Journal of Palaeosciences 72(2023): 43–54
2583–4266/2023
https://doi.org/10.54991/jop.2023.1852

Variation in Dynamics Controls and Impacts of Agulhas Leakage through Late Pleistocene: A Review

DIVYA VERMA[1,2], PAWAN GOVIL[1,2*], BRIJESH KUMAR[1,2] AND HIDAYATULLAH KHAN[1,2]

[1]*Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow 226 007, India.*
[2]*Academy of Scientific and Innovative Research (AcSIR), Sector 19, Kamla Nehru Nagar, Ghaziabad 201 002, India.*
[*]*Corresponding author: pawan_govil@bsip.res.in*

(Received 03 March, 2023; revised version accepted 01 June, 2023)

ABSTRACT

Verma D, Govil P, Kumar B & Khan H 2023. Variation in Dynamics, Controls and Impacts of Agulhas Leakage through Late Pleistocene: A Review. Journal of Palaeosciences 72(1): 43–54.

The Indian–Atlantic water exchange that occurs south of Africa, commonly known as the Agulhas Leakage, is a significant component of global ocean circulation. Apart from supplying warm, saline water to the South Atlantic, the Agulhas Leakage plays an essential role in the global thermohaline circulation. Variations in leakage cause changes in the strength of Atlantic meridional overturning and oscillations in the formation of North Atlantic Deep Water (NADW). This review paper attempts to understand better the dynamics of the Southern Hemisphere's Agulhas Leakage based on various proxies. The first aspect of this paper concentrates on planktonic foraminifera and other proxies–based reconstruction of the strength of paleo Agulhas Leakage. Secondly, the emphasis would be placed on the controls of the Agulhas Leakage, its impact and its linkage with the Indian Summer Monsoon (ISM). The interactions between the fluctuating westerlies in the Southern Hemisphere, the Subtropical Front (STF) and the Indian Summer Monsoon may affect the variability of Agulhas Leakage. During glacial terminations and following interglacial periods, there is a notable intensification of leakage, which subsequently enhances the Atlantic Meridional Overturning Circulation (AMOC) and assumes a pivotal function in the global transportation of heat. By synthesizing current knowledge, this review highlights the need for further research to better understand and predict the ramifications of Agulhas Leakage in the face of a changing climate.

Key–words—Agulhas Current, Agulhas Leakage, Indian Ocean, Atlantic Ocean, Atlantic Meridional Overturning Circulation, Indian Summer Monsoon, Subtropical Front, Southern Ocean.

INTRODUCTION

IN the present–day global ocean, the Agulhas Current (AC) is the largest western boundary jet current in the Southern Hemisphere and is a vital component of the South Indian Ocean subtropical gyre circulation, which transport ~70Sv (1Sv = $10^6 m^3/s$) of warm (24°–17°C) and salty (35.5–35.2 psu), tropical and subtropical surface waters to the tip of southern Africa. The AC carries thermocline waters from the subtropical gyre of the southern Indian Ocean associated with the Red Sea, the Arabian Sea, and Indonesian Throughflow (Gordon *et al*., 1992; Bryden & Beal, 2001; Lutjeharms, 2006). When the South Equatorial Current (SEC) reaches Madagascar, it separates into two branches: the South East Madagascar Current (SEMC) and the North East Madagascar Current (NEMC) (Fig. 1). The southern extension of the SEMC moves westward and joins with a train of Mozambique Channel eddies that move southward to form Agulhas Current (Hall *et al*., 2017). Since the middle Tertiary, the Agulhas Current has been a characteristic of the Indian Ocean (Martin *et al*., 1982). The current retroflects off the southern tip of Africa between 15°E and 20°E, with most of the water returning to the Indian Ocean in the form of Agulhas Return Current (ARC) (Fig. 1) (Lutjeharms & Ansorge, 2001; Quartly *et al*., 2006). While the Agulhas Return Current generally tracks the Subtropical Front (STF), it occasionally splits between 13°E and 25°E to form a double front comprised of the Agulhas Retroflection Front and STF. Indian Subtropical Surface Water (STSW), Atlantic STSW, and waters from sub–Antarctic zones all make up the water mass between the Agulhas Retroflection Front and STF (Belkin & Gordon, 1996). Every year, between 5 and 20 Sv of warm and salty Agulhas waters leak into the Atlantic Ocean through sporadic shedding of four to six anticyclonic eddies (Agulhas rings) having a radius of up to 400 km. This process is termed as 'Agulhas Leakage' (Lutjeharms, 1996, 2006; de Ruijter *et al*., 1999; Richardson, 2007; Arhan *et al*., 2011). This water is mainly made up of the intermediate and surface waters of the Indian Ocean (de Ruijter *et al*., 1999). This interchange of water between the Indian and the Atlantic Ocean is an essential component of global oceanic thermohaline "conveyor belt" circulation (Gordon, 2003; Biastoch *et al*., 2008, 2009). Increases or decreases in this leakage cause the strengthening or weakening of the Atlantic meridional overturning, as well as variations in the formation of North Atlantic Deep Water (NADW) (Knorr & Lohmann, 2003). The water leakage into the Cape Basin depresses the isotherm and isohaline in the thermocline because it is hotter and saltier than the surrounding environment. The resulting isopycnal undulations cause dynamic disturbances that propagate slowly in the form of Rossby waves in the South Atlantic Ocean (Giulivi & Gordon, 2006; van Sebille & van Leeuwen, 2007). These waves reach the coasts of South America in 4–6 years with their dynamic impressions of the Agulhas Leakage and then quickly conveyed over the equator through the coastal Kelvin waves. As a result, within a decade, leakage impacts the Atlantic's zonally integrated flow, known as the Atlantic Meridional Overturning Circulation (AMOC) (Weijer *et al*., 2002; Cunningham & Marsh, 2010) and thus has crucial role in the evolution of future climate. These waters currently serve as the primary source of heat and salt for the surface branch of the AMOC (Biastoch *et al*., 2009). Changes in Agulhas Leakage can have an effect on climate variability over a range of timescales, from interannual to millennial (Beal *et al*., 2011). Previous studies suggest that, due to increasing greenhouse gas concentrations combined with ozone depletion, Southern Hemisphere westerly winds have been strengthening (Biastoch & Böning, 2013; Ivanciu *et al*., 2021), resulting in an increase in Agulhas Leakage during anthropogenic climate change (Rouault *et al*., 2009; Schwarzkopf *et al*., 2019). This has led to an enhanced transport of salt into the South Atlantic, potentially countering any weakening of the Atlantic Meridional Overturning Circulation (AMOC) caused by warming and melting ice

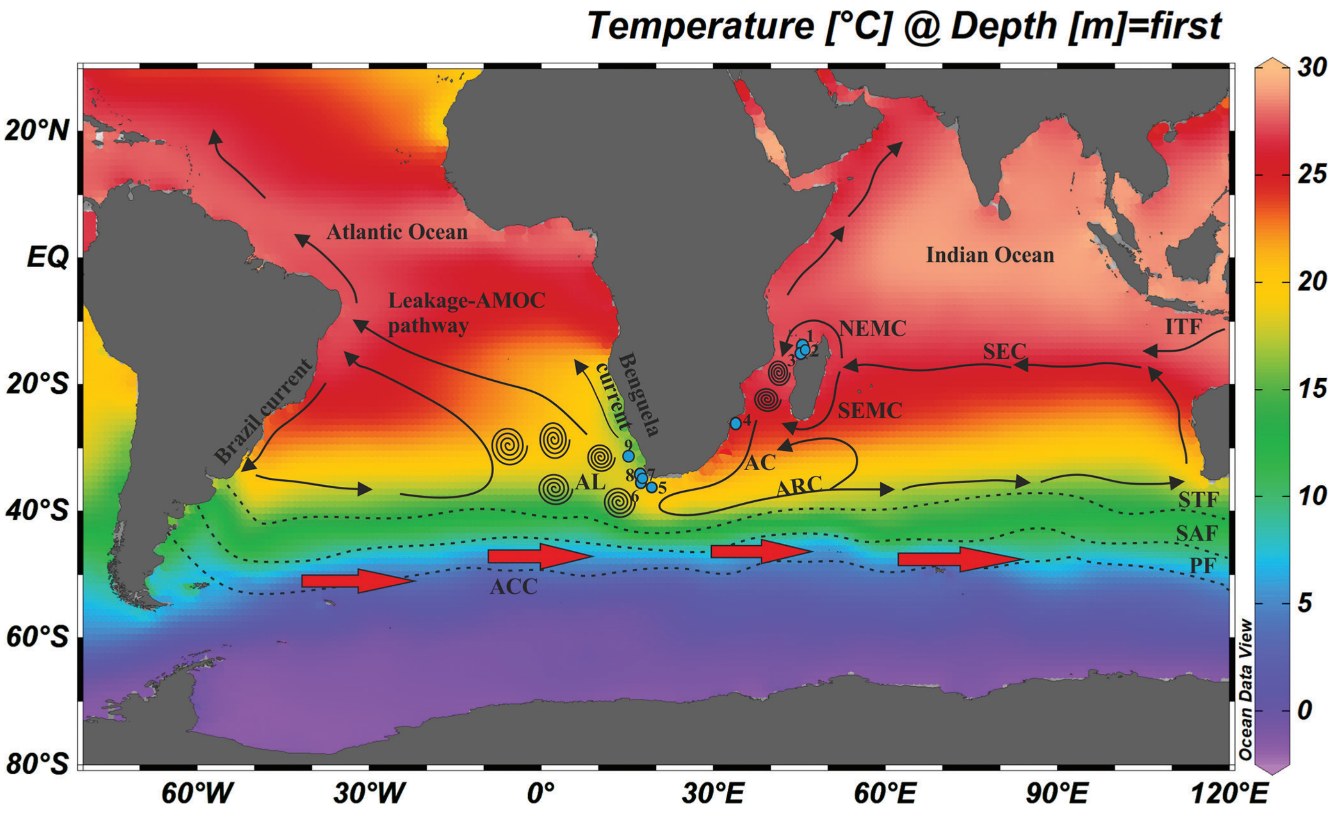

Fig. 1—Map showing the locations of cores (in circle) used in previous studies (detailed in Table 1) (1) GIK16163–2 (2) GIK16166–2 (3) GIK16164–2 (4) MD96–2048 (5) MD96–2080 (6) MD96–2081 (7) GeoB–3603–2 (8) MD02–2594 (9) ODP site 1087 with main surface currents (arrows) in the southwest Indian Ocean. AC= Agulhas Current, ARC = Agulhas Return Current, SEC = South Equatorial Current, SEMC = South East Madagascar Current, NEMC = North East Madagascar Current, ITF= Indonesian Throughflow, ACC = Antarctic Circumpolar Current, STF = Subtropical Front, SAF = Subantarctic Front, PF = Polar Front (modified after Martínez–Méndez *et al*., 2010).

sheets (Weijer *et al*., 2002; Biastoch & Böning, 2013). Despite this, Agulhas Leakage is hard to observe and simulate, meaning estimates for its past and future evolution are limited and subject to considerable uncertainty (Rühs *et al*., 2022).

Agulhas Leakage is connected to interannual patterns of Indian and the Pacific Ocean variability, establishing a relationship with the Indian Ocean Dipole and Pacific Ocean La Niña/El Niño phases (Schouten *et al*., 2002b; Palastanga *et al*., 2006). New observations suggest that AL is connected to the potency of the ITF, the intensification of Asian monsoons, and the vigor of the South Indian sub–tropical gyre (Beck *et al*., 2018; Petrick *et al*., 2019). Scientists have observed variability in Agulhas Leakage during past glacial and interglacial periods, based on their findings. Proxies such as sea surface temperature, salinity, and Agulhas Leakage Fauna (ALF) has the potential to elucidate the variability and intensity of the agulhas leakage. (Peeters *et al*., 2004; Martínez–Mendez *et al*., 2010; Caley *et al*., 2012; Simon *et al*., 2013). Furthermore, several characteristics, such as volume and velocity of agulhas current, fluctuations of hydrographic fronts and wind patterns in the Southern Hemisphere, have been identified that are associated with the change in the intensity of Agulhas Leakage. The STF is a zone of active interaction between atmospheric and ocean circulation, which heavily influences the interocean transfer (Nirmal *et al*., 2023). A northward position of the front serving as a blockage, impeding the transfer of heat and salt through AL (Bard & Rickaby, 2009). The position of the STF and, therefore, the variability of leakage, is influenced by alterations in the Earth's orbital parameters, the position of westerlies, and the amount of solar insolation. The increased leakage during the interglacials strengthens the AMOC and plays an important role in global heat transport (Bard & Rickaby, 2009; Caley *et al*., 2012; Nirmal *et al*., 2023). Agulhas Leakage, has garnered increasing attention due to its profound influence on ocean circulation, heat transport and climate. Research on the Agulhas Leakage and its impact on global climate has grown significantly, and it has been established that inter–oceanic exchange is quite significant for global climate. The majority of paleo AL have been investigated in the past on both centennial and millennial scales. The paper reviews time period up until the Late Pleistocene due to the numerous and significant global climate changes that have occurred (Dansgaard *et al*., 1993). The Late Pleistocene was defined by a succession of climatic cycles, in which interglacial periods and glacial periods occurred alternately, displaying a regular pattern with a periodicity of 100 kyr (Webb & Bartlein 1992). The purpose of the present paper is to review past researches on the paleo AL, including its controlling factors and its impacts based on various proxy records and to provide a perspective on this topic. This allowed us to gain a better understanding of the dynamics of paleo Agulhas Leakage and its effect on global climate.

DECIPHERING THE CHANGES IN PALEO–AGULHAS LEAKAGE BY USING VARIOUS PROXIES

This section presents planktonic foraminifera, temperature, and salinity as a proxy to infer changes in past Agulhas Leakage based on previous studies (Table 1).

Planktonic Foraminifera

Planktonic foraminifera are unicellular marine protozoa with calcareous shells and chambered tests; they account for a small proportion of total zooplankton but contribute 25–50% of total open oceanic carbonate flux and influence organic carbon transport (Schiebel, 2002; Schiebel & Hemleben, 2005; Passow, 2004; Moy *et al*., 2009). Their abundance varies with season, depth and water masses, with light–dependent symbiont–bearing species confined to the euphotic zone. The carbonate equilibrium of ambient seawater is closely linked to the shell formation of planktic foraminifers. As a result, stable oxygen ($^{18}O/^{16}O$ ratio) and carbon isotopes ($^{13}C/^{12}C$ ratio) in shell carbonate are commonly used paleoceanographic proxies for reconstructing the past ocean temperature, salinity, carbonate ion concentration, CO_2 concentration, and primary productivity from deep–sea sediments (Schiebel & Hemleben, 2005). Therefore, planktonic foraminifera can be used as a proxy to infer past oceanographic and climatic changes. For a qualitative analysis of changes in the strength of the Agulhas Leakage, the changes in the fossil planktonic foraminifera assemblage has been studied. The ALF, a reliable proxy in tracing the AL intensity into the south Atlantic, is a group of tropical/sub–tropical planktonic foraminifera species found at detached Agulhas rings and filaments. The ALF involves the species *Globigerinita glutinata, Pulleniatina obliquiloculata, Hastigerina pelagica, Globorotalia menardii, Globigerinella siphonifera, Globigerinoides sacculifer, Globoquadrina hexagona, Orbulina universa, Globigerinoides ruber,* and *Globorotalia scitula* (Peeters *et al*., 2004). The accumulation rate of *Globorotalia menardii* were also studied by a few researchers in marine sediment records from the Agulhas Leakage region to examine the history of leakage.

Giraudeau *et al*. (2001) investigated planktonic foraminiferal assemblage records from the upper Pleistocene section of ODP site 1087, indicative of the previous four glacial–interglacial cycles. According to prior suggestions (Berger & Vincent, 1986; Charles & Morley, 1988), the fluctuations in tropical planktonic foraminifera *Globorotalia menardii* abundance indicate a variable flow of warm and saline Agulhas waters into the southeast Atlantic Ocean. So, the study used the same tracer and concluded that the interchange of water from the Indian to Atlantic oceans was relatively unaffected over the last 460 kyr. On the other hand, interoceanic exchange was most effective during glacial terminations (Fig. 2E), notably Terminations I and II, as well

Table 1—Details of the previous studies, including core, location, proxy, age range and contributing authors to compile present review work.

S. No.	Core	Location	Proxy	Age Range	Reference
1	ODP site 1087	31°28' S 15°19' E	Planktonic Foraminifera *Globorotalia menardii*	0–460 kyr	Giraudeau *et al.*, 2001
2	ODP site 1087	31°28' S 15°19' E	Planktonic Foraminifera *Globorotalia menardii*	0–1,350 kyr	Caley *et al.*, 2012
3	GeoB–3603–2 and MD96–2081	35° 08' S 17° 33' E 35° 35' S 17° 41' E	Planktonic Foraminifera assemblage	0–550 kyr	Peeters *et al.*, 2004
4	MD96–2048 and The Cape Basin cores–GeoB–3603–2 and MD96–2081	26°10' S 34°01' E 35°08' S 17°33' E 35°35' S 17°41' E	Planktonic Foraminifera assemblage	0–640 kyr	Caley *et al.*, 2014
5	MD96–2080 and MD02–2594	36°19.2' S 19°28.2' E 34°42.6' S 17°20.3' E	$\delta^{18}O$ and Mg/Ca (*G. bulloides*)	0–345 kyr	Martínez–Méndez *et al.*, 2010
6	MD96–2080 MD02–2594	36° 19.2' S 19° 28.2' E 34° 42.6' S 17° 20.3' E	$\delta D_{alkenone,}$ TEX^{H}_{86} U^{K}_{37}	Termination 1 and Termination 2	Kasper *et al.*, 2014
7	GIK16163–2 GIK16164–2 GIK16166–2	14°45.47' S 45°59.20' E 15°30.66' S 45°22.46' E 15°16.27' S 45°41.43' E	Mg/Ca and $\delta^{18}O$ in *Globigerinoides ruber*	0–26 kyr	Ma *et al.*, 2021

as the upper portion of MIS 12 (Giraudeau *et al*., 2001). On the same sediment core ODP site 1087, Caley *et al*. (2012) also examined a high–resolution record of accumulation rate (AR) of the *Globorotalia menardii* up to 1,350–ka (In Fig. 2F, data from the last 700 kyr has been used). The study was mainly focused on long–term changes in Agulhas Leakage associated with important paleoceanographic events. The record reveals that, an increase in Agulhas Leakage to the SE Atlantic has affected each of the 17 terminations. For every glacial–interglacial transition, the Agulhas Leakage strengthened at glacial ice–volume maxima (Fig. 2F), with maximum reinforcements ordered according to a 400–ka periodicity (Caley *et al*., 2012). Peeters *et al*. (2004) used a characteristic assemblage of planktonic foraminifera known as the Agulhas Leakage Fauna (ALF) in the cores GeoB–3603–2 and MD96–2081. These cores are situated within the southern Cape Basin at similar depths. The ALF (mentioned above) used as a contemporary equivalent to examine the history of leakage during the last 550kyr. The study demonstrated that interoceanic exchange between the Indian and Atlantic oceans was very varied: it was augmented during the present and past interglacials but significantly decreased during glacial intervals or may have ceased temporarily in MIS–12 (Fig. 2D) (Peeters *et al*., 2004), which represents a notable period during the Quaternary, characterized by the extensive growth of ice sheets in the Northern Hemisphere. It was one of the most powerful glacial periods during the Quaternary (Koutsodendris *et al*., 2019). The findings also revealed that during glacial–interglacial transitions, Agulhas Leakage increased, as seen by the accumulation rate of *G.*

menardii tracer (Giraudeau *et al*., 2001). To build an Agulhas Leakage efficiency index, Caley *et al*. (2014) utilized the planktonic foraminifera assemblage data from two marine sediment records (MD96–2048 and the Cape Basin record) which measured the changes in the interoceanic exchange over the previous 640 kyr. The Agulhas Leakage efficiency (ALE) is proposed as a quantitative approximation for the Agulhas Leakage. *Globorotalia menardii, Globigerinoides ruber, Globigerinoides sacculifer, Globoquadrina hexagona, Pulleniatina obliquiloculata* and *Globigerinella aequilateralis* are the species that are collectively referred to as the Indian Ocean Tropical Group in (IOTG) in this study. Whereas *Globorotalia truncatulinoides, Globorotalia inflata, Globigerina bulloides* and *Neogloboquadrina pachyderma (dextral)* are representatives of the cold, transitional, and subpolar water masses which is known as the Southern Ocean Group (SOG). The Indian Ocean Tropical Group Index [(IOTG/(IOTG+SOG) = Indian Ocean Tropical Group/ (Indian Ocean Tropical Group + Southern Ocean Group)] was established by combining these two groups (Caley *et al*., 2014). The results supported the prior findings based on the ALF index (Peeters *et al*., 2004) and accumulation rate of *G. menardii* tracer (Giraudeau *et al*., 2001; Caley *et al*., 2012) of increased leakage during glacial–interglacial transitions (Fig. 2C). The study also demonstrated that throughout the course of multiple glacial–interglacial cycles, the Agulhas Leakage has varied by ten sverdrups or more during significant climatic shifts, with the leakage perhaps ceasing entirely during MIS12. Based on these previous studies, we may conclude that the Agulhas Leakage has exhibited significant variability in the past, with stronger interoceanic exchange occurring during glacial–interglacial transitions/ glacial terminations. Also, it has decreased during glacial intervals and perhaps ceasing entirely during MIS 12. These findings contribute to our understanding of past oceanographic and climatic changes and highlight the importance of planktonic foraminifera as proxies in reconstructing oceanographic and climatic conditions.

Temperature and Salinity

Sea Surface Temperature (SST) of two sediment cores (MD96–2080 and MD02–2594) derived from planktonic foraminifera $\delta^{18}O$ and Mg/Ca (*G. bulloides*) from the Agulhas corridor, extending past 345 kyr B.P., were examined by Martínez–Méndez *et al*. (2010). The data show that the surface ocean conditions have changed over the course of the last three glacial–interglacial cycles. During glacial periods, there is increasing warming, as evidenced by SST determined from Mg/Ca (Fig. 2A). SST maximums were reached during glacial maxima and glacial Terminations I to III, and T–IV is projected to follow suit. During the glacial period, the warm SST implies a strong influence of warm and saline Agulhas water at the core location (Martínez–Méndez *et al*., 2010). Also, Kasper *et al*. (2014) investigated the Agulhas Leakage region using salinity and temperature proxies. They reconstructed the relative salinity of the Agulhas system using $\delta D_{alkenone}$ produced by haptophyte algae and the paleo sea surface temperature of the Agulhas system using TEX^{H}_{86} and U^{K}_{37}. This study has used the same cores which were previously employed by Martinez–Mendez *et al*. (2010) to focus on Termination I (TI) and Termination II (TII). In this study, sea surface temperatures in the Agulhas Leakage region during the glacial periods were shown to be low based on the multiple proxies. Furthermore, temperatures rise dramatically with the commencement of the deglaciation (Termination I and II), which supports the previous temperature records based on U^{K}_{37} of the core GeoB–3603–2, used by Peeters *et al*. (2004) (Fig.2B). $\delta D_{alkenone}$ values indicated that there was an increase in salinity level throughout glacial periods and then decreased during glacial terminations. These findings suggest that more Agulhas water is being spilled into the South Atlantic Ocean during the terminations due to an improved Agulhas Leakage. These studies by Martínez–Méndez *et al*. (2010) and Kasper *et al*. (2014) with Peeters *et al*. (2004) on temperature reconstructions are in conflict with one other. According to Mg/Ca SST data, warming began during the early glacial periods and lasted through glacial termination (Martínez–Méndez *et al*., 2010). However, U^{K}_{37} and TEX^{H}_{86} data indicate that there was more rapid warming at the commencement of glacial terminations (Peeters *et al*., 2004; Kasper *et al*., 2014). These variations in SST might be attributed to uncertainties associated with the various temperature proxies. Mg/Ca ratios in planktonic foraminifera have been demonstrated to reflect temperature and salinity (Ferguson *et al*., 2008; Arbuszewski *et al*., 2010). As a result, the observed increasing trend in Mg/Ca from *G.bulloides* during the glacial period may result from a combined salinity and temperature signal. Furthermore, U^{K}_{37} producers have different depth habitats and growth seasons than the planktonic foraminifera *G. bulloides*, implying that different temperature ranges were recorded (Martínez–Méndez *et al*., 2010; Kasper *et al*., 2014). When looking at U^{K}_{37} and Mg/Ca data, it's clear that the Agulhas Current reconstruction and interoceanic leakage isn't as simple as previously thought due to the different SST reconstructions derived from the two data sets. A recent study by Ma *et al*. (2021) investigated Mg/Ca and $\delta^{18}O$ in *G. ruber*, establishing mixed layer temperature estimations by using Mg/Ca and $\delta^{18}O$ of the mixed layer. They created a time–series of west–east SST gradient estimates of their core by using SST records based on Mg/Ca from the western Mozambique Channel (Wang *et al*., 2013) as well as the composite SST record from the eastern Mozambique Channel based on Mg/ Ca. This comparison of SST data along the Mozambique Channel demonstrates a west–east gradient reversal during Heinrich event 1 (HE1). This reversal indicates that the South Equatorial Current (SEC) driven by wind is diminishing. Due to this, the Mozambique Channel throughflow, which

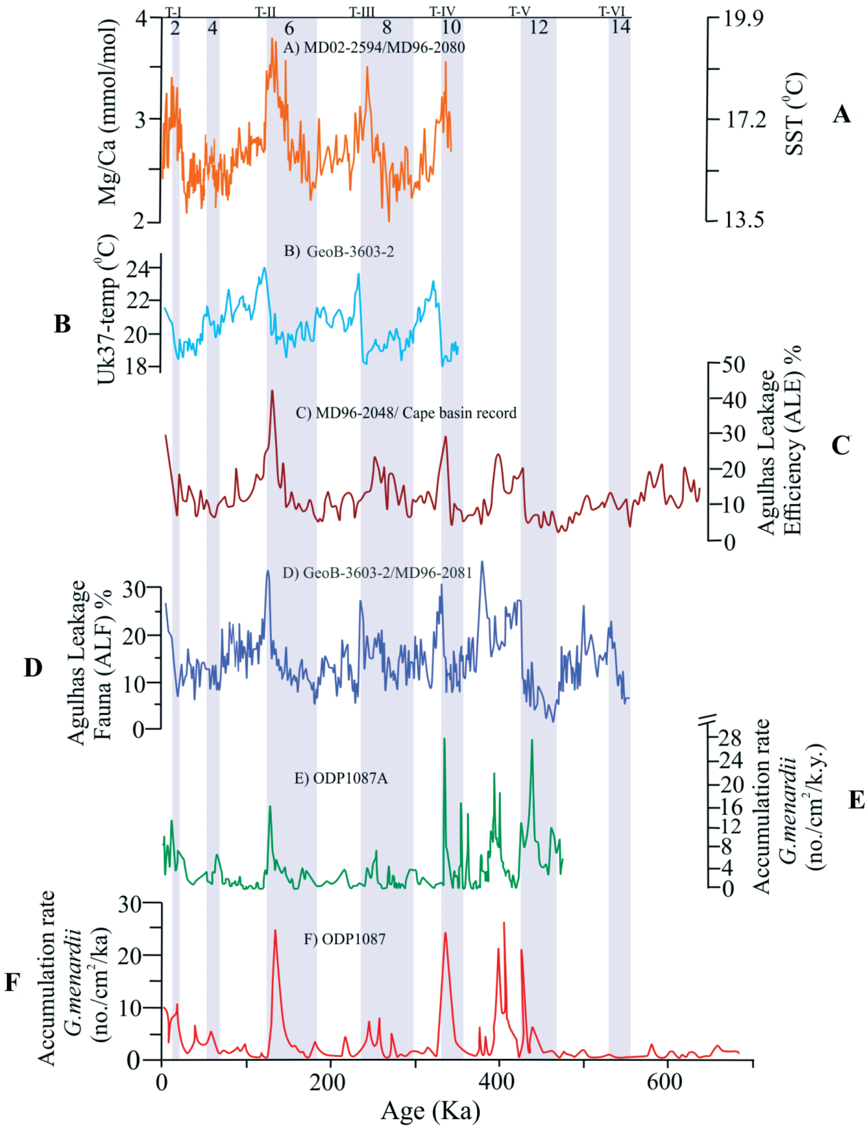

Fig. 2—Paleo–Agulhas Leakage variability based on various proxy records. (A) Mg/Ca record of planktonic foraminifera *G. bulloides* (Martínez–Méndez *et al.*, 2010). (B) U^{K}_{37} based SST records of core GeoB–3603–2 (Peeters *et al*., 2004). (C) Agulhas Leakage Efficiency index (Caley *et al*., 2014). (D) The relative abundance of Agulhas Leakage Fauna at Cape Basin as a measure of Agulhas Leakage (Peeters *et al*., 2004). (E) Accumulation rates of *G. menardii* (Giraudeau *et al*., 2001). (F) Agulhas Leakage as inferred from accumulation rates of *G. menardii* at ODP Site 1087 in the southern Benguela region (Caley *et al*., 2012). Blue bands represent glacial periods.

is a substantial component of the saline water masses that sustain Agulhas Current, is also weakening. As a result, during Heinrich stadials, the quantity of heat and salt leakage into the Atlantic Ocean is reduced. These studies provide valuable insights into the sea surface temperature (SST) variations and Agulhas Leakage in the Agulhas corridor over the past glacial–interglacial cycles. Also, these studies highlight the complex nature of the Agulhas Current reconstruction and the interoceanic exchange. These findings emphasize the need for further research and improved understanding of the various proxies and mechanisms involved in order to obtain a comprehensive picture of the past climate and oceanographic dynamics in the Agulhas corridor.

FACTORS CONTROL THE INTENSITY OF AGULHAS LEAKAGE

Shift in Southern Hemisphere westerlies

The Agulhas system is situated between two significant wind belts: the southeast trades, which run from the equator to approximately 30°S, and the westerlies, which run from

30° to 60°S. The Agulhas Current departs the continental slope as a free jet because the typical latitudinal range of the Indian Ocean's positive wind stress curl zone extends beyond the African continent termination around 34°S (Marshall & Plumb, 2007; Durgadoo *et al*., 2013). Retroflection occurs as a result of a combination of its huge inertia and the location of the maximum westerlies (Ou & de Ruijter, 1986). This process is also responsible for determining the amount of Indian Ocean water leakage into the Atlantic Ocean (de Ruijter *et al*., 1999). Because of this on all time scales, it is anticipated that the strength and/or position of trades and/or westerlies would influence the Agulhas Leakage variability (Durgadoo *et al*., 2013).

Although a gradual shifting of the westerlies to southward has been documented over the last couple of decades and connected to human forcing but due to the scarcity of observational data, it has not been feasible to ascertain if there was a concurrent reaction of Agulhas Leakage. The outcomes of the general circulation model of the Agulhas region were presented in Biastoch *et al*. (2009). This model showed that the flow of Agulhas water into the South Atlantic through the Agulhas Leakage has increased over the last few decades because of changes in wind forcing. Increased Agulhas Leakage as a result of the poleward shift of the Southern Hemisphere westerlies has increased the salinity of the South Atlantic thermocline waters. Both the past measurements and model off the coast of South America show that more Indian Ocean waters have begun to move into the North Atlantic. This could have implications for how the MOC will change in the future (Biastoch *et al*., 2009). Another model study by Durgadoo *et al*. (2013) investigated the possibility that leaking is dependent on the westerlies in the Southern Hemisphere. This study utilized three ocean models—ORCA05, INALT01, and AGIO, and generated solid findings by systematically varying the position and amplitude of the westerly wind band across three model settings. The results demonstrated that the westerlies, namely their strength, regulate the leakage. Up to a degree, Agulhas Leakage is related to the strength of the westerlies, but beyond that, when the large–scale circulation is adjusted, energetic interactions between the ARC and the ACC happen. This results in a state where the leakage is no longer increasing. This transition occurs over the course of a decade or two. These findings further suggest that an equatorward shift in the westerlies increases leakage while the poleward shift in westerlies decreases the leakage, contrary to earlier statements (Durgadoo *et al*., 2013). Observational data limitations make it challenging to determine the concurrent reaction of Agulhas Leakage to the shifting westerlies. However, general circulation models suggest that Agulhas water flow into the South Atlantic has increased in recent decades due to changes in wind forcing. This increase in leakage could have implications for the future of the Meridional Overturning Circulation (MOC). These findings highlight the complex relationship between wind forcing, the Agulhas system, and the leakage of Indian Ocean water.

Shifting of Subtropical Front

The STF separates the subtropical gyres from the broad eastward flow of the ACC. Additionally, it serves as the northernmost boundary of the frontal system of the SO and marks the southern end of the Agulhas system (Bard & Rickaby, 2009). The STF is currently positioned around 39–41°S. It divides the cooler and nutrient–rich waters of the Subantarctic zone from the warmer, saltier, and nutrient–poor subtropical waters (Stramma & Peterson, 1990). STF is located south of the Agulhas Plateau, whereas retroflected waters become the ARC to the north of the Agulhas Plateau owing to bathymetric steering (Lutjeharms, 2006). Changes in foraminiferal assemblages in the southeast Atlantic have been linked to warm Agulhas waters seeping through the Indian-Atlantic Oceanic Gateway (I-AOG). As a result, the variation in Agulhas Leakage fauna abundance has been used as a proxy for AL. This has also been linked to the migration of STF latitudinally over the quaternary (Caley *et al*., 2012; Peeters *et al*., 2004).

Bard and Rickaby (2009**)** looked at STF migration by using core MD962077, which is located beneath the Agulhas Current, to determine the STF's latitude based on hydrographic changes. The study employed SST records derived from U^{K}_{37} and $\delta^{18}O$ of *Globigerina inflata* and coccolithophore fraction, and the productivity records from 800 kyrs to show that during cold periods (especially marine isotope stages 10 and 12) the SST was around 6°C cooler than modern temperature and productivity was at its peak. This implies that STF advanced northward up to 7° latitude during these colder stadials, thus effectively closing down the Agulhas Current. It is the winds strength position that determines the latitude of the STF. The STF migrated northward during the Glacial Period (Fig. 3b), consistent with previous data from foraminiferal and coccolithophore assemblages in this region. They hypothesized that the STF migration northward into South Africa operates as a climatic choke point. Also, they determined that during MIS–12 and MIS–10, STF shifted north to 33°S, which severely reduced the effect of Indian Ocean waters on the Atlantic salinity budget (Bard & Rickaby, 2009). An idealized model predicts that fronts and the peak westerly wind stress locations shift by 7° equatorward due to a 3°C global cooling. (Williams & Bryan, 2006).

Increases in productivity of surface water and colder temperatures within the ARC suggest that the STF and nutrient–rich SAZ waters migrated north during the last 150 kyr of glacial periods (Naik *et al*., 2013). Changes in diatom assemblages, alkenone–based sea surface temperatures (SST), and bulk biogenic silica concentration at the Agulhas Plateau over the last 350 kyr showed that the STF shifted northward throughout glacial periods (Romero *et al*., 2015).

In a recent study by Cartagena–Sierra *et al*. (2021) looked at changes in the STF's latitudinal position during the last 1.4–0.3 Ma. They looked at new temperature records (U^{K}_{37} and TEX^{H}_{86}) and productivity (chlorinates and alkenones) of the upper water column from the IODP Site U1475 on the Agulhas Plateau, which is near the STF. The findings suggest northward and southward migrations of the STF in glacial and interglacial periods, respectively (Fig. 3a, b). Combined with other evidence of STF migrations over the last 350 ky, their reconstructions suggest that the STF may have migrated further south from the Agulhas Plateau throughout the mid–Pleistocene Interim State (MPIS, MIS 23–12) and further north during MIS 34–24 and MIS 10 in the Southwest Indian Ocean (Cartagena–Sierra *et al*., 2021). The STF's extreme northward excursions are connected with decreased Agulhas Leakage (Fig. 3b), according to a reconstruction based on *Globorotalia menardii* from the Cape Basin (Caley *et al*., 2012). In conclusion, the migration of the Subtropical Front (STF) in the Southwest Indian Ocean has been linked to climatic changes and has significant implications for oceanic circulation patterns and nutrient distribution. Understanding the dynamics and past variations of the STF is crucial for studying the Agulhas Leakage and its impact on regional and global oceanic processes.

IMPACT OF AGULHAS LEAKAGE ON AMOC

The AMOC is a key component of the global climate system that plays an important role in interhemispheric connection by transporting warm and salty water northward in the upper ocean (Cunningham *et al*., 2007). They lose heat to the atmosphere, sink, and form North Atlantic Deep Water (NADW) in Greenland and Labrador seas. Then, they flow southward, carrying cold saline water into the Southern Ocean and upwelling elsewhere in the global ocean (Stocker & Broecker, 1994; Kuhlbrodt *et al*., 2007). The heat is efficiently carried by AMOC from the Southern Hemisphere (SH) to the Northern Hemisphere (NH) because the return flow is cooler than the surface flow (Crowley, 1992). Changes in the AMOC can affect a variety of factors, including the North Atlantic storm tracks (Woollings *et al*., 2012), the summer climate in North America and Europe (Sutton & Hodson, 2005), the African and Indian monsoon rainfall (Zhang & Delworth, 2006). Water exchange between the Indian and Atlantic oceans is a critical component of meridional circulation and occurs via the AL (Gordon, 1985). A phenomenon known as the thermal bipolar seesaw effect is projected to result from changes in the AMOC strength, which oppositely affects the climate in both hemispheres (Crowley, 1992; Stocker & Johnsen, 2003). The breakdown of this circulation might lead to substantial cold episodes, such as the Heinrich events, according to numerical simulations (Stouffer *et al*., 2006; Hu *et al*., 2013); and paleo–proxy data (Clark *et al*., 2007; Gutjahr *et al*., 2010,). Paleoceanographic reconstructions indicate that the AL was diminished throughout glacial periods as a result of the northerly position of STF and the spread of Antarctic sea ice (Fig. 3b) (Peeters *et al*., 2004; Bard & Rickaby, 2009;). At the end of long glacial periods, the STF moved southward, which increases the volume of AL (Fig. 3a). Increases in AL enhance the salinity of the MOC's return limb, hence leading to warmer temperatures in the Northern Hemisphere via strong positive MOC feedbacks. (Peeters *et al*., 2004; Caley *et al*., 2014). In contrast, a slow MOC is believed to result in warming of local surface and subsurface waters in the south–eastern Atlantic Ocean, owing to the decreased northward flow of subtropical water masses of the Indian Ocean, which are amassing in the South Atlantic Ocean (Kim *et al*., 2002; Chang *et al*., 2008). Recent research sought to understand salinity supply by AL. An AL with high salinity can directly affect a Heinrich weakened AMOC, leading to recovery even with a prolonged freshwater inflow in the North Atlantic. Furthermore, greater salinities in the AL appear to contribute to quicker reaction times of AMOC and stronger recovery. So, depending on the amount of salt extracted and how quickly it is released through the AL, glacial salinification of surface water in the tropical and subtropical Indian Ocean has a direct impact on global overturning circulation and shape of deglaciations (Nuber *et al*., 2021). The studies show that the Agulhas Leakage variability affects the strength of the AMOC in a significant way. Overall, the variability of Agulhas Leakage has been found to have a significant influence on the strength and dynamics of the AMOC. Understanding these interactions is crucial for improving our knowledge of the global climate system and its response to changes in oceanic circulation. Further research in this area will contribute to more accurate climate models and predictions, helping us address the challenges of future climate change.

LINKAGE OF AGULHAS LEAKAGE TO INDIAN SUMMER MONSOON

This section aims to understand the possible link between the Agulhas Leakage and the Indian Summer Monsoon (ISM). While the majority of studies on teleconnections between the Asian Monsoon and other regions have focused on the Northern Hemisphere, there have been some studies that have suggested teleconnections with regions in the low latitudes and the Southern Hemisphere high latitudes as well (An *et al*., 2011; Gebregiorgis *et al*., 2018). Indian Summer Monsoon variability is linked to the southern Indian Ocean subtropical high (SISH)/Mascarene High through the Hadley circulation (Beck *et al*., 2018). Recent observations suggest that variations in the intensity and location of the SISH, influenced by the low latitude insolation gradient, are associated with changes in the Southeast trade winds, which in turn impact the strength and leakage of the Agulhas Current (Backeberg *et al*., 2012; Beck *et al*., 2018). Band *et al.* (2022) recently conducted a study and found that warmer sea surface

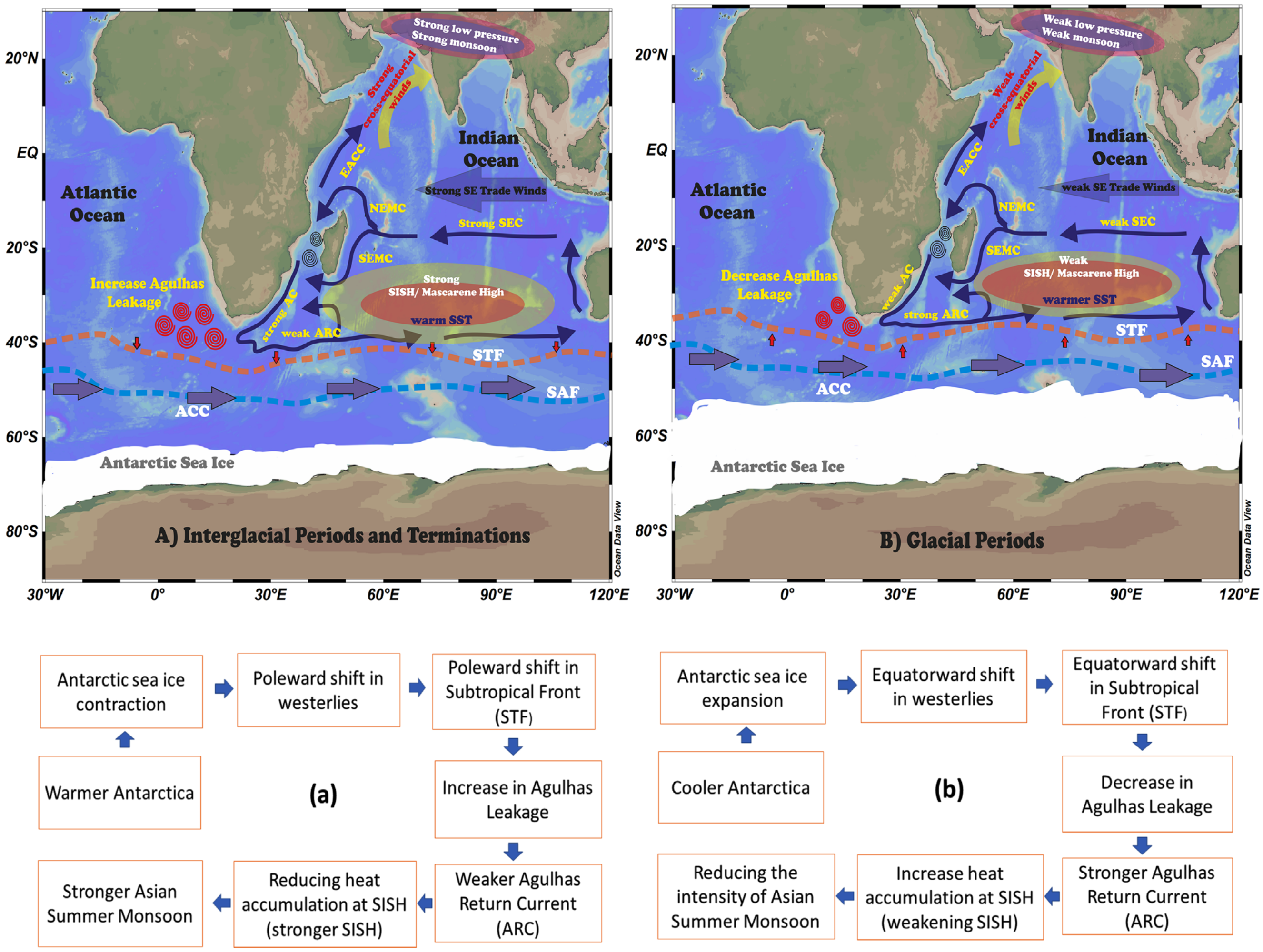

Fig. 3—The schematic diagram shows the variation in Agulhas Leakage due to shifting in subtropical front and the change in Asian Summer Monsoon during (a) interglacial periods and terminations, (b) glacial periods. The arrows represent surface currents, and the small red arrows show the movement of the subtropical front (modified after Nair *et al.,* 2019).

temperatures (SSTs) in the Atlantic due to stronger Agulhas Leakage events are associated with weaker ISM episodes. Nair *et al*. (2019) proposed a possible link between the intensity of Agulhas Leakage and variability in the ISM. A study by Nair *et al*. (2019) analyzed the Asian Monsoon dynamics over the past 75 ka and 500 ka. The findings revealed a more robust monsoon during past interglacial periods, which can be attributed to several factors. Firstly, the intensity of the South–East (SE) trade winds and Somali Jet increased due to the maximum gradient of June isolation between 30°N and 30°S. Additionally, a more prominent low–pressure system over the Asian landmass contributed to the stronger monsoon patterns (Beck *et al*., 2018). The enhanced Asian Summer Monsoon resulted in a more robust flow of southeast trade winds, which bolstered the South Equatorial Current (SEC). This, in turn, led to a significant rise in Agulhas Leakage, influenced by the upstream Agulhas system (Peeters *et al*., 2004). Moreover, there were notable resemblances observed among a more robust Asian Summer Monsoon, amplified Agulhas Leakage Fauna, elevated Antarctic temperature, and the southward shift of the STF, indicating an alternative driving force for the monsoon intensification during interglacial periods. This phenomenon can be elucidated by a mechanism in which a warmer Antarctica causes the southward shift of the STF and other fronts, along with the expansion of the Agulhas Leakage corridor. Consequently, Agulhas Leakage increases, leading to a stronger Asian Summer Monsoon by reducing heat accumulation at the SISH/Mascarene High, transforming it into a potent high–pressure zone (Fig. 3a) (Nair *et al*., 2019).

In contrast, during glacial periods, the reduced gradient of June isolation between latitudes 30°N and 30°S weakens the pressure difference between the SISH and the Asian landmass. Consequently, this could have resulted in a decrease in the cross–equatorial flow of the Southeast (SE) trade winds and the Somali jet. This results in a decline in the intensity of the Asian Summer Monsoon, as well as a reduction in the flow of the Agulhas Current and Agulhas Leakage. This phenomenon can be elucidated by the mechanism in which during glacial stages, cooler temperatures in Antarctica cause the sea ice and fronts to shift northward, narrowing the Agulhas Leakage corridor and decreasing Agulhas Leakage. The decreased AL along with the stronger Agulhas return current (ARC) resulting from intensified westerly winds in the Southern Hemisphere (Simon *et al*., 2013) contributes to heat accumulation in the Indian Ocean during glacial periods. This heat buildup, leads to notable SST anomalies in the southwestern Indian Ocean, weakening the SISH and reducing the intensity of the Asian Summer Monsoon during glacial stages (Fig. 3b) (Nair *et al*.,2019).

In summary, the findings suggest a potential link between Agulhas Leakage and the Indian Summer Monsoon, indicating that changes in Agulhas Leakage intensity can influence sea surface temperatures and atmospheric circulation patterns, ultimately impacting the strength and variability of the Indian Summer Monsoon. The past variations in the intensity of Agulhas Leakage may be attributed to the interplay between the Asian Summer Monsoon and the variability of Southern Ocean frontal systems.

SUMMARY AND CONCLUSIONS

This review study provides valuable insights into the past variability of Agulhas Leakage by examining multiple proxy records. The analysis reveals significant fluctuations in Agulhas Leakage, particularly during glacial–interglacial transitions and glacial terminations, indicating stronger interoceanic exchange during those periods. However, the temperature reconstruction studies present conflicting findings. While the Mg/Ca SST data suggests a gradual warming trend from the early glacial periods to the end of the Glacial Period, the U^{K}_{37} and TEX^{H}_{86} data indicate a more pronounced and rapid warming during the initial stages of glacial terminations. These discrepancies underscore the complexity of Agulhas Current reconstruction and interoceanic leakage, challenging previous assumptions and emphasizing the need for further in–depth investigations and a comprehensive understanding of the diverse proxies and processes involved. Such an approach is crucial for gaining a thorough understanding of past climate and oceanographic dynamics in the Agulhas corridor.

Existing studies on the influence of shifting Southern Hemisphere westerlies and subtropical fronts on Agulhas Leakage present conflicting perspectives. Some researchers argue that an equatorward shift in westerlies enhances leakage, while others suggest a poleward shift has the same effect. These findings emphasize the intricate relationship between wind forcing and the leakage of Indian Ocean water. Additionally, understanding the dynamics and past variations of the STF is essential for studying Agulhas Leakage and its impacts on regional and global oceanic processes. The variability of Agulhas Leakage strongly impacts the strength and dynamics of the AMOC, thus exerting a significant influence on the global climate system. Consequently, investigating these connections is crucial for advancing our understanding of climate patterns and predicting changes in oceanic circulation. Further research not only enhances climate models but also enables improved predictions and addresses future challenges related to climate change. The study also suggests a possible connection between Agulhas Leakage and the Indian Summer Monsoon. It indicates that past variations in leakage intensity may have been influenced by interactions between the Asian Summer Monsoon and Southern Ocean frontal systems. However, to fully comprehend the complex dynamics and mechanisms underlying this relationship, additional research is necessary. Furthermore, there is a great deal of unknown information concerning the movement of deep waters from the Atlantic to the Indian Ocean, although it is a possibility to investigate it further. Therefore, this review study serves as a foundation for future research endeavours aimed at expanding our knowledge of Agulhas Leakage, its drivers, and its implications for regional and global oceanic processes. Understanding these dynamics is crucial for effectively managing and predicting future climate changes.

Acknowledgements*—The authors express their gratitude to the Director, the Birbal Sahni Institute of Palaeosciences (BSIP) for her unwavering support and encouragement throughout the process. D.V. expresses heartfelt gratitude to the University Grant Commission (UGC) for providing fellowship in the form of Junior Research Fellowship (JRF) UGC Ref. No: 396/ (CSIR–UGC NET DEC. 2018). BSIP funded this work under Project 4.3 (2021–2025); publication number 74.*

REFERENCES

An Z, Clemens SC, Shen J, Qiang X, Jin Z, Sun Y, Prell WL, Luo J, Wang S, Xu H, Cai Y, Zhou W, Liu X, Liu W, Shi Z, Yan L, Xiao X, Chang H, Wu F, Ai L & Lu F 2011. Glacial–Interglacial Indian Summer Monsoon Dynamics. Science 333: 719–723.

Arbuszewski J, de Menocal P, Kaplan A, & Farmer EC 2010. On the fidelity of shell derived $\delta^{18}O$ sw estimates. Earth and Planetary Science Letters 300: 185–196.

Arhan M, Speich S, Messager C, Dencausse G, Fine R & Boye M 2011. Anticyclonic and cyclonic eddies of subtropical origin in the subantarctic zone south of Africa. Journal of Geophysical Research: Oceans 116(C11): C11004.

Backeberg BC, Penven P & Rouault M 2012. Impact of intensified Indian Ocean winds on mesoscale variability in the Agulhas system. Nature Climate Change 2(8): 608–612.

Band ST, Yadav MG, Kaushal N, Midhun M, Thirumalai K, Francis T, Laskar, A, Ramesh R, Henderson GM & Narayana AC 2022. Southern hemisphere forced millennial scale Indian Summer Monsoon variability during the late Pleistocene. Scientific Reports 12(1): 10136.

Bard E & Rickaby RE 2009. Migration of the subtropical front as a modulator of glacial climate. Nature 460(7253): 380–383.

Beal LM, De Ruijter WPM, Biastoch A, Zahn R & SCOR/WCRP/IAPSO Working Group 136 2011. On the role of the Agulhas system in ocean circulation and climate. Nature 472: 429–436.

Beck JW, Zhou W, Li C, Wu Z, White L, Xian F, Kong X & An Z 2018. A

550,000–year record of East Asian monsoon rainfall from 10Be in loess. Science 360 (6391): 877–881.

Belkin IM & Gordon AL 1996. Southern Ocean fronts from the Greenwich meridian to Tasmania. Journal of Geophysical Research: Oceans 101(C2): 3675–3696.

Berger WH & Vincent E 1986. Sporadic shutdown of North Atlantic deep water production during the Glacial–Holocene transition? Nature 324(6092): 53–55.

Biastoch A & Böning CW 2013. Anthropogenic impact on Agulhas Leakage. Geophysical Research Letters 40: 1138–1143.

Biastoch A, Böning CW & Lutjeharms JRE 2008. Agulhas Leakage dynamics affects decadal variability in Atlantic overturning circulation. Nature 456: 489–492.

Biastoch A, Böning CW, Schwarzkopf FU & Lutjeharms JRE 2009. Increase in Agulhas Leakage due to poleward shift of Southern Hemisphere westerlies. Nature 462: 495–499.

Bryden HL & Beal LM 2001. Role of the Agulhas Current in Indian Ocean circulation and associated heat and freshwater fluxes. Deep Sea Research Part I: Oceanographic Research Papers 48(8): 1821–1845.

Caley T, Giraudeau J, Malaizé B, Rossignol L & Pierre C 2012. Agulhas Leakage as a key process in the modes of Quaternary climate changes. Proceedings of the National Academy of Sciences, USA 109(18): 6835–6839.

Caley T, Peeters FJ, Biastoc, A, Rossignol L, Van Sebille E, Durgadoo J, Malaizé B, Giraudeau J, Arthur K & Zahn R 2014. Quantitative estimate of the paleo–Agulhas Leakage. Geophysical Research Letters 41(4): 1238–1246.

Cartagena–Sierra A, Berke MA, Robinson RS, Marcks B, Castañeda IS, Starr A, Hall IR, Hemming SR, LeVay LJ & Expedition 361 Scientific Party 2021. Latitudinal migrations of the subtropical front at the Agulhas Plateau through the Mid–Pleistocene Transition. Paleoceanography and Paleoclimatology 36(7): p.e2020PA004084.

Chang P, Zhang R, Hazeleger W, Wen C, Wan X, Ji L, Haarsma RJ, Breugem WP & Seidel H 2008. Oceanic link between abrupt changes in the North Atlantic Ocean and the African monsoon. Nature Geoscience 1(7): 444–448.

Charles CD & Morley JJ 1988. The paleoceanographic significance of the radiolarian *Didymocyrtis tetrathalamus* in eastern Cape Basin sediments. Palaeogeography, Palaeoclimatology, Palaeoecology 66(1–2): 113–126.

Clark PU, Hostetler SW, Pisias NG, Schmittner A & Meissner KJ 2007. Mechanisms for an~ 7–kyr climate and sea–level oscillation during marine isotope stage 3. Geophysical Monograph–American Geophysical Union 173: p 209.

Crowley TJ 1992. North Atlantic deep water cools the Southern Hemisphere. Paleoceanography 7(4): 489–497.

Cunningham SA, Kanzow T, Rayner D, Baringer MO, Johns WE, Marotzke J, Longworth HR, Grant EM, Hirschi JJM, Beal LM & Meinen CS 2007. Temporal variability of the Atlantic meridional overturning circulation at 26.5 N. Science 317(5840): 935–938.

Cunningham SA & Marsh R 2010. Observing and modelling changes in the Atlantic MOC. Wiley Interdisciplinary Reviews: Climate Change 1: 180–191.

Dansgaard W, Johnsen SJ, Clausen HB, Dahl–Jensen D, Gundestrup NS, Hammer CU, Hvidberg CS, Steffensen JP, Sveinbjörnsdottir AE, Jouzel J & Bond G 1993. Evidence for general instability of past climate from a 250–kyr ice–core record. Nature 364(6434): 218–220.

de Ruijter WD, Biastoch A, Drijfhout SS, Lutjeharms JRE, Matano RP, Pichevin T, van Leeuwen PJ & Weijer W 1999. Indian–Atlantic interocean exchange: Dynamics, estimation and impact. Journal of Geophysical Research: Oceans 104(C9): 20885–20910.

Durgadoo JV, Loveday BR, Reason CJ, Penven P & Biastoch A 2013. Agulhas Leakage predominantly responds to the Southern Hemisphere westerlies. Journal of Physical Oceanography 43(10): 2113–2131.

Ferguson JE, Henderson GM, Kucera M & Rickaby REM 2008. Systematic change of foraminiferal Mg/Ca ratios across a strong salinity gradient. Earth and Planetary Science Letters 265: 153–166.

Gebregiorgis D, Hathorne1 EC, Giosan L, Clemens S, Nürnberg D & Frank M 2018. Southern Hemisphere forcing of South Asian monsoon precipitation over the past ~1 million Years. Nature Communications 9: 4702.

Giraudeau J, Pierre C & Herve L 2001. A Late quaternary, high–resolution record of Planktonic Foraminiferal species distribution in the southern Benguela region: site 10871.

Giulivi CF & Gordon AL 2006. Isopycnal displacements within the Cape Basin thermocline as revealed by the Hydrographic Data Archive. Deep Sea Research 53: 1285–1300.

Gordon AL 1985. Indian–Atlantic transfer of thermocline water at the Agulhas retroflection. Science 227(4690): 1030–1033.

Gordon AL 2003. The brawniest retroflection. Nature 421: 904–905.

Gordon AL, Weiss RF, Smethie WM Jr & Warner MJ 1992. Thermocline and intermediate water communication between the south Atlantic and Indian Oceans. Journal of Geophysical Research: Oceans 97(C5): 7223–7240.

Gutjahr M, Hoogakker BA, Frank M & McCave IN 2010. Changes in North Atlantic Deep Water strength and bottom water masses during Marine Isotope Stage 3 (45–35 ka BP). Quaternary Science Reviews 29(19–20): 2451–2461.

Hall IR, Hemming SR, LeVay LJ, Barker S, Berke MA, Brentegani L, Caley T, Cartagena–Sierra A, Charles CD, Coenen JJ & Crespin JG 2017. Expedition 361 summary. *In*: Proceedings of the International Ocean Discovery Program, 361. International Ocean Discovery Program.

Hu A, Meehl GA, Han W, Lu J & Strand WG 2013. Energy balance in a warm world without the ocean conveyor belt and sea ice. Geophysical Research Letters 40: 6242–6246.

Ivanciu I, Matthes K, Wahl S, Harlaß J & Biastoch A 2021. Effects of prescribed CMIP6 ozone on simulating the Southern Hemisphere atmospheric circulation response to ozone depletion. Atmospheric Chemistry and Physics 21: 5777–5806.

Kasper S, Van der Meer MTJ, Mets A, Zahn R, Sinninghe Damsté JS & Schouten S 2014. Salinity changes in the Agulhas Leakage area recorded by stable hydrogen isotopes of C 37 alkenones during Termination I and II. Climate of the Past 10(1): 251–260.

Kim JH, Schneider RR, Müller PJ & Wefer G 2002. Interhemispheric comparison of deglacial sea–surface temperature patterns in Atlantic eastern boundary currents. Earth and Planetary Science Letters 194(3–4): 383–393.

Knorr G & Lohmann G 2003. Southern Ocean origin for the resumption of Atlantic thermohaline circulation during deglaciation. Nature 424: 532–536.

Koutsodendris A, Kousis I, Peyron O, Wagner B & Pross J 2019. The Marine Isotope Stage 12 pollen record from Lake Ohrid (SE Europe): Investigating short-term climate change under extreme glacial conditions. Quaternary Science Reviews 221: 105873.

Kuhlbrodt T, Griesel A, Montoya M, Levermann A, Hofmann M & Rahmstorf S 2007. On the driving processes of the Atlantic meridional overturning circulation. Reviews of Geophysics 45(2).

Lutjeharms JRE 1996. The exchange of water between the South Indian and South Atlantic Oceans. *In*: Wefer G, Berger WH, Siedler G & Webb DJ (Editors)–The South Atlantic: Present and Past Circulation: 125–162.

Lutjeharms JRE 2006. The Agulhas Current retroflection. Springer, Berlin Heidelberg (Vol. 329).

Lutjeharms JRE & Ansorge IJ 2001. The Agulhas return current. Journal of Marine Systems 30: 115–138.

Ma Y, Weldeab S, Schneider RR, Andersen N, Garbe–Schönberg D & Friedrich T 2021. Strong Southern African Monsoon and weak Mozambique Channel throughflow during Heinrich events: Implication for Agulhas Leakage. Earth and Planetary Science Letters 574: 117148.

Marshall J & Plumb RA 2007. Atmosphere, Ocean and Climate Dynamics: An Introductory Text (International Geophysics).

Martin AK, Goodlad SW & Salmon DA 1982. Sedimentary basin in–fill in the northernmost Natal Valley, hiatus development and Agulhas Current Palaeoceanography. Journal of the Geological Society, London 139: 183–201.

Martínez–Mendez G, Zahn R, Hall IR, Peeters FJC, Pena LD, Cacho I & Negre C 2010. Contrasting multiproxy reconstructions of surface ocean hydrography in the Agulhas Corridor and implications for the Agulhas

Leakage during the last 345,000 years. Paleoceanography 25(4): PA4227.

Moy AD, Howard WR, Bray SG & Trull TW 2009. Reduced calcification in modern Southern Ocean planktonic foraminifera. Nature Geoscience 2(4): 276–280.

Naik DK, Saraswat R, Khare N, Pandey AC & Nigam R 2013. Migrating subtropical front and Agulhas Return Current affect the southwestern Indian Ocean during the late Quaternary. Climate of the Past Discussions 9(5): 5521–5551.

Nair A, Mohan R, Crosta X, Manoj MC, Thamban M & Marieu V 2019. Southern Ocean sea ice and frontal changes during the Late Quaternary and their linkages to Asian Summer Monsoon. Quaternary Science Reviews 213: 93–104.

Nirmal B, Mohan K, Tripati A, Christensen BA, Mortyn PG, De Vleeschouwer D, Prakasam M & Saravanan K 2023. Agulhas Leakage extension and its influences on South Atlantic surface water hydrography during the Pleistocene. Palaeogeography, Palaeoclimatology, Palaeoecology 615: 111447.

Nuber S, Rae J, Andersen M, Zhang X, de Boer B, Dumont M, Sun Y, Mithan H, Hall I & Barker S 2021. Sea Level controls on Agulhas Leakage Salinity and the Atlantic Overturning Circulation. Research Square (Version 1).

Ou HW & de Ruijter WP 1986. Separation of an inertial boundary current from a curved coastline. Journal of Physical Oceanography 16(2): 280–289.

Palastanga V, van Leeuwen PJ & de Ruijter WPM 2006. A link between low–frequency mesoscale eddy variability around Madagascar and the large–scale Indian Ocean variability. Journal of Geophysical Research: Oceans 111(C9).

Passow U 2004. Switching perspectives: Do mineral fluxes determine particulate organic carbon fluxes or vice versa? Geochemistry Geophysics Geosystems 5: Q04002.

Peeters FJC, Acheson R, Brummer G–JA, de Ruijter WPM, Schneider R, Ganssen G, Ufkes ME & Kroon D 2004. Vigorous exchange between the Indian and Atlantic Oceans at the end of the past five glacial periods. Nature 430: 661–665.

Petrick B, Martínez–García A, Auer G, Reuning L, Auderset A, Deik H, Takayanagi H, De Vleeschouwer D, Iryu Y & Haug GH 2019. Glacial Indonesian throughflow weakening across the mid–pleistocene climatic transition. Scientific Reports 9 (1): 1–13.

Quartly GD, Buck JJH, Srokosz MA & Coward AC 2006. Eddies around Madagascar: the retroflection re–considered. Journal of Marine Systems 63: 115–129

Richardson PL 2007. Agulhas Leakage into the Atlantic estimated with subsurface floats and surface drifters. Deep Sea Research Part I: Oceanographic Research Papers 54(8): 1361–1389.

Romero OE, Kim J–H, Barcena MA, Hall IR, Zahn R & Schneider R 2015. High–latitude forcing of diatom productivity in the southern Agulhas Plateau during the past 350 kyr: Late Pleistocene diatom productivity. Paleoceanography 30(2): 118–132.

Rouault M, Penven P & Pohl B 2009. Warming in the Agulhas Current system since the 1980's. Geophysical Research Letters 36: L12602.

Rühs S, Schmidt C, Schubert R, Schulzki TG, Schwarzkopf FU, Le Bars D & Biastoch A 2022. Robust estimates for the decadal evolution of Agulhas Leakage from the 1960s to the 2010s. Communications Earth & Environment 3(1): 318.

Schiebel R 2002. Planktic foraminiferal sedimentation and the marine calcite budget. Global Biogeochemical Cycles 16: 1065.

Schiebel R & Hemleben C 2005. Modern planktic foraminifera. Paläontologische Zeitschrift 79(1): 135–148.

Schouten MW, de Ruijter WPM, van Leeuwen PJ & Dijkstra HA 2002. An oceanic teleconnection between the equatorial and southern Indian Ocean. Geophysical Research Letters. 29(16): 59–1.

Schwarzkopf FU, Biastoch A, Böning CW, Chanut J, Durgadoo JV, Getzlaff K, Harlaß J, Rieck JK, Roth C, Scheinert MM & Schubert R 2019. The INALT family–a set of high–resolution nests for the Agulhas Current system within global NEMO ocean/sea–ice configurations. Geoscientific Model Development 12(7): 3329–3355.

Simon MH, Arthur KL, Hall IR, Peeters FJ, Loveday BR, Barker S, Ziegler M & Zahn R 2013. Millennial–scale Agulhas Current variability and its implications for salt–leakage through the Indian–Atlantic Ocean Gateway. Earth and Planetary Science Letters 383: 101–112.

Stocker TF & Broecker WS 1994. Observation and modelling of North Atlantic deepwater formation and its variability: Introduction. Journal of Geophysical Research: Oceans 99(C6): 12317–12317.

Stocker TF & Johnsen SJ 2003. A minimum thermodynamic model for the bipolar seesaw. Paleoceanography & Palaeoclimatology: 18(4). DOI: 10.1029/2003PA000920.

Stouffer RJ, Yin J, Gregory JM, Dixon KW, Spelman MJ, Hurlin W, Weaver AJ, Eby M, Flato GM, Hasumi H, Hu A, Jungclaus JH, Kamenkovich IV, Levermann A, Montoya M, Murakami S, Nawrath S, Oka A, Peltier WR, Robitaille DY, Sokolov A, Vettoretti G & Weber SL 2006. Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. Journal of Climate 19: 1365–1387.

Stramma L & Peterson RG 1990. The South Atlantic Current. Journal of Physical Oceanography 20(6): 846–859.

Sutton RT & Hodson DL 2005. Atlantic Ocean forcing of North American and European summer climate. Science 309(5731): 115–118.

van Sebille E & van Leeuwen PJ 2007. Fast Northward Energy Transfer in the Atlantic due to Agulhas Rings. Journal of Physical Oceanography 37: 2305–2315.

Wang YV, Leduc G, Regenberg M, Andersen N, Larsen T, Blanz T & Schneider RR 2013. Northern and Southern Hemisphere controls on seasonal sea surface temperatures in the Indian Ocean during the last deglaciation. Paleoceanography 28(4): 619–632.

Webb III T & Bartlein PJ 1992. Global changes during the last 3 million years: climatic controls and biotic responses. Annual review of Ecology and Systematics 23(1): 141–173.

Weijer W, De Ruijter WPM, Sterl A & Drijfhout SS 2002. Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy. Global Planet Change 34: 293–311.

Williams GP & Bryan K 2006. Ice age winds: An aquaplanet model. Journal of climate 19(9): 1706–1715.

Woollings T, Gregory JM, Pinto JG, Reyers M & Brayshaw DJ 2012. Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling. Nature Geoscience 5(5): 313–317.

Zhang R & Delworth TL 2006. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. Geophysical research letters 33(17).