

The Agulhas Current System as an Important Driver for Oceanic and Terrestrial Climate

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Abstract

The Agulhas Current system around South Africa combines the dynamics of strong ocean currents in the Indian Ocean with eddy–mean flow interactions. The system includes an associated interoceanic transport towards the Atlantic, Agulhas leakage, which varies on both interannual and decadal timescales. Agulhas leakage is subject to a general increase under increasing greenhouse gases, with higher leakage causing a warming and salinification of the upper ocean in the South Atlantic. The far-field consequences include the impact of the

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Agulhas Current on the Benguela Upwelling system, a major eastern boundary upwelling system that supports a lucrative fishing industry. Through sea surface temperatures and associated air–sea fluxes, the Agulhas Current system also influences regional climate in southern Africa, leading to a heterogeneous pattern of rainfall over southern Africa and to a reduction of precipitation in most areas under global warming conditions. Changes in the Agulhas Current system and the regional climate also cause changes in regional sea-level and wind-induced waves that deviate from global trends. Combining these oceanic changes with extreme precipitation events, global warming can considerably amplify flood impacts along the coast of South Africa if no adaptation measures are implemented.

8.1 Introduction

The waters around South Africa host a unique setting of ocean currents and water masses that is mainly determined by the Agulhas Current system, one of the world's most intense and vigorous western boundary current systems. Owing to the southern termination of the African continent being located further north than the other continents in the Southern Hemisphere, circulation and hydrography of the Agulhas Current system are impacted by both the Atlantic and Indian Ocean dynamics. In turn, the Agulhas Current system also is an important driver of global oceanic climate, in particular, of the Atlantic Meridional Overturning Circulation (AMOC).

We start our chapter with an outline of the characteristics and dynamics of the Agulhas Current flowing southward along the South African coast (Sect. 8.2).

A significant portion of the Agulhas Current provides an interoceanic transport of mass, heat, and salt into the South Atlantic. This “Agulhas leakage” becomes part of the global overturning circulation and has far-field implications for the Atlantic circulation and hydrography. This includes a direct impact on one of the world's four highly productive eastern boundary upwelling systems: the Benguela Current upwelling system. Dynamics and oceanic impacts of Agulhas leakage are analysed in Sect. 8.3.

Both the Agulhas Current east of Africa and Agulhas leakage (south)west of Africa influence the regional climate through its impact on sea surface temperature and associated air–sea flux patterns. The result is a heterogeneous distribution of rainfall over southern Africa with drying in the future, but also potential risks for extreme events such as droughts and floodings, amplified under a warming climate (Sect. 8.4).

Changes in the Agulhas Current and leakage can affect the regional oceanic heat budget, leading, in combination with eustatic sea-level rise, to regionally variable changes in coastal sea levels. Additionally, changes in climatic drivers (e.g., pressure, wind) can potentially affect the characteristics of waves, which constitute a primary driver of coastal flooding in the region. Together, those changes in the

oceanic drivers, increased precipitation, and river discharge can exacerbate coastal impacts through compound flooding along the South African coasts (Sect. 8.5).

Here we provide an introduction to the individual components of the Agulhas Current system, their temporal evolution during ongoing anthropogenic climate change, and their impact on oceanic and terrestrial climate, as well as flood vulnerability of African coastlines. The individual sections contain new insights from research within the project “Changes in the Agulhas System and its Impact on Southern African Coasts” (CASISAC, BMBF grant 03F0796). An important aspect of this chapter is the thread evolving from basic understanding to predictions and to impact studies, while specific details are published in separate topical studies. Technically, this chapter follows a chain of high-resolution ocean models under past atmospheric conditions, climate and wave models under future conditions, towards impact studies with direct socio-economic consequences in a changing climate.

8.2 The Agulhas Current

The Agulhas Current is the western boundary current of the South Indian Ocean (Lutjeharms 2006). Its structure and transport are shaped by a combination of wind-related and thermohaline drivers from the atmosphere. While the trade winds over the Indian Ocean set up a horizontal basin-scale circulation in the Indian Ocean (Biaostoch et al. 2009; Loveday et al. 2014), an additional global component arrives from the Pacific Ocean (Le Bars et al. 2013; Durgadoo et al. 2017). As a result, the Agulhas Current flows southward along the South African coast in the Indian Ocean and transports warm and saline waters from equatorial to higher latitudes. The combination of its own inertia and the westerly winds in the Southern Hemisphere cause the Agulhas Current to overshoot the southern tip of Africa and to retroflect back into the Indian Ocean. Since this retroflexion is not complete, a significant part of the Agulhas Current finds its way into the South Atlantic. This “Agulhas leakage” combines the subtropical gyres in the Indian Ocean and the South Atlantic towards one “supergyre” (Speich et al. 2007; Biaostoch et al. 2009). Agulhas leakage is not only a direct inflow, but also happens in the form of mesoscale Agulhas rings and filaments, which make the region around southern Africa one of the most eddying regions in the world ocean (Chelton et al. 2011).

Fully constituted at $\sim 27^\circ$ S, the Agulhas Current flows with surface velocities of 1.5 m s^{-1} and above (Lutjeharms 2006). At 32° S, it reaches down to below 2000 m, in a typical v-shaped profile that hugs the African continental slope. With a width of 200 km, it transports more than 75 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) (Bryden et al. 2005). Owing to recirculations in the Southwest Indian Ocean Subgyre, the transport increases and reaches 84 Sv at $\sim 34^\circ$ S (Beal et al. 2015). On its further way towards the south, the shelf widens, leaving more room for evolving instabilities. South of Cape Agulhas, the Agulhas Current flows into the South Atlantic, before it abruptly turns back towards the east into the Indian Ocean as the Agulhas Return Current (Lutjeharms 2006). The dynamics of the retroflexion are still not fully understood but built on a combination of the inertia of the current, the bathymetry, and the

strength and position of the westerlies (Beal et al. 2011). At the retroflexion, large mesoscale meanders are generated by loop exclusion as well as barotropic and baroclinic instabilities, leaving Agulhas rings with diameters of several 100 km and velocities reaching below 2000 m depth as a prominent characteristic (Van Aken et al. 2003b). Agulhas rings transport warm and saline waters from the Indian Ocean into the Atlantic Ocean and act as contributors to the surface branch of the Atlantic Meridional Overturning Circulation (AMOC), although the major portion recirculates in the subtropical gyre within the South Atlantic (Speich et al. 2001; Beal 2009; R  hs et al. 2019).

Velocities and transport of the Agulhas Current are subject to temporal variability at a range of different timescales. The seasonal cycle with a minimum in austral winter and a maximum in austral summer is related to the wind field driving the subtropical gyre in the Indian Ocean (McMonigal et al. 2018). Although parts of the interannual variability have been linked to El Ni  o/Southern Oscillation (ENSO), the dominant mode of interannual variability in the Pacific Ocean (Putrasahan et al. 2016; Elipot and Beal 2018), it was also shown in a model study that the Agulhas Current can generate a year-to-year variability in the range of the observed variability through internal instabilities (Biastoch et al. 2009).

A prominent feature of the Agulhas Current is the intermittent perturbations that impact the Agulhas Current. These ‘‘Natal Pulses’’ occur ~ 1.6 times per year (Elipot and Beal 2015) but strongly vary from year to year (Yamagami et al. 2019). Caused by eddy–mean flow interaction of arriving mesoscale eddies from the Mozambique Channel and from the South-East Madagascar Current (Biastoch and Krauss 1999), the Natal Pulses rapidly travel downstream and have the potential to generate the shedding of Agulhas rings (Schouten et al. 2002).

Figure 8.1 shows the circulation around South Africa as simulated in the eddy-rich ocean general circulation model INALT20 (Schwarzkopf et al. 2019) driven by the recent JRA55-do atmospheric forcing dataset (Tsujino et al. 2018) over the past six decades from 1958 to 2019. The Agulhas Current is fed by flow through the Mozambique Channel and the South-East Madagascar Current and reaches highest mean south-westward velocities of 1.6 m s^{-1} at $\sim 33.5^\circ \text{ S}$. On its way further south, the Agulhas Current crosses the location of the Agulhas Current Timeseries (ACT) array (Beal and Elipot 2016, indicated by the black line in Fig. 8.1a) before it detaches from the coast. At the ACT transect, the Agulhas Current is represented by a ~ 350 -km-wide coastal, surface-intensified current reaching down to ~ 1500 m depth (Fig. 8.1c). Further downstream, it changes its direction towards the west, where it retroflects between 15° E and 20° E into the meandering Agulhas Return Current back into the Indian Ocean. Although the 20-year mean surface velocity shows a straight path of the Agulhas Current and a robust meandering Agulhas Return Current, the velocity field is highly variable and eddying, not only along its main path but especially where the retroflexion takes place (Fig. 8.1b). Another area of high variability is a corridor towards the Atlantic Ocean where Agulhas rings

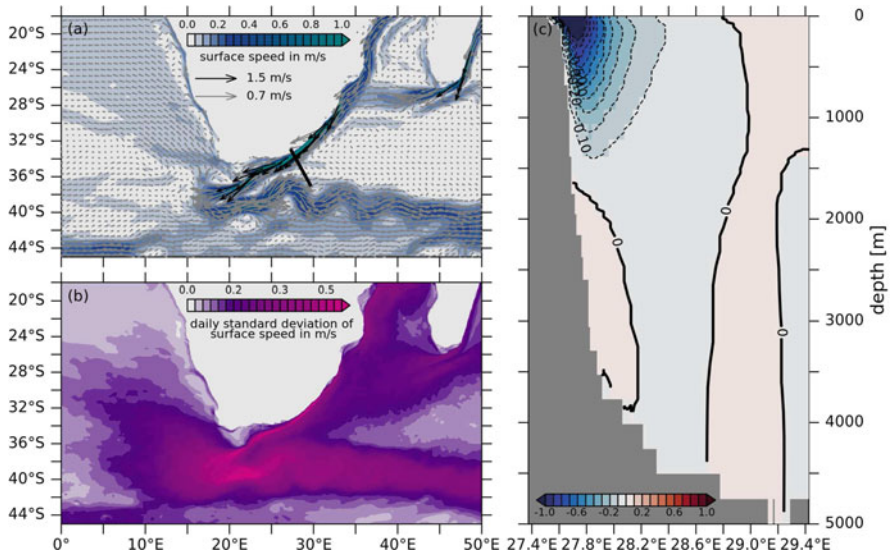


Fig. 8.1 Circulation in the Agulhas Current system around South Africa as simulated by a 1/20° ocean model (Schwarzkopf et al. 2019): (a) mean and (b) standard deviation of surface speed in the period 2000–2019 (in (a) vectors shown every 15th grid point). (c) Mean section across the Agulhas Current at ~34° S (location indicated in (a))

transport Indian Ocean waters into the neighbouring basin, contributing to Agulhas leakage.

8.3 Agulhas Leakage and Its Impact on the South Atlantic and the Benguela Upwelling System

Agulhas leakage is defined as the transfer of relatively warm and salty water from the Agulhas Current in the Indian Ocean to the South Atlantic Ocean (Lutjeharms 2006; Beal et al. 2011). It constitutes a key process of the global overturning circulation (Broecker 1991) and has been suggested to impact regional to global climate variability through various processes on a vast range of timescales (Beal et al. 2011).

Agulhas leakage occurs at the retroflexion of the Agulhas Current. It is mediated in large parts through anticyclonic Agulhas rings (Schouten et al. 2000) as well as cyclonic mesoscale eddies and filaments that are shed at the retroflexion and travel north-westward into the South Atlantic. The generation of these mesoscale features in the retroflexion region has been linked to barotropic instabilities of the Southern Hemisphere supergyre (that is, the interconnected subtropical gyres of the Atlantic, Pacific, and Indian Ocean) (Elipot and Beal 2015; Weijer et al. 2013), but individual ring shedding events can further be impacted by mesoscale upstream

perturbations (Biastoch et al. 2008; Schouten et al. 2002) as well as regional sub-mesoscale variability (Schubert et al. 2019, 2021).

The turbulent and intermittent (sub-)mesoscale eddy-driven component makes Agulhas leakage difficult to measure. Different approaches to estimate its magnitude and variability from ocean observations were introduced. The evaluation of subsurface floats and surface drifter pathways yielded the canonical number of 15 Sv for the leakage transport in the upper 1000 m (Richardson 2007) and a more recent estimate of 21 Sv for the upper 2000 m (Daher et al. 2020). The imprints of Agulhas leakage on observed sea surface height (Le Bars et al. 2014) and sea surface temperature (Biastoch et al. 2015) patterns have been used to reconstruct timeseries of Agulhas leakage transport anomalies, revealing a large interannual to decadal variability. However, the observation-based estimates are limited in time and associated with great uncertainties.

To test the observation-based estimates, to retrieve timeseries over a longer time period, and to better understand the processes that determine Agulhas leakage variability, ocean and climate models have been employed. In this context, Lagrangian model analysis (van Sebille et al. 2018) has proven particularly valuable (see Schmidt et al. 2021 for a review and comparison of the different Lagrangian tools and experiment designs used to estimate Agulhas leakage). Model-based studies suggest that interannual to decadal variability in Agulhas leakage can be related to larger-scale changes in the Southern Hemisphere winds (Biastoch et al. 2009; Durgadoo et al. 2013; Cheng et al. 2018). Moreover, they indicate that Agulhas leakage has increased since the 1960s (Biastoch et al. 2009; Rouault et al. 2009), due to a strengthening in the westerlies caused by increasing anthropogenic greenhouse gases and ozone depletion (Biastoch and Böning 2013; Ivanciu et al. 2021). A continuation of Agulhas leakage strengthening during future climate change and a resulting enhanced transport of salt into the South Atlantic may stabilise the Atlantic Meridional Overturning Circulation (Weijer et al. 2002; Biastoch and Böning 2013; Biastoch et al. 2015), while warming and ice sheet melting are projected to weaken it (Beal et al. 2011).

Nevertheless, due to, e.g., (i) outstanding challenges in correctly representing Agulhas leakage in ocean and climate models (at minimum mesoscale resolving resolution is needed), (ii) the dependence of ocean-only model simulations on the availability and accuracy of the atmospheric forcing, as well as (iii) uncertainty regarding the future emission of anthropogenic greenhouse gases (GHGs) and the potential recovery of the ozone depletion, there are still many open questions regarding past and future changes of Agulhas leakage and their impact on climate (change).

The exact temporal evolution of Agulhas leakage, in particular over the last decades, is still ambiguous. While some ocean model simulations (for example, a simulation in INALT20 under CORE forcing Schwarzkopf et al. 2019) indicate a nearly continuous increase since the mid-1960s that further accelerates in the 1990s and 2000s, other model simulations (for example, a simulation in INALT20 under JRA55-do forcing Schmidt et al. 2021) and observation-based reconstructions (for example, a timeseries reconstructed from HadISST Biastoch et al. 2015) do not

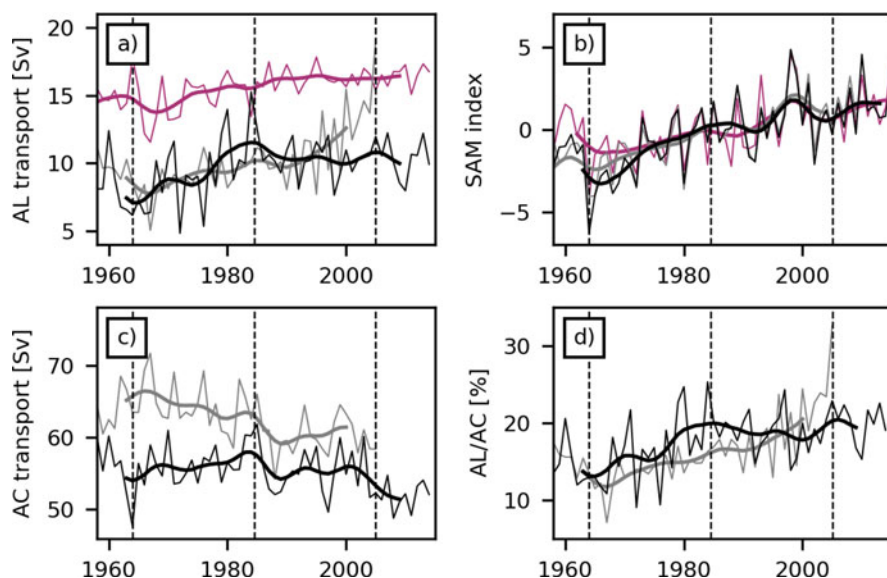


Fig. 8.2 Temporal evolution of (a) Agulhas leakage (AL), (b) annual Southern Annular Mode (SAM) index calculated following Marshall (2003), (c) Agulhas current (AC), and (d) ratio AL / AC within simulations with the eddy-rich ocean model configuration INALT20 under JRA55-do forcing (Schmidt et al. 2021, black) and CORE forcing (Schwarzkopf et al. 2019, gray). An AL timeseries reconstructed from HadISST (Biaostoch et al. 2015, pink line in (a)) and the station-based annual SAM index (pink line in (b)) are also shown

exhibit a significant trend over the full time period and show a levelling since the 1990s (Fig. 8.2a). Previous studies suggest that the different temporal evolutions of Agulhas leakage could be due to a different representation of the wind fields in the different atmospheric forcing datasets. However, such a relationship is not trivial and cannot be represented by simple integrative parameters such as the proposed Southern Annular Mode index (SAM, a measure of the strength of the westerly winds that shows only minor differences between the different simulations, Fig. 8.2b). It should also be emphasised that not only the temporal evolution of Agulhas leakage differs between the different simulations, but also that of other components of the Agulhas Current system. In particular, in contrast to Van Sebille et al. (2009) but consistent with Loveday et al. (2014), Durgadoo et al. (2013), Cheng et al. (2018), there is no clear relationship between the temporal evolution of the strength of the Agulhas Current and Agulhas leakage (Fig. 8.2c). Rather, interannual and longer-term fluctuations in Agulhas leakage represent a changing proportion of the transport of the Agulhas Current flowing into the South Atlantic (Fig. 8.2d). Hence, Agulhas leakage and Agulhas Current variability are driven by distinct processes and show different responses to changes in Southern Hemisphere winds. While the Agulhas Current responds to larger-scale changes in subtropical wind curl, including westerlies and trades and their modulation via ENSO (Elipot

and Beal 2018), Agulhas leakage mainly responds to more regional changes in the westerlies (Durgadoo et al. 2013). However, changes in the winds alone cannot fully explain interannual to decadal Agulhas Current and leakage variability, and more research is required to better understand additional drivers as well as potential modes of intrinsic variability.

The future temporal evolution of the Agulhas leakage transport will strongly depend on the changes experienced by the Southern Hemisphere westerly winds. The fate of the westerlies during the twenty-first century is controlled by two opposing factors: the increase in GHG concentrations and the recovery of the Antarctic ozone hole. The impact of these two factors on the westerlies, and hence on Agulhas leakage, was studied using three ensembles of three simulations: one ensemble included only the increase in GHGs, following the high-emission scenario SSP5-8.5 (Meinshausen et al. 2020), one ensemble included only the recovery of the ozone hole, and one ensemble included both. The simulations were performed with the coupled climate model FOCI (Matthes et al. 2020), which calculates the stratospheric ozone chemistry interactively and in which the ocean around southern Africa is represented at 0.1° horizontal resolution in order to resolve the mesoscale features of the region (FOCI_INALT10X Matthes et al. 2020).

Timeseries of the westerly winds and of Agulhas leakage in the three ensembles are depicted in Fig. 8.3e and f, respectively. The increase in GHGs leads to a pronounced poleward intensification of the westerlies and, as a result, to a positive Agulhas leakage trend of 0.36 ± 0.12 Sv per decade until the end of the century. This translates in about 28% more Agulhas leakage entering the Atlantic Ocean at the end of the twenty-first century compared to the current day. In contrast, the recovery of the ozone hole leads to a weakening of the westerly winds and to a weak but significant decrease in Agulhas leakage of -0.13 ± 0.12 Sv per decade. This implies that, in the absence of an increase in GHGs, Agulhas leakage would be 7% weaker at the end of the century compared to today. When the impacts of ozone recovery and increasing GHGs are considered together, the impact of the increasing GHGs dominates. Agulhas leakage exhibits a trend of 0.18 ± 0.12 Sv per decade, which implies an increase of 13% at the end of the century compared to today. These results are dependent on the high-GHG-emission scenario used.

The future increase in Agulhas leakage has implications for the Atlantic Ocean. The waters contained in Agulhas rings are warmer and more saline compared to the surrounding waters (Van Aken et al. 2003b). Observations of Agulhas rings (Van Aken et al. 2003b; Giulivi and Gordon 2006) revealed that below a well-mixed surface layer, the rings carry subtropical mode water formed in the southwestern Indian Ocean, South Indian Ocean Central Water, and Sub-Antarctic Mode Water, while in the underlying intermediate layer the Antarctic Intermediate Water dominates, but the Red Sea Water is also present. As parts of Agulhas leakage feed into the upper limb of the AMOC, changes in its transport are linked to changes in the thermohaline properties of the Atlantic Ocean. This is revealed by a composite analysis, whereby low-pass filtered (5-year cut-off period) and detrended temperature and salinity anomalies were selected for the years when Agulhas leakage exceeded the 90th percentile of its distribution (Fig. 8.3). Periods

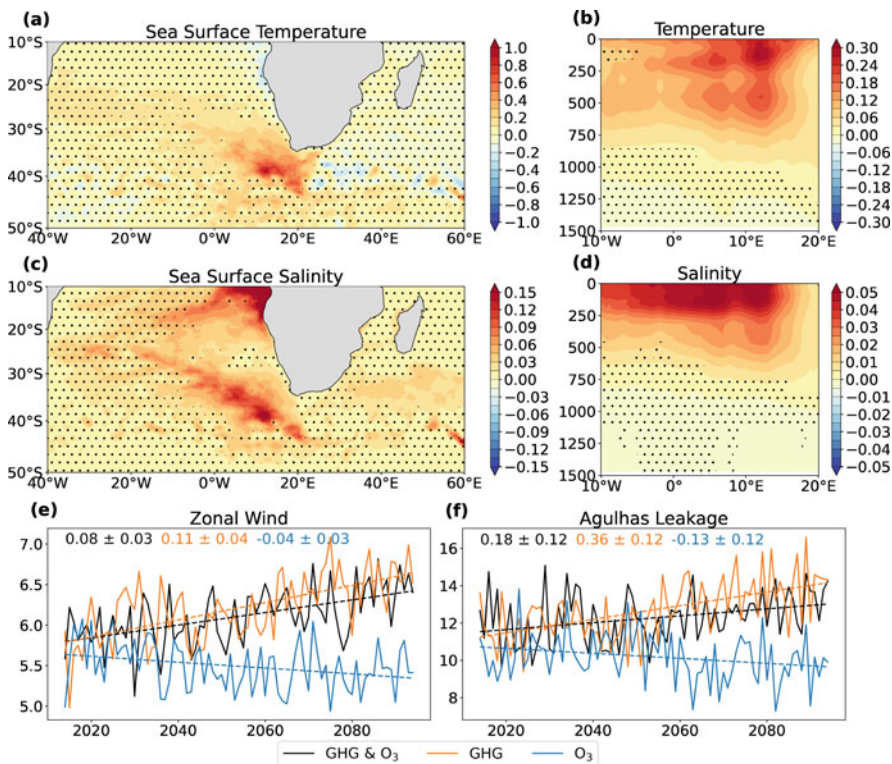


Fig. 8.3 Composites of (a) sea surface temperature anomalies, (b) temperature anomalies averaged over 20° S–40° S, in °C, (c) sea surface salinity anomalies, and (d) salinity anomalies averaged over 20° S–40° S for the years when Agulhas leakage exceeds the 90th percentile of its distribution. The output from the simulations with fixed GHGs was used. The anomalies, as well as Agulhas leakage, were low-pass filtered to retain variations with periods above 5 years and a linear trend was removed. The stippling masks anomalies that are not significantly different from the time mean according to the Monte Carlo method. Timeseries of (e) zonal mean zonal wind averaged between 45° S–60° S, in m s⁻¹, (f) Agulhas leakage in Sv for the ensemble (which may average out some of the individual ensemble members in this highly stochastic process) that includes only ozone recovery (blue), only the increase in GHGs (orange), and both forcings (black). The dashed lines depict the corresponding linear trends, and the numbers at the top of the panels give the values of the trends per decade

of high Agulhas leakage are associated with positive sea surface temperature (SST) and surface salinity anomalies, which propagate north-westward from the Agulhas retroflection region into the South Atlantic (Fig. 8.3a, c). These temperature and salinity anomalies extend below the surface, as seen in Fig. 8.3b and d, which shows the vertical profile of the anomalies averaged over the latitudinal band 20° S–40° S. The temperature anomalies extend down to 1000 m, while significant salinity anomalies can be found down to about 750 m. Therefore, an increase in Agulhas leakage leads to a warming and salinification of the South Atlantic. While the model

does not exhibit salinity anomalies at intermediate depth, observations of Agulhas rings found positive salinity anomalies at these depths marking the presence of Red Sea Intermediate Water (van Aken et al. 2003a). The temperature anomalies appear to decay westward faster than the salinity anomalies do, as they are damped at the surface by heat release to the atmosphere. There is observational and modelling evidence that waters originating from the Agulhas region reach the North Atlantic and its deep convection regions (van Sebille et al. 2011; Biastoch and Böning 2013; Weijer and van Sebille 2014). From the Agulhas Current, the most frequent transit time to the North Brazil Current is 7 years (Rühs et al. 2019), to 26° N one to two decades (Rühs et al. 2013), and to the deep convection regions between one and four decades (van Sebille et al. 2011). These are estimates for the peak in the distributions of the transit times to the specific locations. The fastest reported transit time of Agulhas waters to the North Atlantic is only 4 years (van Sebille et al. 2011). The Agulhas thermohaline anomalies can potentially affect the AMOC. The positive Agulhas leakage trend predicted for the twenty-first century will contribute to the warming of the South Atlantic, as discussed in more detail in Sect. 8.4.

While Agulhas leakage has an important role to play in the Indo-Atlantic ocean exchange segment of the global conveyor belt circulation, it also establishes the direct interaction between a western and an eastern boundary current system that is unique among the world's oceans. This results in a region of intense turbulence (Matano and Beier 2003; Veitch and Penven 2017) within the Cape Basin where features associated with Agulhas leakage interact with those of the highly productive southern Benguela upwelling system that supports a lucrative fishing industry. This high level of turbulence has been shown to result in enhanced lateral mixing and reduced surface chlorophyll (Rossi et al. 2008) and, therefore, productivity within the Cape Basin. More direct impacts of the Agulhas on the Benguela upwelling system include its contribution to the development of a shelf-edge jet current (Veitch et al. 2017) that transports fish eggs and larvae from their spawning ground on the Agulhas Bank to their nursery area within St Helena Bay (Shelton and Hutchings 1982; Fowler and Boyd 1998). Furthermore, this jet current presents a barrier to cross-shelf exchanges (Barange et al. 1992; Pitcher and Nelson 2006) on the southern Benguela shelf, which helps to promote both the concentration of upwelled nutrients and nearshore retention, thereby enhancing productivity. Additionally, Agulhas Rings have been observed to have a role to play in the generation of large upwelling filaments that have the potential to cause the offshore advection of large quantities of nutrient-rich waters (Duncombe-Rae et al. 1992). The characteristics of the upwelling source waters of the southern Benguela are a key component of the productive marine ecosystem.

They enter the system directly from the south (Tim et al. 2018) via Agulhas rings at the continental slope, causing cross-shelf intrusions of water (and its properties) from the Agulhas leakage into the upwelling region (Baker-Yeboah et al. 2010).

8.4 Impact on Climate in Southern Africa

Southern African climate is strongly modified by the high-altitude interior plateau and the termination of the relatively narrow landmass in the mid-ocean subtropics that allows the Agulhas to flow in close proximity to the Benguela upwelling system. As a result of these moderating oceanic and topographic factors, surface land temperatures are typically less extreme in southern Africa than would be expected, and there are important implications for weather system development and rainfall patterns.

As a simple example, Durban ($29^{\circ} 53'S$) on the east coast adjacent to the Agulhas has an annual mean rainfall of 1019 mm compared to about 50 mm for Alexander Bay ($28^{\circ} 35'S$) on the west coast in the central Benguela upwelling system. Annual mean temperatures at Durban are almost $5^{\circ}C$ warmer than those at Alexander Bay. The influence of the broader Agulhas Current region on South African climate in particular has long been recognised. Large surface heat fluxes were associated with the southern Agulhas Current (Walker and Mey 1988). Latent heat fluxes in the central Agulhas Current (south of Port Alfred) have been found to be about 75% greater in the core of the current than further seawards and up to about 7 times greater than those measured inshore of the current, leading to modifications of the marine boundary layer and large increases in precipitable water content as air advected across the current (Lee-Thorp et al. 1999). These high fluxes associated with the core of the current are difficult to represent in operational models since it is typically only $\sim 70\text{--}80$ km wide (Rouault et al. 2003). Statistical relationships between interannual variability of SST in the Agulhas Current and summer rainfall over central and eastern South Africa were found (Walker 1990; Mason 1995). Evidence that the relative proximity of the Agulhas Current core to the coastline helps to account for the large increase in average rainfall along the east coast was given (Jury et al. 1993). For example, Port Elizabeth ($\sim 34^{\circ} S$), where the continental shelf is wide and the current far from the coast, has an annual average rainfall of 624 mm, whereas Durban ($\sim 30^{\circ} S$) with its narrow shelf is much wetter on average (1019 mm). Given that South Africa is semi-arid but with generally mild temperatures, most research on the influences of the Agulhas Current on regional climate has focused on rainfall or on the development of rain-producing weather systems. Emphasis has also typically been placed on the summer half of the year, since this is by far the dominant rainfall season over almost all of southern Africa.

Various model studies have explored relationships between SST variability in the Agulhas Current region and southern African rainfall together with the potential mechanisms involved. In the simplest case, these studies have imposed idealised SST anomalies in the South-West Indian Ocean on the climatological SST forcing fields applied to coarse resolution atmospheric general circulation models (AGCMs). Warming in the Agulhas region resulted in statistically significant increased rainfall over southeastern Africa via enhanced latent fluxes over the SST anomaly, and advection of the anomalously moist unstable air towards the landmass (Reason and Mulenga 1999). While the greatest model response was

found in summer, there were also large rainfall increases in autumn and particularly spring. In a similar idealised AGCM experiment, it was found that smoothing out the current so that the observed SST in the broader Agulhas Current region was replaced by zonally averaged SST and hence cooled led to a southward shift and weakening of midlatitude cyclonic weather systems tracking south of South Africa and reduced rainfall over southern South Africa (Reason 2001). The same type of experiment was performed about two decades later with a regional climate model (Nkwinkwa Njouodo et al. 2018). The results confirmed earlier work that the core of the Agulhas Current is associated with sharp gradients in SST and sea-level pressure, together with a band of convective cloud, and sometimes rainfall. Under favourable synoptic conditions, rainfall can then also occur over the nearby coastal landmass. There is evidence that SST gradients associated with Agulhas Current eddies and meanders affect the vertical air column up to the tropopause (Desbiolles et al. 2018).

Other experiments have provided evidence that latent heat fluxes from the Agulhas Current can significantly impact the rainfall over coastal South Africa of high-impact weather events such as cut-off lows (Singleton and Reason 2006, 2007) and mesoscale convective systems (Blamey and Reason 2009). In all cases, the presence of a low-level wind jet blowing across the current towards the land was important in transporting moist, unstable air that, when forced to rise by the coastal mountains, led to heavy rainfall. By removing the effect of the current in the model, it was shown that most of the moisture transported by the jet evaporated off the current.

Over eastern South Africa, long-lived mesoscale convective systems, which are often associated with heavy rainfall in summer, tend to occur downstream of the Drakensberg mountains and over the northern Agulhas Current where convective available potential energy (CAPE) and wind shear environments are favourable (Morake et al. 2021). More generally, the northern Agulhas Current and adjacent southeastern Africa have been identified as one of the convective hotspots in the global atmosphere (Brooks et al. 2003; Zipser et al. 2006). Lagrangian trajectory analyses have confirmed that the Agulhas Current is one of the important moisture sources for summer rainfall over a large interior region in subtropical southern Africa (the Limpopo River Basin) on both seasonal and synoptic scales (Rapolaki et al. 2020, 2021). However, its role seems to be one of enhancing moisture uptake along the trajectory path (which often originates in the midlatitude South Atlantic), associated with large-scale weather systems such as ridging anticyclones and cloud bands, rather than as a source region in its own right. Nevertheless, summer dry spell frequencies (the number of wet days) have decreasing (increasing) trends between 1981–2019 over the Eastern Cape/central South Africa related to changes in moisture fluxes / winds over the southern Agulhas Current region (Thoithi et al. 2021).

In terms of the southern Agulhas Current region, there are as yet no continuous measurements of the strength of the Agulhas leakage here. Thus, analysis of the impact of this leakage on regional climate has usually been based on their inferred fingerprints on oceanic sea surface temperatures. For instance, a stronger advection

of warm water masses from the Indian Ocean by a stronger leakage leads to warmer sea surface temperatures in the southeast Atlantic. Due to this data limitation, the simulations with ocean–atmosphere models have been conducted to provide more direct analysis of the regional climate anomalies that, in the simulations, may be correlated with the intensity of the Agulhas Current and leakage. These simulations also allow for a quantification of their contribution to the long-term trends of regional precipitation, and this is both in the current and in projected future climate. In the following, we summarise some of these analysis obtained for both periods with the global coupled ocean–atmosphere model (FOCI_INALT10X Matthes et al. 2020), with interactive ozone chemistry, used in Sect. 8.3) for the past (1951–2013) and future (2014–2099, SSP5-8.5 scenario). These simulations were used to drive a high-resolution regional atmospheric model (CCLM, COSMO model in CLimate Mode, <https://www.clm-community.eu/>) that can better represent regional precipitation (Tim et al. 2023). Agulhas leakage is defined here as the amount of water crossing the Good Hope Line within a 5-year window, thus leaving the Agulhas system and entering the South Atlantic (Tim et al. 2018). A similar study based on a different atmosphere–ocean global model CCSM3.5 had previously been conducted for the current period (Cheng et al. 2018), and thus we can assess the robustness of the results when a different model is used.

In the simulations of the current and future climate, a stronger Agulhas leakage leads, as expected, to warmer SST southwest of the Western Cape region as mentioned in the previous section (Fig. 8.3a). This results in a relatively high-positive temporal correlation ($r = \sim 0.5$) between Agulhas leakage and SST in the Agulhas retroflection region, southwest of it, and in the corridor where Agulhas rings transport warm Indian Ocean water into the South Atlantic. The increase in Agulhas leakage over the last decades (as described in the previous section) and the warming of the Agulhas Current system (Rouault et al. 2010, 2009) both result in warming of the SSTs southwest of the Western Cape region, up to 2 °C (historical period) and 4 °C (in the scenario period). A linear regression analysis of the simulated temperature and leakage timeseries indicates that around 1/6 of both warming rates is due to the increase of Agulhas leakage.

In the historical period, Agulhas leakage and precipitation along the southeast coast of South Africa are found to be positively correlated (Fig. 8.4a). A more intense Agulhas leakage imprints the SSTs patterns in the region, with warmer SSTs in the retroflection region and colder SSTs in the southwest Indian Ocean. Warmer SSTs are linked with higher convective precipitation at the southeast coast of South Africa during summer (Walker 1990), a result also found in the simulations with the model CCSM3.5 (Cheng et al. 2018). By contrast, the correlations of Agulhas leakage with precipitation in the winter rainfall zone around the Western Cape region are negative (Fig. 8.4a), as also found by Cheng et al. (2018). This may be due to the modification of cyclonic activity by the SSTs in this season, as discussed before. Concerning the long-term trends, the simulated precipitation displays a weak negative trend in most of southern Africa, with some precipitation intensification along the southeast coast (Fig. 8.4c). Around 1/10 of this trend can be statistically explained by Agulhas leakage (Fig. 8.4e). The areas with a positive

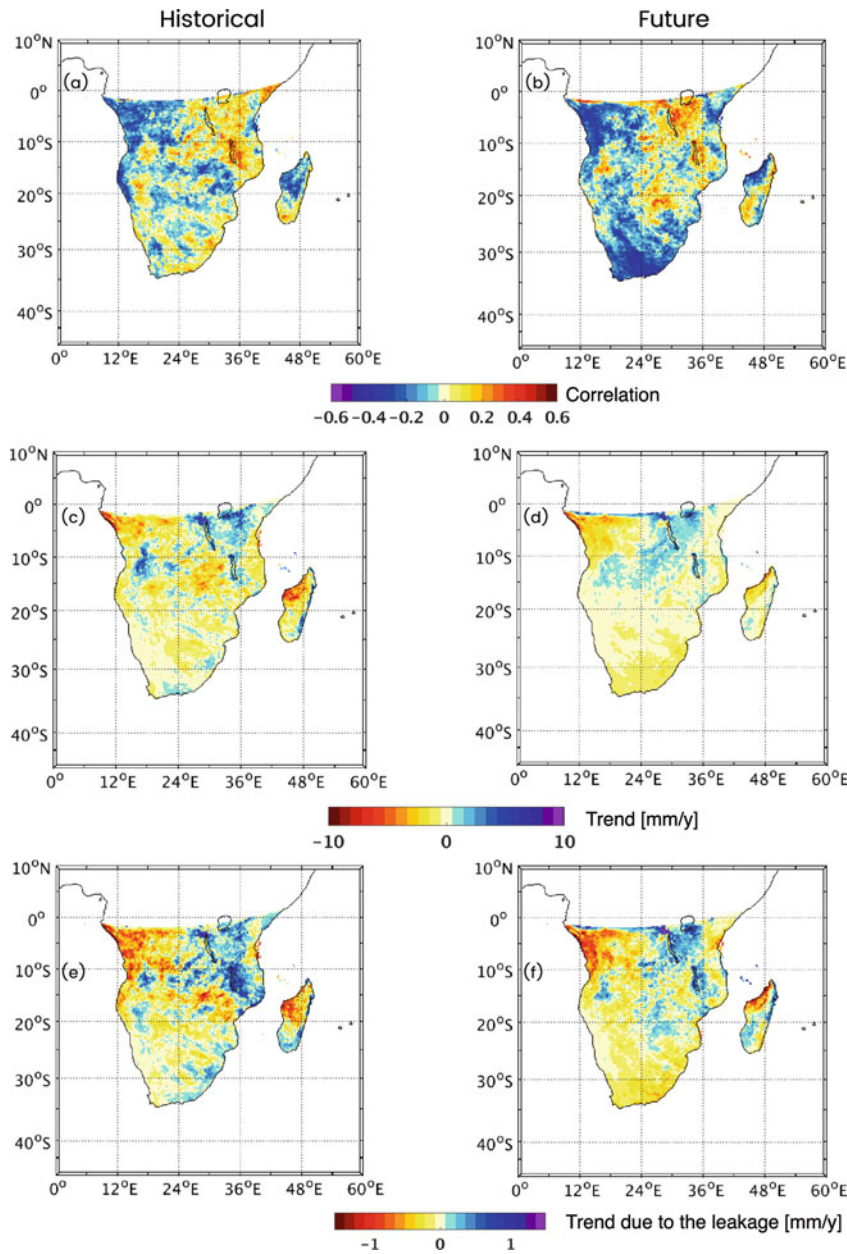


Fig. 8.4 The correlation of (a, b) Agulhas leakage (FOCI simulation) and the precipitation (CCLM simulation), (c, d) the precipitation trend over the simulation period, and (e, f) the contribution of Agulhas Leakage to the precipitation trend, in the (left column) historical simulation covering the period 1951–2013 and (right column) the scenario simulation covering the period 2014–2099. At a significance level of 95%, correlations of (a) 0.26 and (b) 0.22 and larger are significant. Based on typical standard deviation, precipitation trends of (c) 1.2 mm/y and (d) 0.76 mm/y and larger are significant

precipitation trend are also the ones that are positively correlated to the leakage. In the Western Cape region (Fig. 8.4d), precipitation displays a long-term decline. Both trends reflect the long-term impact of the intensifying leakage on precipitation at the southeast coast of South Africa.

Regarding changes in precipitation in the future scenario simulation, Agulhas leakage and precipitation in South Africa appear negatively correlated (Fig. 8.4b), contrary to the historical period. Thus, the simulation indicates both an intensification of leakage and a diminishing precipitation along the whole coast and the southern inland, as also found by, e.g., Dosio et al. (2019) and Rojas et al. (2019). Again, around 1/10 of the trend in precipitation is due to Agulhas leakage (Fig. 8.4f). The change in the dependency of Agulhas leakage strength and precipitation comparing the current and future periods requires further investigation. One explanation could be related to the southward shift of the Agulhas Current in the future scenario. According to this explanation, Agulhas leakage intensifies, while the Agulhas Current weakens (Ivanciu et al. 2022) and is displaced poleward away from the coast (Yang et al. 2016). As found by Jury et al. (1993), the precipitation at the southeast coast is stronger when the core of the Agulhas Current is located closer to the coast. This leads us to the conclusion that the future trend in simulated precipitation in the winter rainfall zone may be directly linked to the strength of the Agulhas leakage, whereas the trend in precipitation at the southeast coast may be more strongly linked to the position and intensity of whole Agulhas Current system. It should be, however, kept in mind that other remote influences, for instance that of ENSO, can also modulate precipitation trends in this region (see Chap. 6).

8.5 Impact on Coasts

With more than 2500 km of coastline, South Africa is largely exposed to flooding and erosion from extreme water levels and waves. The majority of the largest South African cities such as Cape Town and Durban are located at the coastline, comprising around 40% of the South African population and 60% of the country's economy (CSIR 2019). Exposure to coastal hazards is further exacerbated by socio-economic development. Coastal cities are growing and developing at a rapid rate (ASCLME/SWIOFP 2012), with some areas of the coast having experienced a building boom over the past two decades (Smith et al. 2007). The main ports of South Africa such as Durban, Cape Town, and Port Elizabeth/Gqeberha are located in big cities along this coastline and provide the largest trades for the region (Mather and Stretch 2012). In addition, the tourism sector has a large contribution to the economy of the country (Fitchett et al. 2016). However, the risk of flooding has not been taken into account in coastal development planning, and several coastal cities, such as those previously mentioned as well as resorts, are built in low-lying areas, estuaries, and beachfront close to the high-water mark (Theron and Rossouw 2008; Mather and Stretch 2012), where the probability of flooding is often the highest.

As a result, coastal flooding and erosion from extreme events can potentially cause large damages along the South African coastline. This was the case in March

2007, when a combined spring tide and extreme swells produced up to a billion Rand (about 70 Mill €) of damages along the region of KwaZulu-Natal, South Africa (Smith et al. 2007). Despite these large damages, the event of March 2007 is estimated of having an average return period of only 10–12 years (Palmer et al. 2011). As was the case in the event of March 2007, flooding can arise from a combination of different drivers such as tides, waves, and storm surges but also in combination with precipitation and river discharge. These so-called compound events are particularly important for estuarine areas, where the interaction between the flood drivers can exacerbate flood impacts (Zscheischler and Seneviratne 2017).

Changes in the climate of the region due to changes in the circulation and atmospheric patterns discussed in former Sects. 8.2, 8.3, and 8.4 may lead to changes in the flood drivers and sea level. The IPCC AR6 (IPCC 2021) estimates a likely global mean sea-level rise (SLR) by 2100 up to 1.01 m under a very high emissions scenario (SSP5-8.5, upper likely range). However, higher sea-level rise scenarios above the likely range cannot be excluded due to large uncertainties in the ice sheet processes. In addition, regional deviations from the global estimates can be expected along the South African coastline as the west coast is dominated by variations in offshore buoyancy by the Benguela system (such as those caused by wind-driven coastal Kelvin waves) (Schumann and Brink 1990), while water levels along the east coast are influenced by fluctuations in the Agulhas Current system (van Sebillie et al. 2010). However, the effects of the Agulhas System on coastal sea levels are not fully understood due to the variability of several characteristics of the Agulhas current system (e.g., position of the core, eddies) and the lack of in situ measurements (Nhantumbo et al. 2020).

In addition, future warming of the ocean will not be spatially uniform, so regional differences in the thermal expansion of the water column are also expected (Yin et al. 2010). For instance, the sea-level trend in the period 1992–2018 monitored by satellite altimetry shows that along the southern African coastline sea level has risen (Hamlington et al. 2020) faster than the global rate of 3.1 mm/year over the same period (Cazenave et al. 2018). However, the data from tidal-monitoring stations near Cape Town in the period 1957–2017 display temporal data gaps, especially in the last decades of the twentieth century, a situation that is common in Africa (Woodworth, Philip L. et al. 2007) and the linear trend derived from those data points to a rate of sea level of about 2 mm/year (Dube et al. 2021a). This is in agreement with the results of the analysis of the Durban tide gauge (Mather 2007), and of other Namibian and South African tide gauges (Mather et al. 2009). Nevertheless, even along the southern African coast, regional differences in the relative sea-level trends are apparent, with sea level along the east coast having risen more rapidly (2.7 mm/year) than along the south (1.5 mm/year) and the west coast (1.9 mm/year). It is therefore difficult to conclude whether sea-level rise in this area has recently accelerated, since the measurements of tidal gauges and of satellite altimetry have different characteristics and very few studies exist so far (Brundrit 1984; Mather et al. 2009). Following state-of-the-art methods and using tide gauge and altimetry records, Allison et al. (2022) suggest 7–14% higher SLR projections compared to the global IPCC estimates along the South African coastline, driven

by larger contributions of all components of the sea-level budget. However, further research is needed for establishing the effects of the Agulhas system on coastal sea levels along the South African coast and to assess the impacts of the future potential changes in the Agulhas system (discussed in Sects. 8.2 and 8.3) on coastal sea-level rise.

Mean sea-level rise and the possible intensification of sea-level extremes are expected to impact coastal regions of southern Africa, as has been observed in recent years for the Cape Town area (Dube et al. 2021b,a). Among the various flood drivers, wind waves have the relative largest contribution to total extreme water levels along the South African coastlines (Theron et al. 2010). A potential intensification of waves in this region due to a projected intensification of winds under high-GHG-emission scenarios may exacerbate present flood risks. Therefore, predicting and analysing possible changes in wave climate during this century is essential for coastal risk and impact assessments for the South African coast.

Although global wave projections for the twenty-first century under different climate change scenarios already exist (e. g. Semedo et al. 2013; Hemer et al. 2015; Casas-Prat et al. 2018; Morim et al. 2020), regional effects can be omitted due to the coarse resolution of atmospheric forcing used at global scales. In CASISAC, we generated a coherent wave hindcast (1958–2018) and wave projections (2014–2098) for a high-end scenario (SSP5-8.5), using Time Delay Neural Networks (TDNN), and downscaled atmospheric forcing from the CCLM model discussed in Sect. 8.4. To train the TDNN, we used mean sea-level pressure (MSLP) data (Kanamitsu et al. 2002) as a forcing predictor and an existing global wave hindcast (Durrant et al. 2013) based on the same reanalysis dataset as response. It is important to mention that the TDNN is able to account for the processes included in the modelling of the training data, but it is not able to capture future changes of these processes or other processes not included such as, e.g., the interaction with the Agulhas current (Grundlingh and Rossouw 1995). This interaction can produce large increases in offshore wave heights, which can be a hazard for the shipping industry, but little effects are observed in coastal waves (Barnes and Rautenbach 2020).

Results show an average increase of 0.2 m in the mean H_S (2.7 m; Fig. 8.5) and 0.6 m in the 1% highest H_S (5.3 m; Fig. 8.6). However, along the west and south coasts, the increase of the mean H_S is of 0.3 m, while a smaller increase of 0.1 m is observed at the east coast. The 1% highest H_S show a similar pattern with increases of 0.8 and 0.9 m at the west and south coast, respectively, and 0.3 m at the east coast. Distinguishing between seasons, the largest increase of 0.3 m of mean H_S appears

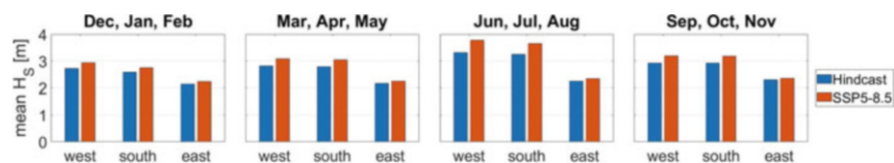


Fig. 8.5 Changes in mean significant wave height (H_S) between the hindcast and SSP5-8.5 scenario

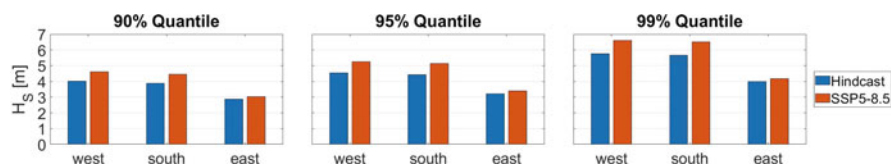


Fig. 8.6 Changes in the 10%, 5%, and 1% highest waves between the hindcast and SSP5-8.5 scenario

in winter, opposing 0.2 m in the other seasons. The 1% highest waves are predicted to increase 0.7 m in winter and spring and 0.5 m in summer and autumn. These changes in the wave climate are also affecting the extreme waves, increasing the 1-in-100 year H_s up to 1.5 m at some locations of the west coast and up to 0.5 m at the east coast.

Due to the high flood exposure of population and assets of the South African coastline, the Council for Scientific and Industrial Research (CSIR) of South Africa in cooperation with universities and government departments produced a national coastal flood assessment in order to support climate-resilient development (Lück-vogel 2019). This assessment was performed for the majority of the coastline of South Africa providing a qualitative flood hazard index based on elevation and extreme events. We refined and extended this analysis by employing the simplified hydrodynamic model LISFLOOD-FP (Bates et al. 2005) to simulate flooding and provide quantitative estimates of flood characteristics for the 100-year return water level along the entire South African coast, at 90-m resolution, using the MERIT Digital Elevation Model (Yamazaki et al. 2017). We used extreme events derived from tidal levels from the global FES2014 (produced by Noveltis, Legos, and CLS and distributed by Aviso+, with support from CNES, <https://www.aviso.altimetry.fr> Carrère et al. 2015); non-tidal residuals for the present day analysis from the ocean model INALT20 (Schwarzkopf et al. 2019) under JRA55-do forcing (Schmidt et al. 2021); for the future SSP5-8.5 scenario outputs from the climate model FOCI-INALT10X (Matthes et al. 2020) (both described in Sects. 8.2 and 8.3; the latter from an experiment with prescribed atmospheric chemistry); and waves from the newly developed wave hindcast discussed above. The wave contribution was included as the wave set-up, which relates the average increase in coastal water levels by offshore waves, typically 20% of the offshore H_s .

The results of the flood simulations show that low-lying regions along estuaries are the areas most exposed to flooding from the current 1-in-100 year event of oceanic drivers (tides, storm surges, and waves). The main coastal cities of South Africa (Cape Town, Port Elizabeth, and Durban) are also affected, albeit to a smaller extent (Fig. 8.7). In these three cities, the largest flooded areas are also observed along the low-lying riverine and harbour regions. The largest flood impacts occur in Cape Town where several settlements, resorts, and a natural reserve are flooded. Under the SSP5-8.5 scenario, we find an average increase of more than 100% in flood extent along the South African coastline from the 1-in-100 year event, which is mostly driven by SLR. However, the potential changes in the wave climate of

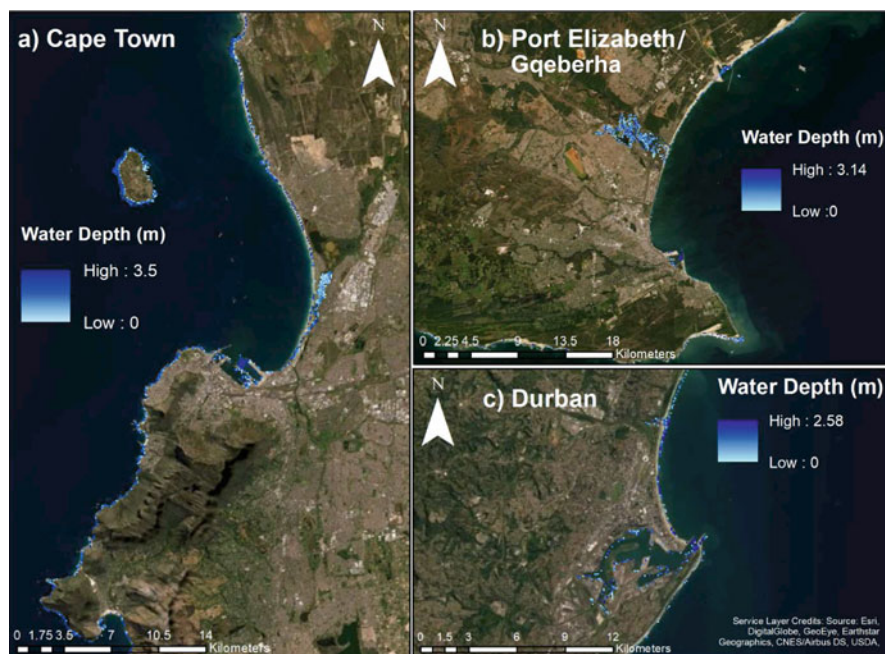


Fig. 8.7 Flood estimation for the present 1-in-100 years extreme event for: (a) Cape Town, (b) Port Elizabeth/Gqeberha, and (c) Durban

South Africa predicted under the SSP5-8.5 scenario and discussed before cause an increase in both flood extent and depth for the 1-in-100 years event (Fig. 8.8). The increase in extreme wave height leads to an increase up to 10% in flood depth as well as an increase of 19% in flood extent compared to present estimates (Fig. 8.8). These increases vary spatially along the coast due to the variability of the waves but also due to changes in the coastal characteristics. For example, there is an increase of 0.74 m in the 1-in-100 year H_S at Cape Town and of 0.51 m at Durban, but we find a larger increase in flood depths at the latter due to the characteristics of the floodplain. For Durban, coastal flooding can be further exacerbated in the future from the changes in precipitation discussed in Sect. 8.4, which can amplify flooding by compounding effects with the oceanic drivers as discussed later in this section.

Future coastal flooding estimates are primarily driven by SLR, but changes in wave climate solely will increase flooding and thus need to be considered in coastal planning and management in this region. Both SLR and changes in wave climate may also increase coastal erosion, which in turn can amplify coastal flooding by reducing the protection offered by natural systems such as dunes and wetlands.

In estuarine areas, coastal flooding can also occur from a combination of ocean drivers (i.e., water levels and waves) and river discharge. The South African coastline is particularly prone to compound flooding from waves and river discharge as cold fronts, cut-off lows, and cyclones produce large swells but also heavy rainfalls

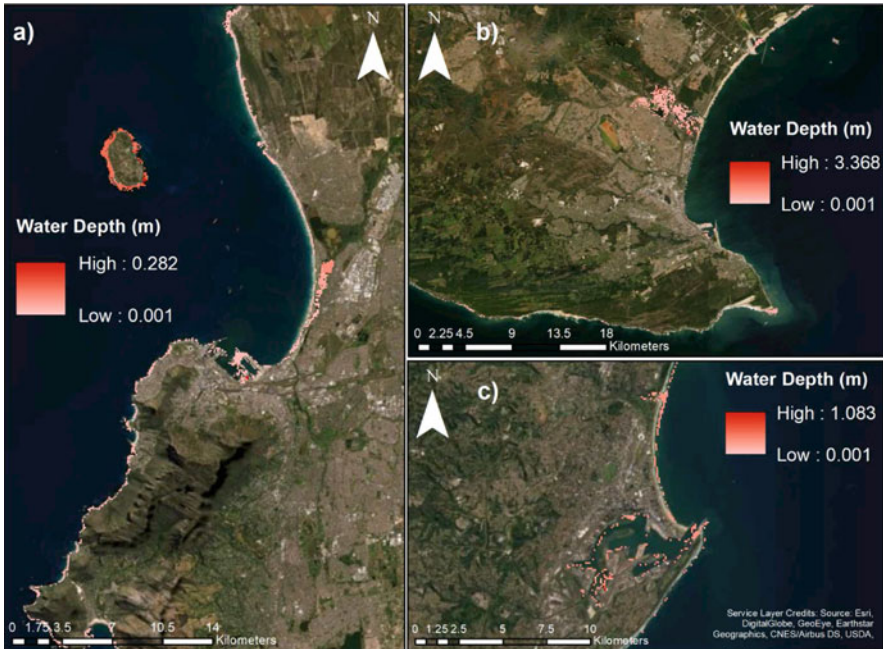


Fig. 8.8 Flood differences between the present 1-in-100 years event and the 1-in-100 years under SSP5-8.5 scenario (not accounting for SLR) for: (a) Cape Town, (b) Port Elizabeth/Gqeberha, and (c) Durban. Flood differences are caused due to changes in wave climate under SSP5-8.5

that can cause fluvial flash floods (Pyle and Jacobs 2016). However, compound flooding in South Africa has not been addressed yet, despite the large number of estuaries along the South African coastline that can be prone to compound flooding (van Niekerk et al. 2020). To explore the interactions between flood drivers in South African estuaries, we investigated compound flooding from river discharge and waves through the case study of the Breede estuary (Kupfer et al. 2021). This estuary is one of the largest permanently open estuaries (van Niekerk et al. 2020) and has the fourth largest annual runoff in South Africa (Taljaard 2003). Using the hydrodynamic modelling suite Delft3D (Lesser et al. 2004), we simulated river discharge, tides, waves, and their interactions to analyse the effects of each driver on the resulting flooding. For detailed description of the study, see Kupfer et al. (2021).

Our results showed differences in flood depth and extent when comparing the compound scenarios (Fig. 8.9). Co-occurring extreme river discharge and extreme waves (S_{TWQ}) result in an increase of 45% in flood extent in the upper part of the domain, compared to the low river discharge scenario (S_{TW}). However, when the waves are omitted, only a reduction of 10% of the flood extent is observed in regions of the estuary mouth and centre, where populated areas are located. An increase in the magnitude of the waves causes an increase of 12% in flood extent and up to 40 cm in flood depth, mostly in the lower part of the estuary. Therefore, waves

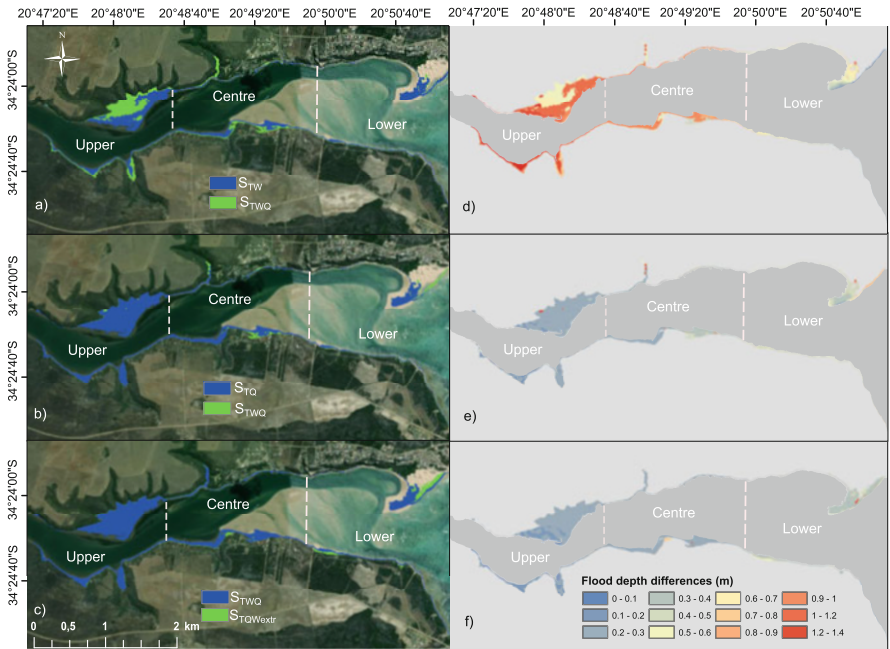


Fig. 8.9 Comparison of flood extents of the compound and excluding driver scenarios at the Breede estuary (South Africa) (left panel, (a), (c) and (e)) and differences in flood depths (right panel). Panel (b) shows the flood depths of $S_{TWQ}-S_{TW}$, (d) shows $S_{TWQ}-S_{TWQ}$, and (f) $S_{TWQextr}$ (Kupfer et al. 2021)

can exacerbate flooding when combined with an extreme river discharge event by blocking river flow to the sea. Compound flooding can be further amplified in these regions where an increase in precipitation under a high GHG scenario is expected (Sect. 8.4).

8.6 Summary

The proper simulation of the Agulhas Current system dynamics requires sufficient ocean resolution, such that the mesoscale processes dominating the region can be simulated. At the same time, the variability of the Agulhas system in ocean-only simulations largely depends on the applied atmospheric forcing. The Agulhas leakage has been subject to decadal changes in the past and is likely to increase substantially towards the end of the century owing to rising GHGs, as predicted by our coupled climate model. The increase in Agulhas leakage is expected to result in a warming and salinification of the southeastern South Atlantic, impacting further downstream water masses in the Benguela upwelling system and in the pan-Atlantic circulation including the AMOC.

The increased offshore warming associated with the projected increase in Agulhas leakage, coupled with a hypothesised increase in upwelling favourable winds in the southern Benguela upwelling system and therefore cooler coastal waters, would lead to the enhancement of the already intense shelf-edge frontal system and jet current. The impact of the Agulhas, both directly and indirectly, on the southern Benguela region needs to be continually monitored to support good governance of the highly productive system that supports a lucrative fishing industry.

The warming also provides an important boundary condition through SST to the atmosphere. The southern African climate is therefore directly impacted by the Agulhas Current system. An increase of Agulhas leakage under global warming is, although not exclusively, linked to decreasing precipitation in South Africa.

The atmospheric changes under a high GHGs scenario cause an intensification of extreme waves along the coast of South Africa, which combined with (regional) sea-level rise and increased precipitation events has the potential to increase compound flooding along the coast of South Africa, considerably amplifying impacts to coastal communities.

The different disciplines in this chapter have outlined the need for inter- and transdisciplinary collaboration, a core attribute of CASISAC. When a regional climate model relies on a proper SST distribution under current-day and future conditions, it is, in particular for the Agulhas Current system, important to simulate those at sufficient high resolution. The same applies to the impact studies examining the vulnerability of the African coastlines. Detailed precipitation maps and distributions of regional level in response to ocean currents and spatial warming are required. Even in a collaborative project, this is not fulfilled up to the last instance because of the large range of scales and the different importance of mechanisms for different disciplines. It is important to keep in mind that our results are based on numerical models. In particular for the oceanic fields, currents and hydrography, but also sea level, waves and flooding, observations are required to ground-truth the models and to correct model deficiencies originating from a poor representation of unresolved processes.

Our studies outline the strong impact of the surrounding ocean on the land climate in Southern Africa. Changes through global warming arising from large-scale climate models need not only to be downscaled but may also be regionalised, in our case to correctly take into account the specific effect of the Agulhas Current system.

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