A regional hydrodynamic model of upwelling in the Southern Benguela

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The Benguela upwelling system, off the southwest coast of southern Africa, is productive but also highly dispersive. Sardines and anchovies have adapted their reproductive strategy by spawning on the Agulhas Bank, away from the upwelling region. Transport from the spawning grounds to the nursery area is believed to be one of the main environmental processes that control recruitment. To understand the transport processes along the southwest African coast better, we set up an eddy-resolving, primitive equation model of the regional oceanic circulation. The model domain covers the shelves and oceanic plains from 40°S to 28°S and from 10° E to 24°E. To obtain statistically meaningful solutions, long simulations (more than 10 years) were conducted. The high-order accuracy of the model schemes and grid resolution allow the development of plumes, filaments and eddies, which are characteristic features of upwelling systems. While only large-scale and seasonal variations are forced, this energetic mesoscale activity induces an important variability. This intrinsic variability could limit the predictability of the transport processes and fish recruitment in the Benguela Current.

Background

Hydrodynamic modelling is an active field in oceanography. The increase in available computing power as well as the incorporation of advanced features in numerical codes allow hydrodynamic models efficiently and robustly to simulate the oceanic circulation at high spatial resolution in the coastal domain.[1] The ability of the more advanced numerical codes to resolve mesoscale circulation features such as eddies and fronts is of particular interest for investigating the dynamics of coastal circulation and its impact on coastal ecosystems.[2]

There have been few attempts to model ocean dynamics over the coastal shelf and slope off South Africa. Recently, the Princeton Ocean Model (POM) was used to simulate the circulation around southern Africa from about 46°S to 12°S and 4°E to 30°E with a spatial resolution of 20 km.[3] This model reproduces most of the characteristic, large-scale features of the circulation over the Benguela region, but the resolution is too coarse and the numerical choices are such that it is difficult to resolve accurately the mesoscale patterns that develop over the shelf off the west coast as well as off the Cape Peninsula and western Agulhas Bank.

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The need for a high-resolution, eddy resolving, coastal model of the Southern Benguela region was expressed during the implementation of the VIBES (for **VI**ability of exploited pelagic fish resources in the **B**enguela **E**cosystems in relation to the environment and **S**patial aspects) programme. VIBES' main focus is to model the spatial dynamics of the environment and of the pelagic fish populations such as sardine and anchovy. This project aims to provide a better understanding and quantification of the environmental and biological processes affecting fish recruitment in the Benguela. Transport of eggs and larvae by the Cape Peninsula coastal jet from the Agulhas Bank spawning ground to the west coast nursery grounds, as well as offshore dispersion associated with upwelling, are thought to be important processes affecting fish recruitment success.[4] The first step in VIBES modelling was to set up a numerical tool that would simulate the dynamics of the circulation over the main spawning and nursery grounds. Within the wide range of numerical models available, we selected the Regional Ocean Model System (ROMS), a numerical code developed at Rutgers University and at the University of California at Los Angeles, to implement a 3-D hydrodynamic model of the Southern Benguela upwelling system.[2]

Implementation of ROMS in the Benguela

ROMS is a community model shared by a large user group around the world, with applications ranging from the study of entire ocean basins to coastal subregions. ROMS incorporates advanced features and high-order numerics, allowing efficient and robust resolution of mesoscale dynamics in the oceanic and coastal domains. The model solves the free surface, hydrostatic, primitive equations of the fluid dynamics over variable topography using stretched, terrain-following coordinates in the vertical and orthogonal, curvilinear coordinates in the horizontal. This allows enhancement of the spatial resolution in the regions of interest. Active open boundaries, connecting the regional model with the open ocean, are also incorporated.[5] A pie-shaped grid that follows the southwestern corner of the African continent from 40°S to 28°S and from 10°E to 24° E was developed. The topography is derived from the ETOPO2 dataset. Both a low- (18 km at the coast) and a high-resolution (9 km at the coast) grid are configured (Fig. 1). Along the vertical, stretched terrain-following coordinates and 20 levels provide enhanced resolution at the surface while preserving an adequate resolution in the deeper layers (Fig. 1). The third-order, upstream-biased advection scheme implemented in ROMS allows the generation of steep gradients, enhancing the effective resolution of the solution for a given grid size.[6] The model is forced with winds, heat and salinity fluxes extracted from the COADS ocean surface monthly climatology.[7] At the three lateral boundaries facing the

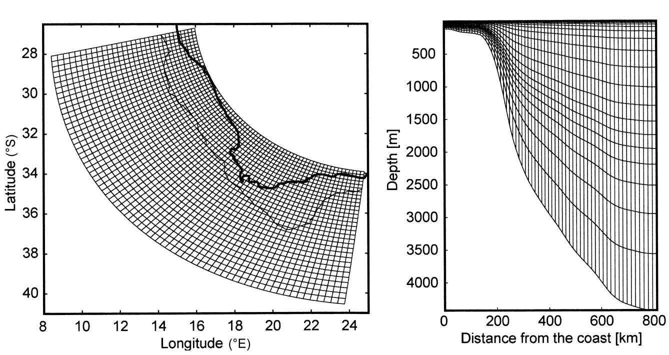

Fig. 1. The low-resolution spatial grid (left) and the vertical grid (right) used in the regional configuration of ROMS in the Southern Benguela.

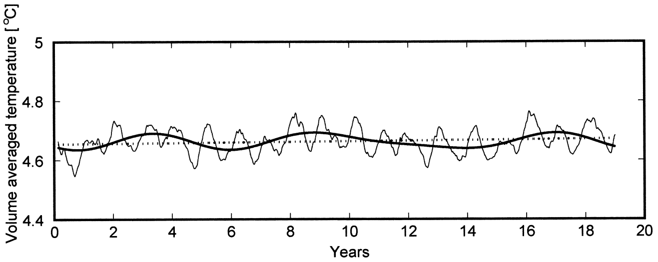

Fig. 2. Twenty-year time series of volume-averaged temperature (°C) using the low-resolution configuration.

open ocean, an implicit radiative boundary scheme, forced by a seasonal climatology computed from the AGAPE basin-scale ocean model,[8] connects the model to the surroundings. We have completed the set of open boundaries by introducing a condition for the depth-integrated transport originally proposed by Flather for tidal models;[9] this proved to handle more robustly the highly energetic and meandering Agulhas Current that flows westward in the southeast corner of the domain.

The summer values of the climatology are used for the initial conditions. The domain being relatively small, the solution, starting from rest, quickly adjusts to the initial stratification and the model reaches a statistical equilibrium after a spin-up of about one to two years. Details of the configuration implemented in the southern Benguela and an in-depth analysis of the spin up are given in Penven.[10] Several experiments have been performed, using the low- and high-resolution configurations.

Low-resolution configuration

A 20-year run was first carried out with the low-resolution configuration to test the stability and robustness of the regional configuration of ROMS. An important measure of the model fidelity is the degree to which it preserves the globally averaged value of its tracer fields. This is tested by averaging temperature over the entire domain, from surface to bottom. The 20-year time series shows that the volume-averaged temperature has a pronounced seasonal cycle, that after 2–3 years it oscillates around a mean of approximately 4.6°C and that no significant trend is noticeable (Fig. 2). Nevertheless, the solution exhibits important variations at the inter-annual scale. This can be related to the presence of the Agulhas Current, that generates at irregular intervals eddies that are quite large compared with the size of the model domain. Another test of the stability of the model is given by the surface kinetic energy averaged over the model domain (Fig. 3). The 20-year time series shows that there is a marked response of the ocean to the seasonally varying surface forcing. As expected, the surface-averaged kinetic energy is maximum in summer during the upwelling season. The absence of a significant trend is also an indication of the correct response of the model. Although these results are encouraging and indicate that the model using the low-resolution grid is able to simulate some of the large-scale regional circulation features, aspects of the circulation are not well represented. This is the case for the Agulhas Current retroflection as well as mesoscale coastal circulation features such as the Cape Columbine upwelling plume. Hence, a new set of experiments was conducted by doubling the number of horizontal grid points in each direction.

High-resolution configuration

The high-resolution horizontal grid has a spatial step varying from 9 km at the coast to 18 km offshore, which grid allows implementation of a more realistic topography than the low-resolution configuration. Because the bathymetry is of primary importance in the control of the circulation dynamics over the continental shelf and slopes, it is expected that this configuration of the model would better resolve the topographically controlled features observed over the continental shelf and adjacent waters. Whereas very small-scale processes are still not solved by the model, the 9-km resolution grid is fine enough to reproduce most of the mesoscale dynamics of the Benguela upwelling system. Using the same forcing conditions as in the low-resolution experiment, a 10-year simulation was conducted. The output data were stored every two simulated days in order to analyse the outputs with a high level of spatial and temporal accuracy as well as to provide the basis for providing inputs for biological models with high-resolution environmental data. An example of simulated sea-surface temperature (SST) over the entire domain is given in Fig. 4. A high level of mesoscale activity

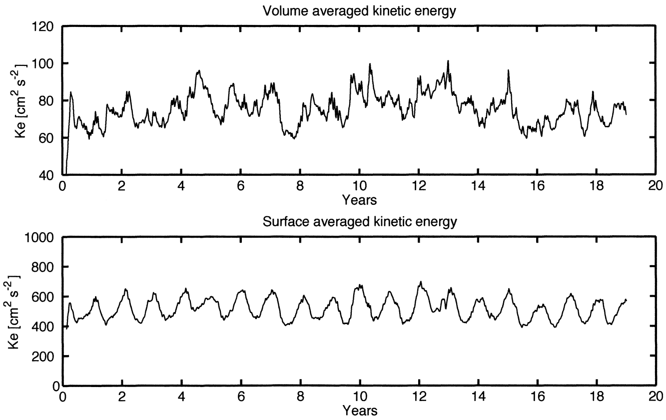

Fig. 3. Top: volume-averaged kinetic energy ($cm^2 s^{-2}$) for the low-resolution experiment; bottom: surface-averaged kinetic energy ($cm^2 s^{-2}$) for the low-resolution experiment.

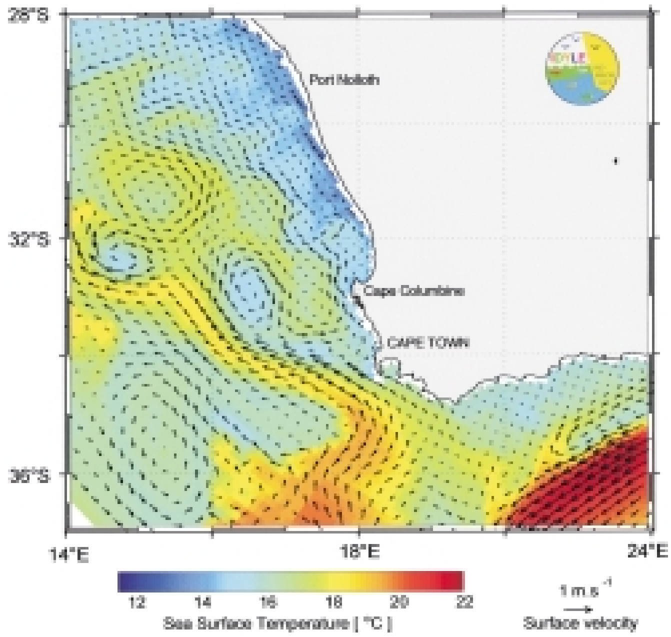

Fig. 4. An example of the surface structure of the temperature and currents (arrows) in the Southern Benguela region simulated by the high-resolution configuration. This snapshot of the surface structure on 1 September of the second year of the simulation shows the main oceanographic features of the region: 1) the warm and intense Agulhas Current flowing westward in the southern part of the domain, and 2) the coastal upwelling off the west coast. Upwelling filaments off the west coast, a shear edge eddy on the eastern part of the Agulhas Bank as well as eddy shedding in the vicinity of the Agulhas Current, of the Cape Peninsula and of Cape Columbine are examples of the mesoscale activity simulated by the model.

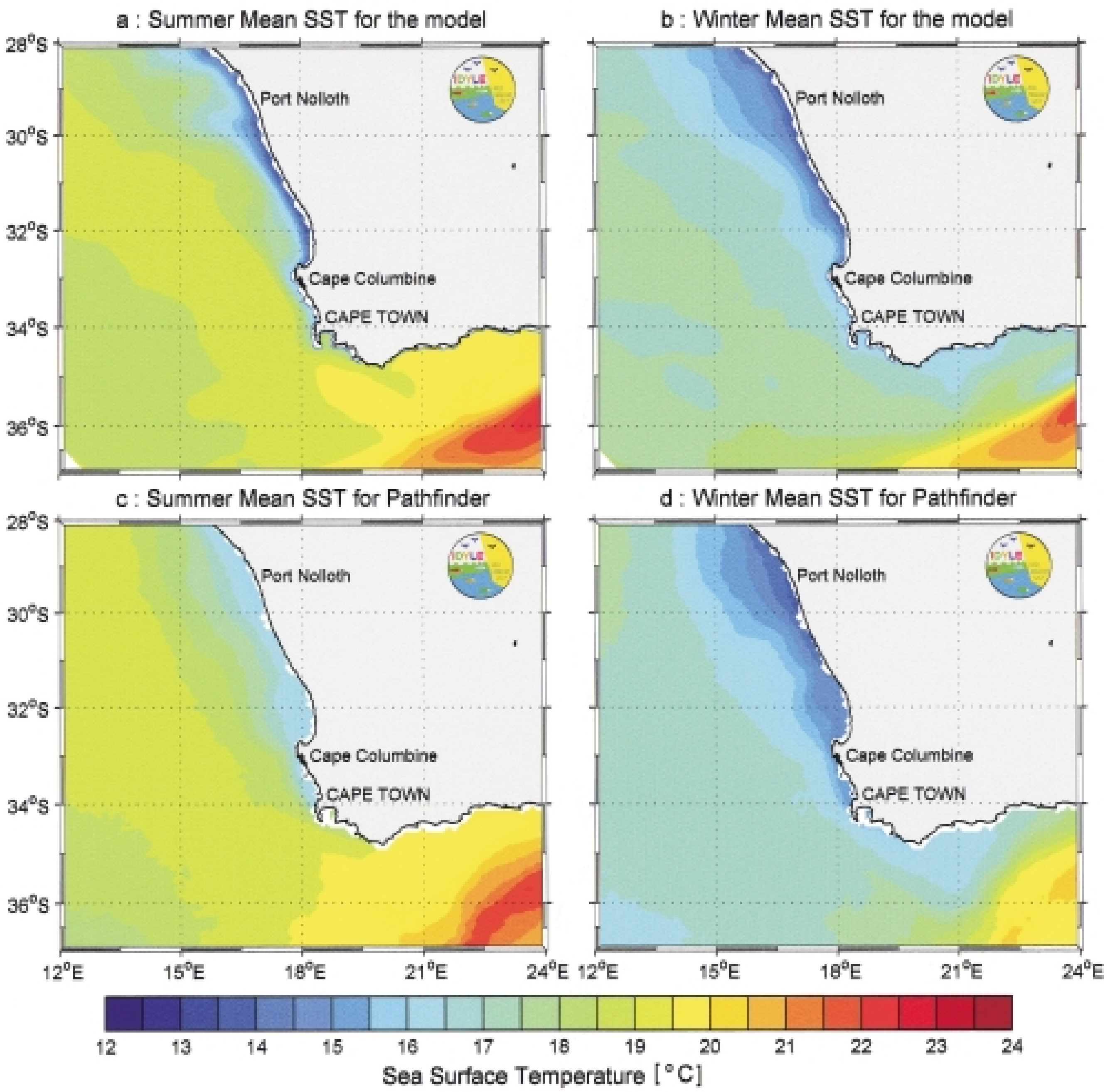

Fig. 5. Comparison of the seasonal mean spatial structures of sea-surface temperature (°C) from the model and the PATHFINDER satellite SST database.

is observed during this 10-year simulation, with the generation of Agulhas rings, and the shedding of cyclonic eddies starting from the southern tip of the Agulhas Bank, Cape Peninsula and Cape Columbine. Off the west coast, the upwelling front shows an important variability, developing a series of meanders, plumes and filaments in a realistic manner.

We have analysed the average behaviour of the model solution, of its variability as well as a comparison of the outputs of the high-resolution model and either those of the low-resolution scheme or with observed data.[10] A generally reasonable agreement was found between the simulated and observed circulation structures, both at the surface and at deeper levels. In the southern part of the model domain a comparison with surface and subsurface data shows that the model reproduces cyclonic eddies in the lee of the Agulhas Bank in good agreement with observed features, in particular regarding vertical and horizontal scales.[11]

Although the model is forced by a repeated climatology (no inter-annual variability in the forcing fields), there are pronounced differences in the simulation outputs between individual years (for example, the thermal structure and the current fields of year 4 are significantly different from those of year 3 at the same time of year). Intrinsic mesoscale activity is the main contribution to this inter-annual variability,[10] and results from oceanic instability processes in the absence of added forced variability by synoptic and inter-annual atmospheric fluctuations. This is in agreement with previous studies of the dynamics of the California Current upwelling ecosystem.[5,12] However, when using our model to provide inputs to biological models, one should keep in mind that the response of the thermal structure and of the current fields to inter-annual atmospheric fluctuations has not yet been resolved by our simulations. How the inter-year variability observed in the model outputs compares with that resulting from contrasted atmospheric forcing (such as a relaxed or intensified southeasterly wind regime) or remote oceanic forcing (such as Rossby or Kelvin waves generated outside the model domain) is still an open question.

The main discrepancy between the model outputs and observed data appears off the west coast region during summer, when simulated SSTs are significantly lower than those observed from satellites, whereas in winter there is better agreement (Fig. 5). By using wind data from a monthly climatology, the high-frequency variability (from days to weeks) of the wind is smoothed out. This results in a continuous and persistent upwelling-favourable wind forcing during the whole summer season. The pulsing pattern of the southeasterly wind is a well-known characteristic of the local wind in summer, however, resulting in the alternation of reduced and enhanced upwelling off the west coast. These variations in wind forcing could induce reversals in the alongshore currents[13] and warming close to the shore. The low spatial resolution (1° square) of the climatological wind fields does not resolve the medium-scale spatial structure of the wind. As a result, the onshore-offshore gradient of the wind in the coastal domain is not adequately represented. Both the low temporal and spatial resolution of the climatological wind used to drive the model contribute to enhancing the upwelling-favourable wind forcing along the coast and intensify the injection of cold water over the continental shelf in our simulations.

Conclusion

Analysis of the 10-year run of the high-resolution configuration is currently being extended by focusing on the structure and variability of the west coast upwelling and on shear edge features along the Agulhas Bank that have been observed both in the simulations and in satellite data. New experiments are being conducted to investigate the response of the Cape Peninsula jet and of the west coast upwelling to high-frequency wind forcing as well as to an abrupt relaxation of the upwelling-favourable wind. This latter experiment is aimed at simulating the relaxation of the wind observed in December 1999 and at investigating its impact on the success of anchovy eggs and larvae transport to the west coast nursery grounds.[14]

The implementation of a 3-D hydrodynamic model in the southern Benguela using the ROMS numerical code has made available an advanced tool for efficiently and robustly simulating the circulation at high spatial resolution in the coastal domain. Coupling the hydrodynamic model to biological models is being done using two complementary approaches: a nutrient-phytoplankton-zooplankton model to simulate plankton production, and an individual-based model to investigate the fate of eggs and larvae within a 3-D advective environment.

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