Long-term Variability of Agulhas Leakage and its Embedding into the Global Overturning

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Master Thesis

M. Sc. Climate Physics

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I. Abstract

The Agulhas Leakage (AL) transports warm and salty Indian Ocean waters into the Atlantic Ocean and as such is an important component of the global ocean circulation. These waters are part of the upper limb of the Atlantic Meridional Overturning Circulation (AMOC) and AL variability has been linked to AMOC variability. The AL is expected to increase under a warming climate due to a shift in the Southern Hemisphere westerlies, which could further influence the AMOC dynamics. This study investigates the AL transport variability on long time scales in the pre-industrial and under a warming climate and its relation to the AMOC. It uses a high-resolution configuration of the Community Earth System Model (CESM) with a nominal horizontal resolution of 0.1° for the ocean and sea-ice and 0.25° for the atmosphere and land, which resolves the necessary spatial scales. The simulated AL transport of $19.7 \pm 3\,Sv$ lies well within the observed range of $21.3 \pm 4.7\,Sv$. A positive correlation between the Agulhas Current and the AL is shown, meaning that an increase of the Agulhas Current transport leads to an increase in AL. Furthermore, the salt flux associated with the AL influences AMOC dynamics through the salt-advection feedback by reducing the AMOC's freshwater transport at 34°S. In a warming climate, the AL transport was indeed found to increase due to strengthened and southward shifting winds while the Agulhas Current transport was found to decrease. Consequently, a larger fraction of the Agulhas Current will flow into the Atlantic Ocean rather than being recirculated into the Indian Ocean. The increase in AL is accompanied by a higher salt flux into the Atlantic Ocean, which destabilises the AMOC within the salt-advection-feedback. But whether and to what extent this additional salt advected to the North Atlantic could also dampen an AMOC weakening induced by increased meltwater input under climate change still needs further research.

II. Table of Contents

1. Introduction

The Agulhas Leakage (AL) is part of a current system around South Africa which connects the Atlantic Ocean to the Indian Ocean and is an important component for the global ocean circulation. Warm water from the Indian Ocean flows southward along the coast of South Africa as a Western Boundary Current, the Agulhas Current, until it detaches from the coast and reaches a region of strong westerly winds (Figure 1). The dynamics of the flow then become an interplay between its southward inertia and the wind forcing (*Beal et al.*, 2011): The winds push most of the water back eastward into the Indian Ocean which is called the Agulhas Retroflection. However, some part of the water leaks into the Atlantic Ocean due to instabilities and non-linear dynamics. Prominent mesoscale eddies form, the so-called Agulhas Rings, and propagate north-westward carrying the warm and salty waters of the Indian Ocean into the South Atlantic. This transport of heat and salt into the upper Atlantic Ocean plays a role in the Atlantic Meridional Overturning Circulation (AMOC) and subsequently the global conveyer belt (*Biastoch et al.*, 2008).

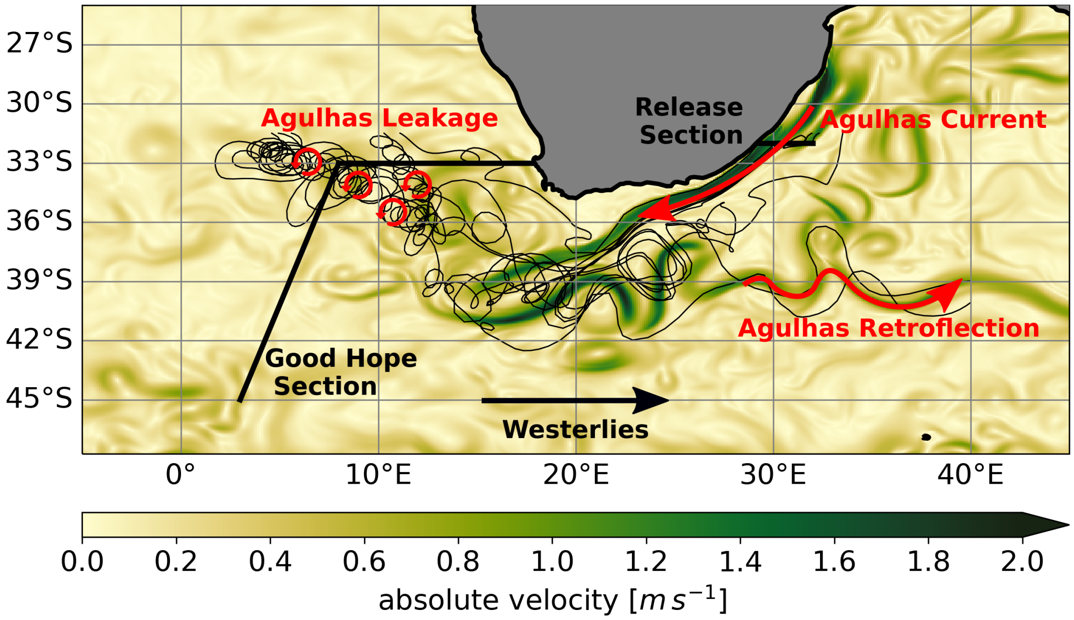

Figure 1: Map of the Agulhas region; colors show a snapshot of the five-daily mean absolute velocity field, thin black lines are example tracks of lagrangian particles, thick black lines show the release and crossing section, red arrows schematically represent the circulation features and the black arrow represents the westerly winds.

The trade winds in the Indian and Atlantic Ocean together with the strong westerlies in the Southern Hemisphere form sub-tropical gyres in each basin. Due to the African continent not reaching as far south as South America and Australia, both systems are connected and can be described as one supergyre (*Speich et al.*, 2007). The Agulhas system is this connection and therefore opens up a pathway between both ocean basins. The amount of trans-basin transport is controlled by the wind field (*Beal et al.*, 2011). The winds over the Indian ocean determine the inertia of the Agulhas Current, which, together with the strength of the westerlies, controls whether the current turns west into the Atlantic or loops back into the Indian Ocean. Ultimately, it is an interplay between both, which controls, how much water is leaking into the Atlantic (*Durgadoo et al.*, 2013). *Rühs et al.* (2022) found that especially an increase in the wind stress curl over the Indian Ocean based on strengthened winds leads to an increase in the AL.

The AL is not a straight current that flows into the Atlantic Ocean, but rather consists of mesoscale eddies, which form in the retroflection region and then propagate into the Atlantic (*Olson and Evans*, 1986). These eddies are affected by the bathymetry and take different routes into the basin, some even reaching the Brazilian coast (*Dencausse et al.*, 2010). The formation rates and propagation speeds of these eddies lead to variability in the overall transport on interdecadal timescales (*Holton et al.*, 2017). The eddy activity is additionally impacted by large scale climate modes such as the Southern Annular Mode or the El-Niño Southern Oscillation (*Morrow et al.*, 2010). Another but not as important pathway for Indian Ocean waters is the so-called Good Hope Jet, described as an extension of the Agulhas Current along the continental slope (*Gordon et al.*, 1995).

By the AL, warm and salty surface waters from the Indian Ocean are transported into the Atlantic and connect to the upper limb of the Atlantic Meridional Overturning Circulation as part of the "warm-water route" of the global overturning circulation in the Atlantic Ocean (*Gordon*, 1986). It is hypothesized that these water properties influence the formation of deep water in the North Atlantic mainly through the salt input: *Weijer and van Sebille* (2014) investigated the influence of salinity input of the AL into the Atlantic and furthermore the AMOC on interdecadal timescales. While they could show an advective connection from the AL to the North Atlantic, no impact on the AMOC strength could be detected. However, due to a bias in salinity in the model, the salinity anomalies induced by the AL are much weaker than in the observations. *Biastoch et al.* (2008) showed the influence of the AL on AMOC variability on decadal timescales on the same order as deep water formation impacts in the North Atlantic. Another study by *Biastoch et al.* (2015) found that the Atlantic multi-decadal oscillation, a variation of the North Atlantic's sea surface temperatures, covaries with the AL. Still, the exact relation between the AL and the AMOC is not clear, both for the volume transport as well as for the hydrographic influences.

The stability of the AMOC and hence the possibility of a future collapse is a major topic in current research (*Boulton et al.*, 2014; *Hu et al.*, 2021; *Boers*, 2021). One theory involved here is the salt-advection feedback. It describes the AMOC stability as a feedback loop: The AMOC strength in the North Atlantic controls the freshwater transport through 34°S, which influences the density difference between the North and the South Atlantic which then again influences the AMOC strength. The direction of the freshwater transport, either southward or northward, determines the sign of the feedback loop being positive or negative, respectively. The process originates from a theory by *Stommel* (1961) and was further developed by *Rahmstorf* (1996). Only a negative freshwater transport allows for a bi-stable AMOC regime as is suggested for the real ocean (*Rahmstorf*, 1996). The impact of the AL on this freshwater transport and further influences on the AMOC remain to be completely understood (*Weijer et al.*, 2019).

Furthermore, the Indian Ocean Throughflow (ITF), a connection between the Pacific and the Indian Ocean, has an impact on the AL. *Le Bars et al.* (2013) and *Makarim et al.* (2019) showed that the ITF increases the strength of the Agulhas Current and subsequently the AL. *Van Sebille et al.* (2009) have shown that an increase in the Agulhas Current strength leads to a decrease in AL due to higher inertia of the Agulhas Current and therefore stronger retroflection. However, this result has been under discussion since and *Loveday et al.* (2014) describe a decoupling of the AL strength from Agulhas Current Variability. *Zhang et al.* (2023) found variability in the Agulhas Current on decadal and multi-decadal timescales, which might impact the AL depending on the exact relation between both. This highlights the complexity of the region and how many factors can play a role in determining the strength of the AL.

Paleo studies have been investigating the AL and its connection to the AMOC over the last 500,000 years. Proxies of planktonic foraminiferal species can be used to account for the amount of source water masses, i.e. Indian Ocean waters and therefore the AL (*Peeters et al.*, 2004). These show that the AL played a role in the transition periods from glacials to interglacials by impacting the AMOC. *Knorr and Lohmann* (2003) found that an increase in the warm water route occurred during deglaciations, which prevailed over Northern Hemisphere meltwater input and led to an increase in the AMOC and thereby deglaciation.

It is projected and already observed, that the Southern Hemisphere westerlies are strengthening and moving southward under climate change (*Cai*, 2006). This has direct impacts on the controlling dynamics of the AL. *Biastoch et al.* (2009) related the southward shift to an increase in leakage and by that a salinification of the South Atlantic. A modelling study by *Beech et al.* (2022) points out an increase in eddy activity in the region and a connected increase in AL by up to 6 Sv due to climate change. Additionally, *Ivanciu et al.* (2022) used a high-resolution nesting approach as well as interactive ozone forcing to show that AL is increasing by 1.5 Sv over 80 years. Furthermore, a recent study by *Li et al.* (2022) highlights the importance of a poleward shift of mid-latitude easterlies globally in controlling the southern boundary of subtropical ocean gyres and subsequently the southward extent of western boundary currents.

Due to the fact that mesoscale dynamics are highly important in the Agulhas region and especially in the AL, these processes need to be resolved to capture the AL transport (*Schubert et al.*, 2021). Over the past decade, ocean modeling capabilities allowed for eddy-resolving resolutions in the Agulhas region and therefore its investigation. However, these were mainly hindcast simulations covering around 60 years, which limits the modes of variability that one is able to extract. Little is known about the variability of the system on timescales of decades to centuries (*Beal et al.*, 2011; *Rühs et al.*, 2022). The model used for this study is a high-resolution configuration of the Community Earth System Model (CESM) which consists of a 0.1° ocean and therefore resolves mesoscale processes (*Chang et al.*, 2020). The global high-resolution is particularly important to better represent the global overturning circulation. The performed simulations include a 500-year pre-industrial control run and future projections under different scenarios following the RCP protocols. These offer a unique opportunity to examine the AL variability on timescales of and longer than decades and also a possible change under global warming. Additionally, one can investigate the connection of the AL to the global climate in a closed system of an Earth System Model in comparison to forced and regionally focused ocean-only simulations.

This study is structured as follows: Section 2 describes the used model configurations, Section 3 explains how we estimated the AL transport with a particle tracking algorithm and the applied analysis methods, Section 4 investigates the questions: What is the internal variability of the AL on long timescales and what are related driving mechanisms? How is the AL connected to the global overturning circulation and specifically the AMOC? And how might the system change in a warming climate? Section 5 discusses the results with existing literature and concludes our findings.

2. Data

This study is based on the Community Earth System Model version CESM1.3 (*Chang et al.*, 2020), which is currently used to perform high-resolution global fully-coupled simulations. It contains a 0.1° ocean based on the Parallel Ocean Program version POP2 (*Danabasoglu et al.*, 2012; *Smith et al.*, 2010) with 62 vertical levels of increasing layer thickness to the bottom. The atmosphere component is the Community Atmosphere Model version CAM5 (*Neale et al.*, 2012) and has a resolution of 0.25° and 30 vertical levels. The other components are the Community Ice Code version CICE4 (*Hunke and Lipscomb*, 2008) and the Community Land Model version CLM4 (*Lawrence et al.*, 2011) with resolutions of 0.1° and 0.25° , respectively. Within this configuration, a 520 year pre-industrial control run was performed from which the model years 150 to 520 were used for this study (Figure 2).

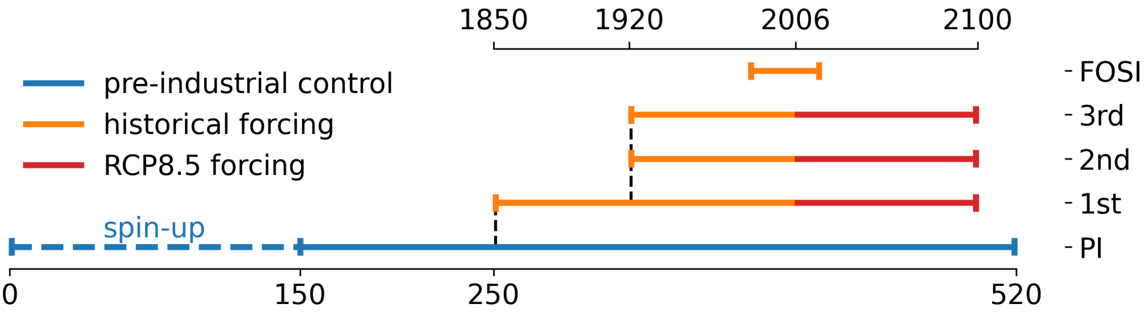

Figure 2: Schematic of the used model experiments based on the community earth system model CESM; the PIcontrol and the three ensemble members are of the fully-coupled earth system model while FOSI is from a forced ocean sea-ice configuration using the same ocean and sea-ice models; colors indicate different CO2-forcing types and the black dashed lines show branching of another run.

The model was still in spin-up in the first 150 years, with the radiative balance at the top of the atmosphere not being in balance until mid-run fixes were applied. It has been shown that this simulation captures the ongoing climate dynamics well and that these are improved compared to a lower resolution version (*Chang et al.*, 2020). Within the same configuration, three ensemble runs were performed applying a transient CO2-forcing to simulate climate change. The first member was branched from the PIcontrol in model year 250 or calendar year 1850. The second and third member were branched from the first member in year 1920, because the first 70 years contain little forcing and to save computing time. Historically observed CO2 forcing was applied until the year 2006 and the Representative Concentration Pathway 8.5 (RCP8.5) scenario (*Vuuren et al.*, 2011) from 2006 onward until 2100. Additionally, we used 35 years from 1983 to 2018 of data from a forced ocean-sea ice (FOSI) hindcast configuration based on the same ocean and sea-ice components. The applied surface forcing was the JRA55-do dataset from *Kobayashi et al.* (2015).

We use satellite based absolute dynamic topography (Sea Surface Height (SSH) above geoid) daily means from 1993 to 2018 to validate the models capability to resolve the necessary mesoscale activity in the region and the overall large scale circulation pattern. The product is provided by the Copernicus Marine Environment Monitoring Service (CMEMS) on a global grid of 0.25° resolution and is established with a data unification and altimeter combination system (*Mertz et al.*, 2017).

3. Methods

3.1. Agulhas Leakage Estimation

To calculate the annual Agulhas Leakage transport, we performed a lagrangian particle tracking method, utilising the python package oceanparcels (*Delandmeter and Van Sebille*, 2019; *Kehl et al.*, 2023). Particles are released every timestep along a section at 32°S from 29-32°E that goes through the Agulhas Current flowing southward along the coast of South Africa (Figure 1). An initial transport is assigned to each particle, based on the volume around them and the velocity at that point and then tracked for five years. The tracking is basically an interpolation using numerical methods, i.e. a fourth-order Runge-Kutta advection scheme (*Delandmeter and Van Sebille*, 2019). We used an internal time step of 32 minutes for the advection scheme, based on the grid size of the model, which keeps the particles in the same grid box for at least two timesteps with still reasonable computational effort. The annual total AL transport then consists of the volume of all particles that crossed the Good Hope section as their first exit of the domain within the five years of tracking. Observations have been done along this section since 2004, including CTD casts and moorings, and it is part of the South Atlantic observing network of the meridional overturning circulation (*Speich et al.*, 2023). Since the majority of particles cross the section in the first year, the whole transport of five years is assigned to the release year. This has been shown to work well in other studies (*Schmidt et al.*, 2021; *Rühs et al.*, 2022).

Ideally, this tracking is performed on the full 3D velocity field and on a high temporal resolution. However, the 3D field was only available in monthly resolution for the fully-coupled simulations. We therefore used different techniques based on different fields and temporal resolutions to find the best possible estimate we could get from the PI-control run. This includes 3-dimensional tracking on five daily and monthly velocity fields, as well as a regression method based on geostrophic velocities calculated from the sea surface height field. This regression method was developed and validated by *Rühs et al.* (2022). We performed the particle tracking in the five daily full 3D velocity field in the 35 years of available data from the FOSI simulation. This gave us an estimate of Agulhas Leakage Transport in high temporal resolution and the same ocean model setup. Additionally, the tracking was done on the five daily 2D field of geostrophic velocities at the surface. The regression between the 3D tracking and the surface tracking and then applied to reconstruct the total AL transport from the surface tracking leads to good alignment between both with a significant correlation of 0.92 based on a 95% level. This shows that the regression is a valid technique of reconstructing the AL transport.

In order to find the longest possible timeseries of AL of the PI-control that was also reasonable, we compared the estimated transport from the available fields based on their correlation and variances. We had 370 years of monthly 3D velocity and SSH data from year 150 to 520 and five daily SSH data from year 338 to 512. The regression of the FOSI simulation was applied to the SSH tracking in the PI-control to get the full transport estimates. We found significant correlations of 0.77 between the five daily SSH and the monthly 3D tracking, while it was only 0.59 between five daily and monthly SSH tracking. On decadally filtered timeseries, we found a significant correlation of 0.82 between the five daily SSH and the monthly 3D tracking. For the monthly SSH tracking, the correlation was less with 0.69 and just not significant with a p-value of 0.06. Regarding the interannual variation of the transport expressed as the standard deviation, a value of 2.48 Sv from the five daily 3D tracking of the FOSI simulation is our best estimate. In the PIcontrol, the variances were 2.85 Sv and 3.01 Sv for the monthly SSH and 3D tracking, respectively, which are both larger than the true value, but still in a close range. Due to the better correlations, interanually as well as on decadally filtered data, and the small differences in variances, we decided to use the monthly 3D tracking to get a 370 year timeseries of the AL transport. *Cheng et al.* (2016) showed as well that monthly data is sufficient to detect variability in longer than seasonal timescales. Additionally, the 3D tracking allows us to track the temperature and salinity along the particle's trajectory, which we can use for further analysis. We define the Agulhas Current transport as the sum of the transport of all released particles. This is different than just calculating the volume transport through the section, since we are only releasing particles at points that have a southward velocity, e.g. into the domain.

3.2. Analysis

To validate the performance of the model to represent the ocean circulation around South Africa, we compared the variability of the daily Sea Surface Height between the model and satellite observations. We used the first ensemble member and the overlapping period from 1993 to 2018 to be most consistent with the observations and calculated their standard deviations. Additionally, observational transport estimates based on floats and drifters for the AL (*Daher et al.*, 2020) as well as mooring data for the Agulhas Current (*Beal et al.*, 2015) were compared to the results of the particle tracking.

To investigate the variability of AL on different timescales, we performed a spectral analysis on the annual timeseries. Due to the length of the timeseries and having annual data, meaning only 370 data points, this was not straight forward. We ended up with just a general Fourier Transform and not a wavelet analysis to better resolve the longer frequencies.

The significance of the peaks is calculated following *Torrence and Compo* (1998). In general, significance in this study always refers to the 95% level. To investigate relationships between two timeseries, we performed lead/lag correlation analysis. For these, the data has been filtered using a five year Hanning window and detrended. Significance is based on a two sided students t-test, that incorporates the autocorrelation of each timeseries. We performed coherence analysis to investigate co-variability between two timeseries and infer possible driving mechanisms. Due to the results of the coherence being quite dependant on the window size for the wavelets, we calculated it over a range of sizes with zero padding for the smaller ones to keep the same frequency resolution and then averaging them afterwards. The confidence levels were estimated following *Thompson* (1979) and averaged in the same way.

We followed *Rühs et al.* (2022) to calculate wind metrics: We extracted the maximum zonal wind stress in the region between 20°E to 110°E and 20°S to 70°S. This then also gives us the latitude of maximum zonal wind stress. Additionally, we calculated the average wind stress curl in the same longitudinal range, but between 35°S and 45°S. The regions can be seen in Figure A5. The Southern Annular Mode (SAM) index is defined as the first EOF Mode of annual mean sea-level pressure south of 20°S and calculated using the Climate Variability Diagnostics Package (CVDP) (*Phillips et al.*, 2014; *Thompson and Wallace*, 2000).

Because of tracking the salinity of each particle along its track, it was possible to calculate the salt flux of AL F_S into the Atlantic Ocean. This has been calculated following the method from *Weijer and van Sebille* (2014), where the amount of salt a particle brings into the Atlantic is the difference between its salinity S_i at the Good Hope Section and the long-term salinity mean S_0 (at the crossing location along the section and in the same depth) times its transport V_i and then sum up all particles that cross the Good Hope section for each year:

$$F_S(t) = \Sigma_i V_i(t)(S_i(t) - S_0(t)$$

Therefore, by referring to the average salinity at the section, salt flux variations are the advection of local salinity anomalies only. Variations in the volume transport alone would not cause any variance in the salt flux (*Weijer and van Sebille*, 2014). However, as there is a small salinity drift in the control run, i.e. a freshening over time, we used a linear fit of the section mean over time instead of just the temporal mean. For the transient simulations, the reference salinity was a constant temporal mean from 1920-2100 to extract a potential trend in the salt flux. Additionally, we only choose particles between 150 m and 1500 m to remove mixed layer influences and being consistent with *Weijer and van Sebille* (2014).

In order to investigate the impact of the AL on the AMOC, we looked at AMOC transports at different latitudes. The AMOC strength is the maximum value of the AMOC stream function in depth space and deeper than 500m, in order to exclude the surface cells. Additionally, we investigated a relation between the AL salt flux and the overall freshwater flux at 34°S. We used the method described in *Jüling et al.* (2021) to calculate the annual freshwater transport F_{ov}:

$$F_{ov} = -\frac{1}{S_0} \int \left(\int_W^E v^* dx \right) (\langle S \rangle - S_0) dz$$

where $S_0 = 35\,psu$, $\langle S \rangle$ being the zonal mean and $v^* = v - \hat{v}$ with $\hat{v}$ being the section mean. This freshwater transport is an important part in the salt-advection feedback about AMOC stability.

When investigating future changes, we took the ensemble mean from the three ensemble members for their overlapping period from 1920 to 2100. While three ensemble members are not a lot, it removes some of the internal variability and therefore increases the robustness of examined trends due to global warming.

4. Results

4.1. Model Representation of the Region

To infer the capability of the model to resolve the necessary dynamics in our region of interest, we compared the variability of the Sea Surface Height (SSH) from the model to satellite observations (Figure 3). This is a measure of mesoscale dynamics and eddy activity. The strongest variability in the observations appears around 20°E and 40°S. This is when the Agulhas Current reacts to the overlying wind field and is being pushed back to the East. Until then, the Agulhas Current is rather stable, leading to a corridor of low variability. The higher variability around Madagascar consists of mesoscale eddies as well, that then feed into the Agulhas Current. The flow back into the Indian Ocean through the Agulhas Retroflection is characterized by a meandering flow, which is visible in the SSH between 35 - 40°S. The AL itself consists mostly of large scale eddies, that then propagate into the Atlantic, shown in the increased variability in this direction. Looking at the model, the overall picture is very similar, meaning that the model resolves the dynamics well. However, some differences are visible as well: the variability around 20°E is stronger in the model and it describes a more pronounced eddy corridor into the Atlantic Ocean. But since the model agrees well with the observations overall, we are confident to use this simulation for our analysis of the AL.

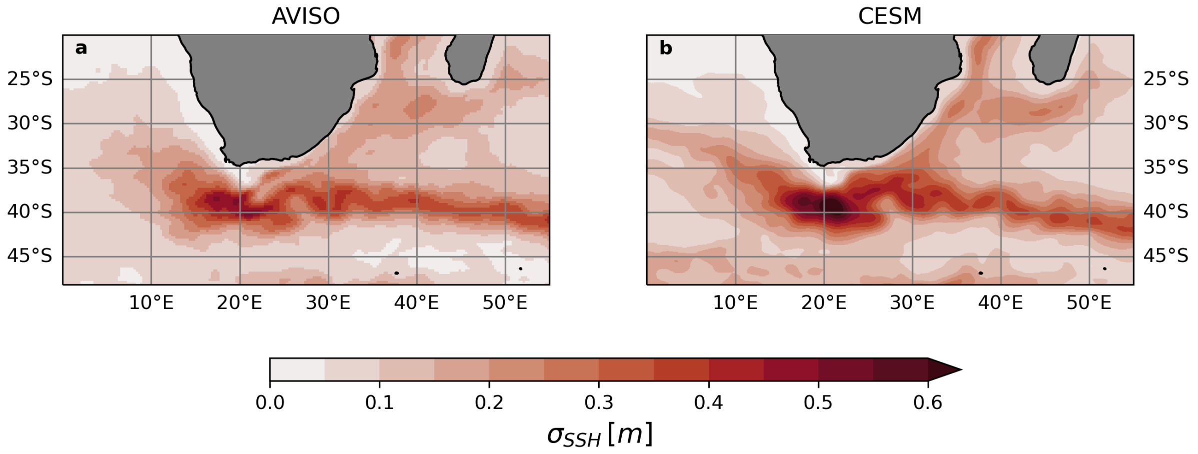

Figure 3: Sea Surface Height variability σ_{SSH} from daily AVISO satellite altimetry (a) and in the first ensemble member of CESM (b) for the overlapping time period from 1993 to 2018.

We got a 370 year annual timeseries of AL transport using a lagrangian particle tracking method (Figure 4). The transport has a magnitude of $19.7 \pm 3.0\,Sv$, which lies well within the most current observational estimate of $21.3 \pm 4.7\,Sv$ based on floats, drifters and a mooring array from *Daher et al.* (2020). The Agulhas Current transport in the model is similar as well with $72 \pm 4.0\,Sv$ in comparison to $77 \pm 4.0\,Sv$ from mooring data (*Beal* *et al.*, 2015). This then results in AL fractions, meaning the amount of leakage to the Agulhas Current transport, of 27.3 ± 4.0 % in CESM and 27.6 ± 2.5 % in the observations (*Daher et al.*, 2020). These very similar transport values give us additional confidence in the model's capabilities.

4.2. Variability on Different Timescales

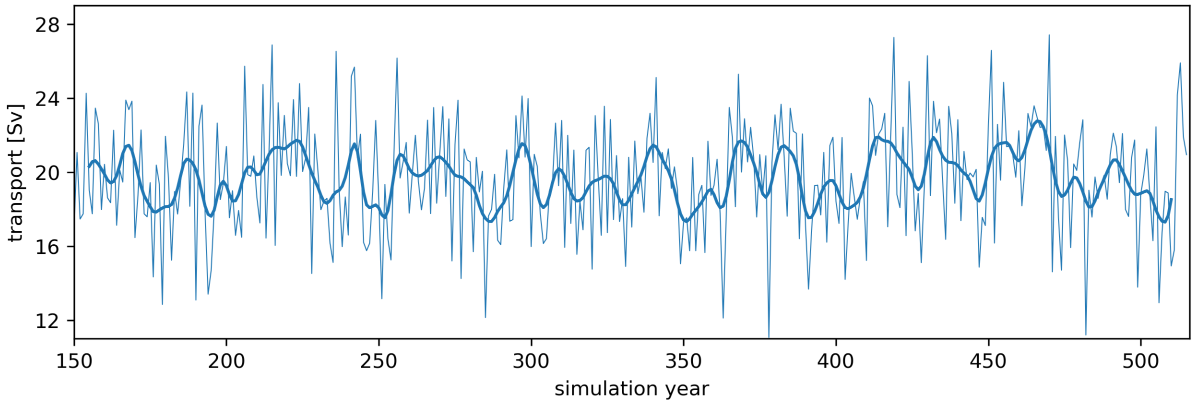

Figure 4: Agulhas Leakage timeseries from the lagrangian particle tracking in the PI-control run; annual data in the thin line, 11-year filtered in the thick line.

The timeseries shows a strong interannual variability, while the decadally filtered timeseries hints at variability on longer timescales. To quantify that, we did a spectral analysis (Figure A1). The interannual variability clearly stands out, which is related to the formation and propagation of Agulhas Rings (*Holton et al.*, 2017). Another significant peak comes out at a 14 year period. However, the whole spectrum is really noisy and it is hard to extract a robust signal. We applied the same analysis on timeseries based on other ways of AL estimation. First, the regression method based on a tracking with geostrophic velocities explained in Section 3 and second, another regression using a sea surface temperature difference between the South Atlantic and the Indian Ocean, described in *Biastoch et al.* (2015). Additionally, we used shorter timeseries from other model runs. It turns out that the power of certain frequencies varies a lot between these (not shown) and that there is no robust long-term variability found between the different approaches and simulations.

4.3. Wind Forcing across Scales

It is known that the AL is driven by the prevailing wind field over the Agulhas region and the southern Indian Ocean (*Beal et al.*, 2011). We investigate this relationship as another proof of concept before looking at longer periods and if the winds might drive the AL across timescales.

Doing a lead/lag correlation analysis (Figure 5a), we find that both the maximum zonal wind stress over the Indian Ocean and the average wind stress curl over the Indian Ocean show significant lead times to the AL of 3-4 years. The correlation values are 0.33 and 0.25 for the wind stress curl and the maximum zonal wind stress, respectively. These are not that high due to the strong interannual variability of the AL, but still significant because of the length of the timeseries. This lead time relates to a Sverdrup response over the Indian Ocean, that takes some time to propagate into the region. When calculating the correlations for each point in space (Figure A2), we find the strongest correlations around 50°S and 50°E. This co-locates with the maximum long-term mean zonal windstress, which means that it is indeed a strengthening of the winds that increases the AL and not a latitudinal shift.

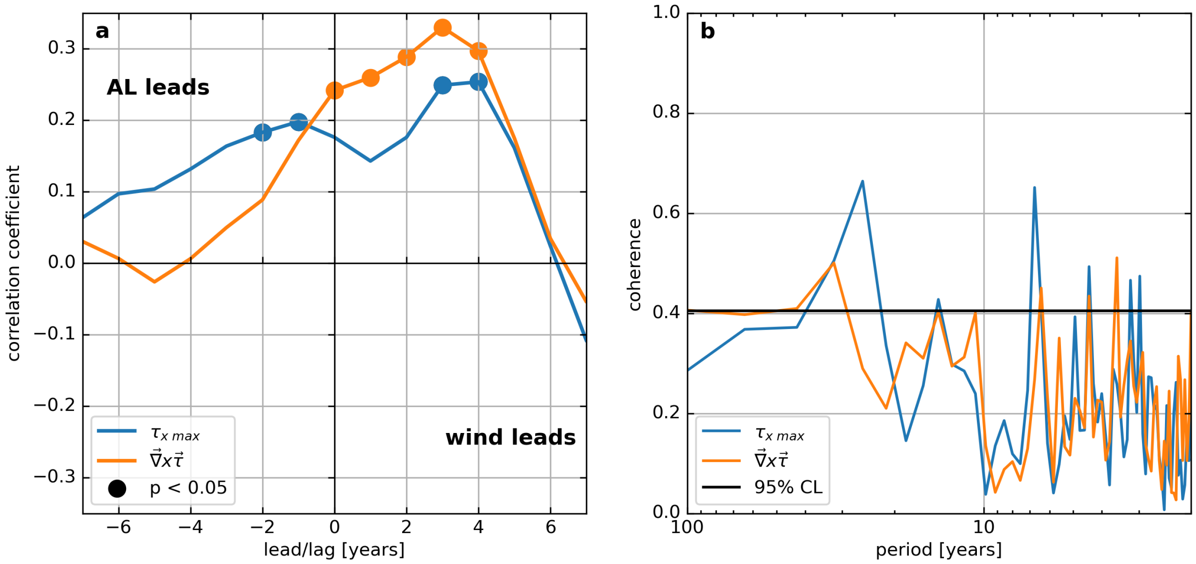

Figure 5: Lead/lag correlation (a) and coherence (b) between the Agulhas Leakage and the prevailing wind, in particular maximum zonal windstress $\tau_{x\,max}$ in 20-110°E and 20-70°S in blue as well as average windstress curl $\vec{\nabla} x \vec{\tau}$ over 20-110°E and 35-45°S in orange, significance is represented in the dots and the horizontal line, respectively.

The coherence analysis (Figure 5b) shows strong and significant coherence values of up to 0.66 at different periods including long-term co-variability at 14 and 30 year cycles. Both wind metrics have a very similar pattern, underlining the wind influence. This suggests, that the wind is the dominant driver of AL across timescales.

4.4. Connection to Local and Global Circulation

The connection of the Agulhas Current strength to the ultimate strength of the AL has been under discussion in the past. We therefore analysed that again and found a positive and significant correlation of 0.19 at zero lag (Figure 6). This means that a stronger Agulhas Current directly leads to a stronger AL in the same year. A lag of zero makes sense since we assign the AL transport to the release year of the particles within the Agulhas Current.

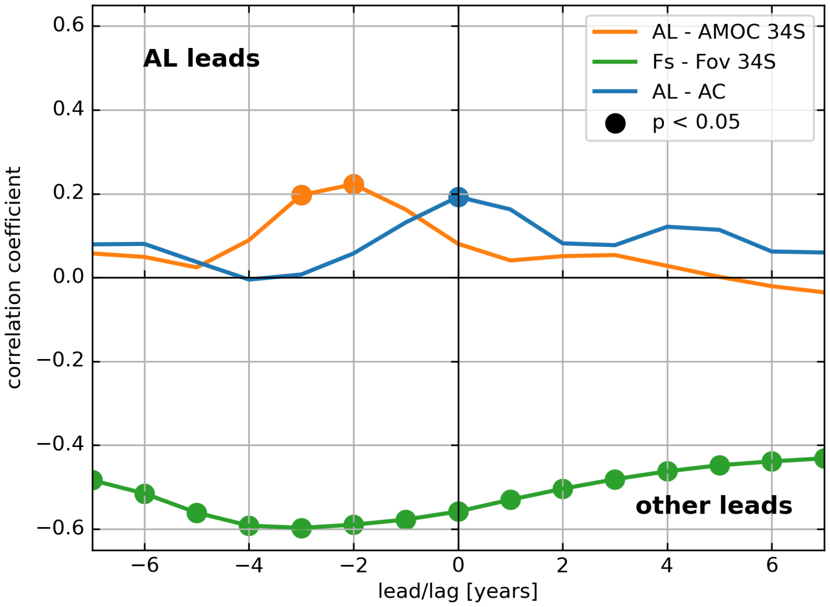

Figure 6: Lead/lag correlations between the Agulhas Leakage and the Agulhas Current (AC) in blue, AMOC strength at 34°S in orange as well as between Agulhas Leakage salt flux (Fs) and freshwater transport (Fov) at 34°S in green, significance is represented in the dots.

The mean AMOC transport at 26.5°N is $18.26 \pm 1.08\,Sv$ which is in the range of the observations from the RAPID array of $17.55 \pm 2.88\,Sv$ (*CMEMS*, 2023). The influence of Agulhas Leakage to the AMOC comes out in the lead/lag correlations as well (Figure 6). We find a significant correlation of 0.22 at a lag time of two years to the AMOC strength at 34°S. This relates to the advective time scale from the Agulhas Current release section to the Atlantic Ocean. Furthermore, we investigated how this relationship evolves with latitude further north into the Atlantic. We find positive correlations up to 20°S with an increasing time lag to 4-5 years. This corresponds to the latitude, where the South Equatorial Current reaches the Brazilian Coast and then splits into a northward and a southward branch (*Garzoli and Matano*, 2011). However, this relationship is not so clear. Similarly, looking at how AL changes impact AMOC changes across the Atlantic (not shown), we find all sorts of relationships. Some periods show a very clear signal of a northward propagating strengthening in AMOC after an AL increase and vice-versa. On the other hand, there are many periods where no impact is visible at all and also some where the AMOC tendency is propagating from the North Atlantic southward. This underlines the complexity of AMOC dynamics.

Another interesting aspect of the AL is not just the volume transport itself, but especially the amount of salt that is brought into the Atlantic Ocean. This salt flux is thought to be the main factor that is ultimately influencing the AMOC (*Weijer and van Sebille*, 2014). Most of the heat of the AL waters is lost to the Atmosphere in the South Atlantic (*Biastoch et al.*, 2008). We therefore calculate the salt flux of the AL based on the salinity of the particles and its difference to the temporal mean salinity at the Good Hope Section. As a factor for AMOC dynamics, we look at the freshwater transport at 34°S. This freshwater transport is an important factor in the salt-advection feedback and influences AMOC strength through the density difference between the North and the South Atlantic (*Rahmstorf*, 1996). We find a mean freshwater transport of $0.10 \pm 0.03\,Sv$ that is positive the whole time, meaning a stable salt-advection feedback. A positive freshwater transport means a northward freshwater transport. We then perform lead/lag correlation of the salt flux to the freshwater transport at 34°S (Figure 6). We find a strong negative correlation of -0.6 with a peak at a lead year of three years, similar to the timescale of the volume transport connection. This means that a stronger salt flux of the AL reduces the freshwater transport. The salt input of the AL is mostly confined to the upper $1000\,m$, which relates to the depth of Agulhas Rings (*Schmid et al.*, 2003)

4.5. Future Changes of the System

An important question is how the AL might change under climate change and what impacts this might have. Studies have suggested an increase in AL due to a changing wind pattern over the region (*Biastoch et al.*, 2009). Observations as well as modelling studies show an increase in the Southern Hemisphere westerly strength combined with a southward shift (*Cai*, 2006; *Ivanciu et al.*, 2022). The three ensemble simulations under an historical and then an RCP8.5 scenario within this model configuration allow us to investigate these changes, especially because they resolve the necessary mesoscale dynamics for the AL.

We find an increase of AL of $0.08\,Sv/dec$ during the period from 1920 to 2100 in the ensemble mean (Figure 7). This trend is not that strong, but still significant and also consistent between all three members with only negligible varying magnitudes in the order of $0.01\,Sv/dec$. On the other hand, it is dependent on the period used for the trend calculation. We do not find a trend anymore when calculating it for just the future forcing, e.g. from 2005 to 2100. To investigate the change of the winds, we calculate the SAM index over that time period as a first representation of the wind field. The SAM index shows an increasing and stronger trend than the AL (Figure 8). But an increase in the SAM index can be based on different changes in the wind patterns, either a strengthening

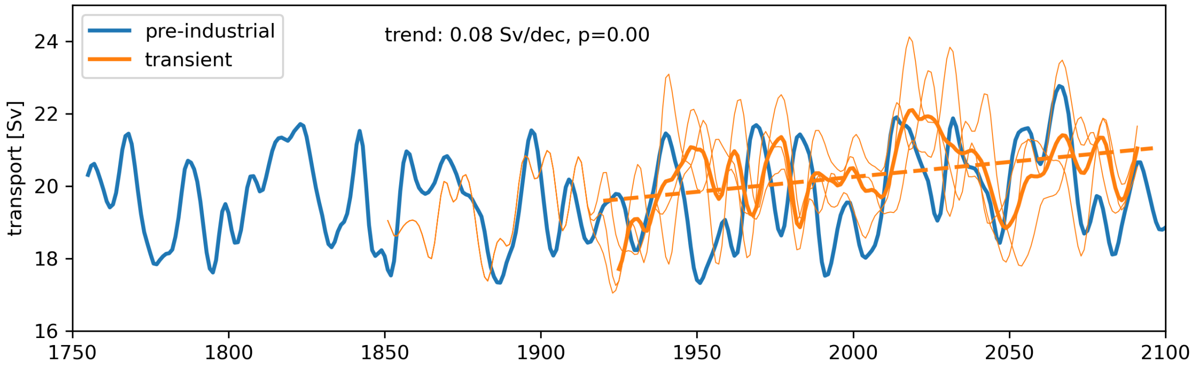

Figure 7: Decadally filtered Agulhas Leakage transport timeseries for the PIcontrol in blue, the ensemble mean of three members under historical and RCP8.5 forcing in orange in the thick line, individual members in the thin lines, linear trend line and metrics for the period from 1920 to 2100 are shown.

or a southward shift and also the regional distribution of these changes. Therefore, we take a closer look at the wind metrics we found to drive the AL in the pre-industrial climate (Figure A3). We find an increase in the maximum zonal windstress over the Indian ocean as well as a southward shift of the latitude of maximum zonal windstress, both significant. This means that both parameters influence the change in the SAM index similarly. Additionally, the wind stress curl increases significantly as well. These wind changes directly connect to the dynamics of AL and lead to its increase.

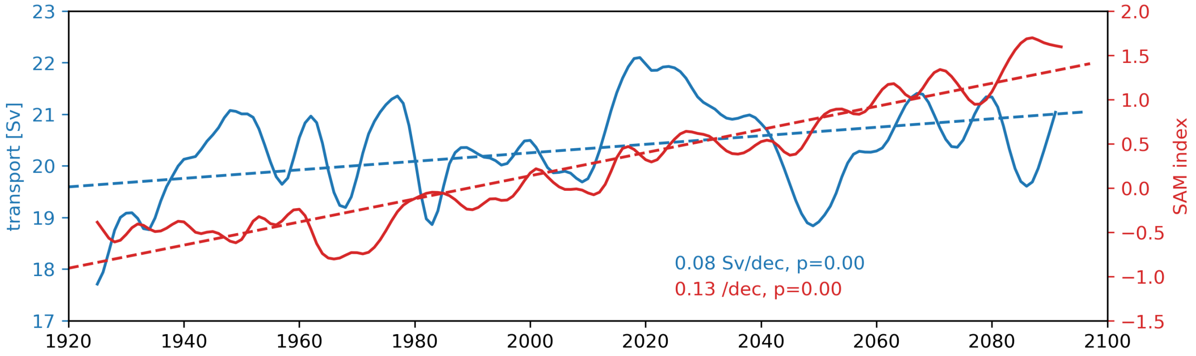

Figure 8: Agulhas Leakage trend in blue and SAM index trend in red for the decadally filtered ensemble average, linear trend values and significance for the period from 1920 to 2100 shown.

Furthermore, we investigated the change of the circulation features in the region and the connection of the AL to the AMOC under a warming climate. Looking at the Agulhas Current, we find a strong negative trend under the greenhouse gas forcing (Figure A4). The transport decreases by up to $20\,Sv$ until 2100. Investigating the causes for this in detail is out of the scope of this study, but a first look at a change in the wind fields shows a decrease in the trade winds over the Indian Ocean (Figure A5). Additionally, the wind stress curl over the southern sub-tropical gyre is decreasing as well. This leads to a decrease in the gyre strength and its western boundary current. Ultimately, we find an increase in the AL fraction which is based on the decrease of the Agulhas Current and the increase of AL. This means that a higher portion of the Indian Ocean waters end up in the Atlantic and that there is less recirculation.

We then investigated what role an increasing AL might have in an AMOC change in the future. It turns out, that the increase in Agulhas Leakage transport is also connected to a higher salt flux into the Atlantic Ocean (Figure 9). We find that the salt flux more than doubles from a pre-industrial mean of $0.24 \pm 0.25\,Sv\,psu$ to about $0.7\,Sv\,psu$ at the end of the 21st century and the trend especially kicks in after 2000. At a similar time, the freshwater transport at 34°S starts to decrease significantly down to $-0.05\,Sv$, as does the AMOC down to around $11\,Sv$. While the AMOC and freshwater decrease is mostly driven by processes in the North Atlantic (*Weijer et al.*, 2019), the relation of the salt flux to the freshwater transport holds and it enhances the negative trend. This qualitatively describes an influence of the AL on AMOC that seems to increase in a warming climate. However, quantifying the impact of the AL change ultimately on the AMOC is not easy, since so many factors have an influence here. The freshwater transport even reaches negative values at the end of the 21st century, which then implies a positive salt-advection feedback and an even stronger AMOC decrease. It would have been interesting to look at another 50-100 years of simulation.

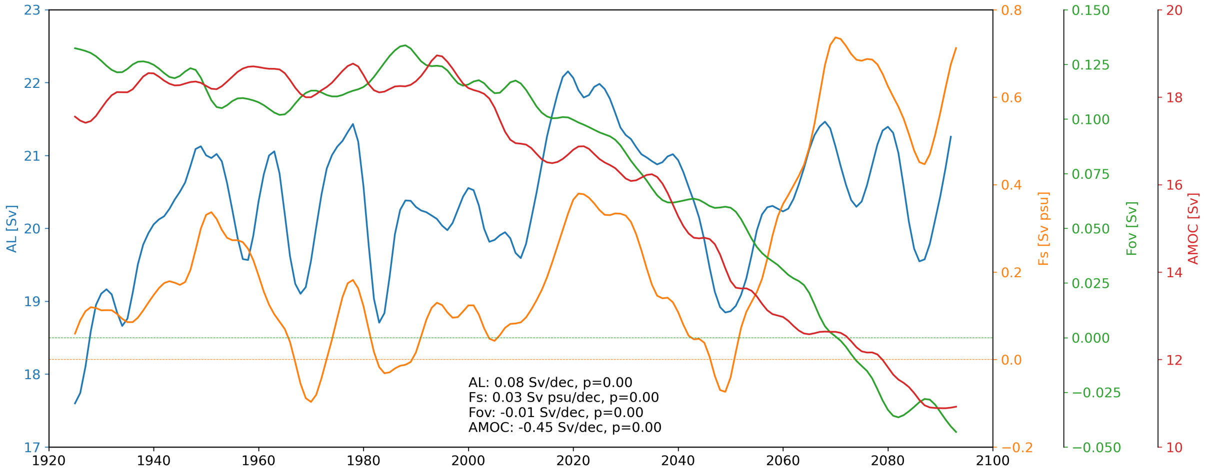

Figure 9: Timeseries of Agulhas Leakage in blue, Agulhas Leakage salt flux (Fs) in orange, AMOC volume transport at 26.5°N in red and AMOC freshwater transport (Fov) at 34°S in green, decadally filtered ensemble average, linear trend values and significance for the period from 1920 to 2100 shown.

5. Discussion and Conclusions

The Agulhas Leakage (AL) is part of the ocean current system around South Africa and plays an important role in the global climate (*Beal et al.*, 2011). The region is highly dynamic and the AL mostly consists of mesoscale eddies that form due to an interplay of the Agulhas Currents inertia and the overlying westerly wind field (*Holton et al.*, 2017). These eddies then propagate north-westward into the Atlantic Ocean. Thereby, warm and salty waters from the Agulhas Current leak into the Atlantic Ocean, are a part of the warm-water route of the global overturning circulation and connect the Atlantic to the Indian Ocean (*Biastoch et al.*, 2008).

Studies so far about the AL and its variability on long time scales were either limited by the length of possible high resolution model simulations or by the use of proxy methods to estimate the AL transport due to the model not resolving the necessary dynamics for a more precise calculation. Here, we use a high-resolution and fully coupled earth system model configuration from the Community Earth System Model CESM with a 0.1° ocean resolution (*Chang et al.*, 2020). A brief validation of sea surface height variability against satellite altimetry as well as other studies based on this model configuration show that the model resolves the necessary scales in the Agulhas System as well as globally (*Chang et al.*, 2020). Within this framework, a multi-centennial pre-industrial control run as well as three ensemble members with a transient CO2-forcing under an RCP8.5 scenario were performed. The high resolution allowed us to apply a lagrangian particle tracking algorithm to calculate the AL transport precisely as the amount of water, that comes from the Agulhas Current and then flows into the Atlantic Ocean through the Good Hope section. Using these model simulation, we could investigate the internal variability of AL on long timescales and its driving mechanisms and impacts on the AMOC. Additionally, we examined how these relationships might evolve in the future under a warming climate.

Our calculated AL transport of $19.7 \pm 3\,Sv$ lies well within the range of the most current observational estimate of $21.3 \pm 4.7\,Sv$ from *Daher et al.* (2020). However, the volume transport from the particle tracking can vary depending on the release section. *Schmidt et al.* (2021) show an increase of $2\,Sv$ from a release at 32° S (as we do) to a release at the ACT (Agulhas Current Time-Series) section at 34° S, where the observational estimates from *Beal et al.* (2015); *Daher et al.* (2020) are based on. On the other hand, using monthly data instead of a higher temporal resolution can lead to a more laminar flow within the tracking and an associated increase in the volume transport. We found an increase of around $2\,Sv$ due to this in the forced ocean sea-ice (FOSI) simulation. Both factors, the different release section and the bias due to the temporal resolution, could even out, but we can not quantify this with the available data. Nevertheless, since the analysis is only looking at variabilities, the total volume transport does not impact our results.

We see a strong interannual variability, which is connected to the forming and propagation of Agulhas rings (*Holton et al.*, 2017). On longer timescales, however, we do not find a robust and significant spectral peak at any period, highlighting the chaotic nature of the system. For our case, resolving decadal or longer frequencies while determining the significance of those peaks still was not straightforward even with a 370 year timeseries. The result depended on the specific method for the spectral analysis. It can, of course, be the case that there is no clear internal variability of the system on these timescales. Still, further research could be done here, meaning either different analysis techniques or the need for an even longer model simulation, which is, however, currently not realisable.

We confirm existing knowledge that the AL is driven by the overlying wind field (*Durgadoo et al.*, 2013; *Rühs et al.*, 2022). Stronger winds of the westerlies connected to a larger wind stress curl over the southern Indian Ocean increase the AL with a time lag of three to four years related to the time scales of baroclinic adjustment. This process is similar to *DiNezio et al.* (2009), who relate transport changes in the Florida Current on interannual to decadal timescales to a change in the windstress curl to the east of the region. A coherence analysis between the winds and the AL shows that the winds are the dominant driver of the system across timescales. Nevertheless, the used region to calculate the wind metrics is quite large and covers the whole southern Indian Ocean. We therefore used this region to represent the large scale wind system because it is not easy to find and define the exact region of the winds which impact the AL. The region where the winds are important determines the timescale of adjustment processes which could therefore vary between eastern or western parts of the domain.

We performed lead/lag-correlations for different circulation features to investigate the impact of the AL. We find a significant positive correlation at zero lag for the Agulhas Current strength. The zero year lag relates to defining the AL transport based on the release year of the particles within the Agulhas Current. Therefore, a stronger Agulhas Current leads to a stronger AL, which contradicts the results from (*Van Sebille et al.*, 2009), who found a negative correlation, e.g. the opposite effect, while (*Loveday et al.*, 2014) described an insensitivity of the AL to the Agulhas Current's strength. The AL as well as the Agulhas Current are further impacted by Indian Ocean sources, also originating from the Pacific Ocean by the Indian Ocean Throughflow (*Durgadoo et al.*, 2017). An open or closed Indonesian passage influences the AL strength by varying the frequency of ring shedding events (*Le Bars et al.*, 2013). *Makarim et al.* (2019) showed that changes in the Indonesian Throughflow can impact the heat and salinity of the Agulhas waters.

The same analysis but for the AMOC strength at 34°S reveals a significant positive correlation at a two year lag, which fits to the advective timescale for the particles to reach that latitude. This shows an impact of the AL onto the South Atlantic's overturning regarding the transport strength. The exact part of the AMOC's circulation dynamics that is impacted by the AL is however not as clear. A closer look at different parts of the AMOC, e.g. the geostrophic part, could reveal more about the interaction between both systems. For the global overturning, the heat and salt transport is as important as the transport volume. By tracking the salinity along the particle track, we calculated the salt transport of the AL into the Atlantic. We then investigated the relation of the salt flux to the freshwater transport at 34°S, which is part of the salt-advection feedback. This feedback describes a connection between the AMOC strength, the freshwater transport at 34°S and the density difference between the North and the South Atlantic. The freshwater transport is positive in the pre-industrial control run, i.e. a stable AMOC. There are model configurations that have a bi-stable AMOC and *Deshayes et al.* (2013) show that this also relates to the resolution with higher resolution leading to a more negative freshwater transport. However, this additionally varies between forced ocean-only experiments and full earth system models (*Cheng et al.*, 2018). *Westen and Dijkstra* (2023) show that a lot of coupled models have errors in the surface salinities based on atmospheric precipitation biases which then influences the freshwater transport in the ocean. They also show that CMIP6 models have both positive and negative freshwater transports, but the ones with a negative transport underestimate the AMOC transport; no model gets both in the observational range. Independent on the general sign, we find a strong negative correlation of the salt flux to the freshwater transport across 34°S. This suggests that the salt input from the AL therefore decreases the stability of the AMOC within this framework.

The ensemble members under the RCP8.5 forcing confirm the existing hypothesis that the AL transport indeed increases under global warming. The increase we find with $0.08\,Sv/dec$ is not as strong as other studies show or suggest (*Ivanciu et al.*, 2022; *Beech et al.*, 2022), but still significant. However, the trend is vanishing when just looking at the 21st century, which is contradicting, when the strong CO2-forcing only kicks in after 2005. The increase is due to a change in the wind field. We find an increase in the SAM index, which is based on a strengthening in the southern hemisphere westerlies as well as a southward shift. These changing winds then drive the AL increase. In contrast to the AL, the Agulhas Current transport decreases drastically until the end of the 21st century. Together with the general positive correlation between the Agulhas Current and the AL, this decrease counteracts the increase in AL due to the winds and could explain the vanishing trend after 2000. Still, this means an increase in the portion of Agulhas Current water that ends up in the Atlantic Ocean. The cause of the Agulhas Current decrease is an interesting topic on its own. A brief look at the winds over the Indian Ocean shows a decrease in the windstress curl, which can explain the lower Agulhas Current strength to a first order. *Ivanciu et al.* (2022) find a similar decrease in the current strength and explain this with a change in the wind stress curl as well. In another study, *Hu et al.* (2021) performed hosing experiments to force an AMOC collapse, which then leads to a reduction in the Agulhas Current of up to 12 Sv over a century, therefore a similar timescale as the decrease we found.

Regarding the AMOC, we also see an increase in the salt transport of the AL. The salt flux is calculated as the difference of the particle salinities to the mean salinity at the crossing section. *Westen and Dijkstra* (2023) investigated the same model runs and find a change in the local salinity at the section during global warming due to more evaporation than precipitation, which then impacts the reference salinity for the salt flux estimation. However, when fitting a linear trend to the section and using this as a reference instead of just a mean, we do find a significant increase of the salt flux as well but with a smaller magnitude. As the salt flux trend is strongest after 2000, in opposite to the AL trend, it seems that this is based on a change in the hydrography rather than the volume transport. The increased salt flux then contributes to a decrease of the freshwater transport, which ultimately decreases the AMOC stability within the salt-advection-feedback theory. *Westen and Dijkstra* (2023) also show, that the decrease in the freshwater flux is salinity based and mostly depends on changes in the upper 1500m, which fits to the impact of the AL salt flux. The decrease evolves even to the point of a negative freshwater transport at the end of the 21st century and could lead to a possible AMOC collapse in the future. On the other hand, hypothesis exist that the salt input from the AL into the Atlantic ultimately reaches the North Atlantic and deep water formation regions (*Weijer and van Sebille*, 2014). The salt can then play a role in setting the local stratification and thereby positively impacting deep water formation. The increasing salt flux under global warming could therefore be a counterpart to the increase in meltwater input in the North Atlantic. However, quantifying these processes and the ultimate impact on the AMOC strength needs focused future research. Straightforward would be to track AL particles further into the Atlantic or back into the Indian Ocean to investigate the fate and the origin of AL waters and their role in the global overturning. Another interesting aspect would be to investigate the internal pathways of the AL and if the portion of transport within and outside of Agulhas rings is changing in the future and thereby also which regions the waters ultimately reach.

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7. Appendix

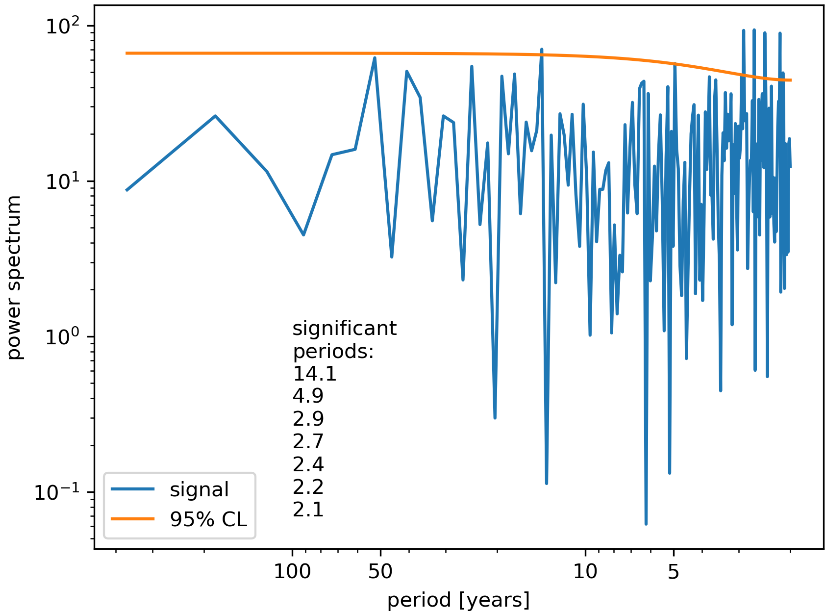

Figure A1: Spectral analysis of the annual Agulhas Leakage timeseries as well as significant periods for the PIcontrol.

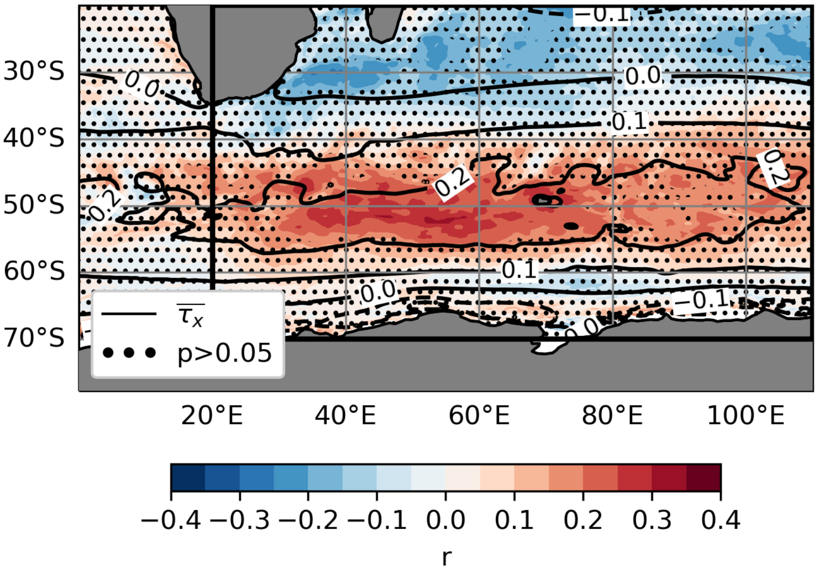

Figure A2: Correlation of Agulhas Leakage Transport to the annual mean zonal windstress at each gridpoint for the PIcontrol; dots show unsignificance; contour lines show the mean zonal windstress and the big black rectangle outlines the area which the maximum zonal windstress is extracted from for the time series analysis.

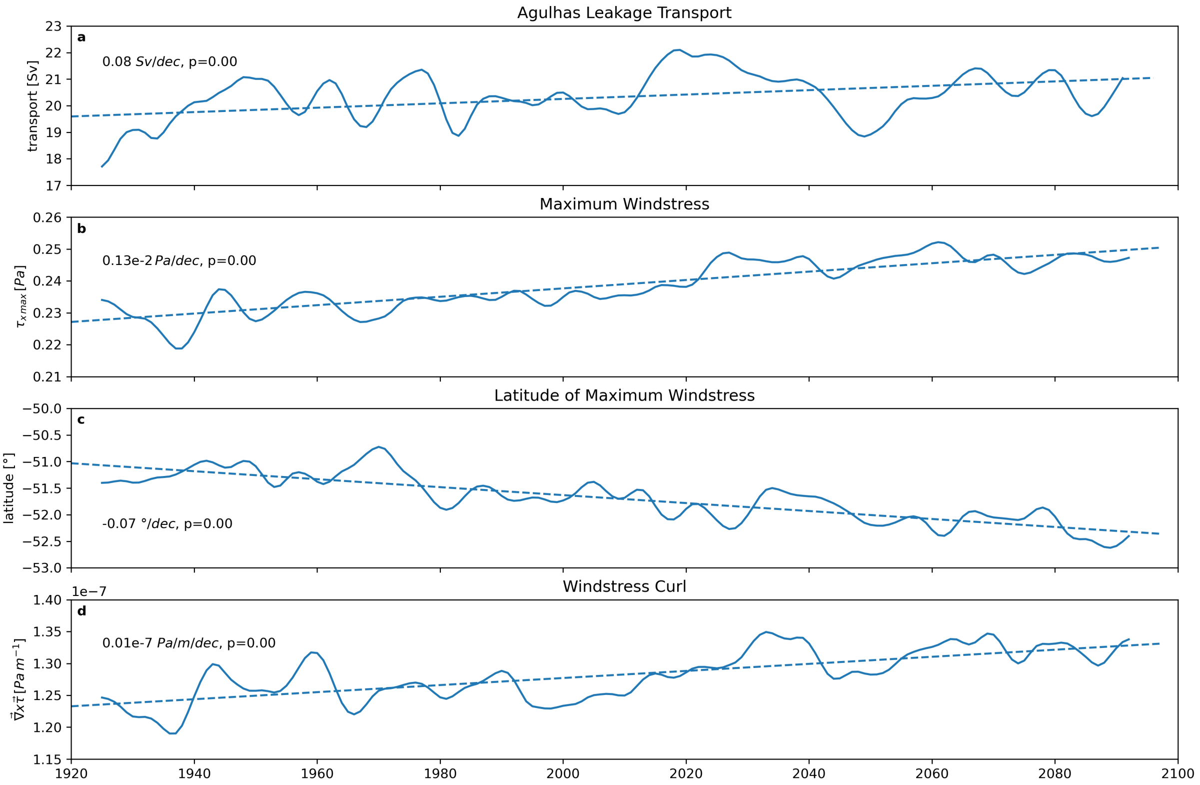

Figure A3: Timeseries and trends for the period from 1920 to 2100 for Agulhas Leakage transport (a), maximum zonal wind stress $\tau_{x\,max}$ (b), latitude of maximum zonal windstress (c) and average wind stress curl $\vec{\nabla}x\vec{\tau}$ (d) as decadally averaged ensemble means.

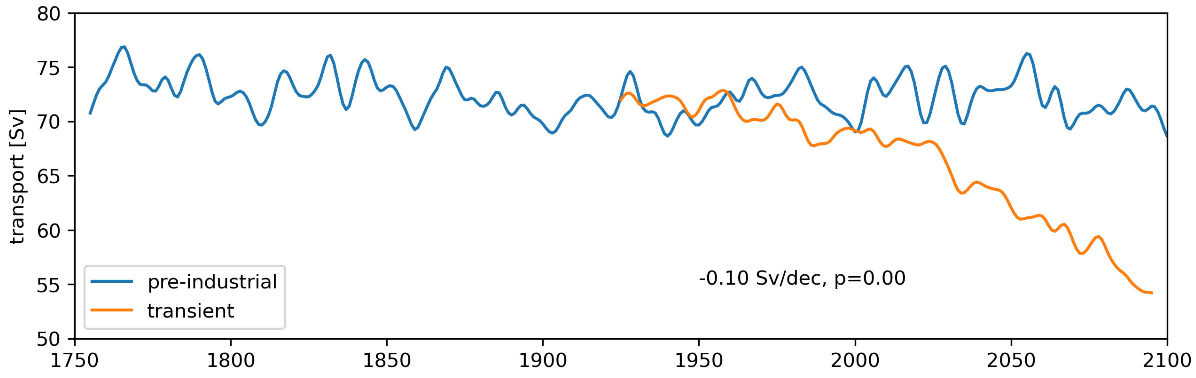

Figure A4: Decadally filtered Agulhas Current transport timeseries of the PIcontrol in blue and the ensemble average under transient historical and RCP8.5 CO2 forcing in orange, trend values shown for the period from 1920 to 2100.

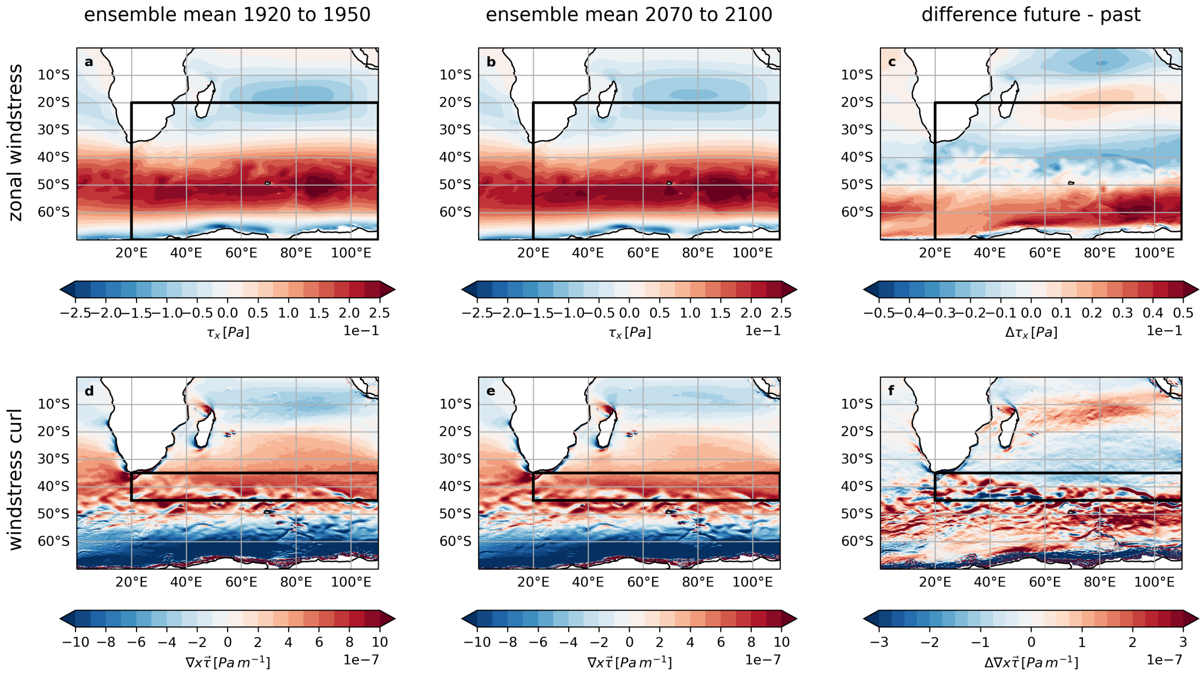

Figure A5: Ensemble averaged zonal windstress τ_x (a-c) and windstress curl $\vec{\nabla} x \vec{\tau}$ (d-f) historical (a,d) and future (b,e) mean states for the periods from 1920 to 1950 and 2070 to 2100 respectively and their change (c,f).

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I want to thank my supervisors Arne Biastoch and Gokhan Danabasoglu as well as Frederic Castruccio for their guidance and input during this study. Additionally, I want to highlight the community contributions to the development of open-source python packages and analysis tools without whom this work would not have been possible and which are beyond acknowledgements over citations.

Declaration

I confirm that this master thesis is the result of my own work. No other person's work has been used without acknowledgement in the main text of this thesis. This thesis has not been submitted for the award of any other degree or thesis in any other institution. All sentences or passages quoted in this thesis from other people's work have been specifically acknowledged by clear cross-referencing to author, work and pages. Any illustrations which are not the work of the author of this thesis are specifically acknowledged. The submitted written version of the thesis corresponds to the version on the electronic storage device

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