

Investigating future climate projections for southern Benguela using downscaled high-resolution climate models from the HighResMIP project (CMIP6)

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Abstract

The Southern Benguela Upwelling System (SBUS) is a climate-sensitive region characterised by significant environmental changes. This study investigates the relationship between the South Atlantic Anticyclone (SAA) and upwelling in the Southern Benguela, assessing how projected shifts in SAA due to climate changes may impact upwelling dynamics. The study used high-resolution models from the HighResMIP project within Coupled Model Intercomparison Project Phase 6 (CMIP6) to evaluate the responses of nearshore processes to large-scale changes caused by climate change. Future climate projections were analysed at a 25-km spatial resolution, allowing an assessment of nearshore responses to large-scale atmospheric changes. Future period simulations are based on the high-emissions scenario SSP5-8.5, similar to CMIP5 RCP8.5, and model simulations span historical (1950-2014) and future (2015-2050) periods.

The results indicate a southward migration and intensification of the SAA, particularly during summer, strengthening local winds that will shift offshore and southward. These shifts will lead to the weakening of the alongshore upwelling intensity and a potential offshore displacement of climate-sensitive upwelling regions, characterised by intensified upwelling. These changes will impact nutrient availability, primary productivity, and the broader marine ecosystem, potentially impacting fisheries and coastal livelihoods. The Benguela Jet, crucial for transporting small pelagic fish eggs and larvae, is also projected to shift offshore weakening, reducing nearshore retention.

While the study provides valuable insights, it acknowledges limitations in resolving finer-scale coastal processes at 25-km resolution and uncertainties inherent in high-emission projections. Future research should focus on refining regional downscaling techniques and further investigate the implications of these changes for adaptive, ecosystem-based management. Enhancing adaptive capacity through science-informed policy recommendations, community resilience strategies, and informed management practices will be essential to safeguard the region's ecological integrity and socio-economic sustainability as we approach 2050.

Keywords: Southern Benguela Upwelling System, Climate Change, upwelling, South Atlantic Anticyclone, nearshore processes, adaptive capacity, ecosystem-based management

List of Contents

Declaration.....	2
Acknowledgements.....	3
Abstract.....	4
List of Contents.....	5
List of Figures.....	8
List of Tables.....	15
1 Introduction.....	16
1.1 Background.....	16
1.2 Aims and objectives.....	18
1.3 Dissertation outline.....	19
2 Literature review.....	21
2.1 Climate change.....	21
2.2 Different emission scenarios.....	24
2.3 Eastern boundary upwelling systems (EBUS).....	28
2.4 Benguela upwelling system.....	30
2.5 Southern Benguela upwelling system.....	31
2.5.1 Atmospheric forcing of the southern Benguela.....	33
2.5.2 The nearshore processes of the SBUS.....	35
2.5.3 The Agulhas influence on the SBUS.....	36
2.5.4 Model uncertainties for projecting the SBUS.....	37
2.6 Conclusion.....	38
3 Data and Methods.....	40
3.1 Dataset Description.....	40
3.1.1 Climate Change Initiative.....	41
3.1.2 World Ocean Atlas 2023.....	42
3.1.3 AVISO altimetry.....	42
3.1.4 ERA 5 reanalysis model.....	42
3.1.5 GLORYS reanalysis model.....	42
3.1.6 HighResMIP.....	43
3.2 Methodology.....	45
3.2.1 Taylor Diagrams.....	46
3.2.2 Surface Geostrophic Currents.....	46
3.2.3 Local winds.....	47
3.3 GLORYS Evaluation.....	49

3.3.1	Sea Surface Temperature (SST)	49
3.3.2	Sea Surface Height and Geostrophic Currents	51
3.3.3	Vertical Temperature	52
4	Evaluation of historical HighResMIP	54
4.1	Local winds, Ekman, and South Atlantic Anticyclone dynamics.....	54
4.1.1	Wind stress.....	54
4.1.2	Wind Stress Curl.....	56
4.1.3	Ekman Transport and Ekman Pumping	57
4.1.4	South Atlantic Anticyclone: Intensity and Position.....	59
4.2	Sea Surface Temperature	63
4.3	Coastal Currents	65
4.3.1	Surface Currents.....	65
4.3.2	Sea Surface Height	66
4.4	Vertical alongshore current and across-shore winds	69
5	Future projections of SBUS from 2015 – 2050 based on HighResMIP models	73
5.1	Local Winds, Ekman dynamics and SAA.....	73
5.1.1	South Atlantic Anticyclone (SAA).....	73
5.1.2	Wind stress.....	75
5.1.3	Wind stress curl	76
5.1.4	Surface Ekman Transport	77
5.2	Sea Surface Temperature (SST).....	79
5.3	Coastal Currents	80
5.3.1	Surface Currents.....	80
5.3.2	Sea Surface Height	81
5.4	Vertical sections of alongshore currents	83
6	Discussion	89
6.1	Influence of South Atlantic Anticyclone on upwelling	89
6.2	Local winds	91
6.3	Current circulation of the SBUS.....	93
6.3.1	Surface currents: Benguela Jet.....	93
6.3.2	Geostrophic currents.....	94
6.3.3	Vertical Transects.....	95
6.4	Implications on the SBUS.....	97
6.4.1	Potential Socio-Ecological Impacts.....	97
6.4.2	Adaptation strategies	98
6.4.3	Added value of High-resolution modelling	99

6.5	Model uncertainties and limitations.....	100
7	Conclusion and Future Work.....	102
8	References	105

List of Figures

Figure 1.1: A map of the South-East Atlantic Ocean that depicts the physical characteristics and surface currents within the BCLME. The black dashed line in the north, from 15° to 17°S, represents the Angola-Benguela Front, which marks the boundary between the warm tropical waters and the colder Benguela waters. At 26.6°S, the Lüderitz cell separates the northern and southern sections of the Benguela system. At the southern boundary, the warm Agulhas Current transports warm water into the South Atlantic through Agulhas rings (depicted as red circular arrows). The map also highlights key bathymetric features, including the Agulhas Bank (a spawning ground for small pelagic fish), the Walvis Ridge, and the Agulhas Ridge. (Source: Adapted from Hutchings et al., 2009). 17

Figure 2.1: Schematic illustrating impacts of climate change on the ocean, including sea level rise, increasing ocean heat content and marine heat waves, ocean deoxygenation, and ocean acidification. It also highlights interconnected processes linking the ocean with the cryosphere, such as melting ice sheets and glaciers, changes in sea ice extent, and permafrost thaw. The increase or decrease in these impacts is indicated by arrows. Source (Adapted from IPCC, 2019). 22

Figure 2.2: The SSP–RCP scenario matrix used in ScenarioMIP (CMIP6). Each cell represents a combination of a Shared Socioeconomic Pathway (SSP) and a level of radiative forcing by 2100 (W/m^2). Dark blue cells indicate Tier 1 scenarios that were prioritised for full climate model simulations. Light blue cells show Tier 2 scenarios, including overshoot pathways and long-term extensions. White cells are not directly simulated but are conceptually linked. The CMIP5 RCPs are shown alongside for comparison. Adapted from O'Neill et al. (2016). 28

Figure 2.3: (a) A schematic representation of the circulation with the SBUS, showing the surface currents, upwelling cells, river outflow and the major oceanographic features at various scales. Key features include the Benguela Oceanic Current (BOC), Benguela Coastal Current (BCC), South Atlantic Current (SAC), Agulhas Current (AgC), subtropical front (STF), subtropical Gyre (STG), Antarctic Circumpolar Current (ACC). The Benguela Current and Benguela Jet are labelled BOC and 'Cape Jet', respectively (Hardman-Mountford et al., 2003). (b) The vertical schematic depicts alongshore currents off Cape Point, based on in situ ADCP measurements, highlighting the Benguela Jet (yellow), the

shelf-edge poleward undercurrent (red), and the nearshore poleward current (green).
Adapted from Nelson (1989) and Ragoasha et al. (2022). 32

Figure 2.4: A schematic representation of major oceanographic and atmospheric features that impact biological processes within the Benguela upwelling system across various temporal and space scales (Shannon et al., 1996). 34

Figure 2.5: The passage of cyclones south of the continent (from Nelson and Hutchings, 1983, 1987) and the formation of a trapped coastal low which promotes pulsed upwelling at 3-10 day intervals (Hutchings et al., 2009). The symbols a-e represent different phases of the South Atlantic Anticyclone and coastal low, and their effects on upwelling: a) The South Atlantic Anticyclone is well-established, with a coastal low at Lüderitz, resulting in southerly winds that promote upwelling in the SBUS; b) The South Atlantic Anticyclone extends eastwards, and the coastal low at Lüderitz shifts south, driving gale-force winds that intensify upwelling; c) A weakening of the South Atlantic Anticyclone allows the front to ridge, inducing westerly winds that suppress upwelling; d) The strengthening of the South Atlantic Anticyclone once again drives southerly winds, promoting upwelling; e) Berg wind conditions, characterised by warm, dry offshore winds originating from the interior of South Africa, inhibit upwelling by reducing vertical mixing and nutrient supply. The L in each figure refers to the coastal low, and the H refers to the high-pressure cell. 35

Figure 3.1 The HighResMIP experimental design, showing the component experiments (Tier 1, Tier 2, and Tier 3) and their relationships. Tier 1 and Tier 3 are represented in the upper panel, while Tier 2 is shown in the bottom panel. 44

Figure 3.2: Annual average of Sea Surface Temperature (SST): a) Annual CCI SST averaged over 1993-2016; b) GLORYS reanalysis SST averaged over 1993-2021; c) Annual mean SST bias (GLORYS-CCI), averaged over 1993-2021; d) monthly climatological mean time series of the SST GLORYS (solid red line) and CCI (dashed blue line) averaged over the domain, and (e) the monthly SST difference between the GLORYS reanalysis model and CCI. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The 16°C isotherm is also superimposed in red. 50

Figure 3.3: A long-term average of SSH (contours) and geostrophic velocities (vectors) a) GLORYS Reanalysis averaged over 1993-2021 and b) AVISO Altimetry data averaged over 1993-2018. The superimposed solid lines indicate the cross-shore transects at St Helena Bay (black solid line), Grotto Bay (red solid line), and Cape Point (blue solid line).

The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.....	51
Figure 3.4: Across-shore profiles of SST (red), SSH (blue), and alongshore geostrophic currents (magenta), GLORYS reanalysis averaged from 1993-2021 (solid), and AVISO altimetry averaged from 1993-2018 (dashed). The cross-shore profiles are shown over the three transects: St Helena Bay, Grotto Bay, and Cape Point (see Figure 3.3).....	52
Figure 3.5: Temperature transect off Grotto Bay (red line in Figure 3.4) with the 16°C isotherm superimposed (red). a) World Ocean Atlas annual average (WOA2023); b) GLORYS annual average; c) Temperature bias (TGLORYS - TWOA2023), the green line denotes the 0°C isotherm.	53
Figure 4.1: Historical Wind stress magnitude and direction for ERA5, VHR4, and FGOALS during summer (a-c) and winter (d-f) seasons. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Time series (g) shows monthly averaged wind stress magnitudes from the three models over the SBUS region.....	55
Figure 4.2: Historical wind stress curl for ERA5, VHR4, and FGOALS during summer (a-c) and winter (d-f) seasons. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Time series (g) shows detailed monthly averaged wind stress curl from the three models over the SBUS region.	57
Figure 4.3: Historical seasonal Ekman transport (vectors, $\text{m}^2\cdot\text{s}^{-1}$) and Ekman pumping (shaded, $\text{m}\cdot\text{day}^{-1}$) from the ERA5 reanalysis model and two HighResMIP models (VHR4 and FGOALS) for the summer (a-c) and winter (d-f) seasons. The Ekman pumping is demonstrated in $\text{m}\cdot\text{day}^{-1}$. Positive (negative) values indicate upwelling (downwelling). A reference vector of $0.5\text{ m}^2\cdot\text{s}^{-1}$ is shown in the top-right of each subplot. The black line represents the region of zero Ekman pumping. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.	59
Figure 4.4: Seasonal surface maps of the MSLP (hPa) from ERA5, HiRAM and FGOALS models illustrating the location and intensity of the South Atlantic Anticyclone (SAA) from the historical climate for summer (a-c) and winter (d-f) seasons. The vectors overlaid represent wind intensity (length of the arrows) and direction (arrow's head).	61
Figure 4.5: Monthly climatology of SAA intensity (a) and latitudinal position (b) from ERA5 reanalysis (blue line) and two HighResMIP models, FGOALS (red line) and HiRAM (magenta line) from the historical climate.	61

Figure 4.6: Taylor Diagram of the southern Benguela region from 1950-2014 showing a statistical relationship between VHR4 (cyan), FGOALS (black), and HiRAM (green) models from HighResMIP, the ERA5 reanalysis model (red) was used as a reference. The diagram gives a summary of the standard deviation (black), correlation (blue), Root Mean Square Difference (magenta) for all the presented atmospheric variables, Meridional and zonal winds (a, b), and Mean Sea Level Pressure (c) across all the models. 62

Figure 4.7: Summer averages of Sea Surface Temperature (SST) from the GLORYS reanalysis model and VHR4, HR4 and CAM5 HighResMIP models (a-d). The SST differences between GLORYS and HighResMIP models are shown(e-g). The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Positive (negative) values in the bias are regions where the model overestimates (underestimates) GLORYS SST..... 64

Figure 4.8: Winter averages of Sea Surface Temperature (SST) from the GLORYS reanalysis model and VHR4, HR4 and CAM5 HighResMIP models (a-d). The SST differences between GLORYS and HighResMIP models are shown(e-g). The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Positive (negative) values in the bias are regions where the model overestimates (underestimates) GLORYS SST..... 65

Figure 4.9: Historical seasonal climatology of surface currents for GLORYS reanalysis model and HighResMIP models (VHR4, HR4, and CAM5) for the summer (a-d) and winter (e-h) seasons. The magnitude of the current is shown in colour ($\text{m}\cdot\text{s}^{-1}$), and current vectors are superimposed, as well as the 200m, 500m, and 2000m isobaths (solid white) from SRTM. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. 66

Figure 4.10: Historical seasonal Sea Surface Height (SSH) with corresponding surface geostrophic currents superimposed vectors from GLORYS reanalysis model and three HighResMIP models (VHR4, HR4, and CAM5) for summer (a-d) and winter (e-h) seasons. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. 67

Figure 4.11: Taylor Diagram of the southern Benguela region from 1950-2014 showing a statistical relationship between VHR4 (cyan), HR4 (black), and CAM5 (green) models from HighResMIP, the GLORYS reanalysis model (red) was used as a reference. The

diagram gives a summary of the standard deviation (black), correlation (blue), Root Mean Square Difference (magenta) for all the presented oceanic variables, Sea Surface Temperature (a), Seawater temperature (b), Sea Surface Height (c), Zonal and meridional velocities (d, e) across all the models..... 68

Figure 4.12: St Helena Bay vertical transect of historical alongshore velocities ($\text{m}\cdot\text{s}^{-1}$), isotherms (white contours), wind stress and wind stress curl from three models, ERA5 reanalysis model (red), VHR4 (magenta), and FGOALS (blue). The first two rows show the alongshore current velocities with temperature, the contours of the current intensity are shown in black, and the zero contour is bold. The third row shows the alongshore wind stress (i) and the wind-stress curl (j) for the across-shore transect, with the zero line (black). Summer is indicated by solid lines, and dashed lines indicate winter..... 70

Figure 4.13: Similar to Figure 4.12 but for the Grotto Bay transect. 71

Figure 4.14: Similar to Figures 4.12 and 4.13 but for the Cape Point transect. 71

Figure 5.1: Historical and projected seasonal change of MSLP (hPa) from HiRAM and FGOALS models illustrating the location and intensity of the South Atlantic Anticyclone (SAA) from 2015 – 2050. Summer is shown in panels (a–d) and winter in panels (e–h). The historical climate is defined by the solid blue line, and the future climate by the solid red line (a, c, e, f). The projected MSLP change (b, d, f, g) between the future (2015 - 2050) and historical climate (1950 -2014). 74

Figure 5.2: Historical and projected future monthly climatology of SAA intensity (a) and latitudinal position (b) from FGOALS (red line) and HiRAM (magenta line) from 1950 - 2050. Projected change (2050-1950) of the SAA intensity (c) and latitudinal position (d). 75

Figure 5.3: Historical and projected seasonal change of wind stress magnitude and direction (Nm^{-2}) from VHR4 and FGOALS models from 1950 – 2050. Panels (a–c) shows VHR4 summer, with (a) representing the historical period, (b) the future projection, and (c) the projected change. Panels (e–g) show the corresponding winter conditions for VHR4. Panels (i–k) and (l–n) present summer and winter from the FGOALS model, respectively, following the same structure. Panel (d) shows average monthly wind stress magnitudes for both the historical and future periods, while panel (h) displays the projected monthly changes. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. 76

Figure 5.4: Historical and projected seasonal change of wind stress curl magnitude ($\text{N}\cdot\text{m}^{-3}$) from VHR4 and FGOALS models from 1950 – 2050. Rows one and three represent summer, and rows two and four represent winter. Rows one and three represent summer, and rows two and four represent winter for the historical (a, e, i, l) and the future climate (b, f, j, m). The projected wind stress curl change (c, g, k, n) between the future (2015 - 2050) and historical (1950 -2014) is in column three. Average monthly time series of the wind stress curl magnitudes for historical and future climate (d) and the projected wind stress change (h) between the future and historical climate. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The black line represents the region of zero wind stress curl..... 77

Figure 5.5: Historical and projected seasonal Ekman transport (vectors, $\text{m}^2\cdot\text{s}^{-1}$) and Ekman pumping and suction (shaded, $\text{m}\cdot\text{day}^{-1}$) change from VHR4 and FGOALS models from 1950 – 2050. Rows one and three represent summer, and rows two and four represent winter for the historical (a, e, i, l) and the future climate (b, f, j, m). The projected Ekman change (c, g, k, n) between the future (2015 -2050) and historical (1950 – 2014) climate is in column three. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The black line represents the region of zero Ekman pumping. A reference vector of $0.5 \text{ m}^2\cdot\text{s}^{-1}$ is shown in the top-right of each subplot..... 78

Figure 5.6: Historical and projected seasonal change of Sea Surface Temperatures from VHR4, HR4, and CAM5 models from 1950 to 2050. Rows one, two, and three represent the historical (1950 -2014), future (2015 -2050), and projected changes in SST (2050-1950), respectively. Columns one, three, and five represent summer projections, and columns two, four, and six represent winter projections. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Average monthly time series of Sea Surface Temperatures for historical and future climate (s) and the projected change (t) between the future and historical period..... 80

Figure 5.7: Historical and projected seasonal change of surface currents from VHR4, HR4, and CAM5 models from 1950 – 2050. Rows one, two and three represent historical (1950 -2014) and future (2015 -2050) climate and the projected change (2050-1950), respectively, for summer (columns one, three, and five) and winter (columns two, four, and six) projections. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The black, magenta and blue lines represent the cross-shore transects at St Helena Bay, Grotto Bay, and Cape Point, where the vertical sections of the alongshore currents were taken. The white contour represents the bathymetry levels (200, 500, 2000 m)..... 81

Figure 5.8: Historical and projected seasonal change of surface geostrophic currents (vectors) and Sea Surface Height (shaded) from VHR4, HR4, and CAM5 models from 1950 – 2050. Rows one, two and three represent the historical (1950 -2014) and future (2015 -2050) climate and the projected change (Future - Historical), respectively. Columns one, three, and five represent summer projections, and columns two, four, and six represent winter projections. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.	82
Figure 5.9: Historical and future projections of the vertical alongshore currents ($\text{m}\cdot\text{s}^{-1}$) and temperature (white contours) from VHR4, HR4, and CAM5 models from 1950 – 2050 from the St Helena Bay transect. Row one, two and three represent historical (1950 -2014), future (2015 -2050) and projected change (Future - Historical), respectively. Columns one, three, and five represent summer projections, and columns two, four, and six represent winter projections. The protrusion of the poleward undercurrent is indicated by the black zero $\text{m}\cdot\text{s}^{-1}$ contour not open at the surface. The black contours on the difference plot represent isotherms associated with temperature changes.	85
Figure 5.10: Historical and projected future seasonal across-shore wind stress (a, c, e) and wind stress curl (b, d, f) from VHR4 (red line) and FGOALS (magenta line) from 1950 – 2050 from the St Helena Bay transect. Projected change (2050-1950) of the wind stress (e) and wind stress curl (f). The solid line represents summer, and the dotted lines represent winter projections.	85
Figure 5.11: Similar to Figure 5.9 but for Grotto Bay.	86
Figure 5.12: Similar to Figure 5.10 but for Grotto Bay.	86
Figure 5.13: Similar to Figures 5.9 and 5.11 but for Cape Point.	87
Figure 5.14: Similar to Figures 5.10 and 5.12 but for Cape Point.	87

List of Tables

Table 2.1: A summary of the SSPs and their narratives (Banda et al., 2022)	25
Table 3.1 :Summary of datasets used in the study, including the variables provided for oceanic and atmospheric analysis to assess the impacts of climate change on the Southern Benguela Upwelling System. All datasets are provided at a monthly temporal resolution.	41
Table 3.2: HighResMIP models used in this study and their reporting institutions and countries, with 0.25° resolution and r1i1p1f1 Ensemble member.	45

1 Introduction

1.1 Background

Oceans are one of the most dynamic ecosystems on Earth, as they cover approximately 70% of the planet's surface (Herr and Galland, 2009). However, these ecosystems are also susceptible to the effects of climate change. Climate change impacts on the marine environment have been reported in nearly all the world's marine ecosystems (Halpern et al., 2019; Chen, 2021; Gissi et al., 2021; Cooley et al., 2022). Climate change has been reported to affect marine ecosystems' physical and biogeochemical processes (Brierley and Kingsford, 2009; Brown et al., 2010; Poloczanska et al., 2016). These changes in marine ecosystems affect the distribution and abundance of some marine species (Frusher et al., 2014; Mathis et al., 2015; Poloczanska et al., 2016; Pecl et al., 2017), thus altering the structure and functioning of marine ecosystems and also resource users.

In southern Africa, the Benguela Current Large Marine Ecosystem (BCLME) extends along the south-west coast of the continent, spanning approximately from 5°S to 37°S and from 0°E to 26°E (Figure 1.1) (Shillington, 2006; Shannon et al., 2006; Blank et al., 2009). It is one of four major eastern boundary upwelling systems (EBUS) in the world (Hill et al. 1998). The BCLME is divided into two by the Lüderitz upwelling cell at 26.6°S, the largest perennial upwelling feature in the region, forming the northern Benguela system and the southern Benguela upwelling system (SBUS) (Figure 1.1). This study investigates the SBUS, geographically defined by the Lüderitz upwelling cell (26.6°S) at its northern limit and the warm Agulhas current (37°S) to the south (Shannon & Nelson, 1996; Weeks et al., 2006). This is a highly variable and complex system that has experienced considerable environmental fluctuations and changes in recent decades. (Cochrane et al., 2009; Hampton, 2012; Blamey et al., 2012; 2015; Jarre et al., 2015; van der Lingen & Hampton, 2018). The environmental variability and change have caused shifts in the distribution of marine resources such as small pelagic (anchovies and sardines), the west coast rock lobster, and several other fish and bird species, consequently affecting the people dependent on fishing and other coastal resources for their livelihoods negatively (Blamey et al., 2015).

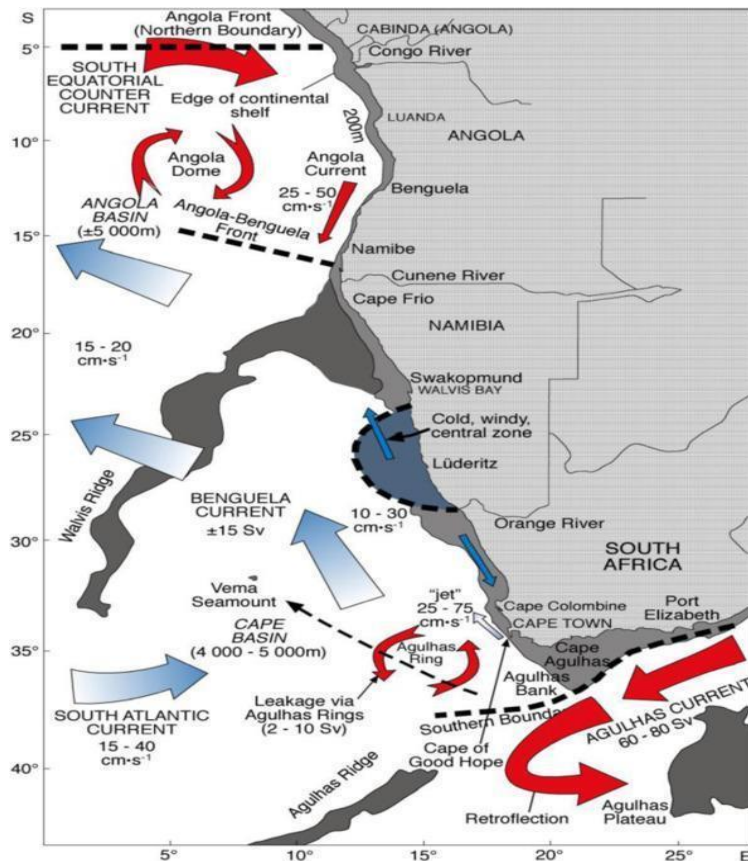


Figure 1.1: A map of the South-East Atlantic Ocean that depicts the physical characteristics and surface currents within the BCLME. The black dashed line in the north, from 15° to 17°S, represents the Angola-Benguela Front, which marks the boundary between the warm tropical waters and the colder Benguela waters. At 26.6°S, the Lüderitz cell separates the northern and southern sections of the Benguela system. At the southern boundary, the warm Agulhas Current transports warm water into the South Atlantic through Agulhas rings (depicted as red circular arrows). The map also highlights key bathymetric features, including the Agulhas Bank (a spawning ground for small pelagic fish), the Walvis Ridge, and the Agulhas Ridge. (Source: Adapted from Hutchings et al., 2009).

The southern Benguela is primarily influenced by two atmospheric systems: the South Atlantic Anticyclone (SAA) and the continental heat low. The SAA is a semi-permanent high-pressure system located over the South Atlantic Ocean, characterised by an anticlockwise circulation of winds in the southern hemisphere (Risien et al., 2004; Lübbecke et al., 2010; Reboita et al., 2019). The presence and the position of the SAA over the subtropical South Atlantic significantly impacts the climate of the SBUS as it generates southeasterly winds, promoting upwelling in the region. These dynamics have direct implications for the productivity of the upwelling system, which plays a crucial role in supporting South African fisheries, which includes the commercial, small-scale, and recreational fisheries sectors. Additionally, the region experiences strong wind stress, driven primarily by the SAA, due to its exposure to the South Atlantic Ocean (Shannon, 1985). The SAA is crucial in driving the southerly wind stress along the coast (Shillington et al., 2006). To the south of the African continent, westerly winds

are typically observed, and these winds intermittently change direction due to the eastward propagation of mid-latitude cyclones (Shillington et al., 2006). During the summer, surface heating over the South African continent generates low-pressure systems, which emerge and contribute to the zonal pressure gradient. These pressure systems interact with the dynamics of the SAA and the upwelling process, thereby influencing the climate patterns and conditions in the southern Benguela region. Therefore, understanding the dynamics of the SAA and the upwelling phenomenon along SBUS is crucial for comprehending the region's climate and oceanographic conditions.

This study focuses on evaluating the responses of the nearshore processes in the southern Benguela and understanding how these processes respond to large-scale changes caused by climate change. These nearshore processes include upwelling, coastal currents, and winds. Understanding the dynamics of the SAA and its interaction with the upwelling system is crucial for accurately projecting future upwelling trends and variability in southern Benguela. This study was developed within the framework of the 'Ecosystem-based adaptive capacity through community engagement (Eco-ACE)' project. Eco-ACE is an interdisciplinary project that aims to build the adaptive capacity of vulnerable groups in coastal communities to change (including climate change) at multiple scales. This study will contribute to the Eco-ACE project by understanding the nearshore processes of South Africa's southern Benguela region and determining how these processes respond to large-scale changes such as climate change. The response of these nearshore processes to climate change is currently not well understood as a result of lacking high resolution downscaled climate models, the high uncertainty in future projections, and the challenges in accurately simulating the complex interactions between atmospheric, oceanic, and coastal dynamics at finer spatial and temporal scales.

1.2 Aims and objectives

Aim

- To evaluate the relationship between the SAA and upwelling dynamics in the southern Benguela and assess how climate change may affect the SAA and ultimately affect upwelling patterns in the region.

Objectives

- To characterise the seasonal variability of the position and intensity of the SAA in the SBUS, and investigate its influence on local winds, coastal upwelling patterns and

regional circulation.

- To assess the projected changes in the seasonal SAA's characteristics (intensity and position) under the CMIP6 SSP5-8.5 scenario and evaluate the response of the nearshore processes to these changes.

To effectively address the aim and objectives, this study seeks to answer the following research questions:

- What is the seasonal variability in the position and intensity of the SAA over the SBUS?
- How does the seasonal variability in the position and intensity of the SAA influence local wind patterns, upwelling-favourable conditions, and regional ocean circulation in the SBUS?
- What are the projected changes in the seasonal position and intensity of the SAA under the CMIP6 SSP5-8.5 scenario?
- What are the projected impacts of changes in the SAA on nearshore wind forcing, Ekman transport, and ocean circulation patterns in the SBUS?

Understanding the physical and environmental processes of coastal regions and predicting future changes in the southern Benguela are crucial for supporting fisheries and coastal communities. Improved knowledge of potential climate change impacts will help these communities prioritise adaptation strategies and enhance their resilience.

1.3 Dissertation outline

The outline of the dissertation is as follows: **Chapter 2** covers a literature review that explores the broader impact of climate change on SAA, ocean circulation, wind patterns, and upwelling, focusing on the SBUS region. The chapter also explores emissions scenarios. **Chapter 3** details the data and methods used in the study. It describes the data sources and outlines the data processing steps used. The chapter also explains the statistical methods employed for model evaluation. **Chapter 4** validates the historical HighResMIP models against the reanalysis models employed in this study (GLORYS and ERA5). It provides a seasonal analysis of historical SAA variability and upwelling dynamics, focusing on seasonal differences between summer and winter, the chapter also provides the statistical methods employed for model evaluation. **Chapter 5** presents analysis results comparing the historical (1950-2014) and projected future climate conditions (2015-2050) in the SBUS using the HighResMIP simulations. It illustrates changes in SAA and upwelling dynamics by evaluating spatial and

temporal differences between the historical and future periods. The impacts of climate change on the SAA and upwelling dynamics within the SBUS are discussed in **Chapter 6**. It explores the potential ecological and socio-economic implications of these changes. The chapter also addresses model uncertainties and limitations. The final chapter, **Chapter 7**, presents the conclusions of the study and outlines potential directions for future research.

2 Literature review

2.1 Climate change

Climate change is considered one of the greatest threats to marine ecosystems and humans (Blanchard et al., 2017; IPBES, 2019; Lotze et al., 2019). Climate impacts are already evident in most marine ecosystems (Cochrane et al., 2009; Frusher et al., 2014; Cooley et al., 2022) and include changes in the ecosystem's structure and functioning, as well as species growth, distribution, and abundance (e.g., Cheung et al., 2013; Cooley et al., 2022). The observed impacts of climate change include changes in temperature, nutrient input, ocean circulation and productivity, and ocean acidification as a result of the ongoing uptake of atmospheric carbon dioxide (Doney et al., 2012; Pörtner et al., 2014; Poloczanska et al., 2016; Cooley et al., 2022). Figure 2.1 provides a visual summary of some of these impacts.

Climate change has already caused an increase in temperatures worldwide, resulting in ocean warming. The warming has led to a decline in fisheries production, with some areas already experiencing approximately 35% decline in Maximum Sustainable Yield (MSY) of important fish stocks since the 1930s (Free et al., 2019). Additionally, fishing communities dependent on fishing for their livelihoods being affected (Barange et al., 2014; Hoegh-Guldberg et al., 2014; Merino et al., 2010). Tittensor et al. (2021), using a state-of-the-art ecosystem modelling ensemble, highlighted a significant decline in the mean global marine animal biomass under both strong mitigation and high emission scenarios due to warming.

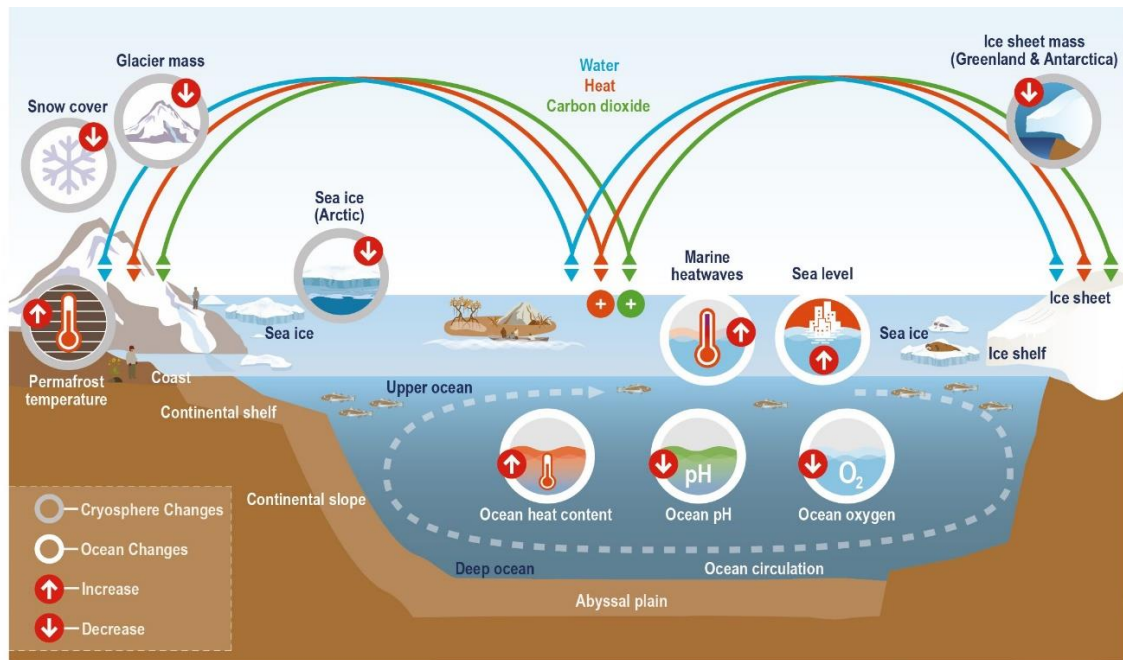


Figure 2.1: Schematic illustrating impacts of climate change on the ocean, including sea level rise, increasing ocean heat content and marine heat waves, ocean deoxygenation, and ocean acidification. It also highlights interconnected processes linking the ocean with the cryosphere, such as melting ice sheets and glaciers, changes in sea ice extent, and permafrost thaw. The increase or decrease in these impacts is indicated by arrows. Source (Adapted from IPCC, 2019).

Projections of future climate change are based on scenarios developed by the Coupled Model Intercomparison Project (CMIP), which serves as a critical framework for comparing outputs from various climate models. In the latest round of CMIP (CMIP6), these projections are constructed using Shared Socioeconomic Pathways (SSPs), which outline different global socioeconomic development trajectories, and are combined with Representative Concentration Pathways (RCPs) to model future greenhouse gas concentrations (O'Neill et al., 2016). For instance, the SSP1/RCP2.6 scenario, which represents a low-emission pathway, predicts a 0.9°C rise in global temperatures by 2100, whereas the high-emission scenario, SSP5/RCP8.5, forecasts a 2.9°C increase by the same year (Fox-Kemper et al., 2021). These scenarios are crucial for understanding the potential impacts of varying levels of global warming on marine ecosystems, providing valuable insights into how future environmental variables may change. Furthermore, these projections are essential for assessing the associated effects on fisheries and marine resources.

It is expected that the climate will continue warming for the duration of the 21st century, mainly due to a continuous increase of greenhouse gas concentration in the atmosphere (IPCC, 2021). With rising ocean temperatures and decreasing dissolved oxygen (DO) and pH due to climate change, there is an urgent need to understand how marine ecosystems will respond

to future ocean conditions (McClatchie et al., 2010; Deutsch et al., 2011; Feely et al., 2018). So far, there have been predictions by the Global Climate Models (GCMs) that by 2100, there will be increases of 4 °C in sea surface temperatures, a decline of up to 0.78 mg L⁻¹ in oxygen, and a decrease in pH of up to 0.35 units under RCP8.5 scenario (Stocker et al., 2013; Bopp et al., 2017; Kwiatkowski and Orr, 2018). This temperature rise will result in changes in the marine system, such as ice melting, rising sea levels, increased ocean stratification, and altered ocean circulation and precipitation patterns (Doney et al., 2011). However, despite the research and studies conducted on climate change projections, some uncertainties remain regarding changes in wind patterns, SST trends and other environmental variables. The uncertainties on future climate projections based on GCMs cannot be avoided as some of these are linked to model resolution and availability of resources, among other factors (Hampton et al., 2022). Uncertainties result in little confidence in the outcome of the projections. Therefore, identifying, quantifying and addressing the source of the uncertainties can improve confidence in future projections (Clark et al., 2015) and address climate mitigation and adaptation measures.

It is crucial to understand the responses of the oceanic processes to climate change. Modelling climate change using simulations from GCMs is important for investigating the impacts of climate change and its future projections. The GCMs were first developed in the 1970s with a coarse resolution of 2.5° ~10° (Manabe et al., 1970; Welck et al., 1971). As a result of this coarse resolution, the GCMs could not provide accurate climate change impacts at the regional and local scales. The GCMs are categorised into two types: Atmospheric General Circulation Models (AGCMs), this model type describes the physical and dynamical processes of the atmosphere and its interaction with land and Oceanic General Circulation Model (OGCMs), which determines the circulation of the ocean and play an important role in climate simulations (Schlesinger 1983; Goose et al., 2010; Idso et al. 2013). To obtain more accurate and reliable predictions of future climate change, the AGCMs and OGCMs have been incorporated together into Atmospheric-Ocean General Circulation Models (AOGCMs). The latter best describes the physical and dynamical processes of the climate system, including the atmosphere, land, ocean, and sea ice (IPCC, 2014).

Climate simulations using OGCMs have evolved to a resolution of 1.5° with Climate Model Intercomparison Project (CMIP3) (Meehl et al., 2007), then to a finer resolution of 1° with CMIP5 (Taylor et al., 2012), and recently to an even finer resolution of less than 0.25° (25-km) with CMIP6 (Haarsma et al., 2016). Such includes a recent development of the High-Resolution Model Intercomparison Project (HighResMIP) with CMIP6, which provides fine-resolution projections with a scale finer than 50km in the atmosphere and 0.25° in the ocean

(Haarsma et al., 2016). To ensure the reliability of the HighResMIP models in assessing climate change impacts, several studies have been conducted to evaluate its simulations (Haarsma et al., 2016, 2020; Ajibola et al., 2020).

2.2 Different emission scenarios

To assess the potential impacts of different emission pathways on the climate system, a framework has been developed to integrate both future climate projections and society for policy making (van Vuuren et al., 2011, 2012, 2014; Kriegler et al., 2012; O'Neill et al., 2014; IPCC, 2021). Recently, a framework called Shared Socioeconomic Pathway (SSP) - Representative Concentration Pathway (RCP) has been developed and adopted, and it consists of potential atmospheric and socioeconomic pathways (O'Neill et al., 2020). This framework allows for a comprehensive analysis of the interactions between society, economic trends, and climate change, providing valuable insights for policymakers and researchers.

To provide standardised climate scenarios for policymakers, the IPCC's Fifth Assessment Report introduced Representative Concentration Pathways (RCPs) as part of the CMIP5 framework (IPCC, 2014). These scenarios represent different greenhouse gas concentration trajectories and are used for climate research and as input for running climate models. The RCPs consist of scenarios that cover the effects of emissions, greenhouse gas concentrations, changes in land use and cover, and climate policies (van Vuuren et al., 2011). According to IPCC (2014), there are four RCP scenarios:

1. RCP2.6: This scenario represents a low greenhouse gas emission pathway. It is characterised by a decline in oil usage and low energy intensity. RCP2.6 is the lowest emission scenario.
2. RCP4.5: This scenario describes a medium-range emission pathway with low energy intensity. It includes moderate mitigation efforts and strong reforestation programs to counteract emissions.
3. RCP6.0: This scenario also represents a medium-range emission pathway, but it is consistent with higher reliance on fossil fuels and intermediate energy intensity. It does not involve as aggressive mitigation efforts as the previous two scenarios.
4. RCP8.5: This scenario depicts a future with very high greenhouse gas emissions due to a lack of policy changes to reduce emissions. It represents a business-as-usual scenario where fossil fuel use continues without any reduction. By 2100, this scenario

could significantly increase global temperatures, with estimates ranging from 2.6 °C to 4.8 °C higher than the temperatures in the year 2000.

Building on this approach, the CMIP6 framework later adopted Shared Socioeconomic Pathways (SSPs), which integrate socioeconomic narratives with emission trajectories to represent better future climate possibilities (O'Neill et al., 2016). This progression reflects the evolution of climate modelling, enabling more comprehensive assessments of future climate impacts. The IPCC Sixth Assessment Report (AR6) has used the SSP in conjunction with the Coupled Model Intercomparison Project Phase 6 (CMIP6) (IPCC, 2021) to assess the impacts of climate change and adaptation measures under different socioeconomic and emission scenarios. The SSPs provide scenarios of future projections in a world without assuming any new or additional climate policies, and they provide potential changes in socioeconomic indicators (van Vuuren et al., 2014). The SSPs are based on five narratives (SSP1 – SSP5) that describe socioeconomic trends that could shape future society, which are characterised as 'challenges to mitigation' and 'challenges to adaptation' (O'Neill et al., 2017; Riahi et al., 2017). These pathways incorporate key socioeconomic trends, such as human development, population growth, urbanisation, technology, energy use, and environmental policies, influencing mitigation and adaptation challenges (O'Neill et al., 2017; Riahi et al., 2017). SSP1, often called 'Sustainability – Taking the Green Road,' describes a world emphasising sustainable development with low population growth, reduced inequality, rapid technological advancement, and strong global cooperation. In contrast, SSP5, 'Fossil-Fueled Development – Taking the Highway,' envisions a future driven by rapid economic growth, high energy demand, and continued reliance on fossil fuels, with minimal focus on environmental sustainability. These pathways are intended to support climate change research and policy analysis, encompassing a wide range of potential challenges to both mitigation and adaptation to climate change (Riahi et al., 2017). An overview of the SSPs and their narratives is presented in Table 2.1 (Banda et al., 2022). While the SSPs provide valuable scenarios, they have limitations, as they do not produce climate projections that are deemed not to specifically relate to societal pathways.

Table 2.1: A summary of the SSPs and their narratives (Banda et al., 2022)

Shared Pathway	Socioeconomic	A Summary of the Narrative
SSP1:	Sustainability—Taking the green road (low challenges to mitigation and adaptation)	This scenario emphasises development goals, increased environmental awareness, and less resource-intensive lifestyles. It anticipates relatively low mitigation challenges due to greater renewable energy adoption. Reduced

Shared Pathway	Socioeconomic	A Summary of the Narrative
		inequality and strong institutions are also projected to minimise adaptation challenges.
SSP2: Middle of the road—(intermediate challenges to mitigation and adaptation)		This scenario depicts a future where social, economic, and technological trends continue along established paths. Progress towards sustainable development goals is gradual. Moderate environmental degradation, population growth, and educational investment are characteristic. Consequently, both mitigation and adaptation will pose moderate global challenges, with significant national variations.
SSP3: Regional rivalry—A rocky road (high challenges to mitigation and adaptation)		This pathway is characterised by increasing nationalism, heightened concerns regarding competitiveness and security, and regional conflicts, ultimately leading nations to prioritise domestic and regional matters. Furthermore, economic growth is sluggish, inequalities are pronounced, and population growth is high in developing countries while low in developed nations.
SSP4: Inequality—A road divided (low mitigation challenges, adaptation challenges dominate)		This scenario projects widening inequalities from uneven investment in human capital, economic opportunity, and political power. Economic growth is moderate in developed and middle-income countries, but low-income countries lag. While mitigation challenges remain low due to increased low-carbon energy use, adaptation challenges are high for less developed societies lacking effective institutions to manage economic and environmental pressures.
SSP5: Fossil-fueled development—Taking the highway (high challenges to mitigation, low challenges to adaptation)		This scenario prioritises competitive markets, innovation, and participation for rapid technological progress and human capital development as the key to sustainable development. Global markets integrate further, with substantial investments in health, education, and institutions. However, heavy reliance on fossil fuels and resource-intensive lifestyles creates significant mitigation challenges, while achieved human development goals, robust economic growth, and advanced infrastructure lead to relatively low adaptation challenges.

The CMIP6 framework further integrates SSPs with RCPs to enable a more integrated and policy-relevant climate scenario analysis (O'Neill et al., 2016; Riahi et al., 2017). For example, SSP1-2.6 represents a sustainability-focused future with strong climate policies leading to low emissions, while SSP5-8.5 describes a fossil-fuel-based economy with high emissions and limited climate action. This integration enables assessments that consider both the socioeconomic conditions and the physical climate response (O'Neill et al., 2020). Importantly, not all SSPs can achieve every forcing level. For example, low forcing levels such as 2.6 W/m²

are only feasible under sustainability-oriented scenarios such as SSP1 or SSP2, while high-emission scenarios like 8.5 W/m² are primarily associated with SSP3 and SSP5 as they have fewer mitigation efforts (O'Neill et al., 2016; Riahi et al., 2017).

This integration represents a key advancement over CMIP5, where RCPs were used independently from socioeconomic narratives. While CMIP5 was effective for modelling physical climate outcomes, it lacked context about how societal developments influence emissions. CMIP6 addresses this limitation by incorporating socioeconomic assumptions directly into scenario design, enabling more comprehensive and policy-relevant projections (O'Neill et al., 2014, 2016).

Within CMIP6, the Scenario Model Intercomparison Project (ScenarioMIP) outlines a protocol which prioritises a selection of Tier 1 and Tier 2 SSP–RCP combinations for comprehensive climate model simulations (O'Neill et al., 2016). This is illustrated in Figure 2.2, adapted from O'Neill et al. (2016), which shows how different SSPs correspond to radiative forcing levels. The matrix highlights which combinations have been prioritised for climate simulations in ScenarioMIP, distinguishing between Tier 1 and Tier 2 experiments. In this design, four scenarios are selected as Tier 1 (dark blue) and these represent top priority for climate modelling, covering a wide range of possible future socio-economic and climate pathways and are designed to align with the CMIP5 scenarios for comparisons. The Tier 2 (light blue) scenarios include additional scenarios of interest, such as overshoot and long-term extension pathways. These were intended for modelling centres with sufficient resources to go beyond the priority Tier 1 experiments (O'Neill et al., 2016).

Nevertheless, both the SSP and RCP frameworks are crucial for gaining a comprehensive understanding of the potential future impacts of climate change under different scenarios (O'Neill et al., 2020). Combining the SSPs and the RCPs scenarios for CMIP6 has proven beneficial in better understanding future changes under different scenarios (Banda et al., 2022).

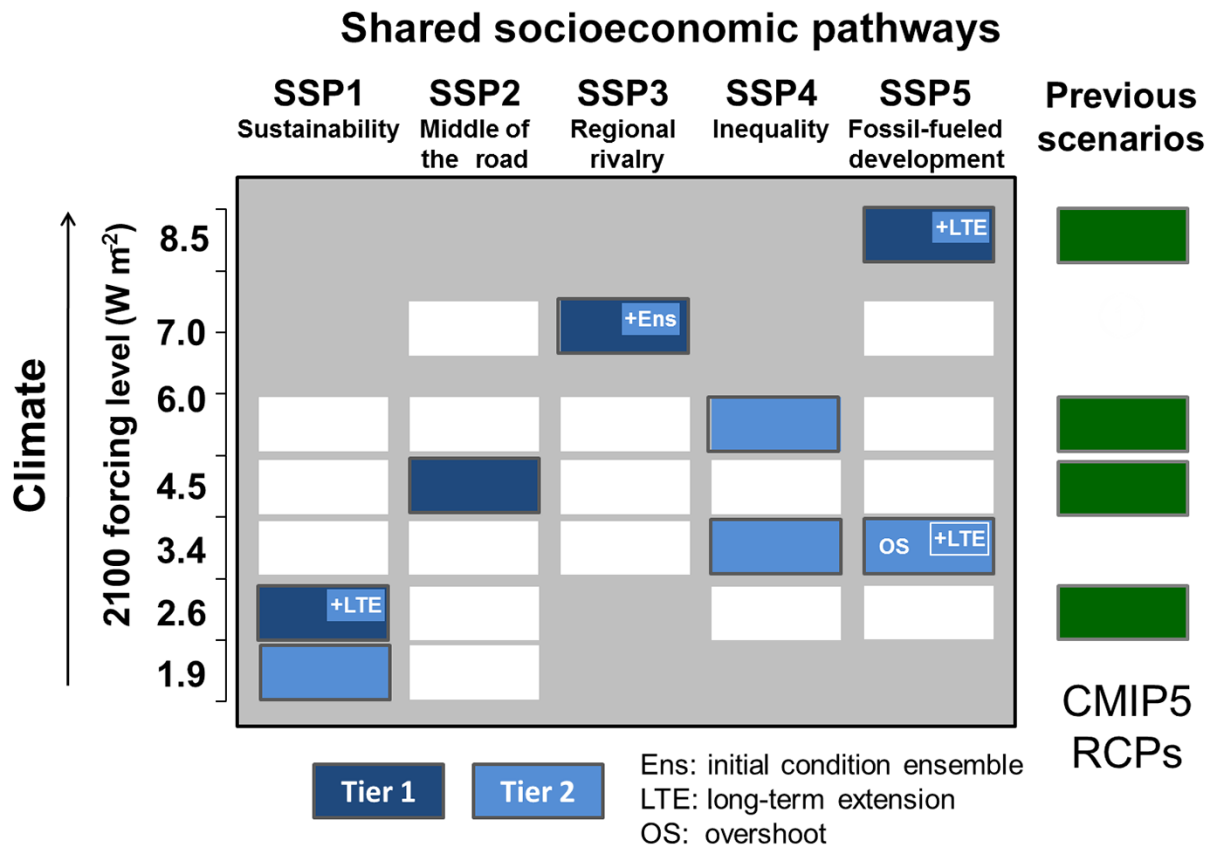


Figure 2.2: The SSP–RCP scenario matrix used in ScenarioMIP (CMIP6). Each cell represents a combination of a Shared Socioeconomic Pathway (SSP) and a level of radiative forcing by 2100 (W/m²). Dark blue cells indicate Tier 1 scenarios that were prioritised for full climate model simulations. Light blue cells show Tier 2 scenarios, including overshoot pathways and long-term extensions. White cells are not directly simulated but are conceptually linked. The CMIP5 RCPs are shown alongside for comparison. Adapted from O'Neill et al. (2016).

2.3 Eastern boundary upwelling systems (EBUS)

Major upwelling systems are found along the eastern boundaries of the world's oceans and are known as the Eastern Boundary Upwelling Systems (EBUS). These include the California, Canary, Humboldt, and Benguela upwelling systems, which, despite covering less than 1% of the global ocean surface, contributes approximately 20% of the world's marine fish catches due to their exceptional biological productivity (Pauly and Christensen, 1995). These systems, however, are particularly vulnerable to climate change (Sydeman et al., 2014; Bakun et al., 2015; Wang et al., 2015, Bograd et al., 2023). Upwelling in the EBUS is predominantly driven by equatorward alongshore winds (Smith, 1995). These winds that promote the upwelling process are mainly driven by the strong cross-shore atmospheric pressure gradients between the anticyclonic and cyclonic systems (García-Reyes et al., 2015).

These winds force the Ekman transport, leading to the upwelling process. Upwelling occurs when the equatorward alongshore winds regulate the offshore transport of surface waters,

resulting in replacement by deep, cold, and nutrient-rich water (Peterson & Stramma, 1991). This leads to the injection of nutrients into the euphotic zone (sunlit), resulting in primary productivity. The high primary productivity of these systems supports high fishery production, making them crucial for socio-economic activities (Rixen et al., 2021; Cooley et al., 2022; Borgrad et al., 2023; Gutiérrez-Guerra et al., 2024). Although these systems are all upwelling systems, they vary in their environmental and atmospheric conditions, both local and remote (Wang et al., 2015). Variability within and among these systems is influenced by both local and remote climatic drivers, including large-scale phenomena such as the El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) (Pitcher & Pillar, 2010; Tim et al., 2015).

To better understand the mechanisms driving upwelling, Bakun (1990) first hypothesised that land masses will warm more rapidly under future warming scenarios than the ocean, leading to an enhanced land-sea thermal gradient. This intensified gradient would drive stronger pressure gradients and, consequently, increased alongshore winds and coastal upwelling. Since Bakun's hypothesis, several studies have sought to test it using IPCC climate model projections and historical long-term observational or model-derived data (Sydeman et al., 2014; Wang et al., 2014; Garcia-Reyes et al., 2015; Rykaczewski et al., 2015; Tim et al., 2016; Bonino et al., 2019; Abrahams et al., 2021). Historical climate change has revealed summer wind intensification in the high latitudes (Sydeman et al., 2014), with low SSTs associated with increased upwelling events (Abrahams et al., 2021). However, it is important to note that there are inconsistent historical and projected changes within and among the upwelling systems, as summarised by Garcia-Reyes et al. (2015), due to multiple drivers at play, complex local processes, and the spatial and temporal scales of the data used. For example, earlier climate models with coarse resolutions ($>1^\circ$) were unable to represent nearshore processes, resulting in coastal biases adequately (Chang et al., 2023). Furthermore, in response to these inconsistencies, Rykaczewski et al. (2015), using CMIP5 simulation, have found that climate change may drive a poleward shift in oceanic high-pressure systems, leading to seasonal and latitude-dependent variations in upwelling-favourable winds. The mechanism behind the phenomenon is still debated, highlighting the need for further research using high-resolution climate models and region-specific observational analyses to reconcile these competing theories and improve predictive accuracy.

Despite these competing theories, uncertainties remain about how EBUSs will evolve with climate. These uncertainties have been suggested to result from resolution issues in GCMs, data availability and the complexity of integrating global and local processes into GCMs (García-Reyes et al., 2015; Hampton et al., 2022). To overcome these limitations, downscaling efforts have been employed. These efforts have assisted in reducing the limitations of the

OGCMs by reducing bias to model the relevant processes and include higher resolution representation of winds (García-Reyes et al., 2015). In the California Current System, dynamical downscaling has been applied to study the response of nutrients and plankton dynamics using a high-resolution model, and their results show increased upwelling intensity with stronger alongshore winds and increased upper ocean stratification (Xiu et al., 2018). In the Benguela Upwelling System (Machu et al., 2015), the Humboldt Current System (Cambon et al., 2013), and the Canary Current Upwelling System (Vazquez et al., 2021), downscaling has been primarily used to enhance the simulation of ocean circulation for better representation and realistic variability of both large-scale and mesoscale processes.

Given the vulnerabilities of the EBUS to climate change, continuation efforts of regionally downscaled future climate change projections in EBUS will improve the ability to provide region-specific, fine-scale, and practical climate information (Howard et al., 2020; Chang et al., 2023; Borgrad et al., 2023, Du et al., 2024). This information can then support informed decision-making, adaptation strategies, and sustainable management of ecosystems and resources in these vulnerable systems.

2.4 Benguela upwelling system

The Benguela Upwelling System (BUS) is one of the four major EBUS. It is a region of strong upwelling and high biological productivity (Hutchings et al., 1995; Hill et al., 1998; Carr, 2002). The BUS is located along the west coast of Southern Africa and spans approximately from 5°S to 37°S and from 0°E to 26°E (Shillington, 2006; Shannon et al., 2006; Blank et al., 2009) (Figure 1.1). The region serves as crucial spawning and nursery grounds for demersal and pelagic fisheries, supporting the growth of various economically important fish species (Hutchings et al., 1998; Japp et al., 2019).

The oceanography of the BUS region is characterised by a complex interplay of wind-driven coastal upwelling cells, the Angola-Benguela Front, mesoscale eddies, and the influence of the Agulhas Current (Figure 1.1) (Shannon, 1985). Shillington et al. (2006) further describe the Benguela upwelling system as consisting of strong upwelling cells, strong and narrow equatorward coastal jets, and a poleward undercurrent. Figure 2.3 illustrates the dynamics of coastal upwelling in the BUS, highlighting key atmospheric forcings such as seasonal winds, land-sea breezes, and coastal low-pressure systems. The BUS exhibits substantial interannual and decadal variability, influenced by various factors such as winds, currents, and large-scale climate phenomena (Hutchings et al., 2009; Tim et al., 2015; Tomety, 2022; Bordbar et al., 2023). For instance, ocean temperatures in this region are influenced at an interannual scale by Kelvin waves and the impact of El Niño Southern Oscillation (ENSO)

(Rouault et al., 2010; Dufois and Rouault, 2012). Seasonally, the winds are typically southerly and southeasterly during summer and westerly during winter (Andrews and Hutchings, 1980).

Similar to other EBUS, the Wind-driven upwelling in the Benguela system is facilitated by two mechanisms: equatorward winds leading to coastal surface divergence in the nearshore areas and wind stress curl driving Ekman pumping further offshore (Jacox and Edwards, 2012; Fennel et al., 2022; Bograd et al., 2023). The BCLME is separated into two subsystems by the largest perennial upwelling cell located off Lüderitz at 26.6°S, namely the northern Benguela system and the southern Benguela upwelling system (SBUS) (Hutchings et al., 2009; Figure 1.1). These subsystems exhibit distinct characteristics and significantly shape the local ecosystem and support associated fisheries, providing valuable habitats and resources for numerous marine species. Therefore, they might respond differently to the impacts of climate change (Wang et al., 2015; Martin et al., 2024).

2.5 Southern Benguela upwelling system

The Southern Benguela Upwelling System (SBUS) forms the southern part of the Benguela upwelling system (Hill et al., 1998). This region extends southward from 27°S to 37°S, from Cape Agulhas Point to Luderitz (Hardman-Mountford et al., 2003; Mullon et al., 2003) (Figure 2.3). The SBUS encompasses three major upwelling cells, namely the Namaqua cell (30°S), the Columbine cell (33°S), and the Cape Peninsula cell (34°S) (Figure 2.3) (Nelson & Hutchings, 1983)). Wind stress curl in the region is higher in the vicinity of these upwelling cells (Shannon & Nelson, 1996).

In the SBUS region, a notable surface current known as the Benguela Jet flows equatorward along the shelf. This jet is driven by the cross-shore temperature gradient resulting from cold upwelled waters on the shelf and the warm offshore waters linked to the Agulhas leakage (Shannon et al., 1996; Veitch et al., 2017). Shelf and nearshore currents in the region fluctuate in response to local short-term atmospheric forcing variations (Nelson, 1989).

The SBUS exhibits strong vertical stratification of the water column, particularly in summer, while the water column is generally highly mixed during winter (McMurray et al., 1992). These seasonal changes in stratification significantly influence the distribution of nutrients,

phytoplankton, and overall biological productivity (Burger et al., 2020; Brandt et al., 2024; Du et al., 2024).

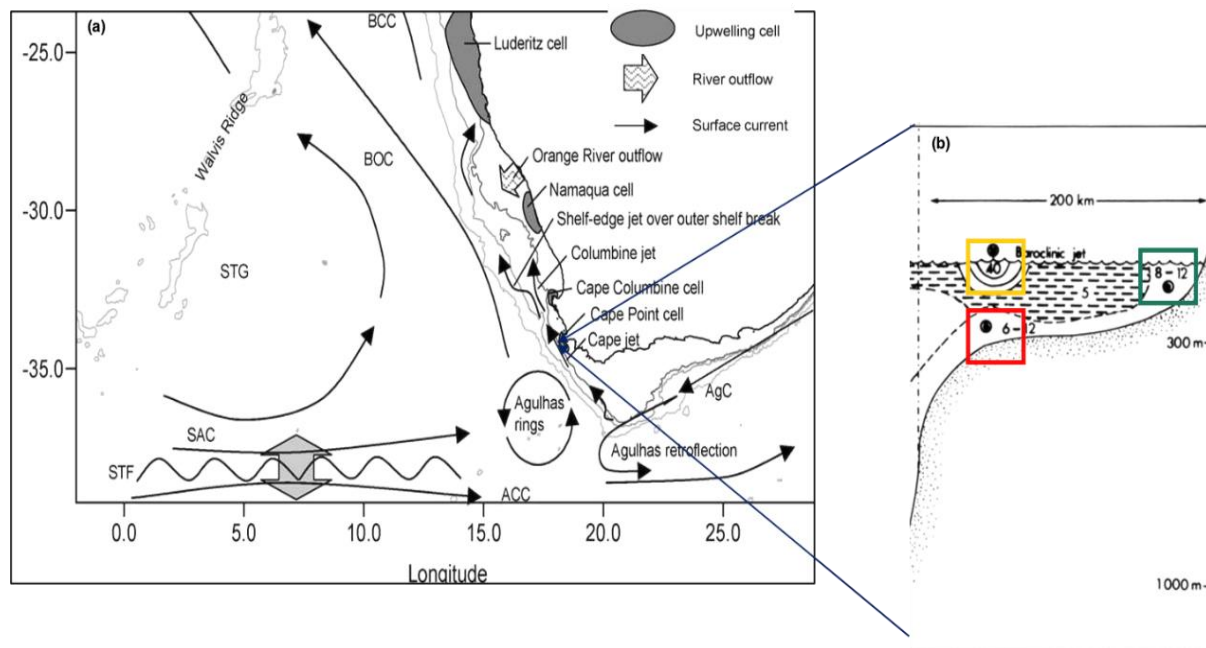


Figure 2.3: (a) A schematic representation of the circulation with the SBUS, showing the surface currents, upwelling cells, river outflow and the major oceanographic features at various scales. Key features include the Benguela Oceanic Current (BOC), Benguela Coastal Current (BCC), South Atlantic Current (SAC), Agulhas Current (AgC), subtropical front (STF), subtropical Gyre (STG), Antarctic Circumpolar Current (ACC). The Benguela Current and Benguela Jet are labelled BOC and 'Cape Jet', respectively (Hardman-Mountford et al., 2003). (b) The vertical schematic depicts alongshore currents off Cape Point, based on in situ ADCP measurements, highlighting the Benguela Jet (yellow), the shelf-edge poleward undercurrent (red), and the nearshore poleward current (green). Adapted from Nelson (1989) and Ragoasha et al. (2022).

The SBUS is likely to be affected by climate change (van der Lingen & Hampton, 2018; Ortega-Cisneros et al., 2018b). Observations over the past two decades have already shown notable changes in environmental properties within the SBUS. These changes include alterations in sea surface temperature, upwelling intensity, and the occurrence and frequency of harmful algal bloom events (Rouault et al., 2010; van der Lingen et al., 2016; Lamont et al., 2018). Specifically, in the northern Benguela, there has been a weakening of upwelling intensity, while the southern Benguela experiences a strong seasonal variation, with a stronger upwelling in austral spring and summer (Hutchings et al., 2009; Shillington et al., 2006).

These observed changes in the SBUS environment are likely influenced by the underlying drivers of climate change and have significant consequences for the region's marine ecosystem. Increasing sea surface temperatures can affect the distribution and abundance of various species, including commercially important fish stocks (Potts et al., 2015; van der

Lingen & Hampton, 2018). Changes in upwelling intensity can impact the availability of nutrients and affect primary productivity, ultimately cascading through the food web and affecting higher trophic levels (Bakun et al., 2015).

Climate projections from the NEMO-MEDUSA 2.0 model indicate that by the end of the 21st century, this region is expected to experience a temperature rise of up to $\sim 3^{\circ}\text{C}$ and a decrease in pH by ~ 0.3 units (Popova et al., 2016). These changes are expected to significantly impact primary production, altering nutrient dynamics, phytoplankton community composition, and overall ecosystem productivity. Ortega-Cisneros et al. (2018b) used the NEMO-MEDUSA 2.0 projections of sea temperature, primary productivity and ocean currents under RCP2.6 and RCP8.5 to force the Atlantic ecosystem model and evaluate how climate change impacts the biomass of marine species and fishing in the SBUS. The study shows that the projected warming negatively affects demersal and large pelagic fishing. These projected changes will have significant implications for the SBUS ecosystem.

2.5.1 Atmospheric forcing of the southern Benguela

The variability in atmospheric forcing plays a crucial role in the continental shelf dynamics, driving upwelling and coastal circulation in the SBUS (Nelson, 1992). The southern Benguela is primarily influenced by two key atmospheric systems: the South Atlantic Anticyclone (SAA) and the continental heat low (Shillington, 1998). The SAA exhibits seasonal movements, with a southward shift during summer and a northward shift during winter (Preston-Whyte & Tyson, 1993). These seasonal movements of the SAA result in corresponding changes in the direction and intensity of upwelling-favourable winds in the southern Benguela.

During summer, the SAA moves southward and generates favourable upwelling winds in the southern Benguela. In contrast, the SAA moves northward during winter, and the continental low-pressure system is replaced by a high-pressure system, leading to north-westerly winds and weakening the upwelling favourable winds (Shillington, 1998). It is worth noting that the IPCC fifth assessment report projects a southward shift of the SAA (IPCC, 2014). This shift in the SAA will result in a stronger pressure gradient and has implications for the atmospheric dynamics and the associated upwelling processes in the southern Benguela (Bordbar et al., 2023).

The surface currents in the southern Benguela are strongly influenced by the changes in the direction and magnitude of the wind forcing, predominately during late austral spring and summer (Huggett et al., 1998). During summer, winds intensify, increasing upwelling and enhancing productivity (Chavez & Messie, 2009).

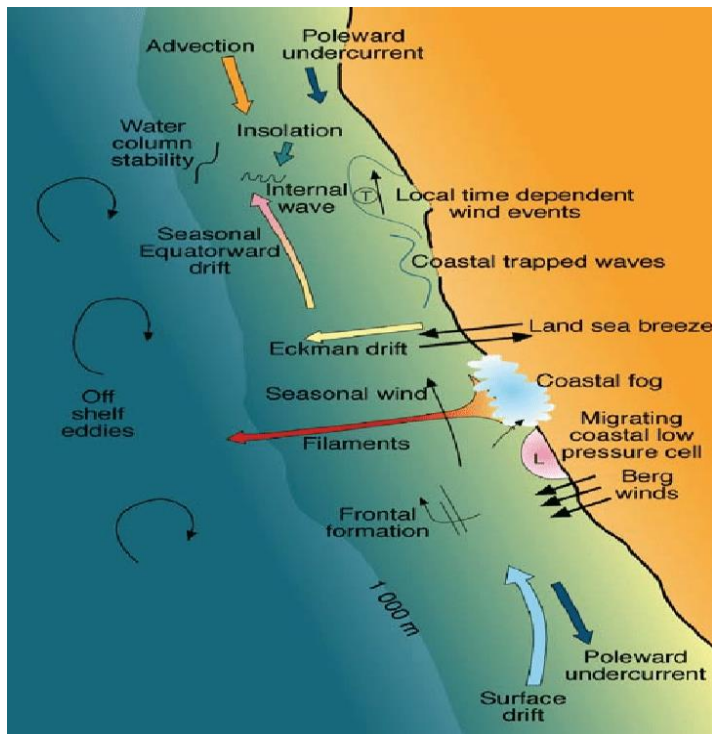


Figure 2.4: A schematic representation of major oceanographic and atmospheric features that impact biological processes within the Benguela upwelling system across various temporal and space scales (Shannon et al., 1996).

In the SBUS, the south-easterly winds are periodically modulated by passing cold fronts, cut-off lows and mesoscale synoptic features such as the Berg winds and sea breeze (Figure 2.4) (Shillington et al., 2006). These atmospheric features disrupt upwelling favourable winds at different time and spatial scales (Shillington et al., 2006) and can either enhance upwelling or trigger downwelling events (Fennel, 1999). Figure 2.5 illustrates the passage of an easterly propagating cyclone originating from the Southern Ocean. This easterly propagating cyclone can modulate upwelling favourable winds, causing periodic relaxation or reversal of equatorward wind, thus promoting pulsed upwelling (Burls, 2008).

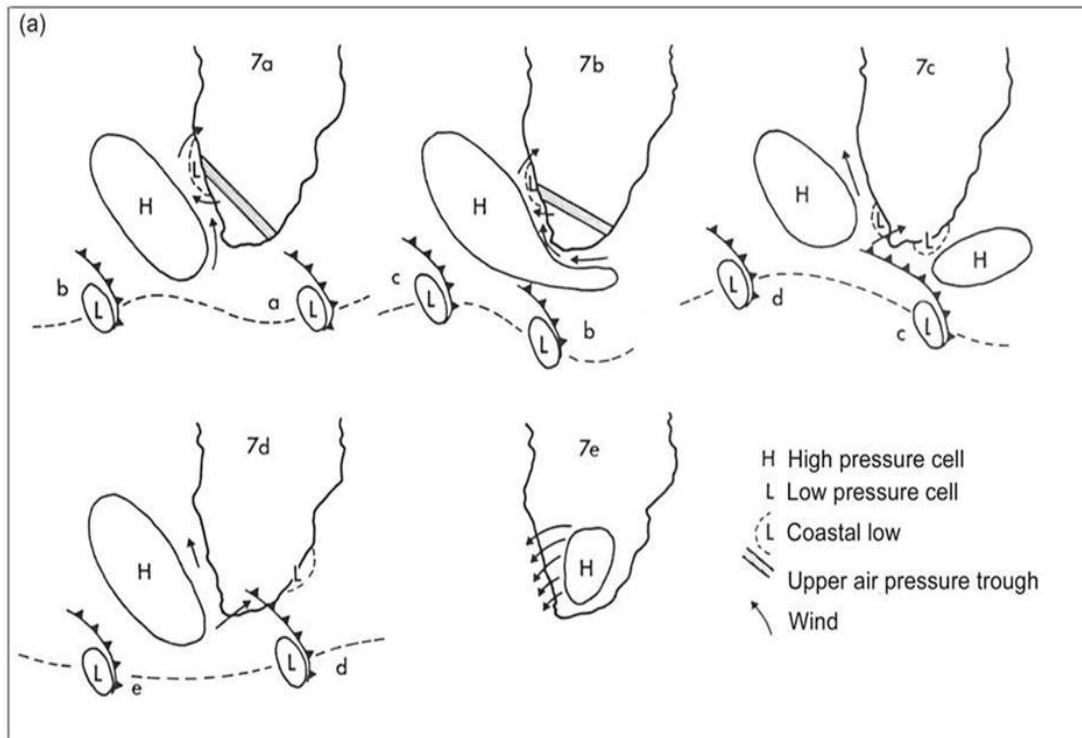


Figure 2.5: The passage of cyclones south of the continent (from Nelson and Hutchings, 1983, 1987) and the formation of a trapped coastal low which promotes pulsed upwelling at 3-10 day intervals (Hutchings et al., 2009). The symbols a-e represent different phases of the South Atlantic Anticyclone and coastal low, and their effects on upwelling: a) The South Atlantic Anticyclone is well-established, with a coastal low at Lüderitz, resulting in southerly winds that promote upwelling in the SBUS; b) The South Atlantic Anticyclone extends eastwards, and the coastal low at Lüderitz shifts south, driving gale-force winds that intensify upwelling; c) A weakening of the South Atlantic Anticyclone allows the front to ridge, inducing westerly winds that suppress upwelling; d) The strengthening of the South Atlantic Anticyclone once again drives southerly winds, promoting upwelling; e) Berg wind conditions, characterised by warm, dry offshore winds originating from the interior of South Africa, inhibit upwelling by reducing vertical mixing and nutrient supply. The L in each figure refers to the coastal low, and the H refers to the high-pressure cell.

2.5.2 The nearshore processes of the SBUS

Understanding the dynamics of nearshore processes in the SBUS is crucial for assessing its response to climate change. This knowledge is essential as it allows us to anticipate how climate change will affect the system, helping to predict potential shifts in upwelling patterns, circulation, and ecosystem responses. The interaction between wind stress, upwelling processes, and current formation significantly impacts the functioning of the system.

Nearshore circulation is strongly driven by local winds (Pitcher et al., 1998), with seasonal and synoptic wind fluctuations determining current patterns and water column structure. The shelf and nearshore currents respond differently to short-term variations in atmospheric forcing (Nelson, 1989). Wind stress curl regulates the poleward surface flow within the top 200m

(Brown and Hutchings, 1987; Marchesiello et al., 2003; Veitch et al., 2009), with cyclonic curl potentially generating a poleward undercurrent via Sverdrup relation (Vallis, 2006) that may merge with the offshore undercurrent (Junker et al., 2015).

There is evidence of current reversals in the SBUS during relaxation events of upwelling-favourable winds, leading to the poleward movement of warm waters along the inner shelf (Fawcett et al., 2008). These wind reversals are primarily driven by the South Atlantic High-Pressure system in winter and intermittently by passing cyclones south of the continent (Nelson & Hutchings, 1983). Such relaxation events can cause a rapid temperature rise of up to 5°C per day in the nearshore region and St Helena Bay. As equatorward wind stress relaxes, the nearshore upwelling circulation is no longer geostrophically balanced (Gan & Allen, 2002). This imbalance results in the formation of a counter-current that flows poleward around headlands, transporting warm waters (Gan & Allen, 2002). Consequently, nearshore surface currents form, flowing northward onshore and southward offshore (Fawcett et al., 2008). These currents are key components of the annual upwelling cycle (Pitcher & Weeks, 2006) and are thought to play a significant role in the southward transport of harmful algal blooms (HABs) (Pitcher et al., 1995, 1998; Pitcher & Nelson, 2006; Fawcett et al., 2008).

The Benguela Jet, a narrower but more intense feature than the Benguela Current, lies at the shelf edge over the poleward undercurrent between Cape Point and Cape Columbine (Bang & Andrews, 1974; Gordon, 1985). It splits into two branches, one entering St Helena Bay (Shannon & Nelson, 1996), and its intensity and position are sensitive to wind stress changes (Ragoasha et al., 2019). Driven by the cross-shore density gradient from upwelled waters and Agulhas warm water intrusion (Mullon et al., 2003; Hutchings et al., 2005), the Benguela Jet is projected to increase in intensity and frequency due to climate change-induced warming, which strengthens thermal and pressure gradients (Lima et al., 2019).

2.5.3 The Agulhas influence on the SBUS

The Agulhas Current, which flows along the southeast coast of Africa, leaks into the South Atlantic Ocean in the SBUS region. The Agulhas Current is a fast-flowing western boundary current of the southern Indian Ocean subtropical gyre (Lutjeharms, 2006). The interactions between the Agulhas and Benguela currents impact the marine ecosystem, oceanographic processes, and climate in the SBUS. The SBUS is largely influenced by the influx of warm waters from the Agulhas Current (Veitch, 2009). This influx of warmer water from the Agulhas Current makes the SBUS unique, as this does not occur in the other major eastern boundary currents (Shillington et al., 2006). The presence of warm waters influences the dynamics of the southern Benguela system, consequently linking the Benguela Current to the Indian Ocean

(Blanke et al., 2009). These warm waters with temperatures greater than 22°C enter the SBUS in the form of eddies, rings, and filaments shed at the Agulhas retroflection, sustaining high energy levels (Van Ballegooyen et al., 1994; Veitch, 2009; Veitch & Penven, 2017). These mesoscale features can influence the local circulation patterns, temperature, and productivity in the SBUS, thereby affecting the distribution and abundance of marine organisms. This influx of heat contributes to the intensification and modulation of the Benguela Jet (Strub et al., 1998; Veitch et al., 2018).

The biology of the SBUS is greatly influenced by the interaction of the shelf with the Agulhas Current (Van der Lingen & Hugget, 2003). The Benguela Jet plays a significant role in the transport of fish eggs and larvae from the Agulhas Bank to the west coast of South Africa, specifically to St. Helena Bay, which serves as an important nursery ground for various fish species (Shelton & Hutchings, 1982; Hutchings et al., 1998; Veitch et al., 2017). The transport success has a strong seasonal cycle, which is influenced by the alongshore currents and the wind-driven Ekman transport, such as when the upwelling-favourable winds start intensifying, the transport success decreases until the end of the upwelling season (Ragoasha et al., 2019). This transport mechanism is critical for the survival and replenishment of fish populations in the SBUS.

2.5.4 Model uncertainties for projecting the SBUS

The SBUS is characterised by highly complex and fine-scale dynamics. These dynamics are critical for understanding the region's climate and ecological responses, yet it remains challenging to represent them accurately. In the SBUS, similar to other EBUS, there is low confidence in projecting the future impacts of climate change due to uncertainties in how intensifying upwelling-favourable winds and coastal warming will interact and influence ecosystem responses (García-Reyes et al., 2015). To help address aspects of this challenge, the present study employs HighResMIP models, which improve the representation of mesoscale and sub-mesoscale dynamics (Haarsma et al., 2016; Fox-Kemper et al., 2019). While these models do not fully resolve all uncertainties, particularly those related to ecosystem feedbacks, they enhance the simulation of key physical drivers in the SBUS. This enhanced simulation will contribute to a more robust foundation for assessing future changes, advancing our understanding of the SBUS and providing a stronger basis for informed management and policy decisions.

2.6 Conclusion

Climate change is a major threat to marine ecosystems, and its impacts have been reported to affect both the physical and biogeochemical processes, thereby altering the functioning of the ecosystem. The literature underscores the impacts of ocean warming, driven by rising temperatures, on the distribution and abundance of marine species, leading to broader socioeconomic consequences for resource users. While substantial progress has been made in documenting these impacts, there have been some noted uncertainties regarding changes in wind patterns and trends in sea surface temperatures. Addressing uncertainties and/or gaps can enhance confidence in future projections and inform climate mitigation and adaptation measures.

To better model climate change and its impacts, the use of GCMs is important. However, GCMs have coarse resolution and may not accurately represent regional and local climate change. To improve the accuracy of future climate change projections at regional and local scales, downscaling techniques are employed to enhance the outputs of GCMs. Whether dynamical or statistical, downscaling techniques have been used to study regional climate processes and inform vulnerability and impact assessments and adaptation at regional scales. These techniques have already contributed significantly to vulnerability assessments and the formulation of adaptation measures. However, the effectiveness of downscaling depends on various factors, including the availability of historical data and resources, the desired spatial and temporal resolution, and the climate variables of interest.

In this context, integrating RCPs with SSPs in the CMIP6 framework offers a more nuanced understanding of future climate scenarios, providing valuable information for policymakers and stakeholders. However, translating these broad-scale insights into actionable knowledge for the SBUS region remains a critical challenge.

This study explores downscaled future climate change projections in the SBUS. The SBUS, characterised by four prominent upwelling cells and the Benguela Jet, is an ecologically and economically vital region and highly sensitive to climate change. The interplay between seasonal stratification, high wind stress, and the Benguela Jet shapes the system's productivity and resilience. However, significant uncertainties remain regarding how these nearshore processes respond to large-scale climatic drivers like the SAA.

Ultimately, this study seeks to address these gaps by evaluating the response of nearshore processes in the SBUS to climate change, focusing on the relationship between the SAA and upwelling intensity. By integrating downscaled climate projections, this study aims to improve predictions of future climate impacts on the SBUS and to support fisheries management

through prioritising climate adaptation options and enhancing adaptive capacity. This study will fill these gaps by providing a comprehensive analysis of the SBUS, emphasising the interplay between physical processes and climate change. These insights are essential for building adaptive capacity and ensuring the resilience of the region's ecosystems and resource users.

The next chapters will provide a detailed analysis of the nearshore processes in the SBUS, circulation patterns, seasonal upwelling, and their responses to projected climate change, as well as the resulting implications for ecosystem structure, resource availability, and socioeconomic impacts.

3 Data and Methods

This chapter describes and evaluates the High-Resolution Model Intercomparison Project (HighResMIP) experiments within Phase 6 of the Coupled Model Intercomparison Project (CMIP6). The focus is on the specific climate models used in this study, assessing their performance in representing key oceanographic features. Only models with a spatial resolution of 25 km were used. The HighResMIP climate model output is compared against the GLORYS and ERA5 reanalysis datasets. Although reanalyses are produced using models, they are strongly guided by observations through data assimilation (Dee et al., 2011), making them reliable representations of historical ocean and atmosphere. This is especially important in regions or periods where direct observations are limited or unavailable. Therefore, using GLORYS and ERA5 as reference datasets helps identify biases in the model and assess how well it captures key historical patterns, which is important for building confidence in its future projections. To establish a baseline for comparison, the GLORYS reanalysis dataset is first evaluated against satellite observations, specifically sea surface temperature data from the Climate Change Initiative (CCI) and altimetry data from the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO).

3.1 Dataset Description

In this study, downscaled climate model datasets are used to investigate the impact of climate change on the southern Benguela upwelling system (SBUS). These datasets provide important variables such as sea surface temperature (SST), sea surface height (SSH), zonal (u_{10}) and meridional (v_{10}) wind components taken 10 m above the sea level, mean sea level pressure (MSLP) and ocean currents (u , v , w), which are critical for understanding upwelling dynamics and the role of the South Atlantic Anticyclone (SAA).

It is important to note that not all variables are available for each model. Specifically, for the HighResMIP models, only the VHR4, HR4, and CAM5 models provided the oceanic variables (SST, SSH, and zonal (u) and meridional (v) seawater velocities). Additionally, VHR4 and FGOALS models provided the wind velocities (u_{10} and v_{10} wind components). Meanwhile, the HiRAM model did not have wind but provided the mean sea level pressure (MSLP). Additionally, FGOALS also contributed MSLP data. Table 3.1 summarises each dataset and the specific variables used in this study.

Table 3.1 :Summary of datasets used in the study, including the variables provided for oceanic and atmospheric analysis to assess the impacts of climate change on the Southern Benguela Upwelling System. All datasets are provided at a monthly temporal resolution.

Dataset	Oceanic Variables	Atmospheric Variables	Spatial resolution
CCI	SST	-	5 km
WOA23	Temperature	-	25 km
AVISO altimetry data	SSH	-	25 km
GLORYS reanalysis model	SST, SSH, seawater velocities (u,v), and seawater potential temperature.	-	25 km
ERA5 reanalysis model	-	Wind velocity (U_{10} , V_{10}), MSLP	25 km
HighResMIP Climate Models			
VHR4	SST, seawater velocities (u,v), and potential temperature	Wind velocities (U_{10} , V_{10})	25 km
HR4	SST, seawater velocities (u,v), and potential temperature	-	25 km
CAM5	SST, seawater velocities (u,v), and potential temperature	-	25 km
HiRAM	-	MSLP	25 km
FGOALS	-	Wind velocities (U_{10} , V_{10}), MSLP	25km

3.1.1 Climate Change Initiative

The Climate Change Initiative (CCI) SST data is a reprocessed daily satellite SST from the European Space Agency's Climate Change Initiative launched by the European Space Agency (ESA). The Climate Change Initiative (CCI) SST dataset used in this study spans 1993–2016 to align with the GLORYS reanalysis period. It spans from 1993-2016, to ensure consistency with the temporal coverage of the reference datasets and has a spatial resolution of 0.05° with a 0.1 K accuracy. The CCI- SST data captures SST conditions at 20 cm depth and is available at <https://data.marine.copernicus.eu/>.

The daily analysis product input fields used are from the sea surface temperature (SST) CCI Along-Track Scanning Radiometer (ATSR), Advanced Very High-Resolution Radiometer (AVHRR), and Sea and Land Surface Temperature Radiometer (SLSTR) datasets and were averaged monthly.

3.1.2 World Ocean Atlas 2023

The World Ocean Atlas 23 (WOA23) is used to evaluate the vertical structure of the temperature of GLORYS. The WOA23 provides objectively analysed fields of temperature, salinity, oxygen and several nutrients. The spatial resolution of this dataset ranges from 1° to 0.25° globally, extending from the surface to a depth of 5500 m at a vertical resolution of 102 depth levels (Locarnini et al., 2023). The data are available as climatologies on annual, seasonal, or monthly timescales at <https://www.ncei.noaa.gov/access/world-ocean-atlas-2023/>. An annual temperature climatology averaged over the 1991-2020 period was used at 0.25° in this study.

3.1.3 AVISO altimetry

The Sea Surface Height (SSH) data used to validate GLORYS was derived from AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic) Altimetry data. The data is from 1993 to 2018, has a spatial resolution of 0.25°, and is available at: <http://www.aviso.altimetry.fr/duacs/>. The SSH from the reanalysis data was used to calculate surface geostrophic velocities in the SBUS. The SSH provides a reliable approximation of the current systems (Cabos et al. 2017; Koseki et al. 2019). These SSH gradients help estimate the strength and direction of these currents, which is essential for understanding large-scale circulation patterns in the region.

3.1.4 ERA 5 reanalysis model

ERA5 is the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis of the global climate and weather for the past 8 decades. The data used in this study is monthly averaged data on single levels, specifically referring to surface-level atmospheric and climate variables from 1940 to the present, available at <https://cds.climate.copernicus.eu/>. This reanalysis data is a combination of model data with observations globally. The ERA5 reanalysis data has a spatial resolution of 0.25°. This study used the ERA5 reanalysis data to evaluate HighResMIP atmospheric variables.

3.1.5 GLORYS reanalysis model

The GLORYS model (GLOBAL_MULTIYEAR_PHY_ENS_001_031) was developed by the Copernicus Marine Environment Monitoring Service to provide a global eddy-resolving ocean and sea reanalysis (Jean-Michel et al., 2021). The reanalysis covers from 1 January 1993 to 31 December 2023, providing monthly outputs with a horizontal resolution of 0.25° (25 km) on 75 vertical levels. GLORYS plays a crucial role in understanding oceanic processes, climate variability, and weather forecasting. This dataset is available at <https://marine.copernicus.eu/>.

This study validated the GLORYS reanalysis model with AVISO altimetry data and CCI (Climate Change Initiative) and subsequently used it to evaluate the HighResMIP models.

3.1.6 HighResMIP

The HighResMIP (High Resolution Model Intercomparison Project) is a CMIP6-endorsed MIP that applies the multi-model approach to investigate the impact of horizontal resolution on the model's ability to represent relevant climate processes (Haarsma et al., 2016). The HighResMIP project considers high resolution from 25km to 50km and covers the period from 1950- 2014 (historical run) and from 2015-2050 (future run), with a possible extension to 2100. The project consists of three sets of experiments, tier 1, 2, and 3, to evaluate ocean and atmosphere impacts at high horizontal resolution simulation (Haarsma et al., 2016; Haarsma et al., 2020). Tier 1 consists of forced atmospheric (*HighResSST-present*) runs only from 1950-2014 using HadISST2.2.0.0 0.25° SST and sea-ice forcing dataset. Tier 2 simulations are coupled model runs from 1950-2050. This tier comprises three components: a Control run (*control-1950*) based on 1950s conditions, a historic run (*his-1950*) that runs from 1950-2014, and future projections (*highres-future*) under different scenarios from 2015-2050. The future period forcing fields are under the SSP5-8.5 scenario, reflecting a future of continued fossil fuel use and minimal climate mitigation efforts. Additionally, tier 2 required a spin-up phase of 50 years using EN4 ocean climatology (Good et al., 2013) with constant 1950s forcing to allow models to stabilise before starting historical and future runs. Tier 3 is a forced atmospheric only run (*highresSST-future*) from 2015-2050 with SSP5-8.5 scenario, and this tier is an extension of tier 1 to up to 2050 with a possible extension to 2100. Figure 3.1 summarises the protocol design used within the HighResMIP models, outlining the structure and progression across the three simulation tiers.

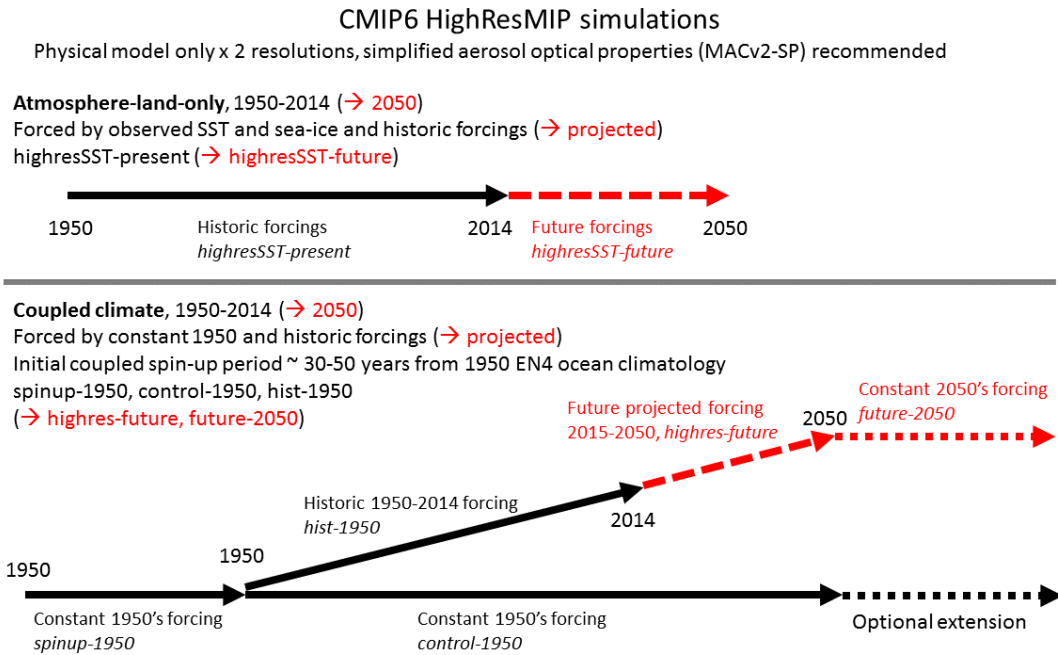


Figure 3.1 The HighResMIP experimental design, showing the component experiments (Tier 1, Tier 2, and Tier 3) and their relationships. Tier 1 and Tier 3 are represented in the upper panel, while Tier 2 is shown in the bottom panel.

This study focuses on tier 2, investigating the historical (1950-2014) and future (2015-2050), which runs only at a 0.25° resolution. HighResMIP models in this study are important for improving our understanding of climate dynamics through enhanced resolution, addressing model biases, and contributing to reliable climate projections. The models used in this study are listed in Table 3.2. This high resolution enables the models to resolve mesoscale variability. In various studies, the HighResMIP models have been validated with observational data and other climate models, and they have been shown to capture the mesoscale and larger-scale variability fairly well (Koenig et al., 2021; Bellucci et al., 2021; Haarsma et al., 2020; Roberts et al., 2019; Muis et al., 2023; Moreno-Chamarro et al., 2024). However, biases exist as the models sometimes tend to overestimate or underestimate the representation of specific processes (Haarsma et al., 2016; Roberts et al., 2020). These biases often arise due to limitations in model resolution, the representation of physical processes, parameterisation or the sensitivity to boundary conditions. Despite these challenges, the high-resolution simulations offer more accurate predictions and a better understanding of small-scale processes. The dataset is available at <https://esgf-node.llnl.gov/projects/cmip6/> and contains monthly files with daily outputs.

Table 3.2: HighResMIP models used in this study and their reporting institutions and countries, with 0.25° resolution and r1i1p1f1 Ensemble member.

Model name	Short name	Model institute(s)	Country
FGOAL-f3-H	FGOALS	Chinese Academy of Sciences (CAS)	China
CMCC-CM2-VHR4	VHR4	Fondazione Centre Euro-Mediterraneo Sui Cambianeti Climatici (CMCC)	Italy
CMCC-CM2-HR4	HR4	Fondazione Centre Euro-Mediterraneo Sui Cambianeti Climatici (CMCC)	Italy
HiRAM-SIT-HR	HiRAM	Research Center for Environmental Changes (AS-RCEC)	Taiwan
CESM1-CAM5-SE-HR	CAM5	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory (NCAR)	USA

3.2 Methodology

This study focuses on the southern Benguela region (Figure 2.3) on the west coast of South Africa (26°S - 36°S and 12°E - 20°E). The study evaluates the mean nearshore processes in the southern Benguela and how they could be impacted by large-scale changes caused by climate change. This was done using data from the High-Resolution Model Intercomparison Project (HighResMIP), which consists of global climate models run at higher spatial resolutions than typical CMIP6 models. These higher-resolution simulations provide improved representation of mesoscale and sub-mesoscale climate processes (Haarsma et al., 2016), allowing for more detailed investigation of future climate change projections in the region. The selection of models was guided by specific criteria to ensure consistency and suitability for detailed analysis of the SBUS. The models were filtered according to the 0.25° ocean resolution, availability of both historical and future experimental runs, and the use of a consistent variant label (r1i1p1f1) to maintain comparability across the ensemble. Additionally, the availability of the essential oceanic and atmospheric variables necessary for comprehensive analysis of SBUS dynamics was a key consideration. However, it is important to note that not all models provided a complete set of variables used; notably, only the VHR4 model includes nearly all the variables analysed. This variation in data availability introduces some limitations, particularly in multi-model comparisons, and this is acknowledged in the discussion chapter (section 6.5). The HighResMIP data is a global dataset, and monthly

climatological means were extracted over the southern Benguela domain. The climate change response in the region would be defined as the difference between the historical (1950-2014) and future climate simulations (2015-2050).

The HighResMIP models were compared against the Global Ocean Physics Reanalysis (GLORYS), the AVISO altimetry for the ocean variables, and the ERA5 reanalysis for the atmospheric variables. Future climate projections at high resolution were downloaded from <https://esgf-node.llnl.gov/projects/cmip6/> and used to ensure that the models capture the coastal processes associated with the region. The bathymetry data used in this study was downloaded from Global Bathymetry and Topography at 15 Arc Sec: SRTM15+ V2.5.5 and is available at <https://portal.opentopography.org/>. The data was processed and interpolated into a common grid, which was used to define seafloor topography and display isobaths on the surface current plots. All datasets used in this study were interpolated onto a common $0.25^\circ \times 0.25^\circ$ grid using bilinear interpolation. This ensured spatial consistency for comparing model outputs, observational data, and bathymetry.

3.2.1 Taylor Diagrams

A Taylor diagram was used to statistically characterise the relationship between the HighResMIP models and the reference models: GLORYS (oceanic variables) and ERA5 reanalysis model (atmospheric variables). Taylor diagrams give a statistical summary of how well the models' patterns agree with the observation in terms of their Pearson correlation coefficient (R), root-mean-square difference (RMSD), and Standard Deviation (SD) (Taylor, 2001). The best agreement between the model output and the reference is when the RMSD is close to 0, and the correlation is close to 1. Therefore, the closer a model's point lies to the reference point, the better its performance in terms of both standard deviation and correlation.

3.2.2 Surface Geostrophic Currents

Surface geostrophic currents were computed from SSH fields, as SSH gradients are a good proxy for geostrophic flow under the assumption of geostrophic balance. The SSH fields from the models used in this study were adjusted by +0.4 m to align the spatially averaged model outputs with satellite altimetry data over the domain of interest. The geostrophic velocity components were calculated using the **geostrophy.m** function from the Climate Data Toolbox for MATLAB (Greene et al., 2019). This function simplifies the implementation of these equations by taking SSH, latitude, and longitude into account to compute the surface geostrophic velocity components. This function was used as follows with zeta as SSH:

$$[u, v] = \text{geostrophy}(\text{lon}, \text{lat}, \text{zeta}) \quad (3.1)$$

It uses the theoretical geostrophic balance equations:

$$u_g = \frac{-g}{f} \frac{\partial \eta}{\partial y} \quad (3.2)$$

$$v_g = \frac{-g}{f} \frac{\partial \eta}{\partial x} \quad (3.3)$$

where g is the acceleration due to gravity (9.80 m s^{-2}), f is the Coriolis parameter (s^{-1}) where $f=2\Omega\sin\phi$ with Ω being Earth's angular velocity and ϕ the latitude, x and y are the longitudinal and latitudinal positions, respectively, and η is the SSH.

3.2.3 Local winds

In the SBUS, the coastal currents and the upwelling dynamics are greatly impacted by the distribution of winds near the coast (Small et al., 2015). Both the alongshore wind stress and wind stress curl are crucial to the coastal upwelling (Kämpf & Chapman, 2016; Jacox et al., 2018; Duy et al., 2022), as these are the primary drivers of the circulation in the upwelling regions. The strong nearshore wind stress along the coast generates significant Ekman transport, leading to offshore movement of surface waters and facilitating coastal upwelling (Bakun, 1990). On the other hand, the negative wind stress curl along the coast generates Ekman transport, inducing upwelling (Enriquez and Friehe, 1995; Colas et al., 2011). It also influences the dynamics of the poleward undercurrent (Capet, 2004). Therefore, it is important to investigate and understand the seasonal cycle and the spatial variability of the wind in the SBUS.

Wind stress and wind stress curl were computed using MATLAB functions **windstress.m** and **cdtcurl.m**, respectively. The **windstress.m** function (Greene et al., 2019) calculates the wind stress as:

$$[\text{Tau}_x, \text{Tau}_y] = \text{windstress}(u_{10}, v_{10}) \quad (3.4)$$

This function simultaneously computes zonal and meridional components of the wind stress from the zonal (u_{10}) and meridional (v_{10}) wind speed components. It uses the theoretical basis for the wind stress calculation given by:

$$\text{Tau}_x = \rho_a c_d u_{10} \sqrt{u_{10}^2 + v_{10}^2} \quad (3.5)$$

$$\tau_y = \rho_a C_d v_{10} \sqrt{u_{10}^2 + v_{10}^2} \quad (3.6)$$

Where ρ_a is the air density, equal to 1.225 kg/m³, C_d is the drag coefficient equal to with a value of 1.25×10^{-3} , u_{10} and v_{10} are the wind speed components at 10 meters above the surface.

The **cdtcurl.m** function (Greene et al., 2019) calculates the curl of the wind stress field given the latitude (lat), longitude (lon), and wind stress components (τ_x and τ_y).

In MATLAB, this calculation was performed as follows:

$$\text{Curl} = \text{cdtcurl}(\text{lat}, \text{lon}, \tau_x, \tau_y) \quad (3.7)$$

This function uses the theoretical basis of wind stress curl given by:

$$\text{curl}_z(\tau) = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \quad (3.8)$$

The Ekman phenomenon was investigated in this study, which describes the ocean surface flow driven by the balance between wind stress and the Coriolis force (Ekman, 1905). This phenomenon encompasses Ekman transport and Ekman pumping. Ekman transport describes the net movement of water in the surface layer, which is perpendicular to the direction of the wind. In the northern hemisphere, this transport occurs to the right of the wind direction. In contrast, in the southern hemisphere, it occurs to the left. This transport can lead to Ekman pumping, where the divergence or convergence of surface waters causes vertical movements. The vertical motion can lead to upwelling or downwelling, significantly impacting marine ecosystems and regional climate.

This study computed the Ekman transport and Ekman pumping to understand better the upwelling dynamics and circulation patterns in the SBUS region. To compute these two upwelling processes, MATLAB function **ekman.m** was used (Greene et al., 2019).

$$[UE, VE, wE] = \text{ekman}(\text{lat}, \text{lon}, u_{10}, v_{10}) \quad (3.9)$$

This function estimates the zonal (UE) and the meridional (VE) components of the Ekman layer transport along with vertical velocities (wE) associated with Ekman pumping using wind speed taken 10 m above the surface and the latitude and longitude of the region of interest.

Here, the 10 m winds are automatically converted to wind stress before performing the Ekman calculations. The Ekman function uses the theoretical basis of Ekman dynamics, which is derived from the balance of forces acting on the surface layer of the ocean. The Ekman transport component:

$$UE = \frac{\tau_y}{\rho f} \quad (3.10)$$

$$VE = -\frac{\tau_x}{\rho f} \quad (3.11)$$

Where UE and VE are the zonal and meridional components of Ekman transport, and T_x and T_y are the zonal and meridional components of wind stress, respectively. ρ (1025 kg/m³)

and f are seawater density and the Coriolis parameter, respectively. The Coriolis parameter is negative in the southern hemisphere.

Ekman pumping:

$$wE = -\frac{1}{\rho f} \frac{\partial \tau_y}{\partial x} - \frac{1}{\rho} \frac{\partial \tau_x}{\partial y} \quad (3.12)$$

Where, $\frac{\partial UE}{\partial x}$ and $\frac{\partial VE}{\partial y}$ represent the spatial derivatives of the Ekman transport components.

3.3 GLORYS Evaluation

This section presents the evaluation modelled GLORYS reanalysis SST with observed CCI SST, assessing their accuracy in representing seasonal SST variations in the SBUS. The evaluation also compared SSH and computed surface geostrophic currents from GLORYS against AVISO altimetry data. Additionally, the vertical structure of temperature was compared with the WOA23.

3.3.1 Sea Surface Temperature (SST)

The GLORYS reanalysis product was validated against the CCI observations data to assess whether it accurately captures the spatial and temporal variability of SST in the SBUS. Positive (negative) values of the difference between the simulated and observed SST indicate regions where GLORYS over- (under-) estimates SST compared to the CCI observations. The

comparison between the GLORYS and the CCI SST products is shown in Figure 3.2. To facilitate a consistent comparison, the CCI SST product was interpolated onto the GLORYS grid to ensure spatial compatibility. The bias between the GLORYS reanalysis model and the CCI SST product was then calculated using the following formula:

$$\text{Bias} = \text{SST}_{\text{GLORYS}} - \text{SST}_{\text{CCI}} \quad (3.13)$$

The observed cooler SST along the coast may indicate the presence of upwelling in the region, while the warmer offshore waters may be associated with Agulhas Current leakage (Figure 3.2a, b). The three major upwelling cells in the SBUS, the Namaqua cell (29°S), the Columbine cell (33°S), and the Cape Point cell (34°S), are evident in the two SST products. However, biases are apparent from the validation, an annual mean warm bias of approximately 1.5°C is observed in GLORYS specifically along the coast (Figure 3.2 c). This suggests that GLORYS is underestimating coastal upwelling. The seasonal cycle of SST in the region, derived from domain-averaged values, is shown as a time series in Figures 3.2d and 3.2e. The highest observed SSTs were during the summer months, with the lowest observed in the winter months. The time series shows minimal seasonal SST variations in the two products, with a warm bias of up to 0.35°C in GLORYS (Figure 3.2 e) during summer months.

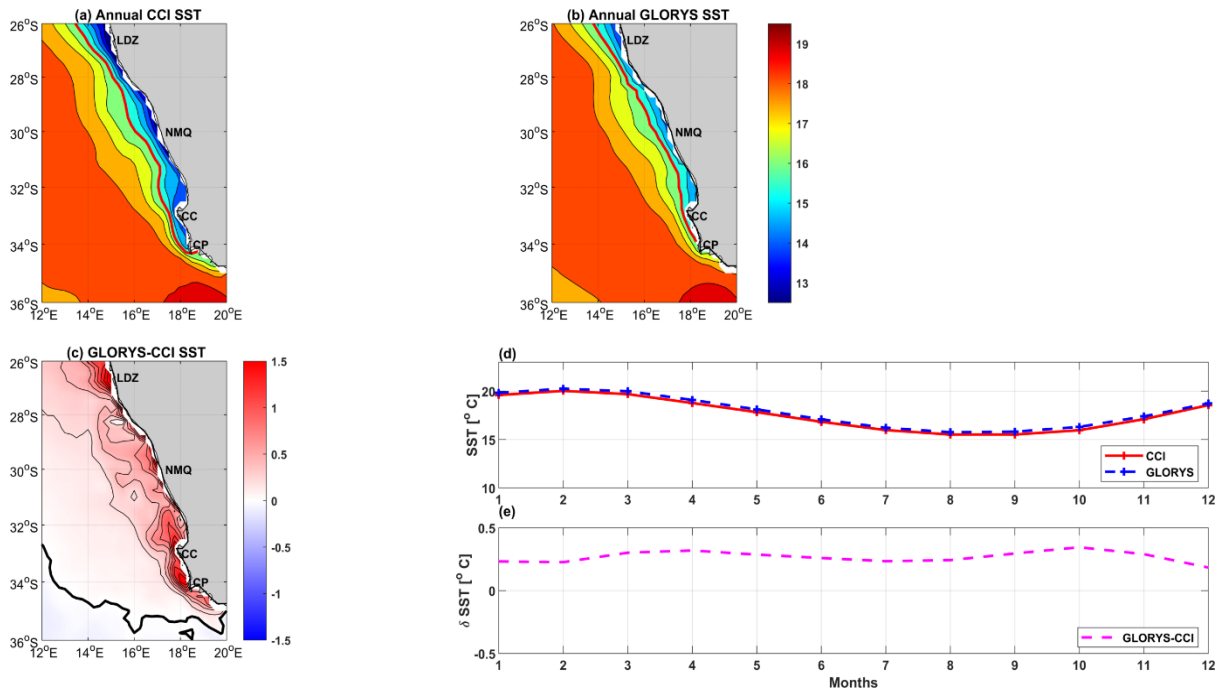


Figure 3.2: Annual average of Sea Surface Temperature (SST): a) Annual CCI SST averaged over 1993-2016; b) GLORYS reanalysis SST averaged over 1993-2021; c) Annual mean SST bias (GLORYS-CCI), averaged over 1993-2021; d) monthly climatological mean time series of the SST GLORYS (solid red line) and CCI (dashed blue line) averaged over the domain, and (e) the monthly SST difference between the GLORYS reanalysis model and CCI. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The 16°C isotherm is also superimposed in red.

3.3.2 Sea Surface Height and Geostrophic Currents

The analysis of SSH shows that the GLORYS reanalysis model has similar characteristics of SSH and surface geostrophic velocities with the AVISO altimetry data, with current flow stronger along Cape Point and Cape Columbine upwelling cells (Figure 3.3 a, b). The northward along-shore Benguela Jet is notable between 200m and 500m isobaths in both GLORYS and AVISO with a pronounced northward flow and high current speed along the coast, especially along the Cape Point region with average velocities approaching $0.2 \text{ m}\cdot\text{s}^{-1}$. There is a notable negative surface alongshore geostrophic current (Figure 3.3 a, b) and cyclonic circulation in St Helena Bay (Figure 3.3 a), north of Cape Columbine, which the GLORYS reanalysis model does not capture. This is observed in St Helena Bay within a 100 km offshore distance and in Grotto Bay within a 50 km offshore distance (Figure 3.4 a, b). The presence of a coastal poleward current is consistent with the current meter measurements of Nelson (1989).

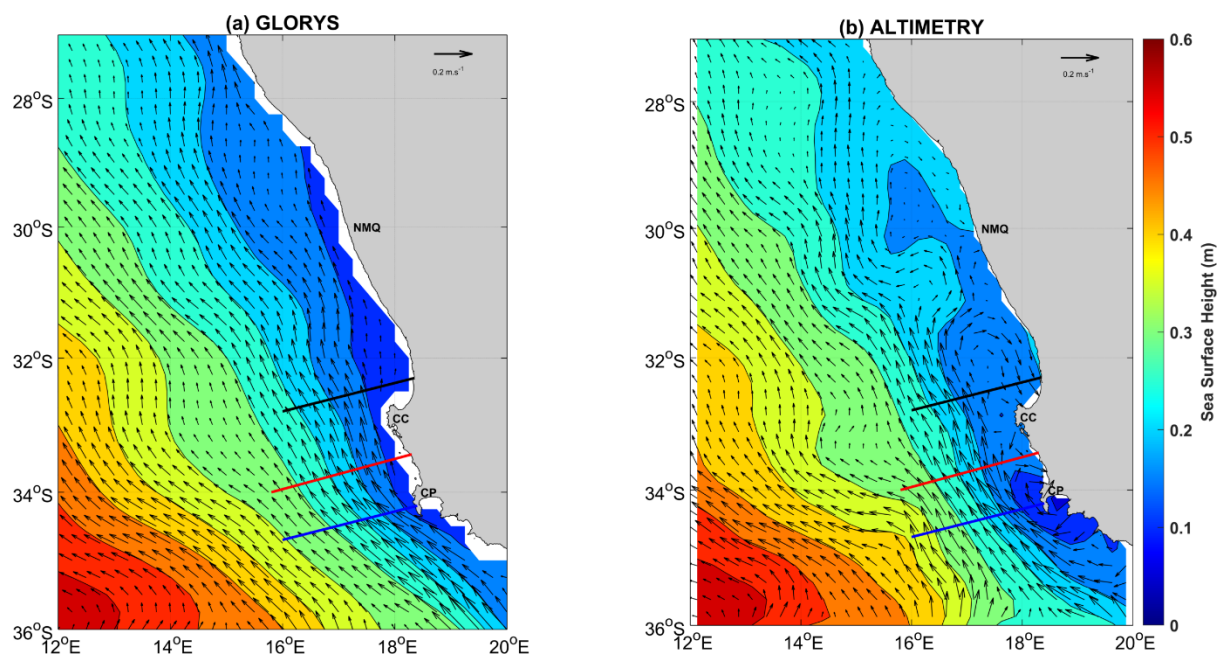


Figure 3.3: A long-term average of SSH (contours) and geostrophic velocities (vectors) a) GLORYS Reanalysis averaged over 1993-2021 and b) AVISO Altimetry data averaged over 1993-2018. The superimposed solid lines indicate the cross-shore transects at St Helena Bay (black solid line), Grotto Bay (red solid line), and Cape Point (blue solid line). The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

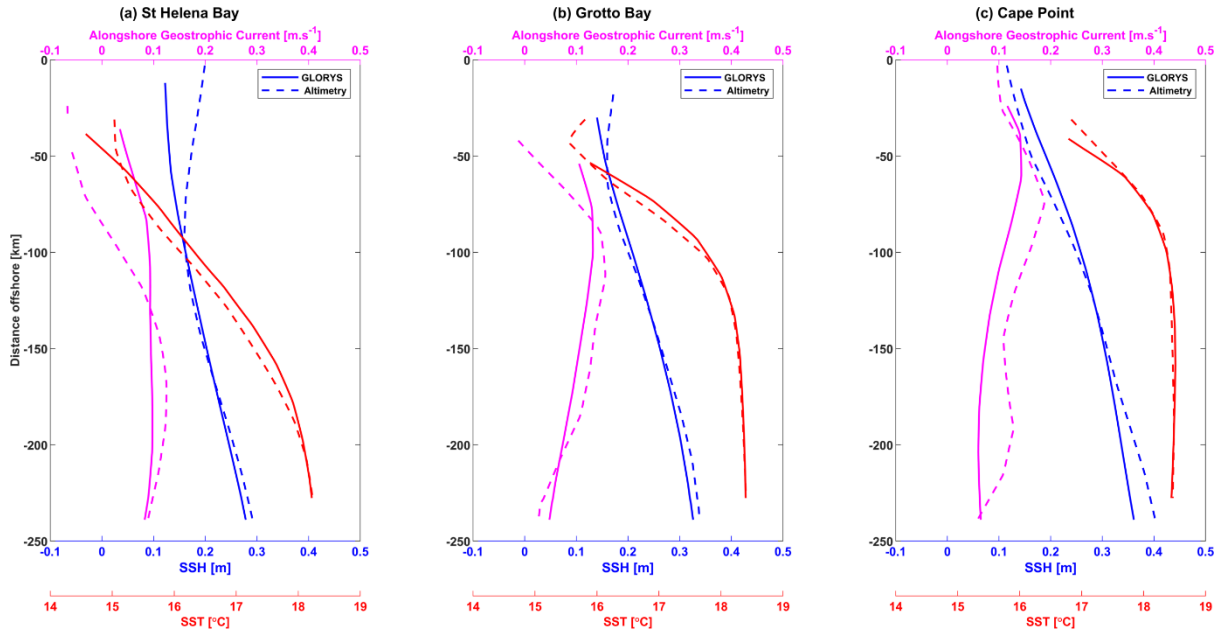


Figure 3.4: Across-shore profiles of SST (red), SSH (blue), and alongshore geostrophic currents (magenta), GLORYS reanalysis averaged from 1993-2021 (solid), and AVISO altimetry averaged from 1993-2018 (dashed). The cross-shore profiles are shown over the three transects: St Helena Bay, Grotto Bay, and Cape Point (see Figure 3.3).

3.3.3 Vertical Temperature

Figure 3.5 shows the cross-shore section of simulated (GLORYS) temperature and gridded observational climatology (WOA2023) temperature from a transect off Grotto Bay (33.5°S), extending 340 km offshore and the upper 450 m depth. Grotto Bay was selected as a representative transect for this initial evaluation to focus the analysis, with cross-shore sections at St Helena Bay and Cape Point to be examined in further analyses to capture broader spatial variability along the SBUS. To enable a consistent spatial comparison, the WOA2023 dataset was interpolated onto the GLORYS grid before calculating the difference shown in panel (c). The comparison between GLORYS and the WOA2023 climatology reveals a positive warm bias ($>1^{\circ}\text{C}$) in the upper 100 m of the inshore region (Figure 3.5). This is consistent with the warm coastal bias seen in Figure 3.2, which confirms the underestimation of coastal upwelling by GLORYS. Despite this bias, the modelled across-shore temperature variations align well with the observed patterns. Inshore temperatures are significantly cooler than those in the offshore region, with an upward-shifted thermocline (16°C isotherm, red) indicative of coastal upwelling.

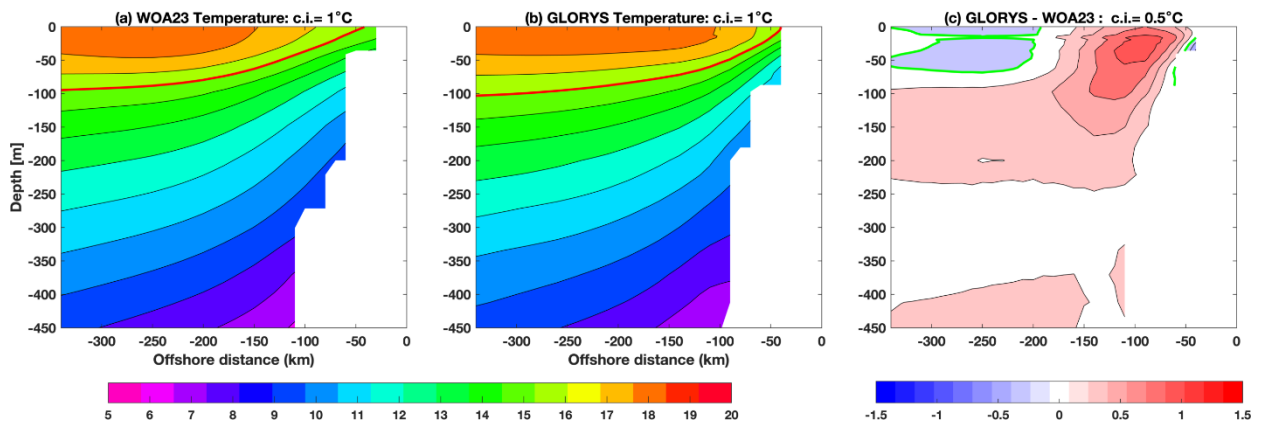


Figure 3.5: Temperature transect off Grotto Bay (red line in Figure 3.4) with the 16°C isotherm superimposed (red). a) World Ocean Atlas annual average (WOA2023); b) GLORYS annual average; c) Temperature bias (TGLORYS - TWOA2023), the green line denotes the 0°C isotherm.

Summary of the GLORYS evaluation:

In this section, when validating GLORYS with observation SST product from CCI, an annual warm SST bias of $\sim 1\text{--}1.5^{\circ}\text{C}$ was identified in the GLORYS reanalysis model, especially during summer upwelling periods, and the upwelling cells were consistently represented across both GLORYS reanalysis model and the CCI. This coastal warm bias was found to be confined in the upper 100 m compared with WOA23, and a similar bias was found by Russo et al. (2022) when they compared GLORYS with OSTIA SST data. Additionally, SSH data from AVISO altimetry was used to validate geostrophic currents in GLORYS, and GLORYS exhibited similar patterns to the AVISO altimetry data, with notable agreement in capturing the northward alongshore Benguela Jet observed with high velocities along the coast. However, some discrepancies in alongshore geostrophic current patterns were observed between GLORYS and AVISO, particularly near St Helena Bay and Grotto Bay. These discrepancies may be caused by GLORYS not resolving the coastal processes well within the 50km band, as Ragoasha noted (2022). Overall, GLORYS is able to capture the general mean circulation patterns and the seasonal variability typical of an upwelling system such as the equatorward jet (Benguela Jet) and coastal temperature gradients. However, it does not fully resolve the coastal geostrophic circulation near St Helena Bay and Cape Point, which may affect how well it represents nearshore upwelling.

4 Evaluation of historical HighResMIP

In this chapter, the historical HighResMIP models from 1950 to 2014 were evaluated with GLORYS for the ocean variables and ERA5 for the atmospheric variables.

The aim is to assess how well these models represent the nearshore processes of the SBUS and, in turn, how reliable they are to be used to investigate future projections. This chapter analyses the historical climate of the SBUS based on GLORYS, ERA5 and HighResMIP models, focusing on the seasonal cycle. The seasons investigated are defined as summer (October, November, December, January, February, and March) and winter (April, May, June, July, August, and September) to better represent the extended periods of upwelling-favourable conditions in summer and predominantly downwelling-favourable conditions in winter. The seasonality of the local winds, circulation of currents, vertical alongshore velocities, the South Atlantic Anticyclone (SAA), and the Ekman transport and Ekman pumping are studied. Additionally, vertical and across-shore sections are derived from the three transects: St Helena Bay, Grotto Bay, and Cape Point.

To statistically evaluate the agreement between the HighResMIP models and the GLORYS (oceanic) and ERA5 (atmospheric) reanalyses, Taylor diagrams were used. Two separate diagrams were generated: one for oceanic variables (Figure 4.11) and another for atmospheric variables (Figure 4.6). The variables were spatially averaged over the study domain prior to analysis.

4.1 Local winds, Ekman, and South Atlantic Anticyclone dynamics

4.1.1 Wind stress

Figure 4.1 compares the wind stress in the SBUS from ERA5 and the HighResMIP models (VR4 and FGOALS). In general, the ERA5 reanalysis model exhibits lower wind stress compared to the HighResMIP models presented. The VR4 model has the strongest winds with the maximum wind stress core wider compared to FGOALS for both seasons (Figure 4.1 g), consistent with the poor performance seen in Figure 4.11. These, however, show some good agreement in representing the wind stress seasonality over SBUS, illustrating a strong seasonal variability with stronger wind stress in summer than in winter.

The wind stress is strongest in summer and directed equatorward (Figure 4.1 a–b, i–j), typically associated with upwelling-favourable conditions and cooler coastal SSTs. The

upwelling favourable wind stress begins to weaken in autumn (March, April, May) (Figure 4.1 g). By the time winter arrives, the equatorward winds weaken further and shift to more northerly and north-westerly directions (Figure 4.1 d - f), reducing upwelling-favourable conditions. By winter, the equatorward winds weaken significantly, especially south of 30°S, and show more variation in direction (Figure 4.1 d-f). Although they remain mostly equatorward, this weakening and directional variability reduces the effectiveness of wind-driven coastal upwelling. This pattern is consistent with the northward and closer-to-shore displacement of the South Atlantic Anticyclone (SAA) shown in Figure 4.4 d-f.

The favourable upwelling winds persist throughout the year near the Lüderitz cell. However, they are weaker in winter than in summer.

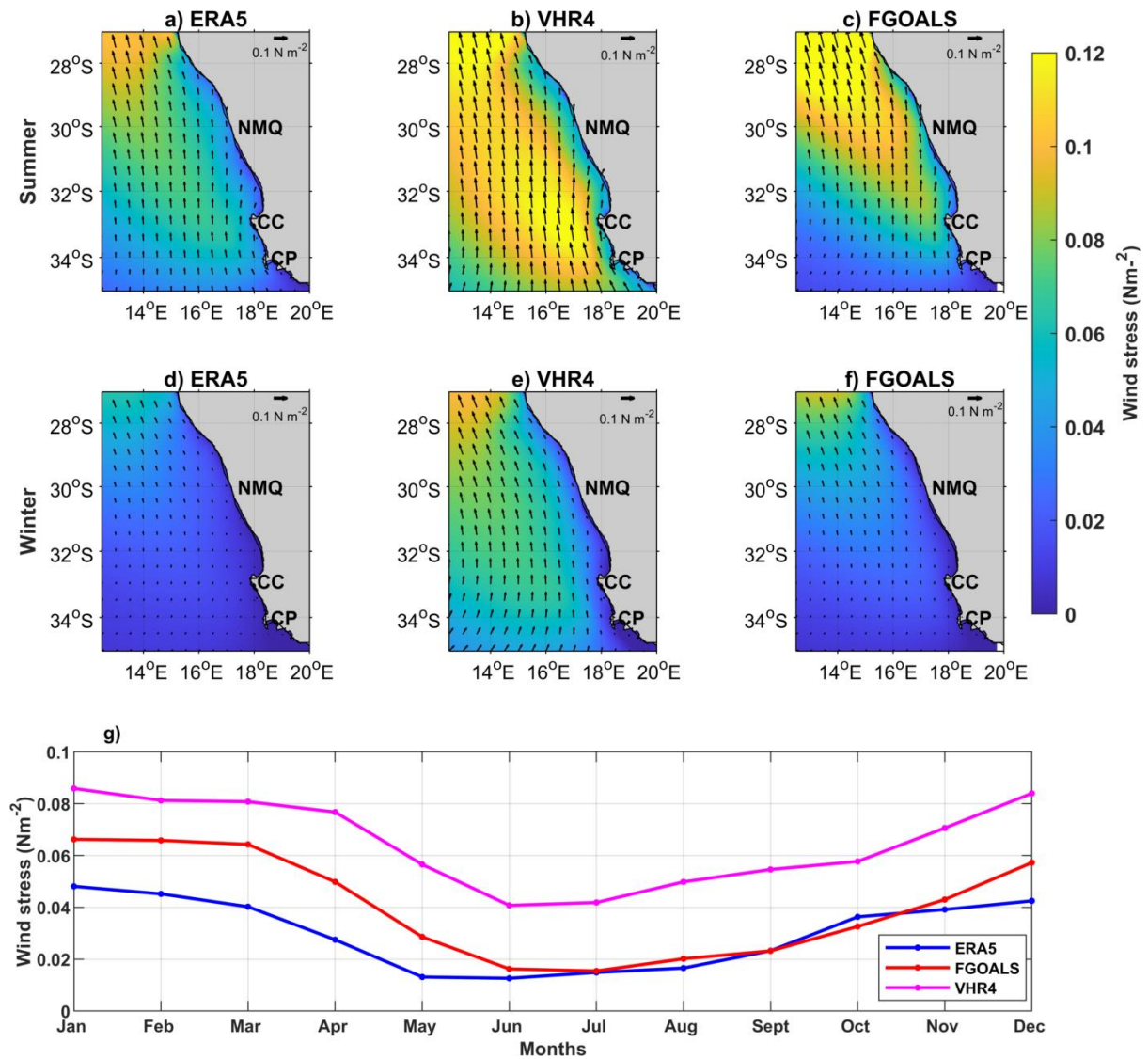


Figure 4.1: Historical Wind stress magnitude and direction for ERA5, VHR4, and FGOALS during summer (a-c) and winter (d-f) seasons. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Time series (g) shows monthly averaged wind stress magnitudes from the three models over the SBUS region.

4.1.2 Wind Stress Curl

The seasonal variation of surface wind stress curl for ERA5, VHR4, and FGOALS models is presented in Figure 4.2. There is notable agreement among the models when comparing the climatology of the ERA5 reanalysis model with the two HighResMIP models. Here, the wind stress curl is strongly negative along the coast and weakens offshore across all seasons, however, the intensity varies. The negative wind stress curl is stronger during summer, consistent with the intense upwelling favourable winds. This pronounced negative wind stress curl enhances Ekman pumping (Figure 4.3), causing the currents to flow offshore. During winter, the negative wind stress curl persists in the northern parts of the SBUS but weakens significantly between Cape Columbine (33°S) and Cape Point (34°S), reducing upwelling-favourable conditions. Although the models show similar wind stress patterns, the wind stress curl appears more intense (overestimated) in the HighResMIP models, especially in VR4, than in ERA5.

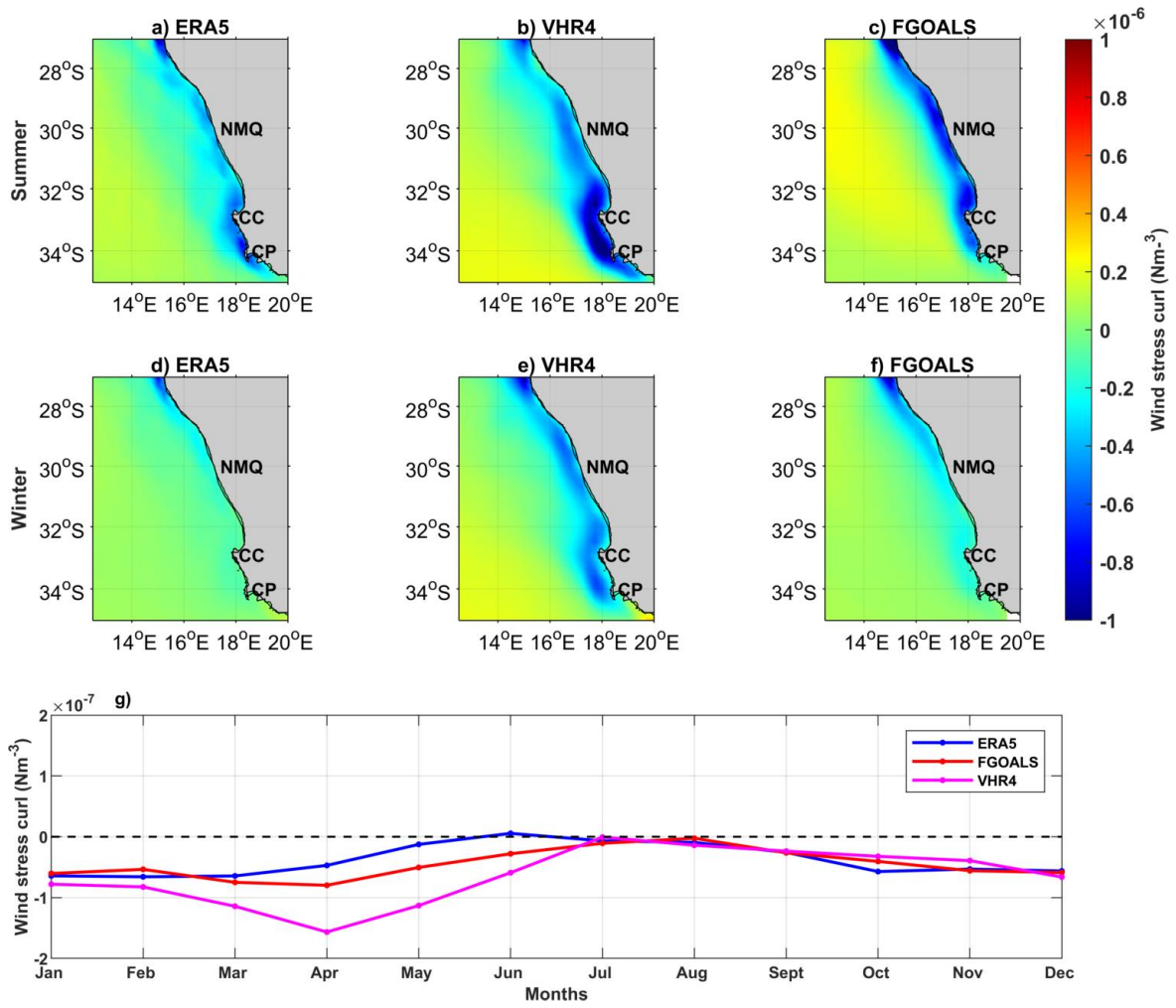


Figure 4.2: Historical wind stress curl for ERA5, VHR4, and FGOALS during summer (a-c) and winter (d-f) seasons. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Time series (g) shows detailed monthly averaged wind stress curl from the three models over the SBUS region.

4.1.3 Ekman Transport and Ekman Pumping

The seasonal Ekman transport and Ekman pumping (vertical velocities) in the SBUS are the key drivers of upwelling, significantly influencing the region's ecosystem. The Ekman transport and Ekman pumping exhibit seasonal variability, stronger in summer than in winter (Figure 4.3). These changes are primarily driven by the seasonality of upwelling favourable winds

influenced by the seasonal migration of SAA. The seasonality of Ekman transport and Ekman pumping from ERA5, HighResMIP models (VHR4, and FGOALS) for the historical climate was examined to understand how well the HighResMIP models represent the Ekman dynamics over SBUS (Figure 4.3).

During summer, Ekman transport represented by vectors, is strongest in the VHR4 model with magnitudes often exceeding $0.5 \text{ m}^2 \cdot \text{s}^{-1}$, indicating strong offshore transport along the SBUS coast. FGOALS also shows notable offshore transport, though slightly weaker and less consistent than in VHR4. In contrast, ERA5 displays weaker Ekman transport, with most vectors showing magnitudes equal to or less than $0.5 \text{ m}^2 \cdot \text{s}^{-1}$. In winter, the magnitude of Ekman transport weakens across all models, reflecting reduced offshore flow due to weaker upwelling-favourable winds.

The vertical velocities on all models are characterised by a narrow alongshore positive band extending further north, similar to the wind stress curl (Figure 4.2). The positive (negative) values indicate upwelling (downwelling), and the zero contour (black line) marks the boundary between the two. The positive values are much larger near upwelling cells with up to $1.14 \text{ m} \cdot \text{day}^{-1}$ in VHR4 and FGOALS and up to $0.5 \text{ m} \cdot \text{day}^{-1}$ in ERA5 during summer. In winter, weaker transport and velocities are observed because of the weaker upwelling favourable winds. As expected, the intensity of upwelling and offshore transport is much higher in VHR4, and the upwelling band is broad, consistent with the structure and intensity of wind stress and curl (Figures 4.1, 4.2).

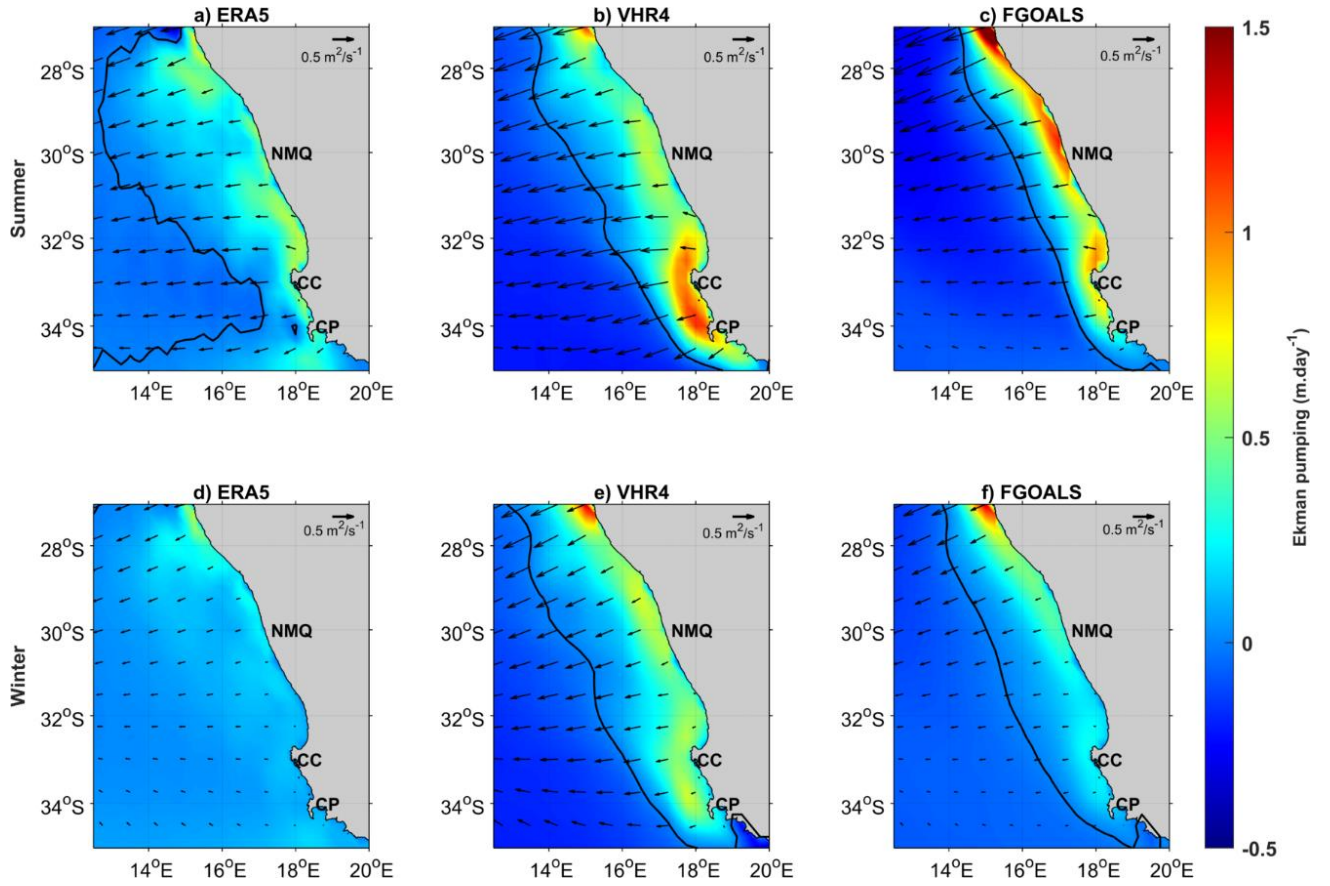


Figure 4.3: Historical seasonal Ekman transport (vectors, $\text{m}^2 \cdot \text{s}^{-1}$) and Ekman pumping (shaded, $\text{m} \cdot \text{day}^{-1}$) from the ERA5 reanalysis model and two HighResMIP models (VHR4 and FGOALS) for the summer (a-c) and winter (d-f) seasons. The Ekman pumping is demonstrated in $\text{m} \cdot \text{day}^{-1}$. Positive (negative) values indicate upwelling (downwelling). A reference vector of $0.5 \text{ m}^2 \cdot \text{s}^{-1}$ is shown in the top-right of each subplot. The black line represents the region of zero Ekman pumping. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

4.1.4 South Atlantic Anticyclone: Intensity and Position

The SBUS is greatly influenced by the SAA and continental heat low (Shillington, 1998). Therefore, it is crucial to understand the atmospheric dynamics within the SAA region. The SAA is known to have seasonal variability, which facilitates the upwelling process and undergoes latitudinal and longitudinal migration. It is known to move southward and further offshore (northward and closer to the coast) in summer (winter), as observed in Figure 4.4. This seasonal shift of the SAA affects the strength and direction of the local winds, leading to variations in upwelling intensity.

To investigate the intensity and position of SAA in the SBUS, the Mean Sea Level Pressure (MSLP) is used to evaluate the intensity and spatial distribution of the SAA in the HighResMIP models. In this section, HiRAM and FGOALS are evaluated against ERA5, as they are the

only models for which the MSLP variable is available. Figure 4.4 shows the seasonal averages of the MSLP from the historical climate, ranging between 1022 hPa and 1010 hPa.

When comparing the representation of SAA in the SBUS, the models illustrate similar intensity and position, with summer being relatively weaker (1018 hPa) and more southward SAA (Figure 4.4 a-c). Whereas in winter the SAA is stronger (1022 hPa) and more coastal SAA. The inland low-pressure system, also known as the thermal low, is found southward in summer and retreats northward in winter. This continental thermal low is replaced by a ridging high-pressure system absent in FGOALS (Figure 4.4 f).

Figure 4.5 shows the monthly climatology of the intensity and latitudinal of the SAA core. The core of the SAA was established by finding the maximum MSLP in the domain over the ocean. The monthly mean SAA core intensity and latitudinal position show that during the summer months (December to February), the SAA is observed to be weaker and positioned southwards across all three models (Figures 4.4, 4.5). The latitude of maximum intensity of SAA reaches its southernmost positions, ranging from approximately -33.25° to -34.00° . This indicates that the SAA's intensity is at its lowest during this period, reflecting a weaker high-pressure system. In contrast, the SAA is stronger and positioned northward during winter (June to August). The intensity of the SAA peaks in different months across the models: ERA5 shows the highest intensity in July (1026.0 hPa), FGOALS peaks in March (1024.8 hPa), and HiRAM reaches its maximum intensity in August (1025.3 hPa).

The results show that while the HighResMIP models and ERA5 captures the general seasonal cycle of SAA, there are notable differences in the simulated intensity and position among the models. Among the HighResMIP models, HiRAM shows closer agreement with ERA5 in representing the seasonal latitudinal shifts and intensity of the SAA, compared to FGOALS. Although both models exhibit biases, they offer valuable insights and can be useful for exploring future changes in SAA behaviour, provided they are interpreted with appropriate caution.

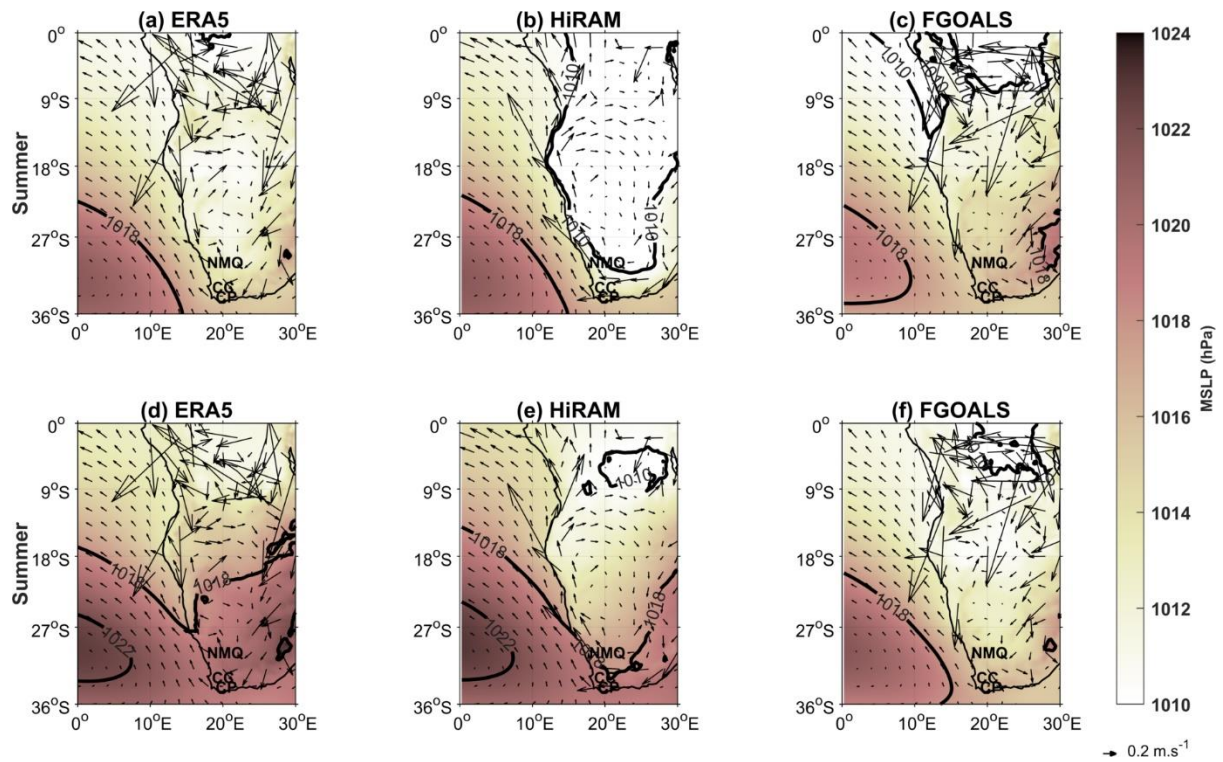


Figure 4.4: Seasonal surface maps of the MSLP (hPa) from ERA5, HiRAM and FGOALS models illustrating the location and intensity of the South Atlantic Anticyclone (SAA) from the historical climate for summer (a-c) and winter (d-f) seasons. The vectors overlaid represent wind intensity (length of the arrows) and direction (arrow's head).

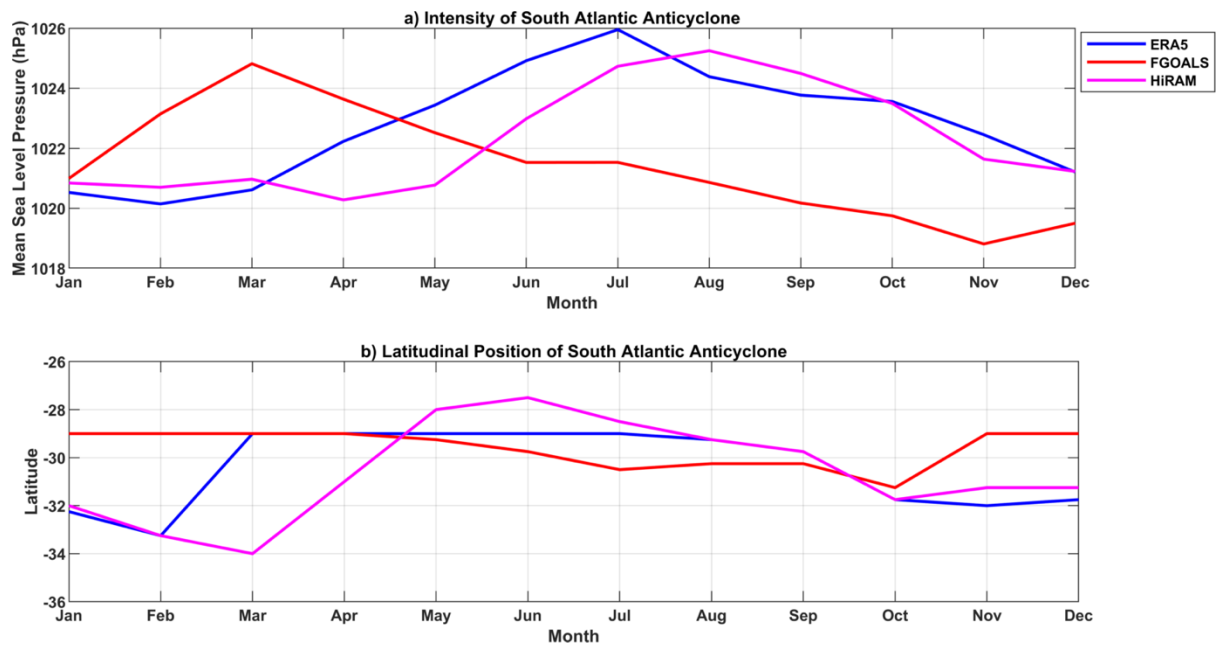


Figure 4.5: Monthly climatology of SAA intensity (a) and latitudinal position (b) from ERA5 reanalysis (blue line) and two HighResMIP models, FGOALS (red line) and HiRAM (magenta line) from the historical climate.

To statistically evaluate how well these models reproduce the observed atmospheric patterns, Taylor diagrams are employed. Figure 4.6 compares the HighResMIP models (FGOALS, HiRAM, and VHR4) with the ERA5 reference model. A high correlation with the reference model ERA5 on all the variables indicates reliable performance in the winds and Mean Sea Level Pressure (MSLP) patterns. However, there are some variations in how each model agrees with the reference. For the meridional and zonal winds (Figure 4.2 a, b), FGOALS performs best in capturing the wind patterns compared to VHR4. This is evidenced by its high correlation (0.8- 0.9), low RMSD (0.096-0.78) and a similar SD to ERA5. In Figure 4.2 c, MSLP in both FGOALS and HiRAM exhibit a high correlation of above 0.9, and their SD are closer to ERA5, with FGOALS showing the best agreement. This indicates that both these models accurately represent MSLP. However, there is a notable slight underestimation in variability as they all exhibit a slightly higher SD.

The statistical analysis (Figure 4.2) shows that FGOALS performed better across all the atmospheric variables, and it best represents the winds components and MSLP in the SBUS region.

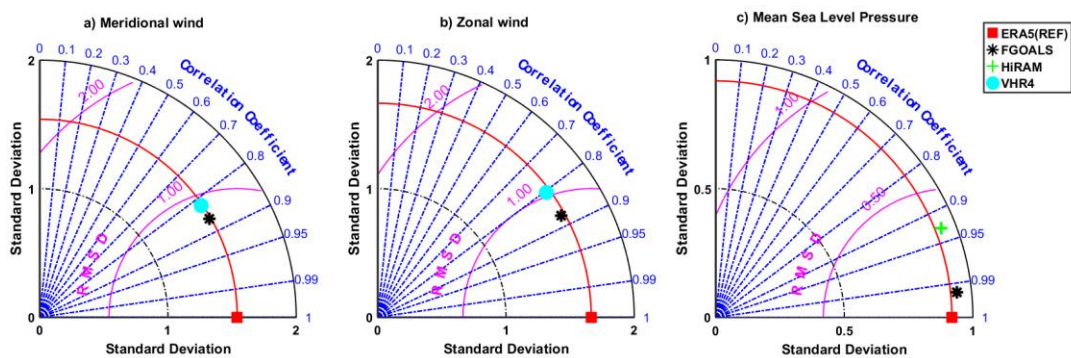


Figure 4.6: Taylor Diagram of the southern Benguela region from 1950-2014 showing a statistical relationship between VHR4 (cyan), FGOALS (black), and HiRAM (green) models from HighResMIP, the ERA5 reanalysis model (red) was used as a reference. The diagram gives a summary of the standard deviation (black), correlation (blue), Root Mean Square Difference (magenta) for all the presented atmospheric variables, Meridional and zonal winds (a, b), and Mean Sea Level Pressure (c) across all the models.

4.2 Sea Surface Temperature

The SST from the HighResMIP models (VHR4, HR4, and CAM5) was validated against SST from the GLORYS reanalysis model to evaluate the models' accuracy and performance in capturing spatial and temporal SST variations within the SBUS. The bias between the HighResMIP models and the GLORYS reanalysis was calculated using the following formula:

$$\text{Bias} = \text{SST}_{\text{HighResMIP}} - \text{SST}_{\text{GLORYS}}$$

Positive (negative) values in the bias represent regions where the model overestimates (underestimates) GLORYS SST.

The bias has shown that the VHR4 and CAM5 models tend to underestimate SST (cold bias) in coastal upwelling regions, indicating an overestimation of upwelling intensity (Figures 4.8, 4.9). Meanwhile, the HR4 model consistently overestimates SST, suggesting an underestimation of upwelling intensity or coastal cooling compared to the GLORYS. However, SST is also affected by surface heat fluxes, including solar radiation which can influence temperature independently of upwelling.

SST shows a clear seasonal variability in the southern Benguela, with higher temperatures observed in summer and cooler temperatures in winter (Figures 4.8, 4.9). In summer, cooler coastal waters bounded by the 16°C isotherm (red line) are observed in GLORYS, VHR4 and CAM5 (Figures 4.8 a, b, d), with the HR4 model not showing any traces of cold SST along the coast (Figure 4.8 c). The HR4 model overestimates coastal SST, as confirmed by the positive bias demonstrated in the bias map (Figure 4.8 f). A notable 2–3°C bias is observed in St. Helena Bay (north of Cape Columbine) and extends northward. In contrast, the VHR4 and CAM5 models (Figures 4.8 e and 4.8 g, respectively) display a negative bias of less than 1°C and 2–3°C. However, in the VHR4 model, this cold bias is confined to the coastal region (Figure 4.8e).

Coastal lower temperatures are observed in winter, with SST ranging from 14°C. to 16°C (Figure 4.9). The bias maps (Figure 4.9 e-g) show that the respective model SST biases are reduced during winter. Contrastingly, the HR4 model exhibits a persistent and strong warm bias in both seasons (Figure 4.8, 4.9 f). While this may suggest an underestimation of upwelling intensity or coastal cooling, imbalances in net surface heat flux—could also contribute to the bias.

These results suggest that the VR4 and CAM5 models underestimate coastal SST, possibly due to the overestimation of upwelling, misinterpretation of surface heating, and vertical mixing. Since the HighResMIP models originate from different modelling centres, vertical

mixing is likely parameterized differently across them. It is also apparent that there is more leakage of warm Agulhas waters in the VHR4 and HR4 models, as indicated by the offshore warm bias.

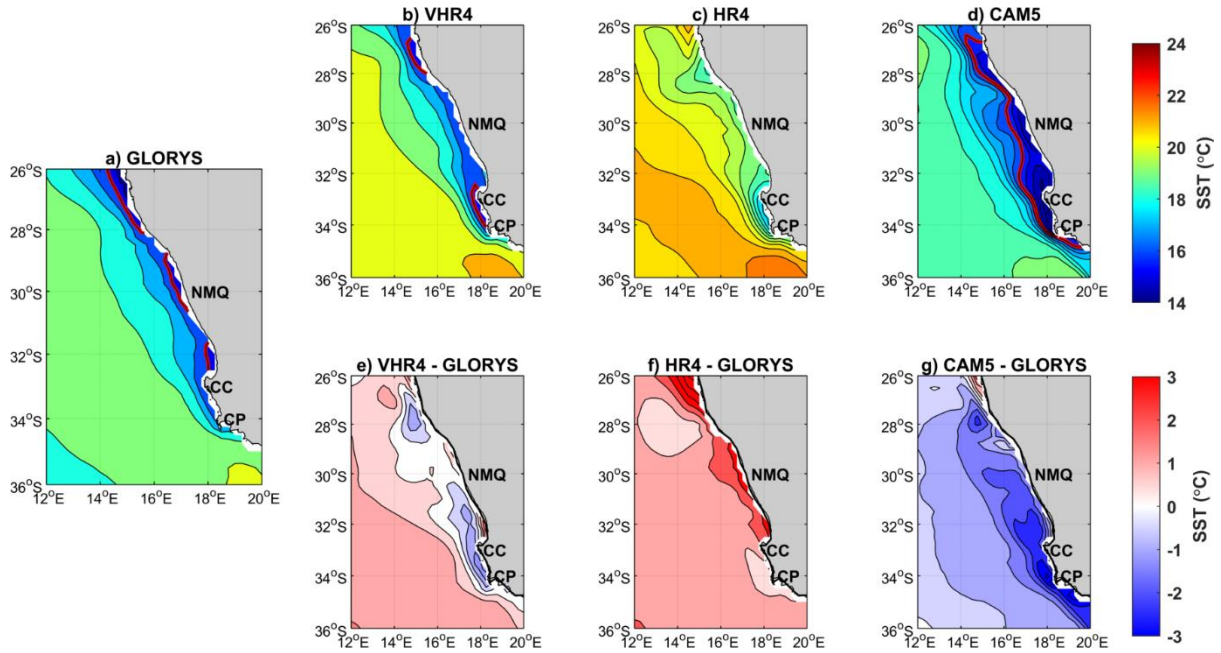


Figure 4.7: Summer averages of Sea Surface Temperature (SST) from the GLORYS reanalysis model and VHR4, HR4 and CAM5 HighResMIP models (a-d). The SST differences between GLORYS and HighResMIP models are shown(e-g). The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Positive (negative) values in the bias are regions where the model overestimates (underestimates) GLORYS SST.

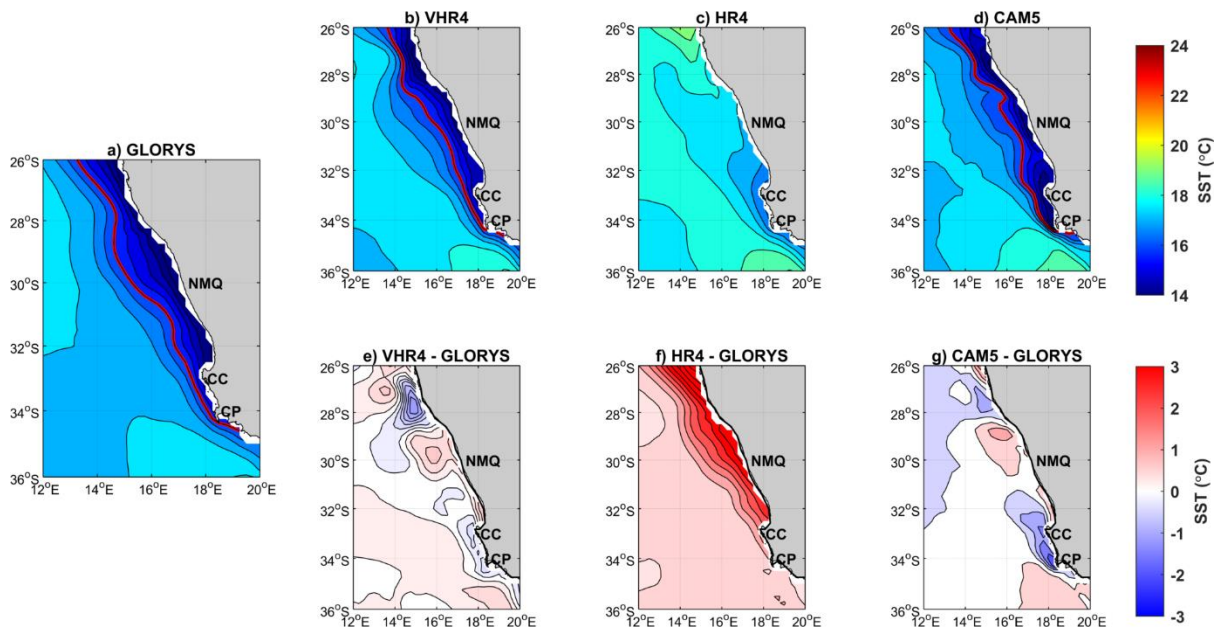


Figure 4.8: Winter averages of Sea Surface Temperature (SST) from the GLORYS reanalysis model and VHR4, HR4 and CAM5 HighResMIP models (a-d). The SST differences between GLORYS and HighResMIP models are shown(e-g). The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Positive (negative) values in the bias are regions where the model overestimates (underestimates) GLORYS SST.

4.3 Coastal Currents

In this section, HighResMIP models are evaluated with GLORYS to determine how well surface and geostrophic currents are represented by the models over SBUS.

4.3.1 Surface Currents

The surface current maps reveal the existence of the Benguela Jet in the region, a region characterised by strong current speed all year round, with varying seasonal intensity (Figures 4.10, 4.11). The Benguela Jet separates into two branches at approximately 33.5°S, with an offshore branch flowing beyond the 2000m isobath in a northwest direction and the coastal branch flowing alongshore between the 200m and the 500m isobath. This current is consistently observed in both the GLORYS and HighResMIP models and exhibits a distinct seasonal cycle.

The Benguela Jet is most intense during the summer season, particularly between Cape Columbine and Cape Point, with a surface current speed of up to $0.35 \text{ m} \cdot \text{s}^{-1}$ flowing northwest. This high intensity coincides with the period of strong wind stress (Figure 4.3 a, b, c) and a strongly negative wind stress curl (Figure 4.4 a, b, c). The flow is notably more intense in the HighResMIP models, particularly in VHR4 and CAM5 than in the GLORYS reanalysis model.

(Figure 4.10, 4.11 a-d). In contrast, the Benguela Jet weakens during winter when wind stress is reduced.

In comparing the Benguela Jet among the models, GLORYS depicts weaker flow than the HighResMIP models. However, all models capture a similar structure of the jet, with a maximum north-westward flow at $0.3 \text{ m}\cdot\text{s}^{-1}$ between Cape Columbine and Cape Point. While the HighResMIP models tend to overestimate the jet's intensity, they reasonably capture its structure and seasonal variability. However, these findings should be interpreted with caution, given the potential limitations of GLORYS.

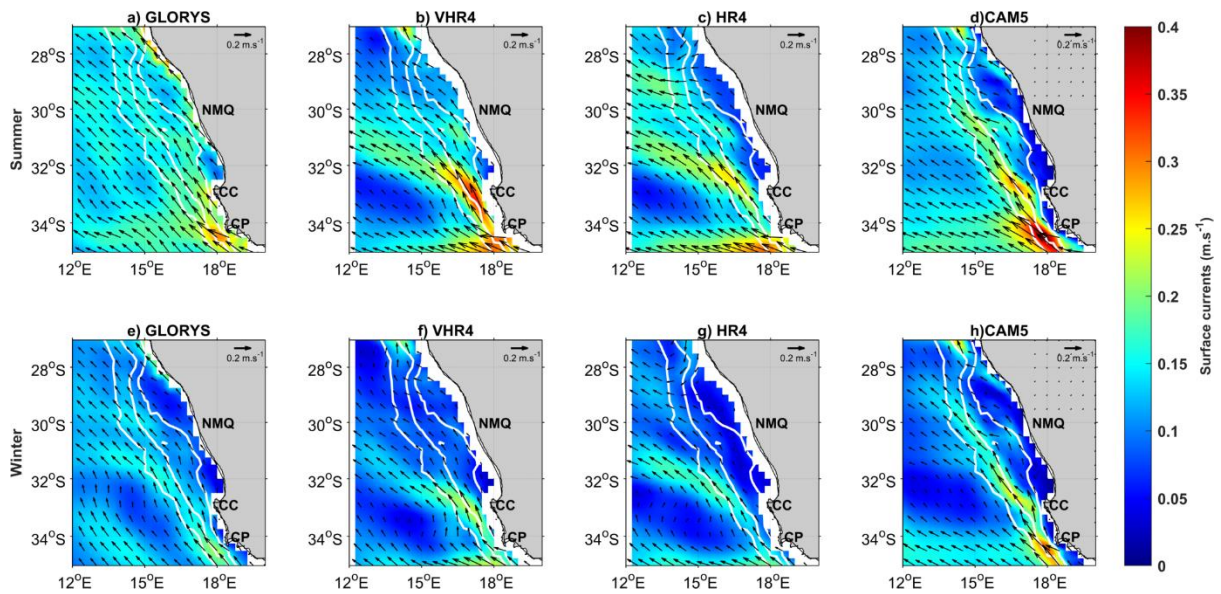


Figure 4.9: Historical seasonal climatology of surface currents for GLORYS reanalysis model and HighResMIP models (VHR4, HR4, and CAM5) for the summer (a-d) and winter (e- h) seasons. The magnitude of the current is shown in colour ($\text{m}\cdot\text{s}^{-1}$), and current vectors are superimposed, as well as the 200m, 500m, and 2000m isobaths (solid white) from SRTM. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

4.3.2 Sea Surface Height

Figure 4.11 presents the seasonal SSH in the SBUS and estimates the geostrophic currents from VHR4, HR4, and CAM5 models compared to those of GLORYS. The HighResMIP models show good agreement with GLORYS in simulating historical SSH levels and geostrophic currents. However, this good performance in the present climate does not necessarily imply reliable projections of future change. Model skill in reproducing observed climatology does not guarantee credible future responses to forcing, due to uncertainties in model responses and internal climate variability (Boé et al., 2009). Nonetheless, the ability of these models to capture key historical circulation features provides a reasonable basis for their application in projecting future climate changes in the SBUS. During summer, lower SSH

levels accompanied by strong SSH gradients are observed along the coast and are more pronounced between Cape Point and Cape Columbine upwelling cells. This is linked to strong upwelling events driven by upwelling-favourable winds (Figures 4.3, 4.4), which induce offshore Ekman transport, resulting to cooler coastal SSTs (Figures 4.8, 4.9) and lower SSH near the coast (Figure 4.11). The resulting cross-shore SSH gradients drive a geostrophic current flowing further offshore. Among the models, the HighResMIP outputs, particularly VHR4 and CAM5 (Figure 4.11 b–d), display lower SSH levels than GLORYS, with more pronounced gradients.

In contrast, during winter, a slight rise in SSH levels occurs due to the weakening of upwelling events (Figure 4.11 e–h). This results in reduced SSH gradients and weaker geostrophic currents. Notably, CAM5 tends to overestimate the SSH gradient and, hence, the current intensity compared to the other models. This overestimation is consistent with the previously found relatively high negative SST biases (Figure 4.8 g, 4.9 g).

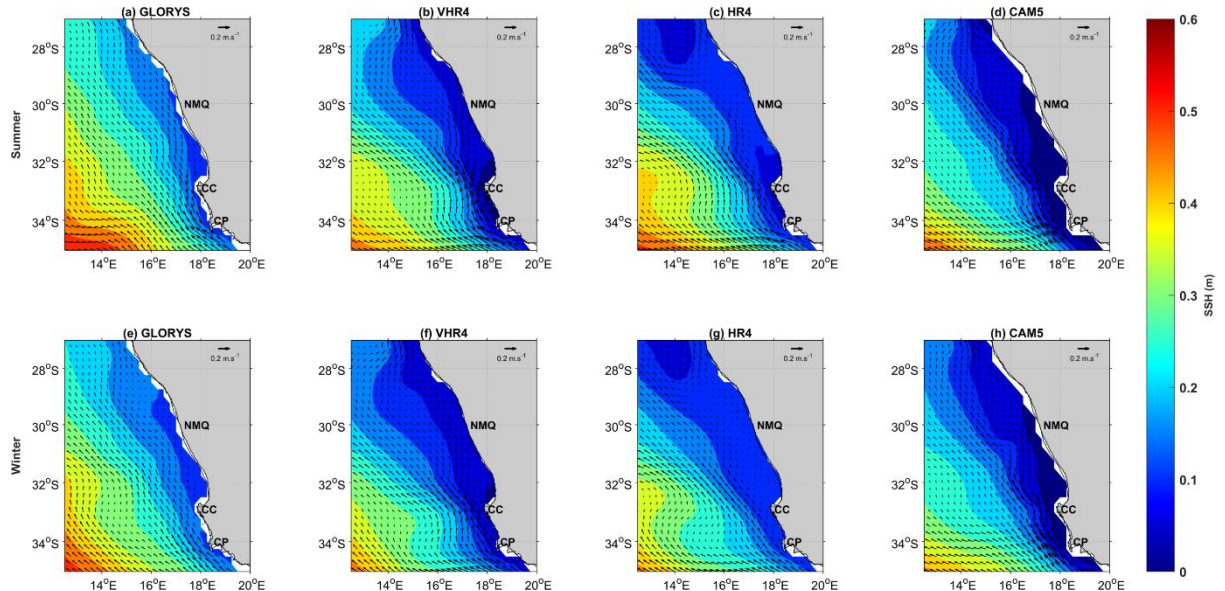


Figure 4.10: Historical seasonal Sea Surface Height (SSH) with corresponding surface geostrophic currents superimposed vectors from GLORYS reanalysis model and three HighResMIP models (VHR4, HR4, and CAM5) for summer (a–d) and winter (e–h) seasons. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

Model performance is further investigated using Taylor diagrams. Figure 4.1 investigates how well the models represent SST, seawater potential temperature, SSH, and zonal and meridional seawater velocities in southern Benguela. The diagram shows that VHR4 closely agrees with the reference model GLORYS, particularly for SST, temperature and SSH, with high correlation (0.88–0.92), lower RMSD (0.05–0.16), and SDs closely matching the reference followed by HR4. This indicates that this model captures the variability and spatial patterns of these variables well. In contrast, CAM5 shows decent performance but is slightly outperformed

by HR4 and VHR4 in terms of correlation and RMSD. This model shows a slightly weaker agreement than VHR4 and HR4, showing slightly lower correlation, standard deviation and high RMSD. However, when representing the zonal and meridional currents, CAM5 shows a very close agreement with GLORYS, followed by HR4 and VHR4 with high correlation and SD that closely aligns with GLORYS. This suggests that the CAM5 model capture the variability of the currents well. Overall, all the models represent the current patterns well.

The statistical analyses indicate that these models are reliable in representing the oceanic conditions of the southern Benguela. Additionally, the analyses highlight that VHR4 performed best in modelling the surface conditions (SST, SSH, temperature), with CAM5 relatively better in modelling the ocean current patterns.

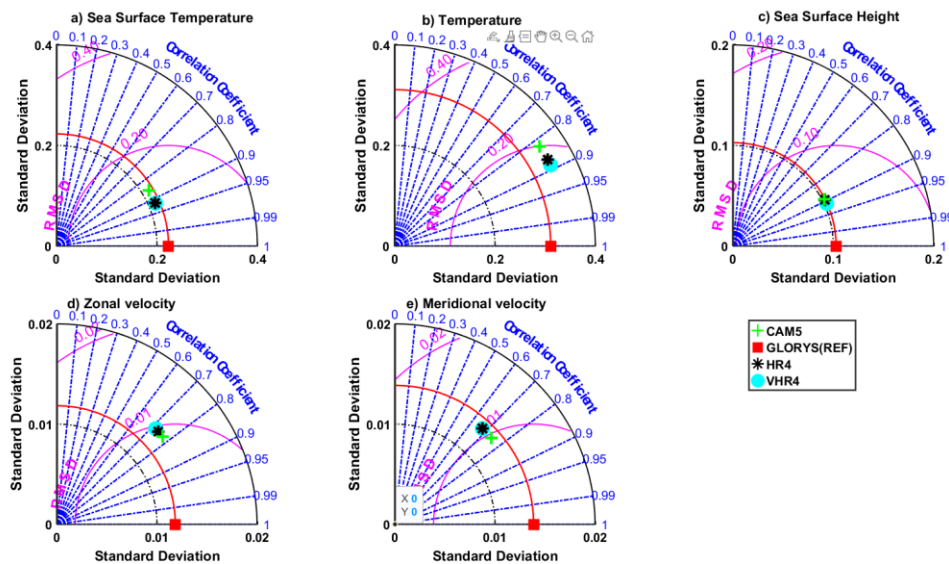


Figure 4.11: Taylor Diagram of the southern Benguela region from 1950-2014 showing a statistical relationship between VHR4 (cyan), HR4 (black), and CAM5 (green) models from HighResMIP, the GLORYS reanalysis model (red) was used as a reference. The diagram gives a summary of the standard deviation (black), correlation (blue), Root Mean Square Difference (magenta) for all the presented oceanic variables, Sea Surface Temperature (a), Seawater temperature (b), Sea Surface Height (c), Zonal and meridional velocities (d, e) across all the models.

4.4 Vertical alongshore current and across-shore winds

This section examines the vertical transects of the alongshore current velocities and temperature, including the wind stress and wind stress curl from the across-shore transects taken from St Helena Bay (32°S), Grotto Bay (33°S), and Cape Point (34°S), as shown in Figure 3.3. These transects reveal the presence of a poleward undercurrent over the continental slope and the equatorward Benguela jet with a strong seasonal difference. In addition, the cross-shore and vertical structures of the currents vary from Cape Point to St Helena Bay. As expected, the currents are relatively weaker, and the temperature is lower in winter than in summer.

The HighResMIP models consistently exhibit a stronger equatorward Benguela Jet, located further offshore (beyond approximately 150 km) and extending deeper into the water column (below 100 m). The offshore positioning of the jet coincides with the strength of the poleward undercurrent and its proximity to the surface.

Off St Helena Bay (Figure 4.12), the jet comprises a single branch, and the poleward undercurrent, particularly strong during summer, is relatively more pronounced in the HR4 and CAM5 models. Both models simulate the undercurrent as a surface-to-bottom feature, whereas the GLORYS reanalysis shows a more weaker and shallower structure, typically confined to intermediate depths. This difference likely reflects a model bias that may be caused by limitations in vertical resolution, bathymetry, or mixing parameterisations, leading to an overestimation of vertical momentum or mixing in subsurface transport. Notably, the 12 to 14°C isotherms in HR4 (Figure 4.12 c) are not uplifted near the coast, indicating an underestimation of coastal upwelling and the associated warm SST bias (Figure 4.8 f). In contrast, the CAM5 model shows the 12°C isotherm uplifted closer to the coast (approximately 50 km offshore), indicating stronger coastal upwelling and a corresponding cool SST bias (Figure 4.8 g).

Off Grotto Bay (Figure 4.13), two branches of the Benguela Jet are observed in the VHR4 model (Figures 4.13 b, f) during both seasons, while the HR4 model shows two branches only in summer (Figure 4.13 c). Similar to St Helena Bay, the poleward undercurrent in the HighResMIP models is both stronger and broader than in GLORYS reanalysis, with relatively stronger currents in VHR4 and CAM5. However, at this location, the representation of the undercurrent is relatively more realistic. The models simulate a subsurface-intensified undercurrent that aligns more closely with the reanalysis, although the models still tend to overestimate its intensity and vertical extent. This improved agreement suggests that the models are better able to capture the local bathymetric features and vertical stratification at this latitude, resulting in a more physically consistent simulation of subsurface flow.

At Cape Point, the two branches of the Benguela Jet are also evident in the VHR4 and HR4 models, characterised by a stronger inshore branch and a weaker offshore branch. In the CAM5 model, the Benguela Jet is relatively stronger and extends deeper (approximately 200 m). However, a significant discrepancy emerges in the representation of the poleward undercurrent: while the GLORYS reanalysis shows no distinct subsurface poleward flow at this latitude, all three models—particularly HR4 and VHR4—simulate a vertically continuous undercurrent extending from the surface to the bottom. Furthermore, there is evidence of increased Agulhas leakage in the VHR4 and HR4 models during summer (Figure 4.14 b, c), indicated by the offshore penetration of the 20°C isotherm up to 100 km.

The low SSTs and strong currents observed during summer are linked to strong upwelling-favourable winds and negative wind stress curl (WSC) (Figures 4.12 to 4.14 i, j). The VHR4 model overestimates wind stress and WSC, explaining the overestimated coastal upwelling and pronounced cold bias.

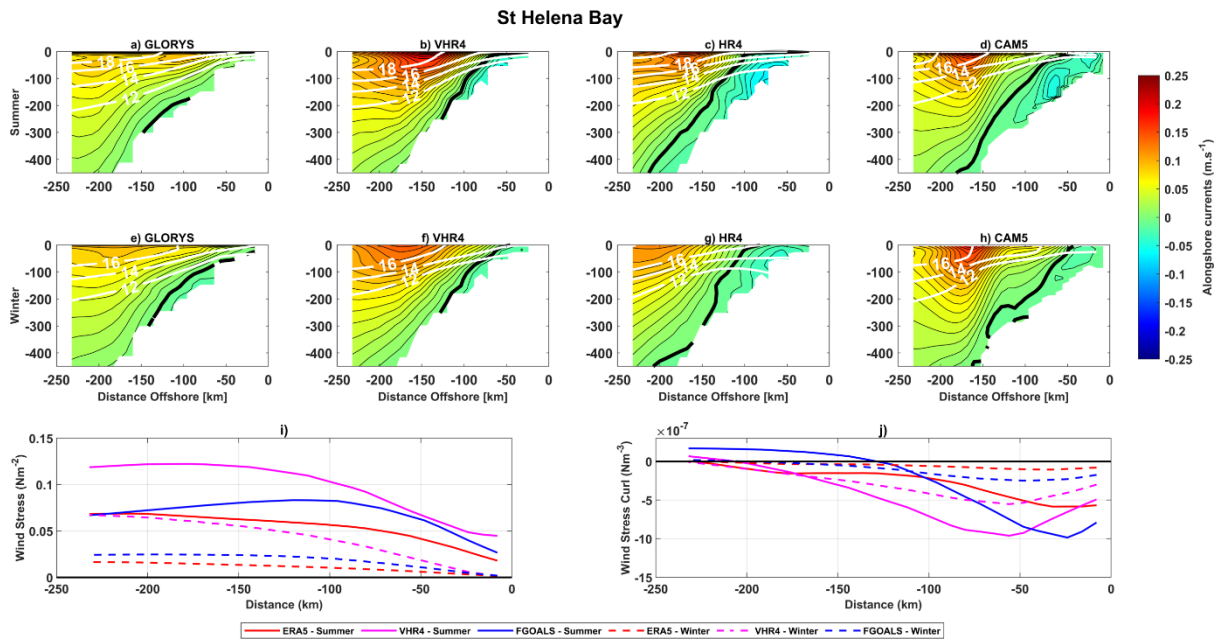


Figure 4.12: St Helena Bay vertical transect of historical alongshore velocities ($\text{m}\cdot\text{s}^{-1}$), isotherms (white contours), wind stress and wind stress curl from three models, ERA5 reanalysis model (red), VHR4 (magenta), and FGOALS (blue). The first two rows show the alongshore current velocities with temperature, the contours of the current intensity are shown in black, and the zero contour is bold. The third row shows the alongshore wind stress (i) and the wind-stress curl (j) for the across-shore transect, with the zero line (black). Summer is indicated by solid lines, and dashed lines indicate winter.

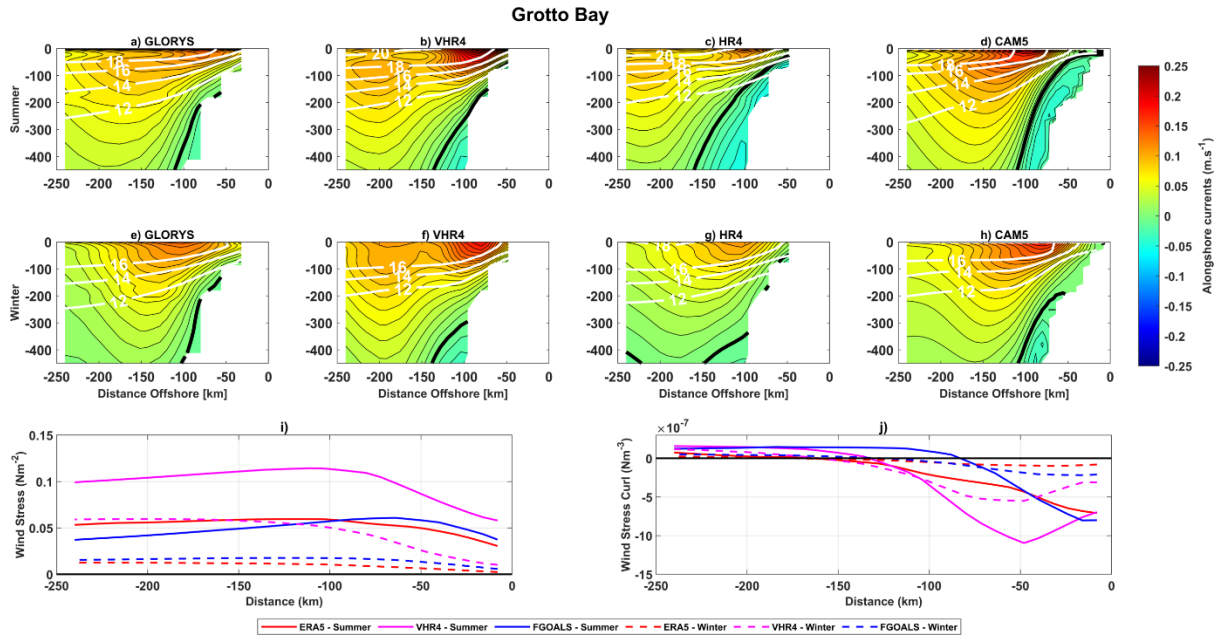


Figure 4.13: Similar to Figure 4.12 but for the Grotto Bay transect.

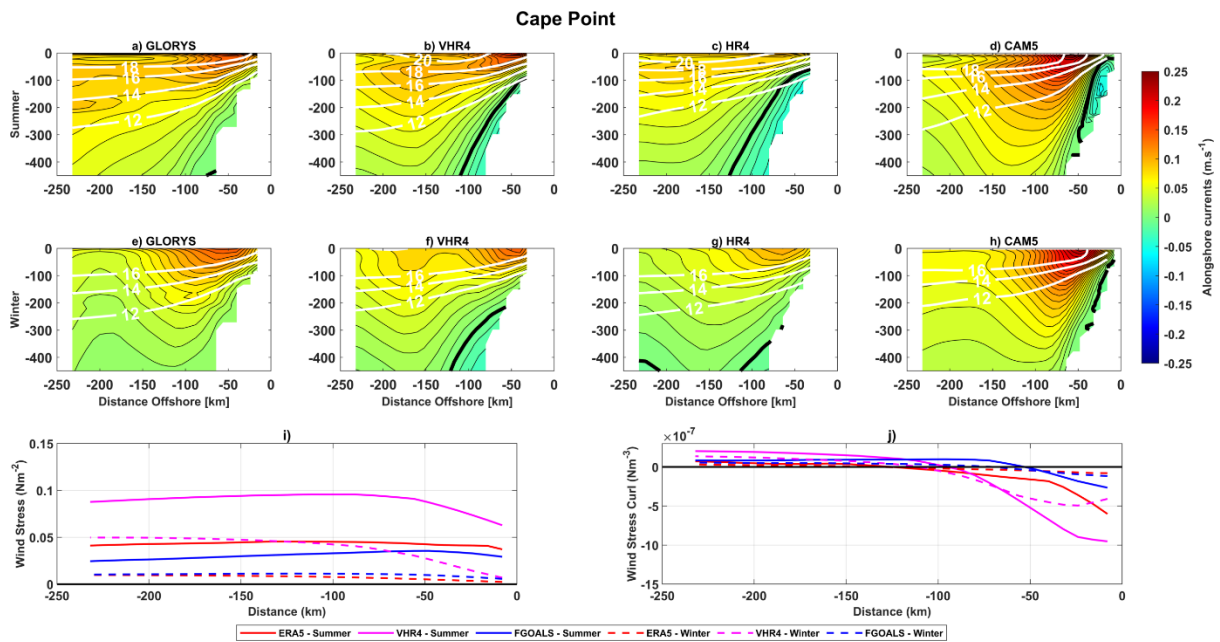


Figure 4.14: Similar to Figures 4.12 and 4.13 but for the Cape Point transect.

Summary of the historical HighResMIP evaluation:

The HighResMIP ocean variables (ocean currents, temperature, SSH) were compared with GLORYS reanalysis, while the atmospheric variables (wind stress, wind stress curl, and MSLP) were compared with ERA5 reanalysis. The evaluations showed varied biases; however, the models are capable of reproducing key physical processes characteristic of an Eastern Boundary Upwelling System (EBUS):

- A coastal upwelling that is strongest in summer and weaker in winter.
- SST and SSH increase offshore, producing a negative gradient that is important for driving the equatorward current.
- A strong surface equatorward Benguela Jet, located on the shelf between the 200 m and the 500 m isobath.
- A poleward undercurrent off the slope edge.

However, notable differences exist in intensity and spatial extent, depending on the model:

- VHR4: Exhibited strong upwelling and more Agulhas leakage, which resulted in a strong SSH/SST gradient, leading to a stronger Benguela Jet.
- HR4: Exhibited weaker upwelling and more Agulhas leakage, which resulted in a weaker SSH/SST gradient and, hence, a weaker Benguela Jet.
- CAM5: Exhibited the strongest upwelling but less Agulhas leakage, resulting in a strong SSH/SST gradient and a stronger Benguela Jet.

It is important to note that some of the coastal biases may be related to the 25 km spatial resolution not being sufficient to resolve coastal processes properly. However, the misinterpretation of wind stress, surface heat fluxes, and vertical mixing are also likely contributors. For example, the overestimation of wind stress and negative WSC in the VHR4 model could explain the cold bias related to overestimated coastal upwelling.

Across all sections, the HighResMIP models simulate a poleward undercurrent that is stronger and more vertically extensive than observed in the GLORYS reanalysis. While the undercurrent is present in both the reanalysis and models off St Helena Bay and Grotto Bay, it is notably more intense and extends deeper in the model simulations. At Cape Point, this discrepancy becomes more pronounced, as the models simulate a surface-to-bottom undercurrent that is absent in the reanalysis. This points to a systematic model overestimation of the subsurface poleward flow, likely due to limitations in vertical resolution, bathymetric representation, or mixing parameterisations.

Despite these limitations, we are confident in studying the future projections with the respective biases in mind, focusing on the differences between historical and future simulations of each model.

5 Future projections of SBUS from 2015 – 2050 based on HighResMIP models

This chapter investigates the potential impacts of climate change on the southern Benguela Upwelling system (SBUS). Utilising high-resolution simulations from the HighResMIP project under the SSP5-8.5 scenario, we analyse projected changes in seasonal circulation patterns, ocean temperatures, upwelling and the South Atlantic Anticyclone (SAA) dynamics for the 2015-2050 period, compared to a historical baseline (1950-2014). The analysis focuses on characterising the projected changes in the seasonality of key oceanic and atmospheric variables, including SST, ocean currents, local wind fields, Ekman transport, and Ekman pumping, as well as the intensity and position of the SAA. Vertical and cross-shore profiles are extracted at three transects to assess spatial changes: St Helena Bay, Grotto Bay, and Cape Point (Figure 3.3). Seasons are defined as summer (October-March) and winter (April-September).

The impact of climate change is quantified by calculating differences in key variables between the future (2015-2050) and historical (1950-2014) periods. The following HighResMIP models are employed in this analysis: VHR4, HR4, and CAM5 for ocean variables and VHR4, HiRAM, and FGOALS for atmospheric variables.

5.1 Local Winds, Ekman dynamics and SAA

5.1.1 South Atlantic Anticyclone (SAA)

To begin with, we analyse the differences in the strength and position of the SAA between future and historical periods, as these factors significantly influence wind variability in the SBUS. Figure 5.1 presents future changes in the SAA and indicates notable changes in intensity and position, particularly during summer.

All models, except FGOALS, effectively capture the seasonality in the spatial distribution and intensity of the mean sea level pressure (MSLP) associated with the SAA and the continental pressure system. Therefore, the future differences presented here are based on the HiRAM model. Positive (negative) differences reflect an increase (decrease) in MSLP.

During summer (Figure 5.1 a-d), positive differences are observed between 0–10°E and poleward, suggesting that the maximum MSLP values associated with the SAA are expected to shift westward and slightly southward. As shown in Figure 5.2a, b, MSLP is projected to increase by less than 0.4 hPa during early summer (October–December), accompanied by a

southward shift of up to -0.2° . Conversely, negative differences (-0.2 to -0.4 hPa) are observed over land, indicating a decrease in MSLP and the development of a more intense continental low.

In contrast, during winter (Figure 5.1 e, f), the SAA is projected to become more zonally expansive (indicating an onshore shift), move southward (up to 27.9°S), and intensify, reaching ~ 1025.4 hPa. The strongest intensification, ~ 0.8 hPa, is expected in September (Figure 5.2 c), while a northward shift of up to 0.25° is projected for July and August (Figure 5.2 d). Additionally, the ridging high-pressure system along the west coast of southern Africa (18 – 35°S) is expected to weaken, as reflected by negative differences in MSLP.

These projected MSLP changes are expected to drive spatial variations in alongshore wind and wind stress curl, directly influencing upwelling dynamics. Consequently, the next section investigates changes in local winds and upwelling and their impacts on SST, SSH, and ocean currents.

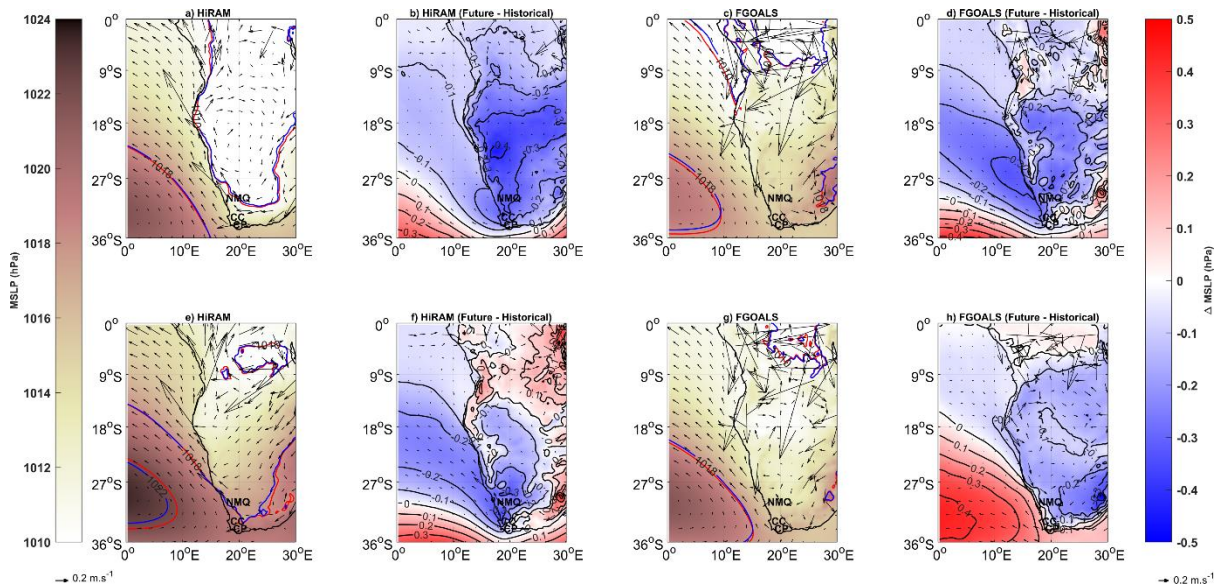


Figure 5.1: Historical and projected seasonal change of MSLP (hPa) from HiRAM and FGOALS models illustrating the location and intensity of the South Atlantic Anticyclone (SAA) from 2015 – 2050. Summer is shown in panels (a–d) and winter in panels (e–h). The historical climate is defined by the solid blue line, and the future climate by the solid red line (a, c, e, f). The projected MSLP change (b, d, f, g) between the future (2015 -2050) and historical climate (1950 -2014).

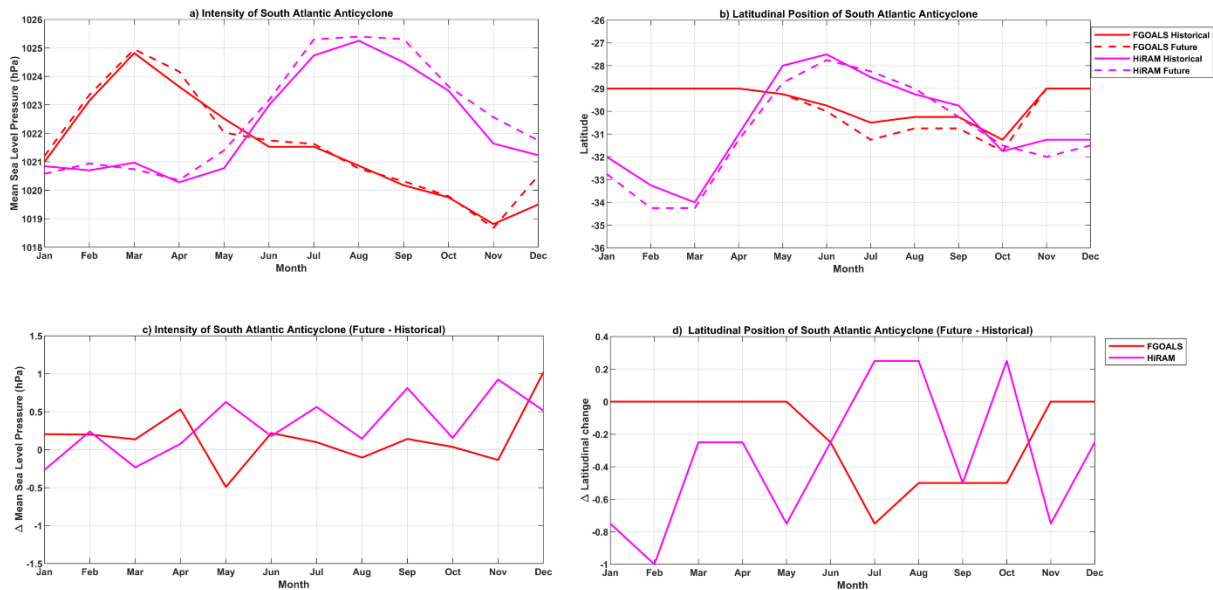


Figure 5.2: Historical and projected future monthly climatology of SAA intensity (a) and latitudinal position (b) from FGOALS (red line) and HiRAM (magenta line) from 1950 - 2050. Projected change (2050-1950) of the SAA intensity (c) and latitudinal position (d).

5.1.2 Wind stress

The alongshore wind stress in the South Benguela Upwelling System (SBUS) exhibits strong seasonal variability, primarily driven by the land and ocean pressure gradient. Both models (VHR4 and FGOALS) effectively capture the equatorward wind stress, with the core of maximum intensity shifting southward during summer (Figure 5.3 a, b, h, j) in both historical and future projections. In contrast, the core shifts northward during winter, centring around 28°S.

As illustrated in Figure 5.3c, g, k, n, not all regions experience strengthened winds in future projections. During summer, a weakening of wind speed is evident near the coast between 28°S and 30°S, while a strengthening occurs south of 30°S, extending offshore (Figure 5.3 c, k). Notably, an increase of approximately $\sim 0.15 \text{ N} \cdot \text{m}^{-2}$ is observed along the Cape Point (34°S) and Cape Columbine (33°S) upwelling cells (Figure 5.3 b, j), with peak intensification during the early upwelling season (October–December) (Figure 5.3h).

In winter, the wind patterns exhibit opposite changes (Figure 5.3 g, n). A weakening of wind speed is observed between Cape Point (34°S) and Cape Columbine (33°S). In the FGOALS model, this weakening extends offshore but diminishes in intensity further from the coast (Figure 5.3 n). In contrast, the VHR4 model projects a strengthening of winds along the coast between Cape Columbine and the Namaqua cell, with weakening winds located offshore and

near Cape Point (Figure 5.3 g). Additionally, an increase in wind speed is noted north of the Namaqua cell in the FGOALS model.

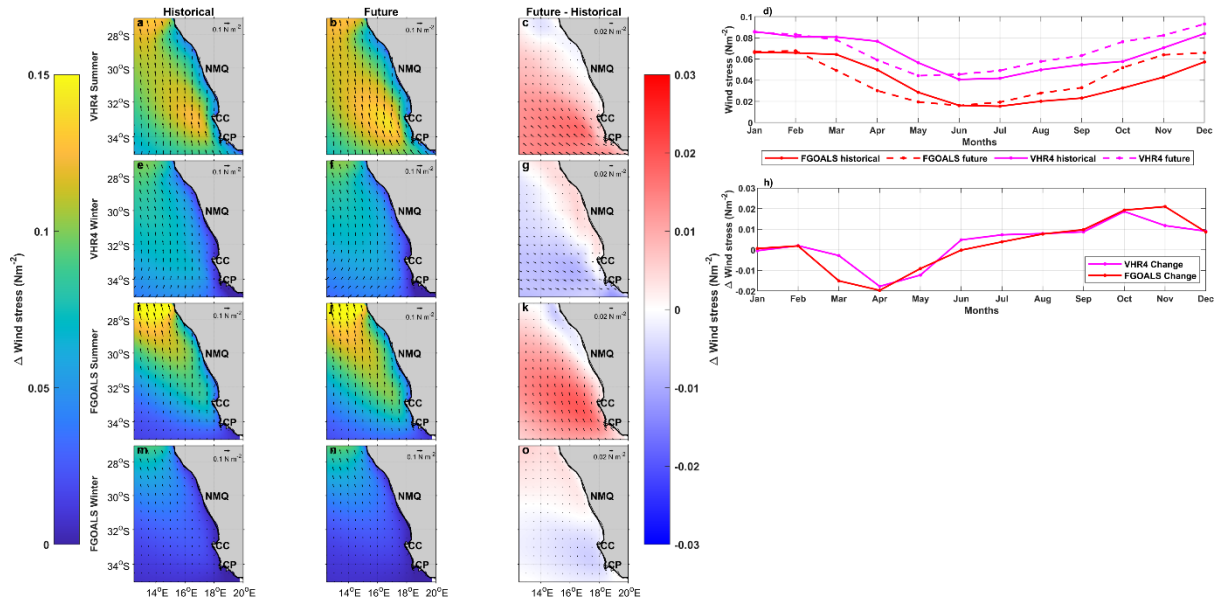


Figure 5.3: Historical and projected seasonal change of wind stress magnitude and direction (Nm^{-2}) from VHR4 and FGOALS models from 1950 – 2050. Panels (a–c) shows VHR4 summer, with (a) representing the historical period, (b) the future projection, and (c) the projected change. Panels (e–g) show the corresponding winter conditions for VHR4. Panels (i–k) and (l–n) present summer and winter from the FGOALS model, respectively, following the same structure. Panel (d) shows average monthly wind stress magnitudes for both the historical and future periods, while panel (h) displays the projected monthly changes. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

5.1.3 Wind stress curl

The previous spatial changes in the wind stress are expected to lead to changes in near-coast wind stress curl (WSC). Consistent with these wind stress changes, future projections indicate an intensification of WSC along the coast during summer (Figure 5.4). Specifically, the WSC intensifies by up to $-1.4 \times 10^{-6} \text{ N}\cdot\text{m}^{-3}$ along the Cape Point and Cape Columbine upwelling cells (Figure 5.4 b, j), with its peak occurring in February, reaching values of approximately $-0.03 \times 10^{-6} \text{ N}\cdot\text{m}^{-3}$ to $-0.05 \times 10^{-6} \text{ N}\cdot\text{m}^{-3}$ (Figure 5.4 h).

Regions with strengthened negative WSC align with areas of strengthened wind stress. Notably, the positive and negative changes in WSC correspond to negative and positive changes in wind stress south of 29°S and around 28°S , respectively (Figure 5.4 c, k). Similar patterns are evident in Figure 5.3 g, o, where positive (negative) changes in WSC are associated with weakening (strengthening) wind stress.

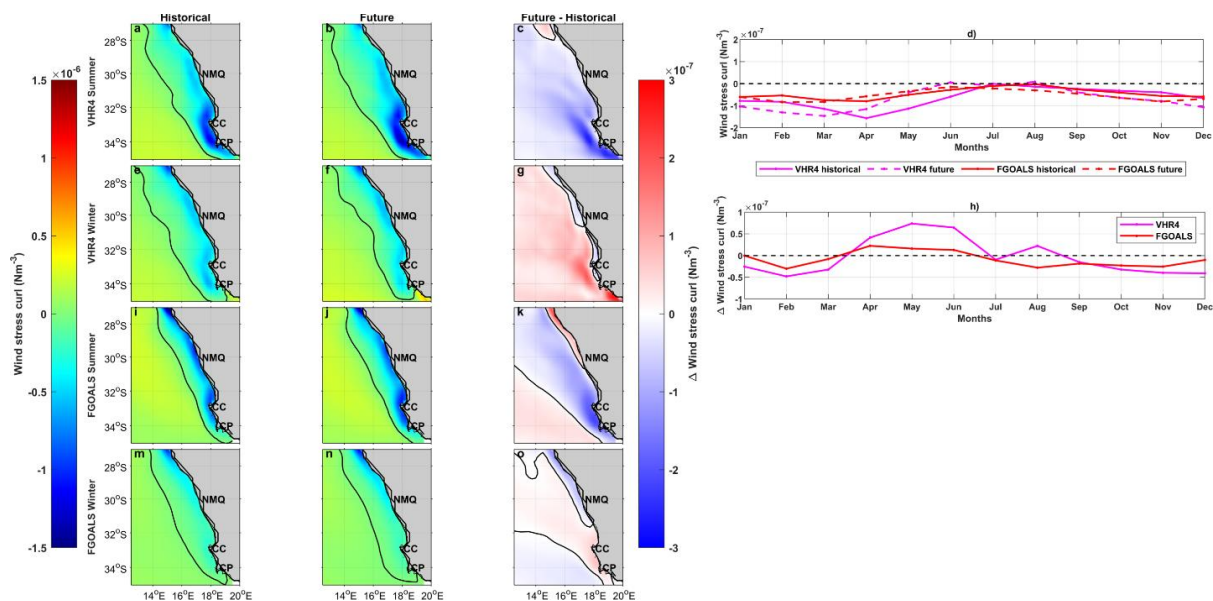


Figure 5.4: Historical and projected seasonal change of wind stress curl magnitude ($\text{N}\cdot\text{m}^{-3}$) from VHR4 and FGOALS models from 1950 – 2050. Rows one and three represent summer, and rows two and four represent winter. Rows one and three represent summer, and rows two and four represent winter for the historical (a, e, i, l) and the future climate (b, f, j, m). The projected wind stress curl change (c, g, k, n) between the future (2015 -2050) and historical (1950 -2014) is in column three. Average monthly time series of the wind stress curl magnitudes for historical and future climate (d) and the projected wind stress change (h) between the future and historical climate. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The black line represents the region of zero wind stress curl.

5.1.4 Surface Ekman Transport

Future projections suggest an intensification of wind-driven Ekman transport and Ekman pumping, consistent with the observed future spatial changes in wind stress and wind stress curl (Figure 5.5). A band of positive vertical velocities, indicative of upwelling, is observed along the coast, with maximum values located at the Cape Point, Cape Columbine, and Namaqua upwelling cells. This upwelling is primarily driven by alongshore winds through Ekman transport and is further enhanced offshore by Ekman suction, associated with negative wind stress curl. This upwelling band varies seasonally, being more intense during the summer upwelling season than in winter.

Future simulations indicate more pronounced vertical velocities of up to $1.4 \text{ m}\cdot\text{day}^{-1}$ (Figure 5.5 d-e, j-k), compared to $\sim 1.14 \text{ m}\cdot\text{day}^{-1}$ in the historical simulations (Figure 5.5 a-b, g-h), with differences reaching up to $0.3 \text{ m}\cdot\text{day}^{-1}$ (Figure 5.5 c, l).

These results align with the projected wind patterns, which show a poleward intensification of wind stress (Figure 5.2) and increased negative WSC (Figure 5.3) along the coast during summer. This intensification enhances poleward upwelling and strengthens offshore transport, particularly in key upwelling regions.

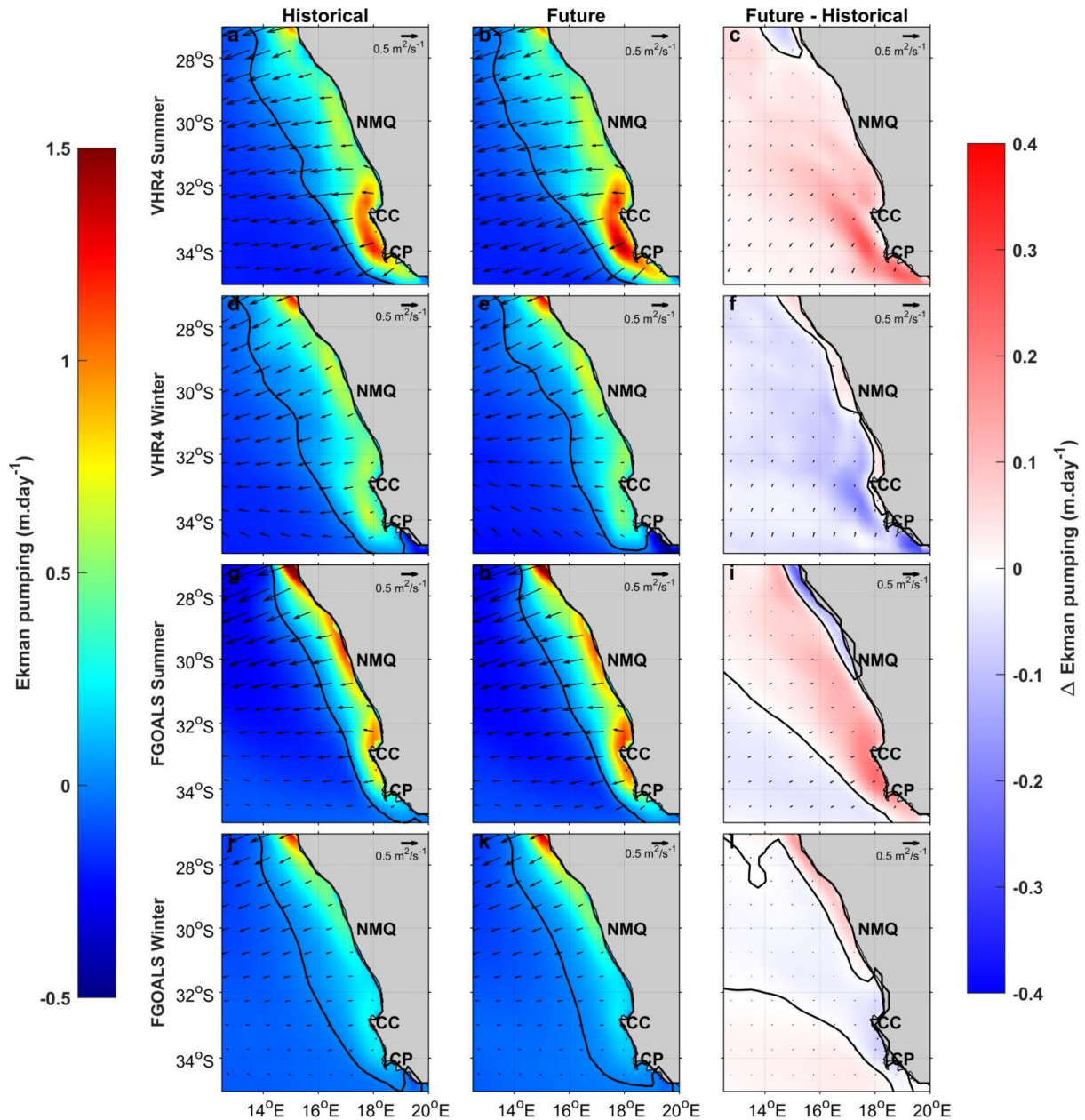


Figure 5.5: Historical and projected seasonal Ekman transport (vectors, m^2s^{-1}) and Ekman pumping and suction (shaded, $\text{m}\cdot\text{day}^{-1}$) change from VHR4 and FGOALS models from 1950 – 2050. Rows one and three represent summer, and rows two and four represent winter for the historical (a, e, i, l) and the future climate (b, f, j, m). The projected Ekman change (c, g, k, n) between the future (2015 -2050) and historical (1950 – 2014) climate is in column three. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

The black line represents the region of zero Ekman pumping. A reference vector of $0.5 \text{ m}^2 \cdot \text{s}^{-1}$ is shown in the top-right of each subplot.

5.2 Sea Surface Temperature (SST)

Surface ocean warming is one of the most robust oceanic responses to climate change, and all three VHR4, HR4, and CAM5 HighResMIP models project a significant increase in sea surface temperature (SST) in the SBUS by 2050 (Figure 5.6). Future projections show a seasonal SST increase compared to the historical simulations across all models (Figure 5.6 g-l, s), with warming more pronounced along the coast than in the open ocean (Figure 5.6 m-r). In all models, the SST exhibits a clear seasonal pattern, with higher temperatures during the summer months in both the historical (Figure 5.6 a, c, e, s) and future projections (Figure 5.6 g, i, k, s). A distinct SST gradient between the coastal region and the open ocean is apparent in both summer and winter simulations, as highlighted by the 16°C isotherm. However, this gradient is absent in the VHR4 simulations due to pronounced coastal warming.

Historically, coastal SSTs ranged from $14\text{--}16^\circ\text{C}$, while open ocean temperatures exceeded 18°C during summer. In future projections, coastal SSTs are expected to increase to $15\text{--}18^\circ\text{C}$, with open ocean temperatures rising above 19°C . This warming trend is more pronounced along the coast than offshore, with an overall SST increase of up to $\sim 1.5^\circ\text{C}$ by 2050. The increase in SST is relatively lower during summer in the region between Cape Point and Cape Columbine, with VHR4 showing a rise of approximately 0.2°C (Figure 5.6m), HR4 indicating an increase of 0.6°C (Figure 5.6o), and CAM5 projecting a rise of $0.8\text{--}1^\circ\text{C}$ (Figure 5.6q). In contrast, summer warming intensifies northward, with maximum SST increases of 1°C in VHR4, $1.2\text{--}1.4^\circ\text{C}$ in HR4, and $1.2\text{--}1.5^\circ\text{C}$ in CAM5, which shows the highest SST increase among the models. During winter, coastal warming of approximately 0.8°C is observed in all models between Cape Point and Cape Columbine, extending northward in the VHR4 and HR4 simulations (Figure 5.6n, p, r). In the CAM5 model, coastal SST increases range from 1°C to 1.2°C off 28°S (Figure 5.6r).

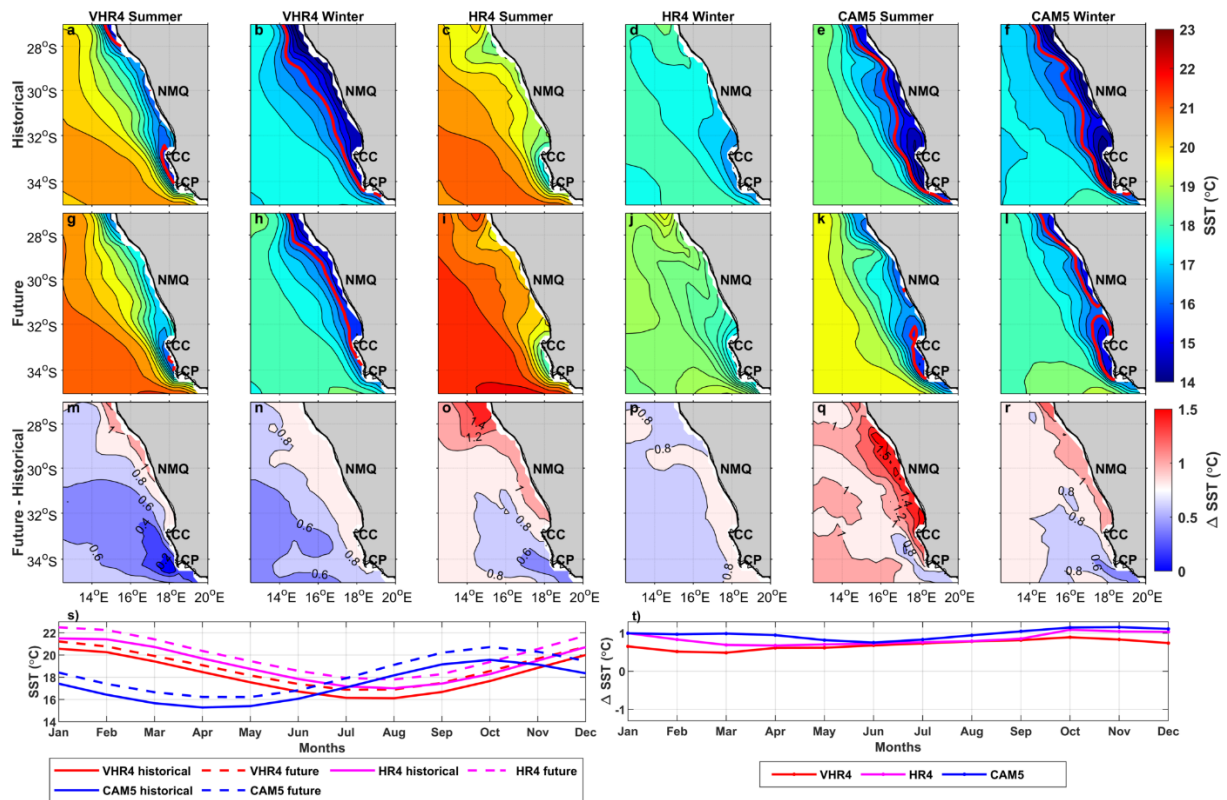


Figure 5.6: Historical and projected seasonal change of Sea Surface Temperatures from VHR4, HR4, and CAM5 models from 1950 to 2050. Rows one, two, and three represent the historical (1950 -2014), future (2015 -2050), and projected changes in SST (2050-1950), respectively. Columns one, three, and five represent summer projections, and columns two, four, and six represent winter projections. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. Average monthly time series of Sea Surface Temperatures for historical and future climate (s) and the projected change (t) between the future and historical period.

5.3 Coastal Currents

Building on the analysis of the local winds and Ekman dynamics presented in the previous sections, this section examines future changes in coastal currents, along with vertical profiles of the alongshore currents, cross-shore winds and WSC. Coastal circulation patterns are influenced by the interaction of local winds, Ekman processes, and cross-shore gradients in SST and SSH. The analysis is based on the VHR4, HR4, and CAM models.

5.3.1 Surface Currents

Figure 5.7 highlights the presence of the strong equatorward surface current, known as the Benguela Jet, across all models historically and in future projections. This jet persists throughout the seasons but is most intense during summer, particularly between Cape Columbine (33°S) and Cape Point (34°S), with surface current speeds reaching up to $0.4 \text{ m} \cdot \text{s}^{-1}$ (Figure 5.7a, c, d). The jet is most pronounced off Cape Point, where it flows north-westward.

The change in the surface current is more complex. However, future projections indicate a slight weakening of the coastal current speed (Figure 5.7g-l), with the reduction estimated at approximately $-0.04 \text{ m} \cdot \text{s}^{-1}$ (Figure 5.7m, o, q). In contrast, increased current speed is observed offshore and south of Cape Point, suggesting that the north-westward flow will intensify and shift slightly offshore and poleward. Consequently, the offshore branch of the jet also moves further offshore near Cape Columbine.

Seasonal variations in the magnitude of these changes are evident. The VHR4 model shows similar patterns of change, albeit with relatively smaller magnitudes (Figure 5.7n). In contrast, the HR4 model indicates a slight increase in nearshore surface current speeds (Figure 5.7p), while the CAM5 model projects a more significant increase near Cape Point (Figure 5.7r).

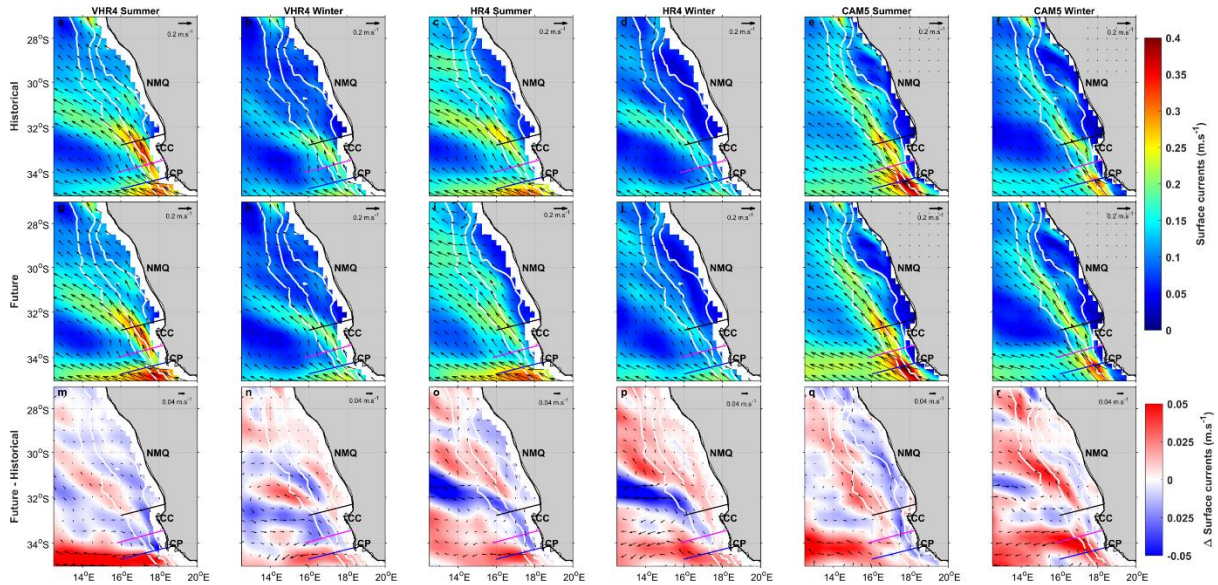


Figure 5.7: Historical and projected seasonal change of surface currents from VHR4, HR4, and CAM5 models from 1950 – 2050. Rows one, two and three represent historical (1950 -2014) and future (2015 -2050) climate and the projected change (2050-1950), respectively, for summer (columns one, three, and five) and winter (columns two, four, and six) projections. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively. The black, magenta and blue lines represent the cross-shore transects at St Helena Bay, Grotto Bay, and Cape Point, where the vertical sections of the alongshore currents were taken. The white contour represents the bathymetry levels (200, 500, 2000 m).

5.3.2 Sea Surface Height

The historical and future projections of geostrophic currents and sea surface height (SSH) levels in the SBUS are illustrated in Figure 5.8. Both historical and future periods show lower SSH levels along the coast, with strong SSH gradients observed during summer (Figure 5.8a, c, e, g, j, k), particularly between Cape Point and Cape Columbine. These pronounced gradients are driven by the contrast between low coastal SSTs, associated with intensified

summer upwelling, and warmer offshore waters. This steep SSH gradient along the coast drives the strong geostrophic currents characteristic of the region.

Under future climate projections, SSH levels are expected to increase from $\sim 0.3\text{--}0.5$ m during the historical period (Figure 5.8a, c) to $\sim 0.35\text{--}0.6$ m in the future (Figure 5.8d, f), particularly in summer. As indicated by negative differences, this increase reduces the coastal SSH gradient, leading to weaker geostrophic currents near the coast. However, offshore of Cape Columbine and Cape Point, the SSH increase is more subdued, ranging from ~ 0.02 to -0.05 m. This suppressed increase supports slightly stronger geostrophic currents offshore, consistent with a projected offshore shift of the Benguela Jet.

Further offshore, particularly north of Cape Columbine, SSH is projected to rise by up to 0.05 m, accompanied by reduced geostrophic current speeds. This offshore SSH increase is likely driven by higher SSTs, reflecting weakened upwelling patterns. Additionally, the influence of the Agulhas Current, which transports warmer waters into the southern Benguela region, may contribute to elevated offshore SSH levels.

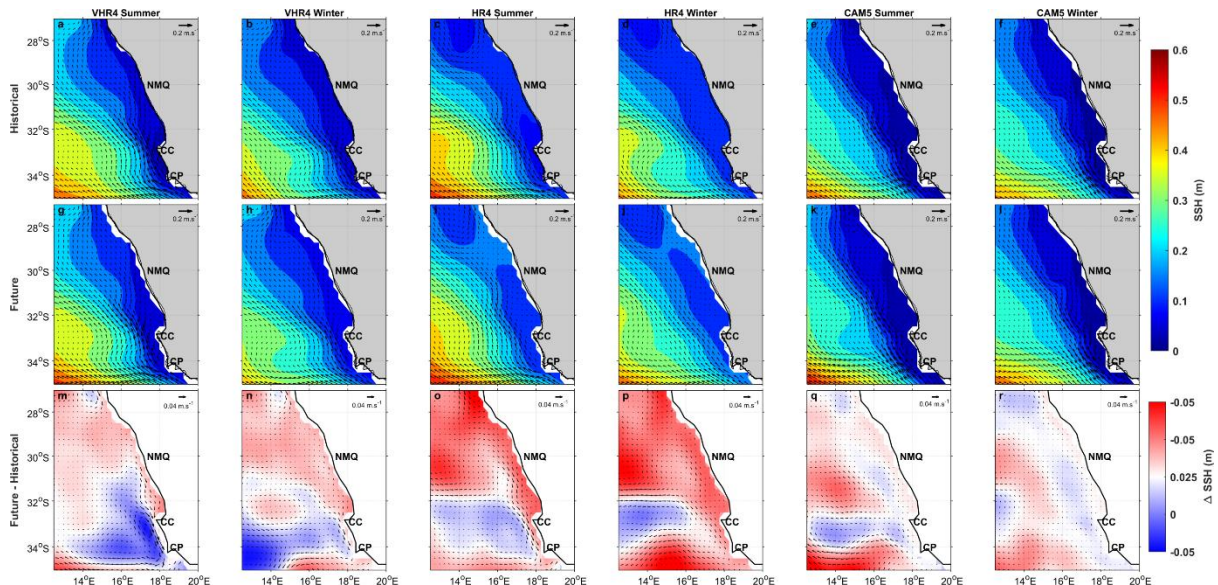


Figure 5.8: Historical and projected seasonal change of surface geostrophic currents (vectors) and Sea Surface Height (shaded) from VHR4, HR4, and CAM5 models from 1950 – 2050. Rows one, two and three represent the historical (1950 -2014) and future (2015 -2050) climate and the projected change (Future - Historical), respectively. Columns one, three, and five represent summer projections, and columns two, four, and six represent winter projections. The Namaqualand, Columbine, and Cape Point Cells are marked NMQ, CC, and CP, respectively.

5.4 Vertical sections of alongshore currents

This section examines the vertical sections and cross-shore transect of the historical and future projections of alongshore current velocities, temperature, wind stress, and wind stress curl (Figures 5.9–5.13) at St Helena Bay, Grotto Bay, and Cape Point. The profiles extend from 0 to 250 km offshore and from the surface to a depth of 450 m across all transects. The profiles extend 250 km offshore and to a depth of 450 m across all transects. Two key circulation features, the poleward undercurrent and the Benguela Jet, dominate the coastal dynamics in this region. The poleward undercurrent is characterised by negative alongshore velocities. At the same time, the Benguela Jet is marked by strong positive alongshore currents, primarily located within 50–200 km offshore and in the upper 100 m of the water column.

Figures 5.9, 5.11, and 5.13 illustrate these features alongside temperature profiles for each transect. Across all transects, all models expect the poleward undercurrent to intensify during summer, reflected by stronger negative differences and weaker (positive velocity differences) during winter.

Under future climate projections, during summer, the poleward undercurrent along the St Helena Bay and Grotto Bay transects (Figures 5.9, 5.11g, i, k) is projected to strengthen, with velocities increasing from $\sim -0.04 \text{ m}\cdot\text{s}^{-1}$ to $\sim -0.07 \text{ m}\cdot\text{s}^{-1}$, reflecting a change of $\sim -0.03 \text{ m}\cdot\text{s}^{-1}$. This intensification causes the undercurrent to shift closer to the surface and expand further offshore, particularly in St Helena Bay (Figure 5.9). As the poleward undercurrent strengthens and expands offshore, it weakens the Benguela Jet along the coast, reducing its maximum velocities to $\sim 0.25 \text{ m}\cdot\text{s}^{-1}$ while strengthening it offshore. This dynamic is consistent with the projected shifts in coastal currents (Figures 5.7, 5.8).

The intensification of both the poleward undercurrent and the Benguela Jet during summer is driven by strong wind stress and negative wind stress curl, ranging between -11×10^{-7} and $-13 \times 10^{-7} \text{ N}\cdot\text{m}^{-3}$ within the 100 km coastal band (Figures 5.10, 5.12, 5.14d). Compared to historical periods, wind stress curl increases by $\sim -1.9 \times 10^{-7}$ to $-2.4 \times 10^{-7} \text{ N}\cdot\text{m}^{-3}$ under future climate conditions (Figures 5.10, 5.12, 5.14e). These intensified winds and wind stress curl enhance the strength and spatial extent of the currents. The strong negative wind stress also promotes surface water divergence, sustaining upwelling conditions that extend further offshore.

Although similar conditions are observed across all regions during summer, variations exist in the intensity, depth, and spatial extent of the poleward undercurrent and Benguela Jet. At St Helena Bay, the poleward undercurrent protrudes to the surface in the HR4 and CAM5 models during both summer and winter (Figure 5.9c-f, i-l), forming the surface poleward current

observed in Figure 5.8, characterised by cyclonic patterns and weaker geostrophic currents. In contrast, the VHR4 model confines the poleward undercurrent below the surface and closer to the coast (Figure 5.9a, b). During summer, the undercurrent in this region extends up to 250 km offshore, with its broad spatial extent displacing the Benguela Jet further offshore, positioning it beyond the 500 m isobath (Figure 5.8).

Moving up to Grotto Bay, the poleward undercurrent is generally confined to deeper depths, indicating a reduced spatial extent compared to St Helena Bay. However, the CAM5 model occasionally projects a protrusion of the undercurrent closer to the surface (Figure 5.11k). Despite this, the poleward undercurrent at Grotto Bay remains narrower than at St Helena Bay. On the other hand, the poleward undercurrent is weaker, confined closer to the coast, and exhibits a limited spatial extent at Cape Point compared to the other transects.

Across all three transects, in the subsurface layers (top 100 m), higher temperature changes are projected during winter ($\sim 1^{\circ}\text{C}$), while smaller changes are observed during summer ($\sim 0.5^{\circ}\text{C}$), with temperature differences decreasing with depth. However, the coastal differences are notably higher in HR4 ($\sim 1^{\circ}\text{C}$) compared to the other models, likely due to the model's weaker bias in simulating upwelling. Consistent with the SST patterns shown in Figure 5.6, coastal warming is more pronounced nearshore than offshore, reflecting the influence of upwelling dynamics and local wind patterns.

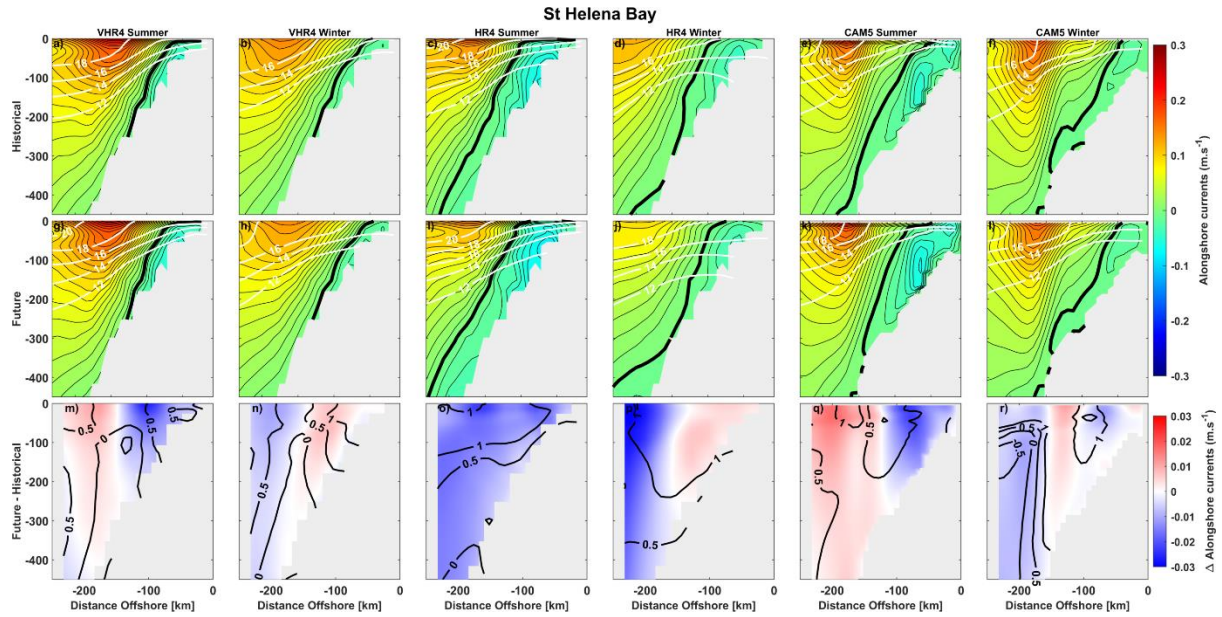


Figure 5.9: Historical and future projections of the vertical alongshore currents ($\text{m}\cdot\text{s}^{-1}$) and temperature (white contours) from VHR4, HR4, and CAM5 models from 1950 – 2050 from the St Helena Bay transect. Row one, two and three represent historical (1950 -2014), future (2015 -2050) and projected change (Future - Historical), respectively. Columns one, three, and five represent summer projections, and columns two, four, and six represent winter projections. The protrusion of the poleward undercurrent is indicated by the black zero $\text{m}\cdot\text{s}^{-1}$ contour not open at the surface. The black contours on the difference plot represent isotherms associated with temperature changes.

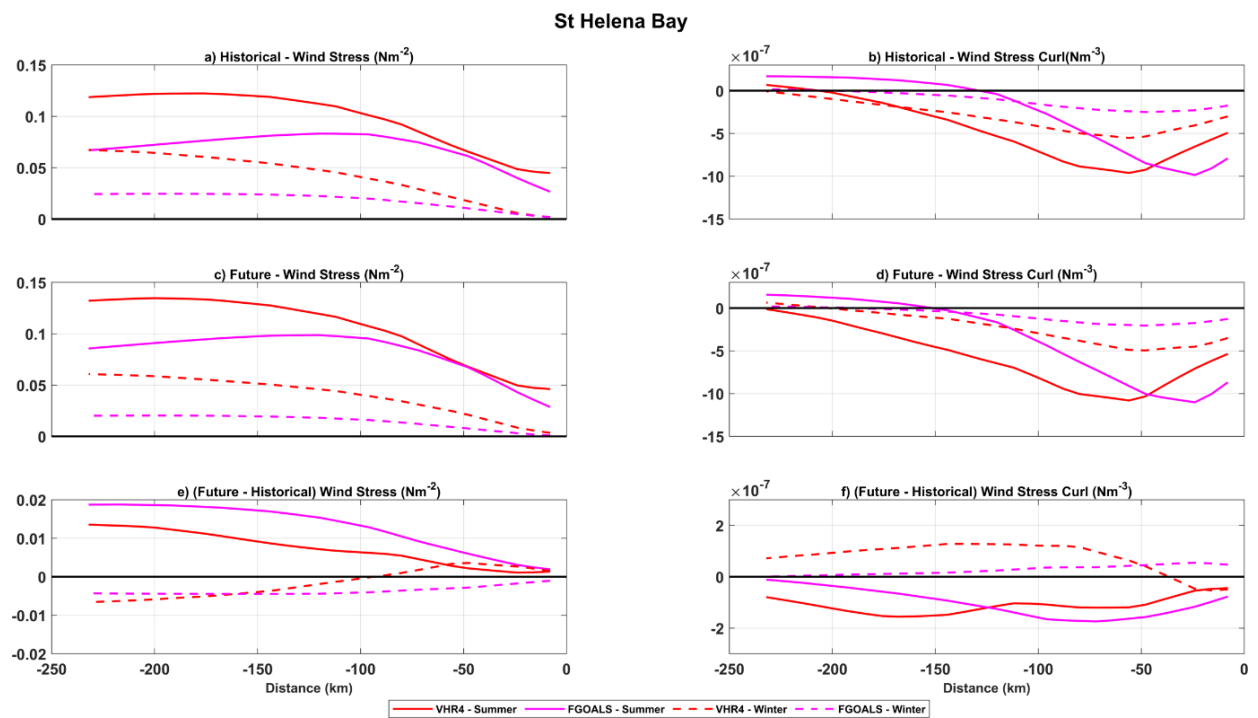


Figure 5.10: Historical and projected future seasonal across-shore wind stress (a, c, e) and wind stress curl (b, d, f) from VHR4 (red line) and FGOALS (magenta line) from 1950 – 2050 from the St Helena Bay transect. Projected

change (2050-1950) of the wind stress (e) and wind stress curl (f). The solid line represents summer, and the dotted lines represent winter projections.

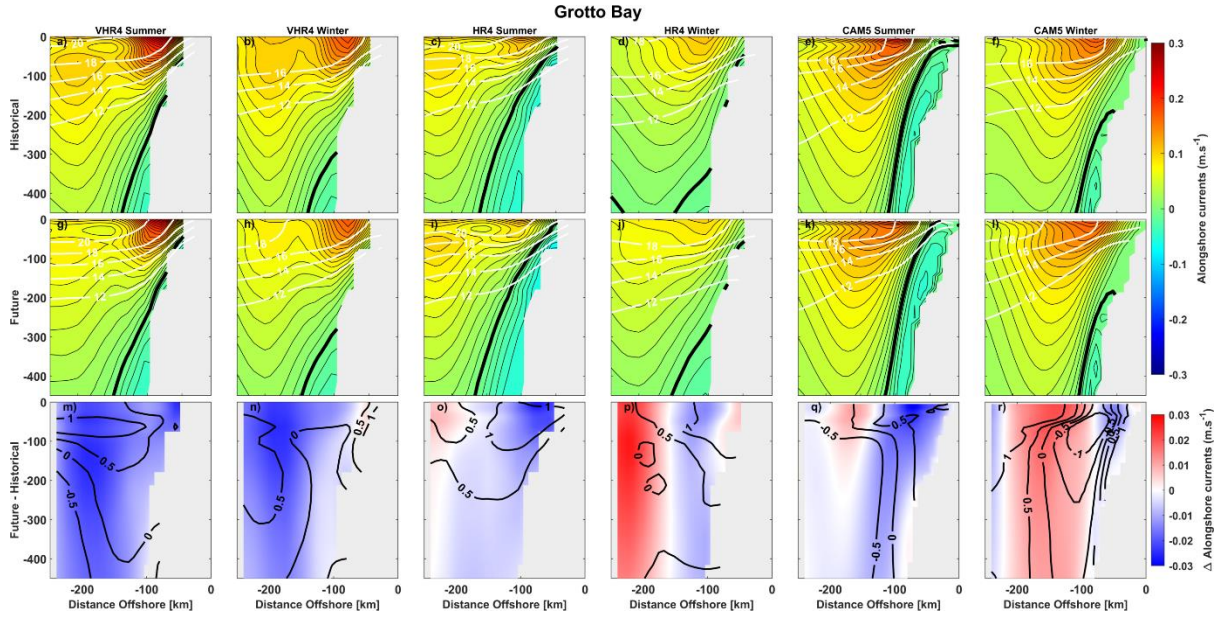


Figure 5.11: Similar to Figure 5.9 but for Grotto Bay.

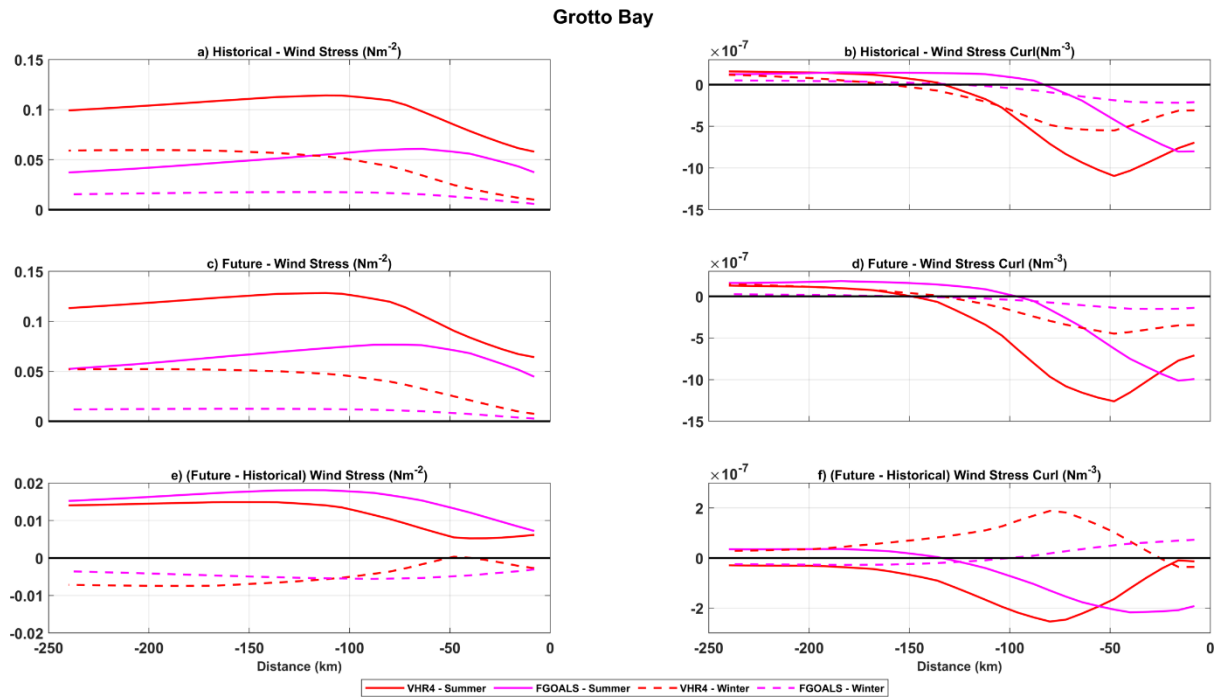


Figure 5.12: Similar to Figure 5.10 but for Grotto Bay.

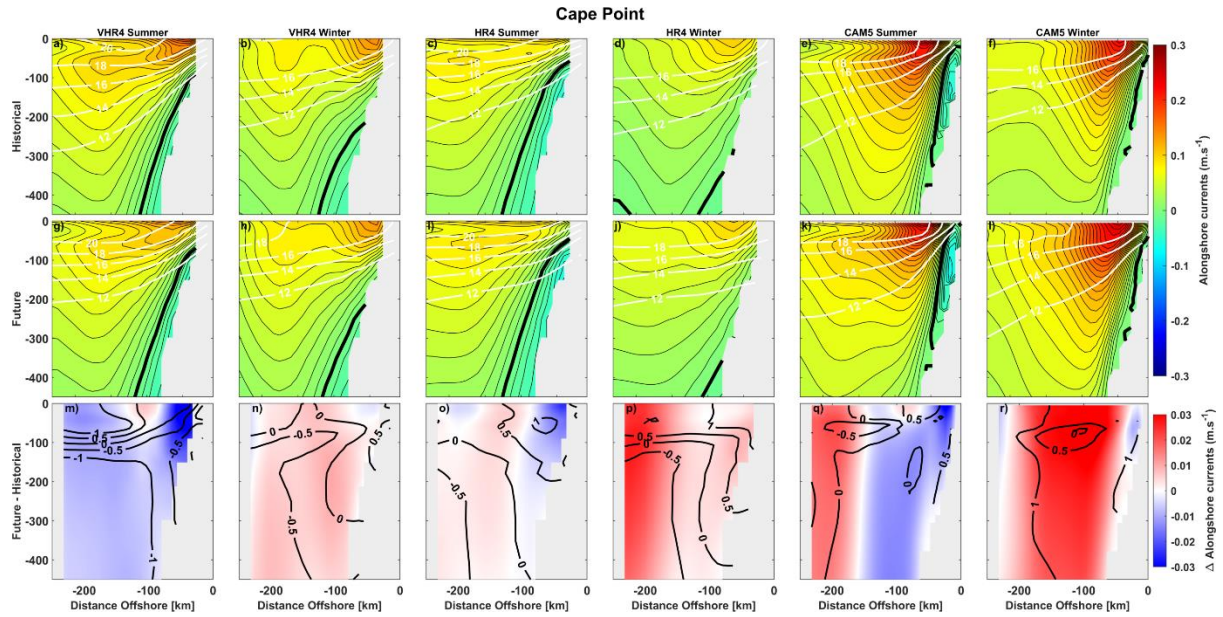


Figure 5.13: Similar to Figures 5.9 and 5.11 but for Cape Point.

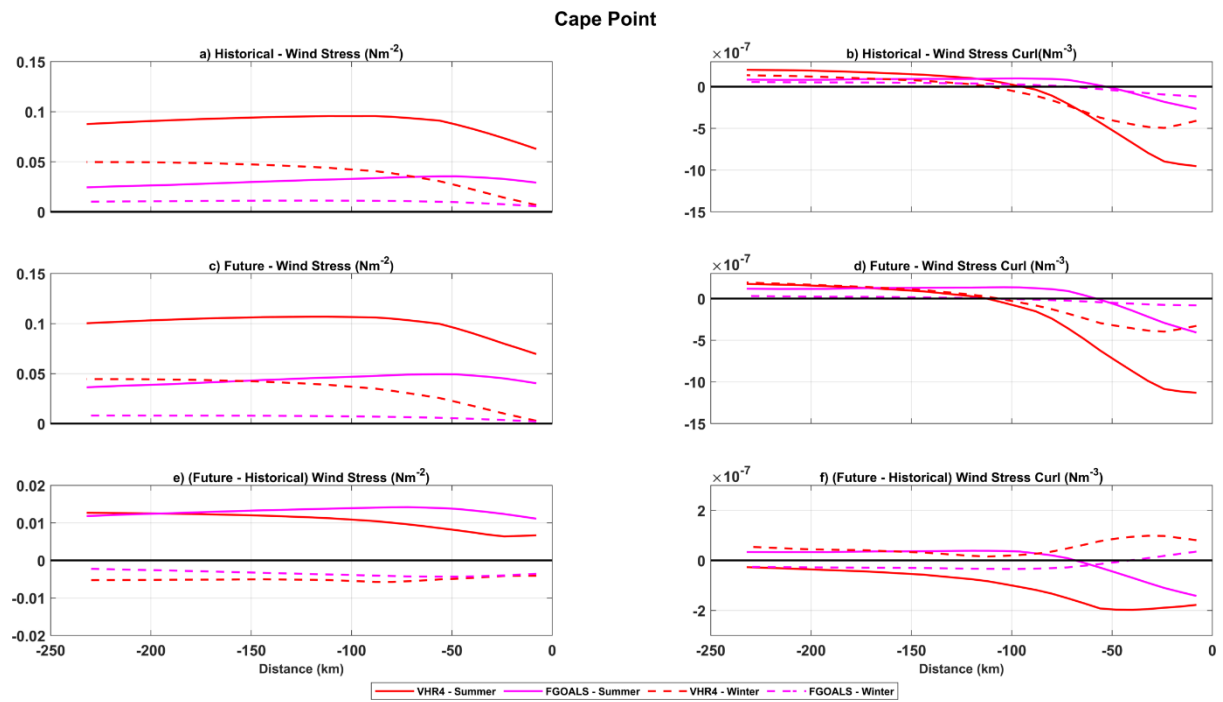


Figure 5.14: Similar to Figures 5.10 and 5.12 but for Cape Point.

Summary of Future Changes

This chapter investigated the projected changes in the local dynamics of the South Benguela Upwelling System (SBUS) for the 2015–2050 period, using outputs from HighResMIP models.

The analysis focused on key drivers of upwelling, including the South Atlantic Anticyclone (SAA), wind stress, wind stress curl (WSC), and their impacts on Ekman dynamics, sea surface temperature (SST), and ocean currents. The results revealed distinct seasonal variations in the SBUS dynamics.

Summer Changes

- **Atmospheric Forcing:**
 - The SAA is projected to weaken and shift poleward and offshore, intensifying alongshore wind stress and wind stress curl near the coast between Cape Point and Columbine.
 - The continental low will strengthen, creating favourable conditions for stronger upwelling, driven by increased Ekman transport and Ekman pumping.
- **Oceanic Response:**
 - Enhanced surface water divergence, supported by intensified negative WSC, helps reduce nearshore warming.
 - The reduced SST and SSH gradient weaken nearshore geostrophic flows.
 - The intensified WSC enhances the poleward undercurrent, pushing the Benguela Jet offshore.
 - Coastal upwelling becomes stronger and shifts further offshore, particularly at Cape Point.

In winter, coastal and subsurface warming is most pronounced, reaching a maximum of 1°C. This warming is likely associated with reduced upwelling and increased solar heating. The diminished surface divergence and weaker WSC also promote downwelling, particularly in the Grotto Bay and St Helena Bay regions.

This chapter highlights the SBUS's complex and interconnected dynamics under future climate scenarios. There are marked seasonal and regional variations in atmospheric forcing, oceanic responses, and upwelling patterns, which are expected to have significant implications for the SBUS's physical environment and marine ecosystems.

6 Discussion

This study investigates future climate projections for the southern Benguela region under the SSP5-8.5 scenario, using HighResMIP models, with a spatial resolution of 25 km, focusing on the 2015-2050 period. To assess the future climate for the southern Benguela upwelling system (SBUS), the relationship between the South Atlantic Anticyclone (SAA) and upwelling in the southern Benguela was examined, assessing how climate change might alter the SAA and, consequently, upwelling patterns. This study examines the intensity and position of the SAA and assess how it is expected to influence upwelling in the region, SST, wind stress, wind stress curl, Ekman transport and Ekman pumping, and ocean currents. The results reveal notable changes due to climate change by 2050, with seasonal variations and regional dependency. These findings suggest an intensification of coastal upwelling dynamics driven by climate-induced shifts in atmospheric and oceanic processes with implications for the marine ecosystem.

The discussion begins by examining the physical drivers of upwelling, focusing on the role of the SAA and local wind patterns, including their seasonal variability and interactions with large-scale atmospheric circulation. It then addresses present circulation patterns within the SBUS, investigating surface currents, geostrophic currents, and the vertical circulation from three transects extracted along the system. The latter part of the discussion evaluates the broader implications of these oceanographic processes, including potential ecosystem and socio-economic impacts. Finally, it explores adaptation strategies to mitigate the effects of changing upwelling dynamics and discusses model uncertainties that may influence predictions of future climate.

6.1 Influence of South Atlantic Anticyclone on upwelling

In the SBUS, the primary atmospheric forcing is the semi-permanent South Atlantic Anticyclone (SAA) and continental heat low (Shillington, 1998), influencing the local winds critical for the SBUS circulation. The analysis of the hindcast data from different HighResMIP models used in this study, evaluated against satellite and reanalysis datasets, reveals that the seasonal migration of the SAA modulates the intensity and position of the southeasterly winds responsible for coastal upwelling. These model results align with observed trends (Rouault & Tomety, 2022), providing confidence in future changes.

The results reveal that the SAA migrates southwards and offshore during summer, and there is also a presence of the continental low pressure over the southern African continent denoted by 1010 hPa (Figures 4.6a-c, 5.1a-d). This continental low strengthens the alongshore equatorward winds, creating favourable conditions for upwelling. In contrast, SAA migrates

northwards during winter and retreats offshore, and a continental high-pressure system develops over southern Africa (Figures 4.6d-f, 5.1e-h). This continental high-pressure system weakens the upwelling-favourable winds and generates westerlies, which lead to downwelling conditions along the SBUS.

The results of this study show that SAA is projected to shift southward and move slightly offshore, particularly in summer (Figure 5.1 a-d). The continental thermal low becomes enhanced due to increases in air temperature. This change in the strength and position of the SAA could be attributed to the rise in global temperature caused by climate change, which enhances the thermal gradient between polar and equator regions under SSP5-8.5 (Reboita et al., 2019; Lima et al., 2019). This enhanced thermal gradient strengthens and causes the southward expansion of the Hadley circulation, resulting in increased subsidence and central pressure of the SAA at subtropical latitudes and shifting the SAA position poleward (García-Reyes et al., 2013; Wang et al., 2015; Reboita et al., 2019). The projected changes are more intense in winter, making SAA zonally wider and more intense during this season (Figure 5.1 e-h).

The enhanced expected variability in SAA may lead to more frequent and intense Benguela Niño events, and these events are characterised by the abnormal increase in SST, resulting in severe ecological and economic impacts (Koseki et al., 2021), highlighting the SAA's key role in future climate dynamics for the Benguela Current Large Marine Ecosystem.

In response to climate change, the EBUS is expected to experience significant warming, with SST projected to increase by 1.5-3.5°C by 2100 under a high emission scenario (SSP5-8.5) (Bograd et al., 2023). These projections are similar to those obtained in this study for the SBUS, with SST expected to increase by 1.5°C by 2050 under the worst-case high-emission scenario (SSP5-8.5), with a strong seasonal cycle being warmest in summer and cooler in winter (Figure 5.6). This increase in SSTs along the SBUS suggests that the region is becoming increasingly sensitive to the impacts of climate change (Ortega-Cisneros et al., 2018b). In this study, the projected increase in SST is observed to be the highest nearshore compared to offshore, especially in bay regions like St Helena Bay moving northward. This leads to an increased thermal vertical gradient between surface and subsurface waters. This, in turn, enhances the thermal stratification of the water column, reducing vertical mixing and limiting the upwelling of cold, nutrient-rich subsurface waters to the surface (Sousa et al., 2020). As a result, this increase in thermal stratification might lead to a reduction in coastal upwelling, thus negatively affecting the ecosystem nearshore. However, during summer, the coastal temperature increase was relatively lower between Cape Point and Cape Columbine, primarily due to enhanced upwelling driven by the southward shift of the South Atlantic

Anticyclone (SAA). This shift strengthens alongshore wind stress, reinforcing offshore Ekman transport and the upwelling of cold, nutrient-rich subsurface waters, mitigating coastal warming. Conversely, north of Cape Columbine, the weakening of upwelling-favourable winds due to the displacement of the SAA results in reduced upwelling intensity, leading to increased coastal warming in this region. Despite projections of stronger wind stress (Figure 5.3) and intense wind stress curl (WSC) (Figure 5.4), the more stratified water column may reduce the effectiveness of these winds in driving upwelling (Sousa et al., 2020). Over time, this could lead to a decline in upwelling intensity, as stronger winds alone may not be sufficient to overcome the stabilising effects of a more stratified water column.

The future projections of the SAA behaviour from the HighResMIP models show consistency in its intensity and position seasonally. However, variations exist between the models, particularly in how they represent the intensity and position. Among the HighResMIP models, HiRAM better represents the position and intensity of the SAA compared to FGOALS, suggesting that HiRAM may provide a more accurate representation of future SAA dynamics. This variability introduces uncertainty into the projections, complicating the ability to make accurate predictions of the behaviour of the SAA in the SBUS. Such uncertainty points out the challenges associated with climate projections and highlights the need for further analysis to refine these projections.

6.2 Local winds

According to Bakun's (1990) hypothesis, climate change is expected to cause an intensification of summer coastal upwelling in EBUS due to the strengthening wind stress due to global warming. The strengthened upwelling favourable winds are due to the enhanced land-sea temperature gradient. However, subsequent studies have highlighted the complexity of this response and suggest that the response to climate change is not uniform across or within EBUS regions.

Rykaczewski et al. (2015), using CMIP5 climate projections, observed a poleward shift in upwelling-favourable winds, suggesting that climate change may enhance upwelling intensity and alter its spatial extent along the coast. Building upon Rykaczewski et al. (2015), recent studies have further examined the potential impacts of climate change on the seasonality of upwelling systems. For instance, Sylla et al. (2019) investigated the Senegalo–Mauritanian Upwelling System (SMUS) and projected a moderate decrease in winter/spring upwelling intensity under future climate scenarios. This projected reduction is primarily attributed to a weakening of wind forcing linked to the northward (poleward) shift of the Azores anticyclone and regional changes in low-pressure systems over North-West Africa.

Future climate projections for the SBUS under the SSP5-8.5 scenario indicate an intensification of alongshore wind stress (Figure 5.3) and negative wind stress curl (Figure 5.4), accompanied by an offshore expansion of these winds by 2050, particularly in summer. These changes are most pronounced between Cape Columbine and Cape Point, consistent with previous studies based on CMIP projections, which suggest an increase in wind strength south of 20°S under RCP8.5 by 2099–2100 (Rykaczewski et al., 2015; Lima et al., 2019) and under SSP5-8.5 by 2100 (Brandt et al., 2024). The projected intensification and offshore expansion of upwelling-favourable winds in summer are consistent with the expected southward and westward migration of the South Atlantic Anticyclone (SAA) (Lima et al., 2019).

The changes in large-scale atmospheric circulation patterns are expected to impact the upwelling dynamics of the region. As a result, some regions may experience intensified upwelling, while others could see a reduction or seasonal shifts in upwelling intensity (Bordbar et al., 2023). This study found that upwelling will be enhanced and intense at key upwelling cells near Cape Columbine and Cape Point (Figure 5.4). While the intensification of coastal wind stress is conducive to upwelling, the displacement of these winds (Figure 5.3c, k) suggests a potential shift in productivity zones. This offshore shift of the upwelling activity could significantly affect nutrient dispersal and ecosystem functioning (Wang et al., 2015). In addition, the shift could have profound ecological consequences, altering the spatial distribution of phytoplankton blooms, fish larvae, and other marine organisms that depend on nearshore high-productivity zones as nursery grounds. Such a reorganisation of productivity zones may disrupt trophic interactions, with cascading effects on the structure and resilience of marine food webs.

Furthermore, the region between Cape Point and Cape Columbine serves as a critical northward transport corridor for the eggs and larvae of small pelagic fish, particularly anchovy (*Engraulis encrasicolus*) and sardine (*Sardinops sagax*), as they drift towards their nursery grounds in St Helena Bay (Shelton & Hutchings, 1982; Hutchings, 1992; Hutchings et al., 1998). However, future changes in wind forcing could significantly impact this transport process. A Lagrangian particle-tracking study by Ragoasha et al. (2019) found that the transport success of particles from Cape Point to St Helena Bay decreases with intensifying alongshore winds, as stronger winds enhance Ekman transport, advecting particles offshore rather than along the coast. This suggests that under future climate scenarios characterised by stronger alongshore winds, the recruitment success of small pelagic fish populations on the west coast of South Africa may be negatively affected. Such changes could have profound ecological and economic implications, potentially altering spawning success, larval retention rates, and regional fishery yields.

These potential implications may be similar to those from the eastward shift driven by variability in SSTs, upwelling patterns, and prey availability observed in sardine and anchovy distributions in the Southern Benguela during the late 1990s and early 2000s (Coetzee et al., 2008; van der Lingen et al., 2002; Watermeyer et al., 2016). As these species moved away from traditional west coast fishing grounds, their distribution shift had cascading impacts on some ecologically and economically important species (Watermeyer et al., 2016). Such distributional shifts significantly affected coastal communities that depend on the small pelagic fishery (Jarre et al., 2013), illustrating the vulnerability of the region's ecosystem and economy to climate-induced changes. These past shifts highlight how sensitive the Southern Benguela ecosystem is to environmental changes. Consequently, future alterations in wind patterns affecting larval transport could lead to similar distribution shifts, potentially harming ecosystem health and fishery productivity in the region.

The wind stress in the study region is anticlockwise throughout all seasons, which is a characteristic of an eastern boundary current (Bakun & Nelson, 1991). During summer, when the wind stress is stronger (positive) (Figures 4.3 a-c, 5.3), the wind stress curl is negative (Figures 4.4 a-c, 5.4). The negative wind stress curl is enhanced between Cape Columbine (33°S) and Cape Point (34°S) and off the Namaqua shelf (30°S) (Figures 4.4 a-c, 5.4). These observations agree with Bakun and Nelson (1991), who stipulated that in EBUS, there are some areas where the wind stress is locally enhanced, thus enhancing the negative wind stress curl. This strong wind stress and wind stress curl during summer facilitates coastal upwelling by inducing offshore Ekman transport and facilitating the vertical movement of nutrient-rich deep waters to the surface (Bakun & Nelson, 1991; Shannon & Nelson, 1996). This process is essential for maintaining the high biological productivity of the SBUS, which supports a diverse marine ecosystem and plays a crucial role in the regional fisheries industry (Shannon & Nelson, 1996; Flynn et al., 2020; Martin et al., 2024; Sell et al., 2024). In contrast, the wind stress relaxes during the winter season and changes direction from a southerly component observed in summer to a more north-westerly component. This change results in a positive wind stress curl and shoreward water transportation, resulting in coastal downwelling and displacing the water shoreward and downwards (Manyakanyaka, 2020).

6.3 Current circulation of the SBUS

6.3.1 Surface currents: Benguela Jet

The Benguela Jet is present in all seasons, confined over the shelf edge of the SBUS and has been recognised as a key mechanism facilitating the transport of small pelagic fish eggs and larvae from the spawning ground on the Agulhas Bank to the recruitment grounds in St Helena

Bay (Shelton & Hutchings, 1982). The jet is strongest during summer across all the presented HighResMIP models, evident in both surface (Figure 4.10, 5.7) and geostrophic (Figure 4.11, 5.8) currents maps. This seasonal intensification coincides with the season of stronger wind stress (Figure 5.3), which enhances the density gradient between cooler coastal SST and warmer offshore waters (Figure 5.6). The reinforcement of the across-shore density gradient mainly drives the strengthening of the jet in summer due to the upwelling of coastal cold water (Veitch & Penven, 2017). On the other hand, the jet weakens during winter as the across-shore density gradient declines due to the reversal in upwelling favourable winds. However, it remains present as it is influenced by the inflow of warm Agulhas Current waters from the south (Twatwa et al., 2005). These findings agree with those of Veitch (2009), Veitch et al. (2018), and Ragoasha (2020), who found the existence of this jet in the region extending from Cape Peninsula to Cape Columbine.

Examining the future projections under the SSP5-8.5 scenario, the Benguela Jet is expected to intensify by an overall speed of up to $0.4 \text{ m}\cdot\text{s}^{-1}$ by 2050 (Figure 5.7). The projected intensification of the Jet is expected to be accompanied by an offshore shift, mirroring the projected strengthening, offshore expansion, and poleward migration of winds and SAA. This offshore shift is further supported by vertical sections of the currents, which indicate that the core of the Benguela Jet will weaken nearshore as it gradually shifts offshore. This displacement is linked to the intensification and broadening of the poleward undercurrent, which responds to the enhanced negative wind stress curl in the region (Ragoasha et al., 2019; 2022). Events associated with the offshore displacement of the Benguela Jet were found by Ragoasha et al. (2022) to result in most particles being transported offshore, where they experience increased dispersion due to high turbulence. These findings suggest that enhanced offshore Ekman transport will reduce alongshore transport success between Cape Point and St Helena Bay and increase offshore advection by the Jet, potentially affecting larval retention and recruitment processes.

6.3.2 Geostrophic currents

The projected rise in nearshore SSH due to climate change will likely reduce the SSH gradient alongshore of southern Benguela, weakening the strength of geostrophic currents, particularly in summer (Figure 5.8 g, j, k). This change is more pronounced along the key upwelling cells, Cape Columbine and Cape Point, where the SSH gradient is expected to expand and intensify offshore. These changes are consistent with the wind-driven shifts, rising SST alongshore, and the offshore displacement of Benguela Jet shifts by 2050. The offshore expansion and intensification suggest the potential development of offshore upwelling, which could lead to

the redistribution of nutrient-rich waters away from the coast, potentially impacting the productivity of the marine ecosystem (Bakun, 1990; Lima et al., 2019).

The weakened geostrophic currents alongshore, particularly north of Cape Columbine, may be attributed to episodic nearshore poleward surface currents. This current occurs when prevailing upwelling favourable winds relax (Fawcett et al., 2008). This nearshore poleward current is driven by the presence of the cross-shore pressure gradients that form in the presence of headlands, inside bays and during episodic weakening of upwelling winds. Alternatively, it may be driven by strong cyclonic wind stress curl from the coastal wind drop-off (Gan & Allen 2002).

6.3.3 Vertical Transects

To further investigate the circulation of the SBUS below the surface, vertical transects from St Helena Bay (32°S), Grotto Bay (33°S), and Cape Point (34°S) were extracted. These transects are consistent with the surface current patterns, revealing that the seasonal circulation variability closely follows the atmospheric forcing (Figures 5.9-5.14). The three transects exhibit two persistent features throughout the year: the Benguela Jet (positive alongshore velocities) in the upper 200 - 300 m and a poleward undercurrent (negative alongshore velocities) on the slope-edge inshore of the jet.

During summer, the Benguela Jet shifts offshore across all transects, with its intensity gradually decreasing from Cape Point to St Helena Bay due to the broader shelf and weaker wind forcing (Lutjeharms & Meeuwis, 1987). This offshore shift conserves potential vorticity as the Jet gains cyclonic relative vorticity from the wind stress curl (Castelao & Barth, 2007). Under the SSP5-8.5 scenario, projections indicate that the behaviour of the Benguela Jet will shift offshore, leading to increased current velocities offshore while weakening alongshore. This change is driven by stronger upwelling-favourable winds projected along the three transects, caused by a poleward-shifted SAA, shifting the negative across-shore thermal gradient offshore and increasing turbulent mixing (Bakun et al., 2010; Boardbar et al., 2023). The weakening jet alongshore is associated with the weaker wind stress and positive wind stress curl, reducing offshore Ekman transport, which weakens coastal upwelling but enhances offshore upwelling (Fennel et al., 2012; Fabien et al., 2016).

In contrast to the jet, the subsurface poleward undercurrent flows nearshore at depths of 100–300 m. Its intensity is strongest at St Helena Bay, followed by Grotto Bay, and weakest at Cape Point. This undercurrent contributes to thermal stratification, reducing vertical mixing and weakening upwelling, particularly in sheltered alongshore regions with weaker wind forcing, such as Grotto Bay and St Helena Bay (Beal et al., 2011). Additionally, this

undercurrent corresponds to the nearshore poleward surface current depicted by the weakened geostrophic currents alongshore in Figure 5.8. The poleward undercurrent is highly sensitive to changes in the wind forcing, with stronger negative wind stress curl resulting in a broader and more intense subsurface current during summer, the peak upwelling season. This aligns with the findings of Fennel & Lass (2007), who showed that stronger upwelling-favourable wind stress curl enhances the poleward undercurrent by making it shallower and more intense.

Under the SSP5-8.5 scenario, the poleward undercurrent is expected to intensify and exert a stronger influence alongshore in regions like Grotto Bay and St Helena Bay. This intensification is projected to increase thermal stratification and further suppress vertical mixing, thereby weakening coastal upwelling (Pitcher et al., 2010; Bograd et al., 2023). The strengthening of the poleward undercurrent is likely driven by an increased intrusion of warmer Agulhas Current waters, which raises nearshore SST and enhances vertical gradients in temperature and salinity (Howard et al., 2020).

Summary of the Projected Atmospheric and Physical Processes

The future climate projections for the SBUS indicate a complex interplay of changes that will significantly impact marine ecosystems and human livelihoods in the surrounding marine-dependent communities. The findings in this study under SSP5-8.5 indicate an intensification and a poleward shift of the SAA, which results in the poleward intensification of upwelling favourable winds. These winds are projected to expand offshore, becoming more intense further from the coast than nearshore, leading to higher SST rise alongshore and potential strong stratification. This shift in wind dynamics will cause the northward current to exhibit similar behaviour, particularly, similar offshore intensification responding to the offshore shift of the upwelling front. The offshore shift of the Benguela Jet is accompanied by the broadening and intensification of the poleward undercurrent along the coast. Such changes in spatial variability in upwelling patterns have important implications for marine productivity, nutrient cycling, and the distribution of fish stocks, potentially affecting the resilience of ecosystems and fisheries-dependent communities (Wang et al., 2015; Lima et al., 2019; Brandt et al., 2024).

6.4 Implications on the SBUS

This section discusses the potential ecosystem and socio-economic impacts, as well as adaptive strategies, in response to projected climate changes in the SBUS.

6.4.1 Potential Socio-Ecological Impacts

The climate projections analysed in this study indicate an intensification of upwelling in the SBUS, expanding offshore and poleward, particularly along Cape Columbine and Cape Point upwelling cells (Chapter 5). The SSP5-8.5 scenario projections highlighted intensification and offshore extension of upwelling-favourable winds and the Benguela Jet, driven by the poleward shift and intensification of the SAA. These climate-driven shifts are expected to significantly impact species distributions, leading to alterations in ecosystem functioning (Blamey et al., 2010, 2015; Hazen et al., 2013; Jarre et al., 2015; Pinsky et al., 2018) and potentially resulting in severe economic consequences. Such shifts may lead to declines in local species especially those that are unable to adapt to the new environmental conditions or coexist with incoming species, thereby leading to cascading effects across the food web (Bograd et al., 2023). For instance, Ortega-Cisneros et al. (2018b) reported that warming by 2050 under RCP 8.5 using forcings at $1/4^\circ$ resolution is projected to negatively affect species biomass in the southern Benguela region. The rising SSTs, along with altered wind dynamics identified in this study, may further exacerbate these impacts by driving shifts in species distributions (Potts et al., 2015; Ramírez et al., 2022) as some organisms might migrate offshore towards cooler and nutrient-rich waters.

Additionally, the projected high SSTs alongshore are expected to induce thermal stratification, which may limit vertical mixing between surface and subsurface nutrient-rich cold waters. This stratification could reduce the availability of nutrients required to sustain and enhance primary productivity in coastal regions.

Furthermore, the projected intensification and the slight offshore expansion of the Benguela Jet, particularly during the summer upwelling season, could enhance the northward transport of anchovy eggs and larvae from the Agulhas Bank to St Helena Bay, potentially disrupting connectivity between spawning grounds and nursery areas (Ragoasha et al., 2019). This is because the offshore route is less effective in the northward alongshore connectivity between Cape Point and St Helena Bay, as these particles travelling offshore were dispersed due to high turbulence (Ragoasha et al., 2019). On the other hand, a Benguela Jet that is located closer to the coast is more favourable. Furthermore, the projected offshore expansion of the Jet may disrupt larval retention by weakening cyclonic wind-stress curl alongshore, which is crucial for retaining upwelled waters in St Helena Bay. Changes in upwelling intensity have

been shown to influence larval retention and recruitment success in the southern Benguela (Roy et al., 2002). This is because strong offshore Ekman transport facilitates the loss of subsurface material to the open ocean, reducing coastal retention and potentially impacting nearshore nutrient availability and ecosystem stability.

These ecological changes have cascading socio-economic implications. Changes in primary productivity, species composition and distribution directly impact fisheries, which are vital for local economies (Blamey et al., 2015). These changes may lead to increased fishing pressure, and without sustainable management, this could lead to overfishing and potential ecosystem collapse (Blamey et al., 2015; Ortega-Cisneros et al., 2018a). Increased fishing pressure could offset the benefits of improved or increased primary production, particularly for high-trophic-level species, emphasising the need for balanced harvesting strategies and closely monitoring environmental variability to maintain ecosystem resilience (Lockerbie & Shannon, 2019).

These ecological and climate-induced risks result in economic challenges, including rising fishing and steaming costs, reduced fish availability, disruptions to landing sites and processing facilities, increased unemployment, increased poaching activities, safety at sea, and poverty levels. These social impacts have significantly impacted the livelihoods of individuals dependent on fisheries (van der Lingen and Hampton, 2018; Cochrane et al., 2020; Ortega-Cisneros et al., 2021). Climate-induced fluctuations in fish stocks also threaten food security, especially for vulnerable communities that rely heavily on fisheries for their livelihoods (Sowman & Raemaekers, 2018; Ramírez et al., 2022). This reliance is particularly pronounced among small-scale fishers, who often depend on fisheries as a primary source of income and nutrition (Isaacs & Hara, 2015).

6.4.2 Adaptation strategies

Understanding climate change's current and projected impacts is essential to effectively adapt to future changes, optimise potential benefits, and reduce negative consequences (Hobday et al., 2016; Pörtner et al., 2022). This study contributes to the understanding of future trends in upwelling patterns. It highlights that these future changes will result in ecological and socio-economic challenges for the southern Benguela under climate change. A comprehensive and adaptive management framework for the Southern Benguela region is required to address these projected challenges. This approach should follow the principles of ecosystem-based management, balancing ecological, governance and social needs and ensuring sustainability for future generations in response to the environmental changes caused by climate change (Long et al., 2015; Stephenson et al., 2021).

Furthermore, this approach should focus on maintaining ecosystem resilience, ensuring food security, and supporting the socio-economic well-being of fisheries-dependent populations.

South Africa's commercial fisheries are currently managed through operational management procedures that adapt to changes in resource abundance and productivity, including those caused by climate change (Plagányi et al., 2007; Ortega-Cisneros et al., 2021). However, a lack of long-term strategic planning for climate risks challenges resource sustainability and the fishing sector's economic resilience (Ortega-Cisneros et al., 2021). To address this, it is essential to evaluate whether current legislation adequately supports climate adaptation and includes explicit measures for managing climate impacts (Bahri et al., 2021). Furthermore, revising the Marine Living Resources Act (MLRA) to address climate change explicitly can bridge short-term management with long-term strategies, supporting sustainable fisheries and climate adaptation (Ortega-Cisneros et al., 2021). In addition, the results of this study, specifically the high-resolution short-term projections (2050) from HighResMIP models, have the potential to inform plausible scenarios for southern Benguela and form the basis for developing conducive policy recommendations.

6.4.3 Added value of High-resolution modelling

Several previous studies have investigated the dynamics and future projections in the South Atlantic Anticyclone (SAA) and the upwelling dynamics influencing the Benguela system including the SBUS using coarse-resolution models, with typical coarse resolution of $\sim 1^\circ$ or more (e.g., Wang et al., 2014; Small et al., 2015; Cabos et al., 2017). While these studies have provided valuable insights in understanding of large-scale dynamics, they are limited in their ability to accurately resolve finer coastal and mesoscale processes critical to accurately simulate upwelling dynamics and ocean- atmosphere interactions.

In this study, the use of HighResMIP models with enhanced resolution of 0.25° has enabled better representation of the SBUS dynamics. This higher resolution improved the simulation of key physical processes, and the position and strength of the SAA.

While no model configuration is without limitations, the use of HighResMIP simulations in this study offered an improved representation of the physical processes critical to SBUS variability and strengthened the robustness of the interpretations presented in this study. This, in turn, strengthens the confidence in interpreting how projected changes in the SAA may influence the SBUS under future climate scenarios.

6.5 Model uncertainties and limitations.

This study provides meaningful insights into the potential impacts of climate change on the SBUS. However, it also highlights several limitations and uncertainties inherent in the modelling approaches. These limitations significantly influence the interpretation and reliability of the results. The quality of input data and boundary conditions plays an important role in the reliability of model projections (Haarsma et al., 2016). In this study, historical datasets from GLORYS and ERA5 reanalysis models were used to validate HighResMIP models, but discrepancies in spatial and temporal resolutions, as well as data assimilation methods, introduce baseline inconsistencies. These inconsistencies may propagate into simulations, influencing historical and future climate projections (Haarsma et al., 2020; Jiménez et al., 2021). HighResMIP models mitigate some challenges by better resolving sub-grid processes like mesoscale eddies and coastal upwelling (Haarsma et al., 2016). However, simplifications are still necessary, particularly for interactions between mesoscale eddies, wind patterns, and coastal topography, leading to potential biases in upwelling variability and intensity (Roberts et al., 2020; Gruber et al., 2022).

The models included in this analysis were selected based on the availability of key atmospheric and oceanic variables across both historical and future periods, which were not consistently provided across the full HighResMIP ensemble. A major limitation encountered was the inconsistent variable availability across HighResMIP models. Notably, only the VHR4 model nearly provided all set of oceanic and atmospheric variables used in the analysis. Since VHR4 could only be compared with a limited number of models, this constrains the scope and robustness of some multi-model comparisons. Additionally, SAA dynamics were assessed using only two HighResMIP models (FGOALS and HiRAM) due to data availability constraints. While both models were included to visualise SAA dynamics, only HiRAM was included in analyses due to FGOALS being not able to adequately represents SAA. This small ensemble size limits the ability to robustly represent regional climate projections, particularly given the variability in model behaviour across the broader HighResMIP ensemble (Haarsma et al., 2016; Roberts et al., 2018). A larger ensemble would strengthen confidence in the regional projections and better account for inter-model uncertainty.

The study's reliance on SSP5-8.5, a high-emission scenario, provides insights into extreme climate outcomes but limits the exploration of alternative futures. This dependence on a single scenario underscores the need for multi-scenario analyses to capture the full spectrum of potential outcomes and improve generalisability (Hausfather & Peters, 2020). These uncertainties affect projections of SBUS dynamics, as the response of large-scale and

nearshore processes may vary significantly depending on the level of radiative forcing. Therefore, incorporating multiple emission scenarios would allow for a more comprehensive assessment of possible outcomes and enhance the robustness of the results.

Despite the advanced resolution of HighResMIP models of 25 km, differences between individual models within HighResMIP may complicate interpretations, highlighting the need for careful evaluation of model diversity to ensure reliable conclusions and further enhanced resolution of up to 10 km (Roberts et al., 2024). Another limitation of this study is the temporal restriction of the HighResMIP dataset to the mid-century (2050) due to computational reasons (Haarsma et al., 2016). While the model provides valuable insights into mid-century trends, this cutoff restricts the ability to assess long-term climate changes beyond this period, particularly for the latter half of the 21st century.

To address these challenges, recent developments and discussions plan to have a further enhanced resolution of up to 10 km and simulations beyond 2050 (Roberts et al., 2024), providing more detailed projections that could improve our understanding of SBUS dynamics. However, this enhanced resolution comes with its own set of challenges, such as increased computational demands and potential biases that need to be addressed for more accurate projections.

7 Conclusion and Future Work

This study has provided an in-depth exploration of the potential impacts of climate change in the Southern Benguela region. It highlights the critical role of the SAA in driving the variability and dynamics of the SBUS. Future climate projections under the SSP5-8.5 scenario anticipate a southward migration and intensification of the SAA, particularly during summer. This change is expected to intensify local winds, with an offshore and southward shift, altering the local atmospheric and oceanic processes that govern upwelling dynamics. The study highlights strengthening the continental low-pressure system and a spatial shift of the SAA further offshore. These atmospheric changes reduce the pressure gradient, which in turn reduces alongshore wind strength and modifies wind stress curl. Such changes are expected to weaken the intensity of upwelling alongshore. Additionally, the shift in high-pressure systems suggests a potential offshore displacement of the climate-sensitive upwelling regions. This could disrupt the distribution of key marine species, alter nutrient dispersal, and impact the food web and the ecosystem structure, leading to significant ecological consequences.

However, the poleward and offshore extension of the Benguela Jet poses risks of disrupting larval retention and reducing primary productivity in nearshore waters, driven by increased thermal stratification. Coastal warming, projected to exceed 1.5°C between 1950 and 2050, will further exacerbate stratification, limiting the vertical exchange of nutrient-rich subsurface waters and making the SBUS increasingly vulnerable to climate change impacts.

The potential implications of these changes are profound, with potential cascading effects on marine ecosystems and socio-economic systems. Spatial shifts in the climate-sensitive upwelling regions may drive ecosystem reorganisation, prompting species migrations and complicating fisheries management and conservation efforts. The cascading effects of these changes highlight the need for integrated research and adaptive management strategies.

To address these challenges, the study highlights the need to effectively implement adaptive and ecosystem-based approaches and develop policies that foster the climate resilience of marine ecosystems and species. Regional cooperation, sustainable fisheries management, and long-term planning will be essential to mitigate the impacts of climate change and promote resilience in the SBUS. Developing policies that account for projected climate variability and extremes will be critical for sustaining biodiversity, supporting food security, and safeguarding the socio-economic well-being of dependent communities.

While this study provides valuable insights, it also acknowledges inherent uncertainties in climate projections. Variability among global and regional models, coupled with the complex dynamics of the SBUS, necessitates further investigation to reduce uncertainties and increase

confidence in these projections. The use of advanced HighResMIP models in this study has enhanced our understanding of SBUS dynamics. However, it has limitations in representing all the nearshore processes of the SBUS. Multi-scenario analyses and advancements in high-resolution modelling are needed to better capture the complex interactions between atmospheric and oceanic processes and improve confidence in climate projections.

Future research should aim to refine projections of upwelling dynamics and to understand their ecological and socio-economic impacts. This will ensure a robust foundation for decision-making and adaptation planning in a rapidly changing climate.

To build upon the insights provided in this study, future research should focus on the following:

- Impact of climate change on the teleconnections that modulate the seasonal migration of the SAA in the SBUS. Our study has observed that SAA in the SBUS undergoes seasonal migration, typically occurring between 25°-35°S (Shelton et al., 1985). At interannual time scales, the atmospheric forcing can be modulated by climate modes of variability, primarily the Southern Annular Mode (SAM) and El Niño-Southern Oscillation (ENSO) (Sun et al., 2017). El Niño events are linked to a northward shift and reduction in southeasterly winds, while La Niña events are associated with stronger winds and a southward located SAA (Rouault et al., 2010; Dufois & Rouault, 2012). However, the impact of climate change on these teleconnections was not analysed in this study and warrants further attention.
- While using 25-km HighResMIP models in this study has enabled the investigation of nearshore processes in the SBUS, employing even higher-resolution models could further refine these analyses. Future research should focus on developing and utilising downscaled regional climate models with enhanced spatial and temporal resolution. Such models would provide a more accurate understanding of localised atmospheric and oceanic dynamics, offering more detailed projections of how the SBUS will respond to climate change.
- Future studies should use fully coupled ocean-atmosphere models to understand better feedback mechanisms between wind stress, SST, and ocean circulation under climate change. These interactions are critical for refining projections of upwelling dynamics and ecosystem responses.

- Expanding the collection of long-term observational data. These datasets will enhance model validation and provide deeper insights into decadal variability and trends in upwelling systems.
- Using simulations beyond 2050 to allow for the exploration of long-term climate projection and their potential impacts on the SBUS.
- Future research should combine climate projections with ecological and fisheries models to explore the impacts of altered upwelling patterns on key species, food webs, and ecosystem services. This approach will help predict fish stocks and biodiversity changes, informing sustainable fisheries management and conservation policies.
- Understanding the socioeconomic impacts of reduced upwelling on marine-dependent communities is essential. Research should focus on prioritising adaptive strategies to mitigate potential economic losses, such as livelihood diversification, sustainable fishing practices, and policy frameworks that balance ecological and economic priorities.
- Investigating different climate change scenarios will provide a more comprehensive understanding of possible futures.
- Monthly time series were computed and averaged over the full domain. Future work should focus on computing averages within a defined coastal band, as this approach may provide a more accurate representation of coastal upwelling dynamics and climate driven changes.

8 References

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