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REVIEW: The Greater Agulhas Current System – Circulation, Variability, Long-Term Trends and Impacts on Weather, Climate and Ecosystems

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Abstract. The Greater Agulhas Current System (GACS) is a dynamically complex western boundary current system that plays a central role in inter-ocean exchange between the Indian and Atlantic Oceans, regional weather and climate over southern Africa, and marine ecosystem variability along the southeast African margin. Since the publication of The Agulhas Current Book nearly two decades ago, major advances in ocean observing systems, satellite remote sensing, numerical modelling, and interdisciplinary research have substantially expanded understanding of the system. Here we provide an integrated review of progress over the period 2006–2025, synthesising recent advances across all components of the GACS, from its upstream source regions to its downstream outflows and global climate connections. We first summarise key technological and methodological developments that have transformed observation and simulation of the Agulhas system, including sustained moored arrays, autonomous platforms, multi-sensor satellite products, and high-resolution numerical models capable of resolving mesoscale and submesoscale dynamics. We then reassess the state of knowledge for each sub-region of the system: the East Madagascar Current, the Mozambique Channel, the Northern and Southern Agulhas Current, the Agulhas Retroflection and leakage, and the Agulhas Return Current, highlighting how recent studies have addressed uncertainties in circulation pathways, variability, and connectivity. Knowledge developments include improved quantification of transport variability and eddy dynamics in upstream source regions, new observational evidence for eddy dissipation and momentum transfer within the Agulhas Current, refined understanding of the processes governing retroflection and leakage, and growing insight into the role of mesoscale and submesoscale dynamics in air–sea interaction, biogeochemical fluxes, and ecosystem responses. We also review emerging evidence linking Agulhas system variability to

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Southern Hemisphere wind forcing and to downstream impacts on the Atlantic Meridional Overturning Circulation. We conclude by identifying remaining knowledge gaps and outlining priority directions for future research, emphasising the importance of sustained observations, improved representation of fine-scale processes in models, and stronger integration across physical, biogeochemical, and ecosystem perspectives.

1. Introduction

The Greater Agulhas Current System (GACS; Fig. 1) is the western boundary current system of the southwestern Indian Ocean, centred on the Agulhas Current (AC), which is considered to be the strongest western boundary current in the Southern Hemisphere, and is embedded within the wind-driven South Indian subtropical gyre (e.g., Beal et al., 2011; Lutjeharms, 2006). The system comprises the source regions in the Mozambique Channel and along east Madagascar (including the East Madagascar Current and associated undercurrent), the Agulhas Current proper along the southeast African margin, the Agulhas Retroflection at the southern tip of Africa, the eastward Agulhas Return Current, and the intermittent Agulhas leakage of warm, saline Indian Ocean waters into the South Atlantic via rings and filaments (e.g., Lutjeharms, 2006; Gordon, 1986). These components are dynamically linked by mesoscale and submesoscale variability, including eddies, meanders, filaments, and shelf–slope interactions, that collectively regulate the transport of heat, salt, and other properties between the Indian, Atlantic, and Southern Oceans and mediate downstream impacts on regional weather and ecosystems (e.g., Casal et al., 2009; Reason, 2001).

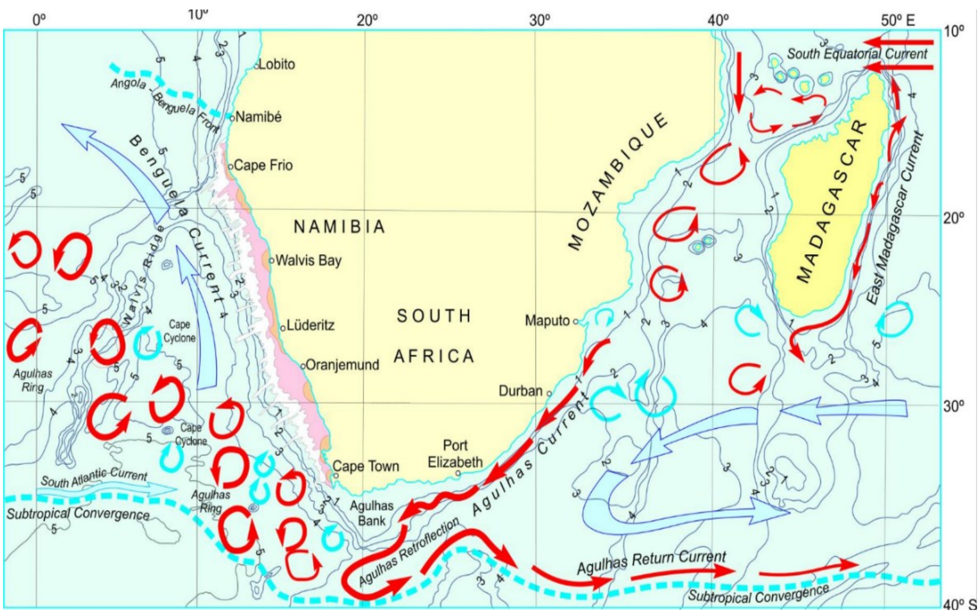

Figure 1. Schematic of surface ocean currents around southern Africa, covering the Benguela and Agulhas Large Marine Ecosystem regions along the southwest and southeast African coasts, respectively. Red (blue) colours denote warm (cold) currents. Background contours indicate bathymetry, shown in kilometres. Adapted from Lutjeharms et al. (2007).

The volume transport of the Greater Agulhas Current System is dominated by the Agulhas Current. Hydrographic and direct velocity measurements indicate that the Agulhas Current carries a mean transport of approximately 84 Sv at the latitude of the South African east coast, making it one of the strongest western boundary currents globally (Donohue et al., 2000; Beal

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et al., 2015). The AC receives most of its waters from two main sources: the Mozambique Channel and the Southern Madagascar region, which are fed primarily by the South Equatorial Current (SEC) that transports an estimated 50–55 Sv between 10–16°S, upstream of the Mascarene Plateau near ~60°E (New et al., 2007; Chapman, 2003; Lutjeharms, 2006). Along the east coast of South Africa the AC flows southwestward with peak velocities exceeding 2 m s^{-1} most of the time, and in situ measurements across the current indicate an estimated volume transport of ~84 Sv (Donohue et al., 2000; Beal et al., 2015; Lutjeharms, 2006). At the southern tip of Africa, the AC retroflects back into the Indian Ocean, shedding Agulhas rings which, together with filaments and other (sub)mesoscale features, carry warm and saline Indian Ocean waters into the southeast Atlantic, the Agulhas leakage, while the remaining flow turns eastward as the Agulhas Return Current (ARC) (Gordon, 1986; Lutjeharms, 2006). Lagrangian estimates further suggest that a non-trivial fraction of the AC transport contributes to leakage in the upper 1000–2000 m on the order of ~15–21 Sv, with the residual returning to the Indian Ocean via the retroflection and ARC; the relative share varies on sub-seasonal to decadal time scales under the combined influence of basin-scale wind forcing and mesoscale variability (Richardson, 2007; Daher et al., 2020; Casal et al., 2009; Beal et al., 2015).

The Indian–Atlantic inter-ocean exchange associated with the Agulhas system modifies the buoyancy structure of currents in the South Atlantic and has the potential to influence the strength and stability of the Atlantic Meridional Overturning Circulation (AMOC), with implications for global climate (Beal et al., 2011; Rühs et al., 2022; Schulzki et al., 2024). In particular, Agulhas leakage, defined as the westward export of warm, saline Indian Ocean waters via rings, filaments, and other (sub)mesoscale features, can increase the salt content of the upper limb of the AMOC and thereby partly offset freshening tendencies in deep water formation regions (Gordon, 1986; Beal et al., 2011). Over the past decades, modelling and observational studies have linked variability and trends in leakage to Southern Hemisphere wind forcing and to large-scale adjustments involving the Antarctic Circumpolar Current, highlighting that the magnitude and timing of leakage are critical for communicating density anomalies into the Atlantic on interannual to decadal time scales (Casal et al., 2009; Loveday et al., 2014; Durgadoo et al., 2013; Rühs et al., 2022). At regional to local scales, the Agulhas Current's intense latent heat fluxes and mesoscale variability also shape the weather and climate of southern Africa, providing moisture and instability to systems that produce heavy rainfall along the east and south coasts (Reason, 2001), thereby underscoring the dual role of the GACS as both a regulator of global overturning and a driver of regional climate impacts.

Beyond its role in large-scale circulation and climate, the dynamics of the Agulhas Current System exert a strong control on regional and local ocean biogeochemistry along the southeast African margin. The intense mesoscale and submesoscale variability of the system, including eddies, meanders, filaments, and shelf–slope interactions, modulates vertical and lateral exchanges of nutrients, oxygen, and carbon between the open ocean and the continental shelf, thereby shaping patterns of biological productivity and ecosystem functioning (Lutjeharms, 2006; Jackson et al., 2012; Jacobs et al., 2022). Interactions between the Agulhas Current and the shelf promote episodic upwelling, cross-frontal exchange, and offshore advection of shelf waters, influencing nutrient supply to the euphotic zone and driving spatially heterogeneous primary production along the coast and over the Agulhas Bank (Lutjeharms et al., 2000; Jackson et al., 2012). In the source regions of the current, particularly the Mozambique Channel and south of Madagascar, mesoscale eddies have been shown to structure nutrient distributions and biological responses across multiple trophic levels, linking physical variability to ecosystem dynamics (Lutjeharms, 2006; Barlow et al., 2014). Through these

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processes, the Agulhas system acts not only as a conduit for water-mass exchange, but also as a regulator of biogeochemical fluxes and marine ecosystem variability at regional to local scales.

Because of its demonstrated importance for global ocean circulation and climate, its influence on regional weather and climate over southern Africa, and its central role in shaping regional and local ocean biogeochemistry and ecosystems, the Agulhas Current System has been the focus of extensive scientific investigation at both regional and international levels. Sustained observational programmes, targeted process studies, and numerical modelling efforts have sought to improve understanding of the structure, variability, and impacts of the system across a wide range of spatial and temporal scales (Lutjeharms, 2006; Beal et al., 2011; Biastoch et al., 2024). This research has been driven by long-standing questions concerning the sources and variability of the Agulhas Current, the mechanisms governing its retroflection and leakage, and the implications of inter-ocean exchange for the Atlantic Meridional Overturning Circulation and global climate, as well as by growing recognition of the system's role in modulating shelf processes, marine productivity, and ecosystem responses along the southern African margin (Reason, 2001; Jackson et al., 2012; Jacobs et al., 2022).

Following this sustained research effort, several syntheses and reviews of the Agulhas Current System have been produced, reflecting its scientific importance and complexity (e.g. Beal et al., 2011; Phillips et al., 2021; Biastoch et al., 2024). Most notably, the book The Agulhas Current by Lutjeharms (2006) provided a comprehensive synthesis of several decades of observational, theoretical, and modelling studies, and has since served as the primary reference describing the physical oceanography and key processes of the Greater Agulhas Current System. This seminal work consolidated knowledge of the current's source regions, structure, variability, retroflection behaviour, and inter-ocean exchange, and identified a number of critical gaps in understanding that required further investigation. Since the publication of this book nearly two decades ago, however, substantial advances in ocean observing systems, satellite remote sensing, numerical modelling, and interdisciplinary research have led to a rapid expansion of knowledge across all components of the Agulhas system. These developments, together with the large and increasingly dispersed body of literature produced since 2006, motivate the need for a new, integrated review that reassesses the state of knowledge, synthesises recent insights, and identifies remaining challenges and future research directions.

Professor Johann R. E. Lutjeharms (1944–2011) was one of the most influential physical oceanographers to emerge from southern Africa and a leading authority on the Agulhas Current system. Through pioneering observational, theoretical, and satellite-based studies, he fundamentally advanced understanding of western boundary currents, mesoscale variability, and inter-ocean exchange between the Indian and Atlantic Oceans. His work established the Agulhas system as a key component of the global overturning circulation and its role in climate variability. Beyond his scientific contributions, Lutjeharms played a defining role in building oceanographic capacity in South Africa through mentorship, institution-building, and international collaboration. His landmark monograph The Agulhas Current remains a foundational reference for researchers worldwide. His legacy endures through the scientific frameworks he established and the generations of oceanographers he trained.

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This review is structured as follows. Section 2 provides an overview of the major technological advances over the past two decades that have enabled new insights into the Greater Agulhas Current System, including developments in in situ observing platforms, satellite remote sensing capabilities, and numerical modelling frameworks. Section 3 synthesises the resulting progress in scientific understanding across the principal components of the system. For each region, the state of knowledge prior to 2006 is briefly summarised, followed by a review of key advances derived from observational, modelling, and ecosystem-based studies. These sections address the East Madagascar Current and its extensions, the Mozambique Channel, the northern and southern Agulhas Current, the Agulhas Retroflection and leakage, and the role of the system in the global climate circulation. Section 4 concludes the review by summarising the major findings, highlighting remaining knowledge gaps, and proposing priority directions for future research aimed at advancing understanding of this dynamically complex and globally significant current system.

2. Observational and modelling advances over the past two decades

Over the past two decades (2006–2025), the capacity and capability to observe and model the Greater Agulhas Current System (GACS) have expanded substantially, leading to significant advances in understanding its circulation, variability, and impacts. This progress has been driven by sustained developments in global and regional ocean observing systems, including the expansion of in situ measurement networks, the emergence of autonomous observing platforms, and improvements in satellite remote sensing coverage and resolution (Beal et al., 2011; Morris et al., 2017; GOOS, 2025). In parallel, advances in numerical modelling, together with improved atmospheric and oceanic reanalysis products, have enabled increasingly realistic simulations of the GACS across a wide range of spatial and temporal scales (Beal et al., 2011; Biastoch et al., 2024). These technological developments have played a central role in addressing many of the knowledge gaps identified by Lutjeharms (2006) (see Section 3) and have underpinned much of the scientific progress reviewed in this paper. The following subsections provide a high-level overview of major advancements in in situ observing systems, satellite remote sensing, and numerical modelling that have supported recent advances in Agulhas Current research.

The present-day state of the in situ and satellite-based observing is summarise in Fig. 2, and described in more detail in Sect 2.1 and 2.2.

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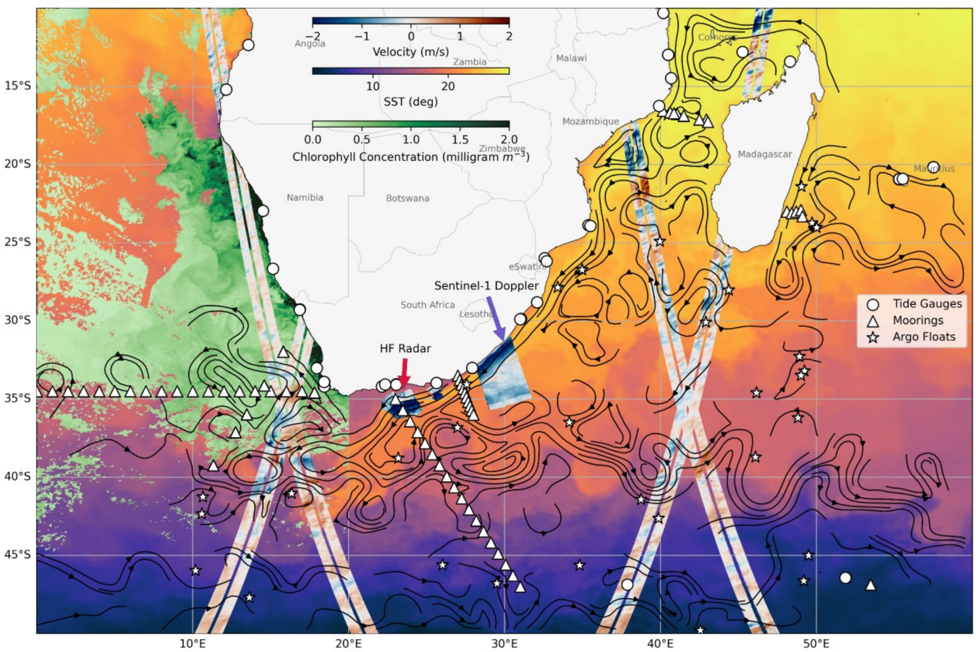

Figure 2. Observing system of the Greater Agulhas Current System. Circles indicate publicly available tide-gauge stations from the GESLA-4 dataset, triangles denote frequent mooring array locations, and stars show a snapshot of Argo float positions. Background shading represents satellite-derived sea surface temperature from the GHRSST product, while surface chlorophyll-a concentrations are obtained from GlobColour. Wide-swath geostrophic surface currents are shown from SWOT. Additional surface velocity measurements are provided by a daily snapshot from HF radar observations and Sentinel-1 Doppler-derived currents. Streamlines represent monthly mean geostrophic currents derived from satellite altimetry using the GlobCurrent product for June 2023.

2.1. Major advancements of in situ observing systems

Since 2006, in situ observing of the Greater Agulhas Current System has advanced substantially through the deployment of long-term moored arrays, repeated hydrographic sections, and the increasing use of autonomous platforms in both the source regions and along the Agulhas Current pathway.

Sustained mooring programmes in strategically important regions—including the Mozambique Channel, south of Madagascar, along the southeast African margin, and in the Cape Basin—have provided continuous, high-frequency time series of velocity, temperature, and salinity, enabling more robust estimates of volume transport and variability on seasonal to decadal time scales (Ullgren et al., 2012; Beal et al., 2015; Elipot and Beal, 2015; McMonigal et al., 2020). In the Mozambique Channel, the Long-term Ocean Climate Observation (LOCO) array delivered a decade-long record of the highly variable flow through the channel, while south of Madagascar the INdian–ATlantic Exchange (INATEX) moorings resolved the vertical structure and transport variability of the East Madagascar Current and its undercurrent (Ullgren et al., 2012; Ponsoni et al., 2015; Ponsoni et al., 2016). Along the Agulhas Current itself, large-scale mooring arrays deployed as part of the Agulhas Current Time-series (ACT) and Agulhas System Climate Array (ASCA) projects yielded new insights into the current's volume transport and variability, while

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downstream observations from the South Atlantic Meridional Overturning Circulation Basin-wide Array (SAMBA) have supported quantification of interannual to decadal variability in Agulhas leakage (Beal et al., 2015; Elipot and Beal, 2015; McMonigal et al., 2020). These sustained moored observations have been complemented by dedicated ship based surveys and repeat hydrographic transects, which have improved understanding of the vertical structure of currents and water masses and provided essential context for interpreting the variability captured by moorings (Ponsoni et al., 2015; Ponsoni et al., 2016; Hutchinson et al., 2013).

Ship based oceanographic surveys have remained a critical component of in situ observing of the Greater Agulhas Current System by providing spatially extensive snapshots of physical, chemical, and biological properties that complement sustained moored observations. Coordinated regional programmes, most notably the Agulhas and Somali Current Large Marine Ecosystems (ASCLME) project, enabled repeated multidisciplinary surveys across the Mozambique Channel, around Madagascar, and along the southeast African margin, significantly expanding hydrographic and ecosystem observations in the source regions of the Agulhas Current (Vousden et al., 2012; Halo et al., 2017). Long-standing survey efforts conducted by the RV *Dr Fridtjof* Nansen under the EAF-Nansen Programme have provided dense coverage of hydrographic stations in the western Indian Ocean, particularly in the Mozambique Channel and around Madagascar, supporting investigations of circulation patterns, water-mass properties, and ecosystem variability (Halo et al., 2017). Additional dedicated surveys, including those associated with the INATEX programme and later IIOE-2 and MADRidge initiatives, have resolved the vertical structure and variability of the East Madagascar Current and its retroflective behaviour, while repeat hydrographic transects such as GoodHope and Crossroads have provided sustained measurements of physical, biogeochemical, and biological properties across the Agulhas Current and Agulhas Return Current systems (Ponsoni et al., 2015; Ponsoni et al., 2016; Hutchinson et al., 2013; Roberts and Ternon, 2020). Many of these ship based surveys and autonomous deployments were multidisciplinary in nature, integrating physical measurements with biogeochemical and biological sampling, thereby enabling investigation of nutrient distributions, primary productivity, and ecosystem responses alongside circulation variability (Vousden et al., 2012; Barlow et al., 2014; Jackson et al., 2012; Bezuidt and Makhalanyane, 2024).

Autonomous observing platforms (Fig. 3) have increasingly complemented ship based surveys and moored arrays by extending spatial and temporal coverage in regions where sustained measurements are logistically challenging. Profiling Argo floats have contributed substantially to observations of the Greater Agulhas Current System, and targeted deployments using high-frequency sampling strategies have proven particularly effective in resolving mesoscale variability in energetic regions such as the Mozambique Channel, south of Madagascar, and along the Agulhas Current pathway (Morris and Lamont, 2019). These specialised deployments enabled new in situ observations of eddy structure, propagation, and associated volume, heat, and salt fluxes, including the first direct estimates of mesoscale eddy contributions to the Agulhas Current derived from autonomous platforms (Morris et al., 2019). Buoyancy-driven ocean gliders have further advanced understanding of fine-scale and submesoscale processes, particularly along the inshore edge of the Agulhas Current, where early deployments revealed the pervasive presence of shear-generated submesoscale cyclonic eddies (Krug et al., 2017). Subsequent glider experiments, including GINA and later deployments along the southeast African shelf, have provided high-resolution observations of frontal structure, turbulence, and shelf–slope exchange processes that are not readily captured by conventional observing systems (Krug et al., 2018; Pringle et al., 2022; d'Hotman et al., 2025). More recently, surface autonomous vehicles, such as waveglider,s saildrones and sailbuoys, have been identified as a

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promising addition to the in situ observing system, with the potential to provide sustained near-surface and air–sea interaction measurements in energetic regions such as the Agulhas Current.

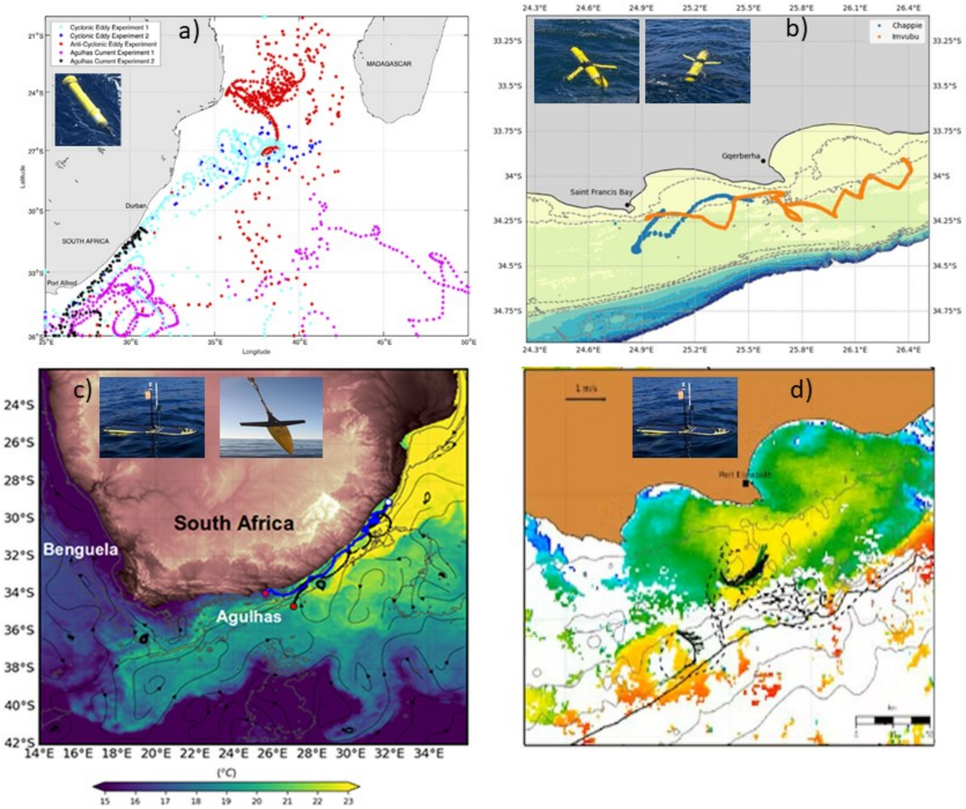

Figure 3. Collage of high-resolution in situ observational efforts in the Greater Agulhas Current System over the past two decades. Panel (a) shows trajectories of 18 high-resolution Argo profiling floats deployed between 2013 and 2017 in the southern Mozambique Channel and along the southeast coast of South Africa (Morris and Lamont, 2019). Panel (b) shows the first South African Polar Research Infrastructure (SAPRI) Slocum ocean glider deployments on the eastern Agulhas Bank, representing the first high-resolution sea-glider experiments conducted under SAPRI (d'Hotman et al., 2025). Panel (c) shows a map of ODYSSEA sea surface temperature and GlobCurrent surface currents on 20 July 2017, with the profiling trajectories of the two gliders deployed during the GINA project in 2017 shown in blue and black; white and red symbols indicate glider deployment and recovery locations, respectively (adapted from Krug et al., 2018, EOS). Panel (d) shows satellite-derived sea surface temperature in the Agulhas Current region, with warm waters highlighted in shades of orange illustrating the surface thermal expression of the Agulhas Current (adapted from Krug et al., Council for Scientific and Industrial Research – Natural Resources and the Environment, CSIR-NRE).

2.2. Major developments in satellite remote sensing

Satellite remote sensing has been central to advancing observation of the Greater Agulhas Current System over the past two decades by providing sustained, synoptic coverage of surface ocean properties across spatial and temporal scales that are not achievable with in situ

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measurements alone. Since 2006, improvements in satellite sensor capabilities, continuity of altimeter missions, and the emergence of multi-sensor products have substantially enhanced the monitoring of sea surface height, surface geostrophic currents, sea surface temperature, winds, and ocean colour across the Agulhas region (Beal et al., 2011; Krug et al., 2010; Pujol et al., 2016). These developments have enabled more detailed characterisation of mesoscale variability, eddy activity, current pathways, and the position and variability of the Agulhas Retroflection, while also supporting investigations of air–sea interaction and ecosystem-relevant surface processes (Johannessen et al., 2014; Krug et al., 2018; Russo et al., 2021).

The major advance in satellite altimetry over the past two decades has been the availability of continuous, multi-mission, reprocessed SSH products, enabling the derivation of surface geostrophic currents over multi-decadal time scales. The availability of merged, multi-mission altimetry products since the early 1990s, and in particular the release of reprocessed Level-4 datasets by the AVISO/DUACS programme, has improved the representation of mesoscale variability, eddy statistics, and current pathways across the Agulhas region (AVISO, 2015; Pujol et al., 2016). These products provide daily fields of SSH and surface geostrophic velocity from 1993 onwards, enabling consistent investigation of circulation variability from seasonal to interannual and longer time scales. Over the past decade, the Sentinel continuity missions have contributed to improved spatial and temporal sampling of the ocean surface, strengthening the robustness of merged altimetry products and supporting more detailed analyses of surface circulation features in the Agulhas system (Fig. 4). Improved mapping algorithms and noise-reduction techniques have extended the usefulness of altimetric observations closer to the continental shelf, enhancing the detection and tracking of mesoscale eddies in the Mozambique Channel, south of Madagascar, and along the Agulhas Current and Agulhas Return Current (Halo et al., 2014a; Halo et al., 2014b; Capet et al., 2014; Pujol et al., 2016). Altimetry-based analyses have also advanced quantitative understanding of the mean and variable position of the Agulhas Retroflection, supporting the development of objective methods to identify the core and edges of the Agulhas Current and to assess changes in retroflection behaviour over time (Russo et al., 2021; Russo et al., 2022).

The launch of the Surface Water and Ocean Topography (SWOT) satellite in 2022 represents a major recent advance in satellite remote sensing, providing the first spaceborne measurements of high-resolution, two-dimensional sea surface height fields. Early analyses using SWOT observations have demonstrated its ability to resolve fine-scale spatial structure in regions of intense mesoscale and submesoscale variability such as the Agulhas Retroflection (Fig. 5). Using data from the fast-sampling phase of the mission, Coadou-Chaventon et al. (2025) showed that conventional nadir altimetry products underestimate the magnitude of surface geostrophic currents in the retroflection region, supporting earlier findings by Hart-Davis et al. (2018), with SWOT-derived velocities exceeding 1 m s^{-1} in localized regions (Fig. 5d,e). To date, two early retroflection events have been identified from SWOT observations, occurring in June 2023 at approximately 25.5°E (Johnson, 2025) and in January 2026 near 22°E. Comparisons of gridded surface fields constructed with and without SWOT data further revealed enhanced representation of fine-scale variability, including submesoscale eddy structure and elevated Rossby numbers in the retroflection region, highlighting the added value of wide-swath altimetry for resolving the detailed surface circulation of the Greater Agulhas Current System (Fig. 5j). Comparisons of gridded surface fields constructed with and without SWOT data further revealed enhanced representation of fine-scale variability, including submesoscale eddy structure and elevated Rossby numbers in the retroflection region, highlighting the added value of wide-swath altimetry for resolving the detailed surface circulation of the Greater Agulhas Current System (Fig. 5j).

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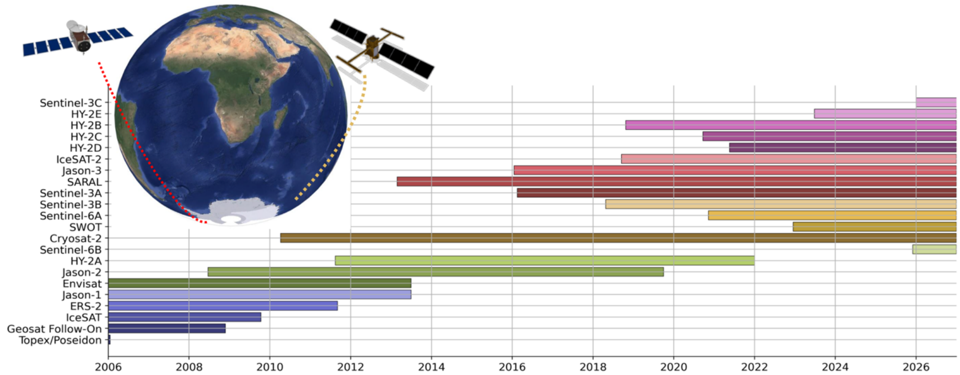

Figure 4. Satellite altimetry temporal coverage over the past two decades.

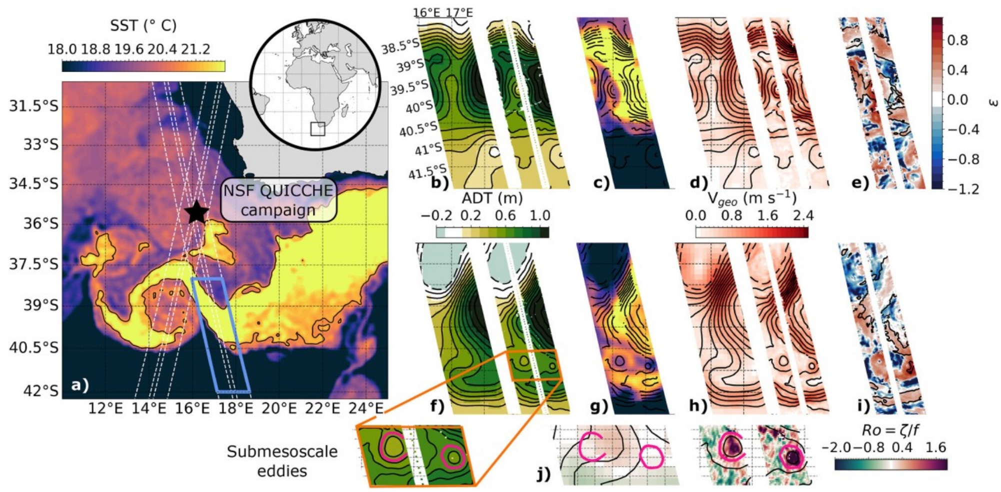

Figure 5. Comparison of nadir altimetry and wide-swath SWOT observations in the Agulhas Retroflection region. Panel (a) shows satellite-derived sea surface temperature (SST; colour scale) on 8 April 2023, with the black star indicating the location of the QUICCHE field site; the blue rectangle outlines the region expanded in panels (b–i). Panels (b) and (f) show absolute dynamic topography (ADT; colour scale and contours) from DUACS (left) and SWOT (right) on 29 March and 23 April 2023, respectively. Panels (c) and (g) show the corresponding SST fields. Panels (d) and (h) show geostrophic velocity fields derived from DUACS (left) and SWOT (right). Panels (e) and (i) show the relative geostrophic velocity anomaly (ϵ) between SWOT and DUACS, with the black contour indicating regions where SWOT-derived geostrophic velocities exceed 1 m s^{-1}. Panel (j) shows Rossby number maps derived from DUACS (left) and SWOT (right), focusing on a zoomed-in region containing two submesoscale eddies, delineated by pink contours in panel (f). Adapted from Coadou-Chaventon et al. (2025).

Advances in Synthetic Aperture Radar (SAR) sensing, particularly high-resolution imaging and Doppler-based techniques, have expanded the ability to observe ocean surface currents within the Greater Agulhas Current System by resolving fine-scale surface features associated with strong current gradients, convergence and divergence zones, and air–sea interaction processes. High-resolution SAR imagery has been used to identify surface roughness signatures linked to

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the Agulhas Current front, mesoscale eddies, and submesoscale features, particularly in regions where intense current shear and frontal activity dominate the surface expression of the flow (Johannessen et al., 2008; Krug et al., 2010). Advances in SAR-based Doppler shift measurements have further enabled retrievals of line-of-sight surface velocities, providing independent estimates of surface current variability that complement geostrophic currents derived from altimetry, including direct comparisons with Lagrangian drifter trajectories (Figure 6a,c; Johannessen et al., 2014; Krug et al., 2018). The combined use of SAR Doppler–derived surface velocities and altimetry-based geostrophic currents has enabled detailed assessment of surface flow structure in the Agulhas Current, demonstrating the complementarity of ageostrophic and geostrophic components (Fig. 6a,c).

Sea surface temperature (SST) observations derived from satellite infrared and microwave sensors have been widely used to characterise the surface expression of the Greater Agulhas Current System, including its frontal structure, mesoscale variability, and interactions with the overlying atmosphere. High-resolution infrared SST imagery has been particularly effective in delineating the Agulhas Current front, tracking mesoscale eddies originating from the Mozambique Channel and south of Madagascar, and documenting variability associated with features such as Natal Pulses (Krug et al., 2010; Weeks et al., 1998), where cold-core structures and associated velocity anomalies are clearly resolved when SST and SAR-derived surface currents are analysed together (Fig. 6b,d). However, the utility of infrared SST observations in the Agulhas region is limited by frequent cloud cover and strong evaporation over the warm current core, which can reduce data availability and introduce biases, particularly in regions of strong thermal gradients (Krug et al., 2010). The combined use of infrared SST with microwave radiometer products and merged altimetry fields has therefore been essential for improving the interpretation of surface thermal variability and its linkage to underlying circulation features (Krug et al., 2010; Imbol et al., 2019). These multi-sensor SST products have also supported investigations of air–sea heat fluxes and mesoscale influences on surface temperature variability in the Agulhas system, highlighting the importance of SST as both a tracer of circulation and a driver of regional air–sea interactions.

Satellite-derived surface wind observations have contributed to improved understanding of air–sea interactions over the Greater Agulhas Current System, particularly in regions of strong surface currents and sharp thermal fronts. Scatterometer and SAR-based wind products have revealed pronounced spatial variability in wind speed and stress associated with the Agulhas Current, highlighting the modulation of the marine atmospheric boundary layer by underlying oceanic features (Krug et al., 2018). High-resolution SAR observations have shown that wind responses to current-induced surface roughness and SST gradients occur at spatial scales that are not adequately resolved by coarser-resolution scatterometer products, underscoring the importance of fine-scale measurements in this dynamically active region (Johannessen et al., 2014; Krug et al., 2018). Satellite-based estimates of turbulent air–sea fluxes, including latent heat flux, have further demonstrated the ability of high-resolution products to capture the intense exchanges of heat and moisture over the warm Agulhas Current, which play an important role in shaping regional weather and climate variability (Imbol et al., 2019).

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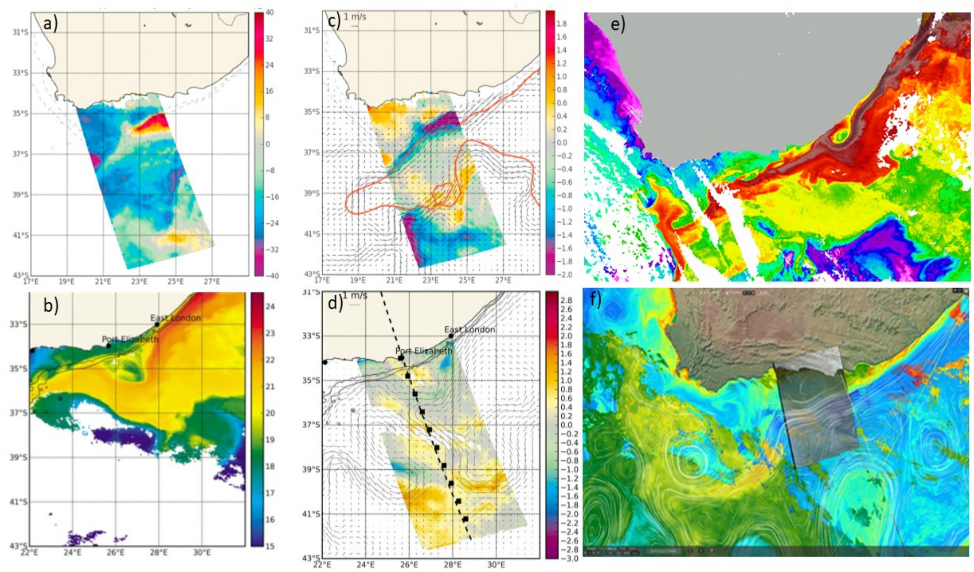

Figure 6. Examples of multi-sensor satellite observations illustrating advances in the retrieval of ocean surface currents and their interaction with thermal and biological surface properties in the Greater Agulhas Current System. Panels (a) and (c) show (a) the ASAR Doppler centroid anomaly (Hz), corrected for along-track variations and land contamination, on 8 May 2008, and (c) the corresponding ASAR-derived range-directed surface current velocity (m s^{-1}), overlaid with geostrophic velocity vectors derived from the CNES–CLS09 mean dynamic topography and the AVISO near-real-time multi-satellite sea level anomaly product. The trajectory of Lagrangian surface drifter 14926 between 9 June and 21 July 2008 is shown in red, and stippled lines indicate the 100 m and 200 m isobaths (adapted from Rouault et al., 2010). Panels (b) and (d) illustrate the passage of a Natal Pulse, showing (b) sea surface temperature from the Meteosat Second Generation sensor, revealing a ~150 km diameter cold-core feature at the inshore edge of the Agulhas Current, and (d) ASAR-derived range-directed surface current velocity on 12 August 2008, overlaid with AVISO-derived geostrophic velocity vectors. Positive (negative) velocities indicate flow toward the northeast (southwest) (adapted from Rouault et al., 2010). The right-hand panels show examples of integrated multi-sensor products, including sea surface temperature from MODIS, high-resolution Sentinel-1 sea surface roughness modulated by the Agulhas Current, satellite-derived chlorophyll concentration from MODIS and VIIRS, regional ODYSSEA SST, GlobCurrent geostrophic currents, and Jason-2 sea level anomalies (visualised using https://seascope.oceandatalab.com/data.html/).

Satellite-derived ocean colour observations have provided important insights into the biological expression of variability within the Greater Agulhas Current System by enabling synoptic monitoring of surface chlorophyll-a concentration and related proxies for phytoplankton biomass. In the southern Benguela Upwelling System and across the Agulhas Bank, however, the optical complexity of coastal and shelf waters, particularly during high-biomass and harmful algal bloom (HAB) events, has posed significant challenges for conventional global chlorophyll-a retrieval algorithms based on blue–green band ratios (Matthews et al., 2012; Goyens et al., 2013). Prior to the development of regionally optimised algorithms, satellite observations were unable to resolve the extreme chlorophyll-a concentrations associated with HABs, and pixel data corresponding to bloom conditions were often excluded from analyses, precluding quantitative assessment of bloom extent and intensity (Ryan et al., 2009; Shanmugam, 2012).

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Major advances have since been achieved through the development of regional bio-optical algorithms tailored to the optically complex waters of the southern Benguela and adjacent regions. These include blended approaches that combine blue–green band-ratio algorithms for low to moderate biomass conditions with red to near-infrared band ratios for moderate to high biomass waters, enabling a smooth transition across biomass regimes (Pitcher et al., 2008; Evers-King, 2014; Robertson-Lain et al., 2014). Smith et al. (2018) introduced such an algorithm for the MERIS and OLCI sensors, validated against a wide range of in situ observations, substantially improving the detection and quantification of high-biomass blooms. A similar blended-algorithm approach has subsequently been applied to MODIS data, enabling robust mapping of bloom extent and frequency in the region (Fig. 7). Together, these developments have transformed the utility of satellite ocean colour observations in the Greater Agulhas Current System, allowing quantitative investigation of phytoplankton variability, bloom dynamics, and physical–biological coupling in regions previously considered inaccessible to standard global algorithms.

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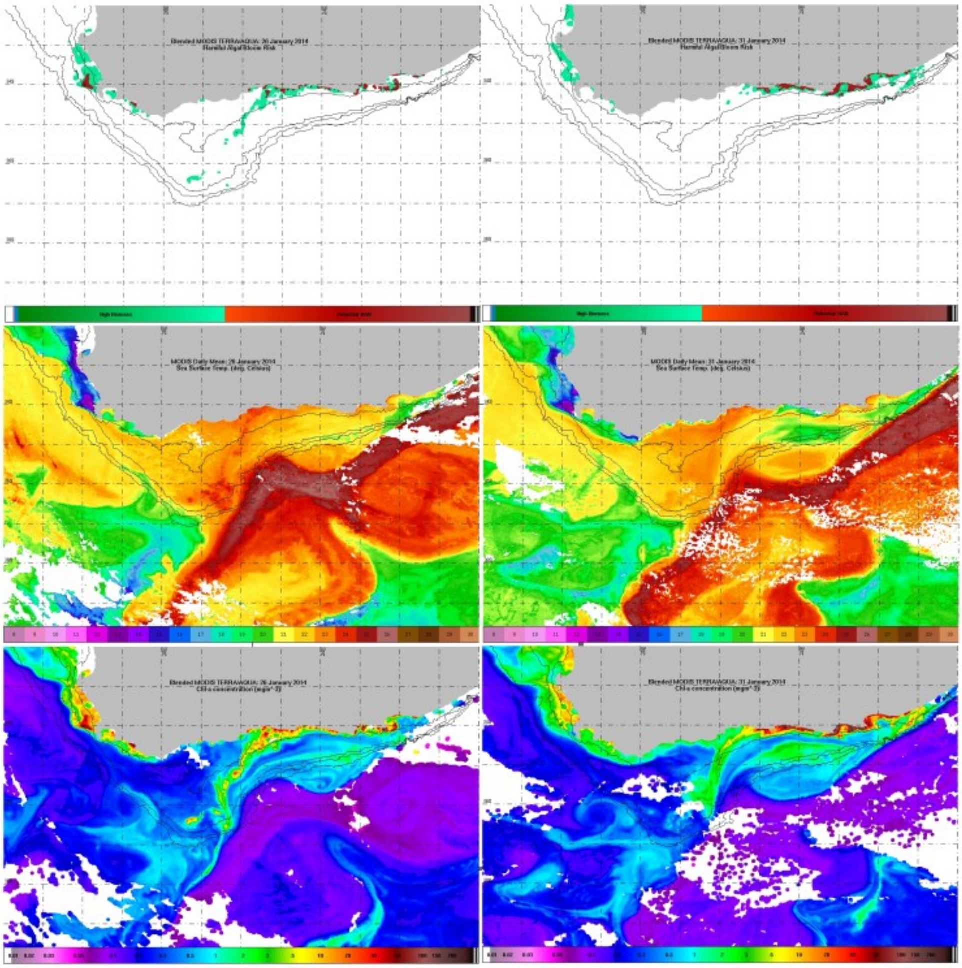

Figure 7. Maps of high biomass bloom derived from the improved algorithm blending satellite retrieved information from the blue-green and red to near-infrared parts of the spectrum applied to MODIS data. Top panels show the Harmful Algal Blooms events, middle panels show the corresponding Sea Surface Temperature, and the bottom panels show the chlorophyll-a concentrations. Left panels refers to the HAB event for 20 January 2014 and right panels show the event by 31 January 2014, revealing the events' duration.

Together, these developments reflect a shift from single-sensor analyses toward integrated, multi-sensor satellite observing frameworks capable of resolving the energetic, multi-scale dynamics of the Greater Agulhas Current System. This transition has been driven not only by the continuity and expansion of satellite missions, but also by major advances in observing geometry, data processing, and algorithm development. In particular, the advent of wide-swath altimetry through the SWOT mission has enabled direct observation of two-dimensional sea surface height variability and fine-scale circulation features that are not resolved by conventional nadir altimetry, while regionally optimised bio-optical algorithms have substantially improved the retrieval of chlorophyll-a concentration in optically complex coastal and shelf waters. These advances, together with improvements in mapping techniques, multi-sensor data integration, and the adoption of free and open-access data policies, including web-based platforms such as the

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Ocean Virtual Laboratory (https://ovl.oceandatalab.com/), have greatly enhanced the ability to co-locate, visualise, and jointly analyse satellite, in situ, and model datasets, thereby strengthening the observational foundation for Agulhas Current research.

2.3. Major advancements in numerical modelling

Numerical modelling of the Greater Agulhas Current System has a long history, marked by persistent challenges. One of the earliest idealised simulations by Boudra and Chassignet (1988) successfully reproduced a wind-driven South Indian Ocean gyre and captured key features such as the Agulhas Retroflection and ring formation, demonstrating the feasibility of modelling the system at mesoscale-permitting resolution. Subsequent eddy-permitting primitive-equation models, notably the Fine Resolution Antarctic Model (FRAM), reproduced the major elements of the Agulhas system but also revealed systematic deficiencies, including a retroflection occurring too far upstream and eastward, exaggerated mesoscale variability, and Agulhas rings propagating westward along unrealistically straight trajectories (Lutjeharms and Webb, 1995; Figure 8b). These biases were later shown to be remarkably robust across a wide range of model frameworks (e.g. Fig. 8) and resolutions, affecting global and regional configurations, forced and coupled simulations, and even data-assimilative state estimates, including ORCA, POP, OFES, NLOM, HYCOM, ECCO2, and more recent high-resolution coupled climate models such as CESM-HR and AWI-CM-1-1-MR (Maltrud and McClean, 2005; Sasaki et al., 2005; Wallcraft et al., 2002; Thoppil et al., 2011; Zhu et al., 2018; Beech et al., 2022; Großelindemann et al., 2025). In many cases, increasing horizontal resolution alone failed to alleviate, and sometimes exacerbated, these errors, underscoring that accurately representing the Agulhas system requires not only finer resolution but also careful treatment of bathymetry, dissipation, air–sea coupling, and energy pathways. These longstanding challenges have strongly shaped subsequent modelling developments and motivated targeted methodological advances over the past two decades.

Recognition of systematic biases in early numerical simulations of the Greater Agulhas Current System, together with substantial increases in available computational power, has motivated targeted improvements in numerical formulation, model configuration, and physical process representation. A range of studies demonstrated that addressing the Agulhas retroflection bias requires more than increased horizontal resolution alone, prompting efforts to improve numerical precision and conservation properties, refine bathymetry and dissipation schemes, and better represent key dynamical feedbacks (Barnier et al., 2006; Backeberg et al., 2009; Biastoch and Krauß, 1999; Penven et al., 2006; Loveday et al., 2014). In particular, refining topographic representation and lateral mixing parameters was shown to substantially improve the stability and location of the retroflection in regional model configurations tailored to the Agulhas system (Biastoch and Krauß, 1999; Penven et al., 2006; Biastoch et al., 2008).

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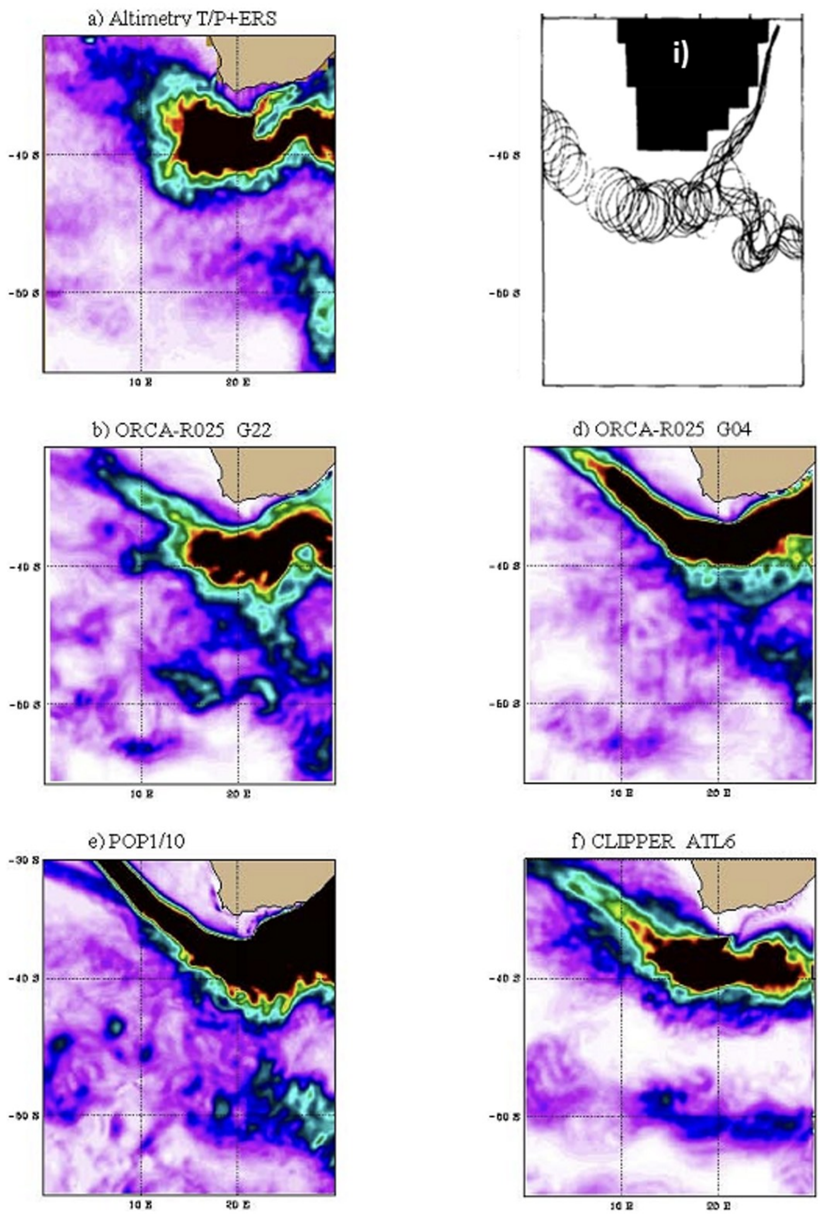

Figure 8. Example of systematic deficiencies in numerical simulations of the Agulhas Retroflection. The characteristic upstream and eastward displacement of the retroflection, together with exaggerated mesoscale variability, leads to unrealistic patterns of eddy kinetic energy (EKE). The top left panel shows EKE derived from satellite altimetry, used here as a reference. The top right panel shows EKE from the FRAM simulation. The middle panels show results from two ORCA simulations at ¼° resolution, using partial-step bathymetry (left) and full-step bathymetry (right). The bottom panels show EKE from the OPA and Clipper model configurations. Adapted from Barnier et al. (2006).

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Further advances were achieved by enabling ocean surface current feedbacks on wind stress, which reduced excessive mesoscale variability and stabilised the retroflection, leading to more realistic circulation patterns and leakage pathways (Renault et al., 2017). Collectively, these developments marked a shift from generic eddy-permitting models toward regionally optimised configurations capable of reproducing the observed structure and variability of the Agulhas Current, laying the foundation for subsequent high-resolution and process-oriented modelling studies (Backeberg et al., 2009; Loveday et al., 2014; Schwarzkopf et al., 2019; Penven et al., 2025a).

Many earlier studies of the Agulhas system relied on free-running numerical simulations, despite the strongly nonlinear mesoscale dynamics governing the Agulhas Current and its retroflection and the limited availability of observations to constrain model solutions (Lutjeharms, 2006; Biastoch et al., 2008). Although several global operational data-assimilation systems were available (e.g. MyOcean, BlueLink, and the HYCOM consortium), none were specifically configured for the southern African region, and regionally focused data-assimilation efforts in the Agulhas system had been limited since the work of Evensen and van Leeuwen (1996). Backeberg et al. (2014) explored the use of a regional HYCOM configuration with Ensemble Optimal Interpolation (EnOI) assimilation of along-track satellite sea-level anomaly data. Their results showed that assimilation could improve the consistency of mesoscale eddy placement, reduce eddy kinetic energy errors relative to free-running simulations, and yield modest improvements in subsurface water-mass properties and deep velocities. At the same time, the study emphasised that assimilating anomalies does not correct biases in the model mean state, and that deficiencies in model numerics, forcing, and multivariate relationships can persist in assimilated solutions. These findings reinforced the view that data assimilation alone cannot resolve the long-standing challenges of modelling the Agulhas system, but can provide added value when used alongside continued improvements in model formulation, resolution, and physical realism (Backeberg et al., 2014; Zhu et al., 2018).

While the modelling advances reviewed here focus primarily on physical circulation, high-resolution simulations have increasingly been used to interpret observed biological and biogeochemical variability in the Agulhas system by linking mesoscale dynamics to nutrient and ecosystem responses. These developments have also highlighted the importance of resolving finer-scale dynamics, as mesoscale-resolving models remain limited in their ability to represent vertical exchanges, frontal processes, and energy pathways that are increasingly recognised as central to Agulhas dynamics.

Substantial increases in computational power have enabled the development of nested and ultra-high-resolution numerical models capable of explicitly resolving submesoscale dynamics. Using a nested modelling approach achieving horizontal resolutions of order 750 m in the core of the Agulhas Current, Tedesco et al. (2019) demonstrated that shear-driven submesoscale frontal eddies are recurrent features of the current, emerging preferentially during stable phases and modulated by large-scale deformation fields. Similarly, submesoscale-resolving simulations based on the INALT model family, with resolutions down to 1/60°, showed that resolving submesoscale motions enhances the strength, structure, and realism of mesoscale eddies and improves the representation of the Agulhas Retroflection and leakage pathways (Schwarzkopf et al., 2019; Figure 9). These studies further revealed that submesoscale processes reinforce shear-edge eddies and can increase Agulhas leakage by modifying the local balance of instabilities and energy transfers (Schubert et al., 2021). Beyond their impact on circulation pathways, submesoscale-resolving models have enabled new insight into energy cascades within the system, showing that the Agulhas Current acts as a local source of mesoscale energy rather than

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a net sink, with dissipation pathways varying markedly between the northern and southern segments of the current (Tedesco et al., 2022). Together, these developments demonstrate that explicitly resolving submesoscale dynamics is critical for accurately representing the structure, variability, and energetics of the Agulhas system, and marks a significant advance beyond earlier mesoscale-resolving modelling approaches.

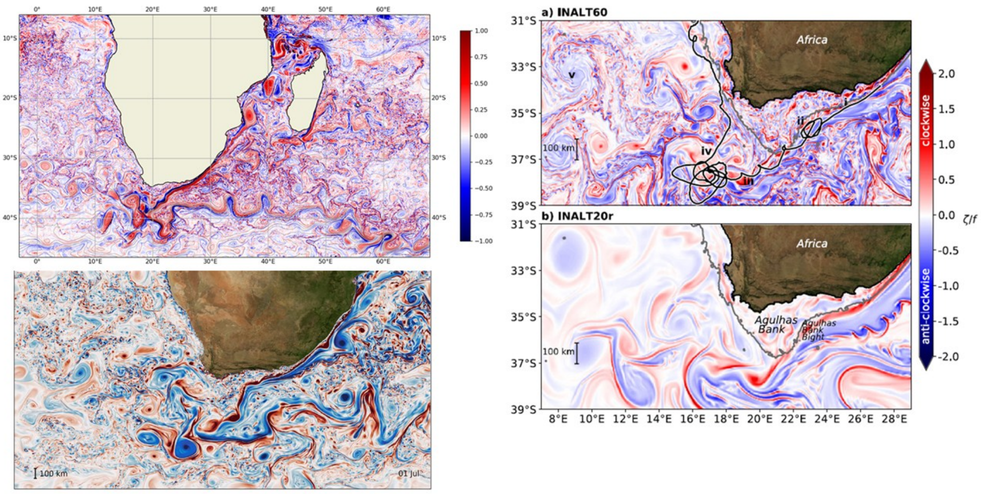

Figure 9. Snapshot of relative vorticity normalised by the planetary vorticity, illustrating the representation of circulation features across a range of spatial scales in numerical simulations of the Greater Agulhas Current System. The left panels show results from high-resolution regional model configurations, with panel (a) from the SWAG36 CROCO simulation (adapted from Penven et al., 2025a) and panel (b) from a NEMO configuration used by Biastoch and Schwarzkopf. The right panels show simulations from the INALT NEMO model at horizontal resolutions of 1/60° and 1/20°, respectively (Schwarzkopf et al., 2019). Across all panels, the models reproduce dominant circulation features of the southern African region at multiple spatial scales, including large-scale currents, mesoscale eddies and rings, and submesoscale meanders and filaments. The influence of submesoscale dynamics in the Agulhas region is highlighted in the zoomed views in the right panels. The black–white line indicates the trajectory of Global Drifter Program drifter 101938, released on 19 February 2013. The extent of the Agulhas Bank is delineated by the 300 m isobath. Key dynamical features are marked, including: (i) submesoscale instabilities along the northern edge of the Agulhas Current; (ii) a shear-edge cyclone in the Agulhas Bank Bight; (iii) a shear-edge cyclone southwest of the Agulhas Bank; (iv) a lee cyclone; and (v) an Agulhas ring surrounded by submesoscale vortices (adapted from Schubert et al., 2022).

Advances in numerical modelling of the Greater Agulhas Current System over the past two decades reflect a shift from largely exploratory, eddy-permitting simulations toward physically consistent, regionally optimised, and increasingly high-resolution modelling frameworks. Progress has been driven by a combination of increased computational power, improved numerical formulation, refined bathymetry and dissipation schemes, incorporation of air–sea current feedbacks, and, more recently, the explicit resolution of submesoscale dynamics. While persistent challenges remain, particularly in accurately representing the Agulhas Retroflection and leakage across model hierarchies, these developments have substantially improved the realism of simulated circulation, variability, and energetics. Importantly, modelling advances

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have evolved in close interaction with observational progress, with in situ measurements and satellite products providing essential benchmarks for model evaluation and interpretation, and models, in turn, offering a dynamical framework to integrate disparate observations and test competing hypotheses.

3. State of knowledge and new insights over the past two decades

Lutjeharms (2006) identified a number of fundamental knowledge gaps spanning all major components of the system, from its upstream source regions to its downstream outflows and global impacts. Many of these gaps related to the structure, variability, and connectivity of the circulation, reflecting the limited observational coverage and modelling capabilities available at the time. Revisiting these unresolved questions provides a coherent framework for assessing progress over the past two decades.

At the upstream sources of the Agulhas Current, key uncertainties concerned the nature of the circulation through the Mozambique Channel and south of Madagascar. In the Mozambique Channel, long-standing debate focused on whether a spatially continuous southward boundary current exists along the Mozambican coast, or whether the flow is instead dominated by mesoscale eddies. South of Madagascar, similarly fundamental questions were raised regarding the existence and dynamical significance of a retroflection of the South East Madagascar Current and the implications of any eastward return flow in a region dominated by westward wind-driven circulation. Closely related were broader uncertainties surrounding the role of Madagascar as a topographic obstacle shaping current pathways, eddy generation, and connectivity between upstream branches of the Agulhas system.

Downstream, significant gaps remained in understanding the behaviour and variability of the Agulhas Current and its outflows. For the Agulhas Return Current, questions concerned its interaction with major bathymetric features, its temporal variability, and its role in redistributing waters within the southwest Indian Ocean subtropical gyre. Despite extensive prior research on Agulhas leakage, important uncertainties also persisted regarding the fate and impact of Agulhas rings, including their role in redistributing heat, salt, and vorticity in the South Atlantic, their interaction with the atmosphere, and the extent to which leakage variability is controlled by regional or basin-scale wind forcing.

The technological and methodological advances outlined in Sect 2 have enabled substantial progress in addressing many of these questions. Expanded in situ observing systems, improved satellite remote sensing, and increasingly realistic numerical models have provided new insight into the structure, variability, and connectivity of the Greater Agulhas Current System across a wide range of spatial and temporal scales. In the following subsections, we revisit each major component of the system in turn. For each region or process, we summarise the state of knowledge up to 2006 and then highlight key advances over the past two decades, drawing on observational, modelling, and interdisciplinary studies to reassess earlier interpretations and identify remaining challenges.

3.1. East Madagascar Current and its northern and southern extension

Prior to 2006, understanding of the East Madagascar Current (EMC) and its northern and southern extensions was limited by sparse in situ observations and by differing interpretations of satellite and hydrographic data. The EMC was recognised as the western boundary current of the southwest Indian Ocean subtropical gyre along the eastern margin of Madagascar and as a major upstream contributor to the Greater Agulhas Current System (Lutjeharms, 2006). However, its

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mean structure, transport, variability, and downstream connectivity remained poorly constrained, particularly relative to better-studied western boundary currents elsewhere.

At its northern extent, the EMC was understood to be fed primarily by the westward-flowing South Equatorial Current (SEC), which bifurcates upon encountering Madagascar (Lutjeharms, 2006). The partitioning of this flow around the island was recognised as an important control on the volume and properties of waters entering the Mozambique Channel and, ultimately, the Agulhas Current. Nevertheless, the relative importance of a continuous boundary current along eastern Madagascar versus episodic transport mediated by mesoscale eddies and filaments remained uncertain, owing to the lack of sustained direct velocity measurements along the margin (Lutjeharms, 2006; de Ruijter et al., 2004).

South of Madagascar, the behaviour of the southern extension of the EMC was particularly contentious. A central unresolved question was whether the EMC undergoes a retroflection south of the island, forming an eastward return flow, or whether it primarily feeds westward into the Mozambique Channel and the Agulhas Current without a coherent turning. Early interpretations based largely on satellite altimetry, drifter trajectories, and limited hydrographic sections suggested the existence of a retroflective pathway (e.g. Siedler et al., 2006), but these interpretations were challenged on dynamical grounds. In particular, an eastward return flow would oppose the generally westward wind-driven circulation of the region, leading some authors to question its physical plausibility and to refer to the proposed feature as a “retro-fiction” (Quartly et al., 2006).

Adding to this ambiguity was the identification of the South Indian Counter Current (SICC), an eastward-flowing current embedded within the subtropical gyre south of Madagascar. Although the SICC was formally described only in the mid-2000s (Palastanga et al., 2006; Siedler et al., 2006), its presence complicated interpretation of eastward flows inferred from satellite data. In particular, it raised the possibility that some observations previously attributed to a retroflecting EMC might instead reflect the broader gyre-scale circulation associated with the SICC (Lutjeharms, 2006; Quartly et al., 2006). Distinguishing between a true southern EMC return flow and the SICC thus remained a major challenge prior to 2006.

The degree of connectivity between the EMC, its southern extension, and downstream pathways also remained unresolved. It was unclear whether the EMC connects continuously to the Agulhas Current via the Mozambique Channel, or whether this connection is intermittently disrupted by the shedding of mesoscale eddies, dipoles, and filaments south of Madagascar (de Ruijter et al., 2004; Siedler et al., 2009). The role of Madagascar’s complex topography in steering the flow, generating mesoscale variability, and modulating these connections was recognised as potentially important but poorly quantified, motivating early sensitivity experiments using regional numerical models (Penven et al., 2006).

Additionally, prior to 2006, biogeochemical and ecosystem characteristics of the East Madagascar Current and its extensions were largely unexplored, with understanding of biological variability limited to indirect inferences from physical circulation and mesoscale activity, reflecting the scarcity of targeted observations in the region (Lutjeharms, 2006).

Since 2006, targeted in situ observations, improved satellite analyses, and high-resolution numerical modelling have substantially clarified the structure, variability, and downstream connectivity of the East Madagascar Current (EMC).

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Sustained mooring observations south of Madagascar, deployed as part of the INdian–ATlantic Exchange (INATEX) programme, provided the first direct time series of velocity and transport variability of the EMC and its undercurrent (Ullgren et al., 2012; Ponsoni et al., 2015; Ponsoni et al., 2016). These measurements demonstrated that the EMC is a coherent, vertically structured boundary current with substantial variability on seasonal to interannual time scales, and that a significant fraction of its transport is carried below the surface. The observations further showed that the EMC does not form a steady downstream pathway, but instead interacts strongly with mesoscale eddies south of Madagascar.

Satellite altimetry and eddy-tracking analyses confirmed that the southern extension of the EMC is embedded in an energetic eddy field characterised by frequent shedding of cyclonic and anticyclonic eddies (Halo et al., 2014a; Halo et al., 2014b). These eddies intermittently divert EMC waters westward toward the Mozambique Channel or eastward into the subtropical gyre, reconciling earlier conflicting interpretations of continuous versus intermittent connectivity to the Agulhas system (de Ruijter et al., 2004; Siedler et al., 2009).

The long-standing debate regarding a retroflection of the EMC south of Madagascar has also been resolved. Observational and modelling studies have shown that while eastward flow occurs in this region, it is more accurately attributed to the South Indian Counter Current (SICC) rather than a persistent retroflection of the EMC itself (Siedler et al., 2009; Ramanantsoa et al., 2021). Satellite altimetry analyses have further demonstrated that the southern extension of the EMC exhibits distinct retroflection regimes with preferred longitudinal and latitudinal positions, rather than a single fixed retroflection point (Fig. 10). This distinction clarified earlier ambiguities arising from satellite-based interpretations and effectively closed the "retro-fiction" debate (Quartly et al., 2006).

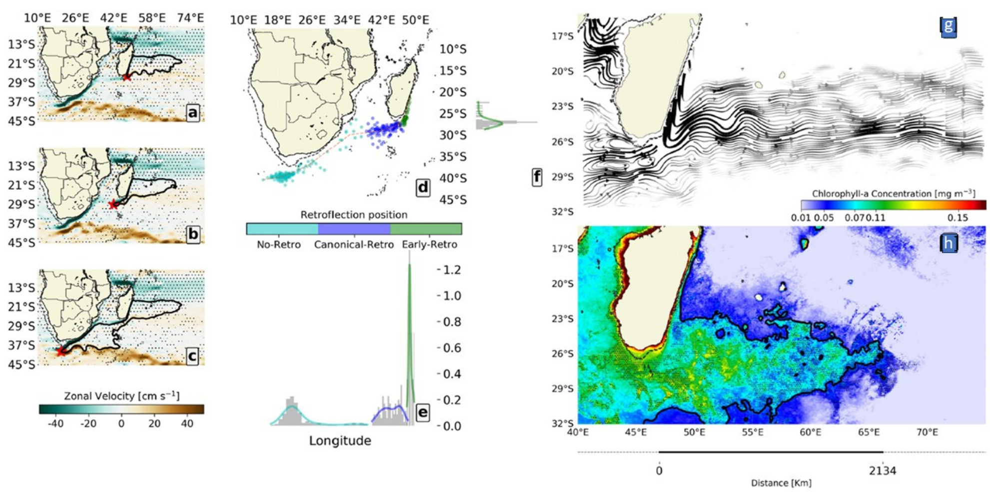

Figure 10. Spatial variability of the southern extension and retroflection of the South East Madagascar Current (SEMC) inferred from satellite altimetry. Panels a to c show composites of SEMC retroflection positions derived from satellite sea surface height (SSH). The black contour outlines the SEMC and its retroflection, while red stars indicate the westernmost point of the selected SSH contour, used here as a proxy for the retroflection location. Background shading shows composites of zonal surface velocity corresponding to each retroflection regime. Hatched black dots denote regions where anomalies are significant at the 95% confidence level based on a two-tailed Student's t-test. Panel (d) presents the spatial classification of SEMC retroflection

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positions obtained using unsupervised k-means clustering, with the dotted red line indicating the most likely retroflection location. Each classified retroflection case is used to construct the composites shown in panels a to c. Panel (e) shows the longitudinal distributions of the three identified retroflection regimes, while panel (f) shows the corresponding latitudinal distribution for the early retroflection case. Adapted from Ramanantsoa et al. (2021).

High-resolution regional modelling has further elucidated the dynamical controls on EMC variability and connectivity. Numerical experiments demonstrated that Madagascar's topography plays a central role in steering the flow, generating mesoscale variability, and regulating the partitioning of transport between the Mozambique Channel and downstream branches of the Agulhas system (Penven et al., 2006; Halo et al., 2014a). Energy conversion analyses revealed the coexistence of barotropic and baroclinic instabilities south of Madagascar, with spatially distinct regimes influencing eddy generation and downstream transport pathways (Halo et al., 2014b). More recent ultra-high-resolution simulations have highlighted strong vertical and seasonal variability in boundary currents and thermal fronts along shelves and island wakes, further refining understanding of EMC dynamics (Sudre et al., 2023; Penven et al., 2025a).

Emerging interdisciplinary studies have also begun to link physical variability in the EMC region to ecosystem responses. Mesoscale eddies south of Madagascar have been shown to influence nutrient distributions and biological productivity, structuring ecosystems from phytoplankton to top predators (Weimerskirch et al., 2004; Barlow et al., 2014). While still limited in scope, these studies represent a shift beyond the predominantly physical focus of pre-2006 research.

The East Madagascar Current is now considered to be a dynamically complex and intermittently connected component of the Greater Agulhas Current System. Although important questions remain regarding long-term variability and climate sensitivity, the fundamental structure and downstream role of the EMC are now substantially better understood than prior to 2006.

3.2. Mozambique Channel

The Mozambique Channel (MC) has historically been recognised as a key upstream source region of the Agulhas Current, yet it remained one of the least well constrained components of the Greater Agulhas Current System because of sparse in situ observations and strong mesoscale variability (Lutjeharms, 2006). Early conceptual models had postulated the existence of a persistent, spatially continuous southward boundary current along the Mozambican coast—the so-called Mozambique Current—but this hypothesis was increasingly questioned in the early 2000s.

Analyses combining hydrographic observations, direct current measurements, and satellite altimetry provided evidence that a coherent, continuous Mozambique Current does not exist. Instead, the circulation of the MC was shown to be dominated by large mesoscale eddies that propagate poleward through the channel and intermittently feed the Agulhas Current (de Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003). These findings fundamentally altered prevailing views of MC dynamics and suggested that upstream forcing of the Agulhas Current is highly variable in time, governed largely by eddies rather than by steady boundary flow (Lutjeharms, 2006).

Despite this conceptual advance, substantial uncertainty remained regarding the detailed structure and dynamics of the MC eddy field. Anticyclonic eddies were widely considered the dominant mesoscale feature, but the presence and significance of cyclonic eddies was disputed.

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In particular, it was argued that apparent cyclonic features identified in altimetric products could arise from artefacts associated with temporal averaging of sea-level anomaly fields rather than from persistent dynamical structures (de Ruijter et al., 2002). As a result, the full spectrum of eddy types, their generation mechanisms, and their vertical structure remained poorly resolved.

Connectivity between the MC and downstream components of the Agulhas system was also incompletely understood. While eddy propagation through the channel was recognised as a primary pathway linking the MC to the Agulhas Current, the degree to which this connection was continuous versus intermittent remained uncertain (de Ruijter et al., 2004; Lutjeharms, 2006). Questions persisted regarding how eddies interacted with channel bathymetry and the continental slope, how frequently they merged with or reinforced the Agulhas Current, and how reliably these processes could be inferred from the limited observational record available at the time.

By 2006, therefore, the Mozambique Channel was viewed as an energetic, eddy-dominated source region whose influence on the Agulhas Current was fundamentally intermittent rather than steady (de Ruijter et al., 2002; Ridderinkhof and de Ruijter, 2003; Lutjeharms, 2006). However, key aspects of the MC circulation—including the persistence of any mean boundary flow, the role of cyclonic versus anticyclonic eddies, and the sensitivity of MC variability to atmospheric and remote forcing—remained unresolved. These uncertainties were explicitly identified as priorities for future observational and modelling efforts aimed at quantifying the role of the MC within the Greater Agulhas Current System (Lutjeharms, 2006).

Over the past two decades, a combination of sustained in situ observations, improved satellite analyses, and high-resolution numerical modelling has fundamentally advanced understanding of circulation and variability in the Mozambique Channel (MC). These efforts have confirmed the eddy-dominated nature of the flow while resolving long-standing uncertainties regarding eddy populations, generation mechanisms, and downstream connectivity to the Agulhas Current.

The most significant observational advance has been the deployment of long-term mooring arrays in the MC, most notably the Long-term Ocean Climate Observation (LOCO) array. These sustained measurements provided the first continuous time series of velocity, temperature, and salinity across the channel, demonstrating unequivocally that the mean flow is not organised as a persistent boundary current but is instead dominated by strong mesoscale variability (Ullgren et al., 2012). The LOCO observations quantified the transport associated with individual eddies and revealed substantial variability on intraseasonal to interannual time scales, directly confirming interpretations previously inferred from satellite altimetry.

High-resolution satellite altimetry and eddy-tracking analyses have further refined understanding of the MC eddy field. These studies demonstrated that the channel hosts a diverse population of mesoscale eddies, including both anticyclonic and cyclonic structures, overturning earlier suggestions that cyclonic eddies were merely artefacts of data processing (Halo et al., 2014a). Eddy trajectories derived from altimetry showed consistent southwestward propagation pathways, with many eddies maintaining coherent structure over several months as they transit the channel and interact with the continental slope (Fig. 11; Halo et al., 2014a; Halo et al., 2014b). These results clarified how MC eddies intermittently feed the Agulhas Current and contribute to its variability.

Regional numerical modelling has played a central role in interpreting these observations and identifying the dynamical mechanisms governing MC variability. High-resolution simulations

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using ROMS_AGRIF, including the South West Indian Ocean Model (SWIM), successfully reproduced observed eddy trajectories, sizes, and lifetimes, lending confidence to their representation of MC dynamics (Fig. 11, middle panels; Halo et al., 2014a). Energy conversion analyses from these simulations revealed a coexistence of barotropic and baroclinic instabilities in the region, with spatially distinct regimes influencing eddy generation north and south of Madagascar (Halo et al., 2014b). More recent ultra-high-resolution simulations have further highlighted the strong vertical structure of MC eddies and their seasonal modulation, particularly along continental shelves and island wakes (Sudre et al., 2023; Penven et al., 2025a).

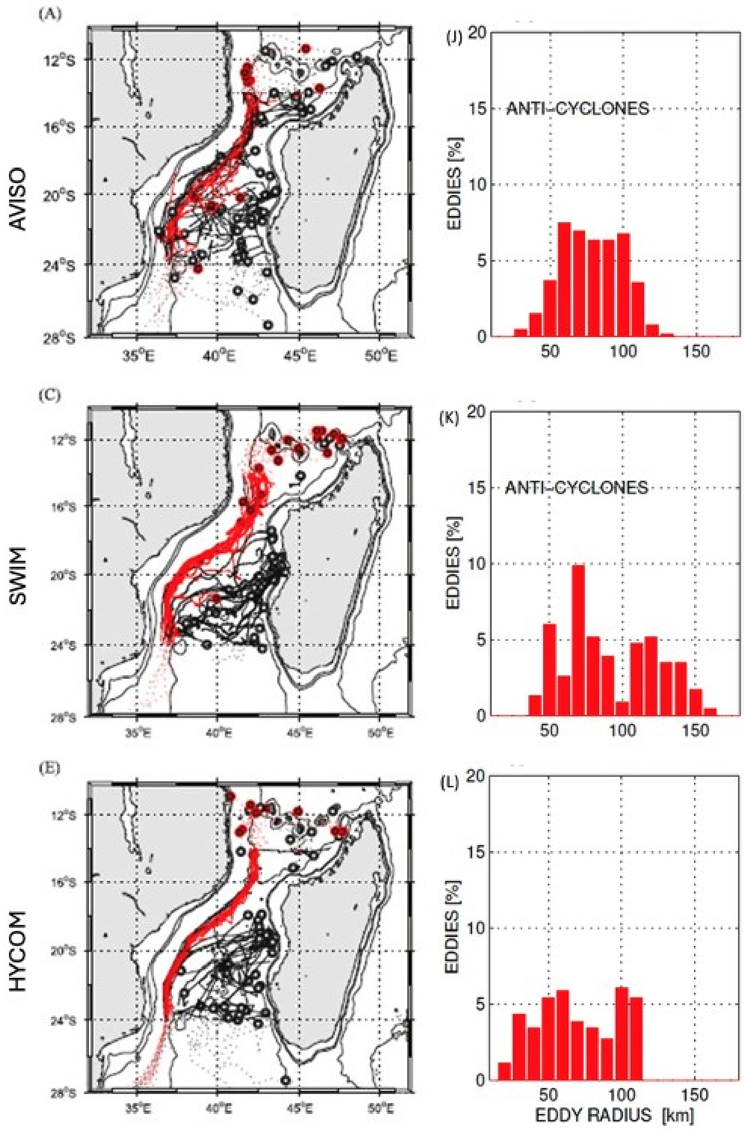

Figure 11. Eddy trajectories and size distributions in the Mozambique Channel derived from observations and numerical models. Left panels show eddy tracks identified from satellite

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altimetry (AVISO; top), the SWIM regional model simulation (middle), and the HYCOM simulation (bottom). Red trajectories highlight large anticyclonic Mozambique Channel rings with radii exceeding 100 km. Right panels show the corresponding probability density distributions of eddy radii for each dataset, binned in 10 km intervals. Adapted from Halo et al. (2014a).

Beyond physical circulation, post-2006 observational and modelling efforts have substantially advanced understanding of how mesoscale variability in the Mozambique Channel influences biological productivity and ecosystem structure. Regional multidisciplinary programmes, including ACEP, ASCLME, MESOP, MESOBIO, MadRidge, WIOURI, and RESILIENCE, have generated a growing body of hydrographic, biological, and biogeochemical observations that allow physical drivers of ecosystem variability in the Mozambique Channel and south of Madagascar to be more clearly identified (Vousden et al., 2012; Barlow et al., 2014; Halo et al., 2017). These studies consistently demonstrate that mesoscale eddies play a central role in structuring nutrient distributions, phytoplankton biomass, and higher trophic-level responses in the source regions of the Agulhas Current.

Coupled physical–biogeochemical modelling experiments using ROMS_AGRIF with the PISCES ecosystem model, developed within the MESOBIO programme, further underscored the importance of eddy history, topographic interactions, and lateral advection of coastal waters in shaping regional productivity patterns (José et al., 2014, 2016). These simulations showed that eddy-driven offshore transport of nutrient-rich coastal waters can enhance offshore productivity while simultaneously reducing nutrient availability near the coast, highlighting the dual role of mesoscale variability in redistributing biogeochemical resources. Similar conclusions have recently been corroborated by long-term, high-resolution simulations using the coupled CROCO–PISCES system, which further emphasised the persistence of eddy-driven modulation of productivity at seasonal to interannual time scales (Chenillat et al., 2024).

Along the Mozambican shelf, particularly over the Sofala Bank, ship based observations and high-resolution regional modelling have revealed a strong coupling between shelf dynamics, mesoscale variability, and ecosystem processes. The Sofala Bank supports a major penaeid shrimp fishery and is characterised by intense tidal currents, with barotropic velocities reaching 40–70 cm s^{-1}, giving rise to distinct inshore, shelf-break, and offshore hydrographic regimes (Chevane et al., 2016). High-resolution modelling studies indicate that mesoscale eddies modulate shelf circulation, hydrography, and the structure of river plumes, notably the bidirectional Zambezi River plume, although wind forcing and river discharge also exert a strong influence (Nehama and Reason, 2015; Malauene et al., 2018). Lagrangian individual-based modelling of shrimp larval dispersal further suggests that mesoscale eddies can have both detrimental and beneficial ecosystem impacts, with cold-core cyclonic eddies increasing larval mortality rates while simultaneously enabling long-distance dispersal and enhancing regional population connectivity (Malauene et al., 2024).

The Delagoa Bight is an ecologically and economically important shelf region off southern Mozambique, characterised by enhanced chlorophyll-a concentrations relative to adjacent open-ocean waters (Lutjeharms, 2006; Quartly and Srokosz, 2004). Circulation is dominated by a quasi-permanent cyclonic eddy trapped within the Bight, which promotes isopycnal doming, nutrient supply to the euphotic zone, and retention of biological productivity (Lutjeharms, 2006; Lamont et al., 2010; Cossa et al., 2016). Nearshore observations off Inhaca Island show strong seasonal variability, with maximum temperatures in austral summer and minima in winter, and elevated nutrients and reduced salinity associated with increased summer river discharge (Paula

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et al., 1998). Despite this, nearshore chlorophyll-a and zooplankton abundances are generally low, with seasonal peaks in September and March–April, suggesting that hydrographic conditions rather than river input dominate phytoplankton biomass variability across the Bight (Paula et al., 1998; Kyewalyanga et al., 2007). Early in situ studies reported chlorophyll-a concentrations of 0.6–1.26 mg m^{-3} and primary production rates of 0.6–1.0 g C m^{-2} day^{-1} or higher, indicative of mesotrophic conditions, with diatoms dominating cooler, nutrient-rich waters in the northeast and smaller flagellates elsewhere (Mitchell-Innes, 1967; Ryther et al., 1966; Mordasova, 1980; Barlow et al., 2008; Sá et al., 2013). However, observations remain sparse, satellite chlorophyll-a substantially underestimates in situ values, and the spatial and temporal variability of plankton biomass and its response to oceanographic forcing in the Delagoa Bight remain poorly quantified (Kyewalyanga et al., 2007; Lamont et al., 2018; Tew-Kai and Marsac, 2009).

With these findings, the channel is now recognised not only as an eddy-dominated dynamical source region of the Agulhas Current, but also as a region where physical–biological coupling strongly shapes productivity, fisheries, and connectivity at regional scales.

3.3. Northern Agulhas Current

Early hydrographic surveys, current-meter measurements, and satellite observations established the Northern Agulhas Current (NAC) as a narrow, intense western boundary current flowing southwestward along the southeast African continental margin (Gründlingh, 1979; Gründlingh, 1986; Lutjeharms and Valentine, 1988). The current was shown to be strongly constrained by the steep continental slope, resulting in a comparatively stable mean path relative to other western boundary currents, with limited lateral meandering over most of its upstream extent (Beal and Bryden, 1997; Beal and Bryden, 1999). Surface velocities frequently exceeded 2 m s^{-1} on the inshore edge of the current, and hydrographic sections revealed a strongly baroclinic structure with a warm, saline surface core overlying cooler intermediate waters (Gründlingh, 1986; Beal and Bryden, 1997).

Transport estimates derived from ship based sections indicated that the NAC carries the majority of the volume transport within the Greater Agulhas Current System, with values increasing downstream as additional source waters are incorporated (Beal and Bryden, 1999). However, the sparsity of repeated sections limited the ability to quantify temporal variability in transport or to resolve changes on seasonal to interannual time scales.

Mesoscale variability in the NAC was recognised as being spatially heterogeneous, with the Natal Bight identified as a key region of enhanced instability. In this region, the widening of the continental shelf permits the development of large offshore meanders known as Natal Pulses (Gründlingh, 1979; Lutjeharms and Roberts, 1988). These features propagate downstream at rates of approximately 10–20 km day^{-1} and are associated with deep-reaching cyclonic eddies embedded within the meander structure (Gründlingh and Pearce, 1984; Lutjeharms and Connell, 1989). Natal Pulses were recognised as the dominant expression of mesoscale variability in the NAC and were hypothesised to modulate downstream circulation, including the stability of the Agulhas Retroflection (Lutjeharms and van Ballegooyen, 1988; van Leeuwen et al., 2000).

Interactions between the NAC and the continental shelf were acknowledged as dynamically important but remained poorly constrained prior to 2006. Observations indicated intermittent shelf-edge upwelling, shear-edge eddies, and cross-shelf exchange, particularly in the Natal Bight and near Cape St Lucia (Gill and Schumann, 1979; Schumann, 1987; Lutjeharms and

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Meeuwis, 1987). However, the frequency, spatial structure, and driving mechanisms of these processes were difficult to resolve from the limited observational record available at the time.

Since 2006, sustained observations and improved satellite products have enabled the Northern Agulhas Current to be described in terms of its time-varying structure rather than only its mean path. Multi-year altimetric analyses provided new perspectives on the occurrence, surface expression, and propagation of Natal Pulses (Krug and Penven, 2011), while longer, more consistent records revealed a robust annual cycle in the Agulhas Current signal that had not been quantified previously (Krug and Tournadre, 2012). Parallel advances in satellite current retrievals, supported by comparisons with observed and virtual drifters, improved confidence in diagnosing surface variability along the Agulhas Current pathway (Krug et al., 2010; Hart-Davis et al., 2018).

A major advance has been the ability to observe and interpret the inshore edge of the current at much finer scales. The first buoyancy-glider deployments within the Agulhas Current revealed the ubiquitous presence of shear-generated submesoscale cyclonic eddies along the inshore boundary, demonstrating that energetic submesoscale variability is a persistent feature of the system (Krug et al., 2017). Subsequent glider experiments further resolved the fine-scale structure of the inshore front and quantified turbulence and mixing processes that are not captured by conventional moorings or standard satellite products (Krug et al., 2018; Pringle et al., 2022).

Recent observations combining satellite altimetry and surface drifters showed that mesoscale eddies originating from the Mozambique Channel and south of Madagascar typically dissipate upon approaching the northern Agulhas Current, transferring momentum to the boundary current rather than remaining coherent features. Anticyclonic eddies were found to locally accelerate the current core, while cyclonic eddies weaken the flow and promote offshore meanders, frequently associated with the development of Natal Pulses, highlighting the northern Agulhas Current as a significant sink of eddy kinetic energy (Braby et al., 2016).

Post-2006 research has also sharpened understanding of coastal and shelf circulation features adjacent to the NAC. Modelling studies identified the Natal Bight Coastal Counter-Current as a dynamically significant inshore flow, providing new insight into shelf–boundary current interactions and their variability (Fig. 12; Heye et al., 2022). In addition, targeted observational and modelling studies along the northeast South African margin, including Sodwana Bay, refined the role of bathymetry, mesoscale eddies, and upwelling processes in driving episodic cold-water events (Wells et al., 2021, 2024, 2025).

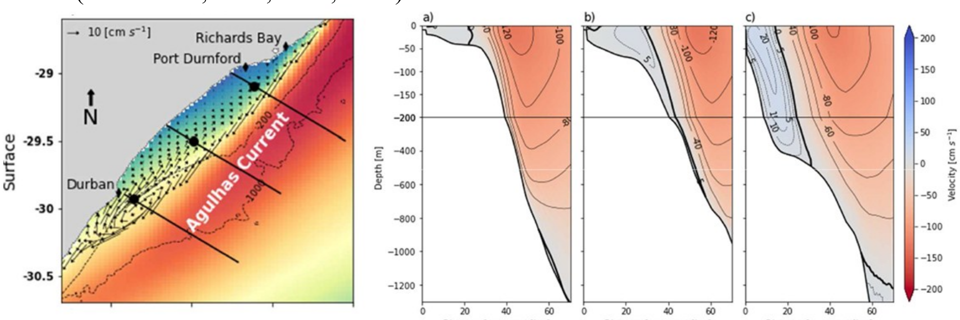

Figure 12. Model-derived mean surface circulation in the Natal Bight region, showing the northward-flowing Natal Bight Coastal Counter-Current (NBC3) inshore of the southward-

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flowing Agulhas Current. Black transect lines indicate the locations at which cross-shelf vertical sections of alongshore velocity were extracted. Panels (a–c) show the corresponding vertical sections for the northern, central, and southern transects, respectively. Adapted from Heye et al. (2022).

Beyond physical circulation, post-2006 observational programmes have substantially improved understanding of productivity and biogeochemical variability inshore of, and within, the Northern Agulhas Current. Ship based surveys along the Agulhas System Climate Array (ASCA) revealed that, despite its warm and saline character, the Agulhas Current supports levels of net primary production comparable to other western boundary currents, particularly during winter, with reported rates of 34–82 mmol C m^{-2} d^{-1} (Sinyanya et al., 2024). Enhanced productivity was consistently associated with mesoscale features, indicating that meanders, eddies, and frontal processes play a central role in nutrient supply to the euphotic zone. Satellite-based global primary production products yield similar ranges (Huang et al., 2021), although limited in situ observations constrain robust validation.

Recent studies further highlighted the role of the Agulhas Current as a conduit for biogeochemical signals originating in the tropical Indian Ocean. The warm, low-nutrient environment of the current provides favourable conditions for nitrogen fixation, with estimated N_2-fixation rates of 7–25 Tg N yr^{-1} across the greater Agulhas region (Marshall et al., 2023), contributing up to ~5 % of primary production during wintertime observations (Sinyanya et al., 2024). The isotopic imprint of nitrogen fixation has been proposed as a potential tracer of Agulhas water masses and their leakage into the South Atlantic (Granger et al., 2024).

Finally, new satellite-based and modelling studies have strengthened evidence that the Northern Agulhas Current is a regional air–sea interaction hotspot. High-resolution remote sensing analyses quantified the intensity and variability of latent heat fluxes over the current (Imbol et al., 2019), while modelling studies demonstrated that Agulhas Current variability can influence southern African precipitation, reinforcing the climate relevance of mesoscale SST and surface-flux anomalies associated with the NAC (Imbol et al., 2021).

3.4. Southern Agulhas Current

The Southern Agulhas Current (SAC), extending from approximately 34°S to the southern tip of Africa, has long been recognised as a dynamically distinct segment of the Agulhas Current system, exhibiting substantially enhanced variability relative to its northern counterpart. Early hydrographic surveys, current-meter measurements, and satellite observations demonstrated that as the current flows over the widening continental shelf and complex bathymetry of the Agulhas Bank, topographic steering weakens and mesoscale activity intensifies (Gründlingh, 1983; Lutjeharms and Roberts, 1988). This transition manifests as frequent meanders, filaments, and eddy formation, particularly along the inshore edge of the current.

Prior to 2006, studies showed that large-amplitude meanders generated along the southern segment can propagate downstream and strongly influence the stability and behaviour of the Agulhas Retroflection (Lutjeharms and van Ballegooyen, 1988; van Leeuwen et al., 2000). These findings established a causal link between SAC variability and retroflection instability, highlighting the importance of the southern current in preconditioning inter-ocean exchange. Hydrographic sections further confirmed that the SAC remains strongly baroclinic, with transport estimates broadly consistent with upstream values but exhibiting increased temporal variability (Gordon et al., 1987; Beal and Bryden, 1997, 1999). However, the episodic nature of these observations limited the ability to resolve seasonal to interannual variability.

Interactions between the SAC and the Agulhas Bank shelf were also recognised early as dynamically and ecologically important. Observations revealed episodic shelf-edge upwelling, cross-shelf exchange, and enhanced retention of shelf waters driven by current meanders, cyclonic eddies, and filaments (Boyd et al., 1992; Lutjeharms et al., 2000). Sea surface temperature analyses highlighted strong thermal variability across the Bank, reflecting the interplay between the Agulhas Current, shelf bathymetry, and atmospheric forcing (Shillington, 1998). Biological studies conducted prior to 2006 provided early evidence of physical–biological coupling, with enhanced phytoplankton biomass and primary production observed during upwelling events and periods of intensified mesoscale activity (Probyn et al., 1994; Pitcher et al., 1998). Despite these insights, the frequency, magnitude, and persistence of SAC-driven shelf processes remained poorly constrained due to limited temporal coverage.

Since 2006, high-resolution satellite altimetry and sea surface temperature analyses have demonstrated that mesoscale activity intensifies markedly downstream of the Agulhas Bank, with frequent large-amplitude meanders, filaments, and eddy shedding events (e.g. Fig. 7 middle panels; Krug et al., 2010; Russo et al., 2021). These datasets revealed coherent spatial patterns and temporal variability that were not resolvable from earlier synoptic observations, strengthening links between SAC variability, shelf interactions, and downstream circulation changes. Targeted process studies further refined understanding of shelf–slope exchange mechanisms. Using satellite observations combined with in situ measurements from autonomous platforms, Krug et al. (2014) showed that interactions between the Agulhas Current and the eastern margin of the Agulhas Bank drive strong, spatially structured cross-shelf exchange mediated by meanders, cyclonic eddies, and frontal instabilities. Along the Transkei shelf, similar interactions alternately induce upwelling and downwelling, uplifting nutrient-rich South Indian Central Water onto the shelf during meandering events while promoting offshore export during downwelling phases (Goschen et al., 2015; Lamont et al., 2016; Russo et al., 2019; Lamont et al., 2024a). Individual meanders differ substantially in their hydrographic impact, leading to pronounced spatial heterogeneity in physical and biological responses along the shelf (Russo et al., 2019).

The enhanced dynamical variability of the SAC has strong ecological and biogeochemical consequences, particularly along the Transkei shelf and the Agulhas Bank. Mesoscale meanders have been linked both to enhanced productivity through nutrient uplift and to losses of coastal biological communities through offshore advection (Porri et al., 2014; Heye et al., 2022; Jacobs et al., 2022b). Satellite-derived chlorophyll-a fields show only weak seasonal cycles along the east coast, reflecting rapid hydrographic variability that can obscure climatological signals (Lamont et al., 2018). In contrast, targeted in situ observations demonstrated that summer phytoplankton biomass can exceed winter values during meander-driven upwelling events, underscoring the limitations of satellite-only interpretations in this region (Russo et al., 2019).

Recent observations have also highlighted emerging biogeochemical concerns along the SAC. Shelf waters along the Transkei margin have been shown to be undersaturated with respect to dissolved oxygen, likely reflecting enhanced biological consumption associated with episodic productivity events (Russo et al., 2019). At larger scales, a modelling study identified a significant decline in surface dissolved oxygen concentrations within the Agulhas Current over the past two decades, attributed primarily to warming-induced reductions in oxygen solubility (Mashifane et al., 2025). Importantly, enhanced cross-frontal mixing during Agulhas meanders can intermittently increase the influence of Antarctic Intermediate Water along the continental

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slope, providing a potential re-oxygenation pathway for bottom shelf waters (Lamont et al., 2024a).

On the Agulhas Bank itself, sustained research since 2006 has revealed strong coupling between SAC variability, shelf hydrography, and ecosystem structure. Long-term temperature trends derived from observations and models indicate both multidecadal warming and episodic cooling events that have influenced the distribution of commercially important sardine and anchovy populations (Roy et al., 2007; Rouault et al., 2009; Malan et al., 2019; Lamont et al., 2024b). Shoreward advection of warm, saline Agulhas waters has been shown to suppress diatom growth while favouring dinoflagellates, occasionally leading to harmful algal blooms with negative impacts on fish condition (van der Lingen et al., 2016).

Lagrangian observations and numerical modelling since 2006 have further clarified the role of the SAC in regulating biological connectivity along the southern African margin. Drifter data and particle-tracking experiments demonstrated that material entrained into the core of the SAC is often rapidly advected offshore, reducing nearshore retention of eggs and larvae, while regions east of Cape Agulhas exhibit comparatively higher retention (Zardi et al., 2011; Lett et al., 2015; McGrath et al., 2020). Agulhas meanders can transport shelf-derived material tens of kilometres offshore, influencing population structure and connectivity across the shelf–slope system (Porri et al., 2014). These findings place the southern Agulhas Current as a dynamic boundary between retention-dominated and export-dominated regimes. East of Cape Agulhas, circulation supports larval transport and recruitment on the Agulhas Bank (Lett et al., 2006; Downey-Breedt et al., 2016; Jacobs et al., 2022b), whereas west of Cape Agulhas the system acts predominantly as a transport regime, feeding larvae and biota into the Benguela Upwelling System via shelf-edge jets such as the Benguela Jet (Veitch et al., 2018; Lett et al., 2024).

High-resolution regional modelling studies have played a central role in interpreting these observations and identifying the mechanisms underlying SAC variability. Models configured over the Agulhas Bank demonstrate that barotropic and baroclinic instabilities develop as the current flows over the widened shelf and complex bathymetry, generating meanders, shear-edge eddies, and filaments that enhance cross-shelf exchange and precondition the retroflection region (Penven et al., 2006; Loveday et al., 2014; Schubert et al., 2019). More recent simulations resolving submesoscale dynamics further highlight the importance of fine-scale processes in shaping SAC structure, variability, and energetics, reinforcing the need for very high-resolution approaches when assessing shelf interactions and downstream impacts.

In contrast to the relatively constrained Northern Agulhas Current, the Southern Agulhas Current is characterised by a marked increase in mesoscale variability as the flow interacts with the widened shelf and complex bathymetry of the Agulhas Bank. This transition fundamentally alters shelf–slope exchange, downstream circulation, and ecosystem connectivity, and plays a key role in preconditioning the Agulhas Retroflection.

3.5. Retroflection and Leakage

The Agulhas Retroflection, located near the southern tip of Africa, marks the point at which the Agulhas Current turns sharply back into the Indian Ocean and forms the eastward-flowing Agulhas Return Current, while intermittently exporting warm, saline Indian Ocean waters into the South Atlantic via rings, filaments, and other mesoscale structures (Gordon, 1986; Lutjeharms et al., 1992; Lutjeharms, 2006). This retroflecting configuration is central to Indian–Atlantic inter-ocean exchange because it governs both the partitioning of transport between the

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return flow and the leakage, and the form in which Indian Ocean properties enter the Cape Basin (Lutjeharms, 2006).

By the mid-1980s, a broad consensus had emerged that the Agulhas Current retroflects almost completely south of Africa, with most of its transport returning to the Indian Ocean and only a fraction entering the South Atlantic as Agulhas leakage (Gordon, 1985; Gordon et al., 1987). Subsequent observational and satellite-based studies demonstrated that this leakage occurs predominantly through the shedding of large Agulhas rings, which transport substantial volumes of thermocline and surface waters into the Cape Basin, with smaller contributions from filaments and intermittent direct exchange (Garzoli and Gordon, 1996; Goñi et al., 1997; Lutjeharms and Cooper, 1996). Together, these studies established the Agulhas system as a major conduit of heat and salt between the Indian and Atlantic Oceans.

Despite this qualitative understanding, early quantitative estimates of leakage magnitude remained highly uncertain. Hydrographic and inverted echo-sounder analyses suggested mean leakage transports on the order of several Sverdrups, but with strong temporal variability and substantial methodological dependence (Garzoli and Gordon, 1996). Satellite altimetry further revealed that individual Agulhas rings carry large heat and salt anomalies into the South Atlantic (Goñi et al., 1997), reinforcing the climatic significance of leakage events. However, the relative contributions of rings, filaments, and background flow, as well as the seasonal to interannual variability of leakage, could not be robustly constrained prior to 2006 because of limited observational coverage.

By 2006, a coherent conceptual model had emerged in which the retroflection loop undergoes repeated westward "progradation" events into the South Atlantic, terminating in ring shedding once the loop extends sufficiently far offshore (Lutjeharms and van Ballegooyen, 1988; Lutjeharms et al., 1992). These progradation–spawning cycles were inferred to operate on time scales of weeks, with gradual westward advance followed by abrupt ring detachment (Lutjeharms and van Ballegooyen, 1988; Lutjeharms, 2006). A key pre-2006 insight was that upstream variability can modulate ring formation: Natal Pulses reaching the retroflection region were frequently observed to precipitate ring shedding, although rings could also form in their absence, indicating a combination of intrinsic instability and upstream triggering (Lutjeharms and van Ballegooyen, 1988; Lutjeharms, 2006).

Agulhas rings were recognised as exceptionally energetic mesoscale vortices and as the primary mechanism of property transport into the South Atlantic (Olson and Evans, 1986; Gordon and Haxby, 1990; Byrne et al., 1995; Lutjeharms, 2006). Pre-2006 estimates of ring-mediated volume exchange varied widely across observational methods and reference levels, but commonly yielded values of order 0.5–3 Sv per ring (Olson and Evans, 1986; Gordon and Haxby, 1990; Byrne et al., 1995; Clement and Gordon, 1995), with much smaller contributions attributed to filaments in the limited cases quantified (Lutjeharms and Cooper, 1996; Lutjeharms, 2006). As a result, early syntheses emphasised that leakage could not be inferred from ring counts alone, because property fluxes depend on ring structure, depth penetration, decay pathways, and the cumulative contribution of non-ring exchange processes (Lutjeharms and Cooper, 1996; Lutjeharms, 2006).

The downstream fate of Agulhas rings was also an explicit pre-2006 uncertainty. Observational and modelling evidence indicated that rings can erode or split through interactions with bathymetric features such as the Erica and Vema seamounts, leading to divergent pathways and progressive modification of thermohaline properties through air–sea fluxes and ambient mixing

(Byrne et al., 1995; Lutjeharms, 2006). While some rings were observed to persist for several years, analyses of sea-surface-height anomalies suggested rapid dissipation in the Cape Basin for a substantial fraction of rings, implying that much of the leaked heat, salt, and vorticity may be absorbed locally and redistributed by mechanisms other than intact ring translation (Lutjeharms, 2006).

Finally, the retroflection–leakage system was recognised to be embedded within a broader, highly turbulent Cape Basin environment that includes cyclonic eddies (Cape Basin cyclones) arising from multiple sources, including Natal Pulse-associated cyclones and lee eddies shed from the Agulhas Bank (Lutjeharms, 2006). These features were thought to play an important role in the mixing, redistribution, and transformation of Agulhas waters after leakage, but their cumulative impact could not be quantified robustly with the observing system available prior to 2006.

Over the past two decades, progress has been driven by (i) longer and more consistent satellite records, (ii) sustained in situ measurements in key boundary-current and downstream regions, and (iii) high-resolution modelling capable of resolving the mesoscale and, increasingly, submesoscale structure that governs exchange. Within this framework, Agulhas leakage is now routinely treated as the combined export of Indian Ocean waters via rings, filaments, and other transient features rather than as ring shedding alone (Biastoch et al., 2024; Chelton et al., 2011).

A major focus of post-2006 work has been quantifying Agulhas leakage variability and its longer-term behaviour, given its relevance to the buoyancy structure of the southeast Atlantic and potential downstream impacts on the Atlantic Meridional Overturning Circulation (AMOC) (e.g. Weijer et al., 2002; Speich et al., 2009; Biastoch et al., 2015; Rühs et al., 2022). Observational analyses revealed that the Agulhas Current system has undergone pronounced thermodynamic change since the 1980s, with widespread warming of the Agulhas Current, the retroflection region, and the Agulhas Return Current inferred from satellite and in situ data (Rouault et al., 2009). This warming was interpreted as a basin-scale signal consistent with enhanced upper-ocean heat content and stratification, suggesting the potential for altered inter-ocean exchange. In parallel, satellite altimetry analyses demonstrated a significant intensification of mesoscale activity across the Greater Agulhas system. Using observations from 1993–2009, Backeberg et al. (2012) showed robust increases in eddy kinetic energy (EKE) in the Mozambique Channel, south of Madagascar, along the Agulhas Current pathway, and within the retroflection region, driven primarily by strengthened trade winds and an intensified South Equatorial Current.

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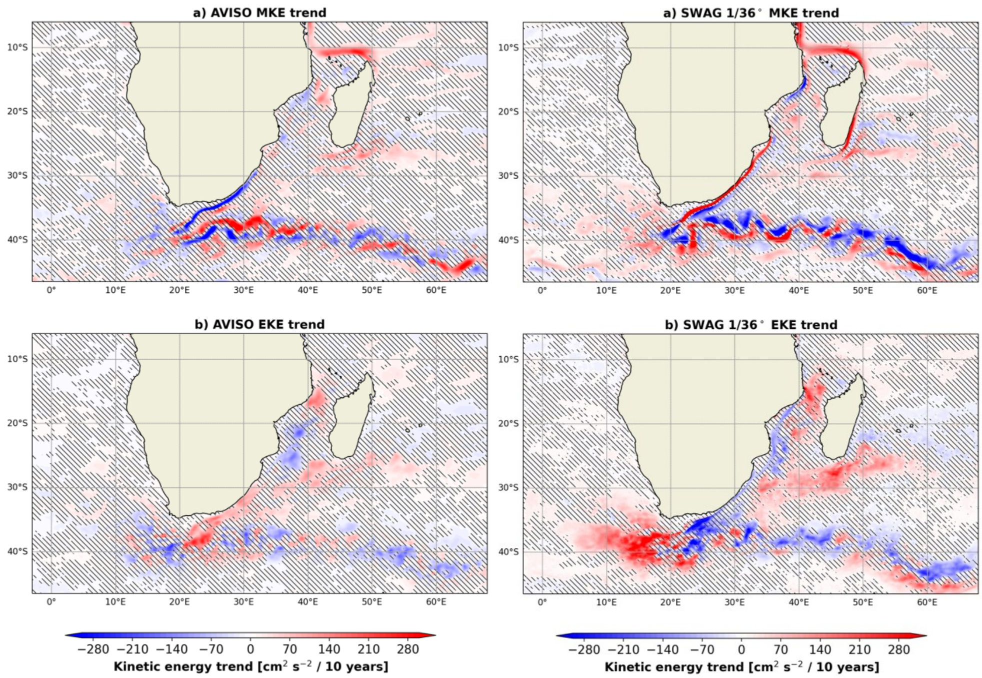

Figure 13. Linear decadal trends in mean kinetic energy (MKE; top panels) and eddy kinetic energy (EKE; bottom panels) over the period 1993–2018. Trends derived from satellite altimetry are shown in the left panels, while trends from the 1/36° CROCO regional simulation are shown in the right panels. Hatched regions indicate areas where trends are not statistically significant at the 95% confidence level. Adapted from Penven et al. (2025a).

More recently, Penven et al. (2025a) extended this trend analysis using a longer satellite altimetry record (1993–2018) and an ultra-high-resolution (1/36°) CROCO simulation (SWAG36), allowing a direct comparison between observed and modelled changes in both mean kinetic energy (MKE) and EKE (Fig. 13). Their results confirm that the intensification identified by Backeberg et al. (2012) persists over the extended period, but also reveal pronounced spatial heterogeneity. These findings imply a dynamical pathway through which increased mesoscale energy may modulate leakage via changes in ring shedding, filament export, and retroflection stability, even in the absence of a systematic shift in the mean retroflection position. Nevertheless, despite these advances, long-term trends in Agulhas leakage remain contested: some studies report increased leakage since the mid-1960s with enhanced export during the 1990s–2000s (Schwarzkopf et al., 2019), whereas others find no significant long-term trend or suggest stabilisation since the 1990s (Biastoch et al., 2015; Schmidt et al., 2021). This divergence highlights the sensitivity of leakage estimates to the diagnostic framework employed (Eulerian versus Lagrangian), the temporal window considered, and the ability of models to resolve the nonlinear mesoscale processes governing exchange at the retroflection.

Interactions between leaked Agulhas waters and the Benguela Upwelling System (BUS) have also been documented as an important cross-system coupling mechanism. Rings and filaments can enhance offshore export of nutrient- and biota-rich shelf waters into the open ocean (Duncombe-Rae et al., 1992) and drive episodic shoreward intrusions of warm Agulhas waters onto the shelf within the BUS (Baker-Yeboah et al., 2010; van der Lingen et al., 2016).

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Lagrangian evidence further illustrates the scale of along-margin connectivity: surface drifters deployed in the KZN Bight have been observed to enter the South Atlantic, with trajectories ranging from offshore Cape Basin pathways to more shelf-confined routes extending as far north as Cape Columbine (Guastella and Roberts, 2016). Complementary examples from pollution-dispersion case studies (e.g., nurdle transport following a Durban harbour spill) similarly reinforce that the Agulhas system can connect widely separated coastal and shelf environments along southern Africa on time scales of weeks to months (Schumann et al., 2019).

Beyond physical connectivity, the ecological interpretation of leakage remains actively debated. Some studies suggest that the episodic nature of leakage can act as a biological barrier that limits plankton dispersal and contributes to lower diversity in the South Atlantic relative to the South Indian Ocean (Villar et al., 2015). In contrast, other work demonstrates effective biological linkage across basins, including inferred connectivity between southern Indian and South Atlantic rock lobster populations and Lagrangian transport pathways capable of carrying turtle hatchlings and mangrove propagules into the South Atlantic (Le Gouvello et al., 2020; Silva et al., 2021; Raw et al., 2023). These apparently divergent perspectives are not mutually exclusive: they emphasise that leakage can be simultaneously intermittent (limiting continuous dispersal for some taxa) and, when active, an efficient pathway for episodic long-distance transport.

Overall, research over the past two decades has preserved the core pre-2006 conceptual picture of a retroflecting current that intermittently sheds rings and filaments, while substantially sharpening understanding of (i) the multiple pathways and controls on leakage (not ring-only), (ii) the rapid transformation and mixing of leaked waters within the Cape Basin, and (iii) the diverse ecological consequences of intermittent inter-ocean exchange. As discussed in Sect 3.3–3.4, a persistent theme is that upstream and along-path variability—including Natal Pulses and Southern Agulhas Current instabilities—can modulate the timing and character of retroflection variability and thus the form and magnitude of Agulhas leakage.

3.6. Agulhas Return Current

Prior to 2006, the Agulhas Return Current (ARC) was recognised as the eastward-flowing limb of the South Indian Ocean subtropical gyre and as the principal pathway by which Agulhas Current waters return to the Indian Ocean following retroflection south of Africa (Lutjeharms et al., 1984; Stramma and Lutjeharms, 1997). The ARC was understood to form the dynamical connection between the South Atlantic Current and the South Indian Ocean Current, flowing broadly along the Subtropical Convergence and contributing to water-mass exchange between the two basins (Lutjeharms and Ansorge, 2001).

By the late 1980s and early 1990s, it had become widely accepted that the Agulhas Current retroflects almost completely south of Africa, such that only a small fraction of its waters enter the South Atlantic directly. Instead, inter-ocean exchange was recognised to occur primarily through the shedding of large Agulhas rings and, to a lesser extent, through Agulhas filaments, while the majority of the Agulhas Current transport feeds the ARC (Gordon, 1985; Gordon et al., 1987; Lutjeharms and van Ballegooyen, 1988; van Ballegooyen et al., 1994; Lutjeharms and Cooper, 1996).

Hydrographic sections, surface drifter trajectories, and early satellite altimetry provided the primary observational basis for describing the structure and pathway of the ARC. These studies showed a predominantly zonal eastward flow centred near 39–40° S south of Africa, with a gradual southward displacement downstream, interrupted by substantial meridional excursions associated with interactions with bottom topography, particularly over major meridional ridges

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such as the Agulhas Plateau (Gründlingh, 1978; Daniault and Ménard, 1985; Lutjeharms and van Ballegooyen, 1984; Lutjeharms and Ansorge, 2001). The region was known to be characterised by intense mesoscale variability, including recurrent eddy generation and pronounced meandering of the ARC along the Subtropical Convergence (Cheney et al., 1983; Lutjeharms and Valentine, 1988).

Quantitative estimates of ARC velocity and transport varied widely among pre-2006 studies. Geostrophic calculations based on hydrographic sections suggested a marked downstream decrease in both velocity and volume transport, with values declining from several tens of Sverdrups near the Agulhas Retroflection to substantially weaker transports farther east (Gründlingh, 1985; Stramma and Lutjeharms, 1997; Lutjeharms and Ansorge, 2001). Water-mass analyses demonstrated that temperature and salinity characteristics associated with Agulhas Current waters could be traced well into the South West Indian Ocean, although the degree of downstream coherence remained debated (Belkin and Gordon, 1996; Park et al., 1991, 1993).

A key unresolved issue prior to 2006 concerned the eastern termination and downstream persistence of the ARC. Some studies argued that Agulhas-derived waters remained coherent beyond 70° E, based on hydrographic and water-mass evidence (Belkin and Gordon, 1996; Park et al., 1991, 1993), while others suggested substantial branching and dissipation farther west, implying that the ARC weakened rapidly downstream (Veronis, 1973; Stramma, 1992; Stramma and Lutjeharms, 1997). As a result, there was no consensus on how far east the ARC remained a coherent dynamical feature, or on the rate at which its transport diminished along its path.

Although air–sea interaction and mixing processes were recognised as important modifiers of Agulhas water properties within the ARC—particularly in the vicinity of the retroflection, where large heat losses and excess evaporation were documented (Mey and Walker, 1990)—the relative roles of surface forcing, topographic steering, and upstream variability in controlling ARC structure and variability could not be robustly quantified. This limitation reflected the reliance on spatially sparse hydrographic snapshots and Lagrangian observations, and the absence of sustained measurements capable of resolving seasonal to interannual variability along the ARC.

Since 2006, sustained satellite altimetry, improved atmospheric reanalysis products, and eddy-resolving numerical models have enabled more quantitative assessments of the Agulhas Return Current (ARC) than were previously possible.

Using satellite altimetry spanning 1993–2020 in combination with ERA5 atmospheric reanalysis and HYCOM model reanalysis, Lin et al. (2023) presented the most comprehensive analysis to date of ARC dynamics. Their results demonstrate that the ARC exhibits pronounced spatial heterogeneity, with distinct dynamical regimes in its western and eastern sectors. The western ARC (approximately 35–48° E), immediately downstream of the Agulhas Retroflection, is characterised by elevated eddy kinetic energy (EKE) associated primarily with strong flow–topography interactions. In contrast, variability in the eastern ARC (approximately 48–70° E) is more strongly influenced by interactions with the Antarctic Circumpolar Current and large-scale wind forcing, leading to different modes of variability across the basin.

Lin et al. (2023) report a statistically significant northward migration of the western ARC and a southward migration of the eastern ARC over the satellite era, resulting in a zonal tilting of the ARC axis. Such changes could not be robustly assessed prior to 2006 because of insufficient temporal coverage and observational density.

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The dynamical role of ARC meanders in modulating Agulhas Retroflection behaviour is also better understood. Numerical modelling studies have shown that large-amplitude ARC meanders and northward excursions can act as precursors to early retroflection events, influencing the timing and geometry of the Agulhas Current separation from the continental margin. Biastoch et al. (2008) identified ARC meanders as a key contributor to early retroflection dynamics, while Johannessen et al. (2020) further demonstrated that the interaction between a large ARC meander and an inshore cyclonic eddy can promote early retroflection, often in conjunction with upstream Natal Pulse activity.

Satellite-based eddy censuses have further documented eddy shedding along the ARC, complementing earlier observations of mesoscale activity. Analyses of multi-sensor satellite datasets indicate that mesoscale eddies frequently detach not only in the retroflection region but also along the ARC pathway, with some eddies subsequently re-merging with the mean flow while others propagate into the interior of the South West Indian Ocean (Casanova-Masjoan et al., 2017; Guerra et al., 2018).

Direct in situ observations of the ARC remain limited, but recent targeted measurements have begun to address this gap. Using data from NOAA Ocean Climate Stations deployed along the northern boundary of the ARC between November 2010 and March 2011, Braby et al. (2025) investigated air–sea interaction processes and assessed the performance of satellite-derived and reanalysis sea surface temperature products. Their analysis (Fig. 14) revealed substantial SST biases in reanalysis and infrared-only satellite products, particularly under conditions of high cloud cover, highlighting persistent observational challenges in the ARC region and emphasising the need for caution when interpreting long-term variability derived solely from remotely sensed datasets.

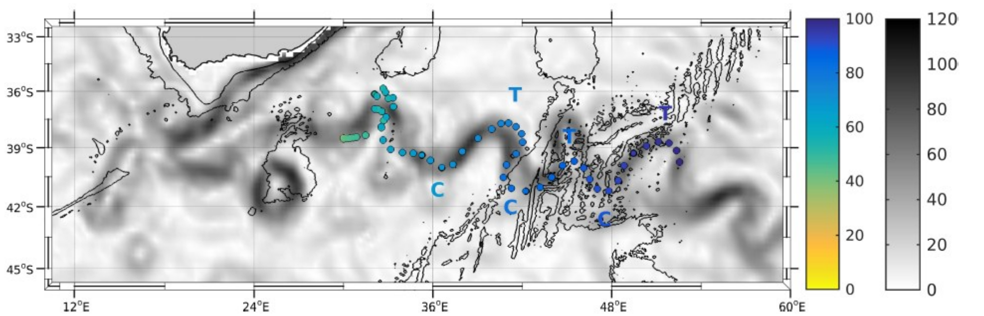

Figure 14. Position of the air–sea flux moorings on the path of the Agulhas Return Current. Grey shading indicates the mean geostrophic current speeds in cm s^{-1} over the time of the deployment, averaged from 30 November 2010 to 8 March 2011. Circles show the position of the mooring and indicate the number of days since deployment (note that the mooring was stationary until 16 January 2011). Thin black contours show the bathymetry at 200 and 3000 m. Letters "T" represent the times, after the mooring had broken loose, where the mooring passes through troughs of Agulhas Return Current meanders, whereas letters "C" represent it passing through the crests of the current (Adapted by Braby et al., 2025).

3.7. Role in the regional and global climate system

On the basis of its salt and heat fluxes, the Agulhas system was hypothesised to influence the strength and stability of the Atlantic Meridional Overturning Circulation (AMOC) through salt compensation of the Atlantic basin. Early numerical modelling studies demonstrated that variations in Agulhas leakage could modify the salinity of the upper South Atlantic and thereby

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affect deep water formation in the North Atlantic (e.g. Weijer et al., 1999). These studies established a conceptual framework in which increased leakage enhanced AMOC strength, while reduced leakage weakened it. Importantly, these links were model-based and highly idealised, and were not supported by direct observational evidence. The sensitivity of the AMOC to Agulhas leakage was shown to depend strongly on model configuration, background stratification, and atmospheric forcing, leading to substantial uncertainty in the magnitude and timescale of the response (Weijer et al., 1999; Biastoch et al., 2003).

In parallel, the Agulhas Current and its extension regions were recognised as sites of exceptionally strong air–sea heat and moisture fluxes, owing to the large sea-surface temperature gradients between warm Agulhas waters and the overlying atmosphere. Observational studies documented mean wintertime heat losses exceeding 200 W m^{-2} in the retroflection region, indicating intense local coupling between the ocean and atmosphere (Mey and Walker, 1990). Subsequent analyses suggested that these fluxes could influence regional atmospheric circulation and storm development south of Africa (Rouault et al., 2003). However, pre-2006 atmospheric reanalysis products were shown to substantially underestimate latent and sensible heat fluxes over the Agulhas Current, limiting confidence in climate-scale assessments of air–sea coupling in this region (Rouault et al., 2003).

Several studies prior to 2006 explored potential links between Agulhas system variability and regional climate, particularly over southern Africa. Statistical associations were reported between sea-surface temperature anomalies in the southwest Indian Ocean and summer rainfall variability over parts of South Africa (Mason, 1990; Walker, 1990; Reason, 2001). More specifically, relationships were identified between coastal rainfall and the proximity of the Agulhas Current to the east coast of South Africa (Jury et al., 1993). Atmospheric general circulation model experiments forced with idealised SST anomalies in the Agulhas system provided further support for a potential influence on regional rainfall through modifications of low-level circulation, atmospheric instability, and moisture fluxes (Reason and Mulenga, 1999; Reason, 2001). Nevertheless, these relationships were largely correlative, and the relative roles of oceanic forcing versus large-scale atmospheric variability remained unresolved.

A major post-2006 advance has been the improved observational constraint on the transport variability of the Agulhas Current and its leakage, enabled by sustained mooring arrays and coordinated observing programmes. The Agulhas Current Time-series (ACT) provided the first long-term, continuous measurements of Agulhas Current transport, revealing strong variability on sub-annual to interannual timescales and demonstrating that snapshot hydrographic estimates substantially underestimate this variability (Beal et al., 2011; Beal et al., 2015). Complementary observations from the Agulhas System Climate Array (ASCA) and SAMBA further supported improved estimates of variability in the downstream export of Indian Ocean waters into the South Atlantic (Elipot and Beal, 2015; McMonigal et al., 2020).

High-resolution modelling studies since 2006 have demonstrated that Agulhas leakage is sensitive to changes in Southern Hemisphere wind patterns, particularly shifts in the westerlies. Eddy-resolving simulations showed that poleward intensification and strengthening of westerly winds enhance leakage by modifying the latitude and stability of the Agulhas Retroflection (Biastoch et al., 2009; Biastoch and Böning, 2013). Subsequent work extended this framework by explicitly linking increased leakage to anthropogenic wind trends, suggesting that human-induced climate change may already be influencing Indo-Atlantic exchange (Biastoch et al., 2015). More recent synthesis studies have reinforced the view that the Greater Agulhas Current

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System acts as a dynamically sensitive gateway in the global circulation, capable of responding rapidly to basin-scale atmospheric forcing (Beal et al., 2011; Biastoch et al., 2024).

Post-2006 modelling studies have also continued to support the physical plausibility of a linkage between Agulhas leakage variability and the AMOC. Eddy-resolving experiments indicate that enhanced leakage increases salinity in the upper South Atlantic, strengthening the upper limb of the overturning circulation, while reduced leakage produces the opposite effect (Biastoch et al., 2009; Biastoch et al., 2015). Longer integrations suggest that such anomalies can propagate into the Atlantic basin on decadal timescales (Biastoch et al., 2024), although direct observational confirmation remains lacking.

At the regional scale, post-2006 advances have substantially clarified the processes by which the Agulhas Current system influences weather and climate over southern Africa. High-resolution regional atmospheric modelling studies demonstrated that extreme rainfall events along the east and south coasts of South Africa are often associated with strong latent heat fluxes from the Agulhas Current, low-level jets transporting moisture onshore, and uplift over coastal orography (Singleton and Reason, 2006, 2007; Blamey and Reason, 2009). These studies showed that the Agulhas system primarily acts to intensify pre-existing weather systems, rather than generating rainfall independently.

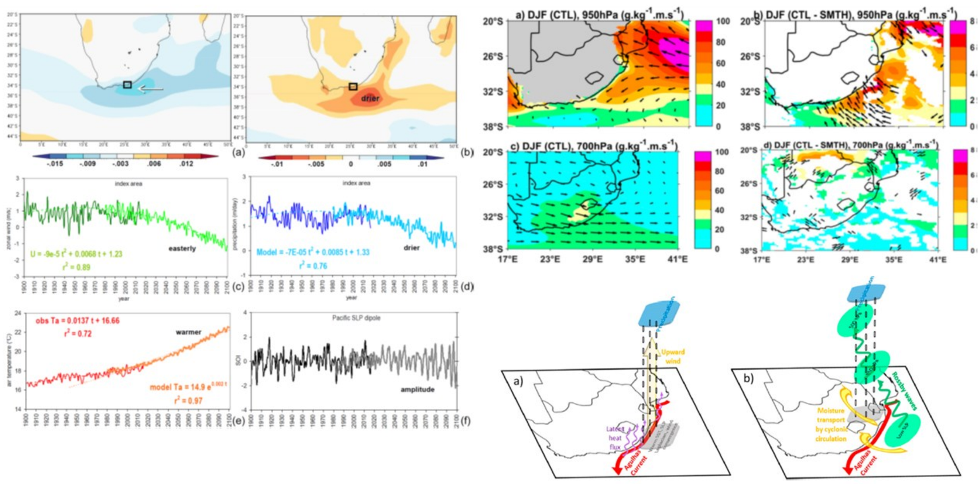

Figure 15. Climate-scale and regional atmospheric responses associated with the Agulhas Current system. Left panels: ECMWF-derived long-term trends (1980–2100, RCP8.5) in (a) zonal wind and (b) precipitation, together with time series of area-averaged (c) zonal wind, (d) precipitation, and (e) air temperature from ECMWF-20C reanalysis (1900–2010) and ECMWF-ESM projections (1980–2100). Panel (f) shows observed and projected Pacific Southern Oscillation Index variability; best-fit trends are indicated and time series are annual means (adapted from Jury et al., 2020). Upper right panels: Moisture flux from WRF control simulations at 950 and 750 hPa, with corresponding moisture flux differences; shading denotes regions significant at the 90% level and arrows indicate moisture transport anomalies (adapted from Nkwinkwa et al., 2021). Lower panels: Schematic mechanisms linking the Agulhas Current to precipitation, illustrating (a) enhanced maritime rainfall over the current due to strong latent heat fluxes and low-level convergence, and (b) inland rainfall driven by onshore moisture transport and cyclonic circulation, most pronounced in summer but also evident in autumn and spring (adapted from Nkwinkwa et al., 2021).

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Seasonal-scale regional climate simulations further indicated that the atmospheric response to the Agulhas system can be interpreted as a quasi-linear response to diabatic heating associated with warm SSTs in the current, with signatures extending throughout the troposphere (Figure 15; Njouodo et al., 2018; Imbol Nkwinkwa et al., 2021; Desbiolles et al., 2018). Global and regional modelling studies also suggested that anomalously warm Agulhas waters can influence the strength and structure of extratropical cyclones tracking south of Africa, with potential downstream impacts extending into the southern mid-latitudes (Reason, 2001; Nakamura, 2012).

Air–sea interaction over the Agulhas system was thus reframed as a climate-scale modelling challenge rather than a purely regional phenomenon. Improved satellite flux products and reanalysis comparisons revealed that, while representation of surface heat and momentum fluxes has improved since pre-2006 products, significant biases persist over strong currents and frontal zones (Rouault et al., 2009). Targeted mooring observations along the Agulhas Return Current further demonstrated systematic SST biases in reanalysis and infrared-only satellite products under conditions of high cloud cover, highlighting the sensitivity of regional atmospheric analyses to accurate representation of the ocean state (Braby et al., 2025).

4. Summary and conclusions

This review has synthesised advances in understanding of the Greater Agulhas Current System (GACS) over the past two decades, motivated in large part by the substantial knowledge gaps identified by Lutjeharms (2006). At that time, fundamental uncertainties persisted across the source regions, the Agulhas Current itself, and its downstream outflows, reflecting limitations in sustained observations, satellite capabilities, and numerical modelling. Since then, significant progress has been achieved through expanded in situ observing systems, improved satellite remote sensing, and increasingly high-resolution and physically realistic numerical models.

At the upstream sources of the Agulhas Current, several long-standing questions are now better understood. In the Mozambique Channel, early debate concerning the existence of a persistent southward Mozambique Current has been revisited using long-term mooring arrays, satellite altimetry, and high-resolution modelling. The weight of evidence now supports an eddy-dominated circulation rather than a continuous boundary current, with both anticyclonic and cyclonic eddies contributing intermittently to downstream transport. In particular, the existence and dynamical significance of cyclonic eddies, previously questioned as possible artefacts of altimetric averaging, have been firmly established. While some ambiguity remains regarding the presence of weak or intermittent coastal flows under specific conditions, the primary control of mesoscale eddies on transport through the channel is now well established.

South of Madagascar, one of the most contentious debates identified by Lutjeharms (2006): the existence of a retroflection of the southern extension of the South East Madagascar Current (SEMC), has largely been resolved. Subsequent observational and modelling studies have demonstrated that eastward flow in this region is better attributed to the South Indian Counter Current (SICC) rather than a persistent SEMC retroflection, effectively closing the so-called “retro-fiction” debate. However, this resolution has also highlighted the complexity of circulation south of Madagascar, where multiple currents coexist and interact, and where connectivity between the SEMC, the Mozambique Channel, and the Agulhas Current is highly variable and often mediated by mesoscale eddies and dipoles. While understanding of Madagascar’s role as a dynamical obstacle has improved, particularly through sensitivity

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modelling studies, the relative importance of continuous versus intermittent pathways remains an active area of research.

In the northern Agulhas Current, research over the past two decades has clarified the role of upstream variability associated with mesoscale eddies originating in the Mozambique Channel and south of Madagascar, which intermittently feed into and modulate the current. Mooring arrays, high-resolution Argo float deployments, and satellite altimetry have demonstrated that variability in transport, lateral position, and intensity of the northern Agulhas Current is strongly influenced by eddy–current interactions rather than by steady upstream inflow alone. These studies have largely addressed early uncertainties regarding the degree to which the current is continuously supplied by its source regions, although quantifying the relative contributions of different source pathways remains an ongoing challenge.

Knowledge developments in the southern Agulhas Current have centered around resolving temporal variability, mesoscale structure, and interactions with the continental slope and atmosphere. Long-term moored observations from the Agulhas Current Time-series (ACT) and Agulhas System Climate Array (ASCA) have provided unprecedented insight into transport variability, vertical structure, and the frequency of extreme events such as large meanders and Natal Pulses. These observations, complemented by satellite-based methods for objectively tracking the current core and edges, have refined understanding of how variability in the southern Agulhas Current preconditions the retroflection and influences Agulhas leakage. Despite these advances, uncertainties remain regarding long-term trends in transport, the response of the current to changing wind forcing, and the extent to which observed variability reflects natural versus anthropogenically forced changes, underscoring the continued need for sustained observations

Downstream of the Agulhas Current, important progress has also been made, though several questions remain open. The structure and variability of the Agulhas Return Current (ARC) are now better documented, and its interactions with major bathymetric features, including the Southwest and Southeast Indian Ridges, the Madagascar Ridge, and the Agulhas Plateau, have been increasingly explored using observations and models. Nevertheless, uncertainties persist regarding how ARC waters are transferred back into the subtropical gyre, the extent to which the ARC recirculates water toward the Agulhas Current, and the mechanisms governing its temporal variability.

With respect to Agulhas leakage, two decades of research have substantially advanced understanding of ring shedding, propagation, and decay, as well as the role of leakage in inter-ocean exchange and its potential influence on the Atlantic Meridional Overturning Circulation. However, several of the questions posed by Lutjeharms (2006) remain only partially answered. These include how Agulhas rings of differing size, structure, and vertical extent redistribute heat, salt, and vorticity in the South Atlantic; the role of atmospheric forcing and convective overturning in modifying ring evolution; and the sensitivity of leakage magnitude and ring shedding frequency to changes in wind forcing over the southwest Indian Ocean. Addressing these questions remains central to understanding the climate relevance of the GACS.

A major development since 2006 has been the identification of several previously unknown currents. These include the South Indian Counter Current (SICC), now recognised as a multi-branched eastward flow south of Madagascar; the East Madagascar Undercurrent (EMUC), a northward-flowing undercurrent beneath the East Madagascar Current; the Southwest Madagascar Coastal Current (SMACC), a narrow poleward flow along the southern Madagascar

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shelf; and the Natal Bight Coastal Counter Current (NBC3), a weak but dynamically significant northeastward flow along the KwaZulu-Natal shelf. These discoveries have refined our understanding of circulation pathways, vertical structure, and coastal–open-ocean connectivity within the GACS, and have highlighted the importance of resolving shelf and undercurrent processes alongside the major boundary currents.

The advances synthesised in this review are summarised schematically in an updated conceptual representation of the Greater Agulhas Current System (Fig. 16). The figure integrates contemporary understanding of the major boundary currents, newly identified currents, mesoscale and submesoscale features, and key regions of biological productivity, highlighting both resolved circulation pathways and areas of continued uncertainty. In particular, it reflects improved knowledge of upstream source regions, eddy-mediated connectivity, the structure and variability of the Agulhas Current and its downstream extensions, and the spatial coupling between physical dynamics and ecosystem responses. This updated schematic provides a consolidated, system-wide view of the GACS as currently understood, and serves as a reference framework for identifying remaining knowledge gaps and guiding future observational and modelling efforts.

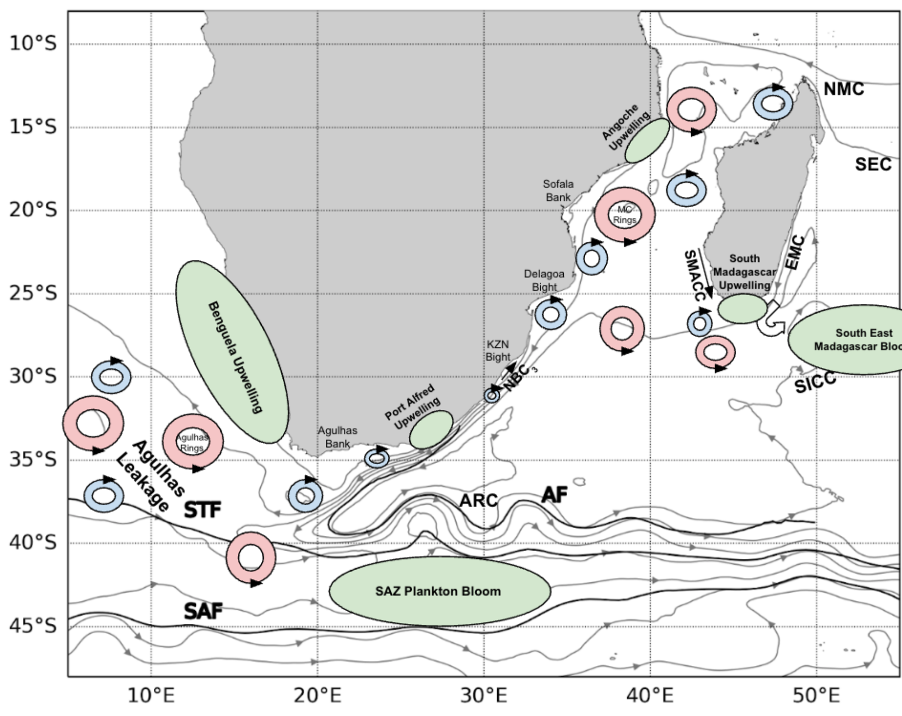

Figure 16. Updated schematic of the Greater Agulhas Current System, synthesising advances in understanding of circulation pathways, mesoscale and submesoscale features, and regions of enhanced biological activity identified over the past two decades. The schematic highlights major boundary currents, newly identified currents, dominant eddy structures, frontal systems, and key areas of productivity, providing an integrated conceptual overview of the physical and biophysical components of the system.

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4.1. Proposed future directions

Over the past two decades, inter- and multidisciplinary research within the Greater Agulhas Current System (GACS) has driven major advances in observational capability, numerical modelling, and understanding of the system's physical, climatic, and ecological roles. The integration of satellite remote sensing, long-term mooring arrays, advanced Argo float and glider technologies, and high-resolution coupled regional models has fundamentally transformed knowledge of the Agulhas Current and its variability. Large international collaborative initiatives, including ASCA, ACEP and SAMOC, have addressed many of the key gaps identified by Lutjeharms (2006), while simultaneously revealing a far greater complexity in the system's multi-scale dynamics, climate influence, and inter-ocean exchanges than previously recognised. Despite this progress, substantial challenges and knowledge gaps remain.

A critical priority for future research is the improved observation and representation of submesoscale and fine-scale processes, which remain poorly resolved by both existing observing systems and numerical models. These processes are expected to play a central role in vertical and horizontal mixing, the modulation of Agulhas leakage, and the seasonal to decadal variability of the system, as well as in associated biogeochemical fluxes. Capturing the transfer of energy across spatial scales, from submesoscale to mesoscale features such as eddies, meanders, and Natal Pulses, will require sustained ultra-high-resolution in situ observations combined with nested and coupled modelling approaches. At present, many dynamically important phenomena, including Agulhas meanders, Natal Pulses and retroflection shifts, remain sparsely sampled in situ, with their internal structures largely inferred from models rather than directly observed.

These scientific challenges are compounded by persistent logistical and financial constraints. Rising operational costs, limited personnel, and intermittent funding have restricted the continuity of long-term, high-frequency observations, limiting the ability to quantify transient processes and detect multi-decadal trends. Addressing these limitations will require strategic investment in modernising and expanding ocean observing infrastructure, including sustained moored arrays, increased deployment of autonomous platforms such as gliders and biogeochemical Argo floats, and continued access to satellite missions with improved spatial resolution and measurement accuracy. Innovative public–private partnerships and cost-effective approaches, such as integrating sensors onto fishing gear and supporting citizen-science initiatives, offer promising pathways to enhance coastal observations while increasing societal engagement and stakeholder value.

Equally important is sustained investment in human capacity development. The growing volume and complexity of data generated by modern observing systems demand a highly skilled technical and scientific workforce capable of maintaining instruments, analysing observations, and integrating data across disciplines. Programmes such as SEAmester provide essential early exposure to sea-going research and the Agulhas system, but must be complemented by long-term training, mentorship, and career development pathways. Strengthening technical and scientific expertise is particularly critical in the context of climate change, increasing resource pressures, and highly competitive funding environments, where advanced infrastructure alone is insufficient without the capacity to fully exploit it.

Finally, the future trajectory of Agulhas Current research will depend on coordinated governance and sustained commitment from national, regional, and international stakeholders. Recognising the Agulhas Current system as a strategic natural asset, central to climate regulation, ecosystem productivity, and global overturning circulation, should underpin stable funding for long-term observations, acquisition of state-of-the-art technology, and retention of skilled personnel. The next two decades represent a pivotal opportunity: with adequate investment, integrated observing and modelling frameworks, and a well-trained interdisciplinary workforce, South Africa is uniquely positioned to lead globally in Agulhas Current research. Failure to capitalise on this opportunity risks not only scientific setbacks, but also weakened climate adaptation and conservation efforts in an increasingly coupled ocean–climate–ecosystem system.

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