Abstract The oceanic circulation south of Africa is characterised by a complex dynamics with a strong variability due to the presence of the Agulhas current and numerous eddies. The area of interest of this paper, is also the location of several natural gas fields under seafloor which are targeted for drilling and exploitation. The complex and powerful ocean currents induces significant issues for ship operations at the surface as well as under the surface for deep sea operations. Therefore, the knowledge of the state of the currents and the ability to forecast them in a realistic manners could greatly enforce the safety of various marine operation. Following this objective an array of HF radar systems were deployed to allow a detailed knowledge of the Agulhas currents and its associated eddy activity. It is shown in this study that 4DVAR assimilation of HF radar allow to represent the surface circulation more realistically. Two kind of experiments have been performed, a one month analysis and two days forecast. The one month 4DVAR experiment have been compared to geostrophic currents issued from altimeters and highlight an important improvement of the geostrophic currents. Furthermore despite the restricted size of the area covered with HF radar, we show that the solution is improved almost in the whole domain, mainly upstream and downstream of the HF radar’s covered area. We also show that while benefits of the assimilation on the surface current intensity is significantly reduced in the first 6 hours of the forecast, the correction in direction persists after 48 hours.

Keywords 4DVAR · Agulhas current · HF radar · ROMS · forecast
1 Introduction

The oceanic circulation south of Africa is characterised by a complex dynamics with a strong variability due to the presence of the Agulhas current and numerous mesoscale eddies from the Mozambique Channel (Penven et al., 2006; Halo et al., 2014). More recently, high resolution modeling study by Tedesco et al. (2019) has highlighted the existence of numerous submesoscale eddies along the Agulhas cyclonic front.

Lutjeharms et al. (2003) observed the presence of cyclonic eddies embedded in the landward border of the southern Agulhas Current. These eddies have a diameter of about 50 km and are associated with a surface warm signature. Simulations suggest that those eddies remain trapped in the Agulhas Bank shelf bight and that eddies that travel downstream of the current represent leakages from the resident shear eddy. This occurs at a roughly 20 days occurrence frequency. The intensity of the meso-scale activity in this key region for the retro-flexion modulate the exchanges of heat and salt between oceans (Lutjeharms, 1981; Reason et al., 2003; Van-Aken et al., 2013; Guerra et al., 2018) as well as towards the atmosphere (Messager and Stuart, 2016).

This region exhibits furthermore a dynamical upwelling induced by the Agulhas Currents (Arnone et al., 2017) as observed by Goschen et al. (2015) during Natal Pulses. This upwelling, as been shown by Lutjeharms et al. (2000) to occurs on the landward side of the Agulhas Current and have an effect on the nutrient availability, stratification and primary productivity in the eastern Agulhas Bank. It as also been shown by Meyer and Niekerk (2016) that implementing an ocean current power plant in this region would outperforms onshore wind power plants and could increase the load carrying capacity of the country.

The area of interest of this paper, represented on Figure 1 is also the location of several natural gas fields under seafloor which are targeted for drilling and exploitation. The complex and powerful ocean currents induces significant issues for ship operations at the surface as well as under the surface for deep sea operations. Strong ocean currents can also modify the height and direction of ocean waves, causing dangerous sea states (Quilfen et al., 2018). The risk of extreme waves is an important hazard for the shipping activity and off shore industry when crossing the main current systems. Therefore, knowledge of the currents state and the ability to forecast it in a realistic manners could greatly enforce the safety of various marine operations.

Following this objective an array of HF radar was deployed along the coast to allow a detailed knowledge of the Agulhas currents and its associated eddy activity. The purpose of the present document is to present and evaluate the impact of the 4DVAR assimilation of those radar data on ocean model simulation and forecast of the sea surface currents.

Data used for assimilation and validation are described in the following section. The model setup and the assimilation procedure are described in a third section while results are presented in section four and further discuss in the conclusion.
2 DATA

To monitor the variability of the Agulhas currents during offshore operations, three HF radar were installed on the south coast of South Africa. The location of the radar system (black square) and the averaged area of measurement during April 2020 is represented on Figure 2. After a first treatment of the radar data using manufacturer software, radial velocities are combined on a Cartesian grid at 6km resolution using the method describe by Barth et al. (2010) and made available every 30 minutes.

Altimeters data used were generated by a processing system including data from all altimeter missions: Sentinel-3A/B, Jason-3, HY-2A, Saral[DP]/AltiKa, Cryosat-2, OSTM/Jason-2, Jason-1, Topex/Poseidon, Envisat, GFO, ERS-1/2 and delivered by E.U. Copernicus Marine Service Information. Being at a significant lower resolution than both model experiment those data were excluded from the assimilation process (although there are somehow assimilated in the Mercator ocean simulation used as boundary forcing) and may be considered as an independent source of observations for our validation process. Nonetheless an import bias in the representation of the Agulhas current by the altimeters data has been highlighted by Rouault et al. (2010).

3 Model setup & 4DVAR

The ocean circulation model used in this study was the Regional Oceanic Modeling System described in detail in Shchepetkin and McWilliams (2003, 2005). ROMS is a split-explicit, free-surface and terrain-following vertical coordinate oceanic model with 4DVAR capabilities (Moore et al., 2011c). Tracers momentum advection use a third order upstream biased advection scheme with no additional explicit
horizontal dissipation/diffusion while on the vertical a GLS scheme is used to determine vertical mixing coefficients (Warner et al., 2005). The model grid, the atmospheric forcing, the initial and boundary conditions were all built using pyroms package freely available at www.myroms.org (doi:10.5281/zenodo.3727272). The bottom topography is derived from Etopo1 (doi:10.7289/V5C8276M). To ensure an acceptable resolution in the upper ocean, 35 vertical levels with stretched s-coordinates improved double stretching function (Shchepetkin and McWilliams, 2005, 2009) were used, using surface and bottom stretching parameters $\theta_s = 4$, $\theta_b = 1$ respectively. ROMS was initialized and forced at the lateral boundaries, by temperature, salinity and velocities profiles extracted from Mercator ocean global analyses_forecast_phy_001_024 which provide weekly analyses and daily forecast. Atmospheric fluxes (heat and water) were extracted from ERA5 (fifth generation of ECMWF atmospheric reanalyses of the global climate - Copernicus Climate Change Service (C3S) (2017)) and introduced in the ocean model through a bulk formulae (Fairall et al., 2003). The model domain extends from 21E to 26E and from -37S to -33S, on a 1.8 km regular grid. The ocean model has been run without data assimilation from January 2019 to April 2020 (called FREE experiment hereafter) and 4DVAR data assimilation of HF radar surface currents was performed during April 2020 only and compared to April issued from FREE.

Detailed description and evaluation of the 4DVAR data assimilation can be found in Di Lorenzo et al. (2007); Powell et al. (2008); Powell and Moore (2009); Broquet et al. (2009, 2011); Moore et al. (2011a,b,c); Song et al. (2016) and is out of the scope of the present document. In the present work, the dual formulation approach (Moore et al., 2011b; Gürol et al., 2014; Levin et al., 2019) has been used with 6 inner-loops and 2 outer-loops. This setting has been determined after several experiments to reach an optimum between accuracy of the results and computational time. It is furthermore coherent with Levin et al. (2019) who used 7 inner-loops and 2 outer-loops in their Mid-Atlantic Bight configuration. The data were assimilated using 1-day assimilation windows. The 4D-Var analysis produced
at the end of each day was used as initial condition for the next assimilation cycle. Computational cost of this choice is around 90 min by days (using 224 cpus)

4 Results

4.1 Hindcast

As detailed in section 3, the 4DVAR simulation have been made for April 2020 and our analysis therefore target this periods. The outputs of FREE and 4DVAR simulation were compared to altimeter derived geostrophic currents. Spatially averaged Root Mean Square Error (RMSE) between both simulations and altimeters derived geostrophic currents are shown on figure 3. Top panel of Figure 3 represents the spatial average of the RMSE over the whole domain (hereafter global area), while bottom panel represents the RMSE averaged over the area corresponding to the HF radar observation zone (hereafter local area). Both panels show a significant decrease of the RMSE for the geostrophic currents with data assimilation, but while the local improvements are almost immediate it takes about 15 days to propagate them over the whole domain.

Figure 4 represents the RMSE’s maps for April 2020. Panel (a) shows a significant RMSE for the FREE simulation regarding the intensity of the Agulhas currents while panel (b) shows a lower RMSE. The panel (c) which represents the differences of panel (a) and (b) (4DVAR minus FREE) confirms the pattern and intensity improvement for the Agulhas current. As already shown by the Figure 3a, Figure 4 highlight the positive impact of the data assimilation outside the area where HF radar data are assimilated.

While previous RMSE times series (Figure 3) and maps (Figure 4) illustrated a global improvement of the geostrophic currents over the whole month of April, Figure 5 focuses on a daily averaged (23 of April 2020). Panels (a) and (b) show the daily averaged geostrophic currents for FREE and 4DVAR respectively. Panels (c) and (d) show the averaged geostrophic currents derived from altimeter data and the surface currents measured by the HF radar and assimilated in the model during this day. This figure illustrates the improvement between FREE and 4DVAR experiments. Indeed, west of 24°E the current is curving southward in FREE while 4DVAR is able to reproduce the northward bent seen by altimeters (panel (c)). Also, the area east of 24°E and north of 36°S is characterised by the presence of an anticyclonic eddy matching the eddy detected by altimeters. Finally 4DVAR also reproduces the intensity of the current in the southern branch of the eddy. It is furthermore interesting to note once again that beside the scarcity of the assimilated data (depicted on panel (d)) the 4DVAR assimilation is able to correct the circulation almost in the whole simulated domain.

4.2 Forecast

In the previous section it has been shown that assimilating HF radar currents allows to improve the geostrophic circulation when compared to satellite derived velocities. Nonetheless, those altimeter data are at low resolution (25km) with daily data only, while HF radar are available at 6km resolution every 30 minutes. Since
HF radar currents are assimilated in the model and therefore cannot be used for further validations, some forecast have been made starting from assimilated initial condition and FREE condition. This allow to validate the forecast against the HF radar data and explore the benefits of the assimilation on smaller scales and on the forecast capabilities of the current configuration.

Two 48 hours forecast initiated from the 20 of April 00H00 were performed. One forecast were initiated from FREE run and the second one from the 4DVAR. RMSE time series of both forecast against HF radar data are presented on Figure 6. They show a strong improvement in intensity (top panel) and direction (bottom panel) when the forecast is initiated from 4DVAR. While the reduction of RMSE of the surface current intensity tend to decrease from 50% to 15% during the 48 hr forecast, the RMSE of the surface current direction is reduced from 73% to 50% during this same period. Therefore the main improvement of the forecast is related to the currents direction. Figure 7 represents the maps of RMSE for surface current intensity (Figure 7a,b,c) and direction (Figure 7d,e,f) along the 48 hours of the forecast. Although it confirms that most of the forecast improvement is related to the current direction it also shows that current intensity and direction were significantly improved in the center of the area covered by the HF radar measurement.
Fig. 4 FREE (a) and 4DVAR (b) geostrophic velocities RMSE map (against altimeter derived velocities) and their differences (c) for April 2020. Dotted contour shows where HF radar data are assimilated.
The Figure 8 shows the surface circulation of FREE, 4DVAR and HF radar currents averaged over each day of forecast as a superposition of arrows. It illustrates that the use of an assimilated initial condition allows to dramatically correct the path of the surface currents. Indeed while the FREE forecast is characterized by a southward deviation and an cyclonic circulation between 24°E and 25°E, the 4DVAR forecast surface circulation is almost the opposite. Indeed it is characterized by a northward shift inducing an anti-cyclonic circulation between 24°E and 25°E. While the whole eddy cannot be depicted by the HF radar measurement, the northward shift of the Agulhas corresponds to what it is observed by the HF radar. This southward shift, seen in the FREE forecast is therefore an artefact of the model which can be corrected by using an assimilated initial condition.

5 Conclusion

In this study the benefits of the 4DVAR assimilation of surface currents issued from HF radar in one of the most highly dynamic region of the world is presented. While the intense dynamics of the region make difficult for most of the numerical oceanic models to realistically reproduce the position and intensity of the Agulhas current and associated eddies, it has been shown that a 4DVAR assimilation of
HF radar allow to represent the surface circulation more realistically. Two kind of experiments have been performed, a one month analyses (April 2020) and two days of forecast (20 and 21 of April). The one month 4DVAR experiment have been compared to geostrophic currents issued from altimeters and highlight an important improvement of the geostrophic currents in 4DVAR when compared to FREE. Furthermore despite the size of the area covered with HF radar, it has been shown that the solution is improved almost in the whole domain, mainly upstream and downstream of the HF radar’s covered area. To evaluate the forecast capability of such a configuration and to be able to use the HF radar surface currents as an independent set of data, two days of forecast, starting from the analysed have been realised and compared to FREE. It as been shown that while benefits of the assimilation on the surface current intensity is reduced by 50% in the first 6 hours of the forecast, the correction in direction persist with only 30% of reduction after 48 hours. This improvement of the simulation, thanks to 4DVAR assimilation of HF radar surface currents, could have many impacts at all scales. Indeed long term reanalyses could provide better insight of the position of the Agulhas retroflexion and the resulting ocean leakage between the Indian to the Atlantic ocean or the carbon uptake by the biological activity due to better representation of
Fig. 7 RMSE maps between the two forecast initiated from FREE and 4DVAR and the HF radar data. Left panels (a,b,c) show surface currents intensities RMSE and right panels (d,e,f) show direction RMSE.

the up-welling areas and their variability. Furthermore, in this region of strong maritime activity, a realistic forecast of surface currents would increase marine safety and allow drilling campaign to be planed or suspended depending on the future surface current. Moreover although being out of the scope of this study, small scale currents having a strong impact on wave height variability (Ardhuin et al., 2017), the use of assimilated surface currents is also expected to improve wave forecast and therefore marine safety.
Fig. 8 Daily averaged surface currents for the 20th and the 21st of April 2020. Blue arrows correspond to the FREE experiment. Red arrows correspond to the forecast and the green arrows correspond to the HF radar measured currents.

Declarations

Availability of data and materials

- ERA5 data were downloaded from Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home
- Mercator ocean GLOBAL_ANALYSES_FORECAST_PHY_001_024 where obtained from https://resources.marine.copernicus.eu
- Altimeters data SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046 where obtained from https://resources.marine.copernicus.eu
- HF radar data that support the findings of this study are available from TOTAL but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of TOTAL.

Competing interests

There is no competing interests.

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Authors’ contributions

XC built the numerical setup made the simulations the analyses and wrote this letter. CM and PP contributed to definition of the numerical setup and made
substantial revision of the letter. PL contributed to the conception, design and motivations of the present work.

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