The greater Agulhas Current system: An integrated study of its mesoscale variability

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For the purpose of developing an operational oceanography system for the greater Agulhas Current regime, a high resolution Hybrid Coordinate Ocean Model (HYCOM) has been set in a nested configuration. The intense and complex current regime poses a challenge in modelling. However, access to satellite and *in-situ* data with strong and persistent signals of the dynamics and mesoscale variability ensure that adequate model validation is feasible. The study concludes that HYCOM reproduces the general larger scale circulation of the greater Agulhas Current reasonably accurately in addition to the regionally specific characteristics and mesoscale variability. Furthermore, strong anticyclonic eddies occurring in the Mozambique Channel at a frequency of 5–6 per year, are found to drift southward and merge with the northern Agulhas Current. Evidence of these eddies can also be tracked further southwestwards into the southern Agulhas Current and sometimes all the way towards the Agulhas retroflection region. Operational forecasting of the greater Agulhas Current, and in particular the retroflection, must therefore adequately account for the presence and influence of the Mozambique Channel eddies, in order to forecast their evolution on time scales from days to weeks

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BC Backeberg is a PhD student in the Department of Oceanography at the University of Cape Town, South Africa. The PhD study is undertaken in collaboration with the Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography and the Nansen Environmental and Remote Sensing Center in Bergen, Norway. The main aim of the PhD is to demonstrate the readiness in using integrated satellite observations, *in-situ* data and a validated numerical ocean model for operational forecasting of the greater Agulhas Current regime.

INTRODUCTION

The Agulhas Current has been described as one of the strongest western boundary currents in the world's oceans.[27] Forming part of the South-West Indian Ocean sub-gyre, the current flows polewards along the southeastern coast of Southern Africa from 27ºS, eventually retroflecting and flowing eastward back into the South Indian Ocean south of Africa between 40º and 42ºS.[18,38]

The upstream source region for the Agulhas Current has distinct contributions from the flow through the Mozambique Channel, the poleward flowing East Madagascar Current (EMC), and recirculation from the South-West Indian Ocean sub-gyre, which supplies the greater part of the volume transport in the Agulhas Current, ie, 40 Sv of a total 60 Sv in the upper 1000m.[38] The flow in the Mozambique Channel is dominated by southward moving anticyclonic eddies.[33,3,13] These eddies have spatial scales of approximately 300–350km and propagate southwards at speeds of approximately 3–6km/day.[34,35] Concurrently, the EMC retroflects southwest of Madagascar,[36] generating cyclonic and anticyclonic eddies up to 250km diameter.[31] These propagate westwards towards the Agulhas Current.[14] Although the Mozambique Channel eddies and the EMC do not form a continuum with the Agulhas Current, they both affect its dynamics[27] and contribute to the fluxes of volume, heat and salt.

Mesoscale variability in the northern Agulhas Current[19] occurs in the form of intermittent cyclonic meanders, known as Natal Pulses. These form at the Natal Bight, between 29°S and 30°S, where the gentler continental slope and wider shelf present favourable conditions for the occurrence of instabilities and subsequent growth of meanders.[12] Natal Pulses form approximately six times per year and propagate downstream at rates of 10km/day.[23] A further source of variability is the Mozambique Channel eddies. Their propagation into the source region of the Agulhas Current has been confirmed by previous altimetry studies.[3,34] Additionally, their interaction with the Agulhas Current has been shown to influence the timing and frequency of Agulhas ring shedding events at the retroflection. It is suggested[34] this occurs via two mechanisms. Firstly, the southward progressing Mozambique Channel eddies trigger the formation of the aforementioned Natal Pulse, and these are known to precede ring shedding events at the retroflection by approximately 180 days.[42] Secondly, the migration of Mozambique Channel eddies into the Agulhas retroflection region may lead to an early occlusion of the retroflection loop allowing Agulhas Ring shedding to occur.

Numerical models need to adequately resolve the mesoscale dynamics and variability of the greater Agulhas Current regime in order to be considered for use in an operational oceanography system.

In this paper, we demonstrate that the intense dynamics and mesoscale variability of the greater Agulhas Current system act as an excellent natural laboratory for studies using integrated satellite and *in-situ* observations with model simulations. As well as allowing model validation, the integrated approach also ensures advances in process understanding of this complicated current regime. The data sources and model characteristics are described in the next section, followed by an intercomparison of the model simulation results with observations, considering spatial, temporal and drift analyses of the mesoscale variability and dynamics over an 11-year period from 1996–2006. The paper ends with the summary and conclusion.

DATA DESCRIPTION

The strong thermal gradients and sea level anomalies associated with the dynamics and mesoscale variability of the greater Agulhas Current system make it particularly amenable to monitoring via satellite remote sensing observations such as those from radiometry and microwave altimetry. In addition, a comprehensive database of Lagrangian surface drifter data allows complementary quantitative analyses of the surface currents.

Satellite data

Sea surface temperature (SST) observations from the cloud independent Tropical Rainfall Measuring Mission (TRMM) Microwave Imager and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) are used in the model validation process. TRMM follows an equatorial orbit with a 35° inclination, allowing for coverage between 40°N and 40°S, while the National Aeronautic and Space Administration (NASA) Aqua satellite follows a near polar orbit allowing for global coverage. These data are used to calculate optimally interpolated sea surface temperature fields (OI SST) on a daily basis with a spatial resolution of ~25km. The Microwave OI SST data are produced by Remote Sensing Systems and sponsored by National Oceanographic Partnership Program (NOPP), the NASA Earth Science Physical Oceanography Program, and the NASA REASoN DISCOVER Project. Weekly averages have been calculated from the daily data available at www.remss.com.

Moreover, gridded data of sea level anomaly (SLA) and surface geostrophic velocities derived from maps of absolute dynamic topography are used for comparison against the model fields. The gridded data are merged from multiple altimeter missions, namely TOPEX/Poseidon, Jason-1, ERS-1/2, GFO and ENVISAT. They span the time period from January 1996 to December 2006. The data were obtained from the SSALTO/DUACS near-real time and delayed mode multimission altimeter data processing system at Centre National d'Etudes Spatiales (CNES; www.aviso.oceanobs.com). The mapping technique used to produce the gridded maps has been outlined in detail.[15] The gridded data has a horizontal resolution of $^1/_3$° on a Mercator grid, which therefore provides grid-resolution of 24km to 37km in the Agulhas region. These maps are available at weekly intervals.

Surface drifter data

The surface drifter data with drogues at 15m include position and time observations. Archived data from the Global Drifter Program, formerly World Ocean Circulation experiment Surface Velocity Programme (WOCE-SVP), are available from the Marine and Environmental Data Services at Fisheries & Oceans Canada (www.meds-sdmm.dfo-mpo.gc.ca).

Daily average drift velocities were calculated from the successive positions and times given for the individual drifters. The data were then binned into a 1° spatial grid. For the purpose of this study only drifter data for the region of the Mozambique Channel, the Agulhas Current proper, the Agulhas Retroflection and the ring shedding corridor is considered for the period 1996–2006.

Model characteristics and setup

The Hybrid Coordinate Ocean Model (HYCOM) used in this study was developed from the Miami Isopycnic Coordinate Model (MICOM[5]). It is a primitive equation model that smoothly inter-changes the vertical coordinates between z-level coordinates for resolving upper-ocean mixed layer processes, isopycnic in the stratified open ocean, and sigma-coordinates that follow the bathymetry in the shallow coastal regions.[4] The name 'hybrid' is derived from its ability to inter-change between these three vertical coordinate schemes.

The HYCOM system set up to simulate the greater Agulhas Current region involves two models (Fig 1); a coarse resolution, basin-scale model of the Indian and Southern Oceans (INDIA), and a nested, regional model for the Agulhas Current system (AGULHAS). The model grids have been created using conformal mapping tools.[2] The basin-scale model INDIA provides boundary conditions for the regional model of the Agulhas Current. In the region of the greater Agulhas Current, INDIA has a horizontal resolution ranging from 30 to 40km. The nested regional model set up to simulate ocean dynamics and mesoscale variability of the greater Agulhas Current system covers the region from the Mozambique Channel to the Agulhas retroflection and the Agulhas Return Current. The resulting geographical grid extends from approximately 0º to 60º east and from 10º to 50º south (Fig 1). Its horizontal resolution ranges from 9 to 11km, which should adequately resolve the mesoscale dynamics since the first baroclinic Rossby radius of deformation in this region is about 30km.[9] Both models use realistic bathymetry interpolated from the General Bathymetric Chart of the Oceans 1in resolution dataset (GEBCO; www.ngdc.noaa.gov/mgg/gebco).

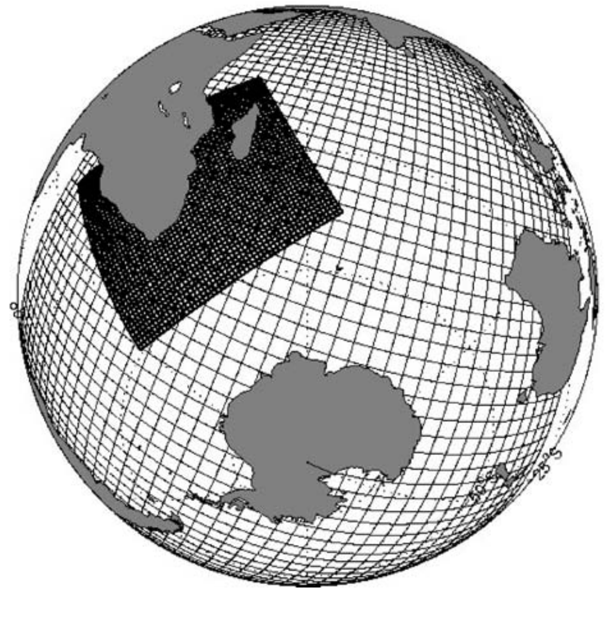

Fig 1: The HYCOM model system. Every tenth grid point was plotted to produce the respective mesh grids, therefore each box consists of 10x10 grid cells. The coarse mesh grid indicates the domain of the parent model grid and the fine mesh grid the nested high resolution Agulhas model

The vertical discretisation in both models uses 30 hybrid layers, with target densities, referenced to σ_0 (=1000 kg.m^{-3}), ranging from 21.0 to 28.3. Neither of the models includes tides.

INDIA was initialised from the Generalized Digital Environmental Model (GDEM[39]) data, and an eight year spin-up period was run to reach equilibrium. The forcing data used during the spin-up period is based on the ERA40 re-analysis data,[41] with a correction applied to dampen the strong precipitation bias in the tropical oceans.[40] The nested AGULHAS model was then initialised from the equilibrium field of INDIA, interpolated to the high resolution grid.

Both models were run simultaneously in a simulation experiment spanning from January 1996 to December 2006. Atmospheric forcing fields for both models were provided at six hourly intervals from a combination of sources; namely, ERA40 at 9/8° horizontal resolution for the period from 1996–2002, followed by the operational analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the remainder of the simulation experiment.

Additional forcing fields include cloud cover data from the Comprehensive Ocean-Atmosphere Data Set (COADS[37]) and precipitation data.[21] The exchange of heat and momentum at the surface is calculated from bulk formulas. River runoff is modelled as a negative salinity flux using the monthly climatologies from Dümenil *et al* and Dai & Trenberth.[16,10] The major rivers in the Indian Ocean basins are included in the INDIA HYCOM simulation.

OBSERVATION-MODEL INTERCOMPARISON

In this section the spatial characteristics of the model surface fields are compared with observations. The discussion is arranged according to passive microwaves, satellite altimetry and surface drifter data.

Passive microwaves

Model validation using the microwave SST fields is shown in Fig 2, where maps of weekly average TMI AMSR-E OI SST (left panel) are compared to maps of weekly HYCOM surface temperatures (right panel) for a period from October to December 2002. The black contours in both panels represent the isotherms 3.4°, 7.0°, 14.2°, 17.9°, 20°, 22°, 25° and 28°C. The first four are selected to respectively represent the mean SST of the Antarctic Polar Front (APF), the Sub-Antarctic Front (SAF), the Sub-Tropical Convergence (STC) and its northern extent derived from ship-board observations.[24]

Comparable large scale surface temperature patterns are found including the southward progression from October to December 2002 of the warm tropical surface water, as represented by the 25°C isotherm, which reaches approximately 25°S in the Mozambique Channel. Moreover, it is apparent that HYCOM simulates the dominant wavelengths

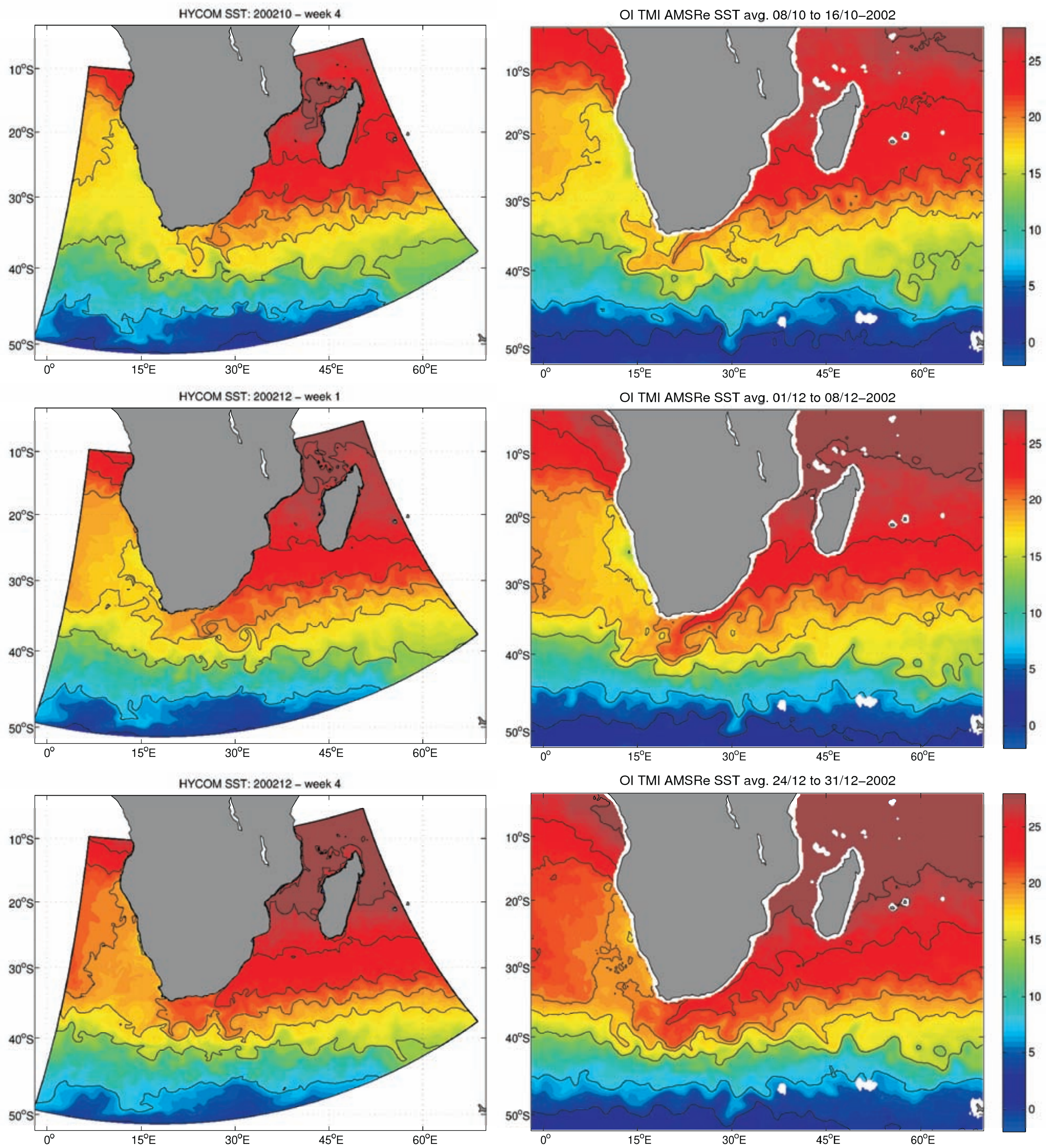

Fig 2: Weekly average sea surface temperature (°C) fields from HYCOM (left panel) and from passive microwave observations from the TRMM Microwave Imager and AMSR-E (right panel). The black contours represent isotherms 3.4°, 7°, 14.2°, 17.9°, 20°, 22°, 25° and 28°C.

of the meandering surface temperature isotherms in reasonable agreement with the observed SST fields.

HYCOM shows a reduced southwestward extent of the Agulhas Current surface temperature signal towards the retroflection region, represented by the 20° and 22°C isotherms. This deficiency may have some implications for accurate simulation of the Indo-Atlantic inter-ocean fluxes of heat and salt.

The Sub-Tropical Convergence (STC) is the northernmost front associated with the Antarctic Circumpolar Current (ACC), and it exhibits the most prominent thermal and salinity gradients both at the sea surface and at depth.[22] The STC surface temperature expression and its northern extent is represented by the zone between the 14.2°C and the 17.9°C isotherms and reveals its meandering nature. The Sub-Antarctic Front (SAF) displays weaker horizontal surface temperature gradients than the STC, and is demarcated by the 7°C isotherm. The Antarctic Polar Front (APF) has a less distinct surface expression with an average middle temperature expression of 3.4°C. The mean latitudinal positions of the STC, SAF and APF as outlined in[24] of 41°, 46° and 50°S respectively agree reasonable well to locations given by the microwave SST. Moreover HYCOM is also able to reproduce agreeable mean latitudinal positions of these fronts in the southern regions except the APF which does not fall within the model domain.

Altimetry

Weekly model surface velocity fields in the AGULHAS HYCOM (Fig 3, left panel), taken from week 4 in October and from weeks 1 and 4 in December 2002, are compared to coincident altimeter-based surface geostrophic velocities (Fig 3, right panel). In this comparison it is found that the altimetry derived velocities may be underestimated by a

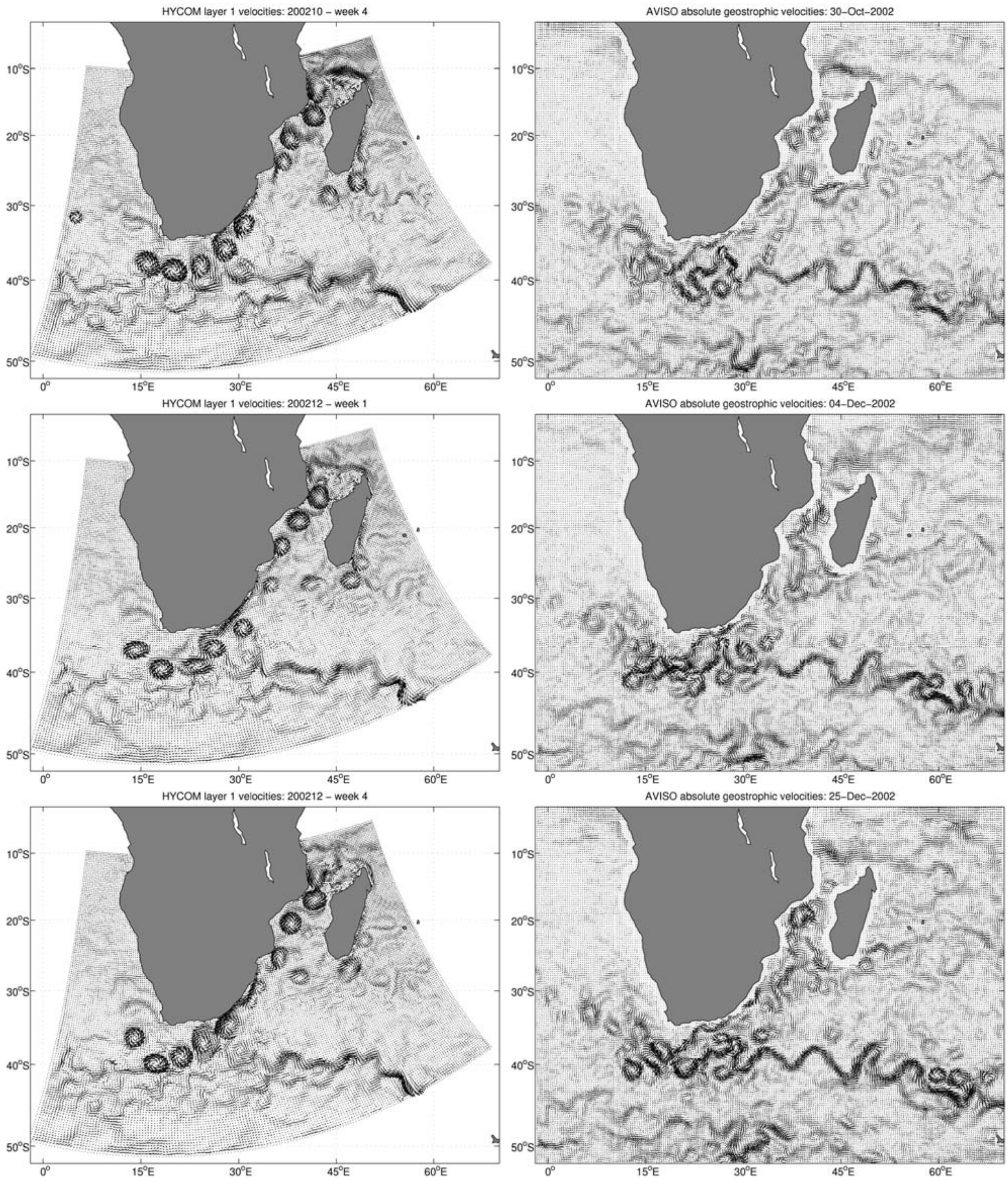

Fig 3: Weekly surface velocities from HYCOM (left panel), and weekly surface geostrophic velocities from AVISO (right panel)

factor of 1.5. This is probably due to the subsampling of the altimeter, and the fact that a geostrophic velocities may contribute substantially to the overall flow. Furthermore, as the altimeter satellite tracks are not consistently perpendicular to the main flow direction of the Agulhas Current, the maximum slope and surface geostrophic current are not always captured. Hence, the more intense model velocity field is not necessarily unrealistic. Overall these comparisons reveal that the observed circulation features in the greater Agulhas Current system are reasonably well simulated in HYCOM.

Both the HYCOM velocity fields and the surface geostrophic velocities suggest that the flow in the Mozambique Channel is dominated by southward propagating anticyclonic eddies, as previously documented.[35] The horizontal scales of the Mozambique Channel eddies simulated in HYCOM are of comparable sizes to those observed from altimetry, and are approximately 300km diameter. However, in HYCOM these seem much more energetic. The model indicates that these eddies tend to form north of the Davies Ridge, near 15ºS, and then move southward along the western edge of the channel. Near 30°S, they appear to merge with the northern Agulhas Current. This behaviour is strongly emphasised in HYCOM (see Fig 3, left panel). Biastoch and Krauss[3] document similar results in their regional model of the Agulhas Current system, and claim that a clear connection exists between eddies in the Mozambique Channel and the Agulhas Current. The consistent merger of Mozambique Channel eddies with the northern Agulhas Current may thus be due to the fact that these eddies are more energetic in HYCOM.

HYCOM shows that the East Madagascar Current (EMC) splits into the northern and southern branches near 17ºS, in agreement with previous literature.[26] Surface velocities from HYCOM in the southern branch reach up to 0.7m/s, with even stronger velocities, up to 1m/s, evident at the northern tip of Madagascar. At the southern tip of Madagascar, the southern EMC reveals a tendency to undertake an anticyclonic return loop. Eddies, episodically detach from this loop and travel westward where they eventually interact with the northern Agulhas Current. As satellite altimetry is unable to capture mesoscale ocean dynamics close to the coast, it neither reveals the EMC split, nor the strong southward flowing ‘mini’ western boundary current. Altimetry does, however, provide evidence of a strong westward flow north of Madagascar and also strongly supports the notion of a retroflecting EMC south of Madagascar with the formation of cyclonic and anticyclonic eddies as discussed.

The main features of the Agulhas Current are well represented in the model. In the north, the Agulhas Current intensifies near 27ºS and closely follows the shelf edge, which lies close to the coast, consistent with observations.[19] Weekly mean surface velocities exceeding 1.5m/s are simulated near the coast between 30ºS and 35ºS in agreement with direct current meter measurements reported.[8] HYCOM suggests that the dominant mode of variability here occurs in association with large anticyclonic eddies, approximately 300–350km diameter, propagating southwestwards from the Mozambique Channel (Fig 3, left panel). Moreover, it seems that these eddies consistently trigger Natal Pulses as they pass the Natal Bight at 30°S. The interaction of Mozambique Channel eddies with the northern Agulhas Current is also evident in the surface geostrophic velocity observations from altimetry. However, upon approaching the northern Agulhas Current, the spatial scales of the eddies in the altimetry observations are smaller than those in the model, and they also display weaker orbital velocities.

The shelf edge separates from the coast near 33°S. As a result, the current is steered away from the coast, becoming increasingly unstable in its mean southwestward path. This growing meandering nature of the southern Agulhas Current is well represented in the surface geostrophic velocity observations from altimetry, as the core of the current is now sufficiently far away from the coast. In comparison, the mesoscale variability in HYCOM is simulated as a succession of southwestward propagating eddies in this region.

In the vicinity of the retroflection region the ocean dynamics become intense and very complex. In the weekly altimeter maps the surface current is observed to retroflect in an anticyclonic loop somewhere near 16ºE and between 39º and 40ºS (Fig 3, right panel) with a diameter exceeding 300km, consistent with previous literature.[28] Complete understanding of the mechanisms that influence and control the retroflection of the Agulhas Current is lacking although a number of theories have been put forward, such as conservation of potential vorticity and inertia (summarised in[11]). In HYCOM, a train of southwestward propagating eddies with diameters of about 200–250km seem to reach the retroflection area, hence supplying mesoscale energy to the complicated dynamics of the region (Fig 3, left panel). This train of eddies extending from the Agulhas Plateau to the retroflection has been a common feature in numerical model simulations of the region. It was first reported by Lutjeharms and Webb[25] using the Fine Resolution Antarctic Model (FRAM). Recently, Barnier *et al*[1] showed that improved numerics, in particular of the momentum advection scheme, clearly improve the numerical simulation of this region. Although the dominant weekly surface velocity pattern induced by this train of eddies masks the position of the retroflection in HYCOM, it is fairly well represented in the longer term mean as addressed later.

Both altimetry and model data reveal that ring shedding events occur at the retroflection. Agulhas Rings are unique, because they form in association with a zonal protrusion of the parent current, and are typically larger than rings formed in association with current and frontal instabilities, such as Gulf Stream or Kuroshio rings.[30] Furthermore, Agulhas Rings form a vital link through which warm, saline water from the Indian Ocean is transported to the Atlantic Ocean.[18]

In HYCOM, predominantly anticyclonic eddies with scales of approximately 300km, can be seen propagating in a general northwesterly direction into the Southeast Atlantic Ocean. The horizontal scales and current intensities of these vortices are somewhat exaggerated. In comparison to the altimetry study,[17] HYCOM fails to simulate the broad fan of eddy trajectories into the Southeast Atlantic Ocean. Fu[17] concluded that eddies in this region propagate in a relatively broad northwestward direction at a mean speed of 3–4 km/day.

The eastward flowing current from the retroflection region between 39°S and 40°S is known as the Agulhas Return Current. HYCOM simulates the mean position of this meandering return current in good agreement with the altimeter observations as well as the satellite SST observations reported above. The semi-permanent meanders, previously documented,[6] are visible in the surface geostrophic velocity fields as well as in HYCOM, with their southern crests evident near 29°E, 35°E and 43°E. The gradual shift of the core of the Agulhas Return Current towards higher latitudes in the east is also evident in the model.

Surface drifter data

Lagrangian surface drift data usually pose a challenge for direct comparison to Eulerian velocities.[20] In order to benefit from these drifter data for model validation, the mean gridded velocities calculated from HYCOM and the SVP drifters were normalised against the spatially averaged standard deviation of their respective velocities. This implies that areas where the magnitude of the normalised velocities are larger than 1 represent regions where the mean current is stronger than the current variability averaged over the entire region. In general the gridded mean velocities were calculated from 20–100 daily averages. However large regional differences are encountered, eg, in the Mozambique Channel and northern Agulhas Current region the amount of SVP drifter data is quite sparse, whilst there were considerably more observations, some bins exceeding 200 daily averages, in the Southeast Atlantic Ocean.

Comparing the normalised velocities of these SVP drifters (Fig 4, top) and HYCOM (Fig 4, bottom) there is reasonably good agreement in the large scale patterns. In the Mozambique Channel the normalised SVP velocities exceed 1.5 to 2 and reveal a fairly broad and uniform pattern. In contrast, HYCOM displays narrower and stron-

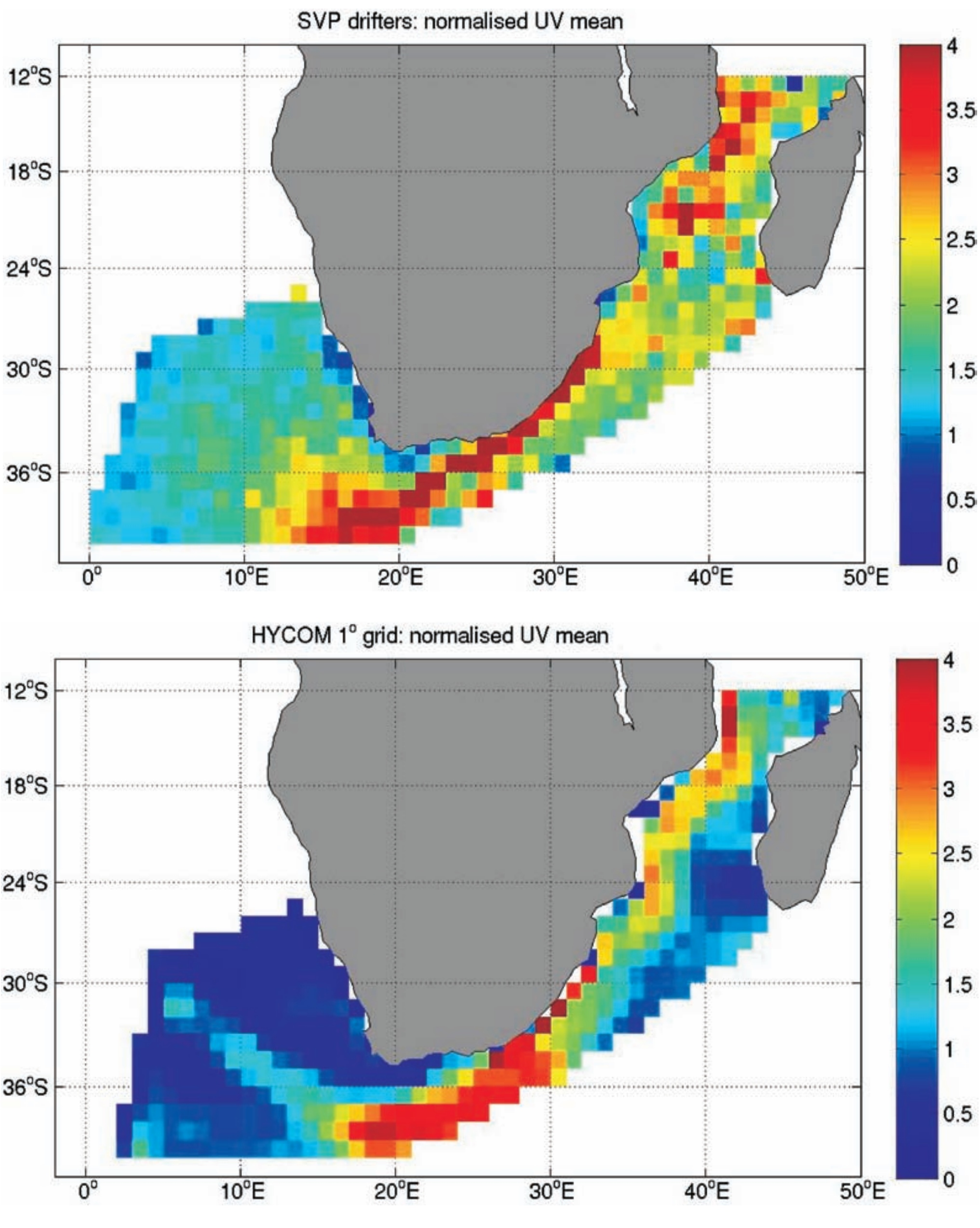

Fig 4: Average velocity (UV) calculated for the period 1996–2006, and normalised against the spatial average standard deviation. SVP drift velocities gridded to 1° spatial grid (top), and HYCOM velocities subsampled to 1° longitude/latitude (bottom)

ger normalised velocity pattern confined to the western edge of the channel. The lack of a stronger signal southwest of Madagascar may indicate that HYCOM places comparatively less emphasis on the contribution from the EMC retroflection to the total volume flux in the Agulhas Current. This aspect was also evident when considering the zonal component of the flow (not shown).

The drifter data provides valuable information about the Agulhas Current core, which is not represented in altimetry observations due to their inability to provide accurate observations near the coast. Throughout the Agulhas Current, both the drifter data and HYCOM show that the mean current is generally stronger than the average variability. At approximately 28°-29°S, the mean southwestward current can be seen to intensify. This intensification is well represented in HYCOM and in good agreement with previous literature. Evidence of the strong mean currents can also be seen to extend southwestward toward the retroflection. Due to the barotropic structure of the Agulhas Current, it closely follows the shelf break, which widens near 24°E, 34°S. Further downstream, at the southern most point of the Agulhas Bank, the current separates from the shelf break. Although the number of drifters are few, this is well captured in the surface drifter data and compares relatively well with HYCOM.

The core locations of the retroflection area as depicted in the normalised velocities of the drifters and HYCOM at about 16–20°E and 39–40°S are in overall good agreement. This core location is also in agreement with the altimeter observations addressed above.

Distinct differences in normalised velocities are found in the ring shedding corridor. The narrow path in the normalised velocities confirms the tendency that the ring shedding in HYCOM follows a northwestward path from the retroflection. This is in contrast to the broader fan of normalised drift velocities spreading out from the retroflection in the drifter data. This is in agreement with the satellite altimetry observations above.

Overall, the comparison to the satellite and *in-situ* observations indicates that HYCOM is able to simulate the mesoscale variability and dynamics of the greater Agulhas Current regime with satisfactory accuracy, although some deficiencies are recognised. The large scale SST distribution in HYCOM is well represented, and with the exception of reduced southwestward penetration of the southern Agulhas Current, the characteristic SST patterns are evident. The flow in the Mozambique Channel is dominated by southward propagating eddies, and the horizontal scales in HYCOM are comparable to surface geostrophic velocity observations from altimetry. The northern Agulhas Current intensification near 28°-29°S and its separation from the coast further south is evident in the normalised velocities of both the drifter observations as well as in HYCOM. The mean position of the Agulhas retroflection is well represented, as well as the eastward flow of the Agulhas Return Current with its semi-permanent meanders. The model simulates ring shedding at the retroflection. However, in contrast to altimetry and drifter observations, these rings tend to follow a too narrow northwestward path into the Southeast Atlantic Ocean.

In the next section, this observation-model inter comparison is extended with a space-time analysis of the mesoscale features.

SPACE-TIME ANALYSIS

SLAs from HYCOM are produced by removal of the model mean dynamic topography (assumed constant). Weekly maps of SLA from altimetry and HYCOM are then used to examine characteristic spatial and temporal frequency patterns of the mesocale variability along the section marked in Fig 5. This analysis was adopted from the approach reported by Schouten *et al.*[34] Data points along the sections are assumed to capture the mesoscale variability in the pathway of the greater Agulhas Current, extending from the Mozambique Channel (data points 111–152) through the northern Agulhas Current (75–111) and southern Agulhas Current (45–75) to the retroflection area (40–45) and then into the ring shedding corridor in the Southeast Atlantic Ocean (1–40). Mesoscale feature occurrences and propagation speeds were estimated from Hovmoeller plots along the section, while a fast Fourier transform (FFT) was applied to the SLA time series at locations along the section to gain further insight into the dominant variability modes in the Agulhas Current system. A limitation of the approach chosen is that the signals are interrupted whenever a mesoscale feature moves off the section. We have, however, taken care of picking the points on the apparent preferential paths so that the statistics should be most stable. The results from these analyses are further addressed in the next subsections.

Hovmoeller analyses

Hovmoeller plots of SLA features from the altimeter and the model are shown in Fig 6 and 7 from January 1996 until December 2006. Positive SLA signals are assumed to represent anticyclonic eddies within the greater Agulhas Current system. In general, the patterns displayed in the Hovmoeller plots suggest the presence of southwestward propagating mesoscale features with speeds ranging from about 7–10km/day in the Mozambique Channel and northern Agulhas Current to approximately 5km/day in the southern Agulhas Current and retroflection region. In the ring shedding corridor (points 1–40) the propagation speed is the same as in the southern Agulhas current while the direction shifts towards west-northwest with more distinct elongated positive SLA features depicted in HYCOM.

In the Mozambique Channel (111–152) the altimeter data shows that both positive and negative SLA features with amplitude reaching up to ± 60cm exist. A closer look suggests a slight dominance of negative SLA features. HYCOM shows a persistent train of positive features propagating downstream from the Mozambique Channel, which compared to the altimetry seems too regular and structured. Similarly, Biastoch and Krauss[3] mention that the time and space structure simulated in their model was less complicated than in reality. Note that a slight negative trend in the model sea surface height (SSH) was encountered for this study period. This probably accounts for the apparent in-

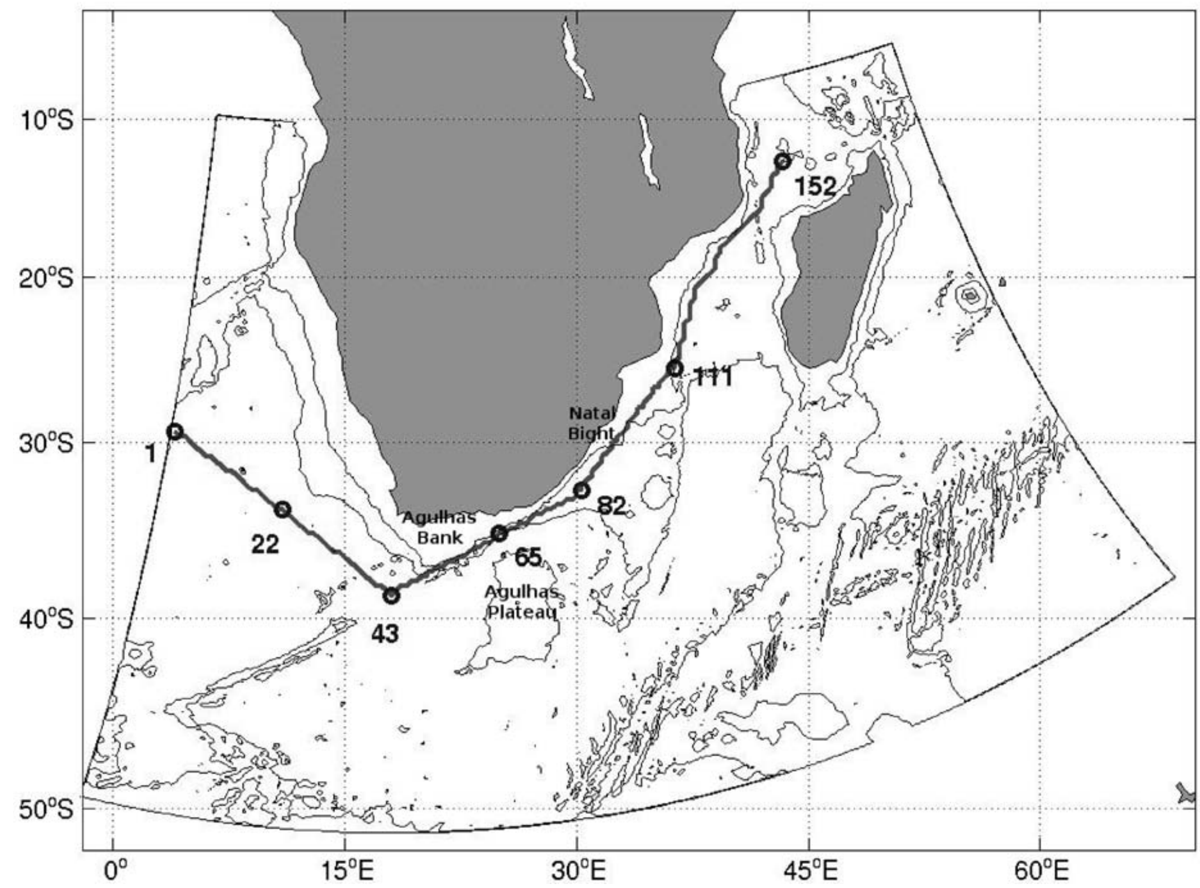

Fig 5: Map of section extracted from merged gridded altimeter and HYCOM SLA fields, with data point indices, model grid outline and bathymetry contoured for every 2000m between 6000m and the surface

crease in negative SLA signals upstream of index point 70 from the year 2000 onwards.

Moving into the northern Agulhas Current (75–111) the altimeter data show a shift towards weaker positive SLA features of about 10–20cm, although the continuation of negative SLA features are also visible. This shift is not clear in HYCOM for the reason explained above, where bands of narrow positive SLA signals persist throughout the northern Agulhas Current region. In the area corresponding to points 75–90 (Fig 5), the core of the northern Agulhas Current is reported to be located mostly within 31km of the coast.[8] Consequently, the SLA signals displayed along the section (being close to the coast) probably represent signals of meanders and anticyclonic eddies along the offshore shear zone of the Agulhas Current. This would also favour the observed tendency for the predominance of positive SLA features in the area.

In the southern Agulhas Current (45–75), predominantly positive SLA signals are present in the altimeter field, while fairly strong positive SLA signals (50–60cm) intermittently interrupted by negative SLA signals start to develop in HYCOM. In this southern region, the Agulhas Current is sufficiently far from the coast that the extracted section is again able to capture its signal. The negative SLA signals (20–30cm) occurring here are thought to be associated with cyclonic meanders, otherwise known as Natal Pulses. Both the negative and positive HYCOM SLA features seem to gradually reduce in their downstream propagation. The anticyclonic eddies extend to depths of 1200m and are thus likely slowed down due to their interaction with the shallow Agulhas Bank.

In the retroflection area (40–45) and slightly upstream in the southern Agulhas Current (45–55), there is evidence of enhanced mesoscale variability in the form of increased presence of positive and negative SLA features, in particular in the altimeter data. The general agreement between the model and altimeter data further supports the previous finding that HYCOM is able to accurately simulate the mean position of the Agulhas retroflection.

Rings that are shed from the retroflection area and propagate into the Southeast Atlantic Ocean have been observed to do so in a broad, predominantly northwestward variable pathway.[17] Hence, the extracted section in the ring shedding corridor only intermittently captures the signals associated with these features. A significant number of Agulhas Rings are seen propagating northwestward along the section in immediate vicinity of the retroflection (Fig 6 and 7, 1–40). However, while the altimeter suggests frequent ring shedding events at the retroflection with a subsequent broadening of their pathway into the Southeast Atlantic, HYCOM underestimates the number of such events and clearly favours a distinct northwesterly trajectory of the rings.

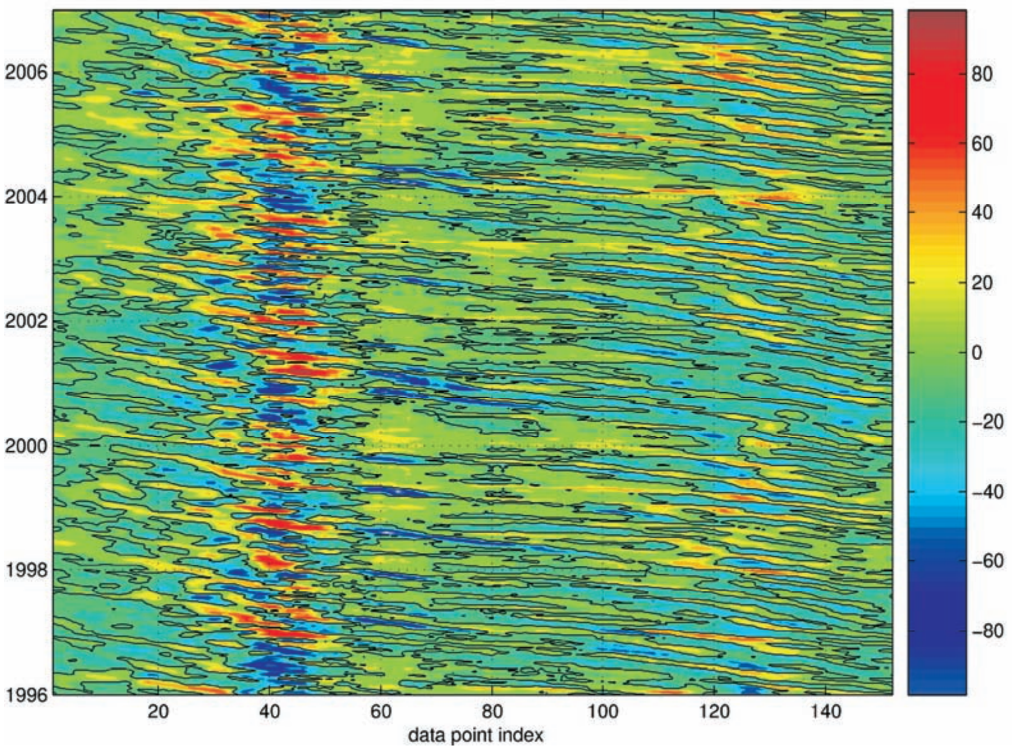

Fig 6: Hovmoeller plot of altimeter SLA fields (SLA in cm) extracted from the section marked in Fig 4

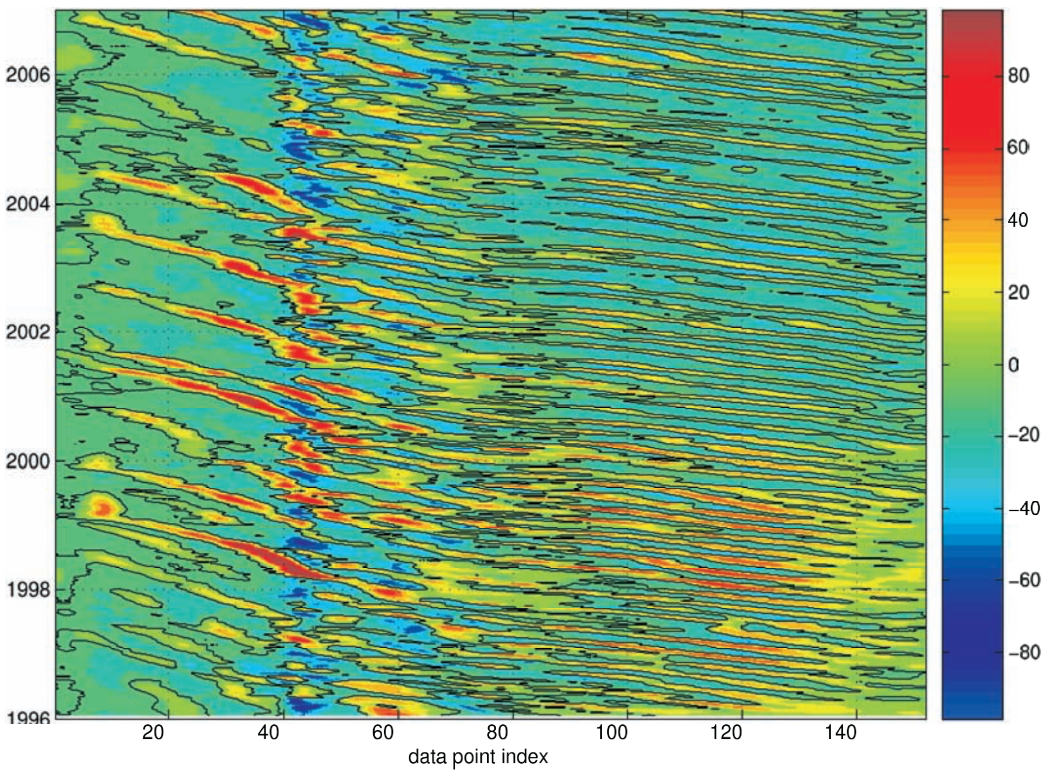

Fig 7: Hovmoeller plot of HYCOM SLA fields (SLA in cm) extracted from the section marked in Fig 4

Frequency analysis

In order to gain further insight into the dominant variability modes in the Agulhas Current system, a fast Fourier transform (FFT) was applied to the 11 year altimetry and HYCOM SLA time series at every point along the section (Fig 5). Prior to the FFT, a linear detrending function was applied, and the outer 10% of the data were smoothed by means of sinusoidal tapering function to minimise signal noise and leakage. Further details and explanation of the FFT is given in.[7]

The power spectra (Figs 8 and 9) obtained from the Fourier analysis support the previous findings that there is strong and regionally distinct variability throughout the greater Agulhas Current system from the Mozambique

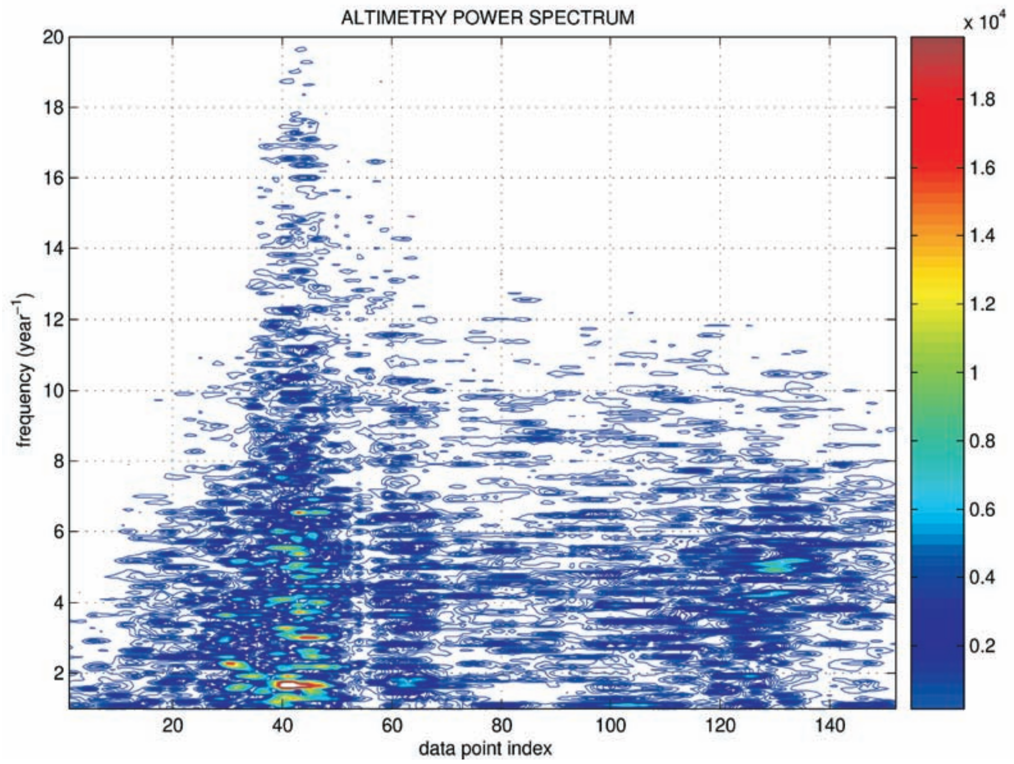

Fig 8: Power spectrum for extracted section (Fig 4) derived from 11 years of merged gridded altimeter SLA fields

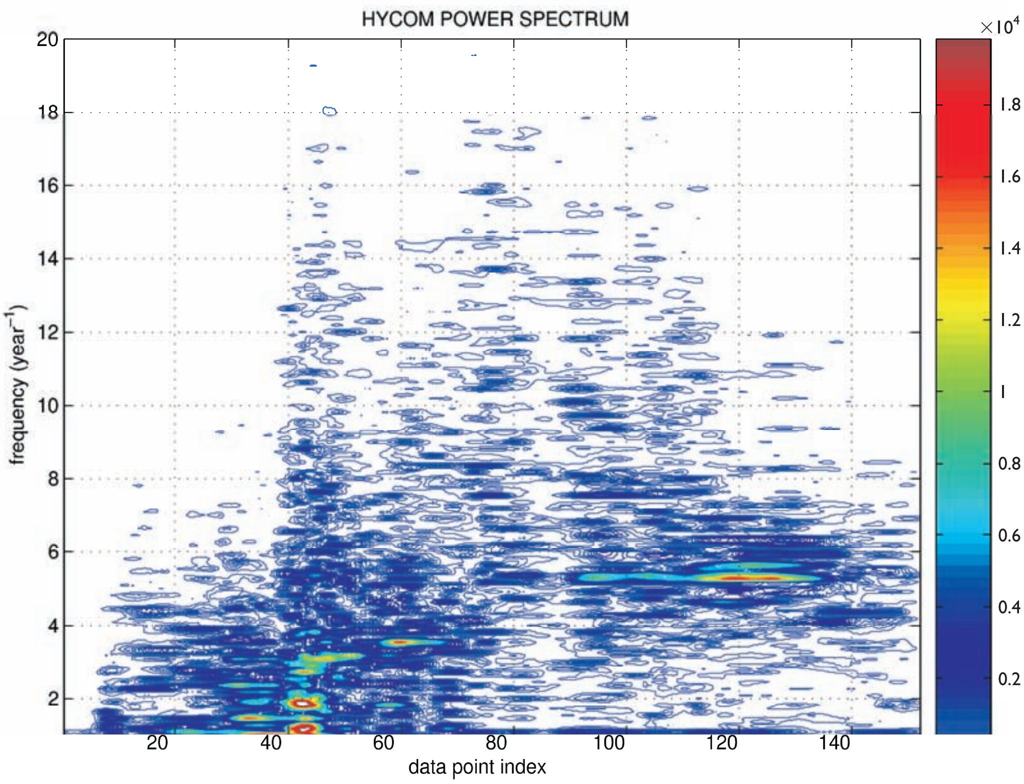

Fig 9: Power spectrum for extracted section (Fig 4) derived from 11 years of HYCOM SLA fields

Channel to the ring shedding corridor. A broad spectrum of frequencies is evident (Nyquist frequency is at about 24 per year), ranging from about 21 days (18 per year) to monthly (12 per year), seasonal (4–6 per year) and annual. There are differences between the two spectra, in particular manifested from region to region. In addition to the distribution, we consider the individual frequencies which clearly stand out from the background.

The northern Agulhas Current and Mozambique Channel

In the northern Agulhas Current and Mozambique Channel (indices 75 to 152), the frequency range is slightly compressed to the lower frequencies from about 2–6 per year in altimetry versus 4–6 per year in HYCOM. This suggests that the model is not able to properly represent the half-annual signal in this area as captured in altimetry. On the other hand, HYCOM simulates more high frequency variability of about 12–16 per year in the southern part of the Mozambique Channel and northern Agulhas Current (75–120). These higher frequencies, which are not present in the altimetry SLAs, are perhaps a result of the abundant number of meanders and eddies propagating downstream from the Mozambique Channel in HYCOM as was addressed in the previous section (Fig 3, left panel).

A distinct frequency peak at 5–6 per year in the Mozambique Channel is visible in both HYCOM (90–140) and altimetry (but only extending from indices 120–140). This is consistent with the southwestward propagation of SLA features depicted in the Hovmoeller plots (Fig 6 and 7) and provide statistical evidence that eddies occur 5–6 times per year in the Mozambique Channel. Schouten *et al*[34] show that the number of anomalies per year in the Mozambique Channel reduce from 7 in the north to 4 in the south due to smaller eddies dissipating or merging with larger ones. This could explain some of the slight differences evident between HYCOM and altimetry. In HYCOM, this 5–6 per year signal is clearly seen to extend southwestward into the northern Agulhas Current (until index 90), again in agreement with the Hovmoeller plot. As mentioned previously this is an indication that an inter-connection between upstream mesoscale eddies in the Mozambique Channel and the Agulhas Current system exists at this frequency. Further downstream in the northern Agulhas Current (located at indices 85–90), there seems to be a discontinuity of the frequency signals in HYCOM. In the Hovmoeller plot (Fig 7), this seems to be a region where the mesoscale features are intermittently suppressed in HYCOM. This is not equally evident in the altimeter Hovmoeller and power spectrum.

The southern Agulhas Current and retroflection

The southern part of the Agulhas Current system (45–75) appears to maintain evidence of the southwestward extension of the frequency peak at 5–6 per year to about index 70 in HYCOM. In the altimeter data a southwestward extension to about the same position is observed at a frequency peak of about 4–5 per year. Southwestward from this position the frequency distribution in the altimeter data broadens from the annual frequency up to 7 per year. HYCOM also shows this, in addition to a strong 3–4 per year signal. It remains unclear to what extent and by which mechanisms the Agulhas Plateau (south of point 65) influences the mesoscale variability in this area. While the 3–4 per year frequency signal seems to extend towards the retroflection area (40–45) in HYCOM, there is an apparent discontinuity present in the altimeter derived frequencies at point 55. This area of the Agulhas Current (40–45) is considered to have limited influence from the monsoon circulation.[32] The annual to seasonal signals may thus be attributed to a variety of other sources including seasonal signals of the regional wind field.[29]

Southwestward from point 55 to the retroflection area both the altimeter and HYCOM contain strong signals from the annual frequency up to 8 per year. The broadening of the frequency distribution here provides a good indication of the position of the retroflection in the section, and both the model and altimetry power spectra indicate a mean position of the Agulhas retroflection at index 43. Whereas HYCOM lacks distinct expressions of frequencies larger than the monthly signal, the altimeter data shows strong signals in the retroflection area reaching almost up to 18 per year. This result is consistent with the increased amount of instabilities in the southern Agulhas Current and the retroflection region observed in the Hovmoeller plots (Fig 6 and 7). Similarly, the lack of the higher frequencies in HYCOM is also anticipated from the pattern of propagating SLA features seen in the Hovmoeller plot (Fig 7).

The ring shedding corridor

In the ring shedding corridor (1–40) the frequency range rapidly decreases with distance from the retroflection area, eg, from 10–11 to 1 per year in the altimetry and from 8–9 to 1–2 per year in HYCOM. This is expected for the area, where rings are known to travel along a variety of pathways, resulting in a broad fan-shaped area of ring propagation and mesoscale variability in the Southeast Atlantic Ocean.[17] In agreement with the Hovmoeller plots this frequency decrease indicates that the signals of the rings drifting into the Southeast Atlantic Ocean become less frequently captured with increasing distance from the retroflection area. In the upstream part near the retroflection (30–40) the altimetry reveals northwestward extending signals of an enhanced frequency at 5, 3–4 and 1.5–2 per year. In comparison, HYCOM reveals signals at 3–4, 2–3 and 1.5–2 per year extending northwestward into the Southeast Atlantic Ocean. These signals suggest that eddies are shed from the retroflection area up to five times per year in the altimetery data, while the more suppressed frequency range in HYCOM suggests that ring shedding events occur about three times per year. The overall suppression of mesoscale frequency signals westward of data index point 5 (20 grid cells from the HYCOM model boundary) arises from the one-way nesting scheme implemented in HYCOM, which dissipates the mesoscale signal near the western open boundary of the model.

From the above analyses, we conclude that intense instabilities and hence strong mesoscale variability is found throughout the Agulhas Current system. Furthermore, it is highlighted that mesoscale features propagating downstream from their origin in the Mozambique Channel at approximately 5–6 times per year play an important role in contributing to the overall mesoscale variability in the central and northern parts of the Agulhas Current. There is also evidence that upstream meanders and eddies occasionally influence the ring shedding processes at the retroflection.

Feature tracking and drift estimates

The annual average occurrence of southwestward propagating meanders and anticyclonic eddies, determined from the Hovmoeller and FFT analyses are summarized in Table 1 for both altimetry and HYCOM. The results are grouped according to the different regions along the section from the Mozambique Channel in the northeast via the northern and

		Altimetry observations		HYCOM simulation	
Location observed	Data point indices	FFT	Hovmoeller annual avg.	FFT	Hovmoeller annual avg.
Mozambique Channel	111–152	5–6	4.4	5–6	5.2
Northern Agulhas Current	65–111	N/A	4.5	5–6	5.3
Southern Agulhas Current	43–65	N/A	3.7	3–4	3.6
Agulhas Retroflection	43	3–4	3.4	2–3	2.2
Ring shedding corridor	1–43	3	3.1	2	1.9

Table 1: Frequency estimates, from the Hovmoeller analysis as well as the FFT's, of positive SLA features (anticyclonic eddies) occurring in all four regions of the section

southern Agulhas Current into the Agulhas retroflection area and ring shedding corridor in the southwest.

From altimetry, the eddy occurrence estimates of 4.4, 3.4 and 3.1 per year for the Mozambique Channel, Agulhas retroflection and the ring shedding corridor respectively are in good agreement with the associated power spectrum. In the northern and southern Agulhas Current, the respective altimeter signals in the FFT cannot be confidently isolated from the background signal. In HYCOM, on the other hand, the eddy occurrences from the Hovmoeller analysis are in good agreement with the FFT analysis for all regions of the section.

The comparison provided in Table 1 highlight the good consistency between the results independently obtained from the FFT and Hovmoeller analyses. In particular, the results indicate that Mozambique Channel eddies consistently merge with the northern Agulhas Current, thereby stimulating the formation of Natal Pulses. Furthermore, about 70% of the Mozambique Channel eddies observed in the altimetry appear at the Agulhas Plateau, while almost 2/3 are advected further southwestward towards the Agulhas retroflection, where they contribute to the mesoscale variability and ring shedding processes. These results are supported by HYCOM, except in the retroflection and ring shedding corridor the frequencies of occurrences are slightly weaker.

The mean speeds and standard deviations of the anticyclonic eddies and meanders can be estimated directly from the Hovmoeller plots for the regions from the Mozambique Channel to the retroflection area and ring shedding corridor. These results are presented in Fig 10 together with the average surface speed obtained from the drifters for the same sub-regions.

The drift estimates range from a maximum of 12km/day

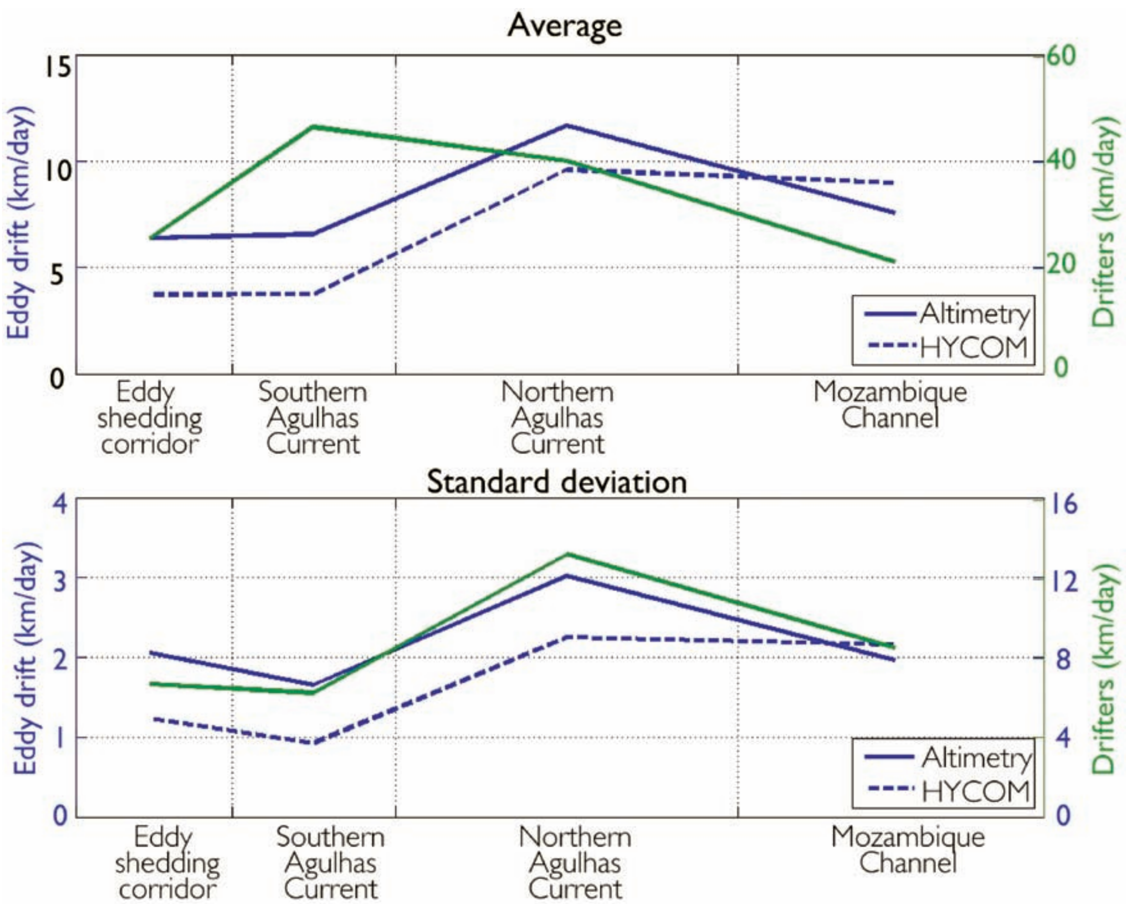

Fig 10: Propagation velocity estimates of positive SLA features (anticyclonic eddies) and SVP drifter velocities for the various sub regions of the greater Agulhas Current

in the central part of the northern Agulhas Current to 3.5km/day in the southern Agulhas Current and ring shedding corridor. On average, throughout the entire section, their propagation velocity is 7.5km/day. The altimeter drift estimates consistently exceed HYCOM by about 3km/day, except in the Mozambique Channel where HYCOM exceeds the altimeter by 1.5km/day. The variability of the eddy drift is also higher in the altimeter data, exceeding HYCOM by 0.75km/day in the standard deviation. The journey of anticyclonic eddies from the Mozambique Channel to the retroflection area, a distance of approximately 3000km, will thus take about 400 days.

These drift estimates are slightly different to previously reported estimates.[34,35] For example, Mozambique Channel eddies travel at 7 ±2km/day/9 ±2km/day (Fig 10, Altimetry/HYCOM observations) both much faster than the speed of 3–6km/day reported[35] from altimetry observations. These differences are due to the fact that the drift velocities here are estimated from the Hovmoeller plots, while Schouten *et al*[35] manually tracked the eddy propagation.

In the northern Agulhas Current the drift is 11 ±3km/day for altimetry and 9 ±2km/day for HYCOM. This is in good agreement to the documented propagation velocity of Natal Pulses (10km/day). Additionally, negative SLA signals, or Natal Pulses, are periodically observed in the Hovmoeller plots (Fig 6 and 7) at 30°S (index 90), and in almost all cases they are preceded by a positive SLA signal. This strongly supports that Natal Pulses are in fact induced by passing Mozambique Channel eddies, as was suggested.[34] This behaviour can be seen to occur regularly in HYCOM (eg, Fig 3, left panel).

As expressed by Jacobsen *et al*[20] the direct comparison of these drift estimates to the Lagrangian current velocities calculated from the surface drifters (Fig 10, green curves) is not straight forward, and neither is the relationship between the mean current velocity and the propagation speed of eddies. However, we would like to examine whether the eddy propagation speed and the mean current velocities are spatially correlated. The surface drifters provide a good indication of the background mean current and its standard deviation, which ranges from 20 ±8km/day (0.2 ±0.09m/s) in the Mozambique Channel to 50 ±13km/day (0.6 ±0.15m/s) in the region of the Agulhas Current and 30 ±6km/day (0.3 ±0.07m/s) in the ring shedding corridor. For most parts the estimated eddy drifts and standard deviations in altimetry and HYCOM reach only a quarter of this mean surface drift and standard deviation obtained from the drifters. The anticyclonic eddies extend to depths of about 1200m in HYCOM. It is therefore not unrealistic that the mean eddy drift in altimetry and HYCOM are less than the mean surface drift derived form the drifters. In addition, the deeper part of the eddies are expected to interact with bathymetry which will further tend to slow down their drift.

On the other hand, the spatial patterns of the standard deviations detected in altimetry, HYCOM and the surface drifters are more consistent. The variability of the eddy drift in HYCOM and altimetry therefore appears to be correlated with the variations observed in the mean surface current. Hence, the strength of the mean surface current and eddy drift correlate well with the variations in eddy drift.

SUMMARY AND CONCLUSION

The greater Agulhas Current system known for its intense dynamics and mesoscale variability is an excellent natural laboratory for studies combining numerical ocean models with satellite and *in-situ* observations. This is demonstrated in this study for a period of 11 years from 1996 to 2006. HYCOM reproduces the general circulation pattern with the regional characteristic spatial and temporal variability reasonably well, although some deficiencies are encountered, notably the train of eddies extending from the Agulhas Plateau to the retroflection, and the exaggerated spatial scales of Agulhas Rings that display a too narrow drift pathway into the ring shedding corridor in the Southeast Atlantic Ocean.

The space-time analyses provide quantitative means for validation of the model variability, and are also applicable to other ocean current regimes, such as the Gulf Stream and Kuroshio Current. Anticyclonic eddies occur in the Mozambique Channel at a frequency of 5–6 per year. In both HYCOM and altimetry SLA fields these anticyclonic eddies drift southwards and merge with the offshore side of the northern Agulhas Current. The model indicates that this occurs consistently at this frequency and that this merger contributes to the triggering of Natal Pulses. Furthermore, eddy propagation velocities determined from the Hovmoeller analyses suggest that the anticyclonic eddies in the northern Agulhas Current propagate at approximately the same velocity as Natal Pulses, which further supports the idea that these southwestward propagating eddies induce the formation of Natal Pulses. About 70% of the Mozambique Channel eddies are tracked southwestward to the southern Agulhas Current, and ultimately nearly 2/3 of these appear at the retroflection where they contribute towards the mesoscale variability and ring shedding.

Upon approaching the retroflection region, the magnitude of the SLA in altimetry and HYCOM enhances and the SLA oscillates more frequently between positive and negative signals and the power spectra indicate this through a broadening of the frequency spectrum. HYCOM and the altimetry data are moreover in very close agreement concerning the mean position of the Agulhas retroflection. The ring shedding events are revealed to occur in the altimetry at a frequency of 5 per year. In comparison HYCOM displays ring shedding events occurring approximately 3–4 times per year.

Adequate validation of HYCOM is mandatory for further investigation of the greater Agulhas Current regime. In this study the model capacity has been satisfactorily documented by intercomparison to satellite passive microwave radiometry, radar altimetry and surface drifter data. In particular, evidence of anticyclonic eddy drift from the Mozambique Channel to the retroflection area is demonstrated. HYCOM is therefore qualified for operational forecasting experiments of the greater Agulhas Current regime. Moreover, since the Indo-Atlantic inter-ocean exchange of volume, heat and salt occurs predominantly via shedding of Agulhas Rings, it is important to accurately simulate the combination of local and upstream processes that triggers these shedding events. Operational use of HYCOM can therefore also contribute to advancing the understanding of these episodic dynamic events.

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