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The Benguela: A laboratory for comparative modeling studies

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ABSTRACT

Equilibrium dynamics of the Benguela system is investigated using the holistic nature of the spatially and temporally cohesive output of a numerical model. The Regional Ocean Modeling System (ROMS) is used to simulate the Benguela system in its entirety. It successfully simulates the cool coastal upwelling regime and its division into seven distinctly separate cells, as well as the large-scale offshore regime and the respective seasonal fluctuations. It does however, present a cool bias at the coast due to an underestimation of the coastal wind drop-off as well as a warm bias offshore in the southern Benguela due to the overestimation of Agulhas Current input. The Benguela can be divided into northern and southern regimes, based on dynamic as well as topographic differences. Topographically, the division between the northern and southern regimes coincides with an abrupt narrowing of the continental shelf toward the north at 28°S. The large-scale depth-integrated flow to the north of this feature is weak but distinctly poleward, while to the south the flow regime is governed by the meandering nature of the equatorward Benguela Current and is the pathway for eddies that originate at the Agulhas retroflection. The poleward flowing regime of the northern Benguela is tied to the Sverdrup relation, which links meridional transport with wind stress curl. The Lüderitz upwelling cell at 27°S experiences the most vigorous upwelling throughout the year and, as a result, offshore volume fluxes in this region are extremely large. This upwelling cell divides the northern and southern Benguela coastal upwelling systems into separate regimes, based on the fact that their seasonal signals are out of phase. The offshore gradient of eddy kinetic energy (EKE) is generally strong in the Benguela system and exceptionally so in the southern Benguela due to vigorous mesoscale activity offshore of the shelf-edge, originating from the Agulhas retroflection area. The juxtaposition between the steep offshore EKE gradients in the south and much weaker offshore gradients of EKE in the northern Benguela has different implications for cross-shore exchanges.

1. Introduction

The Benguela is unique among the four major eastern boundary upwelling systems of the world's oceans in that both its northern and southern boundaries are dynamically linked to warm water current regimes, namely the Angola Current in the north and the western boundary Agulhas Current in the south (Shannon and Nelson, 1996; Shillington, 1998; Field and Shillington, 2004; Shillington et al., 2006). The northern and southern regions of the Benguela system are therefore subject to influence from the tropical Atlantic and Indian Oceans, respectively. Low oxygen water, originating in the tropical Atlantic episodically advects far south into the northern Benguela upwelling regime and has, often catastrophic, implications for the living marine resources there (Shannon and Pillar, 1986; Monteiro and van der Plas, 2006; Monteiro et al., 2008). In the south, the interaction of the north-westward path of Agulhas eddies with the upwelling front has been implicated in advective losses of fish larvae (Duncombe-Rae et al., 1992).

The upwelling regime of the Benguela system is forced by south-easterly winds that are set up by the south Atlantic high pressure system and the continental low pressure trough and is seasonally modulated by variations of these two pressure systems. Meridional variations of the wind regime result in differences in the seasonal cycle of the northern and southern Benguela upwelling regimes such that the seasonal signal is strongest in the southern part of the system, with maximum upwelling intensities during spring and summer months (Strub et al., 1998).

Another feature, that might also be considered a boundary, of significance is the so-called 'LUCORC' (Lüderitz Orange river cone) barrier (Hutchings, 2004) that separates the system into northern and southern regimes on the basis of their different biological and physical characteristics (Agenbag and Shannon, 1988; Taunton-Clark and Shannon, 1988; Duncombe-Rae, 2004; Lett et al., 2007). The LUCORC barrier is commensurate with the Lüderitz upwelling cell,

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that is often cited as the most vigorous upwelling cell in the world (Bakun, 1996) and is certainly the most vigorous in the Benguela upwelling system (Lutjeharms and Meeuwis, 1987).

This paper addresses the equilibrium dynamics of the apparently disparate northern and southern regimes of Benguela system, including the large-scale circulation patterns as well as the coastal upwelling regions and their associated nearshore circulation features. A brief, systematic comparative discussion is presented that is based on the spatially and temporally cohesive data obtained from a model simulation.

2. Methods

The Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) is used to simulate the salient features of the large-scale circulation patterns as well as the coastal upwelling features of the Benguela system. It is a split-explicit and free-surface model that makes the Boussinesq and hydrostatic assumptions when solving the primitive equations. The model is discretized in the vertical on a sigma, or topography-following stretched coordinate system. In order to maximize computing efficiency, the simulation employs the two-way embedding capability of ROMS (Debreu and Mazauric, 2006), which is designed such that the output from a lower resolution 'parent' domain provides boundary conditions for the higher resolution 'child' domain nested within it and the 'child' domain in turn feeds the parent domain. This technique allows for more consistent boundary conditions than in situ products based on often temporally and spatially scarce measurements and is far less costly than running the parent domain at the resolution of the child.

The parent domain used in this simulation is the eddy-resolving Southern African Experiment (SAfE), a configuration designed by Penven et al. (2006) to capture salient oceanographic features around southern Africa. The SAfE domain is built on a Mercator grid, spanning 2.5°W–54.75°E and 46.75°S–4.8°S and has a horizontal resolution ranging from 19 km in the south to 27.6 km in the north. Temperature and salinity open boundary data are supplied by World Ocean Atlas 2005 (WOA: Conkright et al., 2002), from which, together with QuikSCAT winds, geostrophic and Ekman velocities are calculated (based on a reference level of 1000 m).

The child domain encompasses the greater Benguela system, spanning 3.9°E–19.8°E and 35.6°S–12.1°S, with a horizontal resolution that ranges from 7.5 km in the south to 9 km in the north. Both the parent and child grids have 32 sigma-levels that are stretched so that near-surface resolution increases. The topography for the nested configuration is based on the 1′ GEBCO (GEneral Bathymetric Chart of the Oceans: http://www.gebco.net) product and has been smoothed in order to avoid possible pressure gradient errors over steep topography.

The initial conditions of the nested configuration is an ocean at rest with WOA temperature and salinities for the month of January. The wind forcing of the model is a climatological wind stress product, based on a 0.5° QuikSCAT (Liu et al., 1998) climatology product, based on data spanning 2000–2007. The deliberate choice of using a climatological wind forcing for a simulation that is forced for multiple years, is in accordance with the focus on equilibrium dynamics. Moreover, it allows for an investigation of intrinsic, or unforced, system variability which is not addressed here. The surface fluxes are based on the climatological mean COADS heat and salt fluxes. The configuration is run for a total of 10 years, the first 2 years of which are required to reach statistical equilibrium. Model years 3–10 are used to create a climatology from which all of the analyses in this work are conducted.

3. Model results

Fig. 1 compares model-derived and satellite Sea Surface Temperatures (SSTs) from the 9 km Pathfinder data set for summer and winter. The solid white line approximates the position of the upwelling front and the dotted white line represents the shelf-edge. Satellite and model-derived data both suggest that a distinct topographical control exists in the southern Benguela, south of 28°S, such that the offshore extent of the upwelling front is somewhat limited by the shelf-edge. The model also captures large offshore expanses of the cool water regime at 27°S and at 30°S. The model tends to overestimate upwelling near the coast due to an underestimation of the wind drop-off, so that the alongshore wind stress is too strong (Capet et al., 2004; Colas et al., 2008). This results in a coastal SST cool bias of the order of 1.5 °C. The warm bias in the offshore regions of the southern Benguela system, south of 30°S is a result of topographical smoothing (Speich et al., 2006) that allows for an overestimation of the flux of Agulhas waters in the southern Benguela.

3.1. Large-scale circulation features

The annual mean, large-scale pattern of flow of the Benguela system is shown in Fig. 2a as streamlines of the depth-integrated (0–1000 m) volume transport ($1\ Sv = 10^6\ m^3\ s^{-1}$) and elucidates the division of the Benguela system into two distinct regimes. North of Lüderitz the transport streamfunction shows that the general flow follows the orientation of the coast and is poleward, with a relatively low volume flux of between 1–3 Sv. The flow regime south of Lüderitz is dominated by the north-westerly meandering path of the Benguela Current and passing Agulhas rings, that also tends to follow the orientation of the coastline until 30°S, where it begins to veer offshore.

Transports of the Benguela Current across 30°S, from the coast to 10°E, as resolved by the model are of the order of measurements taken during the 'Benguela Sources and Transports (BEST)' project and can be found in the work of Garzoli and Gordon (1996) and Garzoli et al. (1997). Other than a couple of outliers, model transports agree well with in situ measurements, particularly between 14° and 15°E where both model and in situ measurements decrease from 4 to 2 Sv. Further offshore, at 10°E, model-derived and in situ measurements are also equivalent and are ~6 Sv. Between these regions of good agreement, model and in situ comparisons differ in places due to differently resolved locations of the core of the Benguela Current.

Between the poleward northern regime and equatorward southern regime, is an area where flow crosses the bathymetry (shown in Fig. 2 as shades of grey). Bathymetric contours approximately mimic contours of f/H, where f is the coriolis parameter and H is the local depth. For a feature characterized by a small Rossby number, such as in our case (where $R_o = U/fL$, where U is a characteristic velocity scale, taken to be $4\ cm\ s^{-1}$ and L is a characteristic length scale taken to be 150 km, based on the average speed and width of the poleward flowing regime, respectively), planetary vorticity is large compared to relative vorticity and flow is expected to follow lines of constant f/H. Large-scale flow is indeed steered by topography along the shelf and slope, with the exception of the region between the poleward northern regime and equatorward southern regime where it veers offshore. The process that allows the flow to cross the topography in this region still needs to be elucidated.

It is somewhat counter-intuitive that the prevailing south-easterly winds in the northern Benguela are in the opposite direction to the ambient poleward flow in this region. A possible explanation could lie in the Sverdrup relation, which links wind stress curl with

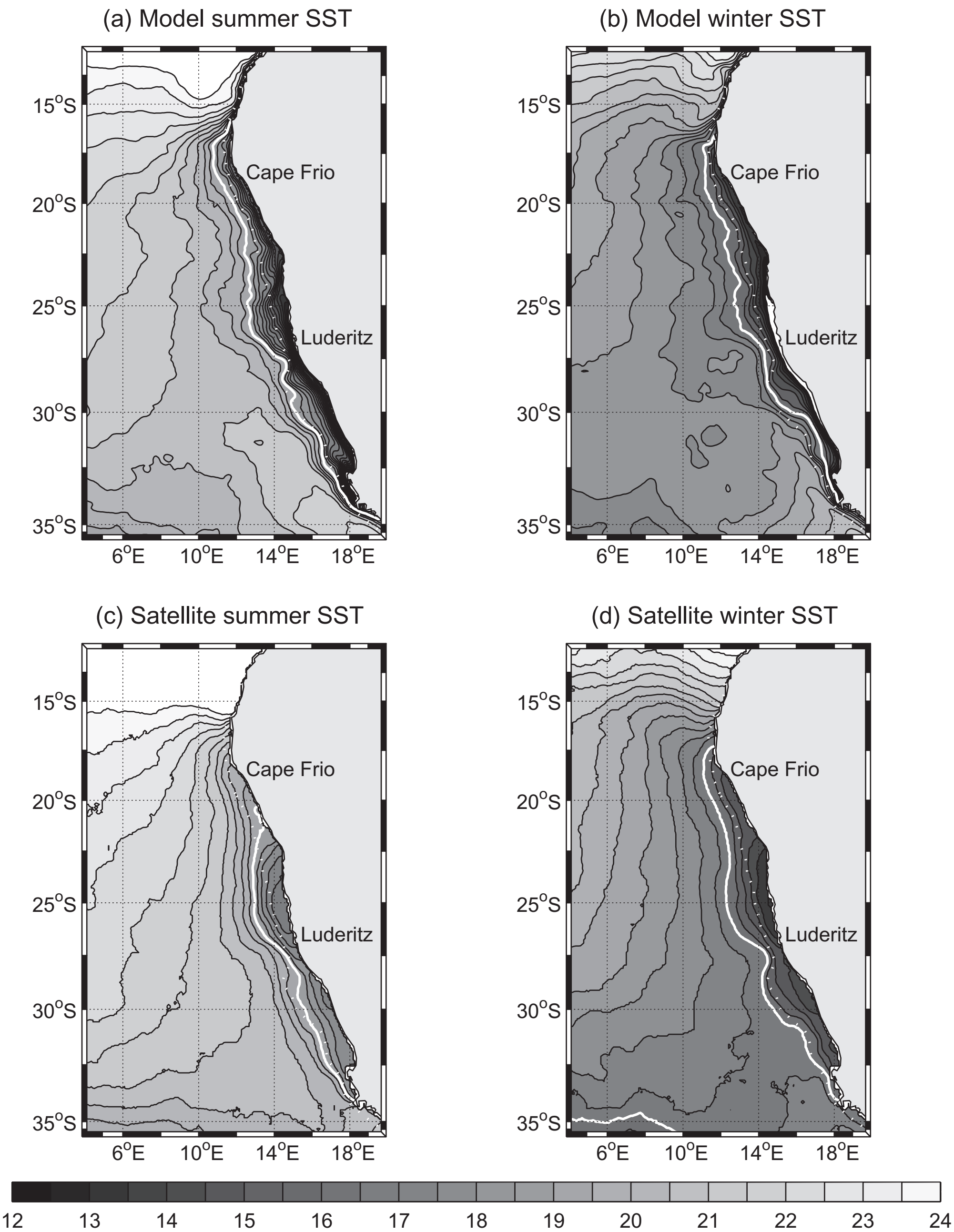

Fig. 1. Summer and winter mean SSTs, based on model-derived (a and b) and satellite data (c and d). The solid white lines represent the approximate position of the upwelling front, taken as the most appropriate isotherm during summer and winter months (19 °C and 15.5 °C, respectively). The dotted while line represents the position of the shelf-edge. Contour interval is 0.5 °C.

meridional velocity. As a transport function, the equation can be written as follows:

$$-\beta \frac{\partial \psi}{\partial x} = \frac{\nabla \times \tau}{\rho_0} \quad (1)$$

where β is the change of the Coriolis parameter with latitude, Ψ is the transport function (in $m^3\ s^{-1}$), τ is the wind stress, ρ_0 is the reference density of seawater, taken to be 1024 kg m^{-3}.

Fig. 2b is a plot of the transport streamfunction (for the upper-1000 m active layer) as derived from the Sverdrup relation and reveals the background flow regime that would be induced by the curl of the wind stress alone. It gives a convincing impression that the poleward flow in the northern Benguela and its offshore advection in the vicinity of Lüderitz is indeed a product of the Sverdrup relation (Eq. (1)), forcing an average southward flow in the upper-1000 m at the eastern boundary of the order of ~2 cm s^{-1}. Flow induced by the Sverdrup relation in the southern Benguela is likely to be masked by the relatively strong northwestward flow of the Benguela Current and the influence of eddies passing from the Indian Ocean into the south Atlantic Ocean.

3.2. Upwelling regime

The bold line in Fig. 3a gives an indication of the alongshore variability in annual mean upwelling intensities, based on model-derived annual mean upward volume fluxes (per kilometer of coastline) across 25 m depth, within approximately 30 km of the coast. Upwelling intensity along the coast is far from contiguous,

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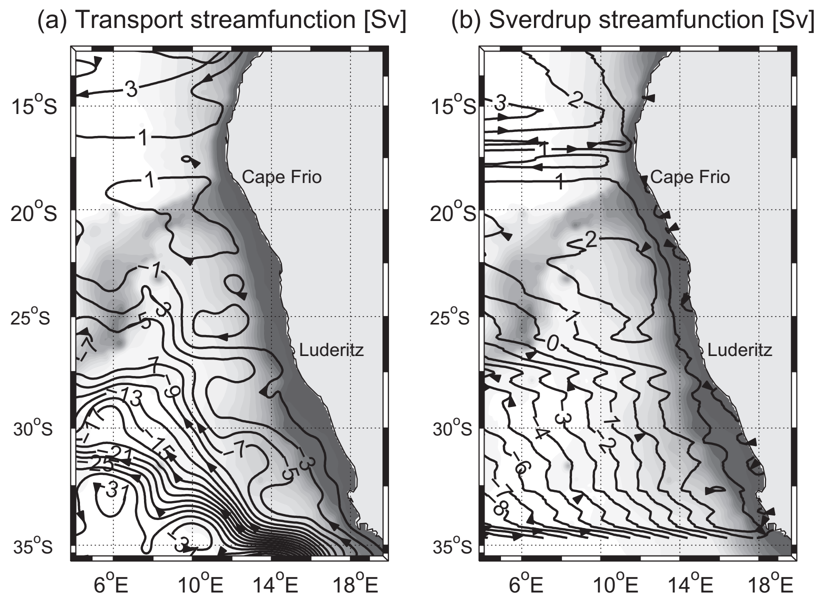

Fig. 2. (a) Transport streamfunction (in Sv: 10^6 m^3 s^{-1}) based on model-derived depth-integrated (0–1000 m) vertical velocities with bathymetry shaded in grey. (b) Streamfunction based on Sverdrup relation (in Sv: 10^6 m^3 s^{-1}) with bathymetry shaded in grey. Contour interval = 2 Sv.

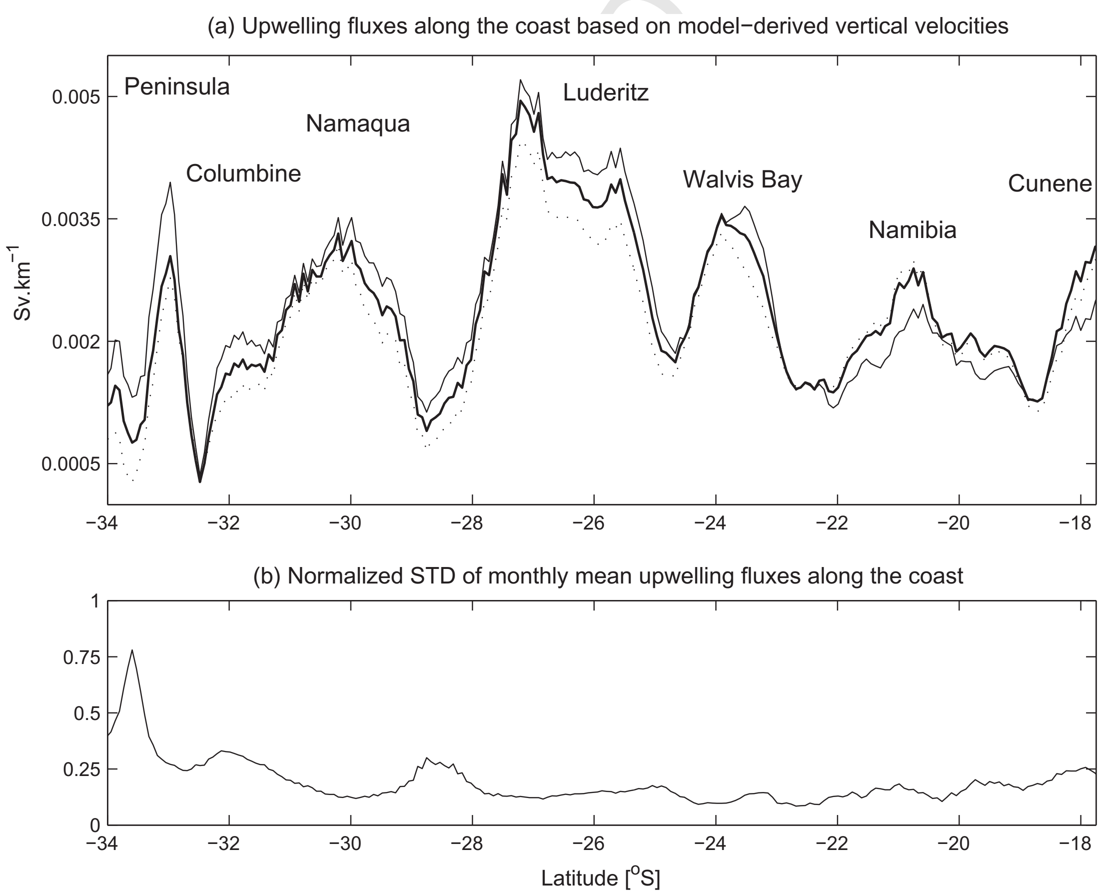

Fig. 3. (a) Model-derived upwelling fluxes per kilometer of coastline (Sv km^{-1}) from 34°S to 17.75°S. The annual mean, summer mean and winter mean fluxes are shown in the bold, solid and dotted lines, respectively. The normalized seasonal mean standard deviation is shown in (b).

but instead is characterized by a number of cells of enhanced activity that are associated with similar fluctuations in the nature of the alongshore wind, which on the smaller scale is related to the orientation of the coastline. With the use of satellite-derived SST maps Demarcq et al. (2003) similarly observed the fragmentation of the Benguela upwelling system into separate cells and they also noted that near Lüderitz was the region of most intense upwelling in the Benguela system and is consistent with our model results (refer to Fig. 3a). Seven distinctly separate upwelling cells can be discerned in the model data, with peaks at approximately 33°S, 30°S, 27.5°S, 24°S, 21°S and 17°S, which can be assigned the naming convention of Lutjeharms and Meeuwis (1987): Columbine, Namaqua, Lüderitz, Walvis Bay, Namibia and Cunene cells, respectively. Demarcq et al. (2003) showed that the highly active Lüderitz upwelling region is somewhat paradoxical due to its very low concentrations of chlorophyll and therefore, productivity (Demarcq et al., 2007), while the less intense upwelling cells to the north and south of this are highly productive and support important demersal and pelagic fisheries (Hutchings, 1992). Fig. 3b is the normalized seasonal standard deviation (i.e. STD/mean) of upwelling fluxes along the southern African coast from 34°S to just north of 18°S. It reflects the fact that the seasonal upwelling signal is strongest in the southern Benguela and decreases toward the north, with a slight increase in the far north. The solid and dotted lines in Fig. 3a represent the summer and winter mean upwelling fluxes and show that the five southern-most cells (Peninsula, Columbine, Namaqua, Lüderitz, Walvis Bay) experience greatest upwelling during summer, while the two northern-most upwelling cells (Namibia and Cunene) are most vigorous during winter.

Table 1 summarizes the annual mean upwelling rates and fluxes for each of the cells. The Lüderitz cell is the most vigorous, with an annual mean total upwelling flux of 1.34 Sv and a corresponding upwelling rate of 11.7 m day^{-1}. While the annual mean upwelling rates and volume fluxes inherently underestimate (overestimate) maximum (minimum) upwelling intensities, this is particularly true for the three upwelling cells to the south of Lüderitz that have the greatest seasonal standard deviations. However, the annual mean upwelling fluxes and rates in the southern Benguela upwelling region provide a gauge from which to quantify and compare the equilibrium state and are 1.2 Sv and 5.2 m day^{-1}, respectively. Lower seasonal variability in the three northern-most upwelling cells provides a somewhat more meaningful annual mean upwelling flux and rate estimates of 2.04 Sv and 7.8 m day^{-1}.

Based on the differences in seasonal-phasing, the Lüderitz upwelling cell may be thought of as separating the more perennial northern Benguela region (with slight upwelling maximum during winter) from the strongly seasonal southern Benguela region (with peak upwelling during summer). The seasonal-phasing of the different regions of the Benguela upwelling system is commensurate with the seasonal shift of the South Atlantic Anticyclone (SAA) that moves northwestward in autumn and southeastward in spring (Preston-Whyte and Tyson, 1993). The northward shift of the SAA in winter results in the dominance of a westerly wind regime in the southern Benguela, but does not affect the approximately perennial upwelling-favourable winds in the northern Benguela.

3.3. Eddy kinetic energy (EKE)

As one of the world's four major eastern boundary upwelling systems, the Benguela is unique in that low variability on the shelf is juxtaposed by exceptionally high variability further offshore (see Capet et al., 2008). For example, the California system typically has nearshore variability (measured as EKE) of the order of 40 cm^2 s^{-2}, increasing to ~120 cm^2 s^{-2} further offshore. In striking contrast to this the inshore and offshore variability of the Benguela ranges from ~10 cm^2 s^{-2} to in excess of 500 cm^2 s^{-2}, respectively (Capet et al., 2008). This dichotomy is particularly true of the southern Benguela regime, which is subject to the influence of passing Agulhas rings and associated features in the region that has come to be known as the 'Agulhas Corridor ' (Garzoli and Gordon, 1996) or the 'Cape Cauldron' (Boebel et al., 2003).

EKE is used as a measure of variability and is calculated, throughout the water-column, from model-derived zonal and meridional velocities. Fig. 4 shows cross-shelf EKE sections typical of the northern and southern Benguela regimes (at 22°S and 32°S, respectively). In stark contrast to, for example, the Californian Current system (see Fig. 7 in Marchesiello et al., 2003), both the northern and southern Benguela regimes are characterized by isolines of EKE that tend toward a vertical orientation, extending to depths of at least 1000 m. This EKE structure is commensurate with a rather steep and deep-reaching offshore gradient of EKE presenting a, possibly important, mechanism for cross-shore exchanges in both the northern and southern regimes.

Although the EKE structures of the northern and southern Benguela systems share the distinction of steep offshore gradients, differences between them are striking. The 100 cm^2 s^{-2} isoline is shown in bold in Fig. 4 and provides a useful measure from which to compare the two regimes. At the surface in the northern Benguela, EKE's of 100 cm^2 s^{-2} and higher are found more than 250 km offshore, while the same measure of variability can be found as close as 100 km offshore in the southern Benguela. The low EKE's at the coast for both the northern and southern regimes are of similar magnitude (~5 cm^2 s^{-2}), thus resulting in offshore surface gradients of 0.38 cm^2 s^{-2} km^{-1} and 0.95 cm^2 s^{-2} km^{-1}, respectively. Higher EKE's extend deeper in the southern Benguela and are potentially related to the barotropic nature of passing Agulhas rings (which have been observed to extend to at least 1600 m depth (Schmid et al., 2003) that abut against the shelf-break, some 200 km offshore, resulting in relatively high EKEs at the shelf-break at depths of 500 m to at least 1000 m. While Agulhas rings are deep-reaching features, they are surface intensified (e.g. see Fig. 6.18 in Lutjeharms, 2006) and therefore result in the surface enhancement of EKE in the southern Benguela.

4. Conclusions

The different characteristics of the northern and southern Benguela regimes and the very distinct nature of their divide presents a natural laboratory and provides the opportunity for a systematic comparative study of different eastern boundary upwelling regimes within one system and within one simulation. Depth-integrated, large-scale circulation patterns of the Benguela system give a convincing impression of separate regimes. The poleward flow of the northern regime meets the stronger, more meandering equatorward flow of the southern regime in the vicinity of Lüderitz where the dominant transport is offshore and upwelling rates and fluxes are the highest and, for this reason, has long been considered the division between the northern and southern Benguela upwelling regimes. Greatest seasonal variability in upwelling intensities occur south of Lüderitz and particularly in the far south, with greatest fluxes during summer. Although seasonal variations decrease toward the north, upwelling intensifies somewhat during winter. The Benguela system in general is unique in its juxtaposition of low variability on the shelf and very high variability further offshore. Though both the northern and southern Benguela regimes are rather unique in this regard, the offshore gradient in EKE is far more intense in the south, reflecting the influence of features associated with the termination of the Agulhas Current. Dif-

Table 1
Model-derived annual mean volume fluxes (in Sv: 10^6 m^3 s^{-1}), upwelling rates (m day^{-1}) and normalized standard deviation (STD) for each of the five upwelling cells resolved by the model simulation.

Upwelling cell	Cun.	Namib.	WB	Lüd.	Namq.	Colum.	Penin.
Length (km)	198	543	278	401	467	120	111
Vol. flux (Sv)	0.47	0.87	0.7	1.34	0.93	0.2	0.07
Rate (m day^{-1})	8.8	6.4	8.3	11.7	7.4	6.3	2
Seasonal STD	0.14	0.09	0.08	0.13	0.18	0.31	1.06

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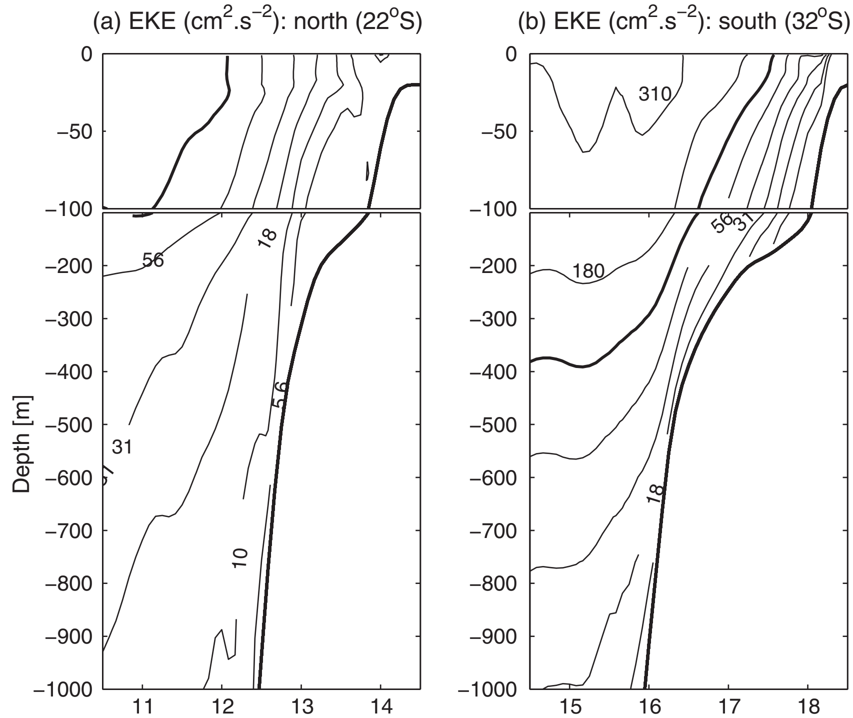

Fig. 4. Model-derived annual mean eddy kinetic energy sections typical of: (a) the northern Benguela (at 22°S) and (b) the southern Benguela (at 32°S). Units in cm^2 s^{-2}. The 100 cm^2 s^{-2} contour is shown in bold.

ferences in the offshore EKE gradients of the two regimes are likely to have different implications for cross-shore exchanges of water properties in these regions.

Perhaps the most unique feature of the Benguela system is the fact that its southern boundary is one of the only places in the world that can be described as a meeting place of eastern and western boundary current systems, resulting in the very high offshore gradients of variability in this region. As opposed to the advection of high EKE in the offshore region of the Benguela via Agulhas rings and eddies, the primary source of EKE in the other three major eastern boundary systems (California, Peru and Canary) is associated with upwelling centers (Capet et al., 2008). Marchesiello et al. (2003) demonstrated that while the main source of EKE nearshore in the California Current system was split between barotropic and baroclinic conversions, offshore it was dominated by baroclinic conversions, thus suggesting that offshore EKE is not only a result of advection of nearshore sources. In other ways, the Benguela system exhibits similarities with other eastern boundary current systems. For example, Sverdrup dynamics appear to drive the large-scale flow regime of the California system (Marchesiello et al., 2003) as well as the Peru system (Penven et al., 2005). Upwelling-favourable winds are strongest during summer along the Californian coast and, similar to the Benguela system, greatest seasonal variability occurs poleward of ~40°S (Marchesiello et al., 2003).

While research of the Benguela upwelling system goes far back, the model simulation on which this work is based, provides the first opportunity to study salient features of the system in a spatially and temporally cohesive manner at a high enough resolution to capture nearshore dynamics. It has allowed us to characterize features definitive of the northern and southern regimes and to investigate the extent to which they are regarded as distinctly separate systems. The northern and southern regions of the Benguela provide an opportunity to compare two separate regimes within one system and within one simulation. This discussion served to highlight the separation of the Benguela into distinct regimes and is presently being extended into a more thorough analysis of equilibrium dynamics of the contrasting regimes as well as intrinsic, mesoscale variability of the system in general.

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