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A numerical investigation of the slope current along the Western European margin

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Abstract

A three-dimensional hydrodynamic model is used to investigate the poleward flow along the Western European slopes. The area of the model domain goes from Northwest Africa to Ireland. At a first stage currents are driven by climatological spring density fields. In a second stage the model is also forced by spring climatological wind favorable to the development of an equatorward coastal jet along the Iberian coast. Results show that the density forcing is able to produce the poleward current along the European Continental shelf. The winds can modify the flow pattern mainly in the southern areas off Iberia, during spring and summer. In the northernmost area of the model domain (Armorican and Celtic slopes), typical winds are in quadrature with the wind direction that produces a maximum barotropic response, thus the residual flow is weak. The poleward current obtained is continuous between the Portuguese and Irish coasts. It follows the isobaths and the core of maximum velocity is located between 300 m and 1500 m, depending both on space and time. This core corresponds to the shelfward divergence of isopycnals. Maximum speeds range from 10 to 20 cm s^{-1}. A poleward intensification of the current is also obtained.

1 Introduction

The presence of sloping bathymetry along the continental margin combined with the general circulation, generates a complex flow pattern along the slope regions. This flow is characterized by important vertical and horizontal gradients of velocity and density, producing eddies, fronts, instabilities and other related phenomena. The use of numerical models can represent an appropriate tool both

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on process studies and on interdisciplinary integration of results. This work was undertaken in the framework of Ocean Margin Exchange (OMEX) and the main goal is to study the generation, development and persistence of the poleward current along the western European margin. Special attention is given to the flow off western Iberian Peninsula.

2 Poleward flows at eastern ocean boundaries

Many authors provided evidence for a poleward flow along European slopes (Ambar et al.,[1] Frouin et al.,[3] Pingree and LeCann[10]). Analysis of AVHRR (Advanced Very High Resolution Radiometer) shows that this situation occurs between November and March nearly every year between 1982 and 1990. Very similar poleward flow was described in other eastern boundary regions such as the California Current System (Lynn and Simpson[7]) and the West Coast of Australia (Leeuwin Current). These flows, mainly concentrated along the upper continental slope and outer continental shelf, appear as an undercurrent (upwelling season) and sometimes as a surface current (non-upwelling season), depending both on the studied region and the time of the year. The poleward current of Iberia runs for 1500 km along the upper continental slope (shelf break zone) of Western Portugal, Northwest Spain, North Spain and Southwest France and is 25 to 40 km wide. Frouin[3] described a flow 200m deep but Ambar[1] indicated that the poleward flow may extend from the bottom (1600 m) of Mediterranean Intermediate Water (MIW) to the bottom of the surface layer, during the upwelling season, or to the surface during the non-upwelling season. Velocities ranging from 0.2 to 0.3 $m\ s^{-1}$ characterize the current. The associated transports are according to Frouin[3], 300,000 $m^3 s^{-1}$ at about 38°N and 500,000 to 700,000 $m^3\ s^{-1}$ at about 41°N. The current intensifies poleward which is also a characteristic of the poleward currents at the eastern boundaries. Several driving mechanisms have been proposed in the past 20 years to explain slope currents around the world ocean. The most considered mechanisms are wind-stress, wind-stress curl and thermohaline forcing. Ambar[1] associated the surface poleward current off Iberia during the winter of 1983 with the northward wind-stress prevailing at that time of the year. Onshore Ekman convergence induced by south-southwesterly winds provides a possible explanation for poleward surface flow. The shelfward transport induced by this kind of wind causes a sea level rising near the coast. The geostrophic adjustment to this sea level distribution will then generate a poleward current. In this case the longshore acceleration is given by $\partial V / \partial t = \tau^y / \rho H$ being H

the depth of the frictional layer, V the longshore velocity, τ the windstress and ρ the seawater density. Frouin[3] used τ=0.03 N m^{-2}, ρ=1027 kg m^{-3} and H=200m to find that the longshore acceleration is 0.013 m s^{-1} d^{-1}, which gives V=0.4 m s^{-1} after 30 days. However they argued that other effects, in particular friction, retard the flow. Assuming a steady state, reached when the bottom stress balances the wind stress ($C_b V^2 = \tau^y / \rho$), they obtained V≈0.17 m s^{-1} which was in agreement with observations. This current should decay seaward from the shelf break. The spatial scale associated with the decay of the current is the internal radius of deformation (about 15 km off Iberia). This is what is generally observed both with satellite images and *in situ* observations (Pingree and Le Cann[10]). When Frouin[3] evaluated the Ekman transport they found that this mechanism provides only one fifth of the observed transport and concluded that this could not be the main driving mechanism for the poleward current. McCreary[9] using ocean models proposed that the most likely cause of the Davidson Current off California, was a positive wind stress curl forcing surface poleward Sverdrup transport. The Sverdrup relation, $\beta M_y = curl_z \tau$ (where $\beta = \partial f / \partial y$ and M_y denotes the northward volume transport) shows that the wind stress curl alone can generate transport in the alongshore direction. Bakun and Nelson[2] showed that the wind stress curl off the Iberian Peninsula is positive. This means that Sverdrup mechanism is a possible cause of the poleward current along the Portuguese and north Spanish continental slopes. Several authors (e.g. Lynn and Simpson,[7] Frouin et al.[3]) suggested that poleward currents along eastern boundaries may be associated with the large scale eastward flow, associated with meridional pressure gradient (thermohaline forcing), that occurs in the upper 200–300 m. Model results obtained by McCreary[8] for the Leeuwin Current confirms this idea. The poleward cooling of the sea surface leads to a meridional increase of surface density causing the dynamic height to drop towards the pole. The result is a weak surface eastward flow from the interior to the ocean boundary forcing coastal downwelling and a surface poleward current. This mechanism explains both the existence of the current and its increase towards the pole, leading to a poleward current that weakens at the surface during spring and summer (equatorward winds related to upwelling events), as may be observed in the Iberia, California and Leeuwin Currents. Huthnance[5] showed that a combination of slope bathymetry with a south-north density gradient provides a mechanism that can drive a poleward current (JEBAR). As $\rho\, \partial\eta / \partial y = -h\, \partial\rho / \partial y$ (being η the sea surface elevation and h the water depth), sea level declines faster in deep water than in shallow water implying a cross-slope gradient in the sea level. The existence of this gradient leads to a poleward flow along the slope bathymetry. The cross-slope sea level gradient is proportional to distance along the slope and has associated an increasing along-slope transport. Huthnance[5] also showed that if the cross-shelf density diffusion is large, the along-slope current is given by:

$$v = \frac{1}{2}\frac{g}{\rho}\frac{\partial\rho}{\partial y}\frac{H}{k}h\left(1-\frac{h}{H}\right) \tag{1}$$

where, H is the oceanic thermal layer depth ($H \approx 1000m$) and k the bottom friction coefficient. Equation (1) gives greatest currents over the slope in water column between sea surface and the thermal layer depth. In reality, the poleward advected water has dynamical effects introducing a baroclinic component that reinforces the flow at upper levels offshore and lower levels inshore. This results from a small cross-shelf diffusion.

3 Numerical model

The model applied in this work (MOHID3D) was developed at Instituto Superior Tecnico and a detailed description of it can be found in Santos[11]. MOHID3D is a three-dimensional baroclinic primitive equations model, using a semi-implicit finite difference scheme with a staggered grid and a double-sigma vertical coordinate. The primitive equations are solved with the Boussinesq, hydrostatic and beta-plane approximations using a turbulence model based on the 4/3 Kolmogorov's law for the horizontal direction. For the vertical eddy viscosity, the mixing length formulation is applied taking into account both the stratification and the shear effect expressed in the Richardson number. At open boundaries a radiation condition allow us to compute the surface level. For the density, if the fluid is moving inside the computational domain the boundary value is modified according to a time decay and if the fluid is moving outside, neglecting diffusion at the boundaries, the density is computed with an upwind scheme.

4 Numerical tests

MOHID3D was implemented in the Northeast Atlantic (30°N to 60°N and 5°E to 25°W) with a high local resolution in the slope and shelf regions. To investigate the north-south density gradient as the driving mechanism for the poleward current, the model was first forced by Levitus[6] spring climatological data. Spring climatological winds (Hellermann and Rosenstein[4]) were then applied to study the role of windstress on the modification of the flow along the coastal and slope regions of Western Europe. The spatial step of the model varies from 40 km near the boundaries to 8 km near continental shelf and slope. The model has 14 layers in the vertical with a sigma interface at 200 m. The upper sigma domain has 8 equal layers and the lower domain the remaining 6. Each of the first 5 layers of the lower domain represents 10 percent of the depth below 200m. Figure 2 shows the circulation at two levels obtained by forcing the model only with spring climatological density fields. This numerical experiment shows that the density distribution is able to produce a poleward flow that reaches the surface. It is suggested that the slope current is continuous along the European Margin, from the Portuguese to the Irish slopes. The transport increases poleward, both, along Portuguese and Celtic-Armorican slopes and decreases along the North Spanish. In the upper layers of the model, northward maximum current speed is 10 cms^{-1} at 39°N and 20 cms^{-1} at 42°N. This agrees with theory that predicts that the cross-slope sea level is proportional to along slope distance in regions where the bottom friction plays a minor role, as happens along the Portuguese/northwest Spain coast. Bottom friction may be important in northern regions (e.g., off Hebrides) where the flow is fully developed. In the slopes of northern Spain, poleward changes in density do not force the current and bottom friction becomes important causing the transport to decrease. Typically the core of the current is founded between 500 and 1000m depth corresponding to the shelfward divergence of isopycnals. During spring, the current rapidly decreases both shelfward and offshore. This result agrees with Huthnance[5] theory (equation 1). Figure 1 shows a comparison between along slope current obtained with equation 1 (with a south-north density gradient $O(10^{-7})$, $H = 1000m$ and $k \approx 10^{-4}$) and interpolated model currents at 39°N for corresponding water depths. A considerable agreement is obtained. The current is confined to the slope regions following the depth contours. Adding the wind forcing, the flow is reversed in the surface layers under the influence of the southward winds. The poleward undercurrent is found below this surface layer and is concentrated in the slope, following the depth contours (Figure 3). Cross sections at 42°N shows that the current extends for about 100 km off the shelf break (Figure 4). Two maximums are consistently found, one in the upper levels offshore and the other at lower levels inshore. The occurrences of these cores of maximum speed are due to the importance of the baroclinic component of the current. The vertical extension of the current is about 1200 m, from 1500 m depth (the depth of MIW) to the bottom of the surface layer.

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5 Conclusions

It is shown that thermohaline forcing can drive a poleward current along the European slopes. The currents obtained with our numerical model, reasonably agree with analytical model of Huthnance[5], revealing that JEBAR (Joint Effect of Baroclinicity and Relief) is a driving mechanism. The volume transport increases poleward and is mainly concentrated in the slope regions. Maximum speeds, lateral and vertical extensions and seasonal variability are in the range of observations. With spring climatological wind forcing, surfacing of the undercurrent is no longer observed.

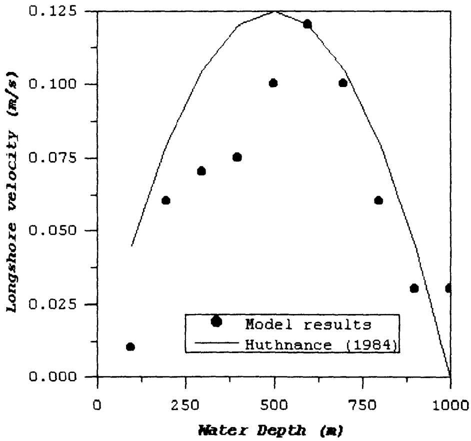

Fig. 1 – Model and theoretical results for the slope current at 39°N.

Fig. 2 – Spring currents at surface/bottom with density forcing.

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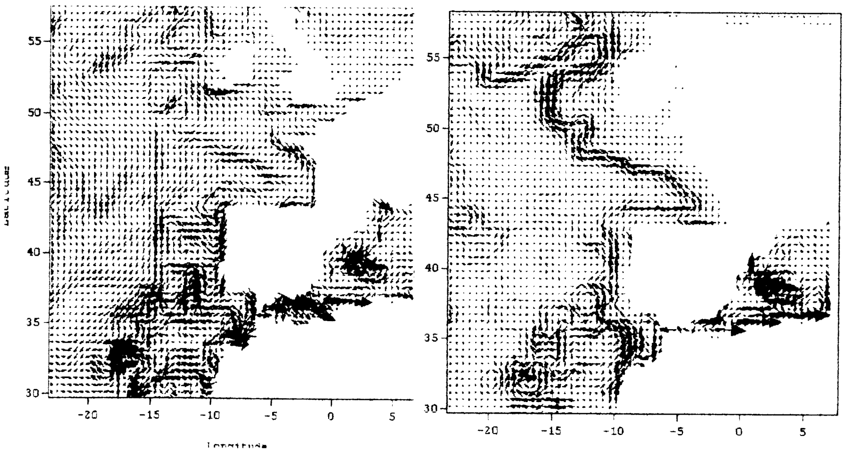

Fig. 3 – Spring currents at surface/bottom with wind and density forcing.

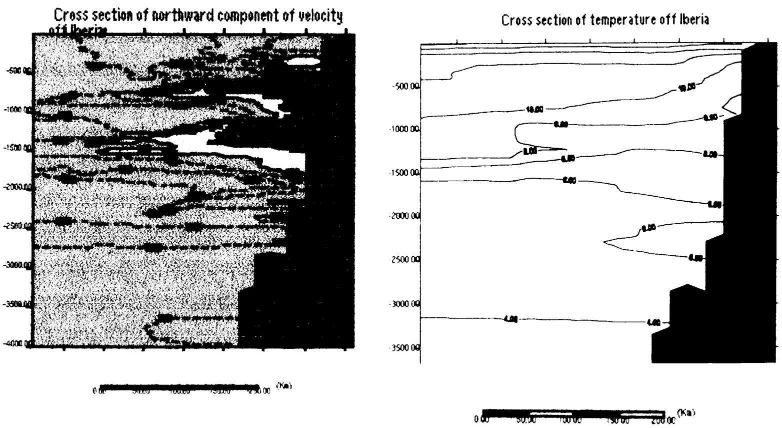

Fig. 4 – Spring cross section (41°N) of density and northward velocity.

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