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On reducing the slope parameter in terrain-following numerical ocean models

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Abstract

Sigma coordinate ocean models, such as the Princeton Ocean Model, are a type of terrain-following model, which are currently being used in regions with large topographic variability such as entire ocean basins, shelf breaks, continental shelves, estuaries and bays. The main concern when using a terrain-following ocean model is to reduce the pressure gradient force error (PGFE). Regardless of the method of calculation of the pressure gradient, the PGFE will not be reduced to an acceptable value without first reducing the slope parameter, defined by the absolute value of the ratio of the difference between two adjacent cell depths and their mean depth. Here two methods for reducing the slope parameter are compared: a traditional two-dimensional smoothing with Gaussian filters and an alternative one-dimensional robust direct iterative technique. While both methods efficiently smooth the bottom topography so that the pressure gradient errors are reduced to acceptable levels, the alternative method is shown to have a unique advantage of maintaining coastline irregularities, continental shelves, and relative maxima such as seamounts and islands.
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1. Introduction

Velocity errors induced by the pressure gradient force are unavoidable in three-dimensional sigma coordinate models. There are two types of sigma coordinate errors: the sigma error of the first kind (SEFK) and sigma error of the second kind (SESK), as defined by Mellor et al. (1998). When reducing the pressure gradient force error (PGFE) in sigma coordinate models (Haney, 1991; Mellor et al., 1994, 1998), both types of sigma coordinate errors must be considered. The SEFK is readily corrected because it goes to zero prognostically by advecting the density field to a new state of equilibrium.

The second one, a vorticity error, is of greater concern because the error does not vanish with time, and is present in both two- and three-dimensional calculations (Mellor, 1996). To reduce these errors, Mellor et al. (1998) recommend smoothing the topography to reduce the slope parameter, using the highest possible resolution, subtracting the horizontally averaged density before the computation of the baroclinic integral as in Batteen (1988), and using a curvilinear grid that follows the bathymetry.

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To determine the magnitude of these pressure gradient force errors and how much they can be reduced, a typical sigma coordinate model, in this case the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987; Mellor, 1996), was initialized with horizontally averaged annual climatological temperatures and salinities, a realistic coastline and realistic (unsmoothed) topography, and no wind or thermohaline forcing for the coastal North Canary Current System (NCCS) region of the eastern Atlantic Ocean. With the horizontal averages of the climatology and no forcing, we should expect that nothing will happen, i.e., the initial state of rest should be maintained with time. In a sigma coordinate model, however, the resultant velocities due solely to pressure gradient force errors in this region with relatively steep topography had magnitudes of 100 cm s^{-1}.

For the NCCS region, the first three techniques of Mellor et al. (1998) were used. However, the last technique, the use of a curvilinear grid, could not be used, because the unique geography of the Gulf of Cadiz would have given rise to singular points. Using the first three techniques, the pressure gradient force error was reduced to less than 0.5 cm s^{-1} by day 10, with maximum velocities within ~30 km from the coast in areas of relatively steep topography where the slope parameter is the largest.

It should be noted that besides the recommendations of Mellor et al. (1998), other SESK reduction techniques have been successful. These include the use of high-order schemes (fourth and sixth) (McCalpin, 1994; Chu and Fan, 1997, 1998), interpolation of the pressure gradient to z-levels (Kliem and Pietrzak, 1999), reconstruction of pressure density fields using parabolic splines (Shchepetkin and McWilliams, 2003), and the introduction of a hydrostatic correction (Chu and Fan, 2003).

Note that, regardless of the method of calculation of the pressure gradient, the PGFE will not be reduced to an acceptable value without first reducing the slope parameter. The slope parameter (SP) is defined as

$$\mathrm{SP} = \frac{|h_\mathrm{B} - h_\mathrm{A}|}{h_\mathrm{B} + h_\mathrm{A}} \tag{1}$$

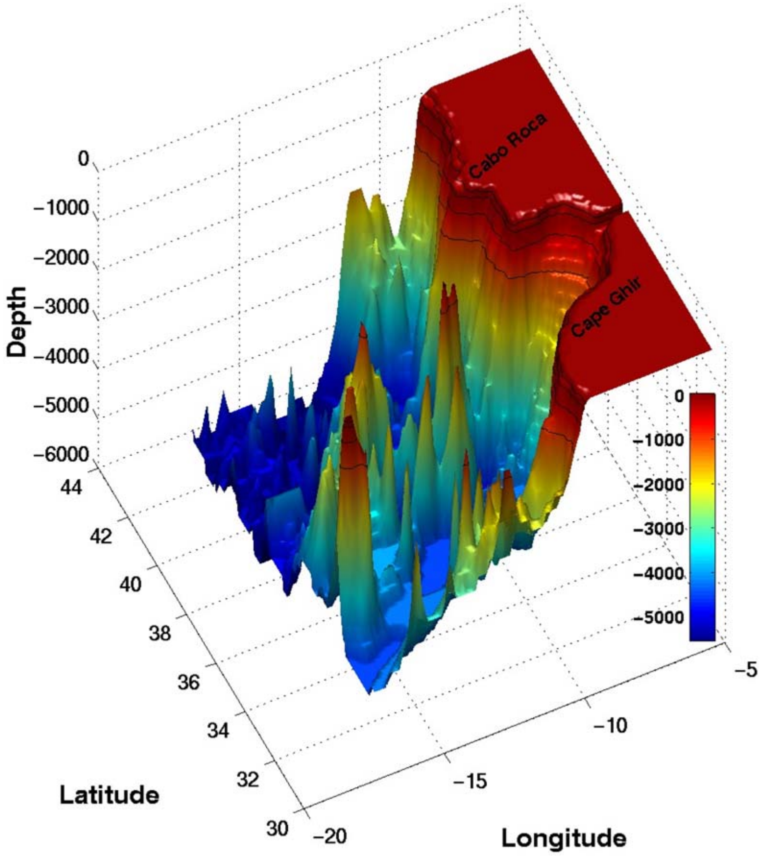

Fig. 1. Raw topography for the Northern Canary Current System, depths in meters. Contour lines at 100, 200, 500 and 1000 m depth.

where h_B and h_A are the depths of adjacent grid points. According to Mellor (1996), the SP must be less than 0.2 for POM because greater values can induce high PGFEs.

Since the numerator in (1) decreases faster than the denominator, the slope parameter can also be reduced by increasing the horizontal resolution of the model. In particular the increase in horizontal resolution necessary to change the slope parameter can be determined by

$$R = \frac{SP_i \times (1 - SP_f)}{SP_f \times (1 - SP_i)} \tag{2}$$

where R is the ratio of increase in resolution, SP_i is the raw slope parameter and SP_f is the final slope parameter.

Using topography from Smith and Sandwell (1997) interpolated for a regional model grid such as the NCCS (see Fig. 1, for example), a conservative value for SP_i is 0.6. To obtain values of the slope parameter less than 0.2, it would be necessary to increase the horizontal resolution by a factor of 6. Note that this higher resolution in latitudinal and longitudinal directions would end up increasing the number of computational points by 36. For the POM, a typical sigma coordinate ocean model, the increase in horizontal resolution would imply a decrease in the internal and external time steps by a factor of 6 (this is necessary to maintain the computational stability condition of Courant–Friedrichs–Levy). If all the algorithms in the model had a

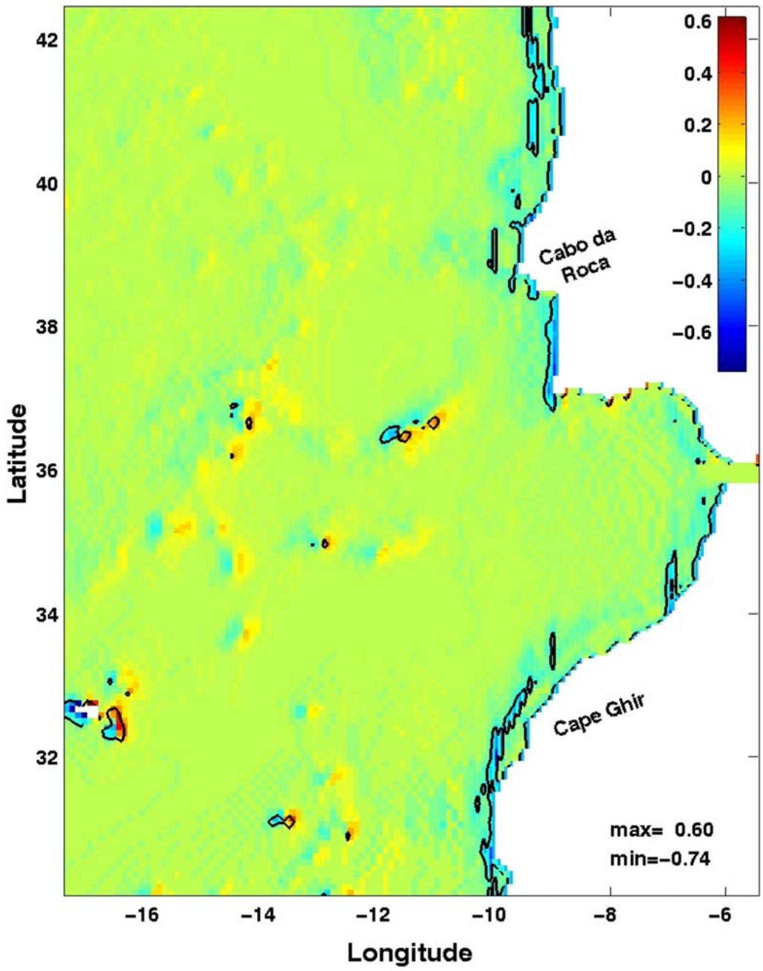

Fig. 2a. Initial signed slope parameter in the x-direction (SSPX). Contour lines for −0.2 and 0.2.

computational effort proportional to N, where N is the total amount of points in the model, the computational effort would be increased by a factor of 216.

Since the increase in resolution to reduce the slope parameter is usually too expensive computationally, an alternative method is suggested to reduce the slope parameter in relatively steep coastal areas. In many coastal regions, the initial topography (without smoothing) already interpolated to the model grid (usually between 4 and 20 km for a regional model) can have typical maximum slope parameter values between 0.6 and 0.8 over the shelf break (see Figs. 2a and 3a, for example).

Typical two-dimensional Gaussian filters used in the smoothing of bottom topography can have the disadvantage of smoothing topographic features that could be of great importance in coastal regions. For example, these filters can smooth coastline irregularities, and may not maintain continental shelves and relative maxima (i.e., they may sink small islands and seamounts). In addition the corrections to the depths can be negative or positive. If negative, additional problems can result because there is usually no initialization or forcing data available below the initial depth values.

Another smoothing method has been provided to POM users (Mellor, 1996). In this method, the slope parameter is calculated at each pair of adjacent points in a given direction. If the slope parameter is greater than the minimum value (0.2 for POM), then the greater depth is decreased and the lesser depth is increased proportionally to make the slope parameter equal to the limiting value. The topography is scanned and smoothed in each direction (east, north, west, south) in sequence to complete the process. Since this method introduces both positive and negative changes to depth, it can cause some of the same problems as Gaussian

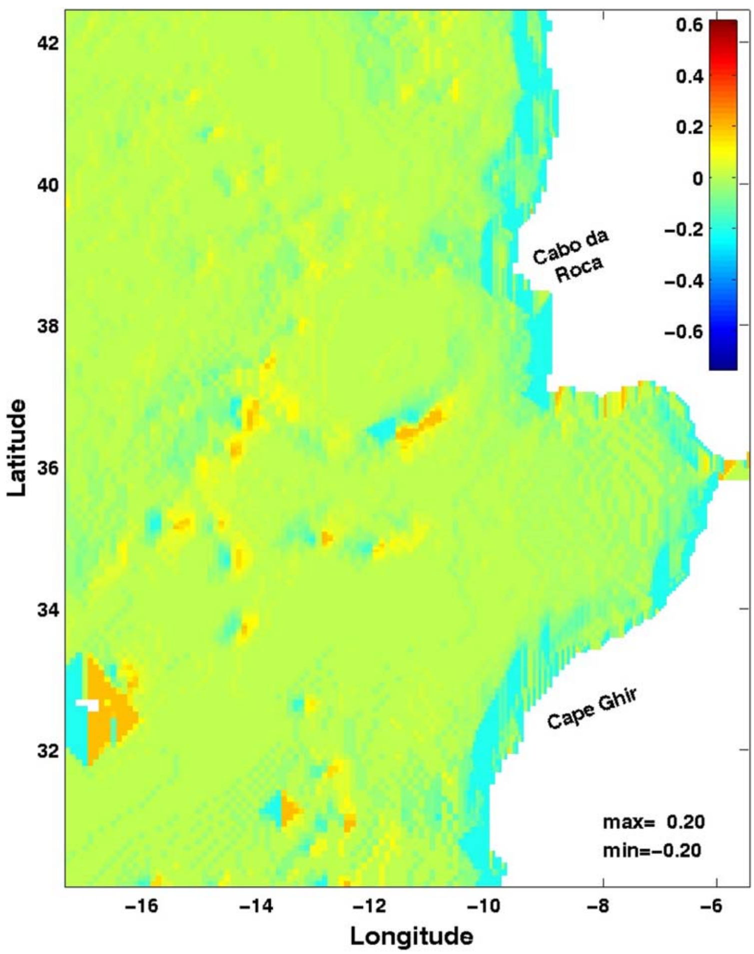

Fig. 2b. Signed slope parameter in the x-direction (SSPX) after the execution of two complete iterations.

smoothing, such as smoothing coastline irregularities, sinking seamounts, and creating depths greater than the original topography.

Here an alternative method to reducing the slope parameter is detailed. In particular, a one-dimensional robust iterative technique is introduced. This method is shown to have a unique advantage of maintaining coastline irregularities, continental shelves, and relative maxima such as seamounts and islands. Let us now describe the process.

2. A practical example

Here an advanced method to reduce the slope parameter, a one-dimensional robust iterative method, is introduced. First, the initial water volume (V_i) for the model domain is calculated. Next, the signed slope parameter is calculated along each grid line in a particular direction over the domain. Where the slope parameter between two adjacent cells is greater than the limit, it is adjusted to the limit value by decreasing the depth of the cell. After each line in the domain has been adjusted for that particular direction, the topography matrix is then rotated by 90°. Each process is repeated until the topography has been adjusted for all the directions (rotated by 360°). This is an iterative process since a change in the topography necessary to reduce the slope parameter in one direction may alter the slope parameter in the perpendicular direction to values greater than the limit. For this example, a limiting slope parameter value of 0.2 is used. After all slope parameter values are

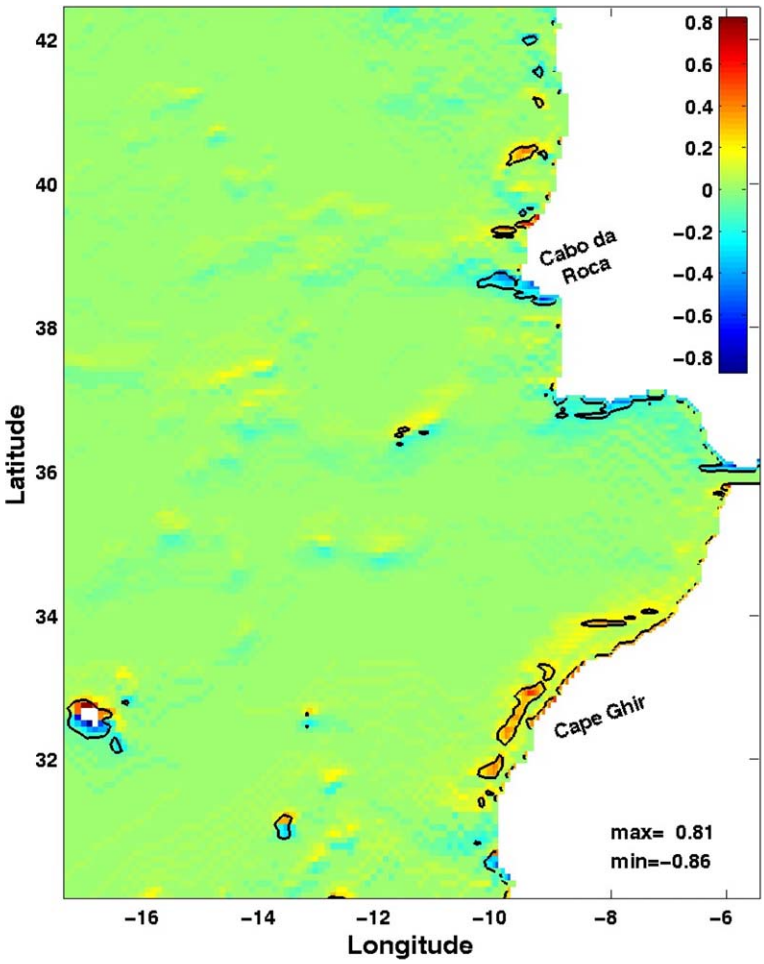

Fig. 3a. Initial signed slope parameter in the y-direction (SSPY). Contour lines for −0.2 and 0.2.

at or below the limiting value, a final water volume (V_f) for the model domain is calculated. All depths are then multiplied by the coefficient

$$K = \frac{V_i}{V_f} \tag{3}$$

Note that multiplying by this coefficient does not change the slope parameter of any sets of adjacent cells. The full step-by-step procedure for constructing this direct iterative filter is contained in Martinho (2003) and is also available as subsidiary material on the Elsevier website.

Figs. 2a, 2b, 3a and 3b show the initial and final values of the signed slope parameter in the x-direction (SSPX) and in the y-direction (SSPY), respectively, for ETOPO 5 topography interpolated to 4.1–9.6 km horizontal resolution for use in a typical sigma coordinate terrain-following ocean model (e.g. POM, Mellor, 1996). Note that the initial topography has relatively high slope parameter values of ~0.8 (see Fig. 3a, for example). Here the results of using the algorithm to successfully reduce the slope parameter from 0.8 to 0.2 are shown. The initial values of SSP have a range between −0.86 and 0.81 for SSPY (Fig. 3a) and between −0.74 and 0.60 for SSPX (Fig. 2a). The application of the smoothing algorithm in the x-direction (which targets negative SSPX values less than −0.2 and each patch of those values individually) changes the minimum value of SSPX from −0.74 to −0.2 (not shown). Note that changing the topography in order to reduce SSPX frequently increases SSPY values (not shown).

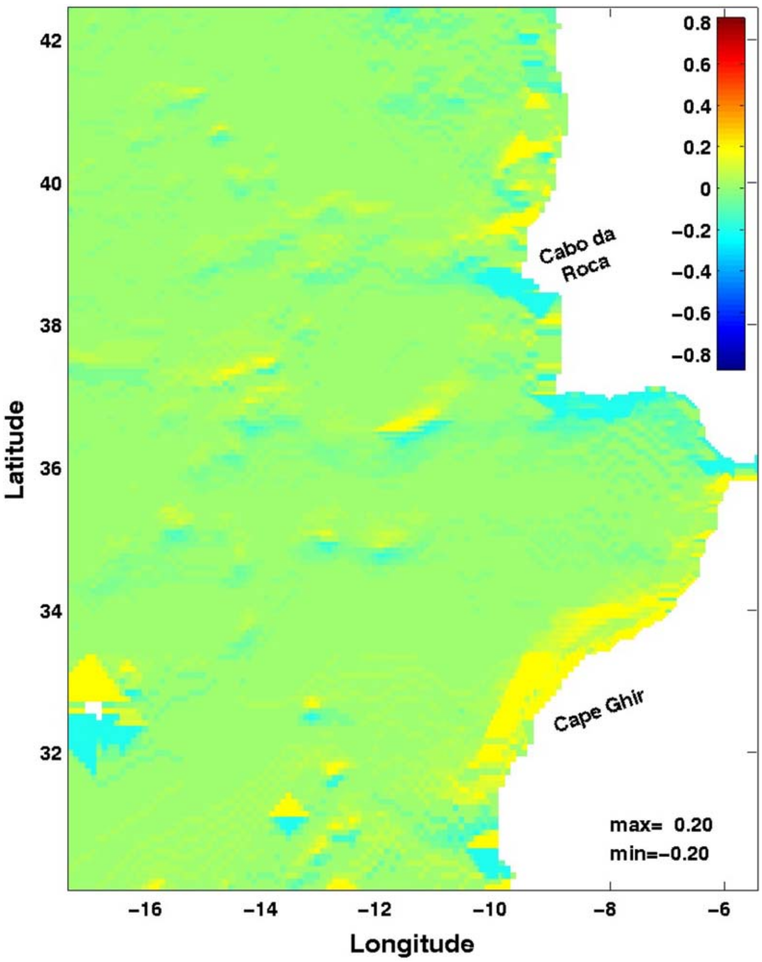

Fig. 3b. Signed slope parameter in the y-direction (SSPY) after the execution of two complete iterations.

To target values of SSPY larger than 0.2, the topography is rotated 90° counter-clockwise and the algorithm is applied again. After this step, all SSPY values have been reduced to less than 0.2. However, just as the first reduction of SSPX values increased some SSPY values, this step to reduce the SSPY values increases some of the SSPY values, which will be targeted on the next rotation.

The rotation and cleaning process, targeting successively four different directions separated by 90°, is called an iteration, and corresponds to the rotation of the topography by 360°. To reduce the remaining values of SSPX to the intended range (−0.2 to 0.2), there is the necessity to do another complete iteration. The result of the second iteration for SSPX (SSPY) is shown in Fig. 2b (Fig. 3b). For the topography used in this case (the NCCS), all the values of the slope parameter were successfully reduced to values less than or equal to 0.2 in two iterations.

3. Topography comparisons

Application of the iterative method to the NCCS showed that only two iterations were necessary to reduce the slope parameter from around 0.8 to less than 0.2. To test the robustness of the one-dimensional iterative method, it was also applied for the California Current System and the western and southern coastal regions of Australia, where similar results were obtained (Phillips, 2002).

The raw and final topography (after direct reduction of slope parameter) for the NCCS is shown in Figs. 1 and 4a, respectively. No discernible differences are seen between the two figures except for a slight widening of the most prominent seamounts. In contrast, when two-dimensional Gaussian smoothing is used, a significant widening of topographic features can be seen (Fig. 4b). In addition there is a clear deepening of seamounts and

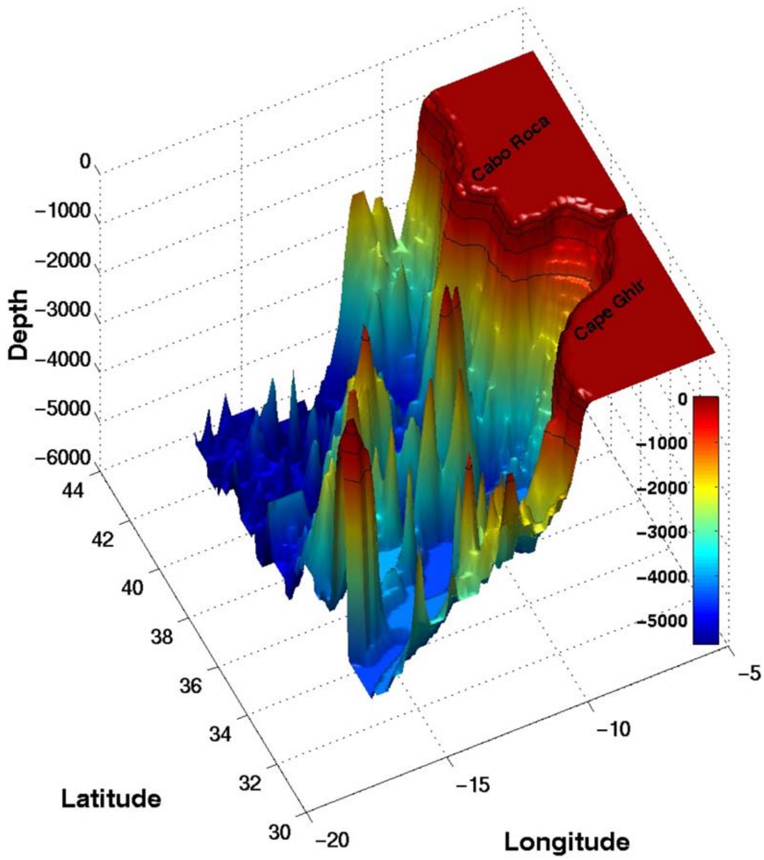

Fig. 4a. Topography smoothed with the direct iterative method for the Northern Canary Current System, depths in meters. Contour lines at 100, 200, 500 and 1000 m depth.

islands. Fig. 4b also shows that there is significant smoothing of coastline irregularities, a decrease of the shelf width and a shallowing of the Strait of Gibraltar.

The difference between the raw topography and the smoothed topography with the one-dimensional direct algorithm, was also calculated and analyzed. This comparison (Martinho, 2003) showed that the algorithm made changes in far fewer points than when traditional smoothing is used. Also the minimum depth of the seamounts is maintained and coastline irregularities and the continental shelf and rise are maintained. The only places where this algorithm changes the topography is in areas near the upper continental slope and around seamounts where there are relatively high slopes and shallow depths.

Finally, the difference between raw topography and the topography smoothed with the POM method was analyzed. This comparison (Martinho, 2003) showed that the one-dimensional direct iterative method changes fewer points than the POM method. In addition many of the corrections made by the POM method are negative as described in Section 1. Note that if there is no initialization and forcing data beyond the initial topography values, there will be problems. Lastly, since the POM smoothing method is not maxima conservative, topographic features such as seamounts and islands will be deepened and changes to the coastline geometry will be made.

In order to more clearly show the differences between the smoothing methods, Fig. 5 shows a cross-section of topography across a seamount at 36.4°N. The direct iterative method only slightly deepens the summit of the seamount, and this slight deepening is due only to the correction applied to conserve water volume, and

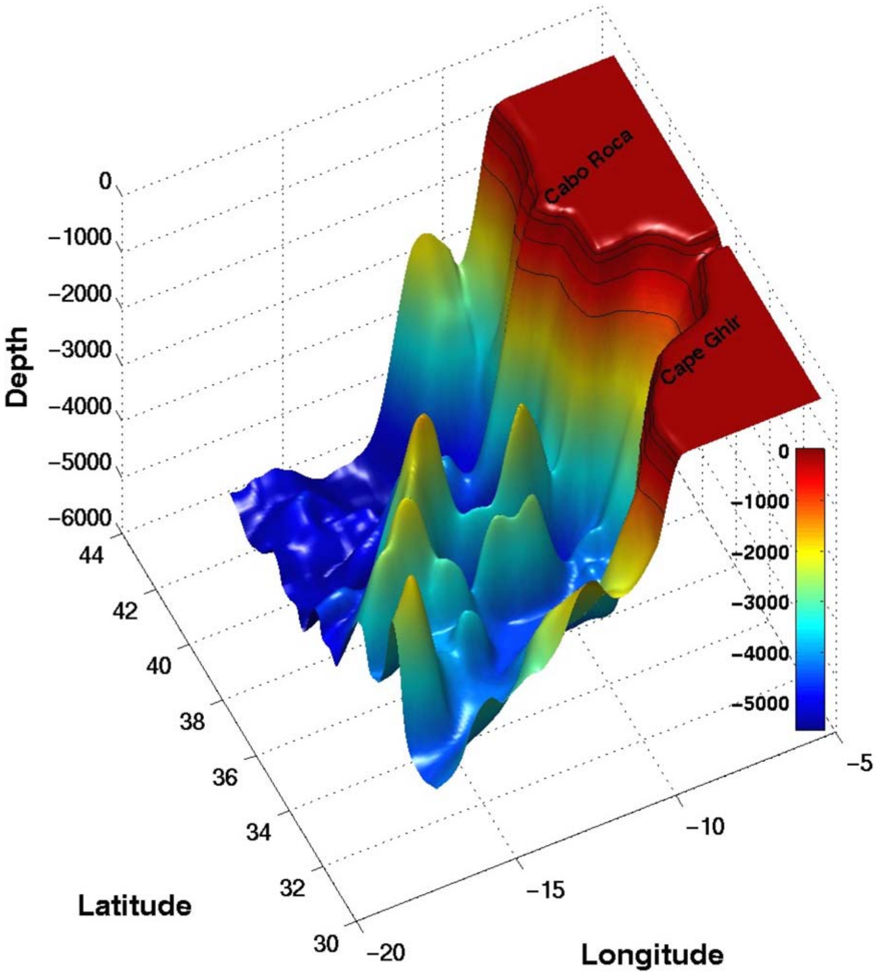

Fig. 4b. Topography smoothed with a Gaussian two-dimensional filter method for the Northern Canary Current System, depths in meters. Contour lines at 100, 200, 500 and 1000 m depth.

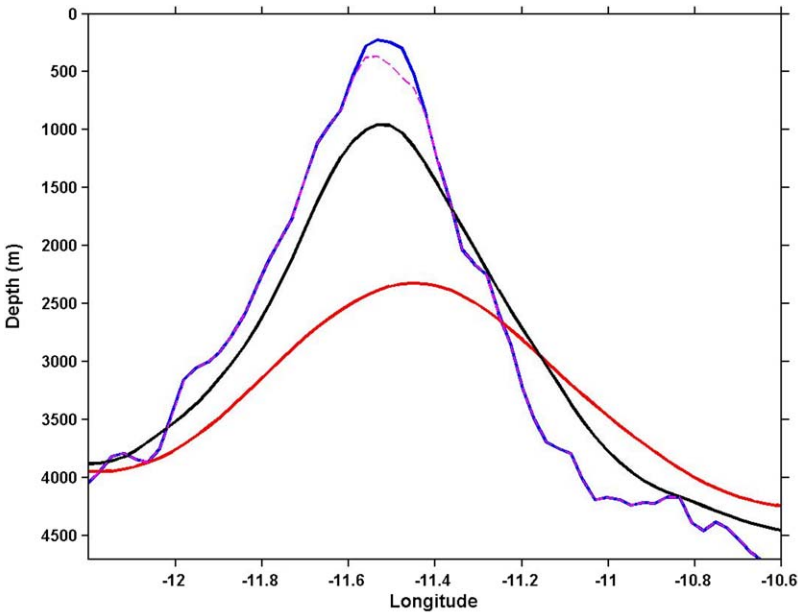

Fig. 5. Cross-sections of topography across a seamount at 36.4°N showing the methods of topography smoothing. The blue line is the raw (unsmoothed topography). The red line is the topography smoothed with a Gaussian filter. The black line is the topography smoothed with the alternative POM method. The dashed magenta line is the topography smoothed using the one-dimensional direct iterative technique described in this paper. (Note that a purple line is seen where the blue and magenta lines overlap.) (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

changes almost no other points. The POM method deepens the seamount significantly more. The more traditional Gaussian smoothing methods deepens the summit of the seamount by over 2000 m while making it several hundred meters shallower nears its base.

4. Coastal circulation effects

To determine how the different types of smoothing (i.e., Gaussian and direct iterative methods) influence the coastal circulation, the NCCS ocean model was run with different types of smoothed topographies. In particular, the POM for the NCCS was run with annual wind forcing and annual climatological forcing of temperature and salinity at the boundaries.

The results (see Martinho, 2003) show the following: In the direct iterative smoothing method the continental shelf remains very similar to the raw topography, while in the regular smoothing the continental shelf almost disappears. The frictional layer that develops due to the presence of the continental shelf in the direct iterative smoothing results is responsible for a smaller surface equatorward current magnitude relative to the Gaussian smoothing results. The smaller surface current in the direct iterative case allows the development of a higher magnitude poleward current off Iberia (i.e., the Iberian Current). The development of the Iberian Current in the direct iterative method constrains even further the coastal equatorward current near the coast with increased friction values. The poleward undercurrent also shows a smaller magnitude and a well-defined friction boundary layer for the direct iterative method results compared with the Gaussian smoothing results. While the difference in results in the two models can be explained by the differences in the topographies, more realistic initialization and forcing of POM with concurrent observations are needed to verify which are the more realistic results.

5. Conclusions

A one-dimensional direct iterative method for reducing the slope parameter was developed. A comparison with Gaussian and POM smoothing showed that the use of the direct iterative technique resulted in a more realistic topography and coastline geometry for use in terrain-following ocean models. The method was tested for three different coastal regions with complex topography. In all the different regions, the slope parameter was reduced from maximum values of ~0.8 to acceptable values of less than 0.2. This reduction was obtained by changing the depth of relatively few grid points and with only two iterations. This method was shown to have the unique advantage of maintaining coastline irregularities, continental shelves, and relative maxima such as seamounts and islands.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ocemod.2006.01.003.

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