A CROCO configuration for Algoa Bay

Validation of hindcast simulation

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Abstract

This report presents the setup and validation of a regional CROCO model configuration for the Algoa Bay region, located on the eastern extent of the Agulhas Bank, South Africa. The performance of the model solution is assessed over a 2.5 year period from May 2009 to December 2011, coinciding with the availability of data from several in-situ moorings within with the bay, including Underwater Temperature Recorders (UTR) and an Acoustic Doppler Current Profiler (ADCP). We test the sensitivity of the model solution to the application of boundary conditions from three different sources, namely the BRAN, HYCOM and GLORYS reanalysis products. Overall, our results suggest that the GLORYS-forced simulation is the best performing model configuration, both in terms of nearshore temperatures and currents. The ensemble mean of the three simulations however provides a significant improvement in the performance over any of the individual simulations. We further test the model sensitivity to two atmospheric forcing products of significantly different spatial resolutions, namely the $\sim$25 km resolution CFSR product and a $\sim$3 km resolution WRF model for the region developed as part of the Wind Atlas for South Africa (WASA) project. The wind sensitivity test indicates that the high resolution wind product has a marked improvement in the nearshore current correlation coefficients, highlighting the potential benefit of resolving fine-scale wind variability in modelling the dynamics of the bay. The results of this report are intended to guide the design of an operational forecast system for Algoa Bay with many potential uses, including the forecasting of oil spill trajectories which could occur from the ongoing fuel bunker transfer operations (vessel refuelling) in the port of Ngqura anchorage areas.

Contents

1

Introduction

There is an increasing need for estimating the past, present and future three-dimensional ocean state for a wide range of scientific and industrial purposes. Global ocean reanalysis products aim at providing optimal estimates of the ocean state through the assimilation of ocean observations into ocean models. These products are routinely used to generate open boundary conditions for higher resolution regional simulations which include additional physics of local importance, such as higher spatial variability in coastal winds, surface waves, river input, tides and the influence of local bathymetric features. The performance of regional simulations is however largely constrained by limitations in the boundary conditions for these models. Uncertainty in the global ocean reanalysis products has been shown to be particularly large in the deep ocean, the Southern Ocean, coastal areas and in the vicinity of western boundary currents (Balmaseda et al., 2015).

In this study we make use of three independent global ocean reanalysis products to force a regional model of Algoa Bay, located on the eastern extent of the Agulhas Bank, South Africa (Figure 2.1). The ocean dynamics over the study area are complex and greatly influenced by the variability in the Agulhas Current, the largest western boundary current in the southern hemisphere. Variability in the strength of the Agulhas Current controls Ekman veering and the consequent upwelling of cool water along the inshore edge of the current (REF). Divergent flow associated with the topographic influence of the Agulhas Bank on the Agulhas Current is a further cause of upwelling (REF). The passage of Natal Pulses has been given particular attention for their influence on variability on the Agulhas Bank.

These large meanders of the Agulhas Current are characterised by cyclonic circulation which can bring warm surface water onto the shelf at the leading edge of the meander, while upward doming of isotherms in their centre promotes the the movement of cold water onto the Agulhas Bank (REFS). Natal pulses have been shown to impact the eastern Agulhas Bank 110 days per year (Krug et al., 2014). The effect of such meanders have been detected within Algoa Bay itself through nearshore in-situ observations (Goschen et al., 2015). While it is clear that the circulation and hydrography within Algoa Bay is largely influenced by variability in the Agulhas Current, the relative importance of this large-scale variability relative to local phenomena such as wind-driven upwelling and circulation is however less well understood.

The need for a deeper understanding of the drivers of bay-scale circulation within Algoa Bay is becoming increasingly salient due to increasing economic activity in the region and the associated environmental impacts. For example, the ongoing fuel bunker transfer operations (vessel refuelling) in the port of Ngqura anchorage areas (shown in Figure 2.1) are of immediate environmental concern, as highlighted by two small operational oil spill events of 14 August 2016 and 6 July 2019 which necessitated significant clean-up operations.

Given the environmental risks involved, the highly dynamic offshore boundary and the relatively good network of measurements in the bay, Algoa Bay has been identified by DEFF/SAEON as a pilot site for the development of an operational forecast system. Here, we present the first step toward this goal, being high-resolution, limited duration hindcast simulations optimised for the region. The performance of the model solution is assessed using in-situ temperature and current observations within Algoa Bay. We test the sensitivity of the model solution to the application of boundary conditions from three global ocean reanalysis products commonly used in both scientific and industrial contexts. We further test the model sensitivity to two atmospheric forcing products of significantly different spatial resolutions. The results of these sensitivity tests inform recommendations for the development of the operational forecast system.

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Materials and methods

2.1. Observations

In this study, we revisit a subset of the temperature observations described and presented in Goschen et al. (2015). The network of fixed moorings provide good horizontal and vertical coverage of temperature variability within Algoa Bay (Figure 2.1). The Bay Mouth Underwater Temperature Recorder (UTR) is located in $\sim$80 m water depth at the entrance to Algoa Bay, providing hourly temperature observations at 10 m intervals from 10 m to 70 m depths. The St Croix UTR is located in $\sim$30 m water depth in the nearshore region of the bay, and provides hourly temperature observations at depths of 15 m, 20 m and 30 m. The Woody Cape mooring provides temperature in a gully on the shoreline, representative of nearshore surface temperatures. Deployments of an Acoustic Doppler Current Profiler (ADCP) by Lwandle Marine Environment Services on behalf of Petro SA in $\sim$36 m water depth provide current observations at 1 m vertical increments and 10 min temporal intervals. These data were filtered in time to provide hourly averaged observations for comparison with the model output.

2.2. Global ocean reanalysis products

The global ocean reanalysis products referred to throughout this study are the BRAN, HYCOM and GLORYS products. Each product has been developed using different ocean models, different data assimilation methodologies, and different atmospheric forcing products, as briefly summarised below.

The Bluelink ReANalysis (BRAN) is based on the GFDL Modular Ocean Model (MOM) and assimilates observations using an Ensemble Optimal Interpolation (EnOI) data assimilation system. Atmospheric forcing for the model is taken from the Japanese 55-year reanalysis (Kobayashi et al. 2015). A full description of the BRAN ocean reanalysis is provided in Oke et al. (2013). In this study we make use of the latest reanalysis product (BRAN2016, as described in Zhang et al., 2016), which adopts a 1/10° horizontal resolution and 51 z-levels. The product is downloadable from `https://wp.csiro.au/bluelink/global/bran/`.

The HYCOM consortium for data assimilative modelling has developed various analysis and reanalysis products using a multi-variate optimal interpolation scheme (Cummings, 2005). In this study we make use of the GOFS 3.1 Global Reanalysis product (GLBv0.08/expt_53.X, downloadable from `https://www.hycom.org/dataserver`). The model is forced at the surface by the Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010), and adopts a horizontal resolution of 1/12°. Although the vertical grid of the HYCOM model is a hybrid of z-level, terrain-following (σ) and isopycnic coordinates, the reanalysis product is interpolated to 41 standard z-levels.

The GLORYS version 12v1 reanalysis product is the latest ocean reanalysis from the 'Copernicus Marine Environment Monitoring Service' (CMEMS). The product has been developed using the the 'Nucleus for European Modelling of the Ocean' (NEMO) ocean model, and assimilates ocean observations using a reduced-order Kalman Filter scheme. The model is forced at the surface by the ECMWF ERA-Interim reanalysis. It adopts a horizontal resolution of 1/12° and 50 z-levels. More details can be found at `http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_030`.

2.3. Atmospheric forcing products

Two atmospheric forcing products have been considered in this study, aimed at assessing the importance of the resolution of the atmospheric forcing on simulated bay-scale processes in Algoa Bay. The first is a Weather Research and Forecasting (WRF) model configuration developed by the Climate Systems Analysis Group (CSAG) at the University of Cape Town

(UCT). The atmospheric simulation is a downscaling of the ECMWF ERA- Interim reanalysis and forms part of the Wind Atlas for South Africa (WASA) project (Lennard et al., 2015). Model output is available on a 3 km horizontal resolution grid at hourly intervals for the period November 2005 to October 2013 (8 years). The second atmospheric product is the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010). The product provides hourly surface forcing from 1979 to 2010 at a horizontal resolution of $\sim$0.3°, although the product has been extended at a horizontal resolution of $\sim$0.2° from January 2011 to present.

2.4. Model description

The ocean model used for downscaling the global reanalysis products to high resolution over Algoa Bay is the V1.1 official release of the Coastal and Regional Ocean COmmunity model (CROCO[1]), an ocean modelling system built upon ROMS_AGRIF (Shchepetkin and McWilliams, 2005). CROCO is a free-surface, terrain-following coordinate oceanic model which solves the primitive equations by invoking the Boussinesq and hydrostatic approximations. The model solves equations governing the conservation of horizontal momentum, hydrostatic balance, incompressibility and the conservation of tracers (temperature and salinity). A curvilinear Arakawa C-grid is used for the discretisation of the horizontal plane, while the vertical grid is discretised using a terrain-following (σ) coordinate reference system. Vertical turbulent viscosity and diffusivity are parametrised in this study using the k-ε turbulent closure scheme within the Generic Length-Scale (GLS) formulation (Umlauf and Burchard, 2003; Umlauf and Burchard, 2005). Horizontal dissipation in the model is included through dissipation associated with a third-order upstream biased horizontal advection scheme. A nonlinear equation of state adapted from Jackett and Mcdougall (1995) is used for the computation of density.

2.5. Model configuration

The curvilinear computational grid adopted for this study was developed using the Delft3D-RGFGRID package (Deltares, 2017) and is shown in Figure 2.1. The grid has variable resolution ranging from $\sim$3 km at the lateral offshore boundaries to $\sim$500 m within Algoa Bay. 20

[1] `http://www.croco-ocean.org/`

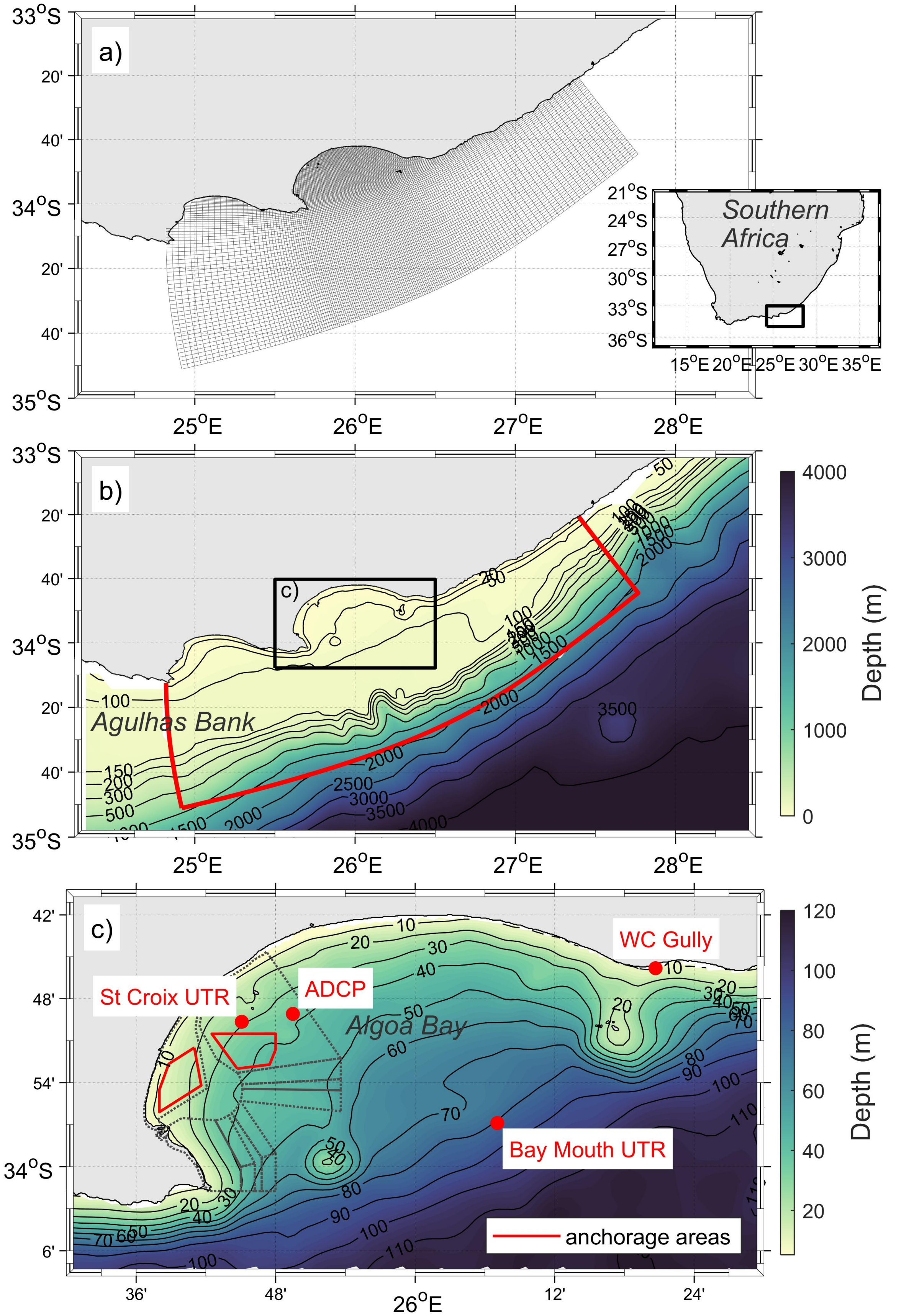

Figure 2.1: (a) Locality map and the curvilinear model grid. (b) Overview of model bathymetry (bathymetry within the model domain is derived from digital navigation charts, while data outside the model is from the 30-arc second GEBCO dataset). (c) Detailed bathymetry over Algoa Bay, including locations of in-situ moorings and anchorage areas where bunkering operations are permitted.

σ-layers are used to define the vertical grid. The model is integrated in time from May 2009 to December 2011 (a 2.5 year period selected based on the availability of in-situ observations and model forcing products) using baroclinic and barotropic timesteps of 40 s and 1 s, respectively. The model output is comprised of 6 hourly averaged output at each grid point, hourly output for the surface layer of the model, and hourly output throughout the water column at each location where observation data are available.

The depths assigned to the model grid points are interpolated from digital versions of the most detailed available navigation charts for the region, as provided by the Hydrographer of the South African Navy. The interpolated bathymetry is smoothed to maintain a slope parameter ($r = \frac{\nabla H}{H}$) of less than 0.2 everywhere in the domain in an attempt to circumvent the well-known horizontal pressure gradient errors associated with σ-coordinate models with steep slopes (e.g. Haney, 1991). A minimum depth of 5 m is enforced to avoid vertical advection errors associated with thin vertical layers in shallow water. A hyperbolic tangent function is used over the sponge layer of the grid (10 grid cells wide) to gradually ramp up the model bathymetry to the 30-arc second GEBCO[2] dataset at the open boundaries of the model. In so doing, the bathymetry at the model boundaries matches that of the global reanalysis products providing lateral boundary forcing conditions to the model. The resulting model bathymetry is shown in Figure 2.1.

Surface boundary conditions for momentum (i.e. wind stress) and surface heat fluxes are computed from the respective atmospheric forcing product data using bulk parameterisation (Fairall et al., 1996; Fairall et al., 2003). Bottom boundary conditions for momentum are computed from the von Kármán quadratic bottom stress formulation using a spatially constant bottom roughness length scale of 0.01 m. Open boundary conditions for the model are interpolated from daily surface elevation (η), temperature (T), salinity (S), and horizontal velocity components (u, v) obtained from the respective global reanalysis products described in Section 2.2. The model solution is 'nudged' to the specified boundary values using relaxation times 1 day and 1 year for inward and outward radiation, respectively (Marchesiello et al., 2001). Nudging is applied within the sponge layer of the model (10 grid cells wide) using a

[2] https://www.gebco.net/

gradual decrease (cosine profile) from the open boundary to the inner border of the sponge layer.

3 Results

3.1. Sensitivity to boundary forcing

Figure 3.1 presents the sea surface temperature (SST) and surface current velocity vectors for a snapshot in time from the Algoa Bay CROCO model, nested inside the three considered global ocean reanalysis products. The relatively seamless interface between the reanalysis products and the nested model indicates that the large-scale features are adequately represented in the nested model. Also shown in Figure 3.1 is the corresponding satellite derived SST field from the Group for High Resolution Sea Surface Temperature (GHRSST) version 4 Multiscale Ultrahigh Resolution (MUR) level 4 product (NASA/JPL, 2015). The GHRSST-MUR and global ocean reanalysis products all show the typical SST signature of warm waters associated with the Agulhas current, and cooler nearshore waters within Algoa Bay. While all three reanalysis products and their nested simulations display similar features, the intensity and spatial variability of each is notably different. For instance, the GLORYS-forced simulation displays both warmer offshore temperatures and more intense upwelling on either side of Algoa Bay than the other two simulations, for the shown time-step. The sensitivity of the nested model solutions to the different boundary forcing products will now be formally assessed through a comparison with in-situ observations within Algoa Bay.

Figure 3.2 presents a 2 year time-series comparison of modelled and observed temperature at the offshore extent of Algoa Bay (Bay Mouth UTR mooring), while an analogous nearshore comparison at the St Croix UTR and Woody Cape moorings is shown in Figure 3.3.

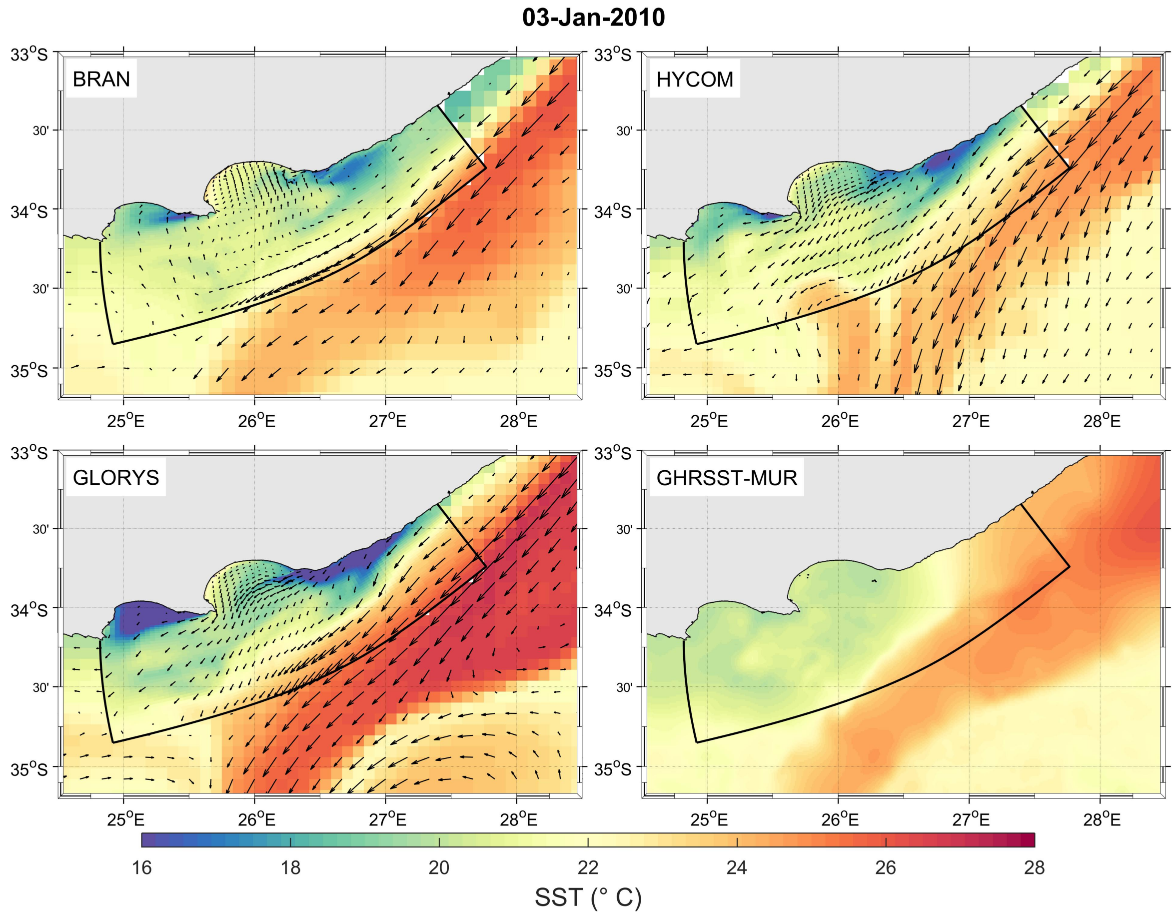

Figure 3.1: Sea surface temperature (SST) and surface current velocity vectors for a snapshot in time from the three global ocean reanalysis products, the nested Algoa Bay CROCO model (contained within the black outline of the model extents) and the GHRSST-MUR satellite SST product at the corresponding time.

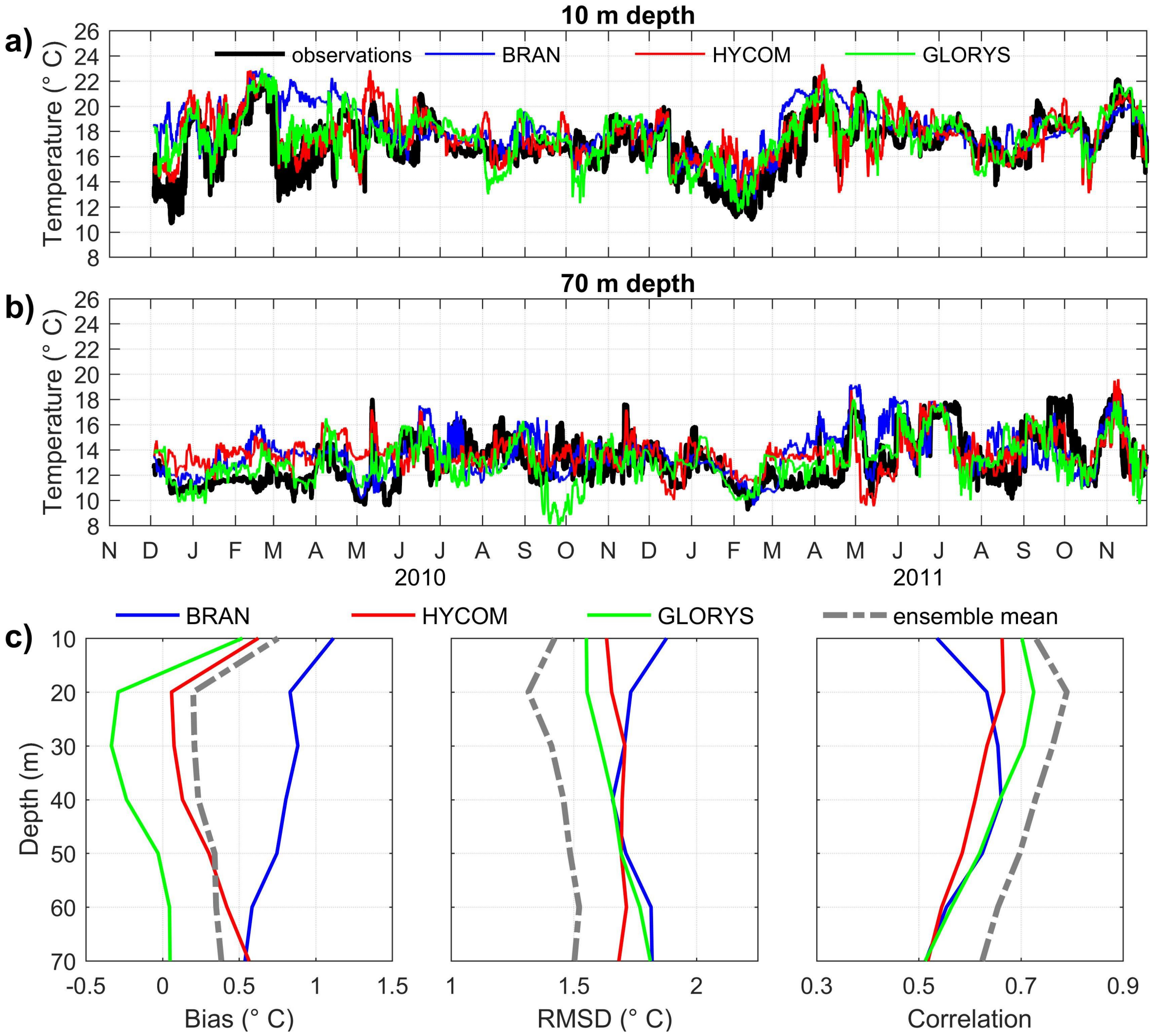

Figure 3.2: Comparison of temperature observations at the Bay Mouth UTR mooring (Figure 2.1) with the Algoa Bay CROCO model forced with different global ocean reanalysis products at the lateral boundaries. The WASA atmospheric product was used for surface forcing in all three experiments. (a) Time-series of temperature at 10 m depth. (b) Time-series of temperature at 70 m depth. (c) Summary statistics of model performance throughout the water column.

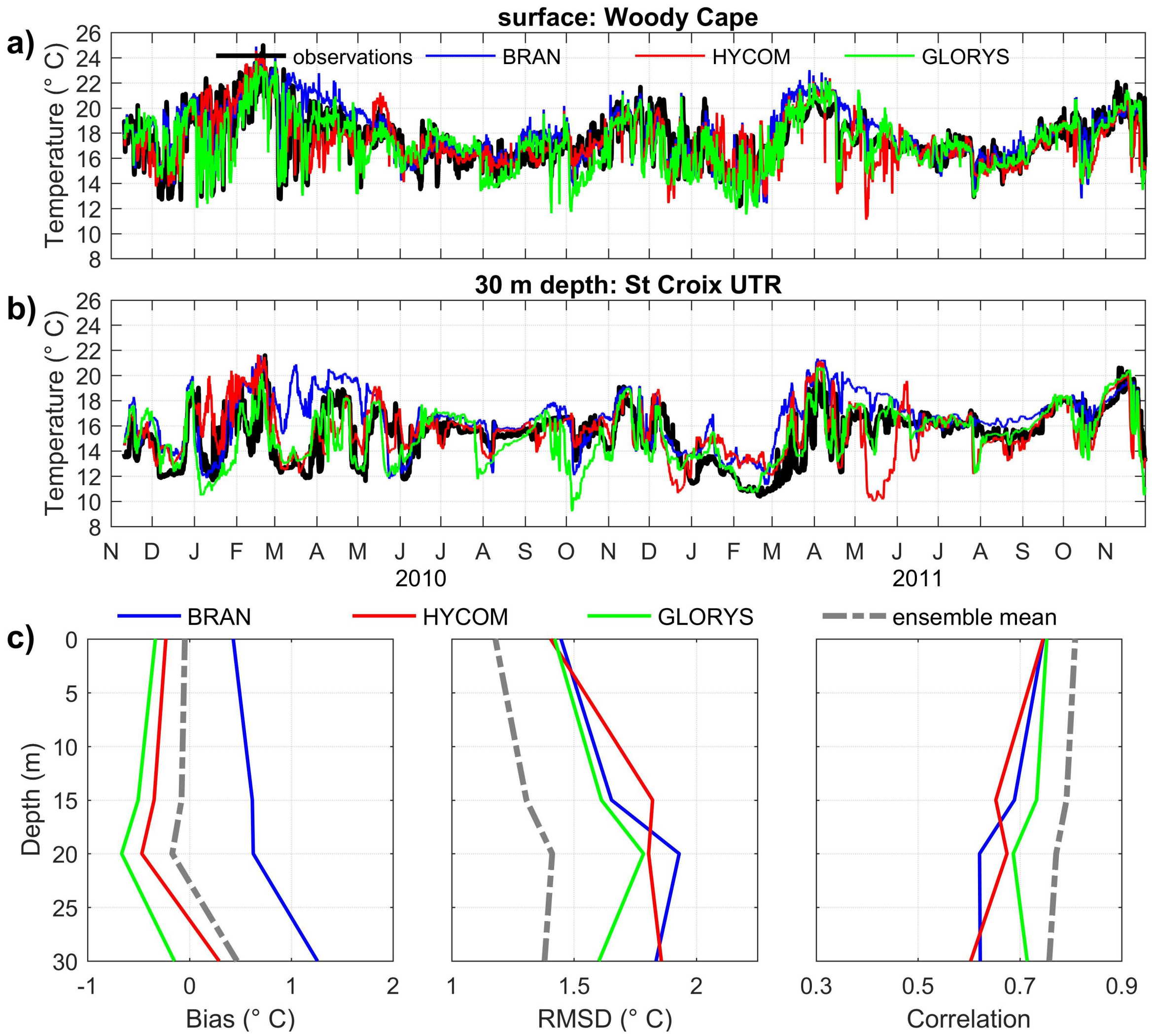

Figure 3.3: Comparison of nearshore temperature observations with the Algoa Bay CROCO model forced with different global ocean reanalysis products at the lateral boundaries. The WASA atmospheric product was used for surface forcing in all three experiments. (a) Time-series of surface temperature at the Woody Cape mooring. (b) Time-series of bottom temperature (30 m depth) at the St Croix UTR mooring. (c) Summary statistics of model performance throughout the water column (data for depths of 15-30 m correspond to the St Croix mooring while surface data corresponds to the Woody Cape mooring).

The model performance is quantified through the bias, centered root mean square difference ($RMSD$) and Pearson's correlation coefficient (R). For a series of N measured values x and the corresponding model values y, the performance metrics are computed as follows:

$$Bias = \overline{y} - \overline{x}, \tag{3.1}$$

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N} \left((y_i - \overline{y}) - (x_i - \overline{x})\right)^2}{N}}, \tag{3.2}$$

$$R = \frac{\sum_{i=1}^{N} \left((y_i - \overline{y})(x_i - \overline{x})\right)}{N\sigma_x\sigma_y} \tag{3.3}$$

where $\overline{x}$ and $\overline{y}$ are the mean values over the observed and model output time-series, respectively. σ_x and σ_y are the standard deviations of the measured and modelled values, respectively. The presented statistics are limited to periods where both measurements and model output are available. Summary statistics are presented for each simulation as well as the ensemble mean of all three simulations.

As noted by Goschen et al. (2015), the in-situ observations indicate some seasonality in the nearshore temperatures, although the seasonal signal is somewhat masked by the complexity of the system. The winter-spring period (June-November) is shown to be characterised by relatively stable temperatures ($\sim$16-18°C) and a well mixed water column. The summer-autumn period (October-May) is characterised by greater variability in nearshore temperatures and events of enhanced stratification. The warming/cooling events can persist for durations of weeks to months, with large inter-annual variability. For example, the January-March 2011 period was characterised by persistently cooler temperatures than the same period in 2010. Agulhas Current influences are cited as a major contributor to the observed warming and cooling of the entire water column within Algoa Bay, while some cooling events are linked to upwelling driven by persistent easterly winds (Goschen et al., 2015).

It is encouraging to note that all three simulations show some skill at capturing the event-scale dynamics of these warming/cooling events. The ability of the model to capture any specific event is shown to be sensitive to the choice of lateral forcing. For example, the BRAN-forced simulation is shown to significantly over-estimate temperatures over the period March-May 2010, the GLORYS-forced simulation exaggerates cooling events of July 2010 and October 2010, while the same is true of the HYCOM-forced simulation in May 2011 (Figure 3.3). Of the three simulations, the BRAN-forced simulation displays the largest nearshore bias, with a range of between +0.5°C and +1.25°C, depending on the location and depth. Nearshore temperature biases in the HYCOM- and GLORYS-forced simulations are comparable with each other, and range between -0.7°C to 0.7°C, depending on the location and depth. Overall, the GLORYS-forced simulation displays the highest correlation (and lowest $RMSD$) to the observed temperatures throughout the water column at both St Croix and Bay Mouth. In this simulation a correlation of $\sim$0.7 is achieved throughout the water column at St Croix as well as over the top 30 m of the water column at Bay Mouth. Correlations drop to $\sim$0.5 near the bottom at Bay Mouth, where variability in temperature is lower. The ensemble mean of the three simulations is shown to yield a notable increase (decrease) in correlation ($RMSD$) at all water depths and locations, indicating that the ensemble mean out-performs any individual simulation at reproducing nearshore temperature variability within Algoa Bay.

Figure 3.4 presents current roses at a depth of 7 m, as well as summary statistics for the modelled horizontal current components (u, v) throughout the water column. The plotted current directions are by convention the direction toward which the currents are flowing. Data at depths shallower than 7 m are excluded from the analysis due to surface contamination of the ADCP data. The observations indicate a dominant south-westerly flow at the location of the ADCP, roughly parallel with the local bathymetric contours (Figure 2.1). All three simulations reasonably capture the dominant south-westerly flow at this location, although the directional variability in the modelled currents tends to be lower than in the the observations, particularly for weaker current current speeds. Although the directional variability, as revealed by the current roses, is largely insensitive to the choice of boundary conditions, the current speeds at the ADCP are noticeably affected. The BRAN- and HYCOM-forced simulations result in the lowest and highest current speeds, respectively, while the the GLORYS-forced simulation results in mean speeds between the two, and in better agreement with the observations. The HYCOM-forced simulation is shown to display the lowest correlation (and highest $RMSD$) when compared to the ADCP observations. The GLORYS- and BRAN-forced sim-

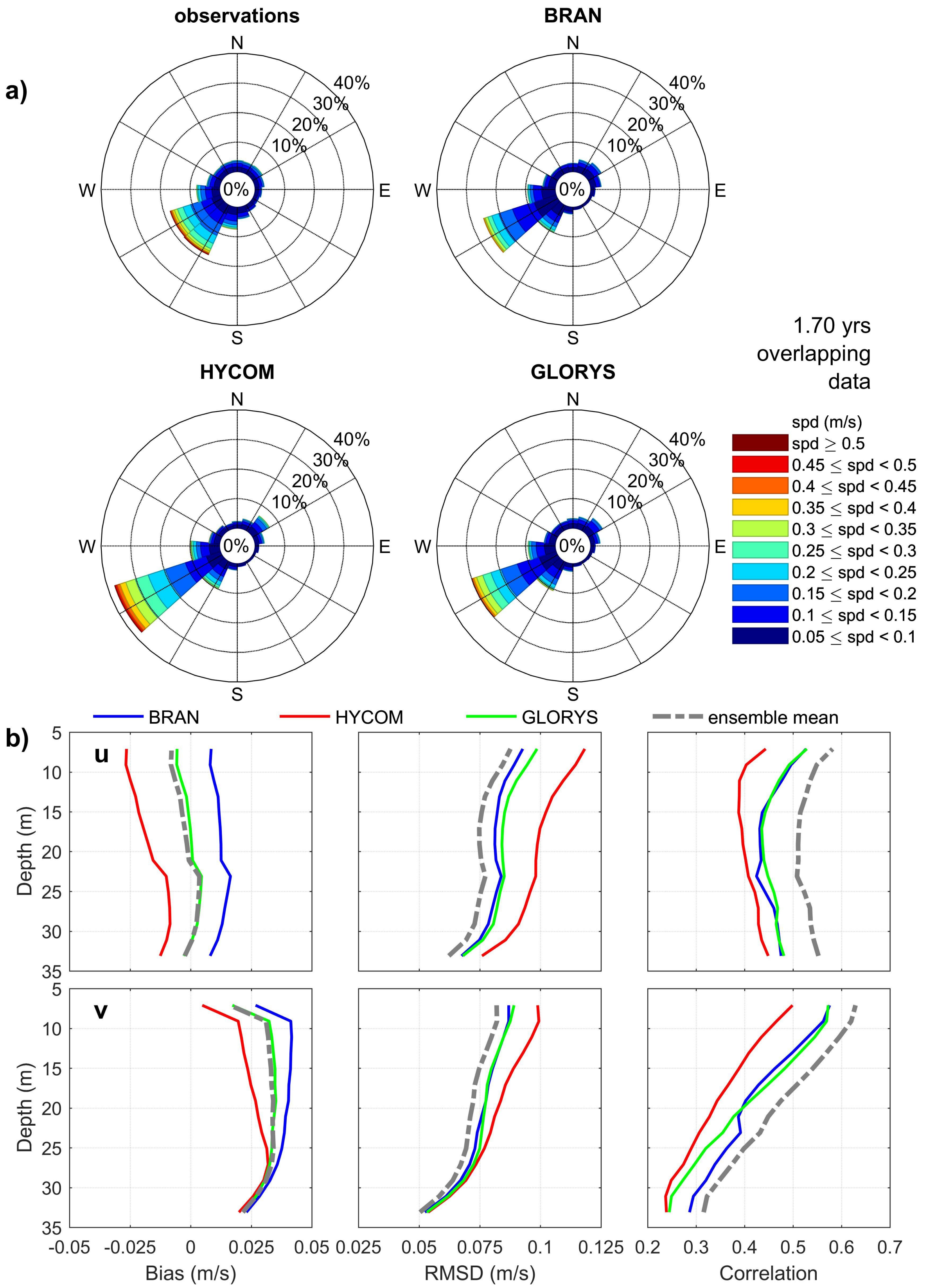

Figure 3.4: Comparison of ADCP current observations (Figure 2.1) with the Algoa Bay CROCO model forced with different global ocean reanalysis products at the lateral boundaries. The WASA atmospheric product was used for surface forcing in all three experiments. (a) Current roses at a depth of 7 m. (b) Summary statistics for the horizontal current components (u, v) throughout the water column.

ulations display very similar correlations and $RMSD$s throughout the water column. As per the temperature results, the ensemble mean of the three simulations is shown to indicate a notable improvement in the model performance throughout the water column at the location of the ADCP.

3.2. Sensitivity to atmospheric forcing

Figure 3.5 and Figure 3.6 compare time-series of observed temperature in Algoa Bay with the CROCO model forced with both the WASA and CFSR atmospheric forcing products. The comparison indicates that the atmospheric product has an insignificant impact on the modelled temperatures at the entrance to the bay (i.e. at the Bay Mouth UTR - Figure 3.5). The higher resolution WASA product is however shown to provide a marginal improvement in modelled temperatures in the nearshore regions of the bay over the coarser resolution CFSR product (Figure 3.6). The ensemble mean of the two simulations does not yield any improvement in the nearshore temperatures of the WASA-forced simulation.

Figure 3.7 presents the impact of the atmospheric forcing product on nearshore currents at the ADCP. The comparison suggests that the mean current state is not noticeably impacted by the choice of atmospheric forcing product. The higher resolution WASA product does however lead to a marked improvement in the correlations of the modelled currents with the observations throughout the water column. The ensemble mean of the two simulations does not yield any improvement in the nearshore currents of the WASA-forced simulation.

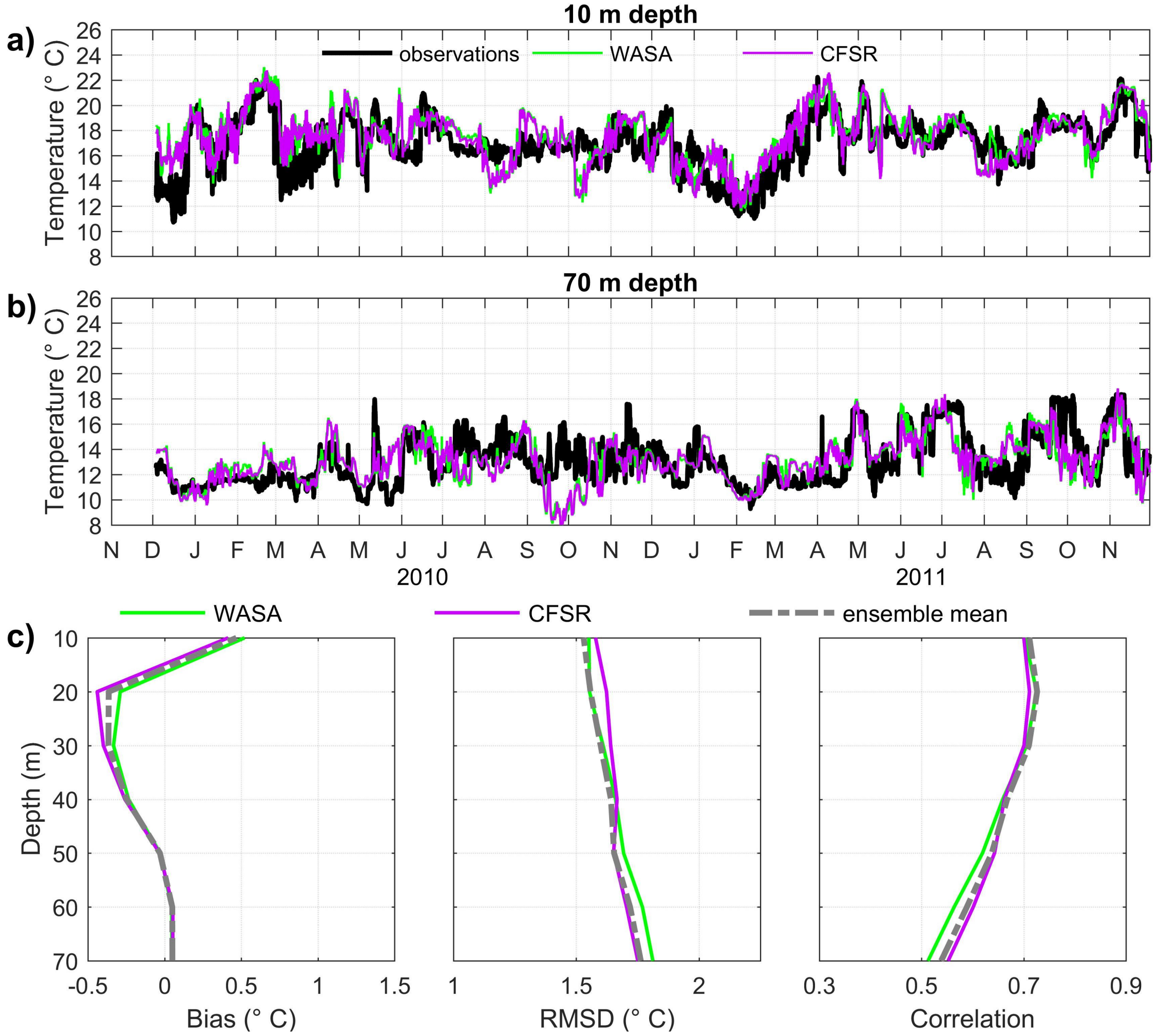

Figure 3.5: Comparison of temperature observations at the Bay Mouth UTR mooring (Figure 2.1) with the Algoa Bay model forced at the surface with different atmospheric products. The GLORYS reanalysis product was used to force the lateral boundaries in both experiments. (a) Time-series of temperature at 10 m depth. (b) Time-series of temperature at 70 m depth. (c) Time-series of stratification index (10 m - 70 m temperature). (d) Summary statistics of model performance throughout the water column.

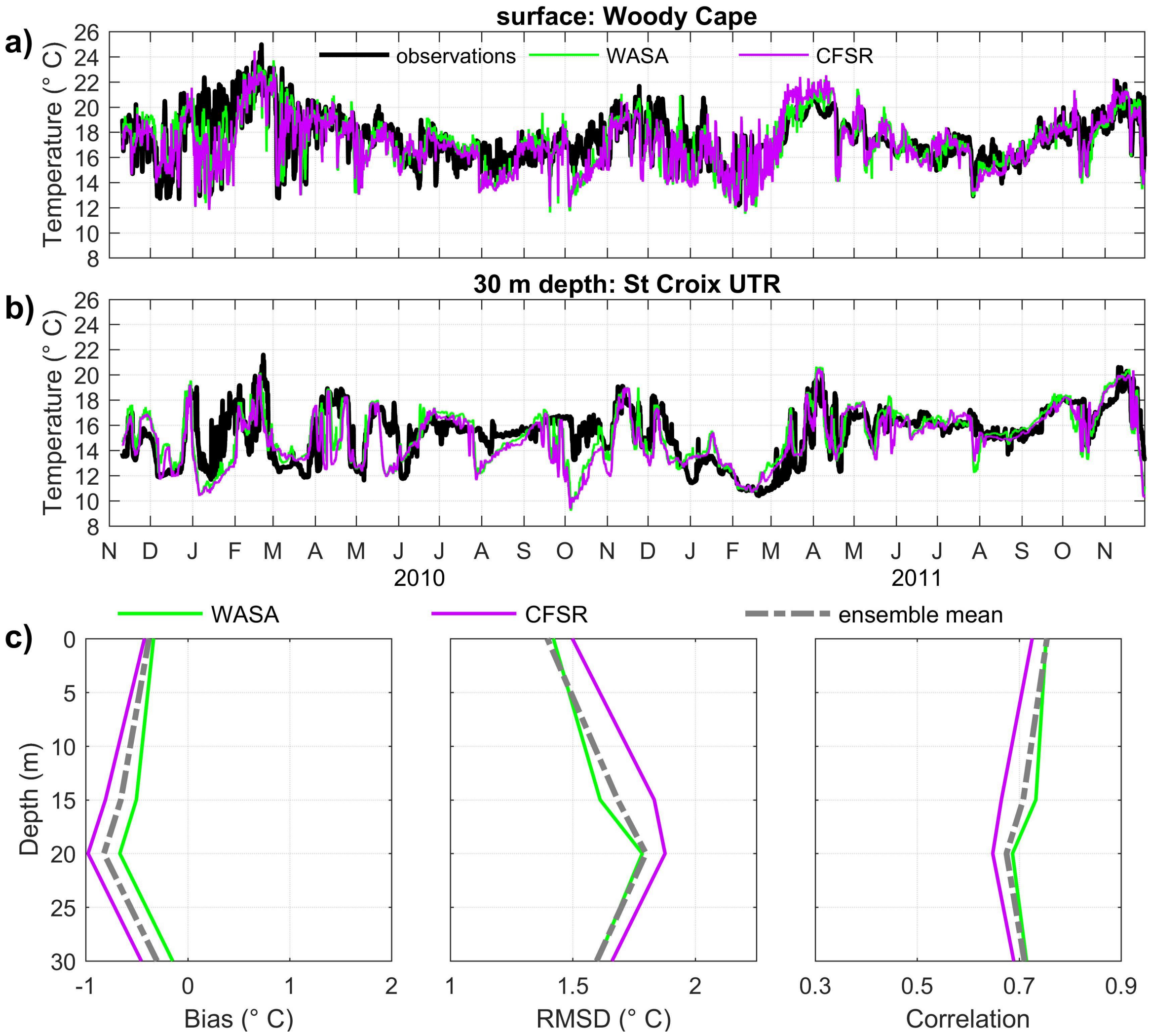

Figure 3.6: As per Figure 3.5, but for the Woody Cape Gully and St Croix UTR moorings. Data for depths of 15-30 m correspond to the St Croix moorings while surface data corresponds to the Woody Cape mooring.

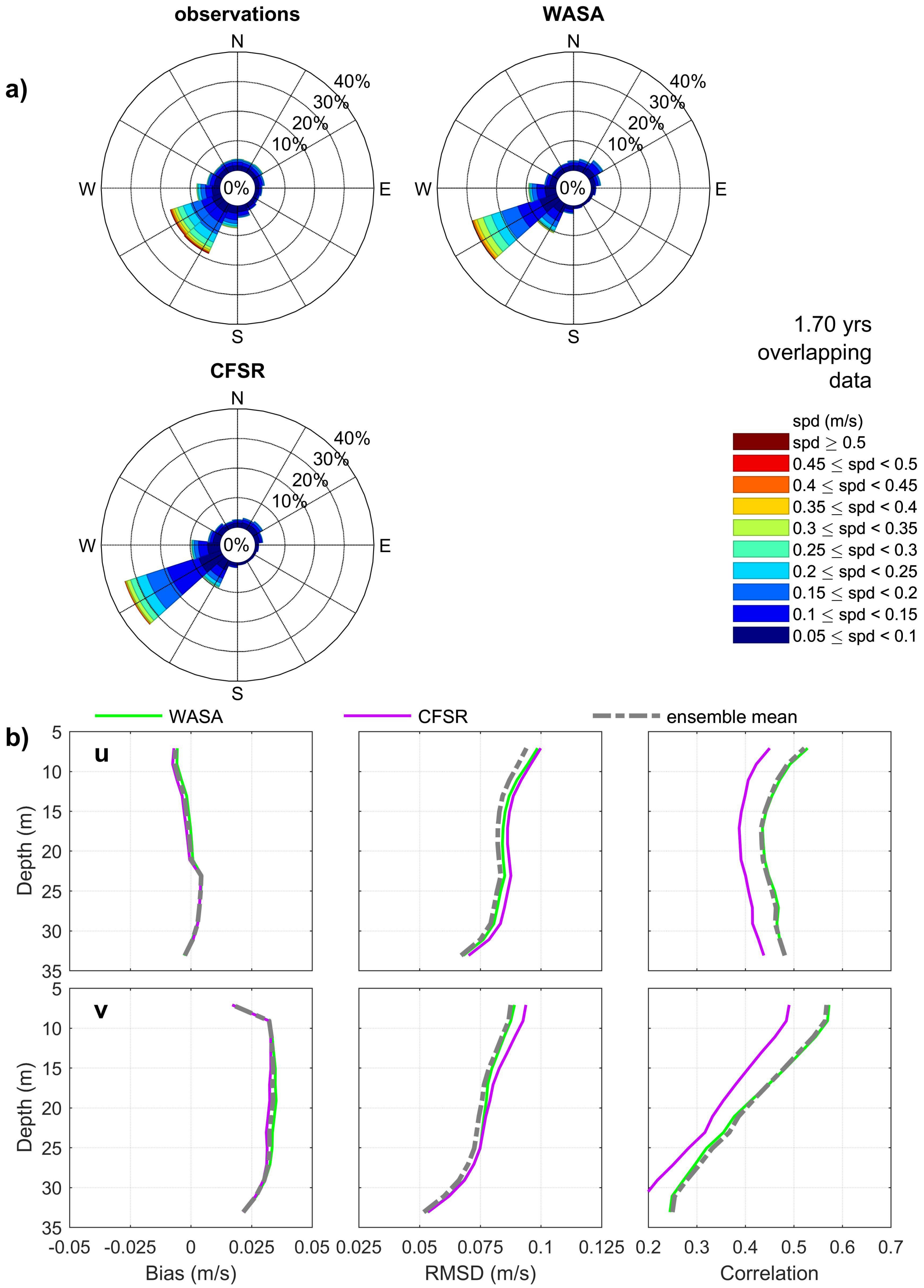

Figure 3.7: Comparison of ADCP current observations (Figure 2.1) with the Algoa Bay model forced at the surface with different atmospheric products. The GLORYS reanalysis product was used to force the lateral boundaries in both experiments. (a) Current roses at a depth of 7 m. (b) Summary statistics for the horizontal current components (u, v) throughout the water column.

4

Conclusions and recommendations

This report has presented the development of a high resolution CROCO model aimed at simulating nearshore dynamics within Algoa Bay. Comparing the model solution with in-situ observations of temperature and currents within the bay has allowed for an assessment of the realism of the model when forced with various available boundary conditions and atmospheric forcing products. The model forms the basis for the ongoing development of an operational forecast system for the bay.

Sensitivity tests to forcing the model with different global ocean reanalysis products (BRAN, HYCOM and GLORYS) suggest that all three products represent ‘acceptable’ choices, each with their own strengths and weaknesses. The HYCOM-forced simulation yields the lowest nearshore temperature biases, but is the poorest performer in terms of nearshore currents. The BRAN-forced simulation posses the highest nearshore temperature bias, but provides correlations to nearshore currents in line with the GLORYS-forced simulation. Overall, our results suggest that the GLORYS-forced simulation is the best performing model configuration, both in terms of nearshore temperatures and currents. It is interesting to note that the GLORYS product was also recommended for forcing regional simulations in New Zealand waters (de Souza et al., 2020). Each reanalysis product is associated with a similarly configured global operational forecast product. It is assumed that the relative performance of the reanalysis products as presented here will translate into the performance of the forecast products, although this has not been explicitly tested.

The ensemble mean of the three simulations provides a significant improvement in the performance of any of the individual simulations, both in terms of nearshore temperatures and nearshore currents. This is consistent with previous studies showing that the ensemble mean is usually a better estimation of the ocean state than any individual ocean reanalyses Balmaseda et al., 2015. The operational forecast system would therefore benefit from utilising multiple global forecast products for the generation of an ensemble of nested simulations. It is suggested that the ensemble approach will allow for more reliable predictions in the forecasting of pollutant advection, such as oil spills. The benefits of this approach may however need to be balanced against the additional computational cost in light of the available infrastructure for running the model.

It is interesting to note that the sensitivity tests on atmospheric forcing suggest that although the resolution of the WASA forcing product is an order of magnitude higher than that of the CFSR product, temperatures at the mouth of the bay are not significantly impacted, while a marginal improvement is seen in the nearshore temperatures. The largest impact of the high resolution winds is seen in a marked improvement in the correlation coefficients with the nearshore ADCP current observations, noting that the mean current variability is not greatly affected by the choice of atmospheric forcing product. This highlights the importance of small scale orographic features in affecting near-coastal winds and associated currents within the bay. In the absence of such a high-resolution product, the results suggest that a freely available global atmospheric product (e.g. GFS) may provide acceptable results which will still add value in the management of operations in the bay.

While the work presented in this report provides insight into the design of the operational forecast system for Algoa Bay, the drivers of bay-scale variability have not been diagnosed. It is known that the bay-scale dynamics are complex, responding to both local wind-driven variability as well as large-scale affects from the Agulhas Current. Ongoing work is aimed at elucidating the relative impact of the various driving mechanisms, thereby providing a more complete understanding of the bay-scale variability. This extended work is planned to be submitted for peer-reviewed publication.

Acknowledgements

We thank the Climate Systems Analysis Group (CSAG) for the provision of their WASA atmospheric product and the South African Navy Hydrographic Office (SANHO) for the provision of bathymetric data. The ADCP observations used in this study were undertaken by Lwandle Marine Environment Services on behalf of Petro SA, while the UTR observations were made available by the SAEON Elwandle Coastal Node. The study benefitted from computational facilities provided by the University of Cape Town's ICTS High Performance Computing team: hpc.uct.ac.za.

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