Dissertations in Physical Geography No. 27

Stockholm University

Understanding West African Monsoon Variability

Insights from Paleoclimate Modelling of Past Warm Climates

Ellen Berntell

Doctoral Thesis in Physical Geography at Stockholm University, Sweden 2023

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Academic dissertation for the Degree of Doctor of Philosophy in Physical Geography at Stockholm University to be publicly defended on Friday 9 June 2023 at 13.00 in De Geersalen, Geovetenskapens hus, Svante Arrhenius väg 14 and online via Zoom: https://stockholmuniversity.zoom.us/j/61869014655.

Abstract

The Sahel, a water-vulnerable region in West Africa, relies heavily on rainfed agriculture. The region experienced pronounced droughts during the 20th Century, emphasising the socio-economic importance of understanding the drivers of the rainfall variability. However, future rainfall projections remain uncertain due to the complex nature of the West African Monsoon (WAM), which is influenced by internal climate variability, external forcing, and feedback processes. Limited observational records in West Africa and the need for longer time series further complicate the understanding of these drivers.

This thesis uses paleoclimate modelling to investigate internal and external drivers of monsoon variability in West Africa across four distinct periods. Our study confirms that atmosphere-only model simulations can capture the observed multidecadal rainfall variability in the 20th Century, even though reanalyses struggle to reproduce the correct timing. Analysis of a last millennium simulation using the Earth System Model EC-Earth3 identified two drivers of multidecadal rainfall variability, accounting for 90% of the total co-variability between the West African rainfall and Atlantic sea surface temperatures (SSTs). This finding strengthens our understanding of SST-WAM relationships observed during the 20th Century. An ensemble of climate model simulations (PlioMIP2) shows that high CO_2 levels and a different paleogeography during the mid-Pliocene Warm Period led to increased rainfall and a strengthened WAM. Our study emphasised vegetation's crucial role in enhancing the monsoon in past climates.

However, simulations forced with prescribed vegetation only capture a one-directional forcing. A mid-Holocene simulation using an Earth System Model with dynamic vegetation revealed that vegetation feedbacks strengthen the WAM response to external orbital forcing but are insufficient to shift the monsoon northward or increase vegetation cover over the Sahara. These results reveal a dry bias and under-representation of simulated vegetation compared to proxy records, highlighting the importance of model development and the need for additional feedback processes in driving an enhanced, northward WAM and extending vegetation to the Sahara.

Overall, this thesis advances our understanding of the drivers of West African monsoon variability and provides valuable insights for improving future rainfall projections in this vulnerable region.

Keywords: *West African Monsoon, Monsoon Variability, Paleoclimate, Climate modelling.*

Stockholm 2023
http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-216584

ISBN 978-91-8014-310-3
ISBN 978-91-8014-311-0
ISSN 2003-2358

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Printed in Sweden by Universitetsservice US-AB, Stockholm 2023

Abstract

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Overall, this thesis advances our understanding of the drivers of West African monsoon variability and provides valuable insights for improving future rainfall projections in this vulnerable region.

Sammanfattning

Sahel är ett område definierat av halvaridt klimat, som sträcker sig genom norra Afrika från Atlantkusten i väster till Röda havet i öster. Sahel, vars namn har arabiskt ursprung och betyder ”kust”, ligger mellan det torra Sahara i norr och tropiska, fuktiga klimatet i söder. Jordbruket i området stöds främst av regn som förs in med den västafrikanska monsunen, och är därigenom känsligt för förändringar i nederbörd. Under 1900-talet drabbades regionen av utbredd torka och svält, vilket betonade den socioekonomiska betydelsen av att förstå vad som driver nederbördsvariationer i området. Framtidens nederbörd förblir dock osäker på grund av den komplexa karaktären hos den västafrikanska monsunen, som påverkas av inre klimatvariationer, extern påverkan och olika återkopplingsprocesser. Den låga mängden observationer i Västafrika och bristen på längre tidsserier komplicerar förståelsen av dessa processer ytterligare.

Denna avhandling använder paleo-klimatmodellering för att undersöka interna och externa drivkrafter som påverkar monsunen i Västafrika. Vår studie bekräftade att modeller som endast simulerar atmosfären kan fånga den flera decennier långa observerade nederbördsvariabiliteten under 1900-talet, även om reanalysdata inte lyckas reproducera rätt tidpunkt. Analys av en 1001 år lång simulering, gjord med jordsystemmodellen EC-Earth3, identifierade två drivkrafter för nederbördsvariationer på denna skala, vilka tillsammans står för 90% av den totala samvariationen mellan den västafrikanska nederbörden och yttemperaturerna i Atlanten. Detta resultat stärker vår förståelse av relationen mellan havstemperaturer och den västafrikanska monsunen som observerades under 1900-talet. En ensemble av klimatmodellsimuleringar av mellan-Pliocenen (PlioMIP2) visar att höga CO_2-nivåer och en annorlunda paleogeografi under denna period ledde till ökad nederbörd och en förstärkt västafrikansk monsun. Vår analys betonade dessutom vegetationens avgörande roll för att förstärka monsunen i tidigare varma klimat.

Simuleringar med fördefinierad vegetation fångar dock bara en inverkan i en riktning, från vegetationen på klimatet. Den senaste gången Sahara täcktes av vegetation var under mellan-Holocenen, då en ändrad bana kring solen ledde till en förstärkt västafrikansk monsun och ökad nederbörd i Sahel och Sahara. En simulering av denna period, gjord med en jordsystemmodell med kopplad dynamisk vegetation, visade att vegetationsåterkopplingar förstärker monsunen ytterligare, men är otillräckliga för att flytta monsunen norrut eller öka vegetationstäcket över Sahara. Dessa resultat avslöjar ett torrare klimat och en underrepresentation av simulerad vegetation jämfört med proxydata, vilket understryker vikten av ytterligare återkopplingsprocesser för att skapa en starkare monsun som når längre norrut i Västafrika, och öka mängden vegetationen i Sahara.

Sammantaget främjar den här avhandlingen vår förståelse av drivkrafterna bakom variationer i den västafrikanska monsunen och ger värdefulla insikter för att förbättra framtida nederbördsprognoser i denna sårbara region.

Dissertation content

This doctoral compilation dissertation consists of a summarising text and the 4 articles listed below.

I Berntell, E., Zhang, Q., Chafik, L., Körnich, H.: Representation of multidecadal Sahel rainfall variability in 20th Century reanalyses, Scientific Reports, 8, 10937, https://doi.org/10.1038/s41598-018-29217-9, 2018.

II Zhang, Q., Berntell, E., Li, Q., Charpentier Ljungqvist, F.: Understanding the variability of the rainfall dipole in West Africa using the EC-Earth last millennium simulation, Climate Dynamics, 57, 93–107, https://doi.org/10.1007/s00382-021-05696-x, 2021.

III Berntell, E., Zhang, Q., Li, Q., Haywood, A.M., Tindall, J.C., Hunter, S.J., Zhang, Z., Li, X., Guo, C., Nisancioglu, K.H., Stepanek, C., Lohmann, G., Sohl, L.E., Chandler, M.A., Tan, N., Contoux, C., Ramstein, G., Baatsen, M.L.J., von der Heydt, A.S., Chandan, D., Peltier, W.R., Abe-Ouchi, A., Chan, W.-L., Kamae, Y., Williams, C.J.R., Lunt, D.J., Feng, R., Otto-Bliesner, B.L., Brady, E.C.: Mid-Pliocene West African Monsoon rainfall as simulated in the PlioMIP2 ensemble, Climate of the Past, 17, 1777–1794, https://doi.org/10.5194/cp-17-1777-2021, 2021.

IV Berntell, E., Zhang, Q.: Mid-Holocene West African Monsoon Rainfall enhanced in high-resolution EC-Earth simulation with dynamic vegetation feedback, *Climate Dynamics, manuscript in review*

Author contributions

The contributions from listed authors are divided as follows for each article.

I The research idea was conceived by Q.Z. and E.B., E.B. performed the analysis and wrote the manuscript under supervision by Q.Z., L.C. and H.K. All authors discussed the results and provided input on the manuscript.

II QZ conceived the research idea and designed the work. EB analysed the data and prepared the figures. QZ wrote the manuscript, EB and FCL commented, edited and provided input to the manuscript. QL performed the EC-Earth simulations.

III EB and QZ designed the work. EB did the analysis and wrote the manuscript. QZ, QL, AMH, JCT, SJH, ZZ, XL, CG, KHN, CS, GL, LES, MAC, NT, CC, GR, MLJB, ASvdH, DC, WRP, AAO, WLC, YK, CJRW, DJL, RF, BLOB, and ECB provided the PlioMIP2 experiments and contributed to the discussion of the results.

IV Both authors contributed to the study conception and design. EB set up and ran the simulations, analyzed the data and wrote the manuscript, QZ commented on previous versions of the manuscript.

Contents

1 Introduction

The Sahel, a water vulnerable region in West Africa, has experienced pronounced rainfall variability in both its recent and distant past (Nicholson et al., 2000; Hulme, 2001; Zhang et al., 2016; Tierney et al., 2017). It is a semi-arid region located between the arid Sahara to the north and the tropical savanna to the south, approximately between 10°and 20°N (Fig. 1.1). While its climate and vegetation exhibits a zonal uniformity, it constitutes a steep transitional zone meridionally, with rainfall going from approx. 600-800 mm/year in the south to 100-200 mm/year in the north (Nicholson, 2013; Biasutti, 2019).

Severe droughts in the 1970s and 1980s highlighted the socioeconomic implications of rainfall variability in the region and sparked increased scientific interest in its drivers (Hulme, 2001; Giannini, 2015). The West African Monsoon (WAM), which brings the majority of the annual rainfall to the region, is a complex system influenced by various internal and external factors, including sea surface temperature (SST) variability, greenhouse gas concentrations, and land-surface changes (Charney et al., 1975; Claussen and Gayler, 1997; Braconnot et al., 1999; Sultan and Janicot, 2003; Rachmayani et al., 2015; Messori et al., 2019; Chandan and Peltier, 2020).

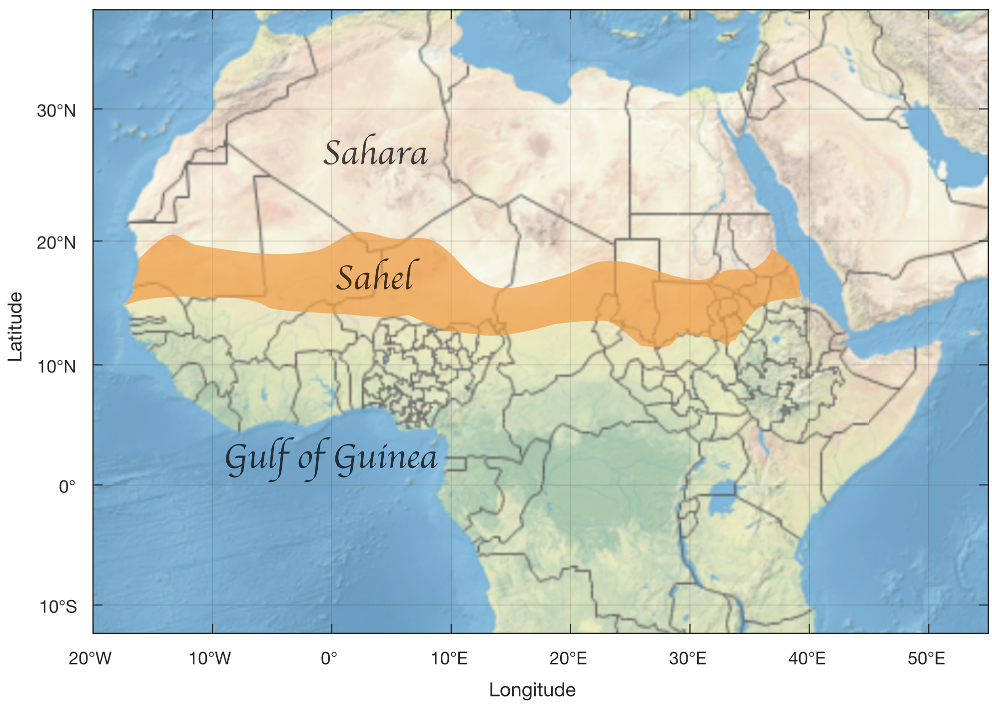


Figure 1.1. Map of West Africa, indicating the approximate location of the Sahel region, the Sahara and the Gulf of Guinea. Figure based on commonly used Sahel delineations, source unknown.

However, research on past rainfall variability in Sahel and its drivers is often hindered by a lack of long observational data sets, low spatial observational coverage, and few available proxy reconstructions (Nash et al., 2016), emphasizing the role of paleoclimate modelling as a valuable tool for advancing our knowledge.

Initially, the prolonged droughts in the second half of the 20th century were believed to be the result of anthropogenically-driven rainfall-vegetation feedbacks, driven by e.g. overgrazing and causing a decline in rainfall in Sahel (Charney, 1975). However, the subsequent recovery of the rainfall in West Africa instead suggested that it is an example of multidecadal climate variability linked to internal SST variability, although some studies point to potential anthropogenic drivers of the SST changes (e.g., Giannini et al., 2003; Mohino et al., 2011; Giannini and Kaplan, 2019).

Multidecadal climate variability is a global phenomenon (Delworth and Mann, 2000; Enfield et al., 2001; Qian and Zhou, 2013), but dynamically consistent datasets are needed to fully explore the dynamics driving this internal, low-frequency variability. Recently available of 20th century reanalysis datsets (e.g., Compo et al., 2011) are increasingly used for such analysis (D' Agostino and Lionello, 2017; Malik et al., 2017), but may not be sufficient to represent and analyse multidecadal climate variability (Wittenberg, 2009; Marullo et al., 2011). Transient simulations, such as the *last millennium* simulation defined in the Paleoclimate Modelling Intercomparison Project (PMIP) (Schmidt et al., 2011, 2012; Kageyama et al., 2018), provide an alternative, but the lack of high-resolution proxy reconstructions of rainfall in West Africa limits the model-data comparison on multidecadal scale. Additionally, studies have shown that climate models often struggle to capture decadal variability (Mohino et al., 2011; Roehrig et al., 2013; Martin and Thorncroft, 2014; Herman et al., 2020), making 20th Century reanalysis datasets essential for evaluating model performance in the region.

While internal variability has driven much of the observed rainfall variability in the near-past, external forcing, such as greenhouse gas (GHG) and orbital forcing, has been the main driver of monsoon variability and climate change in West Africa on longer timescales (Kutzbach, 1981; Kutzbach and Otto-Bliesner, 1982; Williams et al., 2022). Several past warm periods exhibit an enhanced WAM (Zhang et al., 2021a; Williams et al., 2022), with two time periods standing out as particularly interesting for the paleoclimate community. The mid-Pliocene Warm Period, with its near-modern atmospheric CO_2 concentration and paleogeography, acts as an interesting analogue for future climate change (Haywood et al., 2016), and the mid-Holocene, with its orbitally-forced West African greening (Kutzbach et al., 1996), allows for further analysis of the role of different feedback processes in maintaining an enhanced WAM.

In both time periods, the external forcing led to a climate drastically different from today's, characterized by more humid conditions in the Sahel and Sahara regions, and vegetation covering large parts of what is today desert (Salzmann et al., 2008; Tierney et al., 2017). Palynological data records of the mid-Pliocene Warm Period indicate an expansion of woodland and savanna in northern Africa at the expense of deserts, which together with e.g. plant wax and dust records in marine sediment cores taken offshore of West Africa indicate wetter conditions during this period (deMenocal, 2004; Feakins et al., 2005; Salzmann et al., 2008; Bonnefille, 2010). Similarly, proxy records show that during the mid-Holocene the Sahara region was characterized by widespread vegetation and permanent lakes and wetlands, resulting in this period often being referred to as the African Humid Period (e.g., Street-Perrott et al., 1989; deMenocal et al., 2000; Hoelzmann et al., 2001; Hély et al., 2014).

However, model-data comparisons of mid-Holocene simulations show that models regularly struggle with recreating this enhanced WAM rainfall (Brierley et al., 2020).

Changes to the land-surface conditions are known to play an important role in strengthening the WAM (Kutzbach et al., 1996; Chandan and Peltier, 2020), but while prescribing vegetation consistent with proxy records in the Sahara region does strengthen the monsoon (Pausata et al., 2016; Chandan and Peltier, 2020), it represents an idealized, homogeneous paleo-vegetation that captures a one-directional forcing effect rather than the full feedback between the vegetation and the WAM. This approach can also potentially lead to an over/under attribution of the vegetation feedback on the West African climate during the mid-Holocene.

In this thesis I explore how paleoclimate modelling can advance our understanding of internally and externally forced monsoon variability in West Africa. In particular, I contribute to a better understanding of drivers of low-frequency variability in the context of the 20th Century and last millennium, and the role of external greenhouse gas, orographical, and land-surface forcing in the context of the mid-Pliocene Warm Period. I also explore the role of orbitally forced vegetation feedbacks in recreating the Green Sahara during the mid-Holocene. Additionally, I highlight the need for model development and additional sensitivity studies for closing the model-data gap and assessing the usefulness of these past periods as analogues for future climate projections.

2 West African Monsoon and its variability mechanisms

2.1 West African Monsoon dynamics

The WAM is a seasonal feature in West Africa and a main driver of rainfall in the Sahel region (Nicholson, 2013), sustaining the majority of the biomass grown in the area (Herrmann et al., 2005). The monsoon season typically occurs between July and September, accounting for 80% of the annual rainfall (e.g., Biasutti et al., 2008; Nicholson, 2009). The arrival of the WAM is driven by the development of a low-pressure area in the Sahara during the boreal summer, called the Sahara Heat Low, and characterised by a shift from dry, northeasterly so-called *Harmattan* winds, originating in the Sahara region, to humid, south to southwesterly winds which bring moisture and rainfall from the Equatorial Atlantic in over the continent (Fig. 2.1) (Thorncroft et al., 2011).

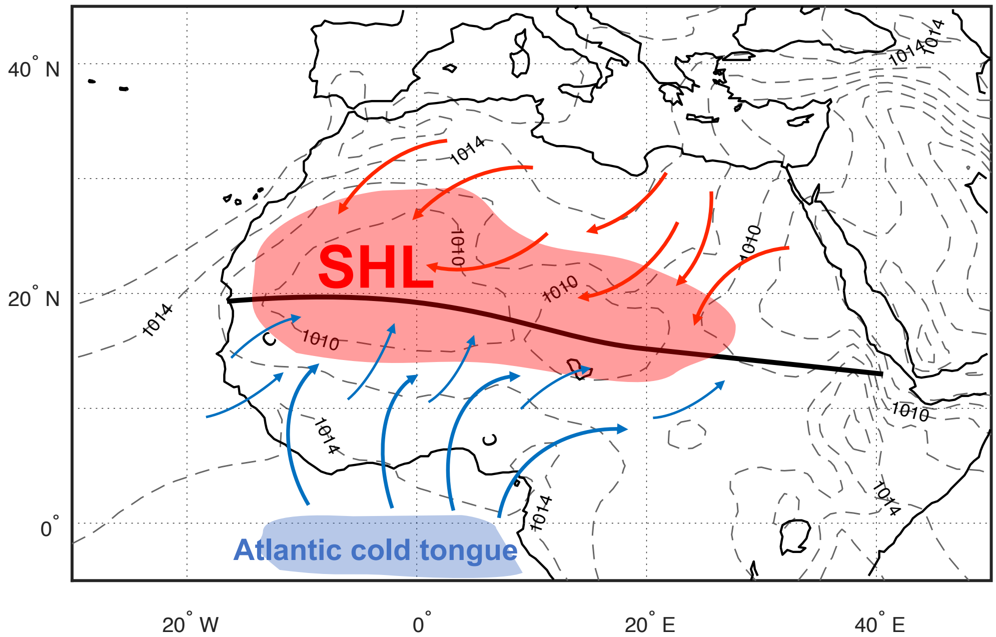


Figure 2.1. 1900-2010 July-September mean sea level pressure (hPa) and surface winds, with blue arrows indicating winds bringing moisture from the equatorial Atlantic to the Sahel region, and red arrows indicating dry, *Harmattan* winds from the Sahara region. The winds converge at the Intertropical Convergence Zone, also known as the inter-tropical discontinuity, indicated in black. The Sahara Heat Low (SHL) is indicated in red and the Atlantic cold tongue is indicated in blue. Based on ERA-20C reanalysis data (Poli et al., 2016).

The WAM was long considered to be an example of tropical rainfall associated with the Intertropical Convergence Zone, where local thermal instability and low-level convergence create a band of high rainfall (e.g., Griffiths, 1972). According to Nicholson (2013), this was in part based on the idea of a global Hadley circulation, and more recent studies have highlighted that this is primarily valid over oceans. Over West Africa the zone of low-level wind convergence is instead separated from the rainbelt by several hundred kilometers (Zhang et al., 2006; Nicholson, 2009), resulting in a paradigm shift in how we view the dynamics governing the WAM.

The rainfall of the WAM, which peaks at around 10°N, is driven by the northward progression of the latitude of maximum insolation during the boreal spring and summer months (Sultan and Janicot, 2000; Thorncroft et al., 2011). The warming of the Sahara region and associated development of the Sahara Heat Low, along with the formation of the Atlantic cold tongue, leads to a strengthened land-ocean temperature and surface pressure gradient (Fig. 2.1). This gradient sets up the main monsoonal wind patterns over West Africa, where south to southwesterly winds from the Atlantic bring moist air onto the continent (Lavaysse et al., 2009, 2010; Thorncroft et al., 2011).

In addition, the WAM is characterized by two meridional overturning circulations, one shallow and one deep, and two jet-streams, the African Easterly Jet (AEJ) and the Tropical Easterly Jet (TEJ) (Fig. 2.2). The shallow cell is linked to the Sahara Heat Low and is associated with contrasts in dry convection (Thorncroft and Blackburn, 1999; Zhang et al., 2008; Thorncroft et al., 2011). In contrast, the deep overturning circulation lies equator-ward, collocated with the rainbelt over West Africa and associated with contrasts in deep moist convection (Nicholson and Grist, 2003; Thorncroft et al., 2011).

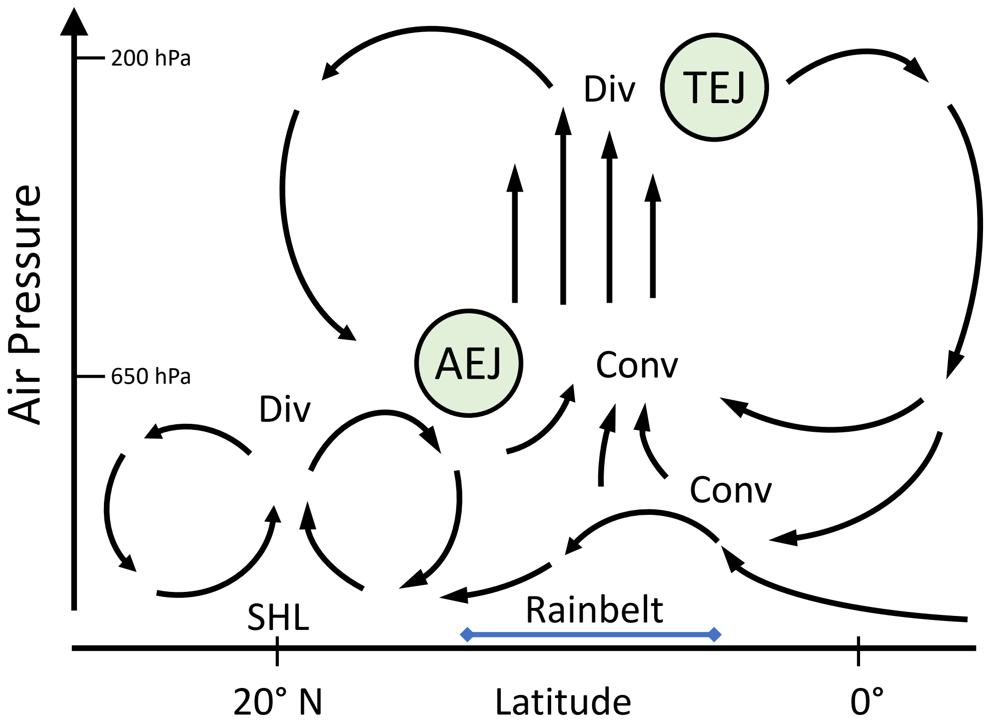


Figure 2.2. Schematic illustration of West African Monsoon dynamics, including the Sahara Heat Low (SHL), the rainbelt, the shallow overturning circulation, the deep overturning circulation, the African Easterly Jet (AEJ) and the Tropical Easterly Jet (TEJ). Schematic based on Nicholson (2013).

The thermally induced AEJ develops at approximately 600-700 hPa in response to the meridional contrast in temperature and moisture between the Sahara region and the Atlantic Ocean (Cook, 1999; Nicholson and Grist, 2003). It is maintained by the dry convection over the Sahara to its north and deep moist convection to its south (Cook, 1999; Thorncroft and Blackburn, 1999; Zhang et al., 2008). To the south of the AEJ and at a level of approximately 200 hPa lies the TEJ, which while being linked to the Asian monsoon, induces a relatively strong divergence over West Africa, poleward of the jet (Grist and Nicholson, 2001). Between these two jet-streams, and associated with the deep meridional overturning circulation and a deep column of moist air, lies the core of the rainbelt (Nicholson and Grist, 2003; Nicholson, 2009).

2.2 West African Monsoon variability mechanisms

Given the complex system that constitutes the WAM, there are many dynamical and physical processes that can influence its variability (Nicholson, 2013). In this thesis, the focus is on **physical processes** linked to orbital and greenhouse gas forcing, land surface processes and aerosol feedback, and **dynamical processes** linked to ocean variability (Fig. 2.3), a review of which will be given in sections 2.2.1 and 2.2.2.

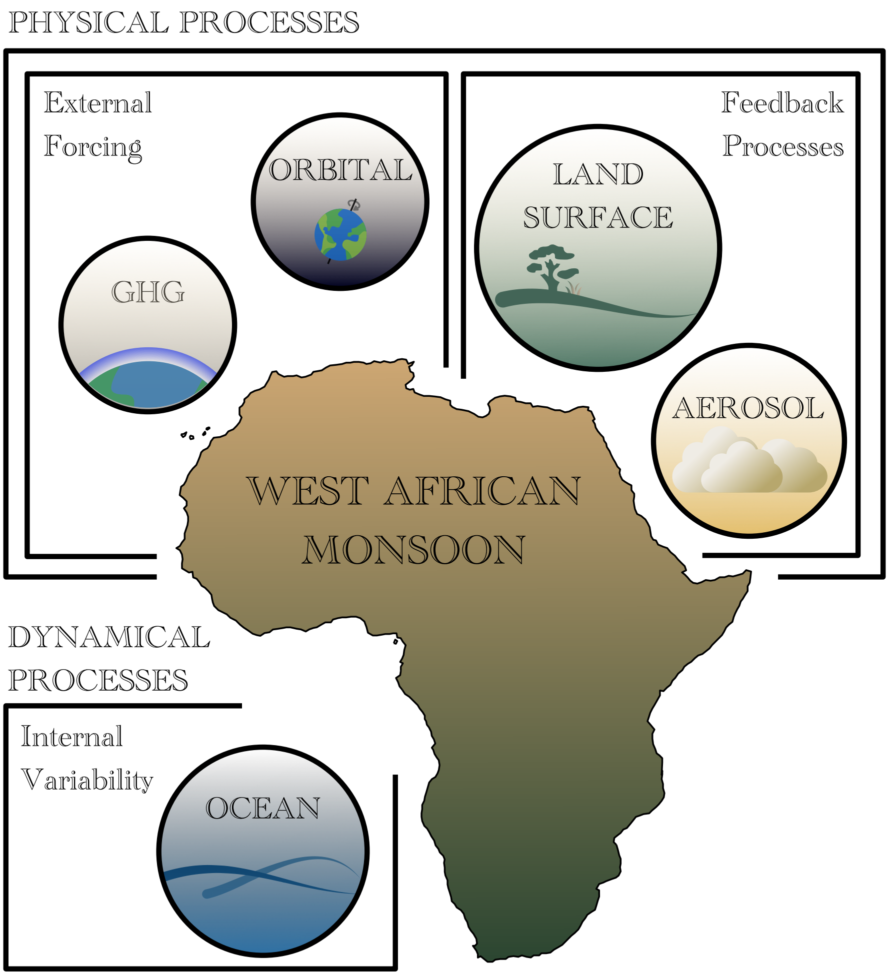


Figure 2.3. Schematic illustration of internal variability (ocean), external forcing (GHG and orbital) and feedback processes (land surface and aerosol) that influence the West African Monsoon.

2.2.1 Physical processes

Various physical processes play a crucial role in modulating the strength and location of the WAM. These processes encompass local feedback mechanisms, such as the vegetation-albedo feedback, as well as long-term influences, such as orbital forcing, which operate on millennial and longer timescales.

Orbital forcing

One significant driver of global climate variability is orbital forcing, which has played a crucial role in modulating past climate change in West Africa (e.g., Kutzbach and Otto-Bliesner, 1982; deMenocal, 1995; Larrasoaña et al., 2013). Earth's orbit around the sun determines the latitudinal and seasonal distribution of shortwave radiation, or sunlight, that reaches Earth's surface. Changes to this orbit can alter the amount of sunlight reaching high- to mid-latitudes by up to 25% (Ruddiman, 2001; Marshak, 2015), thus impacting the regional climate.

Three parameters determine the orbit; eccentricity, precession and obliquity. Eccentricity describes the elliptical orbit, precession refers to the orientation of Earth's axis and obliquity describes Earth's axial tilt (Fig. 2.4). These parameters vary with time in so-called Milankovich cycles, with periods ranging from approximately 100'000 years for eccentricity to 23'000 years for precession (Ruddiman, 2001; Marshak, 2015).

The last time Sahara was covered in vegetation occurred during the early to middle Holocene, 11'000-5000 years before present (BP). This period is often referred to as the African Humid Period or the Green Sahara, and proxy records indicate that the Sahara region was characterized by savanna, with annual rainfall up to 10 times higher than present-day levels (e.g., Tierney et al., 2017). During this period, changes to the orbital parameters amplified the seasonal cycle of insolation, with a change in Earth's precession resulting in the Northern Hemisphere receiving approximately 5% more insolation during the summer season (Kutzbach et al., 1996). This led to enhanced summer warming of the Sahara region, which in turn intensified the land-ocean temperature gradient, strengthened and shifted the WAM northward, and resulted in the observed climate change (Kutzbach, 1981; Kutzbach and Otto-Bliesner, 1982; Kutzbach and Guetter, 1986; Kutzbach et al., 1996).

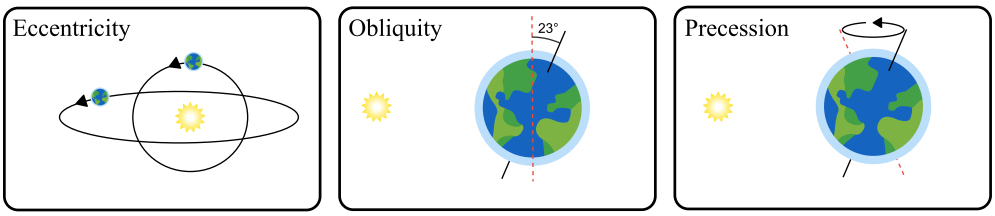


Figure 2.4. Schematic illustration of orbital parameters; eccentricity, obliquity and precession.

Greenhouse Gas forcing

Greenhouse gas concentrations are a main focus for future climate change, but have also varied significantly in the past. Studies of past climates show that higher concentrations of GHGs led to an enhanced hydrological cycle and more humid conditions in West Africa (Salzmann et al., 2008; Zhang et al., 2016; Haywood et al., 2020; Williams et al., 2022). However, the future impact of GHG forcing on the WAM remains uncertain and highly model-dependent (Biasutti et al., 2008; Cook, 2008; Roehrig et al., 2013), with different simulations yielding varying outcomes for West Africa, including drying, wetting or mixed signals (Biasutti and Giannini, 2006; Cook and Vizy, 2006; Druyan, 2011; Monerie et al., 2017; Yan et al., 2019).

Despite the uncertainty, a majority of future simulations, which are largely driven by anthropogenic GHG emissions, show a consistent pattern of drying in western Sahel and wetting in central/eastern Sahel (Fontaine et al., 2011; Monerie et al., 2012, 2013; Biasutti, 2013; Roehrig et al., 2013; Diallo et al., 2016; Akinsanola and Zhou, 2019). The western Sahel experiences drying mainly during May-August, while wetting in the central/eastern Sahel occurs between August and October (Biasutti, 2013; Seth et al., 2013; Monerie et al., 2017; Dunning et al., 2018). A recent study indicates that surface warming in northern Africa contributes to wetting in central/eastern Sahel, and warming SSTs cause drying in the western Sahel (Monerie et al., 2020).

Land surface feedbacks

While orbital and GHG forcings are major drivers of monsoon variability in West Africa, they do not act in isolation. A multitude of land surface processes and feedbacks have been shown to modulate the response (Kutzbach et al., 1996; Claussen and Gayler, 1997; Braconnot et al., 1999; Giannini et al., 2003; Patricola and Cook, 2007, 2008; Berg et al., 2017; Lu et al., 2018; Chandan and Peltier, 2020), and paleoclimate model simulations often fail to recreate the West African climate without taking these features into account (e.g., Kutzbach et al., 1996; Claussen and Gayler, 1997; Braconnot et al., 2000).

Modelling studies using state-of-the-art climate models have indicated that a combination of paleo-consistent land surface changes, such as surface water distributions, soil properties, and more realistic vegetation cover, can enhance the WAM rainfall to proxy-consistent levels (Chandan and Peltier, 2020). Among these, the largest response is suggested to come from introducing enhanced vegetation in West Africa (Chandan and Peltier, 2020).

Following the droughts in the 1970s, Charney et al. (1975) showed that the albedo change from a decrease in vegetation would cause persistent subsidence, suppressing rainfall and causing further vegetation loss. This process is referred to as the vegetation-albedo feedback, a positive feedback loop where changes in rainfall induce vegetation changes, which then cause further changes to the rainfall (Fig. 2.5).

The vegetation-albedo feedback is partly linked to the role of the meridional land-ocean temperature gradient and resulting Sahara Heat Low in driving the WAM. An externally forced increase in rainfall in West Africa, such as from the orbital forcing during the early and middle Holocene (e.g., Kutzbach, 1981; Claussen et al., 1999), would increase the vegetation cover in West Africa and decrease the surface albedo. This change would result in less insolation being reflected away from the surface and increased warming. The surface warming strengthens the land-ocean temperature gradient and deepens the Sahara Heat Low, resulting in a strengthened monsoon and increased rainfall reaching farther pole wards, further increasing vegetation and continuing the positive feedback loop.

In addition to the vegetation-albedo feedback, studies have highlighted the role of vegetation-rainfall feedbacks linked to changes in soil moisture (Patricola and Cook, 2008), evapotranspiration (Rachmayani et al., 2015) and moisture recycling (Yu et al., 2017). These processes strengthen the response of the WAM to external forcing through their effect on low-level moist static energy, convective instability, and surface latent heat flux anomalies (e.g., Claussen and Gayler, 1997; Braconnot et al., 1999; Rachmayani et al., 2015; Messori et al., 2019; Chandan and Peltier, 2020), although the role of soil moisture feedbacks in future rainfall projections remain uncertain (Berg et al., 2017).

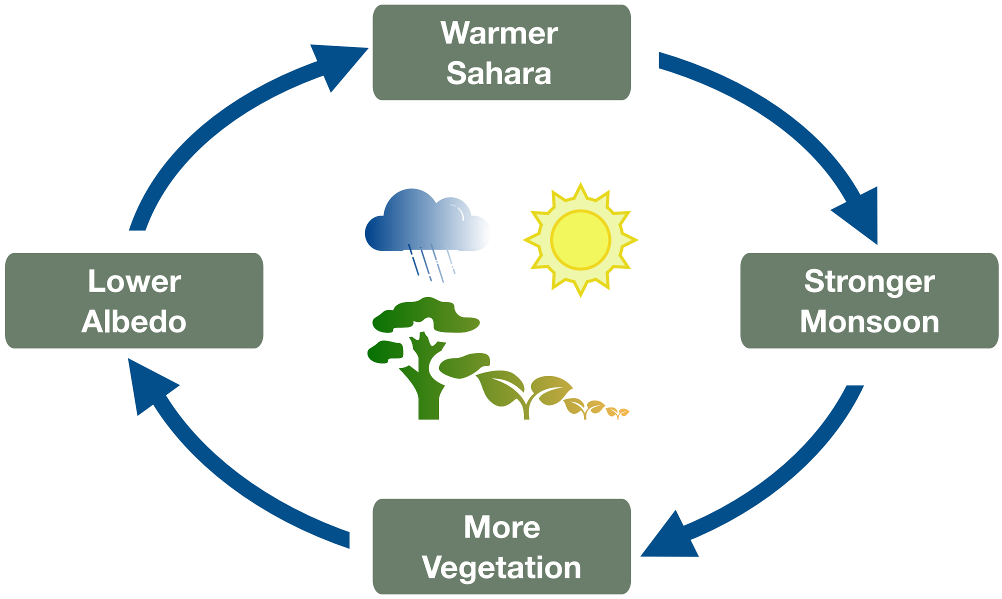


Figure 2.5. Schematic illustration of the vegetation-albedo feedback in the context of external forcing (such as orbital or CO_2 forcing) warming the Sahara region.

Aerosol forcing

In addition to land-surface changes, aerosols have been suggested to modulate the WAM (Huang et al., 2009; Pausata et al., 2016; Undorf et al., 2018; Messori et al., 2019; Thompson et al., 2019; Herman et al., 2020; Monerie et al., 2022). One well-studied processes is the dust-albedo feedback related to vegetation changes in the Sahara (Egerer et al., 2016; Pausata et al., 2016), where increased vegetation leads to decreased atmospheric dust loading over the region, altering the incoming solar radiation.

This direct radiative effect from dust reduction, combined with a lower surface albedo from increased vegetation, has been shown to increase surface warming over the Sahara. The warming results in an enhancement and northward shift of the WAM and its rainfall (Pausata et al., 2016; Messori et al., 2019) though the total dust aerosol effect on rainfall is dampened by the indirect aerosol effect, which involves changes to cloud optical properties and precipitation efficiency (Thompson et al., 2019). However, later studies have questioned the importance of the dust-precipitation feedback, pointing to the high sensitivity of the response in the model to the implemented dust properties (e.g., Hopcroft and Valdes, 2019).

In addition to regional aerosol changes, more recent studies have suggested that volcanic aerosols have played a crucial role in driving the multidecadal SST variability observed in the Atlantic in the last millennium, and through that, driving rainfall variability in West Africa (Mann et al., 2021).

Anthropogenic aerosols have also been suggested to play a role in modulating modern and future rainfall variability in West Africa (Undorf et al., 2018; Giannini and Kaplan, 2019; Herman et al., 2020). However, given the focus on paleoclimate in this thesis, it will be excluded from further study.

2.2.2 Dynamical processes

Throughout the 20th Century, West Africa, particularly the Sahel region, experienced pronounced rainfall variability ranging from inter-annual to multidecadal scale. A main driver of internal rainfall variability in West Africa is believed to be related to ocean variability (Folland, 1986; Giannini et al., 2003; Rowell, 2003; Lu and Delworth, 2005; Hoerling et al., 2006; Biasutti et al., 2008), although additional feedback processes, such as the vegetation-albedo feedback, could influence the response to such variability patterns (e.g., Zeng et al., 1999; Rosenfeld et al., 2001; Giannini et al., 2003).

Given the role of the land-ocean temperature contrast in the seasonal cycle and intensity of the WAM (Thorncroft et al., 2011), internal temperature variability in the surrounding ocean basins have the potential to influence this temperature gradient and, through that, the WAM. In the following, I will discuss SST variability in the Atlantic Ocean and the Mediterranean Sea, as well as the more remote Indian and Pacific Oceans, and their potential impact on the WAM and the rainfall variability in the region.

The Tropical Atlantic

The tropical Atlantic is the primary moisture source for West African monsoon rainfall, and ocean variability in the region plays a significant role in modulating the WAM on an inter-annual timescale (Ward, 1998; Rowell et al., 1995; Janicot et al., 2001; Losada et al., 2010).

In the late spring, a cold tongue develops in the Gulf of Guinea (Fig. 2.1), strengthening the temperature gradient between the Sahara in the north and the Equatorial Atlantic in the south. This gradient is crucial for the onset of the WAM (Thorncroft et al., 2011). The Atlantic Niño, also known as the "zonal mode", is a naturally occurring inter-annual variability of the SSTs in the Gulf of Guinea (Joly and Voldoire, 2010), which describes anomalous changes in the temperature of this cold tongue.

Although most research agrees that the Atlantic Niño impacts the rainfall in West Africa, the spatial pattern of the rainfall anomalies remains unclear. Early research suggested a meridional dipole-like pattern (Janowiak, 1988; Janicot, 1992; Rowell et al., 1995; Ward, 1998), in which positive temperature anomalies in the Gulf of Guinea (i.e. positive phase of the Atlantic Niño) result in negative rainfall anomalies in the Sahel region and positive anomalies over the Gulf of Guinea and surrounding coastal areas.

However, more recent research has questioned this dipole pattern. Giannini et al. (2005) suggested that the dipole pattern might be artificial, while other studies indicated that the dipole pattern is non-stationary and that its presence varies during the 20th Century as it interacts with the influence from other surrounding SST variability patterns (Janicot et al., 2001; Joly and Voldoire, 2010; Losada et al., 2012).

The North Atlantic

Rainfall variability in West Africa, particularly on a multidecadal scale, has been linked to the Atlantic Multidecadal Variability (AMV), previously known as the Atlantic Multidecadal Oscillation (AMO) (Zhang and Delworth, 2006; Ting et al., 2011; Martin and Thorncroft, 2014). The AMV is a basin-wide SST variability pattern with its strongest signal located in the North Atlantic (Kerr, 2000; Knight et al., 2005). It is believed to influence the climate in adjacent continents, hurricane activity over the Atlantic, and rainfall in both the Indian and West African Monsoons (Enfield et al., 2001; Knight et al., 2006; Zhang and Delworth, 2006). In West Africa, the positive phase of the AMV (i.e. warm SSTs in the North Atlantic) is linked to increased rainfall in the Sahel region, with a northward shift of the rainbelt and anomalous westerly to southwesterly surface winds bringing moisture in over the continent (Knight et al., 2006; Zhang and Delworth, 2006). In the negative phase the opposite occurs, with a southward displacement of the rainbelt and negative rainfall anomalies over the Sahel region.

While some observational studies have suggested that the AMV is an internal variability mode of the Atlantic Ocean (Ting et al., 2011), driven primarily by the Atlantic Meridional Overturning Circulation (AMOC) (Delworth and Mann, 2000; Knight et al., 2005), other studies have proposed external, radiative forcing such as solar, volcanic, and aerosol forcing as a main driver of the AMV (Otterå et al., 2010; Booth et al., 2012; Knudsen et al., 2014; Wang et al., 2017; Mann et al., 2021).

The "period" of the AMV has been suggested to be around 60-80 years (Delworth and Mann, 2000), with the warm (cold) phase of the AMV linked to increased (decreased) rainfall over West Africa on a similar timescale (Martin and Thorncroft, 2014). However, given the short observational time-series available, determining any truly oscillatory behaviors of the AMV, as well as statistically and dynamically linking it to the multidecadal rainfall variability in West Africa, has proven to be challenging.

This topic is further explored in **Papers I and II**, where we examine the representation of multidecadal rainfall variability in West Africa in newly published century-long reanalysis products. We also use a last millennium simulation to investigate drivers of rainfall variability in West Africa, allowing for more robust statistical analysis.

The Mediterranean Sea

In addition to the Atlantic Ocean, the Mediterranean Sea has been shown to influence rainfall in the Sahel region, with colder (warmer) SSTs associated with drier (wetter) conditions (Rowell, 2003; Fontaine et al., 2010; Gaetani et al., 2010; Martin et al., 2013). While the influence is present on various timescales, the relationship is most pronounced on decadal and longer timescales (Rowell, 2003).

On a multidecadal scale, SST variability in the Mediterranean Sea is highly correlated to North Atlantic SSTs (Marullo et al., 2011). The AMV pattern also includes a strong signal in the Mediterranean (Mohino et al., 2011), making it difficult to distinguish the roles of the AMV and the Mediterranean in driving multidecadal rainfall variability in the Sahel region.

Nonetheless, studies have indicated that anomalously warm SSTs in the eastern Mediterranean increase the local evaporation and moisture content in the lower troposphere, enhancing the northerly moisture transport into Sahel, strengthening the convective rainfall, and deepening the Saharan Heat Low which drives the WAM (Rowell, 2003; Fontaine et al., 2010, 2011; Gaetani et al., 2010).

The Indian Ocean and the Pacific Ocean

In addition to the direct influence of adjacent ocean basins, teleconnections from more remote SST variability patterns in the Indian the Pacific Oceans, such as those associated with the El Niño-Southern Oscillation (ENSO), have been suggested to drive rainfall variability in the Sahel region (Rowell et al., 1995; Ward, 1998; Janicot et al., 2001; Rowell, 2001; Joly et al., 2007; Giannini et al., 2003; Lu and Delworth, 2005; Lu, 2009; Joly and Voldoire, 2010; Mohino et al., 2011; Losada et al., 2012; Pomposi et al., 2016; Srivastava et al., 2019). Some studies indicate that these patterns impact the strength of the WAM and the advection of low-level moisture over West Africa, influence the stability of the atmosphere above West Africa, and suppress or enhance convection related to the monsoon rainfall (Janicot et al., 2001; Lu et al., 2009; Pomposi et al., 2016).

However, research in this area is complicated by non-stationary relationships, where different SST patterns shift, counteract or enhance the impact of others. Several studies have noted a strengthened negative correlation between the WAM and ENSO after the 1970s (e.g., Janicot et al., 2001), with Srivastava et al. (2019) suggesting this is the result of a zonal shift of the high-altitude ENSO induced temperature anomalies. Similarly, the correlation between the Atlantic Niño and WAM appears to have decreased or disappeared in later decades, believed to be the result of interference by Pacific warming (Joly and Voldoire, 2010; Losada et al., 2012).

These more remote SST variability patterns do not emerge as strong drivers of multidecadal WAM variability in our research for **Papers I and II**, and thus will not be expanded upon further.

3 Aim and research questions

As described in chapter 2, the West African Monsoon and its rainfall are influenced by numerous internal and external factors. However, gaining a deeper understanding of these factors is limited by the short and scarce observational records, further complicated by the lack of observations covering dynamical variables necessary for understanding more complex dynamical links and processes. Given these limitations, paleoclimate modelling is a useful tool for advancing our knowledge of past climates and climate processes, as it results in dynamically consistent simulations and allows for the analysis of longer time series and the creation of sensitivity experiments.

The aim of this thesis is to *further our understanding of internal and external drivers of monsoon variability in West Africa*. This is done using paleoclimate modelling, focusing on four different periods suitable for examining a variety of drivers. The specific research questions of this thesis are:

1. What are the drivers of internal multidecadal rainfall variability in West Africa (Papers I and II)?

2. How did the mid-Pliocene forcing and boundary conditions impact the West African Monsoon, and what implications does this have for the future of rainfall in West Africa (Paper III)?

3. Will implementing a coupled, dynamic vegetation model to EC-Earth provide a more realistic representation of the role of vegetation feedbacks in recreating the enhanced WAM in the mid-Holocene (Paper IV)?

In chapter 4 the data used in the thesis is presented, and in chapter 5 paleoclimate modelling is introduced. In chapter 6, the individual results of each paper included in this thesis are presented. In chapter 7, I discuss some of the insights gained from the analysis and suggest future steps that can be taken to further our understanding and advance the research.

4 Data

4.1 Observational and reanalysis data

Observations

The thesis uses two different observational datasets to examine rainfall and temperature variability in the 20th Century: the high-resolution gridded precipitation data-set from the Climate Research Unit (CRU TS 3.24.01; Harris et al. (2014)) and the Hadley Centre's SST dataset HadSST2 (Rayner et al., 2006). Both datasets contain monthly mean values, with CRU spanning the period 1901-2015 and HadSST2 the period 1901-2014.

The CRU data is based on in-situ observations from meteorological stations, which are interpolated into a 0.5°x 0.5 °resolution grid. However, only approximately 60-80% of grid cells in Africa have an observational coverage for most of the 20th Century. For grid cells lacking observational data at specific time steps, a 1961-1990 climatological mean is supplied (Harris et al., 2014).

The HadSST data relies on observations from various marine sources, such as naval vessels, drifting buoys and voluntary observing ships. These observations are used to construct a dataset on a 5°x 5°resolution grid.

Reanalysis data

Reanalysis data are produced through a process called data assimilation, which combines observational data with short-range weather forecasts using a state-of-the-art weather forecast model, forced by SSTs and sea ice concentrations (SIC) (Poli et al., 2016). The data assimilation often use observations such as surface pressure and low-level wind, creating dynamically consistent atmospheric datasets without temporal or spatial gaps by leveraging sparse observational data. Variables such as precipitation are generated by the model, rather than based on assimilation of observations.

In **Paper I**, four different 20th Century reanalysis datasets are used and evaluated: three produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), and one by the National Oceanic and Atmospheric Administration (NOAA) and the Co-operative Institute for Research in Environmental Sciences (CIRES). The three ECMWF reanalysis datasets are:

1. ERA-20C (Poli et al., 2016): A standard single member reanalysis product forced by SSTs and SIC from HadISST 2.1, and using surface pressure and marine wind observations in the data assimilation.

2. CERA-20C (Laloyaux et al., 2018): A 10-member ensemble with a coupled ocean-atmosphere and the same observational datasets as ERA-20C.

3. ERA-20CM (Hersbach et al., 2015): A 10-member ensemble that does not assimilate any atmospheric observations. Instead, it is an AMIP-style dataset (Atmospheric Model Intercomparison Project, i.e. atmospheric model forced by SSTs rather than coupled ocean-atmosphere) forced by 10 different realizations of the HadISST2.1 dataset.

The spread in ERA-20CM thus represents the uncertainty of the SST/SIC within the HadISST2.1 dataset.

Additionally, the NOAA/CIRES 20th century reanalysis version 2 (20CRv2; Compo et al. (2011)) is included, which is an ensemble mean produced by a 56-member ensemble forced by SST and SIC from HadISST1 and using surface and sea level pressure for data assimilation.

4.2 Proxy reconstructions of past climates

Instrumental records of past climates are limited in time, with only a few European records dating back to the mid 17th Century (Manley, 1974; Parker et al., 1992; Burgdorf, 2022). To study climates further back in time, we rely on documentary historical evidence and natural archives. For example, archaeological evidence from the early Holocene in the Sahara suggests the presence of animals such as hippos, elephants and giraffes, as well as human populations, indicating a significantly different climate than the present-day desert (Barth, 1857; McIntosh and McIntosh, 1983; Barnett et al., 2003; di Lernia, 2019).

While the term "proxy" can refer to any indirect measurement of past climates, it most often refers to natural archives. The historical records are often used in combination with these natural archives, which offer the advantage of extending further back in time.

Quantitative and qualitative proxies

Proxy indicators in natural archives are interpreted based on physical or biophysical principles and used to reconstruct past climate states and variability, often in terms of temperature and humidity/precipitation (Mann et al., 1999; Linderholm and Chen, 2005; Moberg et al., 2005; Shi et al., 2017). These records have been crucial in revealing past hydroclimatic changes in West Africa, with several proxy reconstructions indicating a more humid climate in the region as recently as during the early to middle Holocene (e.g., Jolly et al., 1998; deMenocal et al., 2000).

For instance, a pollen record from the early to mid-Holocene was collected from buried lake sediments in Eastern Sahara (Ritchie et al., 1985). This record contains pollen from deciduous savanna vegetation taxa, which currently exists approximately 500 km to the south of the sample site, indicating a prolonged humid climate in a region currently characterized by desert conditions.

While many proxy reconstructions of temperature often give quantitative temperature anomalies relative to modern times (e.g., Foley and Dowsett, 2019; Haywood et al., 2020), precipitation and humidity reconstructions tend to be more qualitative or semi-quantitative measurements, i.e. more or less humid than modern times (Feng et al., 2022). However, some quantitative proxy reconstructions also exist for precipitation in West Africa. For example, Tierney et al. (2017) used leaf wax isotopes in marine sediments off the western coast of West Africa, spanning the last 25'000 years, to reconstruct annual rainfall rates in the western Sahara.

Data-model comparison

Many proxy data studies have focused on providing global and hemispheric mean temperatures (Mann et al., 1999; Mann and Jones, 2003; Jones and Mann, 2004; Moberg et al., 2005), as well as regional patterns of variability (e.g., Mann et al., 1998; Evans et al., 2002). In paleoclimate modelling, these climate reconstructions serve as benchmarks against which paleoclimate simulations can be compared and evaluated. This is often done through a point-to-point comparison, revealing limitations, biases, and areas for improvement (Brierley et al., 2020; Haywood et al., 2020).

In **Paper IV** we use temperature and precipitation reconstructions from Bartlein et al. (2011) for the mid-Holocene (6 thousand years before present; 6 ka BP), derived from pollen and plant macrofossil proxy records. The study also compares simulated vegetation using an Earth System Model to reconstructed biomes based on the BIOME6000 dataset (Harrison, 2017). In **Paper III**, qualitative model-data agreement is assessed by comparing the indications of a more humid climate in West Africa from previous paleohydrological and paleoenvironmental proxy reconstructions (deMenocal, 2004; Feakins et al., 2005; Salzmann et al., 2008; Bonnefille, 2010; Feng et al., 2022) to the research findings.

Uncertainties and limitations in proxy reconstruction

Proxy reconstructions are invaluable in understanding past climates, but they come with several uncertainties and limitations. Analytical uncertainties, incomplete understanding of processes affecting natural archives, and influences of other climate variables on the natural archive (e.g., Cronin, 2009; Bova et al., 2021) are some of the key challenges. In addition, sparse spatial and temporal coverage, as well as uncertain dating, can hinder climate reconstructions. Africa, for example, has a spatial coverage one order of magnitude lower than Europe and North America over the last 2000 years, making proxy-based climate reconstructions insufficient for regional assessments of change (Masson-Delmotte et al., 2014; Nash et al., 2016).

The field of proxy reconstructions and their associated uncertainties is vast and constantly evolving. To address these uncertainties, researchers are developing new methods such as data assimilation for paleoenvironmental reconstructions, which combine information from observations and Earth system models (e.g., Erb et al., 2022).

5 Paleoclimate modelling

5.1 Climate models

Climate models are mathematical representations of Earth's physical, chemical and/or biological processes that determine its climate (Flato, 2011). They vary in complexity, ranging from box models and energy balance models to General Circulation Models (GCMs) and Earth System Models (ESMs). GCMs include the processes within the major components of the Earth system, such as the atmosphere, ocean, sea ice and land surface, as well as their interactions. These processes are numerically resolved and structured into three dimensional grid cells, which extend from Earth's surface to the top of the atmosphere and down to the ocean floor.

Over time, the complexity of climate models has increased (Flato, 2011). In addition to the processes described in GCMs, ESMs now include a representation of the carbon cycle, dynamic vegetation, atmospheric chemistry and cloud-aerosol interaction, ocean biogeochemistry and more (Fig. 5.1) (Flato, 2011). Processes that cannot be explicitly resolved are parameterized within the model, with convection being a prominent example, and much of the inter-model differences can be attributed to these parameterizations.

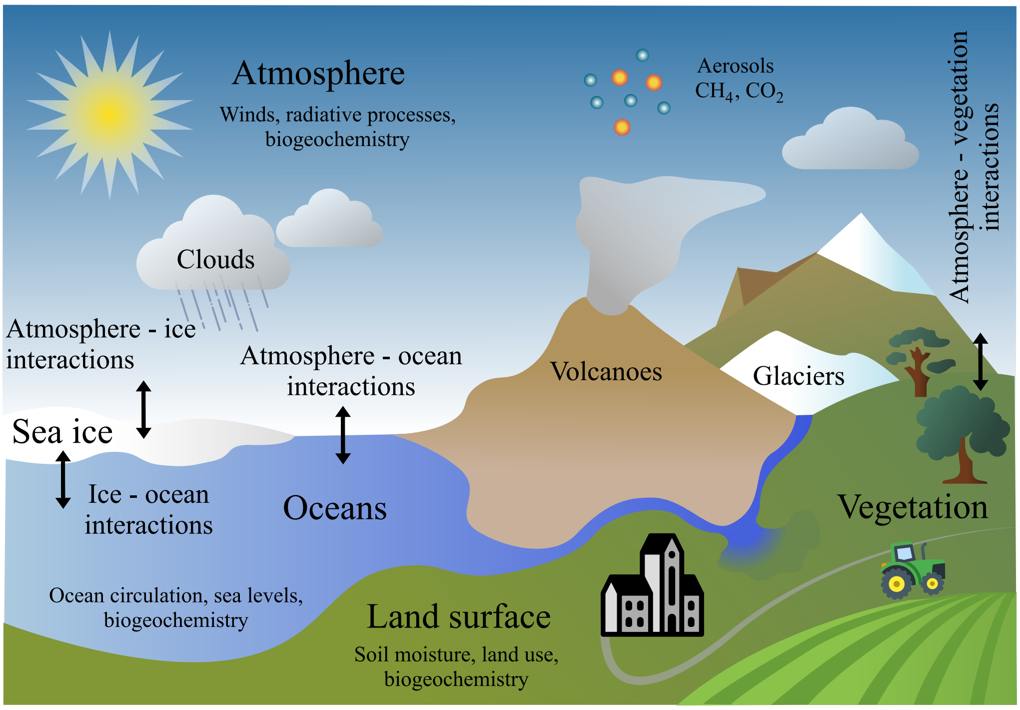


Figure 5.1. Schematic illustration of the Earth System, with different components represented in Earth System Models.

5.2 Modelling Intercomparison Projects

With the growing number of modelling centers around the world, the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM) established the Coupled Model Intercomparison Project (CMIP) to enable comparisons and analyses of large model ensembles. CMIP aims to standardize multi-model outputs, ensure consistent experimental design, and facilitate understanding of past, present and future climate change (Meehl et al., 1997; Eyring et al., 2016). In the latest phase, CMIP6, modeling groups can participate in a core set of simulations and contribute to any of the CMIP-endorsed Model Intercomparison Projects (MIPs) (Eyring et al., 2016). This collaborative effort reflects the interests and needs of the broader scientific community.

Climate model simulations are used for predicting future climate scenarios, performing sensitivity experiments, and reproducing past climates, and they are run with forcing and boundary conditions consistent with the specific climate scenarios. Near-past and future time periods (last millennium: 850-1850 CE (current era), historical: 1850- near present, and future scenarios: near present-2100) are run as transient simulations, where forcing (e.g., GHGs, orbital forcing) changes annually. In contrast, paleoclimate simulations are often run as equilibrium simulations, aiming to reach an equilibrium state with no trend.

Most climate models are currently tuned for and validated against modern conditions, with discrepancies in recreating the near past driving continuous model improvements. Models are then applied for future scenarios and paleoclimate simulations in parallel (Burls and Sagoo, 2022; Döscher et al., 2022). This approach is used to ensure consistency and comparability between the different simulations using the same model. As a result, paleoclimate simulations often fail to reach equilibrium, instead running "towards a semi-equilibrium state". However, some paleo-scientists increasingly argue for including paleoclimate simulations in the calibration process, stating that paleoclimate reconstructions provide useful out-of-sample climates for evaluating climate models' performance (Burls and Sagoo, 2022; Zhu et al., 2022).

5.3 Earth System Model EC-Earth

EC-Earth model description

EC-Earth is an ESM developed by a European consortium, bringing together researchers from 27 research institutes across Europe (Döscher et al., 2022). The model is available in various coupled configurations (see Fig. 5.2 for components and coupling links of EC-Earth3), and the CMIP6 version EC-Earth3 has contributed to several CMIP-endorsed MIP's (Döscher et al., 2022).

The atmospheric component and coupled surface scheme of EC-Earth3 are based on the Integrated Forecast System (IFS; atmospheric component) and the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land model (HTESSEL; Balsamo et al., 2009), both developed by ECMWF. These components are also used in generating three previously mentioned reanalysis datasets (ERA-20C, ERA-20CM and CERA-20C).

The ocean and sea-ice components are the Nucleus for European Modelling of the Ocean (NEMO; Madec, 2015) and the Louvain-la-Neuve Ice Model (LIM3; Vancoppenolle et al., 2009; Rousset et al., 2015). Additional models can be coupled with EC-Earth3 (Fig. 5.2), such as the Tracer Model version 5 (TM5; van Noije et al., 2014) for atmospheric chemistry and aerosol processes, PISCES (Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2; Aumont et al., 2015) for ocean biogeochem-

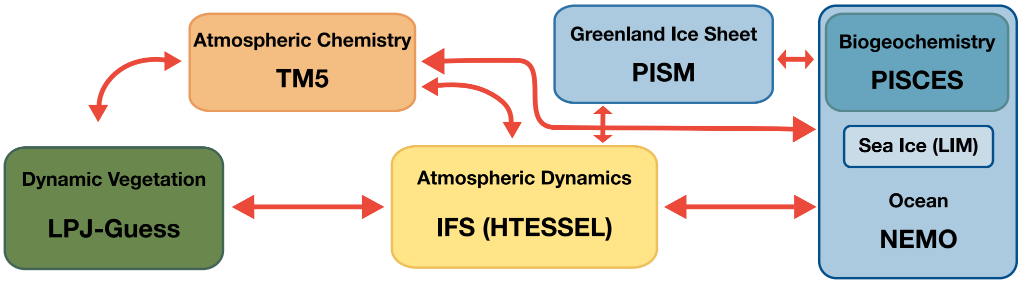


Figure 5.2. Schematic of EC-Earth3 components and coupling, adapted from Figure 1 in Döscher et al. (2022).

istry and the ice sheet model PISM (Parallel Ice Sheet Model v1.1; Bueler and Brown, 2009; Winkelmann et al., 2011) used to model the Greenland Ice Sheet. However, these additional models are not included in the EC-Earth3 configurations used in this thesis.

Dynamical vegetation model LPJ-GUESS

In simulations using coupled dynamic vegetation, the LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) is employed as the dynamic vegetation and biogeochemistry model (Smith et al., 2014; Döscher et al., 2022). LPJ-GUESS receives daily meteorological input from IFS/HTESSEL (Fig. 5.2), including surface air temperature, soil temperature, precipitation, and net shortwave and longwave radiation. Soil moisture for potential plant uptake is calculated independently from the hydrology scheme in HTESSEL.

Vegetation is simulated and classified into different Plant Functional Types, separated into high and low vegetation. Daily output describes the effective cover and leaf area index for both high and low vegetation. At the end of the model year, the dominant high and low vegetation types for each grid cell are calculated and passed on to IFS/HTESSEL. This information is then used to drive biophysical processes at the land surface, such as albedo, runoff, and sensible and latent heat exchange.

5.4 Modelled past climates

Paleoclimate modelling plays a critical role in understanding past climates by providing global climatological pictures of periods with limited proxy data. These simulations shed light on the processes responsible for observed climate states, including those not captured by proxy records, such as atmospheric dynamics and clouds.

Paleoclimate modeling has evolved since 1970s when atmospheric models with idealized surface boundary conditions were used to simulate ice-age climate (Alyea, 1972; Williams et al., 1974). In the early 1990s, PMIP was initiated to coordinate the systematic study of climate models and assessing their ability to simulate large climate changes observed in past periods (Joussaume and Taylor, 1995, 2000). PMIP helps to increase confidence in future climate change simulations and fosters collaboration between climate modelling groups and paleodata scientists (e.g., Joussaume and Taylor, 1995; Prentice and Webb III, 1998).

The current fourth phase PMIP4 covers five time periods: the 1000 years prior to the industrial epoch; the mid-Holocene, 6000 years ago; the Last Glacial Maximum, 21 000

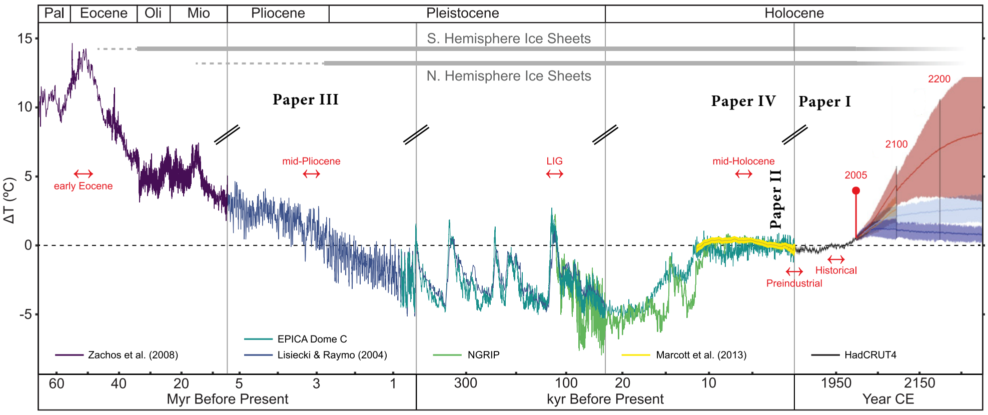


Figure 5.3. Multi-timescale time series of global mean annual temperatures for the last 65 Ma and projected warming trends for four emission pathways relative to 1961-1990 global mean temperature. Time periods used in the thesis are indicated; year 1900-2015 for **Paper I**, 850-1850 CE for **Paper II**, mid-Pliocene (∼3.2 Ma) for **Paper III** and mid-Holocene (6 ka) for **Paper IV**. Figure from Burke et al. (2018), modified with permission to indicate periods used in thesis. Temperature anomalies are composited from five proxy-based reconstructions (NGRIP: North Greenland Ice Core Project members, 2004; Lisiecki and Raymo, 2005; EPICA Dome C: Jouzel et al., 2007; Zachos et al., 2008; Marcott et al., 2013), modern observations (HadCRUT4: Morice et al., 2012), and future temperature projections (IPCC, 2013). Please note that the Pleistocene-Holocene boundary in the figure does not align with the more commonly used definition of 11.65 ka BP (Walker et al., 2009).

years ago; the Last Interglacial, 127 000 years ago; and the mid-Pliocene Warm Period, 3.205 million years ago, organised through the second phase of the Pliocene Model Intercomparison Project (PlioMIP2) (Kageyama et al., 2018). The experimental design and boundary conditions for PMIP, such as the paleogeography, GHGs, and orbital forcing, are defined and provided by collaborations between modellers and paleo-geographers (e.g., Haywood et al., 2016; Kageyama et al., 2018).

This thesis is based on EC-Earth3 simulations following the PMIP3 *last millennium* and the PMIP4 *mid-Holocene* experimental design, as well as the PlioMIP2 model ensemble with results from 17 model simulations. The time periods covered in the thesis are shown in Figure 5.3.

The last millennium

The PMIP3 *last millennium* simulation covers the 1001 years prior to the industrial era (850-1850 CE). It is included also in PMIP4 with the time period changed to 850-1849 CE, and is currently the only transient simulation in PMIP. This period is characterized by varying climate forcing driven by a combination of orbital, solar, volcanic, GHG and land-use changes (Schmidt et al., 2011, 2012; Kageyama et al., 2018). Notably, it includes the Medieval Warm Period (approx. 900-1200 CE) and the Little Ice Age (approx. 1550-1850), both of which are subjects of ongoing debate regarding their timing, naming and attribution (e.g., Jones and Mann, 2004; PAGES 2k Consortium, 2013). The transient nature of the *last millennium* simulation allows for studies of multi-decadal to centennial scale variability which modern observations are unable to capture.

In **Paper II** a *last millennium* simulation run using the EC-Earth3.1 model is used, where the model implements climate forcing following the PMIP3 protocol (Schmidt et al., 2011, 2012).

The mid-Holocene

During the early to middle Holocene, from around 11'000 to 5000 years BP, the Sahara experienced a much more humid climate, characterized by widespread vegetation, grass- and shrublands, and permanent lakes and wetlands (Street-Perrott et al., 1989; Hoelzmann et al., 1998, 2001; Jolly et al., 1998; deMenocal et al., 2000; Gasse, 2000; Prentice et al., 2000; Lézine et al., 2011; Hély et al., 2014). This is attributed to a strengthened WAM which brings rainfall further into the Sahara (Kutzbach, 1981). The period is the latest in a series of precession-forced wet phases, reaching back over the last 11 million years (deMenocal, 1995; Larrasoaña et al., 2013), and has been the focus of numerous proxy reconstructions and climate modeling studies (e.g., Bartlein et al., 2011; Larrasoaña et al., 2013; Otto-Bliesner et al., 2017; Brierley et al., 2020).

The mid-Holocene has been included in PMIP since its first iteration, though defined as 6 ka BP rather than the geological definition of 8.2-4.2 ka BP (Walker et al., 2019). Despite the global climate agreeing well between the PMIP4 mid-Holocene ensemble and proxy data, models still struggle to recreate the humid climate and enhanced monsoon in West Africa (Brierley et al., 2020). While orbital forcing is the main driver of the enhanced mid-Holocene WAM (Kutzbach, 1981; Kutzbach and Otto-Bliesner, 1982; Kutzbach and Guetter, 1986), model simulations reveal that ocean, land surface and dust feedbacks further amplify the response (Kutzbach et al., 1996; Kutzbach and Liu, 1997; Pausata et al., 2016; Lu et al., 2018; Thompson et al., 2019; Chandan and Peltier, 2020).

Recent studies have incorporated prescribed paleo-land surface characteristics (soil, vegetation, lakes) and demonstrated improved model-data agreement with an enhanced WAM, sustained in a northward position (Pausata et al., 2016; Chandan and Peltier, 2020). However, the idealized and often homogeneous maps of these prescribed vegetation fields only allow for one-directional forcing, potentially under- or overestimating the role of the vegetation feedbacks. In **Paper IV**, we explore and discuss the role of vegetation feedbacks in enhancing the WAM using the ESM EC-Earth with coupled dynamic vegetation.

Mid-Pliocene Warm Period

The mid-Pliocene Warm Period (mPWP; 3.264 - 3.025 million years ago; Ma) is a period of warm and stable climate, with an annual global mean temperature several degrees higher than pre-Industrial (PI) conditions (1.7 to 5.2 °C warmer in PlioMIP2) (Dowsett et al., 2010; Haywood et al., 2010, 2020). Geologically, it falls within the Piacenzian Stage of the Late Pliocene (Gradstein and Ogg, 2020) and is also often referred to as the mid-Piacenzian warm period (Dowsett et al., 2012), but for consistency it remains called the mid-Pliocene Warm Period within the paleoclimate modelling community as well as within this thesis. The mid-Pliocene Warm Period is considered an interesting analogue for near-future climate change due to its similar atmospheric CO_2 concentrations (around 400 ppmv) and near-modern geography (Raymo et al., 1996; Tripati et al., 2009; Dowsett et al., 2010; Pagani et al., 2010; Seki et al., 2010; Bartoli et al., 2011; Badger et al., 2013; Haywood et al., 2013, 2020; Salzmann et al., 2013; Martínez-Botí et al., 2015; de la Vega et al., 2020). Paleoenvironmental reconstructions indicate a warmer and more humid climate than today, with an expansion of forests, grasslands, woodlands and savannas at the expense of tundra and desert (Salzmann et al., 2008, 2013; Dowsett et al., 2010).

The mid-Pliocene Warm Period covers a longer time period with variable CO_2 and orbital forcing (Haywood et al., 2010). To facilitate model-data comparison, PlioMIP2 selected a more narrow time window within this period (marine isotope stage KM5c, 3.205 Ma) (Haywood et al., 2016). This choice improved model-data agreement compared to PlioMIP1. The selected time period features near-modern orbital forcing, and PlioMIP2 experimental design specifies that models should be forced by PI values, which allows the MIP to isolate the impact of higher CO_2 concentrations and paleogeographical changes on the climate. Key geographical changes include the closing of the Bering Strait and the Canadian Arctic Archipelago, as well as smaller Greenland and Antarctic Ice sheets, following the PRISM4 paleogeography reconstruction (Dowsett et al., 2016). The mid-Pliocene vegetation, soil, lakes and rivers are incorporated to account for paleoenvironmental changes (Haywood et al., 2016).

6 Result summary

In this chapter I summarize the results of the four studies presented in this thesis, divided according to the three research questions.

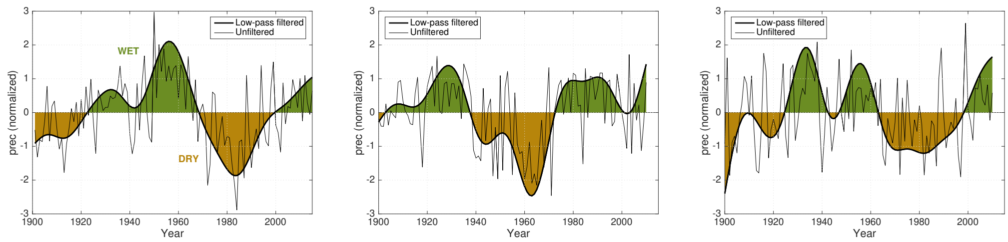
6.1 Multidecadal monsoon variability in West Africa (Papers I and II)

Paper I:

The West African monsoon rainfall has exhibited pronounced multidecadal variability in the 20th Century (Nicholson et al., 2000; Hulme, 2001; Zhang and Delworth, 2006), and while studies have suggested possible links to the North Atlantic SST variability pattern AMV (Knight et al., 2006; Zhang and Delworth, 2006), dynamically consistent datasets are needed to fully examine how such variability is driven. **Paper I** (Berntell et al., 2018) evaluates how well observed multidecadal rainfall variability in Sahel is captured in four different, century-long reanalysis datasets.

The results reveal that most reanalysis datasets struggle to accurately capture low-frequency rainfall variability in West Africa. For instance, the ERA-20C dataset produces a phase that is opposite to the one observed in the CRU data (Fig. 6.1). However, ERA-20CM, which does not include data assimilation of observations, demonstrates a high correlation with observed multidecadal rainfall variability, suggesting that the atmospheric model used in EC-Earth is capable of representing low-frequency variability effectively. This supports the use of EC-Earth model in further analysis in **Paper II**.

Moreover, the wide range of multidecadal variability observed in the ERA-20CM ensemble highlights the importance of realistic SST variability for accurately representing Sahel rainfall variability, consistent with previous studies. This insight contributes to our understanding of the factors influencing rainfall patterns in West Africa, with potential implications for climate modeling and prediction.



(a) CRU (b) ERA-20C (c) ERA-20CM

Figure 6.1. Detrended and low-pass filtered Sahelian July-September precipitation (prec) for (a) CRU, (b) ERA-20C and (c) ERA-20CM. Thin lines are unfiltered, and all anomalies are normalized by the standard deviation of the corresponding data. Figure modified from **Paper I** (Berntell et al., 2018).

Paper II:

Summer rainfall in West Africa has in the 20th Century has exhibited a complex variability in patterns and drivers, from inter-annual to multidecadal timescales. While research suggests that the Atlantic Ocean plays a crucial role in driving these patterns, especially on multidecadal timescales, the limited observational data available makes it challenging to draw statistically significant conclusions. In **Paper II**, we address this challenge by using a 1001-year long simulation of the last millennium (850-1850 CE) from EC-Earth3 to investigate the Atlantic and West African co-variability on decadal- to multidecadal scales.

We identify two key sets of co-variability patterns using Singular Value Decomposition (SVD), which together explain 90% of the total squared covariance (Fig. 6.2). The first patterns (SVD1) indicate an Atlantic Niño type SST variability pattern, featuring a corresponding rainfall dipole pattern with a positive correlation over the Gulf of Guinea and negative correlation over the Sahel region. The second SVD (SVD2) indicates a AMV type SST variability pattern with a strong signal over the Mediterranean and the North Atlantic, and a corresponding rainfall pattern reaching across northern Africa. Both modes show significant periods of variability at decadal to multidecadal timescales (10-14 years, 20-40 years and 10-14 years, 20-30 years, respectively).

This work contributes significantly to our understanding of the complex interplay between the Atlantic Ocean and West African rainfall on decadal to multidecadal timescales. By examining Atlantic Ocean and West African rainfall interactions, we reveal that SST anomalies over the Gulf of Guinea affect sea level pressure and influence the southwesterly flow into the Sahel. In the second pattern, a warm ocean phase in the North Atlantic and Mediterranean Sea deepens the Sahara Heat Low, intensifying the surface pressure gradient and enhancing cyclonic circulation over West Africa. By utilizing a long simulation, we can overcome limitations in observational data, offering valuable insights into the co-variability patterns that drive rainfall in the region.

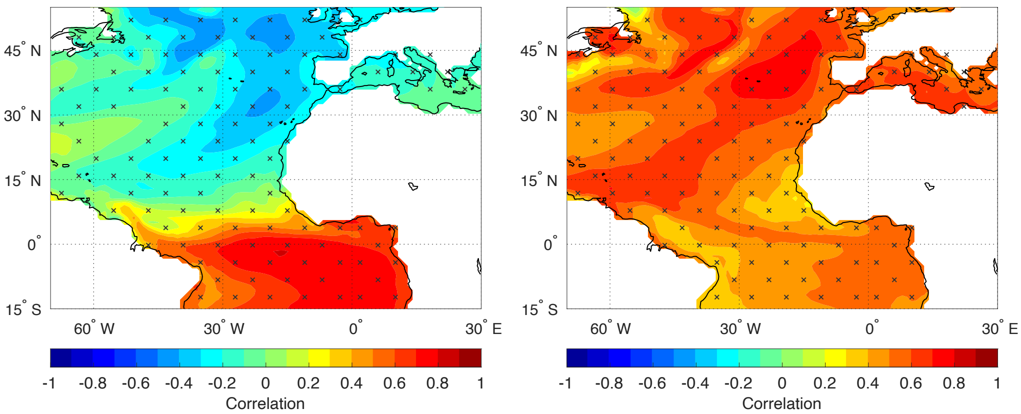


Figure 6.2. Leading SVD modes, presented as homogeneous correlation maps for SST SVD modes 1 (left) and 2 (right). Stippling indicates correlations that are significant at the 95% confidence level. Figure modified from **Paper II** (Zhang et al., 2021b).

6.2 Impact of CO_2 and paleogeography on WAM (Paper III)

Previous research on the West African summer monsoon during the mid-Pliocene Warm Period revealed inconsistencies in model simulations and the need for further analysis. In **Paper III** we use 17 model simulations from PlioMIP2 to investigate the WAM response to near-modern atmospheric CO_2 levels and paleogeography, to provide valuable insights for future climate change scenarios.

The PlioMIP2 multi-model mean (MMM) shows an increase in Sahel summer rainfall over the July-October period compared to PI, with maximum rainfall doubling in August, and a lengthening of the monsoon season. The positive rainfall anomalies reach from 7°N to northern Sahara and negative anomalies are centered at the Gulf of Guinea and Equatorial Atlantic (Fig. 6.3). The signal is robust within the ensemble, with all models showing increased July-October rainfall over Sahel (Fig. 6.4). These simulated wetter conditions are consistent with proxy records (Feng et al., 2022), although a quantitative assessment is currently lacking. The WAM response is stronger in PlioMIP2 compared to PlioMIP1, and analysis reveals an intensification and northward shift of the WAM with positive temperature anomalies across the Sahara, a deepened Sahara Heat Low and strengthened low-level monsoonal flow in over West Africa.

The ensemble shows a significant correlation between the summer temperature anomalies in the Sahara region and the strength of the Sahel rainfall response. Increased atmospheric CO_2 levels contribute to a land-ocean warming contrast, which could play a role in strengthening the WAM during the mid-Pliocene Warm Period. The effects of vegetation and orography changes are difficult to separate as they are applied together, but previous sensitivity studies suggest that they together play an important role in the rainfall increase in West Africa, with vegetation suggested to play a larger role in the hydroclimatic changes than the changes to the topography and land-sea distribution. However, the sensitivity of the individual ensemble members to the mid-Pliocene boundary conditions and the stronger response in PlioMIP2 are likely influenced by model parameterization and initial conditions.

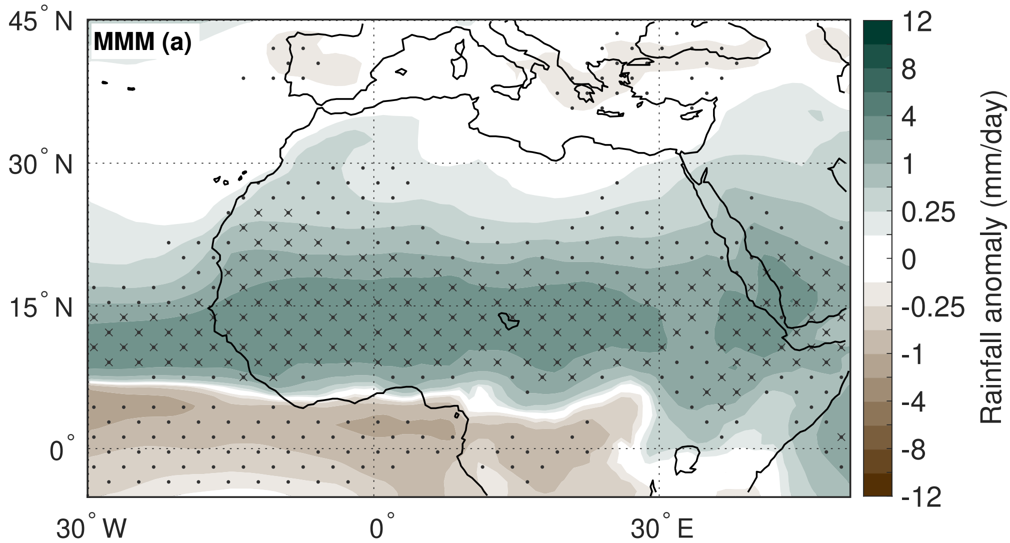


Figure 6.3. The mPWP July–October (JASO) rainfall anomalies (mPWP-PI) for the multi-model mean (MMM). Robust signals are indicated with an x, where >80 % of the models (14 out of 17) show the same sign of anomaly and the anomaly is equal to or larger than the inter-model standard deviation. Dots indicate that only the first criterion is fulfilled. Figure from **Paper III** (Berntell et al., 2021).

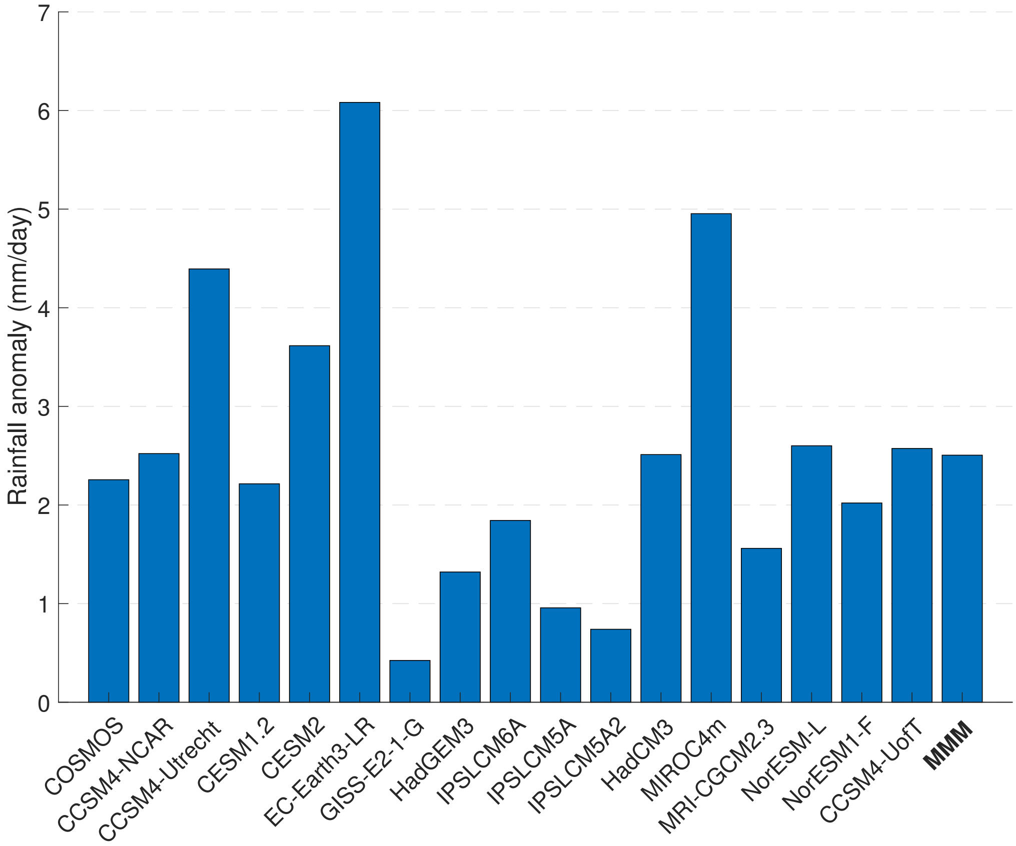


Figure 6.4. Mean July–October Sahel (10–20°N, 20°W–30°E) mPWP rainfall anomalies (mPWP-PI, unit: mm/d) for the individual PlioMIP2 ensemble models, together with the multi-model mean (MMM). Figure from **Paper III** (Berntell et al., 2021).

This work highlights the need to further investigate vegetation feedbacks in sustaining an enhanced WAM, leading to Research Question 3 in **Paper IV**.

6.3 WAM enhanced by vegetation feedback (Paper IV)

In paleoclimate modelling studies, vegetation cover is often prescribed as a boundary condition rather than simulated with a coupled vegetation model. This approach cannot capture the vegetation feedback to the climate and WAM, and might over-/underestimate the role of vegetation. **Paper IV** addresses this limitation by running two mid-Holocene simulations: one with prescribed PI vegetation and another with coupled dynamic vegetation. The aim is to answer Research Question 3 and investigate the role of vegetation feedbacks in recreating the enhanced WAM rainfall during the mid-Holocene.

Including dynamic vegetation significantly increases summer rainfall in West Africa, with July-September rainfall in Sahel increasing by 15% compared to an orbital-only forced mid-Holocene simulation. Additionally, it leads to a weak enhancement of the WAM dynamics, including surface warming across the Sahara region, deepening of the Sahara Heat Low, and strengthened southwesterly flow from the Equatorial Atlantic into the Sahel. However, this work reveals that dynamic vegetation does not create the intense warming in the Sahara or the northward shift of the monsoon seen in proxy reconstructions as well as in simulations with a prescribed Green Sahara vegetation (see model-data comparison of rainfall and temperature in Fig. 6.5). The simulated dynamic vegetation maps show a northward expansion of the grass- and treeline, but there is a under-representation of vegetation cover in the Sahara region compared to proxy evidence.

These results indicate that orbitally forced vegetation feedbacks are insufficient for recreating the enhanced monsoon and northward migration of both the mid-Holocene

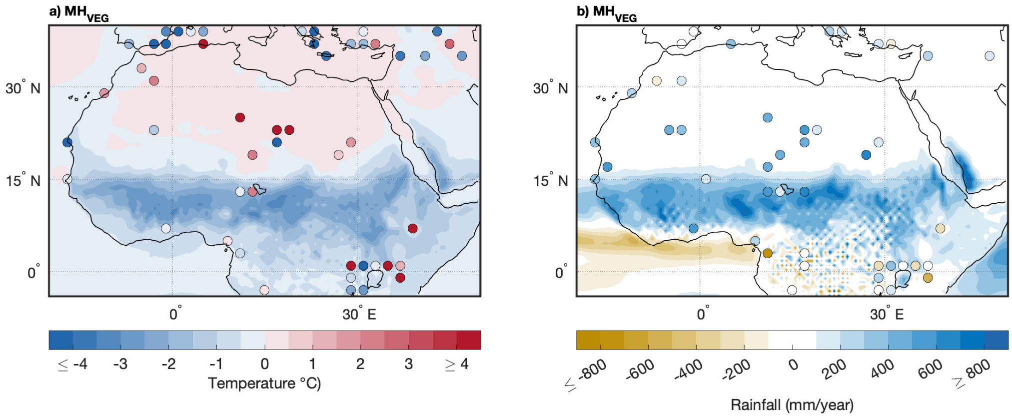


Figure 6.5. Mean annual near-surface temperature anomalies [unit: °C] and annual rainfall anomalies [unit: mm/year] for mid-Holocene simulation with dynamic vegetation (MH_{VEG} - PI), shown together with proxy-inferred temperature and rainfall anomalies (6-0k) from Bartlein et al. (2011). Figure modified from **Paper IV**.

rainfall and grassland using EC-Earth. This indicates that other feedbacks and processes, such as dust-albedo and soil feedbacks, are needed to enhance the rainfall further and strengthen the vegetation response to orbital forcing. Using prescribed mid-Holocene vegetation in model simulations implicitly includes the impact of such feedbacks through their effect on the vegetation.

7 Discussion and future perspectives

Here I discuss our analysis, and suggest future perspectives on how to further our understanding, answer the research questions posed in chapter 3 and push the scientific field forward.

Static vs. variable SST-WAM relationship in the last millennium

In **Paper II** we identify two main drivers of multidecadal rainfall variability in West Africa: an Atlantic Niño-like pattern in the Gulf of Guinea, driving a dipole rainfall pattern over West Africa, and an AMV-like pattern centered in the North Atlantic and Mediterranean Sea, driving rainfall variability centered over Sahel. While SVDs are generally sensitive to the area of analysis, additional analysis using global SSTs has supported these findings (Zhang et al., 2021b), suggesting a robust link between these two ocean variability patterns and West African rainfall. However, as the SVD analysis examines the total explained covariance over the entire time period, it does not reveal any non-static relationships between the two variables. Several studies have shown such non-stationary relationships between SSTs and WAM during the 20th Century, most notably its relationship to ENSO and the Atlantic Niño (Janicot et al., 2001; Joly and Voldoire, 2010; Srivastava et al., 2019).

Preliminary analysis using a running correlation between West African rainfall and SSTs in different ocean basins has shown centennial variability in the correlations, indicating potential non-static relationships. Future research should investigate the reasons for this variability, such as potential spatial differences within the SST-patterns or competing impacts from different ocean basins. Understanding the factors contributing to the variable relationship between ocean basins and West African rainfall will provide valuable insights, and improve our understanding of the complex interactions driving WAM variability.

Sensitivity studies for mid-Pliocene

In **Paper III** we analysed rainfall changes in West Africa in a mid-Pliocene Warm Period scenario with near-modern GHG concentrations and paleogeography. While the mid-Pliocene is often used as an analogue for future climate change, we found notable differences compared to future projections. Our results showed an overall enhancement of the summer rainfall across West Africa, contrasting with the west-east drying-wetting pattern in CMIP3 (SRES A2) and CMIP5 (RCP8.5). As future projections are uncertain (Biasutti et al., 2008; Cook, 2008; Roehrig et al., 2013), our results could suggest a potential alternative outcome under high-CO_2 scenario.

However, attributing the spatial pattern of rainfall anomalies to specific forcing and boundary conditions is challenging in the PlioMIP2 experiments, as orography, land surface and vegetation changes are prescribed together. This limits our ability to separate their individual impact on rainfall and determine how they might affect future rainfall in the region.

The late summer wetting across West Africa observed in **Paper III** is similar to the pattern seen in future scenarios for central and eastern Sahel, and is linked to surface warming in the Sahara in both scenarios (Monerie et al., 2020; Berntell et al., 2021). While vegetation is thought to be the main driver of hydroclimatological changes in West Africa during this period (Berntell et al., 2021; Feng et al., 2022), its suitability as an analogue for future change could depend on a future vegetation response to high CO_2 forcing. Additionally, the drying in western Sahel has been linked to Pacific and tropical Atlantic ocean variability (Monerie et al., 2020), suggesting that orographical changes, which have been linked to changes in SSTs in PlioMIP2 (Haywood et al., 2020), could play a role in modulating such patterns in past high CO_2 scenarios.

This uncertainty in attributing rainfall anomalies to specific forcing and boundary conditions, as well as evaluating its potential as an analogue for future projections, highlights the need for further research. A set of sensitivity experiments could be designed to address this issue. For instance, applying orographical changes without additional vegetation and land-surface changes would enable an assessment of their relative roles in driving the uniform rainfall increase over West Africa.

Multi-model comparison with coupled dynamic vegetation

While previous studies, including **Paper III** by Berntell et al. (2021), have emphasised the role of vegetation in enhancing the WAM in past warm climates, the findings in **Paper IV** suggest that orbitally-forced vegetation feedbacks alone are insufficient to strengthen the WAM to levels indicated in proxy reconstructions. In particular, the coupled vegetation model does not produce the expected northward shift of the WAM or accurately represent the Sahara region's vegetation cover. Although these results imply that additional feedback processes play a more significant role than previously thought, it is important to consider potential biases in the EC-Earth model that might affect the LPJ-Guess response.

For instance, a well-known cold bias in EC-Earth has been suggested to contribute to the under-representation of forest cover in LPJ-Guess in the Asian mid-latitudes, consequently impacting the representation of the Asian monsoon during the mid-Holocene (Chen et al., 2021). Other ESMs with dynamic vegetation have also successfully recreated an enhanced WAM for past warm climates in line with model simulations using prescribed paleo vegetation (Brierley et al., 2020; Stepanek et al., 2020). These findings indicate that experimental design and model differences could influence the observed role of the vegetation feedbacks.

In addition, a recent comparison of an offline vegetation response in LPJ-Guess revealed that it underestimates grassland in low-rainfall areas like the Sahara, requiring twice as much annual rainfall to sustain a 20% grassland cover compared to observations (Hopcroft et al., 2017). This could contribute to the weak response seen in **Paper IV** and highlight the potential model dependence in the representation of vegetation feedbacks.

To draw more robust conclusions about the strength and role of vegetation feedbacks in driving an enhanced WAM during past warm climates, future research should focus on conducting multi-model studies. Investigating the impact of experimental design and model differences on the WAM's response to vegetation feedbacks will further our understanding of their importance in past and future climate scenarios.

Develop dust-maps for the mid-Holocene

In **Paper IV**, we explored the role of dynamic vegetation in recreating a more realistic enhancement of the mid-Holocene WAM, revealing that an orbitally-forced vegetation feedback alone is insufficient to bridge the gap between model simulations and proxy data. This finding suggests that other feedback processes and mechanisms could play a crucial role in the enhancement of the WAM. One such mechanism is the reduced atmospheric dust over West Africa during the mid-Holocene linked to increased vegetation, which has been shown to significantly strengthen the WAM and shift the rainbelt northward (Pausata et al., 2016).

Previous studies have employed idealized and homogeneous reduced-dust scenarios, such as an 80% reduction of dust across West Africa, to investigate this feedback (Pausata et al., 2016; Gaetani et al., 2017; Messori et al., 2019). However, a more realistic approach could involve coupling a dynamic aerosol-chemistry module to the ESM to generate updated dust-aerosol climatologies. In the case of EC-Earth, these processes are performed by TM5, but its current version demands significant computational resources, limiting the number of model years that can be produced per day.

A potential solution to this issue could involve using an iterative process with an offline version of TM5, forced by vegetation and meteorology from mid-Holocene simulations with dynamic vegetation, and updating aerosol-chemistry climatologies within EC-Earth until equilibrium is met. This approach would enable a more accurate representation of dust feedbacks in paleoclimate simulations.

Furthermore, given that dust concentrations in the atmosphere are often of greater interest in paleo-science than atmospheric chemistry, developing simplified dust models focused on larger aerosol sizes could be a valuable alternative to the current, computationally-intensive aerosol-chemistry models. Coupling such simplified models with ESM would not only reduce computational demands but also facilitate model-data comparisons, as dust records constitute a significant portion of available proxy data in West Africa.

8 Conclusion

The main aim of this thesis was to investigate the internal and external drivers of monsoon variability in West Africa using paleoclimate modelling. The study focused on the *last millennium* for internal variability and the *mid-Pliocene Warm Period* and *mid-Holocene* for external forcing and feedback processes. Additionally, a model-data comparison for the 20th Century was conducted to evaluate the model's ability to capture low-frequency variability. The main conclusions related to each of the stated research questions are as follows:

Research Question 1:

What are the drivers of internal multidecadal rainfall variability in West Africa?

The analysis of the *last millennium* simulation identified two main drivers of multidecadal rainfall variability in West Africa. These drivers include an Atlantic Niño-like pattern centered over the Gulf of Guinea, exhibiting significant periods of variability at decadal to multidecadal scales (10-14 years and 20-40 years), and an AMV type pattern centered over the North Atlantic and Mediterranean with similar significant periods of variability (10-14 years and 20-30 years). The Atlantic Niño pattern is associated with a meridional rainfall dipole pattern, while the AMV pattern is linked to a positive rainfall signal over West Africa and the Sahara region. However, these relationships might not be static, and further study is needed to assess drivers of such variability.

Research Question 2:

How did the mid-Pliocene forcing and boundary conditions impact the West African Monsoon, and what what implications does this have for the future of rainfall in West Africa?

The analysis of the PlioMIP2 ensemble reveals a seasonal cycle of rainfall in the Sahel region with positive anomalies in the July-October months compared to Pre-Industrial simulations. This suggests a lengthening of the monsoon season when forced by 400 ppmv CO_2 and paleogeography. Spatially, the ensemble exhibits a robust rainfall increase over the entirety of West Africa, and negative rainfall anomalies over the Equatorial Atlantic and Gulf of Guinea. The ensemble indicates a strengthened WAM with near-surface warming, deepening of the sea level pressure across the Sahara region, and enhanced southwesterly flow into the Sahel. The analysis suggests that GHG, orography and vegetation changes are the main forcings. This uniform rainfall increase contrasts with the west-east drying-wetting pattern observed in CMIP3 and CMIP5 future projections, instead implying an enhanced WAM rainfall under a high CO_2 scenario. Alternatively, the results could indicate that the use of the mid-Pliocene as an analogue for future rainfall change in West Africa might depend on the long-term vegetation response to increased CO_2 forcing.

Research Question 3:

Will implementing a coupled, dynamic vegetation model to EC-Earth provide a more realistic representation of the role of vegetation feedbacks in recreating the enhanced WAM in the mid-Holocene?

Using an EC-Earth3-Veg configuration with a coupled LPJ-Guess for a mid-Holocene simulation significantly increases the WAM rainfall, with summer rainfall in the Sahel region increasing by 15% compared to a simulation run with prescribed PI vegetation cover. However, the enhanced rainfall remains below what is suggested by proxy reconstructions, and neither exhibits a northward shift of the monsoon nor recreates a vegetation cover in the Sahara region. While model limitations may contribute to this weak response, the results indicate that vegetation feedbacks, when only driven by orbital forcing, are not strong enough to induce such a shift. This finding highlights the important role of additional feedback processes in driving an enhanced, northward WAM and causing vegetation to reach the Sahara. It also suggests that forcing models with paleo-vegetation implicitly includes such feedback processes through their impact on vegetation.

In conclusion, this thesis has made contributions to our understanding of the drivers and feedbacks related to West African Monsoon variability in the context of paleoclimate modeling. The thesis has identified key drivers of internal multidecadal rainfall variability and also shed light on the potential implications of the mid-Pliocene forcing and boundary conditions for future West African rainfall. Additionally, the investigation of coupled, dynamic vegetation models has provided valuable insights into the role of vegetation feedbacks in recreating the enhanced WAM in the mid-Holocene. These findings can serve as a foundation for further research into the complex interactions between internal and external drivers, feedback processes, and model limitations in the study of monsoon variability and climate change in West Africa.

Acknowledgements

First of all, I would like to thank my supervisor Qiong Zhang for her guidance over the years. I will always be grateful for having had the opportunity to be your PhD student, and to spend these years doing something I love. In addition, I would like to thank my co-supervisor Gia Destouni for her helpful advice. I would also like to thank my mentor Frederik Schenk, for continuous support and discussions. Having had an additional paleoclimate modeller nearby has been an incredible gift. To the entire CQ-unit, I couldn't have asked for a better and more supportive group of friends and colleagues. Thank you for giving me a home at the department. I would also like to thank my colleagues in Qiong's modelling group, especially Josefine. I'm incredibly grateful that we got to move through this PhD experience together, your support and friendship has made it infinitely more enjoyable and I don't know how I would have made it through without you.

To all my fellow PhD's and post-docs, thanks for sharing in the ups and downs over the years, and for always being there to support me when I needed it. Thanks to Josefin, Benny and Anna for being such good friends and role-models, and for showing me what a future in academia could look like.

And finally, my friends and family outside of academia. Thank you for your continued support and encouragement over the years, and for making sure I was suitably distracted when needed. I couldn't have done it without you.

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