass, energy) has been given. This is summarized in the paper of Marsaleix et al. (2006). We have not found any drawbacks with this scheme. We do not claim its superiority to alternative schemes either.

The two main sources of errors arising with OBC are the errors linked to the equations and numerical implementation of the OBC method and those due to the possible inconsistency between external forcing and interior dynamics; in this study we have made the choice to address the latter only. This is a choice motivated by the need to find a relatively easy and fast-to-implement method, that can be applied in different configurations, as an alternative to the revisit or adjustment of the numerical scheme and equations.

Our objective in this paper is to propose a robust and simple approach that allows to improve the downscaling of barotropic tides for any given set of boundary equations and of external forcing, therefore being non-intrusive in the model equations. In other words, given a certain 3D circulation model, with a given grid and bathymetry, how can we improve the tidal forcing to reduce errors on the interior tidal solution? Our new approach is based on the additional use of a tidal model, here the T-UGOm model of Lyard et al. (2006). Our 3D coastal model is SYMPHONIE (Marsaleix et al., 2008, 2009). To avoid inconsistencies between the prescribed tides and the interior solution due to mesh resolution and bathymetry differences, tidal boundary conditions are generated on the same grid and bathymetry as the ones used by the 3D circulation model. The unstructured 2D spectral model T-UGOm was adapted to perform simulations on a structured, variable horizontal resolution grid, by introducing C-grid equivalent quadrangle elements.

This approach is applied to the Bay of Biscay, where tides are highly energetic, particularly over the western French shelf with tidal ranges reaching 6 m locally at the coast. Tides are dominated by M2 (Cavanie and Hyacinthe, 1976; Cartwright et al., 1980; Le Cann, 1990), with amplitudes ranging between 1 to 2 m, against a few centimeters for K1. Non-linear interactions occurring between semi-diurnal constituents and the topography can result in the generation of overtides such as M4, which can reach amplitudes of 25 cm. Le Cann (1990) showed that the width of the Bay of Biscay is close to resonance for quarter-diurnal tides, leading to a strong amplification of these constituents. Fig. 1 shows the distribution of the M2 tide (elevation and current) in the Bay of Biscay, taken from the FES2012 tidal atlas. In addition, Table 1 gives the minimum, mean and maximum values for the tidal amplitude of M2, S2, M4 and K1, in the Bay of Biscay.

The work of Pairaud et al. (2008, 2010) has shown the ability of the SYMPHONIE model in a regional configuration (horizontal resolution of 1.5 km) to reproduce tides in the Bay of Biscay, the major sources of error being the bathymetry and boundary conditions. The latter are prescribed from a regional atlas. Since these studies, the bathymetry has been significantly improved by merging different datasets (Lyard, pers. comm., 2016). In this study, our configuration of SYMPHONIE covers the bay from the deep plain to the shelf and coastal shallow waters.

In the first part of this paper, the configuration applied to the Bay of Biscay and the data used to assess the solution are presented. The three strategies chosen to constrain the 3D circulation model boundaries with tides are then detailed. The 3rd and 4th sections are dedicated to the performance evaluation of the different tidal boundary conditions. First, the forcing solutions are compared, followed by the 3D circulation