PRELIMINARY INTER-MODEL COMPARISON OF THE AGULHAS CURRENT WITH DIRECT RANGE DOPPLER VELOCITY ESTIMATES FROM ENVISAT'S ADVANCED SYNTHETIC APERTURE RADAR

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ABSTRACT

The greater Agulhas Current is a highly dynamic regime that is known to have significant influence on the local marine environment and ecosystem. It is also recently recognized to play an important role in the global thermohaline circulation, notably due to the transport of heat and salt from the Indian Ocean via the South Atlantic to the North Atlantic. In these contexts, advances in the quantitative understanding of the dominant processes and variability within the greater Agulhas Current is of great importance. In this paper we compare direct surface velocity estimates from Envisat's Advanced Synthetic Aperture Radar with surface velocity fields obtained from two different numerical ocean models. In particular, we focus on the models' performance in the Agulhas Current core at simulating both the strength of the upper layer current as well as the degree of topographic steering. Preliminary findings reveal that the models distinctly underestimate the surface current, while evidence of topographic steering is only satisfactory in one of the models. In turn, we hypothesize that the simulation of the variability and eddy shedding in the retroflection region may be incorrect.

1. INTRODUCTION

The Agulhas Current has been described as the strongest western boundary current in the world's ocean [11]. It flows poleward along the eastern coast of southern Africa from about 27° to 40°S, where it retroflects, sheds eddies into the South Atlantic, and for the most part returns eastward back into the South Indian Ocean. The Agulhas Current core is strongly steared by topography, closely following the continental shelf, which in the north is very steep and lies very close to the coast. In this region the Agulhas is very stable, meandering less than 15 km from its mean path [9]. Observations from a current meter mooring near 32°S have shown that the current lies within the 31 km from the coast almost 80% of the time, displaying surface currents up to 200 cm.s^{-1} [4]. At 35°S the continental shelf separates from the coast, and while the current still follows the shelf edge southwestward along the Agulhas Bank, the current is allowed to become more unstable and begins to exhibit numerous meanders, plumes and eddies [12].

Over the past few years, high performance computing has advanced to a stage where it has become possible to integrate ocean general circulation models that resolve high resolution temporal and spatial scales, important for understanding the mesoscale variability of the ocean, over long periods. Modelling the Agulhas Current system at such high resolutions is a challenging task, in particular in the very energetic and chaotic retroflection region. Developing model simulations useful for both research and operational activities, requires rigorous validation of the model fields, comparing their output to in-situ and satellite remote sensing observations. In this regard satellite altimetry has played a very important role. Satellite altimetry observations are regularly used to validate ocean general circulation models, and it is the only long-term data set describing the global ocean circulation. The data are also routinely used in data assimilation schemes for operational ocean models. However, near coastal regions, satellite altimeter measurements are hampered by various factors, including atmospheric corrections, inaccuracies of the tidal models, land contamination, as well as limitations of the knowledge of the geoid [18, 23]. In particular in its northern parts, the proximity of the Agulhas Current to the coast make it very difficult to use altimetry to study the region. Furthermore, recent comparisons of satellite altimetry and synthetic aperture radar derived currents show that the altimeter data still drastically underestimates the velocity magnitudes of the Agulhas Current [7, 18]. This has significant implications considering that altimetry data is routinely assimilated into operational ocean models.

In this study the output from 3 model simulations is compared to current velocity estimates of the Agulhas derived from satellite altimetry and from Envisat's Advanced Synthetic Aperture Radar (ASAR). Two types of models are used: the Hybrid Coordinate Ocean Model (HYCOM), and the Regional Ocean Modelling System (ROMS).

2. DATA AND METHODS

The focus for this study is the greater Agulhas system from 16°-35°E and 23°-43°S, which includes the Agulhas Current core, the retroflection, and the return current. Surface current velocities derived from ASAR and gridded altimetry data are compared, and further used in validating the model simulations. The vertical structure of the model simulations are then investigated to identify the potential cause of the differences observed between the various simulation experiments.

2.1. Retrieving current velocities from ASAR

Envisat's orbit is -15° from North, and the ASAR is a side-looking imaging instrument by which high resolution, O(10m), images of the ocean surface, perpendicular to the satellite track (the range direction), can be obtained. It is an active instrument, which operates at microwave frequencies, and therefore has the ability to "see" through clouds by day and night. ASAR measures sea surface roughness of the same length scale as the radar frequency emitted. These are known as Bragg waves, and form on the ocean when winds exceed 300 $cm.s^{-1}$. The radar backscatter measured by ASAR is primarily determined by the Bragg scattering, which is a function of the Bragg wave length, the radar wavelength, and the incidence angle. The backscatter from the sea surface roughness is registered by ASAR in both amplitude and phase, and is influenced by winds, waves, currents, surface film – such as biological matter or oil, and sea ice [17].
Recently, a new methodology has been proposed by which surface current information in the range direction may be derived from ASAR [6].

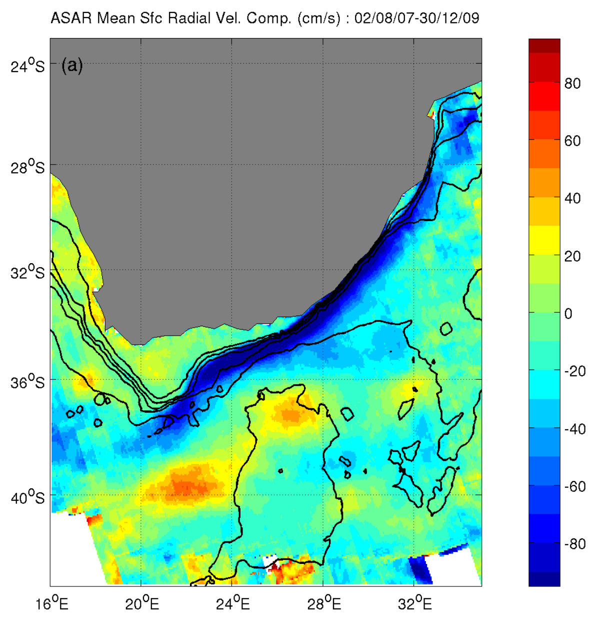


Figure 1. Time-average map of ASAR range velocities from 2007-2009. The 200, 500, 1000, 2000 and 4000 m isobaths are plotted in black.

It uses the Doppler centroid estimates provided by the European Space Agency (ESA) in the metadataset of the ASAR Wide Swath Medium (WSM) resolution images. These data are now regularly processed for the Agulhas Current region at the Collecte Localisation Satellites (CLS). The Doppler centroid anomaly needs to be carefully adjusted for variations induced by instrumental or signal processing errors, as well as for the influence of wind, waves and currents on the mean motion of the sea surface roughness elements. Recent studies deriving ocean surface velocity estimates from ASAR [7, 10] have yielded promising results in determining the range-directed surface current velocities, with and rms error equivalent to approximately 20 $cm.s^{-1}$. The Agulhas Current region is well suited to surface current measurements from ASAR as the mean direction of the current is roughly aligned with the ASAR derived range velocity.
The method of deriving ocean surface currents from ASAR has been thoroughly evaluated for the Agulhas Current region [18]. Based on the present understanding of the Agulhas Current, it was shown that for radar incidence angles greater than 30°, the time-averaged map of ASAR range velocities (Fig. 1) is able to estimate the mean position and intensity of the Agulhas Current very well. Note how the Agulhas Current core follows the 1000 m isobath, in particular along the Agulhas Bank, south of Africa.

2.2. Current measurements derived from altimetry

Inferring properties of the ocean circulation from sea level measurements requires the use of geostrophic approximation as well as a detailed knowledge of the Mean Dynamic Topography (MDT). The MDT, which is the difference between the mean sea level and the geoid, represents the influence of permanent currents on the sea surface height. By combining the MDT with sea level anomalies (SLA) routinely measured by altimetrers, it is possible to re-create the absolute geostrophic current field. Nearly two decades of altimetry-based observations of the sea surface height are now available and these altimetry datasets are routinely used to study the ocean circulation, validate ocean models, and in data assimilation schemes for operational systems. Merged data of absolute geostrophic current velocities are readily available from Ssalto / Duacs and are distributed by Aviso with support from the Centre National d'Etudes Spatiales (CNES, www.aviso.oceanobs.com). The gridded absolute geostrophic velocity product presently distributed by Aviso combines the SLA measurements with the MDT from Rio05 [15]. More recently, an improved MDT was released (Rio09, [16]), which is computed in a similar manner to Rio05, but incorporates an improved estimate of the geoid (using 4½ years of GRACE data), an updated dataset of drifting buoy velocities (1993-2008)

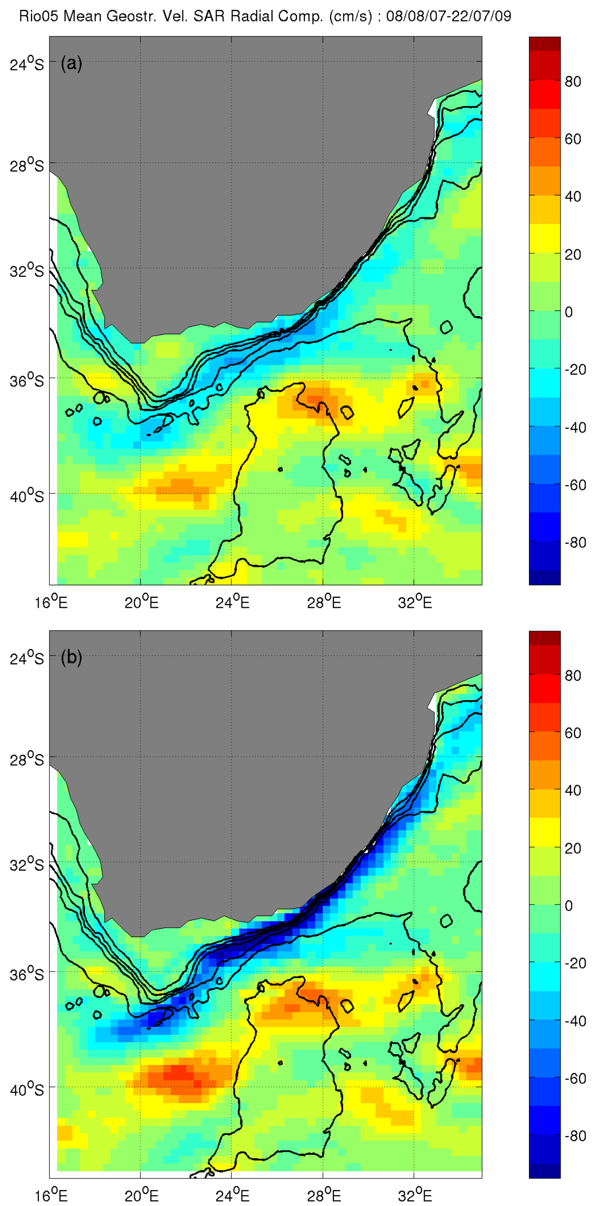


Figure 2. Time-average maps of geostrophic current estimates from 2007-2009, combining altimetry SLA observations with the Rio05 MDT (a), and the Rio09 MDT (b). The 200, 500, 1000, 2000 and 4000 m isobaths are plotted in black.

and dynamic heights (1993-2007), as well as ARGO data. Finally, the estimate of the Rio09 MDT was done on a ¼° resolution grid, compared to the ½° for Rio05.

Fig. 2 shows the geostrophic currents estimated for the Agulhas region by combining SLA measurements for 2007-2009 with the Rio05 MDT (Fig. 2a) and with the Rio09 MDT (Fig. 2b). In both cases the geostrophic current velocities are rotated by 15° to conform with the range direction of the observed velocities observed from ASAR.

Compared to the velocity estimates from ASAR, the resulting geostrophic current estimates for the Agulhas Current using the Rio05 MDT underestimates the current velocity by up to 135 $cm.s^{-1}$. The underestimate is significantly improved when the geostrophic current velocities are calculated by combining altimetry data with the Rio09 MDT for the same period. The underestimate is reduced to 20-60 $cm.s^{-1}$.

2.3. Ocean models

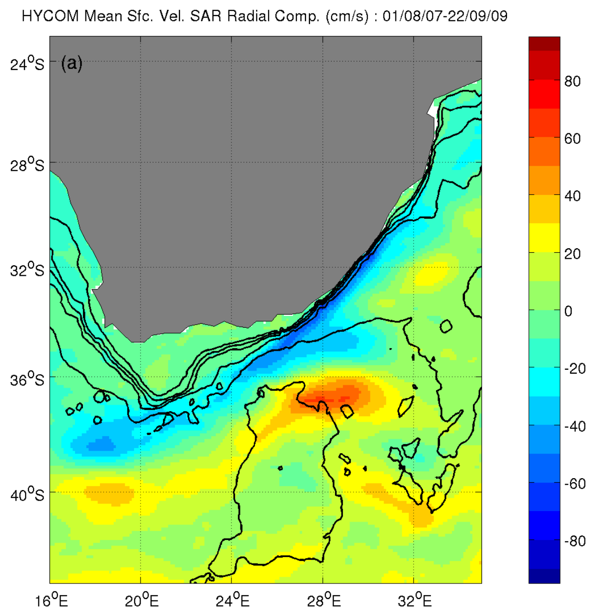
Two types ocean general circulation models of the Agulhas Current are used in this study: HYCOM, which is a layered ocean model, and ROMS, which is a fixed-grid ocean model. Details of the 3 model simulations (1 for HYCOM, 2 for ROMS) are provided in Tab. 1.

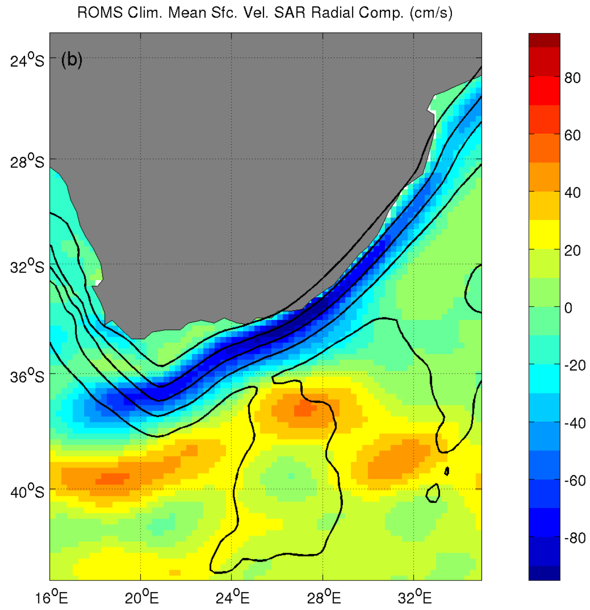
HYCOM combines the optimal features of isopycnic-coordinate and fixed-grid ocean circulation models in one framework [3]. By transforming the finite difference equations into isopycnal space, potential density becomes the independent variable instead of depth, making it easier to satisfy adiabatic constraints of temperature and salinity when estimating their lateral flow. Therefore, in theory, the solution should be more accurate. In such models, no spurious diapycnal mixing occurs due to the numerical representation of advection, rather it can be added in a controlled form. The name “hybrid” is derived from the models ability to efficiently change from isopycnal to cartesian coordinates when needed. The adaptive (hybrid) vertical grid conveniently resolves regions of vertical density gradients, such as the thermocline and surface fronts. An eddy resolving HYCOM simulation of the Agulhas region has been thoroughly validated previously using predominantly satellite altimetry measurements of the region [1].

ROMS is a stretched grid σ-coordinate ocean model, meaning that its vertical layers follow the shape of the ocean bathymetry [20, 21]. The model was originally

	HYCOM	ROMS SAfE	ROMS Agulhas Bank
Domain	0°-60°E 10°-50°S	2.5°W-55°E 5°-47°S	11°-26°E 27°-39°E
Horizontal resolution	1/10°	1/4°	1/12°
Vertical layers	30	32	32
Horizontal forcing	ECMWF	QuickSCAT COADS Sfc Flx	QuickSCAT COADS Sfc Flx
Lateral boundary conditions	India HYCOM	Levitus World Ocean Atlas	SAfE
Data period	1996-2009	Climatology	Climatology

Table 1. Details of the model simulations used in this study.





developed for high resolution process studies, and the stretched coordinates allow for increased resolution in areas of interest, such as the thermocline and bottom boundary layers. The terrain following coordinates avoid spurious effects associated with discontinuous (step-wise) representation of bathymetry. The ROMS configuration known as the Southern Africa Experiment (SAfE, [14]) was designed to capture the salient oceanographic features around southern Africa.
The model also provides lateral boundary conditions to higher resolution models nested within the SAfE domain, as is the case for the limited areas model of the Agulhas Bank [5].

3. MODEL – ASAR VELOCITY COMPARISON

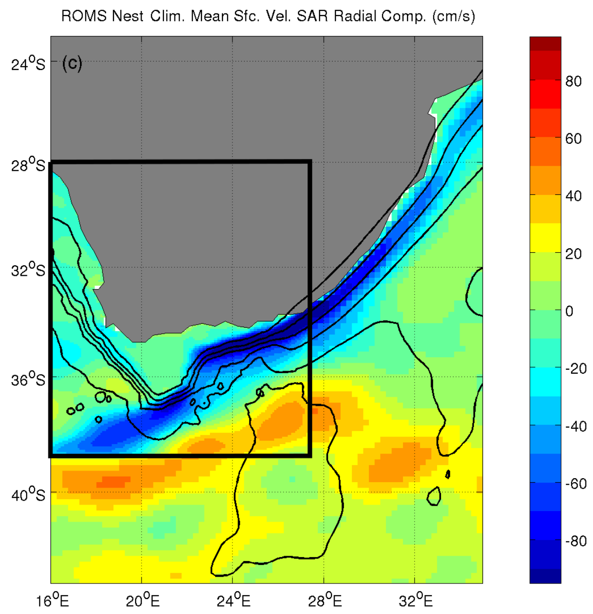


Figure 3. Time-average maps of model surface velocities rotated by 15° to conform with ASAR range velocities. (a) HYCOM from 2007-2009, (b) ROMS-SAfE configuration climatological run, and (c) ROMS-Agulhas Bank nest climatological run. In each case the 200, 500, 1000, 2000 and 4000 m isobaths are plotted in black.

Fig. 3 provides the time-averaged surface velocities simulated in each of the 3 model simulations described in Tab. 1. In each case the velocities were rotated by -15° (from North) to conform with the range velocities derived from the ASAR measurements (Fig. 1).
From these comparisons, it is evident that the 1/10° (~10 km) HYCOM (Fig. 3a) significantly underestimates velocities in the Agulhas Current core, with maximum poleward range velocities only reaching 64 $cm.s^{-1}$, compared to the 166 $cm.s^{-1}$ estimated from ASAR. Furthermore, following the separation of the continental shelf from the coast near 26°E / 34°S, the Agulhas Current core in HYCOM tends to follow the 4000 m isobath on it southwestward path toward the southern termination of the Agulhas Bank, south of Africa. The ASAR observation suggest that the current should rather follow the 1000 m isobath.
The SAfE configuration of ROMS (Fig. 3b) simulates a much stronger Agulhas Current core, with mean poleward range velocities reaching 100 $cm.s^{-1}$, which is an improvement but still significantly slower than observed from ASAR.
Furthermore, qualitatively, the topographic stearing of the Agulhas along the Agulhas Bank in ROMS seems to be in better agreement with the observations. However, it should be noted that the bathymetry in SAfE is unrealistically smoothed due to the low resolution of the model (1/4°, ~25 km).

The high resolution (1/12°, ~9 km) nested model of the Agulhas Bank (Fig. 3c), which receives its lateral boundary conditions from SAfE, has much more realistic bathymetry. In this simulation the southwestward path of the Agulhas Current is in very good agreement with the ASAR observations. Furthermore, the maximum poleward range velocities reach up to 120 cm.s^{-1}, yet a further improvement.

The above comparison implies that for the Agulhas Current region, a σ-coordinate ocean model provides a superior simulation of the strongly topographically steared Agulhas Current. Two questions arise: (1) why does the Agulhas Current in HYCOM tend to follow the 4000 m isobath, and (2) for what reason is the Agulhas Current core so much weaker?

4. MODEL COMPARISON OF THE VERTICAL STRUCTURE IN THE AGULHAS

To investigate the differences in the topographic stearing between the model simulations, a meridional section was defined at 26°E, along which the vertical velocities normal to the section were extracted from the 3 model simulations (Fig. 4).

In HYCOM (Fig. 4a), maximum poleward velocities exceeding 70 cm.s^{-1}, are found between 100 and 200 m depths, not at the surface. The core of the Agulhas Current lies approximately at 35°S, in line with the 4000 m isobath.

In the SAfE configuration of ROMS (Fig. 4b), maximum velocities exceeding 90 cm.s^{-1} lie upward of a depth of 100 m, and are located at approximately 34.5°S, in line with the 1000 m isobath. Furthermore, the vertical structure of the Agulhas Current in ROMS is in much better agreement with the vertical velocity profile observed from a year-long mooring southeast of Durban near 32°S [4]. The latitudinal position of the Agulhas Current core in the high resolution nested ROMS of the Agulhas Bank is similar to that of SAfE, with the difference that stronger velocities, exceeding 100 cm.s^{-1}, are simulated above 100 m depth. The current itself is also narrower and relatively strong velocities extend to deeper depths compared to SAfE, displaying a sharper 'V'-like structure. Overall ROMS provides a much better vertical profile of the Agulhas Current, compared to HYCOM.

The fact that the Agulhas Current in HYCOM is further from the continental shelf edge than in ROMS, may be related to a relatively strong undercurrent (up to 10 cm.s^{-1}) flowing equatorward, pressed closely against the continental slope, and extending from 100 to 2000 m. This undercurrent seems to push the Agulhas offshore. An Agulhas Undercurrent has been measured at 1200 m, with northeastward velocities exceeding 20 cm.s^{-1} [2], but not extending upward to a depth 100 m. In SAfE no undercurrent is evident, which likely has to do with the coarse resolution of the model. However, in the high resolution nest over the Agulhas Bank, an undercurrent is present at depths greater than ~1000 m, but not extending upward to shallower depths as in HYCOM.

Comparing the vertical layer distribution of the 3 model configurations, it is apparent that both ROMS models have a better, or more even, distribution of the vertical layers, while in HYCOM most of the layers are in the upper 200 m, and only 7 layers remain to simulate the remainder of the water column. Furthermore, the layers in the upper 200 m predominantly follow z-level coordinates. This suggests that the reference densities assigned to the individual isopycnal layers in HYCOM are inadequate for the Agulhas region.

Potential densities (σ_0, in kg.m^{-3}) from the World Ocean Circulation Experiment (WOCE) line I6, which extends southward from South Africa at 28°E, and crosses the Agulhas Current, range from 23.6, in the upper 100 m, to 27.6 kg.m^{-3}, below 2000 m. The reference densities assigned to the isopycnal layers in HYCOM range from 21.0 to 28.3 kg.m^{-3}.

Setting the reference densities in HYCOM to inadequate values may lead to an uneven distribution of vertical layers in the water column. In the present model configuration, too many layers are found within the mixed layer, leaving too few below, which may lead to an inaccurate representation of the Agulhas Current. Furthermore, the crude vertical interpolation scheme applied to the mixed layer in this version of HYCOM (2.1.) is erroneous, which causes enhanced, and artificial, diapycnal mixing within the mixed layer that diffuses the core of the current.

5. CONCLUSIONS AND FUTURE WORK

The ASAR mean range velocity estimates provide a means to assess the strength and variability of the upper layer dynamics. In particular for the Agulhas Current, where it lies close to the coast, and the altimetry measurements are limited and the geoid is not properly resolved.

Comparing the (range) geostrophic current estimates derived from the Rio05 and Rio09 MDTs to ASAR range velocities, shows that geostrophic current estimates for the Agulhas are significantly improved with the use of the new Rio09 MDT.

Comparing the surface velocities of 3 model simulations to ASAR, indicates that all models underestimate the mean velocity in the Agulhas Current. HYCOM simulates significantly weaker currents, a factor of 2.6 weaker than observed from ASAR. Furthermore, ROMS seems to be superior over HYCOM at representing the topographic stearing effect of the Agulhas Current, especially in the southern region.

An assessment of the vertical structure of the Agulhas Current in the model simulations, reveals that the layer distribution in HYCOM is uneven, which is due to the reference densities of the layers in HYCOM being set to inadequate values for the Agulhas region. The result is that too many layers are found in the mixed layer, and too few layers in the deep, leading to an inaccurate representation of the current. The low current velocities in HYCOM are likely due to the crude interpolation scheme applied in the mixed layer, which may act to diffuse the velocities.

This study is a preliminary inter-model comparison of the Agulhas Current. The study requires more consistent model datasets for comparison against the ASAR range velocity estimates, which includes a high-resolution (<1/10°) interannual run of ROMS for the Agulhas domain. The study would also greatly benefit from interannual data from a high-resolution z-level model, such as the model known as the Nucleus for European Modelling of the Ocean (NEMO; [13]) developed by the European DRAKKAR multiscale ocean-modelling project [8].

Furthermore, the use of altimeter along-track data combined with ASAR and SST data for studying the change in the width of the Agulhas Current, and the associated implication for surface current speeds and transports needs to be assessed.

The Agulhas leakage has received increased attention recently, with various modelling studies (e.g. [19, 22]) disagreeing over whether or not a strong or weak Agulhas Current causes an increased leakage. The Agulhas leakage has significant implications for regional and global climate, and models of the region need to be critically assessed and used in combination with observations to address this problem.

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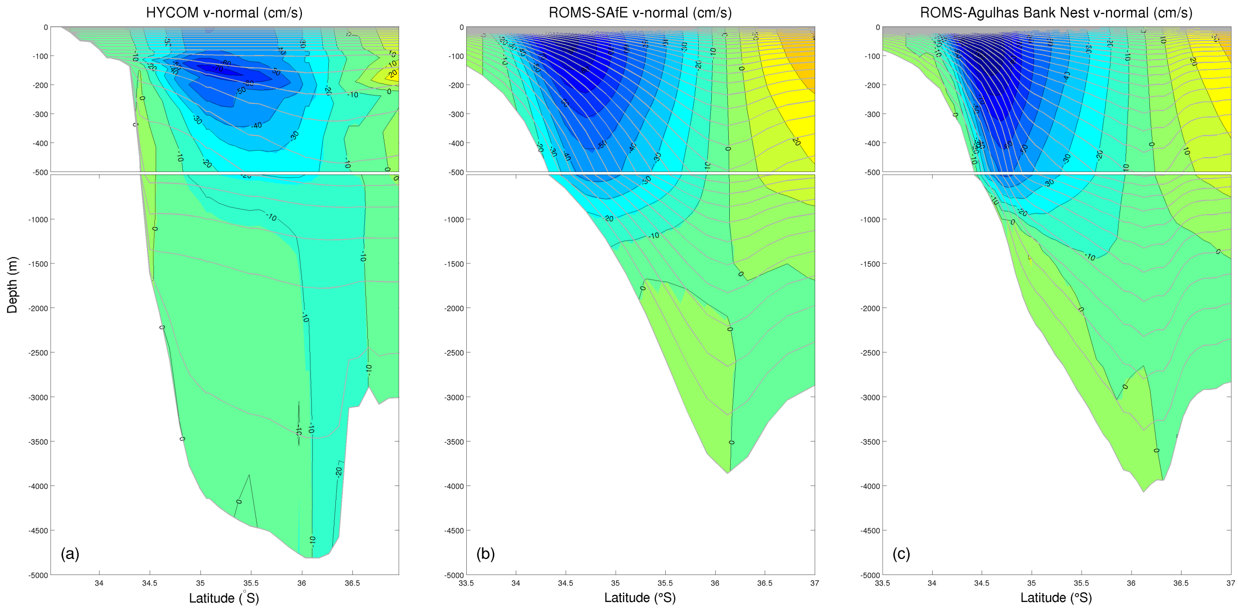

Figure 4. Vertical velocity profiles normal to a meridional section at 26°E, for (a) HYCOM, (b) ROMS-SAfE configuration, and (c) ROMS-Agulhas Bank Nest. Velocities are given in cm.s^{-1} and are negative south- and westward. The grey lines represent the respective model layer interfaces.