

The advantage of a generic coordinate approach for ocean modelling

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Abstract

A main concern in three-dimensional coastal and oceanic modelling is the type of coordinate used for the vertical direction. The appropriate coordinate system should guarantee an adequate resolution in the entire domain and must lead to a stable method with minimal numerical diffusion in order to preserve the vertical structure of the water column. The need for meshes with high aspect ratios of up to 1000:1 makes ocean models highly sensitive to vertical fluxes. A diversity of vertical coordinates has been used in ocean modelling; cartesian, sigma and isopycnic are now widespread. Sigma coordinates are more indicated when topography plays a main role in the flow, while isopycnic coordinates are the most indicated when density is the major forcing. Cartesian coordinates do not privilege any type of forcing and are a good compromise when both are important.

The generic approach implemented in MOHID 2000 system using finite-volumes allows the use of different vertical discretizations simultaneously. The model is applied to the Western Iberian Margin. The objective of this study is to reproduce the poleward slope current. Results were obtained using cartesian, double-sigma and lagrangian type coordinates. Advantages and disadvantages of each coordinate system are discussed.

The velocity field results are compared at 400 meters depth for different type of coordinates. Salinity and temperature profiles will be analysed to verify what type of coordinate is able to maintain the vertical density gradient for a longer period.

1 Introduction

The need for meshes with aspect ratios up to 1000:1 makes ocean models highly sensitive to vertical fluxes. Close to the surface turbulent kinetic energy supplied by wind forcing generate a surface mixed layer. Bottom induced turbulence mixes deep layers. In shallow areas both layers can overlap and well-mixed water column can be obtained. In deeper regions sharp vertical gradients are usually present. Numerical errors on vertical transport resolution can produce artificial water column mixing destroying these gradients.

Cartesian coordinates consider horizontal layers. They are convenient where the flow is mainly horizontal. Topography and density deviate the flow from horizontal. Sigma coordinate consider topography as the most important effect and generates a vertical grid following the bottom topography. On the other extreme is the isopycnic coordinate where the grid follows the density isolines. In both cases a transformed domain is considered and analytical transformations of the original equations to that domain is performed. The computer code becomes specific of the selected vertical coordinate. This is a big limitation of the models based on a vertical transformation of the equations and the modelling space. To overcome this limitation some authors propose generic coordinate transformations [1]. This solution, however, dramatically increases the complexity of the code. In the model described in this paper, different coordinates are implemented using the flexibility of the finite-volume method. Using finite-volumes sigma, cartesian, lagrangian or any combination of these meshes can be used, with the same algorithm. The water column is divided vertically into several domains and a different mesh can be used in each of them. Equations are solved in the integral form in each cell volume without any coordinate transformation. The rates of accumulation are calculated as the integral of the fluxes across the finite-volume surface. Geometry information is carried in the areas and volumes needed to calculate the fluxes. The cells can have any initial shape and suffer any time deformation. This flexible architecture is equivalent to a generic vertical coordinate. All meshes use the same code, saving development and maintenance time.

1.1 Finite-volume approach

In real domains the relative importance of topographical effect, density forcing, inertia and bed shear stress is different from point to point and therefore there is no unique optimal vertical coordinate for the whole domain. Instead, different discretizations should be implemented for different regions.

In the finite volume approach the discrete form of the governing equations is applied macroscopically to the cell control volume, integrating fluxes across its surface. As a consequence this method automatically guarantees the conservation of transported properties [2].

In the generic coordinate approach the model must be able to solve the governing equations using any kind of grid. In the classical way differential equations are transformed using a generic transformation and the actual form of

the grid is controlled by the Jacobean transformation in each grid location [1]. An alternative approach is to define explicitly the shape of the grid and use a suitable method to solve the equations directly on that grid. This can be done using the finite-volume method [3]. A big advantage of this approach is that any law, regardless of the Jacobean complexity that it produces, can be used to define the grid. In this model the domain is divided vertically into sub-domains and a different grid law is applied explicitly to each sub-domain.

In the finite volume method the equations are solved in the real space integrated over each cell. The cell can have any shape since in integral form only the fluxes between adjacent cells are computed. In this way a complete separation between the physical variables and the geometry is accomplished for all mesh types. Cell information is stored in the areas, and volumes. Geometry information of deformable cells is updated every time step. The computational effort necessary to update cell geometry is comparable to that used in solving the Jacobean of the transformation and the method is much more flexible [4].

1.2 Numerical experiment – Relevance

In the present application cell vertices possess only one degree of freedom - along the vertical direction - to reduce model storage and computational requirements. The model solves the three-dimensional primitive equations for incompressible flows. Hydrostatic equilibrium is assumed as well as Boussinesq approximation. A semi-implicit ADI algorithm is used with two time levels per iteration [5]. In shallow areas topographic features play a major role controlling the flow, while in deep ocean density field is a major driving force. Sigma type coordinates [6] optimize topographic representation, allowing the same number of grid points for every depth. This discretization is quite advantageous for the simulation of barotropic flows, which closely follow gridlines, minimizing vertical advective exchanges between cells. When a well-defined thermocline is present and a nearly horizontal mixing layer exists, the flow does not follow the bottom topography and the usual sigma coordinate produces ill-behaved results. Since in most situations the thermocline is close to horizontal some authors use a double sigma coordinate, splitting the water column into an upper domain nearly horizontal above the thermocline, and a lower topography following domain [7]. Isopycnic coordinate models use the density as the vertical coordinate [8], [9]. As a consequence, the mesh is aligned with constant density lines. These models can minimize numerical diffusion and preserve water mass properties when the flow is fully governed by density gradients, but cannot simulate barotropic flows and are not adequate when topography plays a major role in the flow. Cartesian coordinate models are a compromise between former types [10]. In this grid there is no optimization, but the model can be used in any situation if enough computational power is available.

In the literature there are several examples of model comparison ([11] and [12]). Usually different models are associated with different types of coordinates and some conclusions can be taken about the problems associated to each coordinate for a specific application. However it is very difficult to evaluate in a

systematic way the numerical problems associated to each coordinate using different models because they usually have different time integration schemes, parametrization of vertical eddy viscosity and boundary conditions.

With a generic coordinate model it is easy to compare different types of vertical coordinates and select the most adequate one. In this paper, results show how several vertical coordinates perform in the Western Iberia Coast. The flow is density driven, the bathymetry is real and a radiative open boundary condition is used.

In the past this research group (IST/MARETEC) has applied intensively a finite-difference double sigma coordinate model to the Western Iberian Margin mainly in the aim of the OMEX (Ocean Margin Exchange) project [13]. This model can use a radiative open boundary condition (OBC) similar to the one described by [14]. This boundary condition has been applied with great success to 3D barotropic flows [15], [16]. Basic information needed by this condition is the celerity of the free surface waves crossing the boundary. Although celerity is not the same in baroclinic conditions a radiative OBC proposed by [14] can be a good approach for this type of flow [13]. The double-sigma model implemented for Western Iberian Coast is initialized using a climatologic density field and forced by atmospheric fluxes supplied by the European Center for Medium Range Weather Forecast. Numerical diffusion associated to internal oscillations destroys the vertical temperature and salinity profiles in periods of the order of a month. This inhibits long-term simulations without data assimilation. Internal oscillations provoking mixing are generated by small reflections at the open boundary. Mixing can be minimized improving open boundary conditions or using an adaptative vertical grid able to minimize exchanges between layers. The improvement of the open boundary can be achieved in some conditions, but not always. Adaptative grids seem to be the way to follow.

Using MOHID 2000 a lagrangian coordinate was tested. The implemented grid law moves the cell vertex vertically in order to minimize vertical exchanges. This can be done by letting the grid points move with the same vertical velocity as the flow. In this sense it is identical to the isopycnic coordinate. The effectiveness of this movement on exchange reduction depends on the amplitude and period of oscillations. Noise generated at the boundary is an oscillatory process and its mixing effect can be minimized by this coordinate. The results obtained with this coordinate are compared with simulation results carried out with cartesian and double sigma calculations. In this flow the cartesian coordinate is taken as the reference coordinate, since the flow is essentially horizontal.

The velocity field results of 15 days runs are analysed at 400 meters depth because at this depth the poleward current must be evident [17]. Salinity and temperature profiles will be also analysed after 15 days to verify what type of coordinate is able to maintain for a longer period the vertical density gradient.

2 Results

The model was forced with a spring climatologic density field. The horizontal discretization was 121×121 with a spatial step of 0.08 degrees (Figure 1). In the vertical 18 layers were used. In the cartesian grid the layer thickness increase with depth from 10 meters at the surface to 1.5 km at the lowerst layer. For the double sigma grid 18 layers were also used, 9 layers for the lower and for the upper domains. The interface between the 2 domains is located at 1000 m depth (Figure 2). The lagrangian grid was initialized as cartesian. Two types of lagrangian coordinates were tested one with free movement in all layers. In the other one the layers below 1000 m were not allowed to move; above the 1000 m the grid is lagrangian and below is cartesian (lagrangian/cartesian). To avoid numerical problems associated with grid distortion a movement restriction that does not allow the layers to have a thickness inferior to 75% of the initial value was imposed. To simplify the comparison between several types of coordinates constant vertical and horizontal turbulent viscosities were used ($0.0001 \text{ m}^2/\text{s}$ and $300 \text{ m}^2/\text{s}$, respectively). Also for simplicity reasons were imposed Prandtl and Schmidt numbers equal to one.

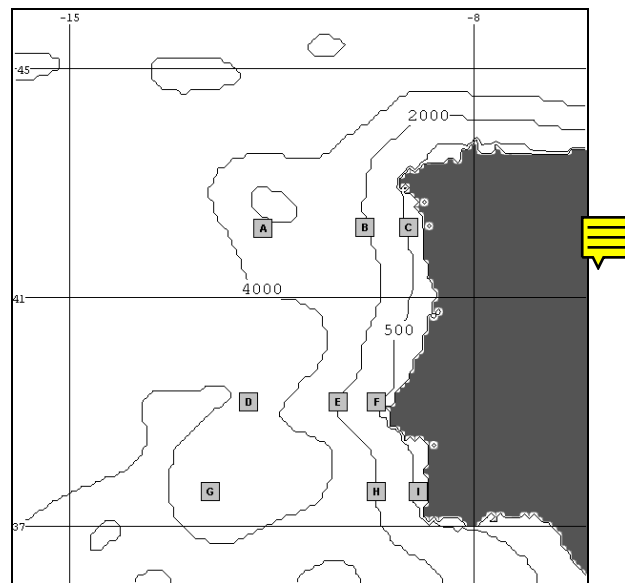


Figure 1: Study area (Western Iberian Margin).

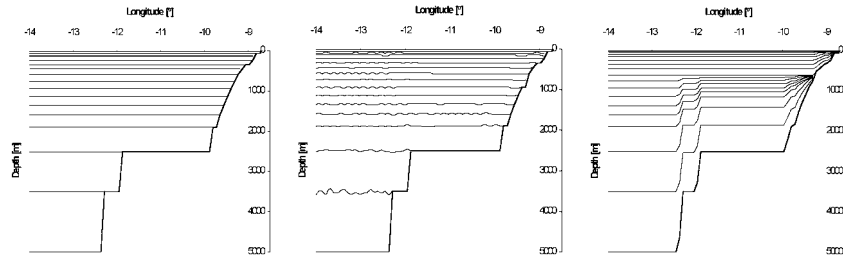


Figure 2: Grid geometry along the parallel 42° N. From left to right: cartesian, lagrangian and double-sigma.

Recently, current meter data obtained in the last 20 years along the western Iberian Margin were analysed in the frame of - Ocean Margin Exchange – OMEX EC Project. Monthly mean currents were calculated for several positions and led to the conclusion that the thermohaline driven poleward current is prominent between 300 and 1200 m deep and almost permanent during the entire year. It was also possible to conclude that the current is very weak both in the southwest and in the northwest Iberia [17]. On the other hand the current is very strong between Sines and Lisboa and between Nazaré canyon and 42°N. Observed values [18] indicate coastal currents up to 40 cm/s near Cabo S. Vicente. Low frequency stability was calculated and indicates that at intermediate levels (300 to 1200 m) currents are very stable especially during the cooling season.

Model results using cartesian coordinates show a poleward current at 400 m very similar to that described above (Figure 3). Relative maximum of the poleward current occur to the south of Lisbon and to the North of Nazaré Canyon. The current is poorly defined on the west coast of Galicia and Algarve. The current near Cabo S. Vicente is much weaker than the observed. This is related to the size of the simulated domain. Other runs reveal that if the model domain includes the Gulf of Cádiz, currents of the order of magnitude of the observed currents are obtained. At 1000 m the flow field shows a very weak poleward current more confined to the slope region, which agrees very well with observations [17]. The double-sigma model results show a poleward current with velocities up to three times larger than the cartesian results (Figure 3). A strong current along the 4000 m bathymetric is also observed. In [12] this artificial increase of currents in slope areas by sigma type models is reported. This problem can be reduced by smoothing the bathymetry. The lagrangian results show a velocity field very similar to the cartesian (Figure 4). Near the coast the results are very similar but in the deeper areas the currents have a more chaotic structure. The lagrangian/cartesian results show very good concordance with the cartesian results (Figure 4).



Figure 3: Velocities obtained with cartesian (left) and double sigma (right) coordinates at 400 m depth.

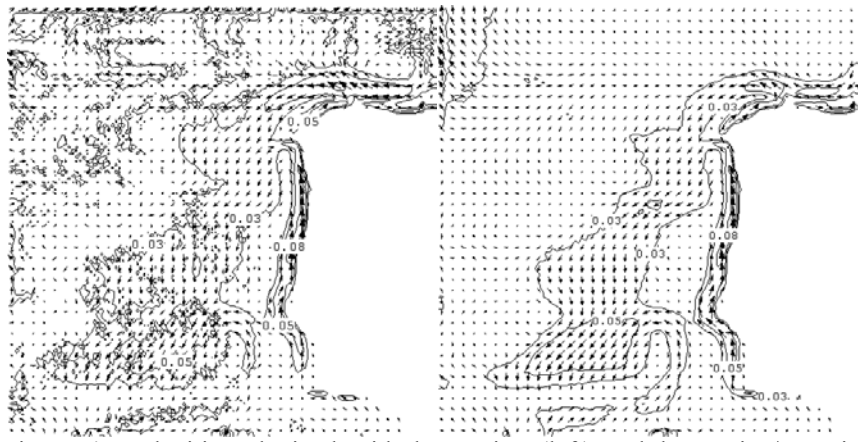


Figure 4: Velocities obtained with Lagrangian (left) and Lagrangian/Cartesian (right) coordinates at 400 m depth.

The temperature and salinity profiles were analysed in 9 stations and differences between the results after 15 days and the initial condition are discussed (Figure 1). The salinity profiles show typical anomalies near the slope characteristic of Mediterranean Water being transported at these depths (500-2000 m) along the western Portuguese margin (Figure 5, Figure 6). Salinity and temperature profiles in stations A, B, E and H located in slope areas show that the vertical density gradient is partially destroyed. This is more drastic for the double-sigma coordinate and for the salinity gradients (Figure 5). In these areas the Cartesian coordinate is the one that gives better results below the 1000 m and above it is the Lagrangian one. In the deeper stations (D and G) the Cartesian results continue to

be better than the double-sigma ones (Figure 6). For this stations the lagrangian results have the greater differences from the initial condition. On the shelf (stations C, F and I) temperature and salinity values are increased due to the transport of Mediterranean water forced by the poleward current (Figure 7). The cartesian and double-sigma results show strong numerical diffusion while the lagrangian coordinate is able to maintain very well the vertical gradients. The lagrangian/cartesian coordinate in all stations is able to benefit of the best performance of the cartesian coordinate below the 1000 m depth and of the lagrangian coordinate accuracy at the surface.

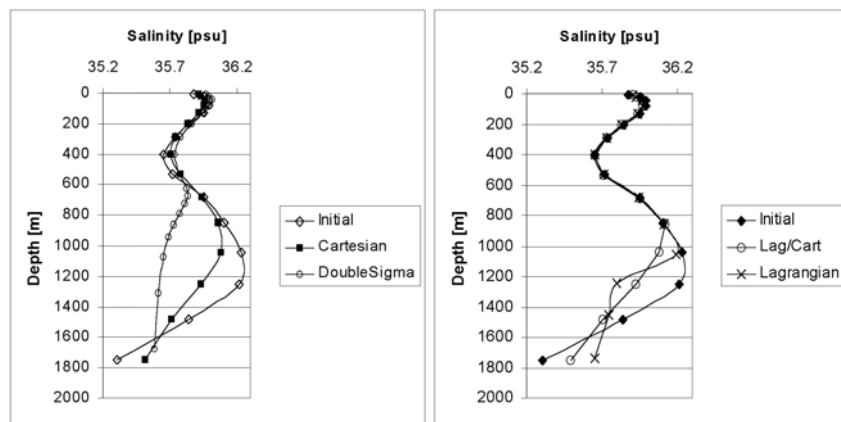


Figure 5: Salinity at station E.

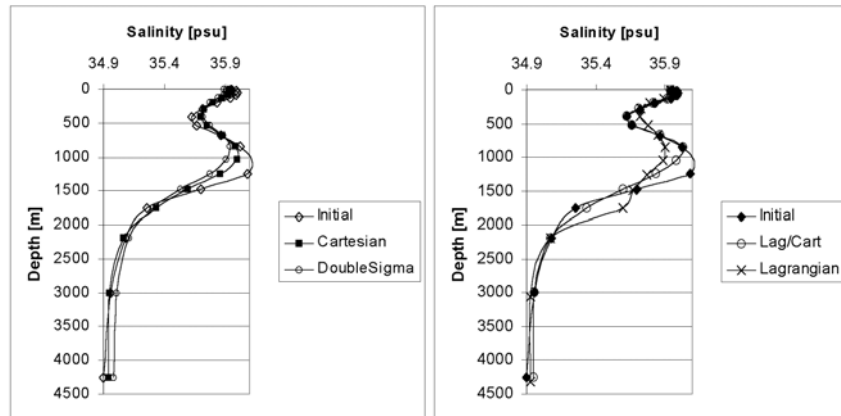


Figure 6: Salinity at station D.

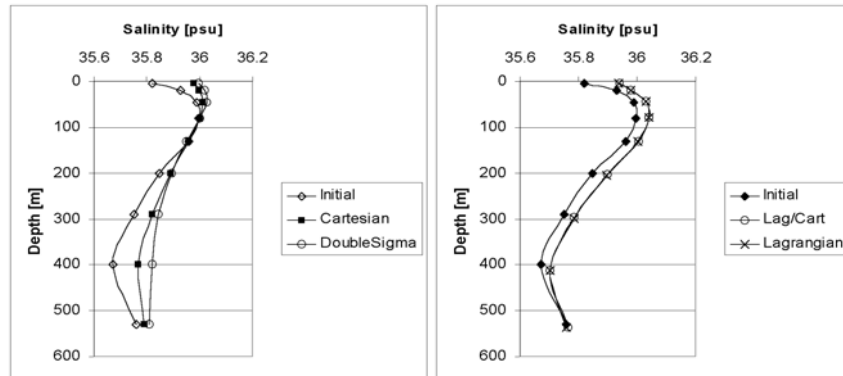


Figure 7: Salinity at station F

3 Discussion

The results indicate that double-sigma coordinates have very large numerical diffusion specially over steeping topography. This problem can be reduced using more refined algorithms for advection and with relaxation for a particular field (e. g. climatologic field). The cartesian coordinate performs well particularly in the deeper areas while the lagrangian coordinate gives the best results at the surface. The grid with a lagrangian behaviour above 1000 m and a cartesian below is the best compromise.

In the future, new distortion laws for the lagrangian approach will be implemented to improve the results in deeper areas. New open boundary conditions will also be implemented like the flow relaxation scheme to assess the solution sensitivity to different types of boundary conditions.

Acknowledgements

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