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A Review of the Arctic-West African Monsoon Nexus: How Arctic Sea Ice Decline Influences Monsoon System

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Abstract

The West African Monsoon (WAM) is a crucial component of the regional climate system, affecting agriculture, water resources and livelihoods across West Africa. Recent studies have suggested that changes in Arctic sea ice extent, driven primarily by anthropogenic climate change, could exert significant influences on the behaviour of the WAM. This review paper summarises the current state of knowledge on how Arctic sea ice melt has affected the WAM system over the last decades. Utilizing observations data and modelling studies aim at enhancing our understanding of the influence of Artic sea ice loss on WAM. This paper also explores the mechanisms driving the connections between Arctic sea ice melting and the WAM, discusses the potential implications for regional climate variability, and identifies key challenges and opportunities for future research in this important area of study.

Keywords: Arctic sea ice melting, West African Monsoon, climate variability, connections, climate change

1 Introduction

The Arctic sea ice melting phenomenon refers to the significant reduction in the extent and thickness of sea ice in the Arctic region, primarily driven by rising temperatures due to global climate change (Walsh 2013;Lee et al. 2022). This trend has been increasingly observed over recent decades and is largely a consequence of human activities, such as the burning of fossil fuels and deforestation, which release greenhouse gases into the atmosphere, thereby exacerbating the warming effect (Papalexiou et al. 2018). The Arctic is experiencing warming at a rate that is roughly twice (Cohen et al. 2014; Yu et al. 2021; Barbero-Palacios et al. 2024) or more than twice (Jansen et al. 2020; Rantanen et al. 2022) as rapid as the global average, leading to the accelerated melting of sea ice (Lind et al. 2018). Anomalously high air temperatures result in the melting of the ice from above, whereas warmer ocean temperatures cause melting from below (Straneo et al. 2011). As sea ice melts, albedo decreased and the darker ocean surface absorbs more solar radiation, leading to further warming and more ice melt (Lu et al. 2018). This positive feedback accelerates the loss of sea ice (Ivanov 2023). In addition, the Arctic multi-year ice, which endures through several melting seasons, is decreasing, giving way to thinner first-year ice that is more prone to melting in the summer months (Zwally and Gloersen 2008). Moreover, changes in the patterns of atmospheric circulation can impact how sea ice is distributed and moves, thus affecting its extent and thickness across various regions (Zhang et al. 2023).

The consequences of Arctic sea ice melting are significant and wide-ranging (Walsh 2013). Arctic plays a crucial role in regulating global climate systems (Yamanouchi and Takata 2020). Changes in sea ice extent can affect weather patterns, ocean circulation and climate stability worldwide (Rahaman et al. 2020). Moreover, sea ice melting does not directly contribute to sea level rise, but the loss of reflective ice cover amplifies warming in the Arctic, accelerating the melting of land-based ice sheets like Greenland, contributing to sea level rise globally. In addition, decline in sea ice habitat impacts several Arctic species, including polar bears, seals, and walruses, which depend on the ice for activities such as breeding, hunting, and resting (Kovacs et al. 2011). Efforts to reduce the melting of Arctic sea ice involve the reduction of greenhouse gas emissions, the adoption of policies promoting renewable energy sources, and the establishment of international agreements targeting climate change (Overland et al. 2019). However, reversing the trend of Arctic sea ice decline will require concerted global action and significant changes in human behaviour (O'Rourke et al. 2020).

West African Monsoon (WAM) system is a climatic phenomenon that holds immense significance for the West African region, influencing agriculture, water resources and regional climate dynamics (Bock et al. 2011; Kothe et al. 2014) as well as weather patterns, environmental conditions and livelihoods on a vast scale (Poan et al. 2016). The West African summer monsoon starts with the Intertropical Convergence Zone (ITCZ) abruptly moving north from 5°N in May–June to 10°N in July–August, with the onset usually around June 24th (Sultan and Janicot 2003). From June to September (JJAS) each year, the WAM system marks a seasonal transition characterized by the reversal of prevailing wind patterns and the onset of widespread rainfall across the region (Talib et al. 2022). Additionally, the timing and duration of monsoon precipitation may fluctuate from year to year, presenting significant challenges for agricultural practices, water resource management and disaster mitigation endeavours (Sultan and Gaetani 2016). In numerous West African nations, agriculture plays a pivotal role in the economy, primarily relying on rainfed methods that sustain the livelihoods of millions (Akudugu et al. 2021). Moreover, the complex interplay between atmospheric and oceanic dynamics shapes the socio-economic of West Africa. The WAM is driven by the interaction between the African continent and the adjacent tropical Atlantic Ocean (Mohino et al. 2024) and Pacific Ocean (Villamayor and Mohino 2015). During the summer months, as the Northern Hemisphere tilts towards the Sun, the ITCZ shifts northward, resulting in the convergence of trade winds and the onset of the monsoon period (Tomaziello et al. 2016). West Africa's proximity to the equator and the maritime effects of the Atlantic Ocean are crucial factors that influence both the timing and intensity of the monsoon rains (Chang et al. 2008). Furthermore, the onset of WAM season is marked by the influx of moisture from the Atlantic Ocean, propelled by the prevailing south-westerly winds (Parker et al. 2016). These warm and humid air masses allow the formation of convective storms and widespread rainfall across the region (Diedhiou et al. 1999). Coastal regions observe the earliest onset of rainfall, owing to their proximity to the south as well as northward progression of the monsoon. As the monsoon season advances, the precipitation gradually extends inland, covering the entirety of the West African region.

The spatial and temporal patterns of rainfall linked to the WAM system demonstrate substantial variability, shaped by a multitude of factors such as topography, vegetation cover and large-scale atmospheric circulation dynamics (Sylla et al. 2012; Diba et al. 2018). Coastal regions and elevated areas typically exhibit higher precipitation levels compared to inland zones, resulting in pronounced variations in rainfall across different geographical settings. The timing and volume of rainfall during the monsoon season significantly influence crop yields, food security and rural incomes (Wossen et al. 2018). Farmers eagerly await the onset of rains, readying their fields for planting and utilizing the moisture to nurture their crops. Conversely, if rainfall is delayed, it can result in crop losses, food scarcities and financial difficulties for rural populations (Kumi and Abiodun 2018). Apart from direct effects of WAM on Agriculture, it also significantly influences the hydrological cycle in the region (Nahmani et al. 2012). The seasonal rainfall influx refills surface water sources, recharge underground water reserves and maintains ecosystems, which in turn support diverse wildlife and habitats. Rivers like the Niger, Senegal, Gambia, Chad and Volta are vital sources of water for millions of people in West Africa, supplying water for various needs such as drinking, farming and industry (Sylla et al. 2018). The WAM system's effects extend beyond agriculture and water resources, significantly impacting regional climate dynamics and atmospheric circulation patterns (Kebe et al. 2017). The monsoon's seasonal wind reversal leads to the creation of the Saharan Heat Low, a sizable thermal low-pressure system that emerges over the Sahara Desert in summer (Lavaysse et al. 2009). This circulation pattern influences weather patterns not just in West Africa but also across the wider Sahel region and beyond.

Recent review papers (Cohen et al. 2012, 2014; Vihma 2014; Steinsland et al. 2023; Loriani et al. 2023) have synthesized numerous studies exploring the potential impacts of Arctic sea ice loss on large-scale atmospheric circulation. These studies indicate that the impact of Arctic sea ice loss on large-scales atmospheric circulation can influence jet stream position and North Atlantic Oscillation (NAO). Arctic sea ice loss affect the position and intensity of the African easterly jet (AEJ) and African easterly waves (AEW), which are important parts of the WAM system (Budikova 2009; Monerie et al. 2019a). Additionally, Arctic sea ice melt can affect temperature and pressure gradients between the Arctic and mid-latitudes, potentially influencing the strength and location of the subtropical ridge or highs over North Africa, which helps steer the WAM (Walsh 2014). The reduction of sea ice impacts not only middle and high latitudes but also results in heightened precipitation near the equator (Deser et al. 2015) and induces changes in the ITCZ (Kang et al. 2008). Smith et al. (2017) recently revealed that the decline in sea ice can lead to increased precipitation in West Africa by altering sea surface temperatures (SSTs) in the North and subtropical Atlantic Ocean. Smith et al. (2017) argue that the decline in Arctic sea ice is linked to changes in WAM dynamics through increased North Atlantic Ocean warming, which enhances atmospheric circulation. This is supported by Talento and Barreiro (2018), who conducted idealized numerical experiments showing that a significant temperature increase at high latitudes leads to warming over the subtropical Atlantic Ocean, the Mediterranean sea and northern Africa. This warming causes the ITCZ to shift northward, resulting in increased precipitation in the Sahel region. The purpose of this review is to combine the existing observational and modelling studies from Scopus, Google Scholar, Research Gate and Web of Science that examine the potential effects of Arctic sea ice melting on the WAM. The review primarily centers on summarizing the influence of Arctic sea ice melting on WAM. Additionally, it discusses the challenges faced by current research in enhancing our understanding of how Arctic sea ice loss affects WAM. Future research opportunities are also highlighted.

This review is organised as follows: After the introduction, Section 2 examines recent processes and drivers of Arctic sea ice melting. Section 3 explores the seasonal cycles, precipitation patterns and key drivers, historical trends, variability and the important of the WAM for regional agriculture, ecosystems and water resources. Section 4 delves into the mechanisms of interaction between Arctic sea ice melting and the WAM, including observational evidence and modelling studies, along with implications for regional climate variability. Section 5 outlines the challenges and opportunities for future research. Finally, Section 6 provides a summary and conclusion.

2 Arctic Sea Ice Melting: Processes and Drivers

2.1 Overview of Arctic Sea Ice Dynamics

Rapid warming in the Arctic has resulted in a substantial loss of sea ice (Cohen et al. 2014). This sea ice plays a critical role in regulating near-surface conditions at high latitudes, which in turn can impact both regional and possibly distant climates. As Arctic sea ice diminishes, the newly exposed open water has a much lower albedo than ice. This lower albedo results in increased absorption of sunlight (Ivanov 2023). Consequently, SST anomalies of 4-5°C are observed in these ice-free areas (Wood et al. 2013). During autumn, when the air temperature drops below that of the ocean surface, the excess heat stored in the ocean during the summer is released into the atmosphere through radiative and turbulent fluxes, significantly warming the lower Arctic troposphere (Stroeve and Notz 2018). This additional heat in the system delays the formation of Arctic sea ice in winter, reducing both its extent and thickness (Stroeve et al. 2011). As a result, winter Arctic sea ice has become thinner, making it more prone to melting, breaking up, and moving. The increased amount of open water during winter leads to the formation of warmer, moister air masses over the Arctic Ocean and nearby continents, which weakens the meridional near-surface temperature gradient. These feedback mechanisms indicate that the observed loss of Arctic sea ice is both a consequence and a driver of Arctic amplification.

2.2 Recent Trend of Arctic Sea Ice Extent and concentration

The majority of research investigating shifts in Arctic sea-ice extent (SIE) has predominantly concentrated on changes occurring in the summer months (Cavalieri and Parkinson 2012; Bushuk et al. 2024). However, changes in the Arctic are now becoming more pronounced in the months beyond the summer season. A recent study by Stroeve and Notz (2018) found that from the early to mid-2000s, there was a marked rise in below-average SIE throughout all months, with significant declines observed during summer, especially in the years 2007 and 2012. In 2012, SIE in August and September dropped more than 3 standard deviations (σ) below the long-term average from 1981 to 2010. While there haven't been any new record lows for summer sea-ice coverage since 2012, the loss of ice throughout the year has been unprecedented in recent years. From January 2016 to July 2018, every month saw sea-ice coverage more than 2σ below average, except for May and September 2017, and July 2018. Additionally, their findings also indicated that in the satellite data record, there has never been such a prolonged period of consecutive months with significantly negative anomalies. In May and November 2016, the anomalies were almost 4σ below the long-term average, marking new record lows in the satellite data record and representing the largest deviations from the average for any month. In the last two years, record low ice extents for specific months were recorded in January (2017 and 2018), February (2017 and 2018), March (2017 and 2018), April (2016 and 2018), May (2016), June (2016), November (2016), and December (2016). Similarly, National Snow and Ice Data Centre (NSIDC) has studied the lifespan of Arctic ice, finding that older ice tends to thicken more during winter due to processes like ridging and bottom ice growth. This thicker, older ice has a significant impact on how much ice survives during the summer melt season compared to new ice that forms each winter. The proportion of old, thick ice has been decreasing. By the end of the summer of 2022, the extent of the oldest ice, over 4 years old, reached its lowest record (see Fig. 1). First-year ice, which forms and melts within a single year, now dominates the Arctic ice cover. Meanwhile, the percentage of ice older than 4 years has sharply declined from over 30% to just 3.1% (Fig. 1).

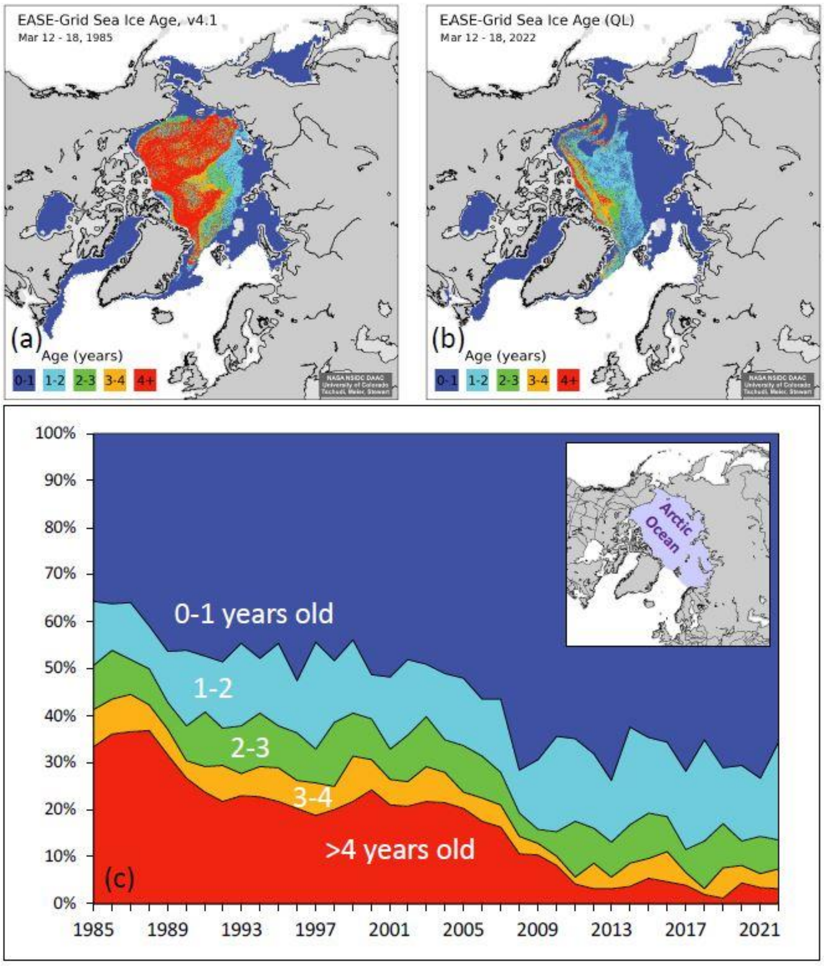

Fig. 1 (a, b) illustrates the age distribution of Arctic sea ice during the period of March 12 to 18 in the years 1985 and 2022, the oldest ice, which is over 4 years old, is depicted in red, (c) presents a time series spanning from 1985 to 2022, showcasing the percentage coverage of the Arctic Ocean domain (highlighted in purple in the inset) by various sea ice ages in the March 12 to 18 period. Credit: M. Tschudi, W. Meier, and Stewart, NASA NSIDC DAAC.

Moreover, Onarheim et al. (2018) conducted a study investigating historical and projected changes in regional SIE across the Northern Hemisphere throughout the year. They utilized sea ice concentration (SIC) data spanning from 1950 to 2016, with satellite observations specifically from 1979 to 2016. The study reveals distinct differences in the regions experiencing anomalous ice losses between summer and winter. During summer, the most significant ice losses occur in the Beaufort, Chukchi and East Siberian seas, which are characterized by substantial ice coverage in winter but exhibit strong negative trends in summer. Beaufort, Chukchi and East Siberian seas have been defined as 'summer mode' by Onarheim et al. (2018), witnessed the largest reductions in sea ice extent in December 2016. Specifically, the East Siberian sea accounted for 22% of the total summer ice loss, followed by the Chukchi sea (17%), the Beaufort sea (16%), the Laptev sea (14%), and the Kara sea (9%) (Fig. 2).

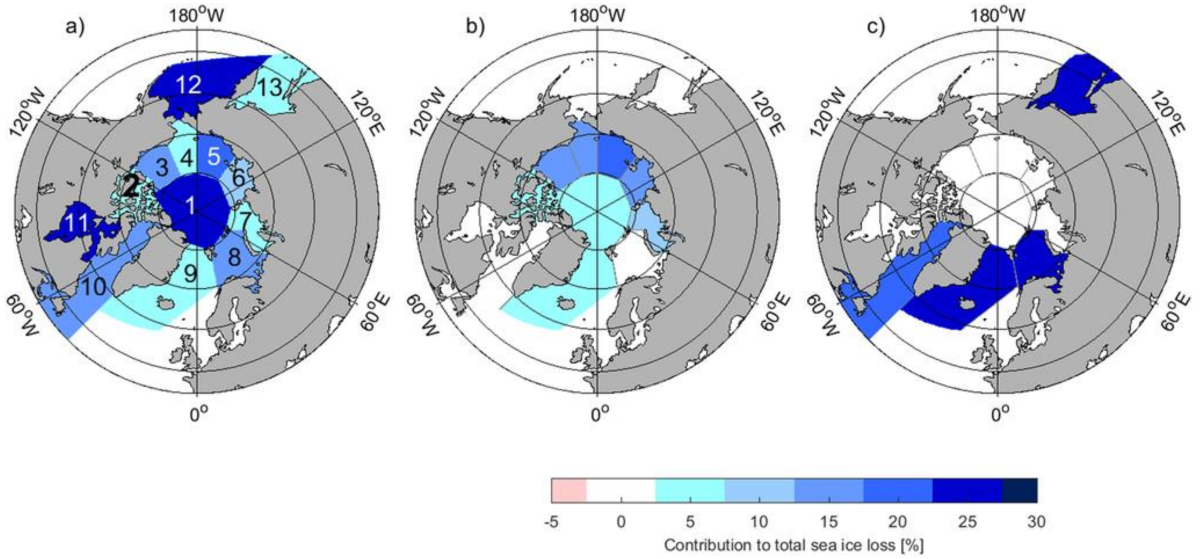

Fig. 2 (a) A depiction of the regional seas in the Northern Hemisphere, listed in order from 90°N in a clockwise direction; (1) central Arctic, (2) Canadian Archipelago, (3) Beaufort sea, (4) Chukchi sea, (5) East Siberian sea, (6) Laptev sea, (7) Kara sea, (8) Barents sea, (9) Greenland sea, (10) Baffin Bay/Gulf of St. Lawrence, (11) Hudson Bay, (12) Bering sea, and (13) Sea of Okhotsk. Additionally, it illustrates the contribution of each regional sea to the trends in (b) September and (c) March sea ice extent across the Northern Hemisphere from 1979 to 2016. This Fig is in Onarheim et al. in 2018.

Similarly, Stroeve and Notz (2018) also examine the ongoing loss of Arctic sea ice across all seasons from January 1979 to July 2018. Their findings indicate significant changes in the proportional contributions of various Arctic seas to sea ice extent by 2018. The East Siberian sea remains the primary contributor at 27%, closely followed by the Beaufort and Chukchi seas at 16% and 15% respectively. The Laptev sea follows with 13%, and the Kara sea with 9%. Together, these six regions account for 89% of the inter-annual variability in September sea ice extent since 1979, with the Central Arctic and Canadian Archipelago making up the remaining 11% (Onarheim et al. in 2018). Notably, compared to the average sea ice coverage during the initial decade of satellite records (1979-1989), the Chukchi sea, Kara sea, and Hudson Bay have seen a substantial decrease, ranging from 90% to 100%, while the Laptev and East Siberian seas have experienced a decrease between 80% and 90%.

In the winter months, the Arctic Ocean typically remains covered in ice, limiting seasonal changes primarily to surrounding seas (Stroeve and Notz 2018). East Siberian sea, Beaufort sea, Chukchi sea, Laptev sea and Kara sea, which lack sea ice during summer months and exhibit the most significant decline in winter, are categorized as being in 'winter mode,' as defined by Onharheim et al (2018). Onharheim et al (2018) highlights that the Barents sea and the sea of Okhotsk have experienced the most substantial reduction, each contributing 27% to the trend in March SIE, while the East Greenland sea (23%) and Baffin Bay/Davis Strait/Gulf of St. Lawrence (22%) contributed the remaining percentages. However, both the East Greenland sea and the sea of Okhotsk now demonstrate similar trends, each contributing approximately 22% to the overall March SIE trend (Stroeve and Notz 2018). Additionally, these regions collectively account for 81% of the inter-annual variance in March SIE over the satellite data record (Onarheim et al., 2018). Relative to ice conditions between 1979 and 1989, the Barents sea and the Gulf of St. Lawrence have each witnessed a decline of approximately 50% in their winter sea ice, whereas the sea of Okhotsk and the Greenland sea have seen their initial winter sea ice cover diminish by about one-third.

In contrast to the extreme conditions observed in Antarctica, the changes in Arctic sea ice extent during 2023 were less dramatic (Roach and Meier 2024). However, the long-term trend of decreasing sea ice persists. Roach and Meier (2024) reveal that the average annual Arctic SIE reached 10.49 million km² (Fig. 3a), marking the 7th lowest in satellite records (refer to Fig. 3b). Consequently, there were no new monthly records set: the September minimum, typical of summer, was 4.37 million km², ranking as the 5th lowest recorded, while the March maximum, typical of winter, was 14.44 million km², ranking as the 6th lowest on record.

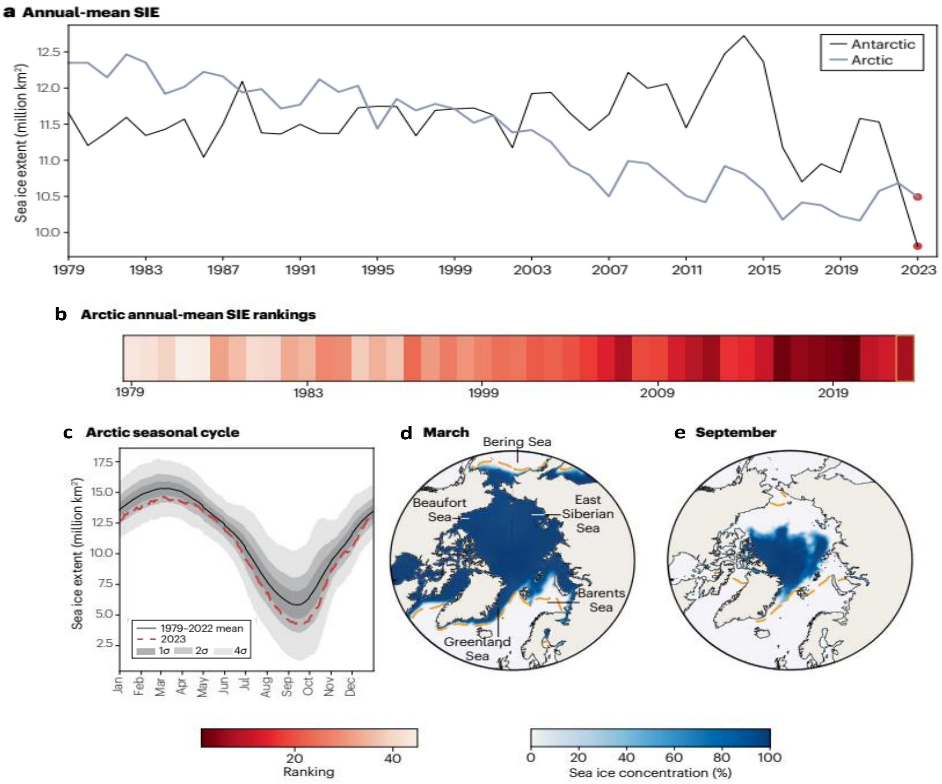

Fig. 3 (a) annual mean SIE for both the Arctic and Antarctic, (b) a representation of the ranking of annual mean Arctic SIE, where the darkest shade indicates the year with the lowest SIE on record and the lightest shade represents the year with the highest SIE on record, (c) the seasonal variation of daily Arctic SIE, with the mean from 1979 to 2022 depicted in black, 2023 in red, and standard deviations indicated by grey shading, (d) Arctic sea ice concentration in March, with the dashed orange line denoting the climatological (1979–2022) sea ice edge (the 15% sea ice concentration boundary), and a similar representation to (d), but for September. This Fig is in Roach and Meier (2024).

Looking back at 2023, the winter SIE exhibited a noticeable but not extreme decline compared to the average from 1979 to 2022 (Roach and Meier 2024). Specifically, between January and March, it was approximately 6% or 1.5σ below the long-term mean (Fig. 3c). This decrease in winter SIE was primarily attributed to reduced sea ice in the Barents sea (Fig. 3d). Despite the generally unremarkable winter, there were four days with record-low SIE: January 31st (13.64 million km^2), February 1st (13.76 million km^2), March 14th (14.33 million km^2), and March 15th (14.35 million km^2). Transitioning into spring (April to June), the total SIE returned closer to the long-term average (Fig. 3c), partly because of increased ice in the Greenland sea. In addition, as the melting began, there was a rapid decline in total SIE. For example, in mid-June, SIE was just 5% (an equivalent to 0.9σ) below climatological values, but by the end of September, it had dropped to 30% or 1.4σ, indicating robust decrease of SIE (refer to Fig. 3c). The lowest daily extent was recorded on September 17th, reaching 4.21 million km^2. Notably, anomalies in sea ice concentration were most pronounced in the Pacific sector, especially in the Beaufort and East Siberian seas (see Fig. 3e). 2023 marked the second-lowest extent on record for the Beaufort sea, with only 2012 having a lower extent. As autumn set in, there was a swift return to freezing conditions, bringing Arctic SIE back towards typical levels by November. In November and December, total SIE was approximately 6% or 1.0σ below the levels observed between 1979 and 2022, with some fluctuations. The most notable recovery during autumn was observed in the Beaufort and East Siberian seas. Furthermore, Roach and Meier (2024) assert that the events of 2023 have no significant influence on the long-term trends of Arctic sea ice. The yearly average trend remains consistent at -4.6 ± 0.2 % per decade for both the periods of 1979 to 2022 and 1979 to 2023. The trends in September SIE, where the most significant declines have been observed, also remain steady at -13.2 ± 1.1% per decade for both timeframes. Despite a slowdown in Arctic sea ice loss since 2008 (as shown in Fig. 3a), it is expected to persist (Babb et al. 2023), with projections indicating the likelihood of an almost ice-free Arctic sometime between 2030 and 2050 (Kim et al. 2023), regardless of emissions over the next thirty years.

A recent study by Chen et al. (2024) examined the dynamics of Arctic SIE, focusing on a significant 4–6-year periodic variation and its driving factors from January 1979 to December 2021. Their study identified this periodicity as the dominant low-frequency variation in SIE. By applying a clustering analysis, they divided the ice-covered regions into two primary zones: Region-1 around the Barents Sea (shown in blue in Fig. 4a) and Region-2 near the Canadian Basin (depicted in yellow in Fig. 4a), both located adjacent to the Arctic Transpolar Drift. They utilized a novel "running linear fitting algorithm" to clearly identify the 4–6-year cycles in both regions. In addition, the temporal variation rate in the Arctic SIE (VR_{IE}) for the two regions was computed using a running linear fitting method, as shown in Fig. 4b and c. Although the VR_{IE} amplitude fluctuated over time, the variation period remained consistent. Both regions displayed low-frequency variations with a 4–6-year periodicity. Before 2005, the VR_{IE} values of Region-1 and Region-2 were strongly negatively correlated, but after 2009, they shifted to almost perfect positive correlations (Fig. 4d), with the transition occurring between 2006 and 2008. The variation cycle of VR_{IE} in Region-1 largely drove the 4–6-year periodic changes in Arctic SIE (not shown), consistent with the findings of Mysak and Venegas (1998).

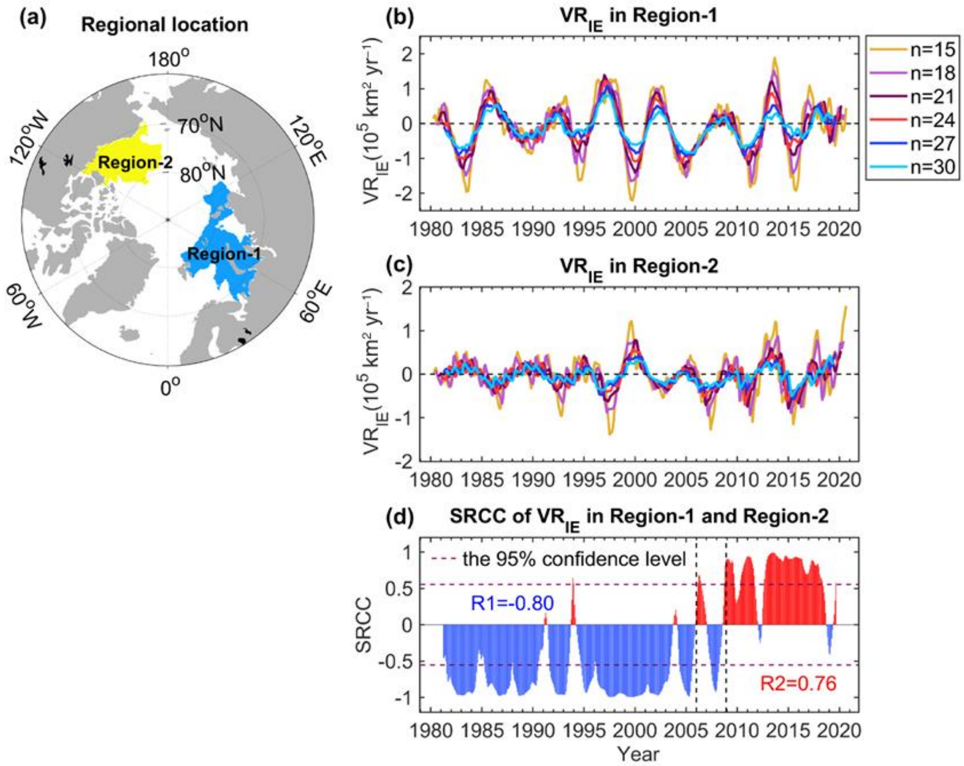

Fig. 4 (a) Shows the locations of the two regions investigated in this study. (b, c) Depict time series of the SIE anomaly variation rate (VR_{IE}) with different window widths (2n + 1) for (b) Region-1 and (c) Region-2. (d) Illustrates the Synthetic Running Correlation Coefficients (SRCCs) [window = 13, SRCC<0 (blue), SRCC>0 (red)] of VR_{IE} ($n = 21$) for both regions. This Fig is in Chen et al. (2024).

Moreover, Chen et al. (2024b) further identify that the rate of change in Arctic SIE was primarily influenced by three factors: regional air temperature, sea-ice areal flux across the Arctic Transpolar Drift, and sea-ice drift divergence. Although the periodic variation remained consistent throughout the study period, the response of SIE to these factors varied before and after 2005, reflecting different dynamics under heavy and light ice conditions. The combined contributions of these factors accounted for over 83% of SIE variability in Region-1 and 59% in Region-2, emphasizing their significant roles in Arctic sea-ice dynamics. In addition, the study established a strong connection between the El Niño–Southern Oscillation (ENSO) and these driving factors, positioning ENSO as a fundamental source of the observed 4–6-year periodic variations in Arctic SIE.

A detailed investigation into the Arctic atmosphere, sea ice, and ocean relationships, conducted by Chen et al. (2024a), highlights the roles of SST and surface air temperature (SAT) in shaping the interannual variability and long-term trends of Arctic SIC from July to October between 1951 and 2021. The study reveals that both SST and SAT significantly influence Arctic SIC, with SST impacting both short-term variations and decadal trends, while SAT has a stronger effect on interannual fluctuations. They also demonstrate that SAT affects SIC trends with a lead time of seven months, attributed to the more pronounced warming in winter compared to summer. Furthermore, their statistical analysis shows that SST explains 53% of the detrended interannual variance in SIC, while SAT accounts for 35%. As SST and SAT are projected to continue rising, the study predicts that SIC trends will continue to decline in the future.

In another recent development, Kolbe et al. (2023) explored future changes in the interannual variability (IAV) of key Arctic climate indicators, such as sea ice and precipitation, which remain highly uncertain. They emphasize that gaining a comprehensive understanding of IAV is critical for improving predictions of sea ice variability, distinguishing between long-term trends and natural fluctuations, and reducing uncertainties related to extreme events. To address these pressing concerns, the study evaluates and ranks CMIP6 models based on their accuracy in replicating observed data and quantifies projected IAV trends (1981–2100) for Arctic surface air temperature, precipitation, and SIC under continued global warming. By calculating IAV at the grid point level before averaging across regions, the study provides a more precise representation of Arctic-wide variability. This approach enhances the clarity of annual mean trends in surface air temperature (SAT), precipitation (PR), and sea ice area (SIA) variability, as illustrated in Fig. 5. The observed decrease in temperature variability, associated with Arctic warming (Fig. 5b), has been noted in previous research, which attributes this negative SAT-IAV trend to winter sea ice loss (Reusen et al. 2019; Landrum and Holland 2020). Additionally, in terms of sea ice variability, significant seasonal differences between summer and winter, along with notable regional variations, are not fully reflected in the annual mean signal (Fig. 5f). Between 2000 and 2050, annually averaged SIA slightly increases due to thinning sea ice, which results in a larger growth and melt area (Holland et al. 2008; Goosse et al. 2009). However, most models project a decline in SIA variability by the end of the century, driven by a marked reduction in the annual mean sea ice area. Meanwhile, PR-IAV shows an increase in both summer and winter (Fig. 5d), attributed to the atmosphere's increased moisture retention capacity and enhanced poleward moisture transport (Bintanja and Selten 2014; Pendergrass et al. 2017; Bogerd et al. 2020).

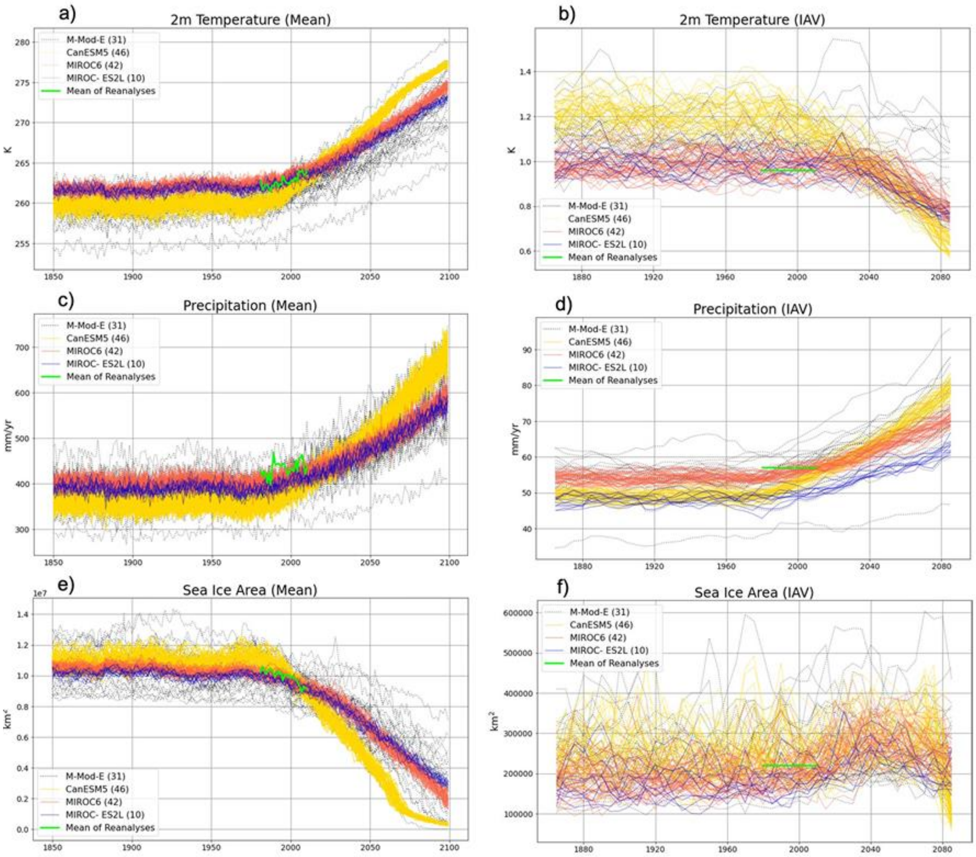

Fig. 5 The area-averaged annual means (a,c,e) and interannual variability (IAV) (b,d,f) for Arctic surface temperature (SAT), precipitation (PR), and sea ice area (SIA) from 1851 to 2100 are presented. This analysis includes 31 individual CMIP6 models (shown in dotted black) and three models with multiple members (depicted in colour). The IAV is calculated on a grid-point basis for SAT and PR (latitude > 65°N) and for total SIA (latitude > 45°N). A horizontal green line indicates the mean values derived from three reanalysis datasets: 20CRv3 and JRA55 for SAT and PR, and GIOMAS, HadISST, and ERA5 for SIA. This Fig is in Kolbe et al. (2023).

Finally, the study concluded that extensive model ensembles show that, over shorter timescales (e.g., 30 years), IAV in all variables is largely driven by natural variability—reaching up to 93% for the March sea ice area. However, long-term IAV trends are more robust, exhibiting pronounced seasonal and regional variations in both magnitude and direction. For instance, IAV in surface air temperature is projected to increase over the Central Arctic, while decreasing in lower latitudes. Similarly, Arctic precipitation variability is expected to rise more sharply in summer than in winter, particularly over land, where future precipitation is projected to predominantly fall as rain. These findings highlight the importance of accounting for seasonal and regional differences when assessing future trends in Arctic climate variability, underscoring the complexity of these changes amid ongoing global warming.

2.3 Causes of Arctic Sea ice melting

Like other climate changes, the decrease in Arctic sea ice results from three main factors shaping climate: external forcing from human-induced changes, external forcing from natural influences and internal climate variability. Recent studies (Notz and Marotzke 2012; Henderson et al. 2021) indicate that the most significant contributors to this decline are human activities and internal variability. These factors don't directly impact sea ice but rather modify atmospheric and oceanic conditions, leading to the reduction in sea ice cover. Consequently, the diminishing sea ice reflects broader shifts in the atmosphere and ocean, making visible changes that are often imperceptible (Döscher et al. 2014).

There are two main mechanisms by which the climate system reduces sea ice in the Arctic Ocean: first, by melting the ice directly in the Arctic region, and second, by exporting sea ice to southern regions (Stroeve and

Notz 2018). These findings are supported by several research studies (Suo et al. 2013; Ding et al. 2019; Halloran et al. 2020; Trends and Chen 2024), which identified that the predominant factors causing the observed reduction in sea ice is the melting of sea ice itself and external forcing (both anthropogenic and natural). It's evident that the increasing air temperature is a primary factor contributing to the heightened melting of sea ice. This conclusion is initially drawn from the basic understanding that warmer temperatures accelerate ice melting. The credibility of the relationship between Arctic sea ice coverage and global mean near-surface air temperature is supported by the consistently strong linear correlation observed in both simulations, observations and reanalysis across long-term trends (Rosenblum and Eisenman 2016; Niederdrenk and Notz 2018; Stroeve and Notz 2018; Ding et al. 2019). Consequently, this suggests that the primary driver behind the observed global warming, which is the rise in atmospheric CO2 concentration due to human activities (IPCC, 2013), serves as the primary driver for the observed decline in Arctic sea ice. Recent studies (Notz and Stroeve 2016; Niederdrenk and Notz 2018; Chen and Sun 2024; Kuttippurath et al. 2024; Wang et al. 2024) further establish a clear connection between the decline of Arctic sea ice and CO2 emissions from human activities, as evidenced by both observations/reanalysis and CMIP5 model simulations. They provided a straightforward theoretical explanation for this correlation, implying a causal link between CO2 emissions and Arctic sea ice decline. Their explanation offers insights into the linear correlation between global average temperature and Arctic sea ice loss.

In addition to human activities playing a clear role in the long-term changes in Arctic sea ice, internal variability can significantly enhance or diminish this decline, especially over short timescales (Jahn et al. 2016; Trends and Chen 2024). However, accurately determining the extent of internal variability's contribution to observed ice loss is challenging due to reliance on climate models, which offer differing assessments of Arctic sea ice internal variability (Stroeve and Notz 2015; Olonscheck and Notz 2017). Limited and relatively recent observations combined with the predominant influence of external factors on trends, pose difficulties in pinpointing the precise scale of internal variability. Similarly, a recent study by Trends and Chen (2024) found that the Arctic has experienced long-term warming, with intermittent periods of rapid warming due to external factors like greenhouse gases and natural influences. These factors primarily explain the overall changes seen since 1900. Internal fluctuations, notably the Arctic Oscillation (AO) and the Atlantic Multidecadal Oscillation (AMO) were significant contributors to the warming observed in the early 20th century, the cooling in the mid-20th century and have played a substantial role (approximately 40%) in the recent rapid warming since 1979.

3 West African Monsoon System

3.1 Overview of the WAM system (seasonal cycles, precipitation patterns and key drivers).

The WAM system plays a vital role in shaping seasonal weather conditions and rainfall patterns throughout West Africa (Cook and Vizy 2019; Tamoffo et al. 2023). The WAM system is strongest from May to September, marking the wet season, while the dry season occurs in the winter months (Huaman et al. 2023). In summer, the convergence of warm humid air from the Atlantic Ocean and drier air from the Sahara desert generates convective clouds and substantial rainfall (Fontaine et al. 2003; Selami et al. 2021) (Fig. 6a). Conversely, in winter, there's a decline in the monsoon flow, leading to reduced precipitation (Thorncroft et al. 2011) (Fig. 6b). Additionally, WAM system is pivotal for bringing rainfall to West Africa, notably the Sahel region (Klein et al. 2015). WAM-associated rainfall fluctuates significantly across both geographical and temporal scales (Ndehedehe et al. 2022; Badji et al. 2022). Generally, coastal areas experience higher rainfall compared to inland regions, with a gradual decline in precipitation towards the Sahara desert in the north (Tano et al. 2023). In addition, precipitation is also maximized over the highest topography in West Africa, such as the Fouta Djallon and Cameroon Highlands (Descroix et al. 2020). Nevertheless, the distribution of rainfall can be erratic, leading to periods of drought and subsequent flooding, which profoundly impact local ecosystems and communities (Biasutti 2019).

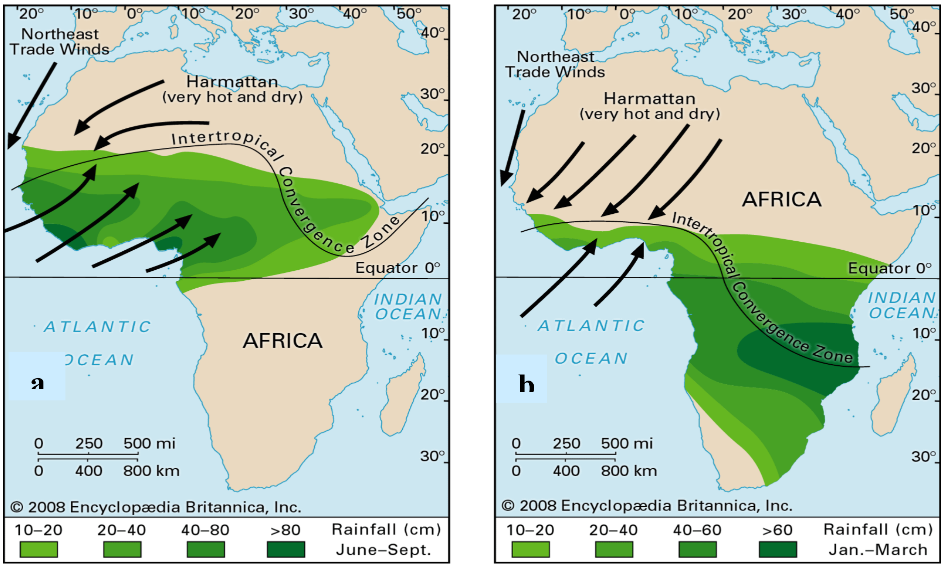

Fig. 6 West African monsoon rainfall during (a) June to September and (b) January to March. Credit to Joseph Gentilli, Phillip J. Smith, John P. Rafferty and Grace Young.

Moreover, the key drivers that influence the WAM strength and variability include the SSTs, West African Land Surface, AEJ, AEWs, Sahara heat low (SHL) and West African westerly Jet (WAWJ). Anomalies in SST, especially in the Atlantic Ocean and the Gulf of Guinea, can have a significant impact on both the strength and timing of the monsoon's onset and duration (Worou et al. 2020). When SSTs are warmer than usual, they tend to enhance moisture movement and atmospheric convection, resulting in higher levels of rainfall (Quagraine et al. 2020). The distribution of land surface features, such as the Sahara desert, vegetation cover and topography, impacts temperature gradients and atmospheric circulation patterns (Xue et al. 2004; Steiner et al. 2009). These effects, in turn, are essential for the development and progression of the monsoon. The AEJ, a westerly wind system at high altitudes, interacts with lower-level monsoon flows and can either enhance or suppress convection and rainfall, depending on its position and strength (Sylla et al. 2011). The AEWs are disturbances that move westward across the African continent and can contribute to the initiation and intensification of convective activity related to the monsoon (Enyew and Mekonnen 2022). SHL influences the WAM by moving poleward before monsoon onset, increasing moisture transport and convergence and showing a warming trend due to water vapor. Its variability affects Sahel rainfall, with mixed impacts: some studies link decreased Saharan pressure to increased rainfall, while others suggest a stronger SHL reduces rainfall (Shekhar and Boos 2017). In addition, the WAWJ significantly influences the WAM by transporting moisture essential for Sahel rainfall. It forms in early June, peaks in August, and dissipates by mid-October. Located primarily over the eastern Atlantic and West African coast, the WAWJ's development and maintenance involve complex interactions between continental and marine weather systems, affecting regional climate variability and change (Pu and Cook 2010). Understanding the dynamics of the WAM system and its interactions with various atmospheric and oceanic processes is crucial for predicting seasonal climate variability, managing water resources, and mitigating the impacts of extreme weather events in West Africa.

3.2 Historical trends and variability in the WAM system.

The WAM system demonstrates significant historical trends and variability, influenced by a complex interplay of atmospheric, oceanic, and land surface processes (Akinsanola and Zhou 2020). Additionally, changes in external forcing also played a significant role in influencing past precipitation trends across West Africa (Monerie et al. 2022, 2023b). On Long-Term timelines, there's been discourse about probable shifts in the WAM system attributed to climate change (Monerie et al. 2020; Tamoffo et al. 2023; Monerie et al. 2023a). Certain research (Sylla et al. 2016; Diallo et al. 2016) indicate that the WAM could undergo alterations in rainfall distribution, with some regions experiencing intensified precipitation and more frequent extreme rainfall occurrences in the future. Similarly, historical records and reconstructions indicate a substantial change in rainfall patterns throughout centuries across West Africa (Bliefernicht et al. 2022). Birkel and Mayewski (2015) indicate that West African undergone alternation of periods of increased and decreased precipitation, along with multi-decade variations in the amount of precipitation. While variations in temperature, especially deviations in SSTs in the Atlantic Ocean and the Gulf of Guinea, have been noted to impact the strength and length of the WAM (Worou et al. 2020, 2022; Mutton et al. 2024). Higher SSTs generally boost moisture advection and convective actions, resulting in heightened rainfall throughout the monsoon period (Chen and Wu 2019). In addition, the interannual variability in the WAM system are notable, showcasing shifts in the timing, strength, and spatial distribution of rainfall (Rodríguez-Fonseca et al. 2011). A primary driver of these variations is the tropical Atlantic Ocean and El Niño-Southern Oscillation (ENSO) phenomenon (Emmanuel 2022). El Niño typically results in reduced rainfall in West Africa, while La Niña often leads to increased rainfall (Nicholson et al. 2000; Wu et al. 2020). Other contributors to these annual changes encompass the NAO, affecting atmospheric air movements, and unusual SST in the tropical Atlantic and Indian Oceans (Gaetani et al. 2017).

The WAM system exhibits decadal to multi-decadal variability, with periods of increased or decreased monsoon activity lasting from several years to several decades (Xue et al. 2016; Sidibe et al. 2019). These fluctuations are closely tied to the AMO, which reflects changes in SSTs in the North Atlantic (Li et al. 2012; Paeth et al. 2017; Monerie et al. 2019b; Mohino et al. 2024). The AMO influences both the intensity and geographical distribution of rainfall across West Africa (Badji et al. 2022; Mohino et al. 2024). Positive AMO phases are associated with increased rainfall in the Sahel region, while negative phases correspond to drier climatic conditions. Moreover, paleoclimate analyses using proxy data like sediment cores, tree rings, and historical records sheds light on the long-term patterns and variations in the WAM system over millennia (Jones et al. 2009; Nash et al. 2016). These studies reveal prolonged dry spells and intense droughts in West Africa, including the well-documented Sahelian droughts in the late 20th century, which greatly affected society, economy and the environment.

3.3 Importance of the WAM for regional agriculture, ecosystems and water resources

3.3.1 Agriculture

The WAM is essential for West Africa, as it brings the critical rainfall that marks the beginning of the farming season (Gordon and Fitzpatrick 2016). Summer precipitation is crucial for rain-fed agriculture, which plays a central role in the area's economy. Staple crops such as millet, sorghum, maize and rice depend heavily on the monsoon rains. Agriculture supports the livelihoods of millions in West Africa (Sissoko et al. 2011). The timely onset and distribution of rainfall during the monsoon season have a direct impact on crop yields, food security, and farmer incomes (Guan et al. 2015). Adequate rainfall ensures that crops have sufficient water, leading to higher agricultural productivity. In addition, the WAM facilitates the cultivation of a diverse range of crops, allowing farmers to adopt crop rotation and diversification strategies (Guan et al. 2015). These practices not only reduce the risks associated with climate variability but also enhances resilience to droughts and other extreme weather events.

3.3.2 Ecosystems

The onset of the WAM initiates the greening of vegetation across the Sahel and Guinea savannas (Pausata et al. 2020). This greening is vital for maintaining biodiversity and ecosystem stability. During the rainy season, plant growth provides habitat and forage for wildlife, supporting diverse ecosystems. The WAM replenishes rivers, lakes, and groundwater reservoirs, which sustain freshwater ecosystems and their associated biodiversity (Ndehedehe 2019). Wetlands and floodplains are revitalized during the monsoon, offering crucial habitats for aquatic species and migratory birds. Moreover, increased vegetation growth during the monsoon season boosts carbon sequestration, helping to mitigate the effects of climate change (Batjes 2001). Healthy ecosystems play a crucial role in regulating the global carbon cycle and maintaining ecological balance (Daba and Dejene 2018).

3.3.3 Water Resources

The WAM is essential for replenishing reservoirs and rivers that are crucial for hydroelectric power generation (Obahoundje and Diedhiou 2022). Countries like Mali, Niger, and Nigeria rely on hydropower as a significant source of electricity, and the monsoon rainfall directly influences power generation capacity. During the monsoon season, surface water reservoirs are refilled, and groundwater levels are replenished, ensuring a sufficient water supply for households, agriculture, and industry (Ndehedehe 2019). Reliable access to safe water resources is critical for human health, sanitation, and socio-economic development. Additionally, monsoon rainfall creates opportunities for rainwater harvesting and irrigation, boosting agricultural productivity and improving livelihoods. Effective management of irrigation infrastructure can help buffer against the impacts of climate variability and extend cropping seasons beyond the rainy period (Namara et al. 2011; Garg et al. 2022).

3.4 Health Impacts

The health landscape of West Africa is heavily influenced by the monsoon, particularly regarding malaria transmission. The season's substantial rainfall leads to the formation of various water bodies, such as ponds and stagnant pools, which serve as prime breeding grounds for mosquitoes (Ryan et al. 2020). These insects thrive in the monsoon's relatively low temperatures and humid conditions, causing a surge in mosquito populations (Arab et al. 2014). As a result, malaria cases rises during and after the monsoon, as Anopheles mosquitoes, which transmit the disease, find ideal conditions for breeding and spreading (Anoopkumar and Aneesh 2022). Understanding the WAM's dynamics is essential for forecasting and mitigating malaria outbreaks, as well as for implementing effective public health strategies to tackle this persistent regional health issue.

3.5 Impact on Large-Scale Atmospheric Circulation

WAM exerts a significant influence on large-scale atmospheric circulation patterns at both regional and global levels (Wang et al. 2017). As the monsoon develops, it modifies the distribution of thermal and moisture over West Africa, which in turn affects wind patterns and atmospheric stability (Lélé et al. 2015). The intense heating of the land surface during the summer months creates a low-pressure system that attracts moisture-rich winds from the Atlantic Ocean. This process not only enhances monsoon rainfall but also impacts the ITCZ, a vital component of global weather systems. The northward shift of the ITCZ during the monsoon season enhances rainfall in West Africa and neighbouring areas, influencing agriculture and water resources (Fontaine et al. 2011). In addition, the WAM impacts weather patterns globally (Janicot et al. 2008), with effects felt as far as North America and Europe (Gaetani et al. 2011; He et al. 2020). It is also interconnected with other monsoon systems, such as the Indian Monsoon (Flaounas et al. 2012). Moreover, the WAM interacts with other large-scale systems, such as the ENSO (Didi et al. 2023). For instance, during El Niño years, the WAM can experience altered rainfall patterns, affecting broader atmospheric circulation and climate patterns globally, including shifts in jet streams and storm tracks. Furthermore, climate models project changes in the WAM due to global warming, including alterations in rainfall distribution and intensity (Sylla et al. 2018). These changes could impact the stability of atmospheric circulation and enhance extreme weather events, further complicating interactions between regional and global climates. Overall, the WAM is a critical component of the global climate system, and understanding its dynamics and interactions with atmospheric circulation is essential for predicting weather patterns, managing water resources, and addressing climate change impacts. This underscores the need for ongoing research to enhance our understanding of the WAM's role in the broader climate system.

4 The Connection between Arctic Sea Ice and WAM

4.1 Mechanisms

WAM system has interconnected relationships with other climatic systems, including tropical cyclones, other monsoons, the Arctic climate and ENSO (Pausata et al. 2020) (Fig. 7). Therefore, understanding the mechanisms driving Arctic sea ice loss and WAM variability is crucial globally, as it enhances predictive capabilities for future changes. Recent research (Krishnamurti et al. 2015; Smith et al. 2017; Monerie et al. 2019) have explored various mechanisms by which changes in Arctic sea ice extent can affect the behaviour and variability of the WAM. One proposed mechanism highlights the impact of Arctic sea ice melting on large-scale atmospheric circulation patterns, such as the AO and the NAO (Al 2003; Goosse and Holland 2005; Vihma 2014; Screen 2017). The reduction in sea ice extent can lead to changes in atmospheric pressure gradients and circulation patterns, thereby influencing the position and intensity of the AEJ, AWJ and the subtropical high-pressure systems over West Africa. These changes in atmospheric circulation can significantly impact moisture transport pathways and precipitation patterns associated with the WAM. Similarly, the melting of Arctic sea ice, for example, influences the temperature gradient between the high-latitude Arctic region and the mid-latitudes (Deser et al. 2015; Monerie et al. 2019a), leading to changes in the strength and position of the polar jet stream. These changes may spread downstream, affecting the movement of Rossby waves and potentially influencing the behaviour of the WAM. Additionally, the reduction in Arctic sea ice extent can modify surface albedo and heat fluxes, causing shifts in regional temperature variations and atmospheric stability, which can further influence the dynamics of the WAM.

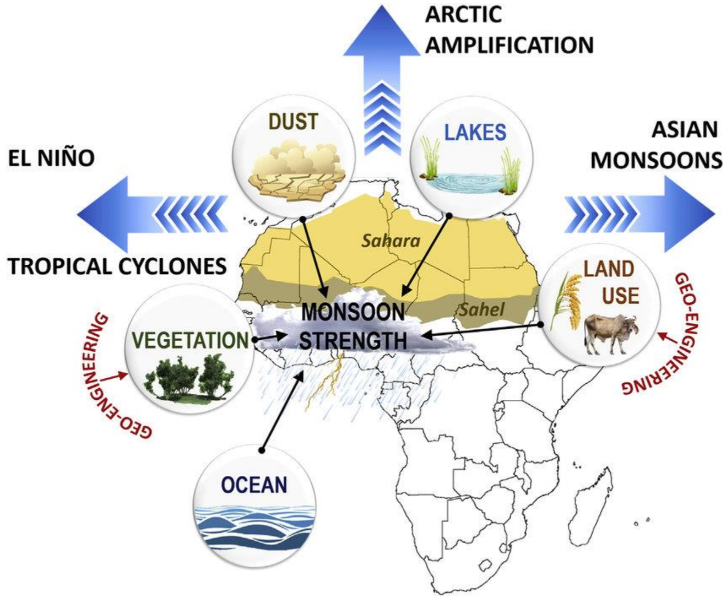

Fig. 7 A diagram depicting the structure of the WAM System and its interconnected relationships with other climate systems. This Fig. is in Pausata et al. (2020)

Moreover, changes in Arctic sea ice can significantly influence ocean circulation patterns, including the Atlantic Meridional Overturning Circulation (AMOC) (Liu et al. 2019; Timmermans and Marshall 2020). Variations in the AMOC are associated with SST and the movement of heat in the North Atlantic, subsequently impacting atmospheric circulation patterns and moisture levels over West Africa (Muir and Fedorov 2015). This, in turn, can have consequences for the WAM. Similarly, the melting of Arctic sea ice can initiate feedback loops, as discussed by Philipp et al. (2020) and Chatterjee et al. (2021), which exacerbate the effects on the WAM. For instance, a decrease in sea ice extent can enhance the absorption of solar radiation by the open ocean, leading to additional warming of the Arctic atmosphere. On this point, it was shown that the melting of the Arctic sea ice has strong effects on the temperature, delaying the temperature seasonal cycle of up to a month (Dwyer et al. 2012; Peings and Magnusdottir 2014), which can lead to a change in the seasonal cycle of other variables over other latitudes (that was the initial point of Monerie et al. 2019). Consequently, this can modify broader atmospheric circulation patterns that impact the WAM.

4.2 Observational Evidence and Modelling Studies

Observational studies have provided evidence of a connection between the melting of Arctic sea ice and the dynamics of the WAM. Analysis of correlations between anomalies in Arctic sea ice extent and atmospheric circulation indicators like the NAO and the AO suggests a potential relationship between Arctic sea ice changes and atmospheric circulation patterns over the North Atlantic area, which could impact the strength of the WAM (Holland 2003; Oshika et al. 2015; Caian et al. 2018; Yu and Zhong 2018). A recent study by Smith et al. (2017) investigated the atmospheric response to Arctic sea ice changes typical of the present day and future using the Met Office Hadley Centre global climate model (HadGEM3). The researchers analysed the atmospheric response by conducting ensemble simulations covering the period 1979-2009, utilizing both observed and perturbed sea ice concentrations. The simulations enabled them to evaluate the influence of ocean-atmosphere coupling and the background atmospheric conditions. They noticed that predicted outcomes may diverge significantly from what statistical correlations suggest, indicating that determining the response based solely on observations is challenging. Their findings indicate that the reduction of Arctic sea ice leads to a decrease in atmospheric pressure locally during the summer and autumn in the Northern Hemisphere. This interaction between the atmosphere and the ocean enables surface temperature changes to influence the ocean, intensifying the atmospheric effects and uncovering further consequences such as warming in the North Atlantic due to diminished Arctic sea ice, alongside a northward movement of the Atlantic intertropical convergence zone and heightened rainfall over West Africa (Sahel regions).

A similar study by Monerie et al. (2019), which investigated the impacts of Arctic sea ice decline and increasing greenhouse gases (GHG) concentration on Sahel precipitation, using idealized coupled experiments with the CNRM-CM5 coupled model, found that the effect of Arctic sea ice loss on Sahel precipitation depends on the background atmospheric GHG levels. When GHG concentrations are relatively low, similar to those in the 1980s, the impact on the Sahel is moderate. However, with higher GHG levels, Arctic sea ice loss results in increased precipitation in the Sahel. This is due to the decreased meridional temperature gradient. In addition, they attribute the non-linear effects of Arctic sea ice decline to variations in temperature and sea level pressure over the North Atlantic Ocean. Therefore, they anticipate that the impact of Arctic sea ice loss on the Sahel will become more significant over time as climate change progresses. Moreover, Shi et al. (2024) examine the intensity and duration of the West African Summer Monsoon (WASM) during the last interglacial (LIG) compared to the pre-industrial (PI) period using a newly developed isotope-enabled climate model, AWI-ESM-wiso. The results indicate that, despite increased summer insolation and a more active hydrological cycle, the WASM season during the LIG was 9 days shorter than during the PI. The increased insolation in late spring and early summer during the LIG intensified the Saharan heat low (SHL) and its associated systems, leading to a faster build-up of potential instability and an earlier onset of the WASM. However, the WASM also withdrew significantly earlier due to an earlier southward shift of the insolation maximum. These findings are further corroborated by models from the 4th phase of the Paleoclimate Modelling Intercomparison Project (PMIP4).

A recent study by Otto-Bliesner et al. (2021) investigated climate responses to stronger orbital forcing during the Last Interglacial period, approximately 127,000 years ago (lig127k), using the Coupled Model Intercomparison Project (CMIP6). The analysis encompassed a multi-model ensemble of 17 climate models, all of which had completed the CMIP6 Diagnostic, Evaluation and Characterization of Klima experiments. These models have equilibrium climate sensitivities (ECS) ranging from 1.8 to 5.6°C. Their finding shows that the seasonal nature of the insolation anomalies led to significant summer warming over Northern Hemisphere continents in the lig127k ensemble compared to the CMIP6 piControl, along with a notable reduction in minimum sea ice in the Arctic. The results from the multi-model ensemble showed increased summer monsoonal precipitation in the Northern Hemisphere and decreased precipitation in the Southern Hemisphere. These climate responses were more pronounced in the lig127k simulations than in the CMIP6 midHolocene simulations, as expected due to the larger insolation anomalies at 127,000 years ago compared to 6,000 years ago. Additionally, new syntheses for surface temperature and precipitation targeting 127,000 years ago were developed for comparison with the multi-model ensemble. The lig127k model ensemble and data reconstructions showed strong agreement for summer temperature anomalies over regions such as Canada, Scandinavia, and the North Atlantic, as well as for precipitation patterns over Northern Hemisphere continents.

4.3 Implications for Regional Climate Variability

The decline in sea ice affects not only the mid and high latitudes but also influences precipitation around the equator (Deser et al. 2015) and causes shifts in the ITCZ (Chiang and Bitz 2005; Kang et al. 2008). The melting of Arctic sea ice has substantial effects on the WAM, affecting regional climate variability and socioeconomic development in West Africa. Changes in precipitation patterns due to altered monsoon dynamics can impact agricultural productivity, water resources and food security in the region. Variability in the onset, duration and intensity of the monsoon rains can lead to changes in crop yields, affecting livelihoods and exacerbating existing vulnerabilities in rural communities. Furthermore, shifts in atmospheric circulation patterns associated with changes in Arctic sea ice extent can influence the frequency and intensity of extreme weather events such as droughts and floods, further impacting socioeconomic activities and infrastructure.

5. Challenges and Opportunities for Future Research

Despite some progress having been made in understanding the impacts of Arctic sea ice melting on the WAM, numerous challenges and uncertainties remain. One major difficulty lies in the complexity of the interactions between Arctic sea ice melting, atmospheric circulation patterns and regional climate dynamics, which require comprehensive observational datasets and advanced modeling techniques to accurately capture and understand. Additionally, there is a need to better understand the mechanisms connecting Arctic sea ice changes to WAM behaviour, including the influence of regional climate drivers such as ENSO and the AMO. Future research should focus on investigating the linkage between the Arctic climate system and the WAM using a multi-model approach, with emphasis on models like the Coupled Model Intercomparison Project (CMIP), Community Earth System Model (CESM), Weather Research and Forecasting (WRF) model, Hadley Centre Global Environment Model (HadGEM) and the Coastal and Regional Ocean Community Model (CROCO). Assessing the impact of future changes in Arctic sea ice extent on the dynamics and variability of the WAM under different climate change scenarios will be essential for understanding these complex interactions. Moreover, Integrated modeling approaches that consider atmosphere-ocean-ice interactions are crucial for improving projections of future WAM changes and informing adaptation strategies in West Africa. Interdisciplinary research collaborations involving climate scientists, meteorologists, hydrologists and social scientists are essential to address the complex impacts of Arctic sea ice melting on the WAM. Such collaborations will aid in developing effective mitigation and adaptation measures to reduce potential risks and enhance resilience in the face of ongoing climate change.

6 Summary and Conclusion

In this review, we have synthesized existing observational and modeling studies that investigate the potential impacts of Arctic sea ice melting on the WAM. The review mainly focuses on summarizing the effects of Arctic sea ice melt on the WAM. Rapid warming in the Arctic has led to substantial sea ice loss, impacting near-surface conditions and regional and distant climates. The reduction in sea ice exposes open water, which has a lower albedo, leading to increased absorption of sunlight and significant sea surface temperature anomalies. This heat is released into the atmosphere in autumn, delaying winter sea ice formation and making it thinner and more prone to melting. These feedback mechanisms contribute to Arctic amplification. In addition, research primarily focuses on SIE changes, but notable decreases have been observed year-round. Since the mid-2000s, below-average SIE has been recorded across all months, with significant summer decreases in 2007 and 2012. From 2016 to 2018, most months saw unprecedented ice loss. The proportion of old, thick ice has significantly declined, with first-year ice dominating. Regional seas like the East Siberian, Beaufort, and Chukchi seas have seen the largest summer ice losses. Winter sea ice reductions are most significant in the Barents and sea of Okhotsk.

Moreover, in 2023, Arctic SIE showed a consistent long-term declining trend, with a marked reduction during winter but not record-breaking. Projections indicate continued sea ice loss, with an almost ice-free Arctic expected between 2030 and 2050. Furthermore, the decline in Arctic sea ice is driven by human-induced changes, natural influences, and internal climate variability. Increased air temperatures, largely due to rising CO2 levels, are the primary factor. There is a strong correlation between global mean near-surface air temperature and Arctic sea ice coverage. Internal variability also contributes significantly to short-term changes. The combination of external forcing and internal variability drives the observed long-term and short-term changes in Arctic sea ice extent.

The WAM system significantly influences the seasonal weather and rainfall patterns in West Africa. It follows a yearly cycle from May to September, marked by a wet season in summer and a dry season in winter. During summer, the convergence of warm, humid air from the Atlantic Ocean with, dry air from the Sahara leads to the formation of convective clouds and substantial rainfall, while winter experiences a reduction in monsoon flow and precipitation. Rainfall distribution is highly variable, with coastal areas receiving more rainfall than inland regions and it can be erratic, causing periods of drought and flooding that impact local ecosystems and communities. The WAM is influenced by SST anomalies, land surface features, AEJ, AEWs, SHL, and WAWJ, impacting rainfall levels. Warmer SSTs enhance and convection, while land features affect temperature gradients and atmospheric circulation. ENSO, NAO and AMO are key factors driving interannual and decadal variability in the WAM system, with climate change expected to alter rainfall distribution, potentially causing extreme weather. The WAM is critical for agriculture, ecosystems, and water resources, supporting livelihoods through rain-fed farming, biodiversity and water supply. Timely monsoon onset and distribution affect crop yields, food security and hydroelectric power generation. Effective rainwater management can boost agricultural productivity and climate resilience.

Recent studies have identified several mechanisms through which changes in Arctic sea ice extent influence WAM: Melting Arctic sea ice alters large-scale circulation patterns like the AO and the NAO, affecting atmospheric pressure gradients and circulation. This influences the AEJ, AWJ and subtropical high-pressure systems over West Africa, ultimately impacting moisture transport and precipitation patterns associated with the WAM. Similarly, Arctic sea ice melting affects the temperature gradient between the high-latitude Arctic region and the mid-latitudes, which in turn modifies the strength and position of the polar jet stream. These changes can propagate downstream, affecting the movement of Rossby waves and potentially influencing WAM behaviour. Additionally, reduction in Arctic sea ice extent alters surface albedo and heat fluxes, leading to shifts in regional temperature variations and atmospheric stability. Melting sea ice also impacts the AMOC, affecting SST and atmospheric circulation over West Africa, thereby influencing the WAM. Observational studies (Holland 2003; Oshika et al. 2015; Caian et al. 2018; Yu and Zhong 2018) have shown correlations between Arctic sea ice extent changes and atmospheric circulation indicators, suggesting a relationship between Arctic sea ice changes and WAM behaviour. Similarly, research using climate models has revealed that reduced Arctic sea ice leads to local atmospheric pressure decreases and influences temperature and rainfall patterns over West Africa. For instance, Smith et al. (2017) found that Arctic sea ice reduction causes warming in the North Atlantic and increased rainfall in West Africa (Sahel). Similarly, Monerie et al. (2019) demonstrated that higher GHG levels amplify the effects of Arctic sea ice loss on Sahel precipitation.

In conclusion, the link between the melting of Arctic sea ice and the WAM represents a complex and multifaceted interaction with significant implications for both regional climate variability and socioeconomic development across West Africa. Understanding the underlying mechanisms and assessing the potential impacts of Arctic sea ice extent changes on the dynamics of the WAM are essential for informing climate adaptation and resilience efforts in the region. Addressing the challenges and uncertainties associated with this relationship requires interdisciplinary research approaches and collaboration between scientists, policymakers and stakeholders to develop effective strategies for mitigating the impacts of climate change on the WAM and enhancing the resilience of vulnerable communities in Africa.

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Statements and Declarations

Competing interests: The authors declare no conflicts of interest.

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