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On coastal ocean embedded modeling

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[1] The initialization and forcing of embedded coastal ocean models is shown to raise several serious difficulties, however, surprisingly enough, very little attention is paid by coastal modelers to resulting dynamical discrepancies introduced over both short and long time scales. A modular and "Knowledge accumulating" approach for coastal ocean embedded modeling is proposed based on a variational approach. The extrapolation situations mostly associated to bathymetry constraints are discussed and are shown to be of great importance for any embedded coastal model. A well adapted extrapolation scheme is proposed. Two variational constraints are more particularly shown to lead to important improvements of the downscaling: the mass balance is satisfied in a dynamically coherent way based on Green's theorem and an optimal scheme is presented to extrapolate both the temperature and the salinity in the deepest regions where no data is available. Citation: Auclair, F., C. Estournel, P. Marsaleix, and I. Pairaud (2006). On coastal ocean embedded modeling, Geophys. Res. Lett., 33, L14602, doi:10.1029/2006GL026099.

1. Introducing Remarks

[2] Coastal ocean modeling is most often presented as a special configuration of global ocean modeling. It should not be the case. Indeed, coastal ocean is first to be seen as an opened system, any modeling being consequently highly dependant on its numerous forcing and in particular on the exchanges with the ocean it is embedded in.

[3] In front of such a situation, coastal ocean modelers have first followed process oriented strategies: a particular benchmark is usually considered in which the in-coming fluxes are specified analytically or are, at least, taken from smooth climatological data. Such studies are interesting in so far as they give some hints on the asymptotic behaviour of the coastal areas. However, their exploitation is implicitly based on the assumption that coastal ocean processes are independent which is obviously dubious. *Ruddick et al.* [1994] show for instance the influence of tidal currents on the turbulent mixing of the Rhine river plume leading to the conclusion that river discharge properties must be associated to a precise specification of the tidal circulation.

[4] In order to go further one would need to specify both the lateral forcing coming in and going out of the domain and the initial state of the coastal ocean. The required pieces of information can be provided either by direct observations or by modeling the larger scales. [5] Coastal models have thus to be initialized and forced based on "interpolated" fields. This is not a fundamental discovering and most of realistic modeling strategies include at one stage or at the other an interpolation step dedicated to the generation of forcing fields either in time or space or both in time and space. The fundamental assumption the interpolation schemes are based on is that the interpolated dynamics is equivalent to the original. As we shall see now, this is however not the case in coastal ocean modeling.

2. On the Initialization of Coastal Models

[6] Several reasons could explain the relative simplicity of the initialization of basin scale ocean models. First of all, as the ocean is deeper, the relative impact of bathymetry mismatches between the forcing ocean model and the embedded model is negligible. Then, at large scales, models are most often based on a rigid lid assumption and, as a consequence, they do not explicitly propagate the very energetic transient external waves, reducing consequently the spurious quickest transients. A final explanation is linked to the geostrophic adjustment over a flat bottomed ocean. In this case, the geostrophic stream lines are indeed parallel to the isobars [*Pedlosky*, 1987]. Any surface elevation anomaly or density structures can consequently lead to an equilibrium state within the corresponding geostrophic adjustment time scale.

[7] The simplicity of initializing a basin scale model does not translate to coastal scale model initialization. To start with, bathymetry mismatches lead to serious concerns in such areas. In the case of a canyon whose larger transverse dimension is smaller than the Low Resolution (LR) grid scale, Klinck [1996] shows for instance that under specific circumstances this canyon can be the locus of an incoming branch of current over the shelf. Over this small scale bathymetry accident, the interpolation problem is tediously transformed into an extrapolation problem. The velocity, the temperature or the salinity have indeed to be specified over the High Resolution (HR) grid right inside the canyon where no information is given by the LR model whose lower level is higher than any point inside the canyon. Such difficulties are of fundamental importance as the quality of the bottom circulation over the shelf break and most often the quality of the exchanges between the shelf and the deep sea both depend on the scheme chosen to "extrapolate" the data along the shelf break [Auclair et al., 2000a]. In this common case, the consequences of the extrapolation can be easily identified but regions where extrapolation is required can be found nearly all along the shelf break and over shallow shelf regions.

[8] Let's now consider the very simple example of a current entering the HR domain through one of its open boundaries. The associated global mass balance of the

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interpolated/extrapolated field will be different from the original mass balance of the LR field. One could argue that based on the difference of resolution, the incoming flow rate can be slightly different due to several small scale dynamical processes, but the fact is that in the present case, nothing but a crude extrapolation scheme is trusted to reconstruct these small scale processes, which is insufficient.

[9] Where the bathymetry mismatches can be neglected and do not lead to particular difficulties, the differences between LR and HR model dynamical assumptions are still to be considered with some care. Each of the LR and HR model domains has its own resolution and its own assumptions. The most basic example is the common use of rigid lid models in basin scale modeling while coastal modeling must most often be based on free surface models. A consequence is that the interpolated LR dynamics is not located on the coastal model HR Slow manifold.

[10] In the coastal area, geostrophy induces sever constraints on the pressure field. Indeed, barotropic geostrophic currents are forced to flow along lines of constant ratio H/f where H is the depth and f the Coriolis parameter. The density stratification partly relaxes this constraint based on the Joint Effect of Baroclinicity and Relief term (JEBAR) [Mertz and Wright, 1992]. However, shelves are most often much shallower than the depth of zero geostrophic current, leading to a non vanishing bottom component of the geostrophic current and as a consequence the adjustment of the circulation during the spin up period is associated to high cross slope velocities. These velocities have at least two consequences: they most often require small time steps in HR coastal models and they advect temperature and salinity fields leading to spurious, numerically-generated density gradients [Auclair et al., 2001].

[11] Thus, while bathymetry differences have to be expected between LR and HR models at least because these models must have different resolutions, any bathymetry mismatch in the coastal region is supposed to lead to a breaking of the fundamental dynamical balances when LR field are interpolated over the HR grid.

[12] In the following, we introduce two variational constraints and we enforce them in different experiments (section 3). In section (4), we discuss a possible "Knowledge accumulating" strategy for universal embedded modeling and we propose a coherent implementation.

3. A Variational Extrapolation Scheme

3.1. Extrapolation Strategy

[13] Although it is a problem of fundamental importance in embedded modeling, extrapolation does not receive any particular attention in most coastal modeling. However, very small changes in interpolation strategies could result in great improvements of the embedded modeling.

[14] As far as interpolation itself is concerned, a classical cost efficient, memory saving, tuneable scheme is chosen. The LR points are selected over a user designed "vertical influence cylinder" before linear interpolation be used vertically and Gaussian interpolation horizontally. Over the vertical axis first, interpolation is a 1D problem over distances which are much smaller than in the horizontal

plane and most often, the data fields are vertical profiles which justifies a simple linear interpolation. On the other hand, the horizontal interpolation is a 2D problem which can be considered, as a first approximation, as isotropic and Gaussian. These assumptions are very dubious in the coastal areas as the presence of the shelf break and the coast gives a fundamental non-isotropic character to this area. The non-isotropicity is taken into account through dynamical constraints, that is, in the second part of the present method and the Gaussian "interpolation" is nothing but a filter used to construct a background field over the HR grid.

[15] Based on the assumption that the vertical scales of a density field in the ocean are smaller than their horizontal counterparts, the starting point of the extrapolation strategy is that the most reliable available piece of information is an averaged vertical density profile obtained in the LR model at points located in the neighbourhood. A density profile is computed because it is most often smoother than temperature and salinity profiles. The second idea is that the smaller the magnitude of the extrapolated field, the smaller the (absolute) error: it is thus much better to extrapolate the difference to a given mean vertical profile than the absolute field itself.

[16] Taking into account these two considerations, an interpolation-extrapolation method can be proposed by computing a regional mean density profile over the LR grid before interpolating (and extrapolating) the anomalies between the LR density and the computed profile over the HR grid. The "interpolation" of density anomalies rather than absolute densities does obviously not eliminate the need for extrapolation and several options can still be chosen to specify the density anomaly below the deepest LR point. One of them is to choose a depth at which density is supposed not to vary. Then the density anomaly is interpolated between the deepest known value and the depth where it is supposed to vanish.

[17] At this point, two HR density fields can be computed: one $(\rho_{ijk}^{(0)})$ can be obtained from the state equation and the crude interpolation of the LR temperature $(T_{ijk}^{(0)})$ and salinity $(S_{ijk}^{(0)})$ fields while the other $(\rho_{ijk}^{(\Delta)})$ is obtained from the interpolation of the LR density anomaly around a LR regional profile. These two density fields have obviously no particular reason to be identical. The latter density field, obtained as the interpolation-extrapolation of the density difference, is thus eventually taken as a reference to optimally adjust the crudely interpolated temperature T_{ijk} and salinity S_{ijk} . At each point, the following cost function is thus minimized:

$$\begin{split} J(T_{ijk}, S_{ijk}) &= \frac{1}{2} \alpha_T \left(T_{ijk} - T_{ijk}{}^{(0)} \right)^2 + \frac{1}{2} \alpha_S \left(S_{ijk} - S_{ijk}{}^{(0)} \right)^2 \\ &+ \frac{1}{2} \left(\rho_{ijk}^{(\Delta)} - \rho_{ijk}^{(0)} \right)^2 \end{split} \tag{1}$$

The very simple resulting optimal algorithm is similar to the one used by *Auclair et al.* [2000a] to adjust temperature and salinity for tuned α_T and α_S weights. The algorithm is numerically efficient as the optimal system is limited to a single point and does not necessitate the consideration of any overall constraint.



Figure 1. Embedded modeling of the Bay of Biscay, NE Atlantic. (a) Relative bathymetry differences between LR-bassin scale model and HR-coastal model. (b) Geostrophic current at 1000 m deep over the LR-grid. (c) Geostrophic current computed over the HR grid after crude interpolation. (d) Geostrophic current computed over the HR grid after optimal extrapolation. Currents are given en cm/s.

[18] Figure 1 shows a comparison of the geostrophic current obtained at the deepest HR Sigma-level over the Bay of Biscay. The differences of bathymetry between the LR and HR models are presented on Figure 1a while Figure 1b shows the basic forcing LR geostrophic field originating from a climatological mean of a modeling of the North-Atlantic with the POP circulation model [*Pairaud*, 2005].

[19] On the following geostrophic plot (Figure 1c), the temperature and salinity fields are crudely interpolated using a Gaussian interpolation and a linear extrapolation for the deepest level (this is consider as order 0 method), while in Figure 1d, the density difference to a LR regional density profile is interpolated and temperature and salinity are eventually optimally corrected. Strong spurious geostrophic currents along the shelf break have nearly disappeared when optimal extrapolation is used and have been replaced by smooth currents very much alike to initial LR currents. The spurious pressure gradients consequently lead to large amplitude numerically generated branches of geostrophic currents.

3.2. Dynamical Adjustment

[20] The objective of the variational optimisation is to enforce some basic constraints. *Auclair et al.* [2000a] proposed the optimization of both external and internal variational constraints associated to free surface and momentum tendencies. Then *Auclair et al.* [2000b] introduced an additional variational constraint reducing the horizontal pressure gradient truncation error over a Sigma grid by adjusting the geostrophic current.

[21] Auclair et al. [2001] show a comparison of the evolution of the mean surface elevation in the region of Marseille (North-Western Mediterranean) with and without the external mode coastal model linear tangent constraints. On top of leading to an optimal adjustment of the circulation to the HR bathymetry and to an increased stability of the coastal model, the use of external mode constraints greatly reduces the spurious numerically generated high frequency oscillations [Auclair, 1999].

[22] The mass balance, which is equivalent to the volume balance under the Boussinesq approximation, can be



Figure 2. Evolution of the coastal model mean sea surface elevation over the Northern Adriatic Sea during the first 15 days of embedded modeling. Dashed line: coastal model is initialized and forced along its boundaries with a crude interpolation of the LR field. Solid line: coastal model is initialized and forced with a variational analysis.

obtained by correcting directly the incoming and outgoing transport along the open boundaries of the HR domain [*Pinardi et al.*, 2003]. However, to do so, one must necessarily know to a good approximation the LR mass balance ($\phi_{LR}(LR)$). In addition, the resulting crudely adjusted transport does not necessarily satisfy the inner dynamical constrains.

[23] Both difficulties can be solved by adding a global constraint based on Green's theorem to the variational constraints introduced before:

$$\varphi_{LR}(HR) = \int_{Frontier(HR)} H_{LR} \bar{V}_{LR}^{\perp} dl = \iint_{Surface(HR)} div(H_{LR} \bar{V}_{LR}) dS \qquad (2)$$

where \bar{V}_{LR} is the LR depth averaged velocity, \bar{V}_{LR}^{\perp} is its component orthogonal to the frontier of the HR domain and H_{LR} is the LR grid bathymetry.

[24] To avoid the computation of the derivative of an interpolated variable (which necessarily occurs when computing the divergence of the interpolated transport), the divergence of the LR transport is computed over the original LR grid before being interpolated over the HR grid. It is then integrated over the HR domain leading to the difference between the incoming and outgoing transport through the opened boundaries and offering an efficient answer to the problem of the computation of the LR volume constraint.

[25] Figure 2 shows the evolution of the mass flux through the open boundaries of the HR domain for a shelf model of the Northern-Adriatic both with and without any global optimization during a period when the LR forcing model shows no significant mass loss [*Pinardi et al.*, 2001]. The use of this global constraint is clearly efficient in controlling the total volume of the coastal ocean model.

4. Conclusion: A Variational Approach for Embedding Modeling

[26] As a conclusion, a coherent and universal methodology for embedded modeling should include several inescapable aspects.

[27] Both global and local variational constraints must be enforced to downscale a GCM field to a HR model grid. Figure 1 illustrates the importance of such constraints in the region of the shelf break and how misleading a crude downscaling can be. The importance of extrapolation has been acknowledged in the present letter and a scheme is proposed to avoid the largest, numerically generated spurious structures of geostrophic currents over HR bathymetry structures. A global constraint is eventually proposed and is added to several other local constraints based on the coastal model tangent linear approximation. Their optimal enforcement is shown to control the coastal model mass balance (Figure 2) in a dynamically coherent way.

[28] The universality of the embedding platform also depends on the data representation, that is, on how heavy the resulting computations are and on how easily they can be implemented and dealt with. As a consequence, an efficient compression scheme must be associated to the data representation (whether gridded or not).

[29] The geography of the local bathymetry together with the many possible associations of GCM and HR models can lead to a large number of specific configurations. A strategy for embedded modeling must consequently be modular, offering several possible configurations of interpolation and extrapolation schemes and of variational constraints. This strategy must also be "Knowledge accumulating" and it must offer the possibility to share new implementations among HR modelers.

[30] In the frame of the Mediterranean Forecasting System (MFSTEP, available at http://www.bo.ingv.it/mfstep/), these "inescapable" functionalities have been implemented in the "open source" Variational Initialization and FOrcing Platform (VIFOP, available at http://www. aero.obs-mip.fr/activite_scientifique/WEB_F_AUCLAIR/Recherche/VIFOP/vifop_index.htm).

References

- Auclair, F. (1999), Modélisation Océanographique Côtière: Initialisation et forçage, Ph.D. thesis, Univ. Paul Sabatier, Toulouse III, Toulouse, France.
- Auclair, F., S. Casitas, and P. Marsaleix (2000a), Application of an inverse method to coastal modeling, J. Atmos. Oceanic Technol., 17, 1368–1391.
- Auclair, F., P. Marsaleix, and C. Estournel (2000b), Truncation errors in coastal modeling: Evaluation and reduction by an inverse method, *J. Atmos. Oceanic Technol.*, 17, 1348–1367.
- Auclair, F., P. Marsaleix, and C. Estournel (2001), Specification of the exchanges through the continental shelf breaks in high resolution coastal models: Penetration of the LPC current over the Gulf of Lion (Mediterranean), Oceanol. Acta., 24(6), 529–544.
- Klinck, J. M. (1996), Circulation near submarine canyons: A modeling study, J. Geophys. Res., 101(C1), 1211–1223.
- Mertz, G., and D. G. Wright (1992), Interpretation of the JEBAR term, *J. Phys. Oceanogr.*, 22, 301–305.
- Pairaud, I. (2005), Modélisation et analyse de la marée interne dans le Golfe de Gascogne, Ph.D. thesis, Univ. Paul Sabatier, Toulouse III, Toulouse, France.
- Pedlosky, J. (1987), Geophysical Fluid Dynamics, 710 pp., Springer, New York.
- Pinardi, N., F. Auclair, C. Cesarini, E. Demirov, S. Fonda-Umani, M. Giani, G. Montanari, P. Oddo, M. Tonani, and M. Zavatarelli (2001), Toward marine environmental prediction in the Mediterranean Sea coastal areas: A monitoring approach, in *Ocean Forecasting: Conceptual Basis and Applications*, edited by N. Pinardi, Springer, New York.
- Pinardi, N., I. Allen, E. Demirov, P. De Mey, G. Korres, A. Lascaratos, P. Y. Le Traon, C. Maillard, G. Manzella, and C. Tziavos (2003), The Mediterranean ocean forecasting system: First phase of implementation (1998–2001), Ann. Geophys., 21(1), 3–20.
- Ruddick, K. G., E. Deleersnijder, T. De Mulder, and P. J. Luyten (1994), A model study of the Rhine discharge front and downwelling circulation, *Tellus, Ser. A*, 46, 149–159.

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