Impacts of Atlantic multi-decadal variability

on the Indo-Pacific and Northern Hemisphere climate

Lea Svendsen

Dissertation for the degree of philosophiae doctor (PhD)
at the University of Bergen

2016

Dissertation date: 03.06.2016

Year: 2016

Title: Impacts of Atlantic multi-decadal variability on the Indo-Pacific and Northern Hemisphere Climate

Author: Lea Svendsen

Print: AiT Bjerch AS / University of Bergen

Acknowledgements

First and foremost I would like to thank my supervisors Noel Keenlyside for interesting discussions and for giving me the help and support I needed, and Yongqi Gao for trusting in my abilities and pushing me to finish towards the end. They have given me both independence and guidance when I needed it.

I want to thank all my co-authors and collaborators, especially Steffen Hetzinger for introducing me to the world of corals and proxies, Prof. Joseph for giving me insight to the many intriguing aspects of the Indian monsoon, and Feifei Luo for undertaking the huge amount of CMIP5 data with me. An extra big thanks is also due to Ingo Bethke and Detelina Ivanova for the much needed and appreciated help with setting up the NorESM simulations, for their exceptional patience and for answering all of my many stupid questions. I also want to thank fellow PhD students and my colleagues at NERSC, GFI and the Bjerknes Centre community for being interested and inspiring.

Furthermore I would like to thank Annalisa Cherchi for hosting me at CMCC in Bologna during the fall of 2014, and ResClim for funding my stay and for organizing interesting courses. I also want to thank my colleagues at NERCI in India for hosting me during both my travels there and Ola M. Johannessen for giving me the opportunity to go. Thanks to Belen Rodríguez-Fonseca for her enthusiasm, and for hosting me at UCM in Madrid during the fall of 2015. I am looking forward to continuing our collaboration in the future. I want to acknowledge the EEA scholarship program for the NILS grant funding my stay at UCM, and the rest of the people at UCM, CMCC and NERCI for making my stays abroad rewarding and fun.

I also have to thank my family; my mother for supporting and reassuring me when things were especially difficult, my father with his insights to the life as a researcher and his understanding of the difficulties involved, and my brother for being enthusiastically helpful with IT issues. I would not have survived without my closest friends who have encouraged me from the very beginning. And last but not least I am truly grateful to Christoffer for his patience and understanding these last months.

This work was supported by the Research Council of Norway through the India-Clim project (no. 216554).

Abstract

Earlier studies have shown that Atlantic multi-decadal variability (AMV) can impact climate variability globally. However the instrumental records are short compared to the timescale of AMV, and mechanisms for these impacts are unresolved. This thesis deals with impacts of AMV on the Indo-Pacific region and over the Northern Hemisphere, investigating both the persistence of multi-decadal variability in the two phenomena and possible mechanisms for interactions between them. Coupled climate models are the main tools used in this study, in the form of output from the Coupled Model Intercomparison Project 5 (CMIP5) ensembles, a freshwater hosing experiment with the Bergen Climate Model (BCM), and partially coupled ensemble simulations with the Norwegian Earth System Model (NorESM). In addition proxy records are used to assess persistence in both AMV and its relation to regional variability in the Indo-Pacific.

The results of this thesis are presented in five papers. In the first paper a new marine-based multi-proxy reconstruction for AMV is produced and presented, showing persistent multi-decadal variability 90 years further back in time than the instrumental records. The second paper evaluates multi-decadal variability in several proxy reconstructions of the Indian summer monsoon (ISM) and compares it with different AMV reconstructions, including the marine-based record from the first paper. Multi-decadal variability is found in ISM reconstructions back to the 15th century, but the relation with AMV is not clear. The AMV-ISM relation is further investigated in CMIP5 simulations in the third paper. While none of the models capture the observed significant AMV-ISM relation in the pre-industrial control simulations, one model simulates the observed correlation in the 20th century historical ensemble, indicating that the observed relation could be externally forced. In the fourth paper of this thesis it is found that changes in North Atlantic SSTs due to variations in the thermohaline circulation can impact variability in the equatorial Atlantic and change the inter-basin relation between Atlantic and Pacific Niños. The fifth paper introduces a novel approach for investigating large-scale impacts in a coupled model, by separating radiative forced and dynamically driven variability. Ensembles of partially coupled 20th century historical simulations indicate that AMV may not have been a key contributor in Northern Hemisphere surface trends on decadal timescales.

Collectively these papers indicate that the AMV is a persistent signal of the climate system, but the impacts on multi-decadal variability in the Indo-Pacific and the Northern Hemisphere may not be as strong as previous studies suggest. AMV can modulate interannual variability and inter-basin teleconnections in the tropics, but the correlation with the ISM could be due to external forcing, and the Pacific seems to make a larger contribution to decadal trends in Northern Hemisphere climate than the Atlantic.

List of papers

I. Svendsen, L., S. Hetzinger, N. Keenlyside, and Y. Gao (2014), Marine-based multiproxy reconstruction of Atlantic multidecadal variability, *Geophysical Research Letters*, *41*(4), 2013GL059076.

II. Sankar, S., L. Svendsen, G. Bindu, P. V. Joseph, and O. M. Johannessen, Teleconnections between Indian summer monsoon rainfall and Atlantic multidecadal variability over the last 500 years (*manuscript in preparation)*.

III. Luo F., Y. Gao, L. Svendsen, N. Keenlyside, S. Li and T. Furevik, External forcing synchronizes Atlantic multidecadal variability and the Indian summer monsoon (*manuscript in preparation)*.

IV. Svendsen, L., N. G. Kvamstø, and N. Keenlyside (2013), Weakening AMOC connects equatorial Atlantic and Pacific interannual variability, *Climate Dynamics*, *43*(11), 2931-2941.

V. Svendsen, L., N. Keenlyside, I. Bethke, and Y. Gao, Investigating the role of the Atlantic and Pacific in the early 20th century warming trend (*manuscript in preparation*).

Contents

1. Background and Motivation

The main objective of this thesis is to investigate the role multi-decadal variability in the Atlantic has for variability in the Indo-Pacific region and over the Northern Hemisphere. In the following I will present earlier studies that have motivated and form the scientific basis for the five papers that constitute this thesis. I will start with introducing Atlantic multi-decadal variability (AMV) and the large-scale impacts that have been recognized in earlier studies. Then I will focus on the specific impacts of AMV that this thesis deals with: decadal variability of the Indian summer monsoon (ISM), decadal modulations of interannual variability in the tropics, and finally the role of AMV in Northern Hemisphere surface temperature variability on decadal timescales.

1.1 Atlantic Multi-Decadal Variability

The observed multi-decadal variability of North Atlantic sea surface temperature (SST) anomalies is referred to as AMV or the Atlantic Multi-decadal Oscillation (AMO; e.g., Enfield et al. 2001). The AMV is characterized by basin-wide North Atlantic SST anomalies that vary between cold and warm periods of 3-4 decades each. The SST anomalies associated with AMV typically have a horseshoe pattern with the largest anomalies in the tropics and the eastern subtropical North Atlantic (Figure 1). An AMV-index (black line in Figure 2) is often defined as the area-averaged annual SST anomalies in the North Atlantic from the equator to 60°N (e.g., Enfield et al. 2001; Wyatt et al. 2012).

Both the drivers of AMV and how AMV impacts other regions are still unclear and heavily debated. When first detected, it was suggested that AMV was a signal of internal variability of the ocean; however later studies have suggested several externally forced components. While AMV can be related to internal variability of the thermohaline circulation in the Atlantic and the Atlantic meridional overturning circulation (AMOC) (e.g., Delworth et al. 1993; Delworth and Mann 2000; Latif et al.

2004; Knight et al. 2005), some studies have suggested that AMV is a result of fluctuations in the atmospheric circulation, for instance by the North Atlantic Oscillation (NAO) (e.g., Eden and Jung 2001; Clement et al. 2015), or that external radiative forcing, natural, anthropogenic or a combination of the two, can modulate AMV (Otterå et al. 2010, Booth et al. 2012). But these results depend on the model and the definition of AMV (e.g., Zhang et al. 2013). Model studies are inconclusive and models vary widely both in terms of amplitude and frequency of AMV (Medhaug and Furevik 2011), while the spatial pattern is rather robust (Ting et al. 2011; Ba et al. 2014). This thesis is not a study of AMV, but rather of its impacts.

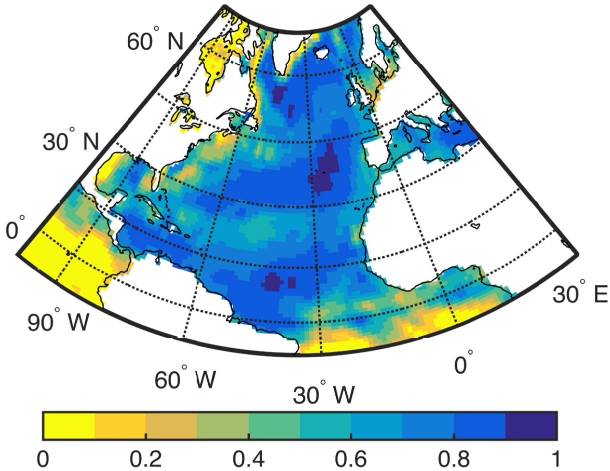

Figure 1: AMV pattern given by the correlation of low-frequency filtered SST anomalies with the AMV-index for the period 1871-2012, based on HadISST data (Rayner et al. 2003).

The short instrumental data only capture two cycles of AMV making it difficult to assess what drives AMV as well as AMV impacts. If AMV is internally driven it may be a persistent signal of the climate system and could have implications for climate prediction. Proxy reconstructions of North Atlantic climate have indicated some persistence of multi-decadal variability, although the records diverge prior to the instrumental era (e.g., Kilbourne et al. 2014). Most of these reconstructions are mainly based on land-records such as tree rings and ice cores (e.g., Gray et al. 2004; Mann et al. 2009; Knudsen et al. 2011). Land-based records assume a stable relation between SST and atmospheric temperatures, but this relation is not fully understood (e.g., D'Arrigo et al. 2008). Proxy reconstructions are important for understanding possible drivers of AMV, but it is also essential for understanding long-term teleconnections by comparing them with reconstructions from other regions. The objective of Paper I in this thesis is to investigate if there is a persistent AMV-like signal in a reconstruction using only marine proxies, a more direct measure of SST compared to land-based records.

1.2 Impacts of Multi-Decadal Variability in the Atlantic

Previous studies have suggested that AMV is important for climate variability globally (e.g., Schlesinger and Ramankutty, 1994; Delworth and Knudsen 2000; Zhang et al. 2007; Steinman et al., 2015). AMV has been linked to European and North American summer climate (e.g., Enfield et al. 2001; McCabe et al. 2004; Sutton and Hodson 2005; Sutton and Hodson 2007; Wyatt et al. 2012), Arctic sea ice cover (e.g., Kinnard et al. 2011; Miles et al. 2014), and Atlantic hurricane activity (e.g., Goldenberg et al. 2001; Knight et al. 2006; Zhang and Delworth 2006; Wang et al. 2012).

AMV has also been related to summer rainfall in African Sahel from June to August through a meridional shift of the Inter-tropical convergence zone (ITCZ); during a positive AMV the ITCZ is shifted northward enhancing precipitation over Sahel (e.g., Folland et al. 1986; Knight et al. 2006; Zhang and Delworth 2006; Mohino et al. 2010; Ting et al., 2011; Wang et al. 2012). Similarly a cold AMV has been found to enhance rainfall in North Eastern Brazil from March to May also through a shift of the ITZC (e.g., Knight 2006; Ting et al. 2011). Multi-decadal variability in the South Asian summer monsoon could also be impacted by AMV, with a positive correlation observed between SST anomalies in the North Atlantic and boreal summer rainfall over South Asia (e.g., Goswami et al. 2006; Zhang and Delworth 2006; Li et al., 2008; Ting et al. 2011). Recent studies have also suggested that multi-decadal variability in the Atlantic can modulate interannual variability and inter-basin coupling in the tropics (e.g., Chen et al. 2010; Polo et al. 2013: Kang et al. 2014; Martín-Rey et al. 2014).

So-called freshwater hosing experiments with global climate models where a large amount of freshwater is artificially added to the North Atlantic resulting in weaker AMOC and a cooler North Atlantic, have also shown that basin-wide changes in the North Atlantic can have far-reaching effects impacting for instance the mean state of the tropical Pacific, but also interannual variability such as the El Niño-Southern Oscillation (ENSO) (e.g., Timmermann et al. 2005; Zhang and Delworth 2005; Dong and Sutton 2007, Rashid et al. 2010), the Atlantic Niño (e.g., Polo et al. 2013), ISM rainfall (e.g., Lu and Dong 2008) and the relation between ENSO and the ISM (e.g., Chen et al. 2010). These studies relate to AMV impacts to the extent that a weaker AMOC results in similar SST changes as those associated with the observed AMV.

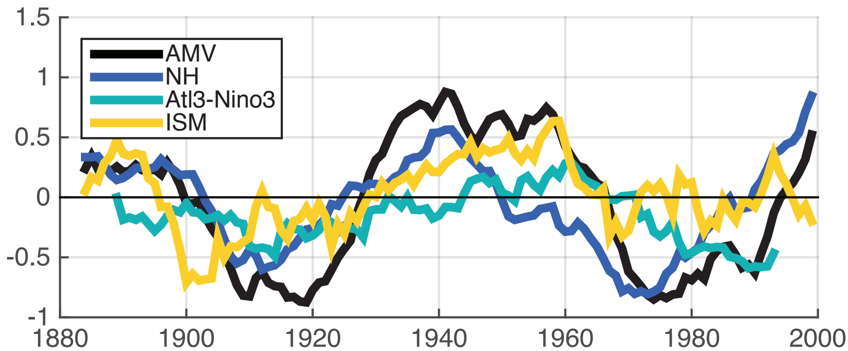

Figure 2: Observed normalized and de-trended low-frequency filtered Northern Hemisphere surface temperature (blue line) from the GISTEMP data (Hansen et al. 2010), All-India monsoon rainfall index (yellow line) from IITM (Parthasarathy et al. 1994), the AMV-index (black line), and the 21-year running correlation between Atl3-index (3°N-3°S, 20°W-0°W) and Nino3-index (5°N-5°S, 90°W-150°W) (green line) from the HadISST data (Rayner et al. 2003).

This thesis deals with the impacts of AMV especially focusing on the Indo-Pacific region. Figure 2 illustrates the three impacts that are the focus on this thesis: the relation to the ISM rainfall (yellow line), the inter-basin connection between the tropical Atlantic and Pacific (green line), and Northern Hemisphere surface temperatures (blue line). In the following I will present recent studies that motivated this work.

1.3 AMV and the Indian Summer Monsoon

A significant correlation between AMV and ISM rainfall has been observed (e.g., Goswami et al. 2006), with periods of warm (cool) North Atlantic SSTs associated with periods of more (less) ISM rainfall (yellow line in Figure 2). Whether the Atlantic is driving multi-decadal variability in the ISM is uncertain and a mechanism for the possible connection is disputed.

The ISM is the rainy season over India. During the months from June to September India receives almost 80 % of its annual rainfall (Figure 3; Tyagi et al. 2012). Based on the seasonal reversal of the wind direction between boreal winter and summer due to annual variations in the incoming solar radiation and the different heating capacity over land and ocean, the ISM can be seen as an enormous “sea breeze”. It can also be viewed as a seasonal migration of the ITCZ (e.g., Gadgil 2003; Privé and Plumb, 2007; Joseph 2014). During spring and summer South Asia warms more than the Indian Ocean, and a meridional pressure gradient in the upper troposphere between the Indian continent and the Southern Indian Ocean is established and air flows southwards in the upper troposphere. Due to mass continuity warm moist air from over the Indian Ocean flows northwards in over South Asia and the Indian Peninsula. The Coriolis force turns the cross-equatorial low-level winds over the Arabian Sea crossing the Indian peninsula from west to east (Figure 3; Tyagi et al. 2012). Simultaneously the monsoon trough over central India brings low-pressure systems inn from the Bay of Bengal (Gadgil 2003). A dryer ISM has typically a weaker monsoon circulation with a weaker Somali Jet (e.g., Findlater 1969; Joseph 2014), weaker Hadley circulation and Walker circulation (e.g., Webster et al. 1998), and cooler temperatures over the Tibetan Plateau reducing the meridional temperature gradient between the Indian Ocean and Eurasia (e.g., Goswami and Xavier 2005). These anomalies are typically reversed for a wetter ISM.

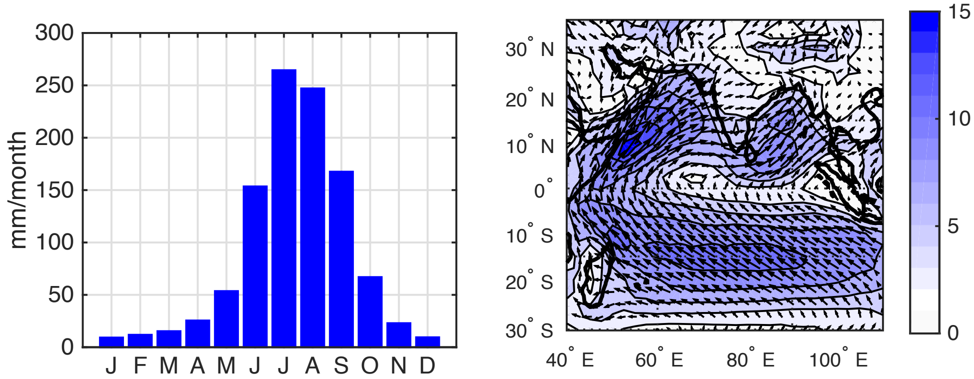

Figure 3: Seasonal cycle of monthly mean rainfall in mm over India (left panel) derived from the Climatic Research Unit (CRU) data set (provided from the NCAS British Atmospheric Data Centre; retrieved from https://climatedataguide.ucar.edu/climate-data/cru-ts321-gridded-precipitation-and-other-meteorological-variables-1901; Harris et al. 2014), and the mean surface wind pattern (right panel) during the ISM (JJAS) in m/s from NCEP/NCAR reanalysis data (provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site http://www.esrl.noaa.gov/psd), for the period 1981-2010 (Kalnay et al. 1996).

1.3.1 The AMV-ISM Link in Proxy Reconstructions

Since the instrumental records are short compared to the multi-decadal timescales of AMV, proxy reconstructions are used to assess the persistence of the AMV-ISM relation. Paleo-climate records provide evidence that low-frequency variation in SST in the Atlantic concurred with variations in the ISM, for instance there is evidence for changes in the Asian monsoon that correspond in timing to Dansgaard/Oeschger events (Burns et al., 2003) and smaller interglacial changes in the North Atlantic (Gupta et al. 2003, Feng and Hu 2008). There is also evidence of multi-decadal variability in annual resolution proxy record of regional rainfall in India (e.g., Berkelhammer et al. 2010; Borgaonkar et al. 2010).

Rainfall approximations from one region in India are not necessarily representative for the monsoon as a whole (Normand 1953). Individual proxy reconstructions include components of local variability, and therefore multi-proxy reconstructions using proxies from several different sites are preferred. For the ISM there are several proxy reconstructions, but few of them are publically available. There are a few records from India, and also a couple of marine records from both the Indian and the Pacific Ocean related to ISM rainfall (e.g., Borgaonkar et. al. 2010; Yadava et al., 2004; Sinha et al., 2007; Chakraborty et al., 2012). In addition to individual proxies, a 700-year drought atlas for the whole Asian monsoon region, the Monsoon Asia Drought Atlas (MADA), is available (Cook et al., 2010). The MADA is a seasonally resolved drought reconstruction including 534 grid points based on 327 tree ring series from Asia. However only four tree ring records are included from sites in India, and only two grid points are significantly correlated with the observed ISM rainfall (not shown).

Low-resolution proxy records indicate that the variability in the North Atlantic and the ISM could be related on longer timescales, and individual records do indicate persistence in multi-decadal variability in the ISM. A multi-proxy analysis of multi-decadal variability of the ISM is missing in the literature, in addition to a comparison with AMV reconstructions. The ISM reconstructions that are available are evaluated and compared with multi-proxy reconstructions of AMV in Paper II.

1.3.2 Dynamical Connection between AMV and the ISM

It is still unclear if the observed correlation between AMV and ISM indicates causality and how the Atlantic could then potentially influence the ISM. Goswami et al. (2006) demonstrated that the quasi 60-year oscillation of the ISM varies coherently with AMV in observations, as well as the low-pass filtered ENSO but with opposite signs. When the AMV was positive there were positive tropospheric temperature anomalies over Eurasia increasing the meridional tropospheric temperature gradient (MTG) between the Indian Ocean and Eurasia. This could delay the withdrawal of and increase the intensity of the ISM. Goswami et al. (2006) found that the AMV influenced the tropospheric temperature through the NAO acting as an atmospheric bridge. A positive summer NAO-index was associated with a similar pattern as a positive AMV, and the changes of the winds and storm tracks associated with NAO variability could be responsible for changes in the ISM (Goswami et al. 2006). Feng and Hu (2008) also found that temperatures over the Tibetan Plateau warm and the Indian Ocean cools during positive AMV phases, consistent with the strengthening of the MTG. A stronger MTG could shift the ITCZ northwards and enhance low-level winds, bringing more moisture over peninsular India, increasing ISM rainfall (Feng and Hu 2008). Similarly Wang et al. (2009) documented that during a positive AMV, northern India had warmer surface temperatures, and southern India had cooler temperatures. The boundary between these two temperature lobes moves northwards through the year, and there was a negative correlation between the AMV index and South Asian surface temperatures, as well as an increase rainfall in boreal summer (Wang et al. 2009).

Model studies both reveal possible mechanisms for an AMV-ISM connection and can indicate whether the connection is a part of natural internal climate variability or externally forced. Decadal trends in the ISM rainfall have been related to anthropogenic aerosol emissions (Bollasina et al. 2011) or solar variability (Meehl et al. 2003; Bhattacharyya and Narasimha 2005). However results from fully coupled model simulations with constant external forcing suggest that the observed correlation between AMV and the ISM can also be due to internal variability of the climate system (e.g., Msadek and Frankignoul 2009; Luo et al. 2011).

The skill in simulating decadal variability of the ISM is found to be better in atmospheric general circulations models (AGCMs) than in coupled GCMs, while interannual variability is better simulated in coupled GCMs, suggesting that ocean-atmosphere coupling is important for the interannual variability, while decadal variability is mainly an atmospheric signal or that the SST pattern is important (Kucharski et al. 2009). However studies using both atmospheric and coupled GCMs have in general found that SST anomalies in the North Atlantic associated with a positive AMV lead to an intensification of the lower level Somali Jet and the south westerly surface winds from the Indian Ocean across India due to a northward shift of the ITCZ and a strengthening at the MTG due to tropospheric heating over Eurasia

(Zhang and Delworth 2006; Li et al. 2008; Lu et al. 2006; Wang et al. 2009; Luo et al. 2011). Similar responses in the Asian summer monsoon circulation have been found for a weaker AMOC and associated negative SST anomalies in the North Atlantic (Lu and Dong 2006; Msadek and Frankignol 2009). However models are not consistent in simulating a response in the ISM rainfall, and several studies only find a significant rainfall response in boreal autumn during the ISM withdrawal phase (Lu et al. 2006; Wang et al. 2009; Luo et al. 2011). Conversely instrumental data show that the wet and dry monsoon decades are mostly related to the amount of July rainfall, the peak monsoon month, rather than the monsoon withdrawal phase (Tyagi et al. 2012).

AMV might impact the ISM through a Rossby wave train from the North Atlantic across Eurasia. North Atlantic SST anomalies can result in baroclinic instability over western Europe, and this perturbation could induce a Rossby wave across Asia. This can lead to a change in the MTG over India and enhance the South Asian high, increasing upper-level divergence and low-level convergence, in turn changing the intensity of the ISM (Li et al. 2008; Luo et al. 2011). A meridional shift of the ITCZ in the Atlantic associated with AMV can also excite a Gill-type response in the eastern Pacific changing the strength of the Walker circulation and consequently the ISM (Lu and Dong 2008; Zhang and Delworth 2005).

However studies disagree on the sign of the response in the ISM. Both Sutton and Hodson (2007) and Li et al. (2008) investigated the role of SST anomalies in the tropical and extra-tropical part of the AMV signal separately in driving ISM variability using different AGCMs with prescribed SST anomalies. Both studies found that tropical North Atlantic SST anomalies had a negative correlation with the ISM, while extra-tropical North Atlantic SST anomalies had a positive correlation with the ISM. Warm anomalies in the tropical North Atlantic inhibit convection in regions outside the tropical Atlantic and weaken the Somali Jet, suppressing rainfall over India and the Bay of Bengal (Sutton and Hodson 2007). Sutton and Hodson (2007) found the greatest response in the ISM from tropical Atlantic SST anomalies, while Li et al. (2008) simulate the greatest response from extra-tropical Atlantic SST anomalies. This resulted in an overall opposite relation between AMV and the ISM in these two studies, with the results in Sutton and Hudson (2007) also opposite of the observed AMV-ISM relation. Air-sea coupling in the tropics might therefore be important to reverse the sign of the response, especially in the Indian Ocean (Sutton and Hodson 2007; Kucharski et al. 2007).

These results emphasize the model dependency of such studies. There is also little agreement in the correlation between AMV and ISM rainfall between the models that participated in the Coupled Model Intercomparison Project Phase 3 (CMIP3), and the correlation is weak in the ensemble mean for the 20th century historical simulations (Ting et al. 2011). GCMs still have difficulties simulating the ISM. These deficiencies have been related to low resolution and the representation of orography, convective parameterizations, and biases in the mean state of the tropics (Turner et al. 2011), but ISM rainfall patterns seem to be better simulated in coupled GCMs with stronger correlations between the ISM rainfall and equatorial Pacific SSTs (Sperber et al. 2013). The weak connection between AMV and the ISM in CMIP3 may be attributed to the response in the Pacific to an AMV signal that is opposite compared to observations: in observations warm North Atlantic SSTs are associated with small negative SST anomalies in the equatorial Pacific, while in the CMIP3 ensemble the equatorial Pacific SST anomalies are positive and significant (Ting et al. 2011). The Pacific response to AMV may be important for simulating the connection with the ISM, and the ability to simulate tropical atmosphere-ocean coupling could be crucial for these teleconnections.

Goswami et al. (2006) found that decadal variability in ISM rainfall is modulated by two teleconnections patterns; first a tropical teleconnection by the low-pass filtered ENSO involving shifts of the Walker circulation influencing the regional monsoon Hadley circulation, second an extra-tropical teleconnection where AMV influenced the monsoon through changing the tropospheric temperatures over Eurasia. The regression pattern in Figure 4 shows that observed multi-decadal variability of the

ISM rainfall is significantly correlated with multi-decadal variability in both the tropical Pacific and the North Atlantic. The CMIP5 models do not seem to be able to simulate both these correlations (Figure 5). Paper III is a further investigation of the AMV-ISM relation in the latest version of the CMIP models (CMIP5; Taylor et al. 2012), the drivers for this relation, and whether the relation is internal variability or externally forced.

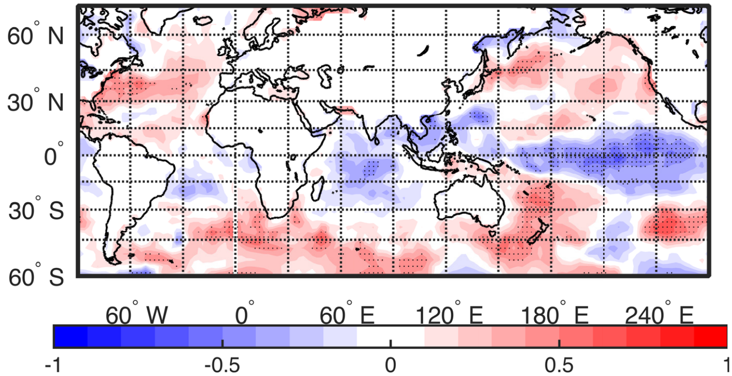

Figure 4: Regression of low-pass filtered global SSTs (HadISST) onto the ISM rainfall index (from IITM) for the period 1871-2004. Black dots indicate significant values at a 5 % level for the effective degrees of freedom.

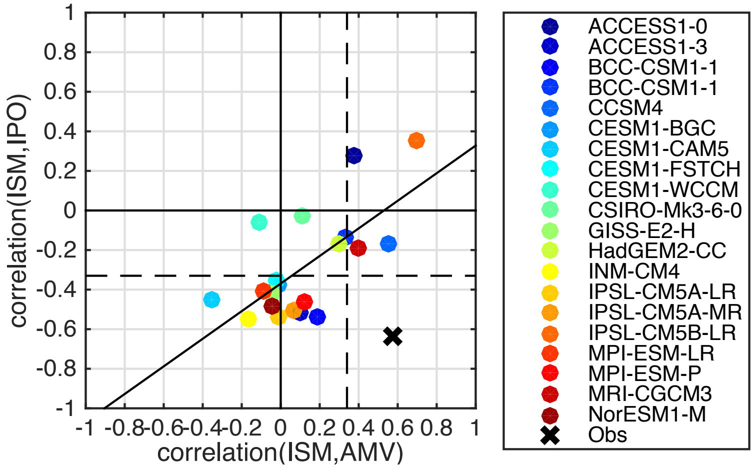

Figure 5: Scatter plot of the correlation between ISM rainfall and AMV (1.axis) and ISM rainfall and Inter-decadal Pacific Oscillation (IPO) given by SST anomalies in the equatorial Pacific (2.axis) for 20 CMIP5 models (colored dots), and instrumental data (black x). Values beyond the dashed lines are significant at a 5 % level.

AMV could also potentially modulate interannual variability of the ISM. During decades of less ISM rainfall interannual variability of the ISM and the frequency of dry years increased (Joseph et al. 2013). Historically dry and wet ISM years have been related to the Southern Oscillation and ENSO events (e.g., Walker 1924; Rasmussen and Carpenter 1983; Ju and Slingo 1995), but this relation is not linear (Webster et al. 1998, Torrence and Webster 1999), and Kumar et al. (1999) found that this relation has weakened in recent decades. The tropical Atlantic can also influence the ISM through similar mechanisms as ENSO (Kucharski et al. 2007; 2008). Decadal changes in the Atlantic could therefore potentially impact the ISM through changing tropical Atlantic variability (e.g., Polo et al. 2013), ENSO variability (e.g., Timmermann et al. 2005; Zhang and Delworth 2005; Dong and Sutton 2007) or the relation between ENSO and the ISM (Chen et al. 2010).

1.4 Interannual Variability Potentially Modulated by AMV

Enfield et al. (2001) suggested that AMV affects rainfall variability over North America associated with ENSO, modulating interannual variability in this region. Recent studies have also suggested that multi-decadal variability in the Atlantic can modulate interannual variability and inter-basin coupling in the tropics (e.g., Kang et al. 2014; Martín-Rey et al. 2014). There is also observational evidence that the relation between tropical Atlantic variability associated with an Atlantic Niño and ENSO has strengthened since the 1970s in phase with a negative AMV (e.g., Rodriguez-Fonseca et al. 2009; Martín-Rey et al. 2014), also apparent in Figure 2 (green line). These modulations could in turn impact for instance the ISM, through its relation to the tropical Atlantic (Kucharski et al. 2007; 2008) or ENSO (Walker 1924; Rasmussen and Carpenter 1983; Ju and Slingo 1995)

ENSO is a coupled atmosphere-ocean oscillation in the tropical Pacific (Bjerknes 1969, Philander 1990), and presents itself as SST anomalies in the equatorial Pacific accompanied by a change in the zonal pressure gradient across the Pacific. As the dominant mode of natural climate variability on interannual timescales, it can affect climate globally as well as being important for the ISM noted above. Similar oscillatory interannual variability also exists in the Atlantic, referred to as the Atlantic zonal mode or Atlantic Niño (e.g., Zebiak 1993). The variability here is less than in the Pacific and has a different annual cycle. While ENSO peaks in boreal winter, the Atlantic Niño peaks in summer (Figure 6).

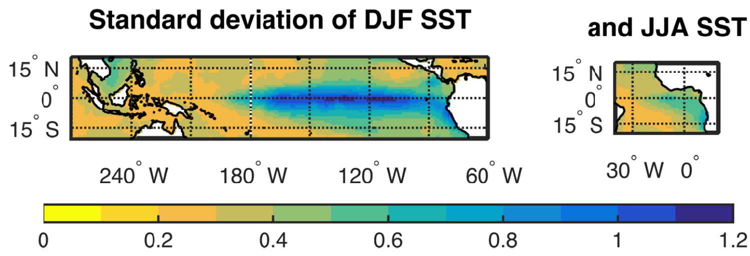

Figure 6: Standard deviation of SST (HadISST) in the tropical Pacific during boreal winter (left panel) and in the tropical Atlantic during boreal summer (right panel).

As mentioned earlier, several waterhosing experiments or similar studies prescribing SSTs in the Atlantic have found that basin-wide changes in North Atlantic can change the mean state of the tropical Pacific and ENSO variability (Dong and Sutton 2002; Timmermann et al. 2005; Zhang and Delworth 2005; Dong and Sutton 2007; Timmermann et al. 2007). A weakening AMOC induces a temperature dipole in the tropical Atlantic shifting the ITCZ southwards, and the atmospheric response changes the mean state of the tropical Pacific (Dong and Sutton 2002; Zhang and Delworth 2005; Dong and Sutton 2007; Timmermann et al. 2007). However not all models agree on if this will increase or decrease ENSO variability (Timmermann et al. 2007). SSTs in the tropical North Atlantic are also found to trigger ENSO events (Ham et al. 2013). Similarly a weakening AMOC could change the variability in the Atlantic Niño through the impact on ENSO (e.g., Polo et al. 2013).

Tropical Atlantic variability can also impact the tropical Pacific on interannual timescales, with SST variations in the tropical Atlantic impacting ENSO through atmospheric teleconnections (Dommenget et al. 2006; Jansen et al. 2009; Rodriguez-Fonseca et al. 2009; Frauen and Dommenget 2012). The correlation between SST anomalies in the central equatorial Pacific and the central equatorial Atlantic is strongest when the Atlantic is leading the Pacific by 6 months (Keenlyside and Latif 2007; Rodriguez-Fonseca et al. 2009). Warm (cold) SST anomalies in boreal summer associated with an Atlantic Niño (Niña) event can drive a shift in the Walker circulation, strengthening (weakening) the equatorial trade winds over the Pacific leading to La Niña-like (El Niño-like) SST anomalies in the Pacific through the positive Bjerknes feedback (Bjerknes 1969). These studies suggest that the variability in the Atlantic Ocean may be important for both increasing the understanding of ENSO variability and predicting ENSO (Rodriguez-Fonseca et al. 2009; Ding et al. 2012; Keenlyside et al. 2013).

Previous studies have indicated a strengthening of the relationship between Atlantic Niño events and ENSO since the 1970s (e.g., Keenlyside and Latif 2007; Rodriguez-Fonseca et al. 2009). This could be due to stochastic changes (Ding et al. 2012), or changes in the background state of the Pacific and the Atlantic (Rodriguez-Fonseca et al. 2009). Martín-Rey et al. (2014) suggests that the AMV is the modulator for the variations of the inter-basin coupling between Atlantic Niños and ENSO events, with a negative AMV strengthening the coupling. Paper IV investigates how this tropical Atlantic-Pacific coupling is influenced by multi-decadal changes in the Atlantic in a waterhosing experiment.

1.5 Global Surface Temperature Variability and the AMV

As seen in the previous sections multi-decadal variability in the North Atlantic can impact climate variability globally. Both global and Arctic temperatures in the recent 150 years have exhibited multi-decadal variability with an early 20th century warming from 1910-1940 with a following cooling period before a second pronounced warming period from the late 1970s (the blue line in Figure 2 illustrates this variability in the Northern Hemisphere). Global and Arctic multi-decadal temperature variability has been related to variability in the Atlantic (e.g., Schlesinger and Ramankutty 1994; Delworth and Mann 2000; Zhang et al. 2007; Steinman et al.

2015), however the Pacific has also been suggested as a driver (e.g., Keenlyside and Ba 2010; Koseka and Xie 2013; Meehl et al. 2013; Dai et al. 2015), as well as anthropogenic or natural external forcing (e.g., Tett et al. 1999; Stott et al. 2000; Tett et al. 2002; Broccoli et al. 2003; Hegerl et al. 2003, Meehl et al. 2004).

For instance volcanic aerosols could lead to a cooling, and the early 20th century warming period has been in part attributed to low volcanic activity. In addition there is evidence that there was an increase of solar insolation during this period. Atmospheric greenhouse gas concentrations have increased, intensifying since the 1970s consistent with the later warming period. All these external factors could have played a role in global surface temperature variability (Tett et al. 1999; Stott et al. 2000; Broccoli et al. 2003; Hegerl et al. 2003, Meehl et al. 2004). Yet global coupled climate models are often not able to simulate the observed phasing of the temperature variability even when the models include external forcing, suggesting that low-frequency variability in the ocean, for instance AMV or the Pacific Decadal Oscillation (PDO; e.g., Mantua and Hare 2002), could be important.

A related topic is the slowdown of the global warming trend in the last decade since the end of the 1990s, and also here there is an ongoing debate whether this is externally forced or due to internal variability. Several studies have suggested a cooling of the Pacific as the cause for this Hiatus (Salomon et al. 2010; Koseka and Xie 2013; Meehl et al. 2013; Trenberth and Fusallo 2013; Fyfe and Gillett 2014; England et al. 2014). Conversely Chen and Tung (2014) suggested the importance of the Atlantic with the heat content of the deeper layers of the Atlantic increasing in the recent decade. However what drives low-frequency variability in the Atlantic and Pacific Ocean is not clear, and some studies have for instance concluded that external forcing can modulate the AMV (Otterå et al. 2010; Booth et al. 2012), indicating the possibility that external forcing could be driving both AMV and global surface temperatures. The role of AMV in multi-decadal global surface temperature variability is the topic of Paper V.

2. Open Questions and Main Objectives

The main objective of this thesis is to investigate impacts of multi-decadal variability in the Atlantic on global variability, and especially on variability in the Indo-Pacific region. The previous chapter showed that multi-decadal variability in the North Atlantic could impact global temperatures and regional climate variability, such as in the tropical Pacific and Atlantic and the ISM, but several open questions remain on this topic.

Answering these questions will increase our knowledge of large-scale climate interaction that can be important for understanding regional climate variability, as well as indentify weaknesses and possible areas of improvement in coupled GCMs, improving the potential for skillful decadal climate predictions and reducing uncertainties in regional climate change projections. Analysis of both proxy reconstructions and GCMs can help us address these questions by recognizing possible links in the climate system and decompose internal variability and externally forced changes.

This thesis focuses on the following underlying research questions:

1. How did North Atlantic SSTs vary on multi-decadal timescales prior to the instrumental records?
2. How is AMV connected to the ISM on multi-decadal timescales?
3. How do multi-decadal changes in the North Atlantic impact inter-basin couplings in the tropics?
4. What part does the North Atlantic play in multi-decadal variability of Northern Hemisphere surface temperatures?

3. Summary of Results

All papers in this thesis relate to the main topic of multi-decadal variability in the North Atlantic, with focus on the impacts on decadal timescales. Paper I deals with the first research question, reconstructing a new multi-proxy marine-based AMV-index to investigate the persistence before the instrumental period. Paper II and III are concerned with research question 2, investigating the relation between AMV and the ISM, in proxy records in paper II and in CMIP5 models in paper III. Paper IV contributes to the topic of research question 3 on how the decadal changes in the AMOC and associated mean state changes in the North Atlantic can modulate inter-basin teleconnections in the tropics. Paper V considers research question 4 suggesting that perhaps the AMV is not the main driver in multi-decadal variability in Northern Hemisphere temperatures, especially for the early 20th century warming. The five papers that constitute this thesis are summarized below, highlighting the key findings.

Paper I: Marine-based multi-proxy reconstruction of Atlantic multidecadal variability, Svendsen, L., S. Hetzinger, N. Keenlyside, and Y. Gao (2014), *Geophysical Research Letters*, *41*(4), 2013GL059076.

The motivation for Paper I was that there are several AMV reconstructions that are heavily used in the scientific literature, both when comparing with other reconstructions and to validate model simulations. These few reconstructions are mostly composed of land-based records, which depend on a stable relation between North Atlantic SST and atmospheric temperatures over surrounding landmasses, which might not be the case. In Paper I a new AMV-reconstruction is made using only marine-based proxies. We find that by combining several coral records with annual resolution from the tropical Atlantic using principle component analysis, we are able to capture the observed multi-decadal variability. This variability also persists throughout the multi-proxy reconstruction back to year 1781 suggesting that AMV is persistent, but differs slightly in the timing from other widely used AMV-reconstructions. The results motivate the use of more marine-based proxies for such reconstructions.

Key findings:

- Multi-decadal variability is found as a common component of variability in coral records from the tropical Atlantic
- AMV is persistent at least back to year 1781.

Paper II: Teleconnections between Indian summer monsoon rainfall and Atlantic multidecadal variability over the last 500 years, Sankar, S., L. Svendsen, G. Bindu, P. V. Joseph, and O. M. Johannessen (*manuscript in preparation*).

Although AMV and the ISM have been linked together in observations, it is not clear if this link is persistent. Paper II evaluates and compares decadal variability in several ISM proxy reconstructions with annual resolution. Although published, some of these records are not publically available and therefore have never been compared before. In addition these ISM reconstructions are for the first time compared with several AMV reconstructions, including the marine-based AMV reconstruction presented in Paper I. Although the analysis shows persistent variations of dry and wet ISM decades before the instrumental record begins, the correlation with AMV, that is significant in the instrumental period, is not clear. The available data for both the Atlantic and the ISM are scarce and have discrepancies, and one of the main conclusions of this study is that more high quality data needs to be available, as well as highlighting the importance of using several proxy records for such comparisons. However, the correlation in the observed records has also weakened in the recent decades suggesting that the observed AMV-ISM link might not be stable.

Key findings:

- Multi-decadal variability in the ISM related to the frequency of drought years is persistent in proxy reconstructions back to the 15th century
- The observed correlation between AMV and ISM rainfall is not stable weakening in the recent decades, and possibly before the 19th century as well.

Paper III: External forcing synchronizes Atlantic multidecadal variability and the Indian summer monsoon, Luo F., Y. Gao, L. Svendsen, N. Keenlyside, S. Li and T. Furevik (*manuscript in preparation*).

Paper III investigates if the CMIP5 models are able to simulate the observed relation between AMV and multi-decadal variability of the ISM, and if this link is internal climate variability or externally forced. After an evaluation of both AMV and ISM in 25 CMIP5 models and selecting the top five of these for further analysis, it is found that only one of these models (GFDL-CM3) simulates the observed AMV-ISM correlation in the historical 20th century simulations as observed. None of the models we evaluated had the observed correlation in the pre-industrial control simulation, indicating that if the connection is internal climate variability, the models are not able to simulate this. An evaluation of the GFDL-CM3 model showed that the observed relation could be externally forced by modulating both AMV and the ISM through a response in upper tropospheric temperatures in the subtropics.

Key findings:

- The observed AMV-ISM link is not a robust feature in CMIP5 models
- The observed correlation between AMV and the ISM could be due to a response in both the ISM and North Atlantic SSTs to external forcing

Paper IV: Weakening AMOC connects equatorial Atlantic and Pacific interannual variability, Svendsen, L., N. G. Kvamstø, and N. Keenlyside (2013), *Climate Dynamics*, *43*(11), 2931-2941.

Several so-called waterhosing experiments where freshwater is artificially added to the North Atlantic have shown a reduction in the AMOC cooling the North Atlantic, as well as significant changes in the mean state of the Pacific and ENSO variability. Paper IV investigates a similar waterhosing experiment with the Bergen Climate Model, and shows that a more moderate weakening of the AMOC does not significantly change the mean state of the tropical Pacific, but increases equatorial Atlantic SST variability and strengthens the connection between the equatorial

Atlantic and Pacific, increasing the ENSO frequency. The strengthening of the Atlantic–Pacific relation when the Atlantic is colder than normal is consistent with observed records where this relation has varied in phase with the AMV. However the reason for the shift in the ENSO frequency is still uncertain. Although not mentioned specifically in the paper, we also see a significant increase in the interannual connection between tropical Atlantic summer SSTs and Indian summer monsoon rainfall (see Figure 8 a and b in Paper IV) when the Atlantic is colder than normal, with warm anomalies in the equatorial Atlantic associated with less ISM rainfall.

Key findings:

- A weakening AMOC can increase variability in the tropical Atlantic
- AMOC variability can modulate the inter-basin connection between Atlantic Niño and Pacific ENSO-events

Paper V: Investigating the role of the Atlantic and Pacific in the early 20th century warming, Svendsen, L., N. Keenlyside, I. Bethke, and Y. Gao (*manuscript in preparation*).

There is an ongoing discussion about the relative contribution of natural and anthropogenic external forcing and internal climate variability on decadal global temperature variability. Paper V investigates the portion of Northern Hemisphere surface temperature variability that is not directly driven by radiative forcing, to see if multi-decadal variability in the Atlantic is a key driver in this signal. Four six-member ensembles of partially coupled experiments were performed with the Norwegian Earth System Model (NorESM), with prescribed momentum flux anomalies from reanalysis data to the global ocean, to the Atlantic or to the Indo-Pacific. By prescribing momentum flux, SST variability is constrained to the observed in the respective regions, while the model is still thermodynamically coupled. Since all the simulations include transient 20th century historical forcing, these experiments represent a new approach for separating radiative forced and dynamically driven variations. We find that external forcing accounts for about half of the early 20th century warming in the Northern Hemisphere and for the Arctic specifically, and dynamically driven variability accounts for the other half. Decadal variability in the Pacific is well simulated, while the amplitude of the simulated AMV is too small and the periodicity is shorter than observed. Even though multi-decadal variability in the Atlantic is not well simulated we still manage to simulate the early 20th century warming in the Northern Hemisphere due to the phasing of decadal variability in the Pacific. We conclude that the phasing of AMV may not be a key contributor to the early 20th century warming.

Key findings:

- PDO can impact Northern Hemisphere and Arctic surface temperature variability on decadal timescales, especially contributing to the early 20th century warming
- AMV is not central to the early 20th century warming in the Northern Hemisphere.

3.1 Main Conclusion

The results from the five papers in this thesis lead to the following conclusions. Multi-decadal variability in the Atlantic seems to persist before the short instrumental record. This variability can impact the Indo-Pacific region, by for instance strengthening the ISM or the inter-basin Atlantic-Pacific Niño relation. However while there seems to be a connection between the ISM and AMV in observations, this connection is neither clear in the proxy records before the 19th century, nor reproducible in state-of-the-art coupled GCMs. However one model can capture the observed correlation in the 20th century historical simulations as a response to external forcing, indicating that other models might be less sensitive to the prescribed external forcing. On a larger scale the AMV also seems less important for driving the early 20th century warming in the Northern Hemisphere and Arctic surface temperatures; our results suggest a dominating role of the Pacific. In short, the persistent AMV can potentially modulate interannual to multi-decadal variability and inter-basin teleconnections in the tropics, but the AMV plays a minor role in both decadal trends in Northern Hemisphere temperatures and the ISM, with the multi-decadal variability in the ISM possibly driven by external forcing.

4. Discussion and Future Perspectives

This thesis synthesizes studies on how AMV impacts the Indo-Pacific and Northern Hemisphere on interannual to multi-decadal timescales. The approach here is based on the hypothesis that multi-decadal variability in the Atlantic can be a key driver of such variability. However there are still great uncertainties and limitations related to this topic, due to for instance biases in coupled GCMs and their range in climate sensitivity and level of internal variability, as well as limited data coverage on these timescales. This thesis has aimed to deal with some of these limitations, by investigating simulations of these interactions in state-of-the-art coupled GCMs and extending the data coverage using proxy reconstructions. The results of this thesis do not fully answer the questions proposed in Chapter 2, but contribute to the knowledge on these topics. This thesis also motivates further research and some of these ideas are presented in the following.

The new marine-based AMV reconstruction presented in Paper I suggests that AMV has persisted prior to the instrumental record. However this new reconstruction is still only 90 years longer than the instrumental records, and a longer multi-proxy reconstruction is preferred. Longer records from the Atlantic are available, but these have lower resolution. These lower resolution records, preferably covering a larger area of the Atlantic, could be combined using a similar method as in Paper I to assess multi-decadal variability even further back in time.

A similar method of combining marine records can be used to assess variability in other regions as well. These multi-proxy reconstructions from different regions can then be compared to determine common variability and to investigate if observed teleconnections hold prior to instrumental records. The method could also be used for land-based records over India to estimate variability in the ISM rainfall. Historical ship records of wind direction and speed from the Atlantic have been used to reconstruct the West African monsoon back to year 1790 (Gallego et al. 2015), and similarly ship records from the Indian Ocean could be used for ISM circulation reconstructions. Paper II highlights the fact that very few records from the ISM region are available, and Paper II is therefore only a comparison or these records. More records from India and the Indian Ocean are needed for the method used in Paper I to be useful to reconstruct large-scale features of the South Asian monsoon.

Instrumental records and several model studies have linked AMV to the ISM. Multi-decadal variability in the North Atlantic seems persistent, but it is not clear if the observed link to the ISM is also persistent. The comparison of ISM and AMV proxy reconstructions presented in Paper II showed that even though records from both regions exhibit multi-decadal variability, they may not always be in phase. However, based on the records that are presently available the persistence of the observed AMV-ISM link is still unclear, and deserves further investigation as well as better quality data.

Furthermore most of the state-of-the-art coupled models are not able to simulate the observed relation between AMV and the ISM, and Paper III found that only one model could simulate this in the 20th century all-forcing ensemble. The analysis of the CMIP5 models in Paper III presents only a first step in the analysis. Further analysis has to be done to understand why most CMIP5 models cannot simulate this relation. Preliminary results on this topic show that the simulation of variability in the Pacific or aerosol indirect effects might be important. A new CMIP will also be available in the near future and it will be interesting to see if this new suite of models performs differently.

The results from Paper III indicate that external forcing can modulate multi-decadal variability in both Atlantic SSTs and the ISM rainfall, in phase with global surface temperatures, giving us the observed correlation between the two regions. Several earlier studies have found that external forcing is important for modulating multi-decadal variability in global surface temperatures and AMV, as well as driving decadal trends in the ISM. For instance aerosol forcing specifically have been related to both AMV (Booth et al. 2011) and trends in the ISM since the 1950s (Bollasina et al. 2012). External forcing is also found to be one of the main drivers in Northern Hemisphere surface temperatures on decadal timescales in Paper V, but dynamically driven variability in the Pacific seems equally important. Multi-decadal variability in both the ISM and AMV in the GFDL-CM3 model analyzed in Paper III are also related to SSTs in the North Pacific. However since GFDL-CM3 is the only model that captures the observed AMV-ISM relation of those analyzed in Paper III and since the simulated ISM is not significantly correlated with the observed even though it is correlated with AMV, this model might be too sensitive to external forcing. Whether multi-decadal variability in Atlantic SSTs and ISM rainfall is due to external forcing or internal climate variability is still unclear as results are model dependent.

Paper V introduced a novel approach to disentangle these factors by separating radiative forced and dynamically driven variability. Earlier studies have shown that both the AMV and variability in the Pacific can be important for driving decadal global temperature variations. Paper V concludes that by only driving the Pacific we can simulate the early 20^{th} century warming in the Northern Hemisphere and especially in the Arctic, and the observed AMV is not crucial for these global variations. We used the 20CR to perform these experiments, and similar ensembles with other long reanalysis products (e.g., ERA-20C) could be performed to assess the uncertainties related to the prescribed wind stress. The ensembles could also be extended to present so that they can be used to investigate the recent hiatus period as well. In addition the same experimental setup can be used to force smaller regions. The setup has shown to be able to simulate the observed ENSO events, and by only prescribing momentum flux anomalies in the tropical Pacific, these experiments can be used to assess ENSO teleconnection patterns and impacts.

While the phasing of PDO is well simulated in the experiments used in Paper V, the AMV is not constrained to observations after the 1950s. Efforts should be made to improve the experimental design for simulating the AMV, for instance by prescribing heat flux anomalies in this region. These experiments could then also be used to assess AMV teleconnections to for instance the ISM, and impacts on the inter-basin relation between the tropical Atlantic and Pacific. Recent studies have shown that while AMV and the ISM are significantly correlated in observations, there are regional differences with rainfall in some regions in India relating more to AMV, while other regions are perhaps more related to PDO or the Indian Ocean (e.g., Joshi and Rai 2014). This could also potentially be assessed using the same experimental design.

Several studies from the last decade have found that changes in the mean state of the Atlantic, such as those induced by a weaker AMOC or a negative AMV, can lead to a change in the mean state of the Pacific and a change in ENSO variability and amplitude. Polo et al. (2013) also found that the increased variability in the Pacific feeds back onto the tropical Atlantic increasing variability here. Paper IV, in contrast, shows that a weakening AMOC can increase the interannual variability in the tropical Atlantic, strengthen the inter-basin connection between the tropical Atlantic and Pacific, increasing the ENSO frequency, while the mean state of the Pacific exhibits no significant change. In addition to the more modest AMOC change compared to similar studies, the model used in Paper IV is flux-adjusted with a well-defined Atlantic cold tongue, which can strengthen the skill in tropical teleconnections on interannual timescales (Turner et al. 2005). However decadal variability in running correlations are innate statistical features of two random time series with interannual variability (Gershunov et al. 2001), and decadal changes in ENSO frequency can also be driven solely by internal variability (Wittenberg et al. 2009; 2014). The results in Paper IV are from one realization of one model, although to some extent consistent with observations (Martín-Rey et al. 2014), should be tested with similar experiments with other models, or in an ensemble with the same model (but technically difficult as the model is no longer in use).

Results in this thesis showed that AMV could be persistent, alluding to predictability (e.g., Keenlyside et al. 2008; Meehl et al. 2009; 2014). However the proxy reconstruction and CMIP5 analysis showed that even though both Atlantic SSTs and ISM have persistent multi-decadal variability, their relation is not stable. The CMIP5 analysis further showed that external forcing, including volcanic eruptions, might be the reason for their apparent relation, abating the possibility for prediction of the ISM on multi-decadal timescales. To complicate the picture further AMV can also modulate interannual variability in the tropics, and while coupled GCMs are able to simulate ENSO to some degree the tropical Atlantic has larger biases, inhibiting the ability to simulate Atlantic Niños (Richter and Xie 2008) and consequently the relation between Atlantic and Pacific Niños. Since decadal variability in the ISM is a modulation of interannual variability, it is not surprising that coupled GCMs have difficulties simulating this. However state-of-the-art coupled models do simulate a variety of AMV amplitudes and frequencies, and the simulated teleconnection patterns might depend on biases in the North Atlantic as well (Wang et al. 2014). Understanding these issues could ultimately lead to skillful decadal predictions of regional climate variability in the Indo-Pacific and over the Northern Hemisphere.

References

Ba, J., N. Keenlyside, M. Latif, W. Park, H. Ding, K. Lohmann, J. Mignot, M. Menary, O. Otterå, B. Wouters, D. Salas y Melia, A. Oka, A. Bellucci and E. Volodin (2014), A multi-model comparison of Atlantic multidecadal variability, *Climate Dynamics*, *43*(9-10), 2333-2348.

Berkelhammer, M., A. Sinha, M. Mudelsee, H. Cheng, R. L. Edwards, and K. Cannariato (2010), Persistent multidecadal power of the Indian Summer Monsoon, *Earth and Planetary Science Letters*, *290*(1-2), 166-172.

Bhattacharyya, S., and R. Narasimha (2005), Possible association between Indian monsoon rainfall and solar activity, *Geophysical Research Letters*, *32*(L05813).

Bjerknes J. (1969), Atmospheric teleconnections from equatorial Pacific, *Monthly Weather Review 97*(3), 163–172.

Bollasina, M. A., Y. Ming, and V. Ramaswamy (2011), Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon, *Science*, *334*(6055), 502-505.

Booth, B. B. B., N. J. Dunstone, P. R. Halloran, T. Andrews, and N. Bellouin (2012), Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability, *Nature*, *484*(7393), 228-232.

Borgaonkar, H. P., A. B. Sikder, S. Ram, and G. B. Pant (2010), El Niño and related monsoon drought signals in 523-year-long ring width records of teak (Tectona grandis L.F.) trees from south India, *Palaeogeography, Palaeoclimatology, Palaeoecology*, *285*(1-2), 74-84.

Broccoli, A. J., K. W. Dixon, T. L. Delworth, T. R. Knutson, and R. J. Stouffer (2003), Twentieth-century temperature and precipitation trends in ensemble climate simulations including natural and anthropogenic forcing*, Journal of Geophysical Research, 108*(D24), 4798.

Burns, S. J., Fleitmann, D., Matter, A., Kramers, J. and Al-Subbary, A. A. (2003), Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13, *Science 301*(5638), 1365-1367.

Chakraborty, S., B. N. Goswami, and K. Dutta (2012), Pacific coral oxygen isotope and the tropospheric temperature gradient over the Asian monsoon region: a tool to reconstruct past Indian summer monsoon rainfall, *Journal of Quaternary Science*, *27*(3), 269-278.

Chen, W., B. W. Dong, and R. Y. Lu (2010), Impact of the Atlantic Ocean on the multidecadal fluctuation of El Nino-Southern Oscillation-South Asian monsoon relationship in a coupled general circulation model, *Journal of Geophysical Research-Atmospheres*, *115*.

Chen, X., and K.-K. Tung (2014), Varying planetary heat sink led to global-warming slowdown and acceleration, *Science*, *345*(6199), 897-903.

Clement, A., K. Bellomo, L. N. Murphy, M. A. Cane, T. Mauritsen, G. Rädel, and B. Stevens (2015), The Atlantic Multidecadal Oscillation without a role for ocean circulation, *Science*, *350*(6258), 320-324.

Cook, E. R., K. J. Anchukaitis, B. M. Buckley, R. D. D'Arrigo, G. C. Jacoby and W. E. Wright (2010), Asian Monsoon Failure and Megadrought During the Last Millennium, *Science, 328*(5977), 486-489.

Dai, A., J. C. Fyfe, S.-P. Xie, and X. Dai (2015), Decadal modulation of global surface temperature by internal climate variability, *Nature Climate Change*, *5*(6), 555-559.

D'Arrigo, R., R. Wilson, B. Liepert, and P. Cherubini (2008), On the 'Divergence Problem' in Northern Forests: A review of the tree-ring evidence and possible causes, *Global and Planetary Change*, *60*(3-4), 289-305.

Delworth, T. L., and T. R. Knutson (2000), Simulation of Early 20th Century Global Warming, *Science*, *287*(5461), 2246-2250.

Delworth, T., S. Manabe, and R. J. Stouffer (1993), Interdecadal Variations of the Thermohaline Circulation in a Coupled Ocean-Atmosphere Model, *Journal of Climate*, *6*(11), 1993-2011.

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Climate Dynamics*, *16*(9), 661-676.

Ding H, N.S. Keenlyside amd M. Latif (2012), Impact of the equatorial Atlantic on the El Niño Southern Oscillation. *Climate Dynamics, 38*,1965-1972

Dommenget, D., V. Semenov, and M. Latif (2006), Impacts of the tropical Indian and Atlantic Oceans on ENSO, *Geophysical Research Letters*, *33*(11).

Dong, B.-W., and R. T. Sutton (2002), Adjustment of the coupled ocean–atmosphere system to a sudden change in the Thermohaline Circulation, *Geophysical Research Letters*, *29*(15).

Dong, B., and R. T. Sutton (2007), Enhancement of ENSO Variability by a Weakened Atlantic Thermohaline Circulation in a Coupled GCM, *Journal of Climate*, *20*(19), 4920-4939.

Eden, C., and T. Jung (2001), North Atlantic Interdecadal Variability: Oceanic Response to the North Atlantic Oscillation (1865–1997), *Journal of Climate*, *14*(5), 676-691.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US, *Geophysical Research Letters*, *28*(10), 2077-2080.

England, M. H., S. McGregor, P. Spence, G. A. Meehl, A. Timmermann, W. Cai, A. S. Gupta, M. J. McPhaden, A. Purich, and A. Santoso (2014), Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus, *Nature Climate Change*, *4*(3), 222-227.

Feng, S. and Q. Hu (2008), How the North Atlantic Multidecadal Oscillation may have influenced the Indian summer monsoon during the past two millennia, *Geophysical Research Letters*, *35*(1).

Findlater, J. (1969), A major low-level air current near the Indian Ocean during the northern summer, *Quarterly Journal of the Royal Meteorological Society*, *95*(404), 362-380.

Folland, C. K., T. N. Palmer, and D. E. Parker (1986), Sahel rainfall and worldwide sea temperatures, 1901-85, *Nature*, *320*(6063), 602-607.

Frauen, C., and D. Dommenget (2012), Influences of the tropical Indian and Atlantic Oceans on the predictability of ENSO, *Geophysical Research Letters*, *39*(2).

Fyfe, J. C., and N. P. Gillett (2014), Recent observed and simulated warming, *Nature Climate Change*, *4*(3), 150-151.

Gadgil, S. (2003), The Indian monsoon and its variability, *Annual Review of Earth and Planetary Sciences*, *31*(1), 429-467.

Gallego, D., P. Ordóñez, P. Ribera, C. Peña-Ortiz, and R. García-Herrera (2015), An instrumental index of the West African Monsoon back to the nineteenth century, *Quarterly Journal of the Royal Meteorological Society*, *141*(693), 3166-3176.

Gershunov, A., N. Schneider, and T. Barnett (2001), Low-Frequency Modulation of the ENSO–Indian Monsoon Rainfall Relationship: Signal or Noise?, *Journal of Climate*, *14*(11), 2486-2492.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nunez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science*, *293*(5529), 474-479.

Goswami, B. N., M. S. Madhusoodanan, C. P. Neema and D. Sengupta (2006), A physical mechanism for North Atlantic SST influence on the Indian summer monsoon, *Geophysical Research Letters 33*(2).

Goswami, B. N. and P. K. Xavier (2005), ENSO control on the south Asian monsoon through the length of the rainy season, *Geophysical Research Letters, 32*(18).

Gray, S. T., L. J. Graumlich, J. L. Betancourt and G. T. Pederson (2004), A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD, *Geophysical Research Letters, 31*(12).

Gupta, A. K., D. M. Anderson, and J. T. Overpeck (2003), Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, *Nature*, *421*(6921), 354-357.

Ham, Y.-G., J.-S. Kug, J.-Y. Park, and F.-F. Jin (2013), Sea surface temperature in the north tropical Atlantic as a trigger for El Nino/Southern Oscillation events, *Nature Geoscience*, *6*(2), 112-116.

Hansen, J., R. Ruedy, M. Sato, and K. Lo (2010), Global surface temperature change, *Reviews of Geophysics*, *48*(4).

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister (2014), Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, *International Journal of Climatology*, *34*(3), 623-642.

Hegerl, G. C., T. J. Crowley, S. K. Baum, K.-Y. Kim, and W. T. Hyde (2003), Detection of volcanic, solar and greenhouse gas signals in paleo-reconstructions of Northern Hemispheric temperature, *Geophysical Research Letters, 30*(5).

Jansen M. F., D. Dommenget, and N. Keenlyside (2009) Tropical atmosphere-ocean interactions in a conceptual framework, *Journal of Climate, 22*(3), 550–567

Joseph, P. V. (2014), Role of Ocean in the Variability of Indian Summer Monsoon Rainfall, *Surveys in Geophysics*, *35*(3), 723-738.

Joseph, P.V., B. Gokulapalan, A. Nair, and S.S. Wilson (2013), Variability of Summer Monsoon Rainfall in India on Inter-Annual and Decadal Time Scales, *Atmospheric And Oceanic Science Letters, 6*(5), 398-403.

Joshi, M. K., and A. Rai (2014), Combined interplay of the Atlantic multidecadal oscillation and the interdecadal Pacific oscillation on rainfall and its extremes over Indian subcontinent, *Climate Dynamics*, *44*(11), 3339-3359.

Ju, J., and J. Slingo (1995), The Asian summer monsoon and ENSO, *Quarterly Journal of the Royal Meteorological Society*, *121*(525), 1133-1168.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne and D. Joseph (1996), The NCEP/NCAR 40-Year Reanalysis Project, *Bulletin of the American Meteorological Society*, *77*(3), 437-471.

Kang, I.-S., H.-h. No, and F. Kucharski (2014), ENSO Amplitude Modulation Associated with the Mean SST Changes in the Tropical Central Pacific Induced by Atlantic Multidecadal Oscillation, *Journal of Climate*, *27*(20), 7911-7920.

Keenlyside, N. S., and J. Ba (2010), Prospects for decadal climate prediction, *Wiley Interdisciplinary Reviews: Climate Change*, *1*(5), 627-635.

Keenlyside, N. S., H. Ding, and M. Latif (2013), Potential of equatorial Atlantic variability to enhance El Niño prediction, *Geophysical Research Letters*, *40*(10), 2278-2283.

Keenlyside N., and M. Latif (2007), Understanding equatorial Atlantic interannual variability, *Journal of Climate 20*(1), 131–142.

Keenlyside, N. S., M. Latif, J. Jungclaus, L. Kornblueh, and E. Roeckner (2008), Advancing decadal-scale climate prediction in the North Atlantic sector, *Nature*, *453*(7191), 84-88.

Kilbourne, K. H., M. A. Alexander, and J. A. Nye (2014), A low latitude paleoclimate perspective on Atlantic multidecadal variability, *Journal of Marine Systems*, *133*, 4-13.

Kinnard, C., C. M. Zdanowicz, D. A. Fisher, E. Isaksson, A. Vernad, and L. G. Thompson (2011), Reconstructed changes in Arctic sea ice over the past 1,450 years, *Nature*, *479*, 509–512.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophysical Research Letters, 32,* L20708.

Knight, J. R., C. K. Folland, and A. A. Scaife (2006), Climate impacts of the Atlantic Multidecadal Oscillation, *Geophysical Research Letters*, *33*(17).

Knudsen, M. F., M. S. Seidenkrantz, B. H. Jacobsen, and A. Kuijpers (2011), Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years, *Nature Communications*, *2*.

Kosaka, Y., and S.-P. Xie (2013), Recent global-warming hiatus tied to equatorial Pacific surface cooling, *Nature*, *501*(7467), 403-407.

Kucharski, F., A. Bracco, J. H. Yoo and F. Molteni (2007), Low-frequency variability of the Indian monsoon-ENSO relationship and the tropical Atlantic: The "Weakening" of the 1980s and 1990s. *Journal of Climate* 20(16): 4255-4266.

Kucharski, F., A. Bracco, J. H. Yoo and F. Molteni (2008), Atlantic forced component of the Indian monsoon interannual variability, Geophysical Research Letters 35(4).

Kucharski, F., A. A. Scaife, J. H. Yoo, C. K. Folland, J. Kinter, J. Knight, D. Fereday, A. M. Fischer, E. K. Jin, J. Kroger, N. C. Lau, T. Nakaegawa, M. J. Nath, P. Pegion, E. Rozanov, S. Schubert, P. V. Sporyshev, J. Syktus, A. Voldoire, J. H. Yoon, N. Zeng and T. Zhou (2009), The CLIVAR C20C project: skill of simulating Indian monsoon rainfall on interannual to decadal timescales. Does GHG forcing play a role?, *Climate Dynamics*, *33*(5), 615-627.

Kumar, K. K., B. Rajagopalan, and M. A. Cane (1999), On the weakening relationship between the Indian monsoon and ENSO, *Science*, *284*(5423), 2156-2159.

Latif, M., E. Roeckner, M. Botzet, M. Esch, H. Haak, S. Hagemann, J. Jungclaus, S. Legutke, S. Marsland, U. Mikolajewicz and J. Mitchell (2004), Reconstructing, Monitoring, and Predicting Multidecadal-Scale Changes in the North Atlantic Thermohaline Circulation with Sea Surface Temperature, *Journal of Climate*, *17*(7), 1605-1614.

Li, S. L., J. Perlwitz, X. W. Quan and M. P. Hoerling (2008), Modelling the influence of North Atlantic multidecadal warmth on the Indian summer rainfall, *Geophysical Research Letters 35*(5).

Lu, R. Y., W. Chen, and B. W. Dong (2008), How does a weakened Atlantic thermohaline circulation lead to an intensification of the ENSO-south Asian summer monsoon interaction?, *Geophysical Research Letters*, *35*(8).

Lu, R. Y., and B. W. Dong (2008), Response of the Asian Summer Monsoon to Weakening of Atlantic Thermohaline Circulation, *Advances in Atmospheric Sciences*, *25*(5), 723-736.

Lu, R. Y., B. W. Dong, and H. Ding (2006), Impact of the Atlantic multidecadal oscillation on the Asian summer monsoon, *Geophysical Research Letters*, *33*(24).

Luo, F. F., S. L. Li, and T. Furevik (2011), The connection between the Atlantic Multidecadal Oscillation and the Indian Summer Monsoon in Bergen Climate Model Version 2.0, *Journal of Geophysical Research-Atmospheres*, *116*.

Mann, M. E., Z. H. Zhang, S. Rutherford, R. S. Bradley, M. K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. B. Ni (2009), Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly, *Science*, *326*(5957), 1256-1260.

Mantua, N., and S. Hare (2002), The Pacific Decadal Oscillation, *Journal of Oceanography*, *58*(1), 35-44.

Martín-Rey, M., B. Rodríguez-Fonseca, I. Polo, and F. Kucharski (2014), On the Atlantic–Pacific Niños connection: a multidecadal modulated mode, *Climate Dynamics*, *43*(11), 3163-3178.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proceedings of the National Academy of Sciences of the United States of America*, *101*(12), 4136-4141.

Medhaug, I., and T. Furevik (2011), North Atlantic 20th century multidecadal variability in coupled climate models: sea surface temperature and ocean overturning circulation, *Ocean Science*, *7*(3), 389-404.

Meehl, G. A., L. Goddard, G. Boer, R. Burgman, G. Branstator, C. Cassou, S. Corti, G. Danabasoglu, F. Doblas-Reyes, E. Hawkins, A. Karspeck, M. Kimoto, A. Kumar, D. Matei, J. Mignot, R. Msadek, A. Navarra, H. Pohlmann, M. Rienecker, T. Rosati, E. Schneider, D. Smith, R. Sutton, H. Teng, G. J. van Oldenborgh, G. Vecchi and S. Yeager (2014), Decadal Climate Prediction: An Update from the Trenches, *Bulletin of the American Meteorological Society*, *95*(2), 243-267.

Meehl, G. A., L. Goddard, J. Murphy, R. J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M. A. Giorgetta, A. M. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer and T. Stockdale (2009), Decadal Prediction, *Bulletin of the American Meteorological Society*, *90*(10), 1467-1485.

Meehl, G. A., A. Hu, J. M. Arblaster, J. Fasullo, and K. E. Trenberth (2013), Externally Forced and Internally Generated Decadal Climate Variability Associated with the Interdecadal Pacific Oscillation, *Journal of Climate*, *26*(18), 7298-7310.

Meehl, G. A., W. M. Washington, C. M. Ammann, J. M. Arblaster, T. M. L. Wigley, and C. Tebaldi (2004), Combinations of Natural and Anthropogenic Forcings in Twentieth-Century Climate, *Journal of Climate*, *17*(19), 3721-3727.

Meehl, G. A., W. M. Washington, T. M. L. Wigley, J. M. Arblaster, and A. Dai (2003), Solar and Greenhouse Gas Forcing and Climate Response in the Twentieth Century, *Journal of Climate*, *16*(3), 426-444.

Miles, M. W., D. V. Divine, T. Furevik, E. Jansen, M. Moros, and A. E. J. Ogilvie (2014), A signal of persistent Atlantic multidecadal variability in Arctic sea ice, *Geophysical Research Letters*, *41*(2), 463-469.

Mohino, E., S. Janicot, and J. Bader (2010), Sahel rainfall and decadal to multi-decadal sea surface temperature variability, *Climate Dynamics*, *37*(3), 419-440.

Msadek, R., and C. Frankignoul (2009), Atlantic multidecadal oceanic variability and its influence on the atmosphere in a climate model, *Climate Dynamics*, *33*(1), 45-62.

Normand, C. (1953), Monsoon seasonal forecasting, *Quarterly Journal of the Royal Meteorological Society*, *79*(342), 463-473.

Otterå, O. H., M. Bentsen, H. Drange, and L. Suo (2010), External forcing as a metronome for Atlantic multidecadal variability, *Nature Geosci*, *3*(10), 688-694.

Parthasarathy, B., A. A. Munot, and D. R. Kothawale All-India monthly and seasonal rainfall series: 1871–1993, *Theor Appl Climatol*, *49*(4), 217-224.

Philander S (1990) El Niño, La Niña, and the Southern Oscillation. Academic Press, San Diego

Polo, I., B. Dong, and R. Sutton (2013), Changes in tropical Atlantic interannual variability from a substantial weakening of the meridional overturning circulation, *Climate Dynamics*, *41*(9-10), 2765-2784.

Privé, N. C., and R. A. Plumb (2007), Monsoon Dynamics with Interactive Forcing. Part I: Axisymmetric Studies, *Journal of the Atmospheric Sciences*, *64*(5), 1417-1430.

Rashid, H. A., S. B. Power, and J. R. Knight (2010), Impact of Multidecadal Fluctuations in the Atlantic Thermohaline Circulation on Indo-Pacific Climate Variability in a Coupled GCM, *Journal of Climate*, *23*(14), 4038-4044.

Rasmusson, E. M., and T. H. Carpenter (1983), The Relationship Between Eastern Equatorial Pacific Sea Surface Temperatures and Rainfall over India and Sri Lanka, *Monthly Weather Review*, *111*(3), 517-528.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *Journal of Geophysical Research-Atmospheres*, *108*(D14).

Richter, I., S.-P. Xie, S. Behera, T. Doi, and Y. Masumoto (2014), Equatorial Atlantic variability and its relation to mean state biases in CMIP5, *Climate Dynamics*, *42*(1-2), 171-188.

Rodríguez-Fonseca, B., I. Polo, J. García-Serrano, T. Losada, E. Mohino, C. R. Mechoso, and F. Kucharski (2009), Are Atlantic Niños enhancing Pacific ENSO events in recent decades?, *Geophysical Research Letters*, *36*(20), L20705.

Schlesinger, M. E., and N. Ramankutty (1994), An oscillation in the global climate system of period 65-70 years, *Nature*, *367*(6465), 723-726.

Sinha, A., K. G. Cannariato, L. D. Stott, H. Cheng, R. L. Edwards, M. G. Yadava, R. Ramesh, and I. B. Singh (2007), A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India, *Geophysical Research Letters*, *34*(16), L16707.

Solomon, S., K. H. Rosenlof, R. W. Portmann, J. S. Daniel, S. M. Davis, T. J. Sanford, and G.-K. Plattner (2010), Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming, *Science*, *327*(5970), 1219-1223.

Sperber, K. R., H. Annamalai, I. S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou (2013), The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century, *Climate Dynamics*, *41*(9-10), 2711-2744.

Steinman, B. A., M. E. Mann, and S. K. Miller (2015), Atlantic and Pacific multidecadal oscillations and Northern Hemisphere temperatures, *Science*, *347*(6225), 988-991.

Stott, P. A., S. F. B. Tett, G. S. Jones, M. R. Allen, J. F. B. Mitchell, and G. J. Jenkins (2000), External Control of 20th Century Temperature by Natural and Anthropogenic Forcings, *Science*, *290*(5499), 2133-2137.

Sutton, R. T., and D. L. R. Hodson (2005), Atlantic Ocean forcing of North American and European summer climate, *Science*, *309*(5731), 115-118.

Sutton, R. T., and D. L. R. Hodson (2007), Climate response to basin-scale warming and cooling of the North Atlantic Ocean, *Journal of Climate*, *20*(5), 891-907.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An Overview of CMIP5 and the Experiment Design, *Bulletin of the American Meteorological Society*, *93*(4), 485-498.

Tett, S. F. B., G. S. Jones, P. A. Stott, D. C. Hill, J. F. B. Mitchell, M. R. Allen, W. J. Ingram, T. C. Johns, C. E. Johnson, A. Jones, D. L. Roberts, D. M. H. Sexton and M. J. Woodage (2002), Estimation of natural and anthropogenic contributions to twentieth century temperature change, *Journal of Geophysical Research*, *107*(D16), 4306.

Tett, S. F. B., Stott, P. A., Allen, M. R., Ingram, W. J. and Mitchell, J. F. B. (1999), Causes of twentieth-century temperature change near the Earth's surface, *Nature, 399*, 569572.

Timmermann, A., S. I. An, U. Krebs, and H. Goosse (2005), ENSO Suppression due to Weakening of the North Atlantic Thermohaline Circulation, *Journal of Climate*, *18*(16), 3122-3139.

Timmermann, A., Y. Okumura, S. I. An, A. Clement, B. Dong, E. Guilyardi, A. Hu, J. H. Jungclaus, M. Renold, T. F. Stocker, R. J. Stouffer, R. Sutton, S. P. Xie and J. Yin (2007), The Influence of a Weakening of the Atlantic Meridional Overturning Circulation on ENSO, *Journal of Climate*, *20*(19), 4899-4919.

Ting, M. F., Y. Kushnir, R. Seager, and C. H. Li (2011), Robust features of Atlantic multi-decadal variability and its climate impacts, *Geophysical Research Letters*, *38*.

Torrence, C., and P. J. Webster (1999), Interdecadal Changes in the ENSO–Monsoon System, *Journal of Climate*, *12*(8), 2679-2690.

Trenberth, K. E. and J. T. Fasullo, (2013) J. An apparent hiatus in global warming?, *Earth's Future 1*, 19–32.

Turner, A. G., P. M. Inness, and J. M. Slingo (2005), The role of the basic state in the ENSO–monsoon relationship and implications for predictability, *Quarterly Journal of the Royal Meteorological Society*, *131*(607), 781-804.

Turner, A. G., K. Sperber, J. M. Slingo, G. Meehl, C. R. Mechoso, M. Kimoto, and A. Giannini (2011), Modelling monsoons: understanding and predicting current and future behaviour. In: Chang, C.-P., Y. Ding, G. N.-C. Lau, R. H. Johnson, B. Wang, and T. Yasunari (eds.), The global monsoon system: research and forecast, 2nd edition. World scientific series on Asia-Pacific weather and climate, 5, World Scientific/WMO, London Singapore New Jersey, 421-454.

Tyagi, A., P. G. Asnani, U. S. De, H. R. Hatwar, and A. B. Mazumdar (2012), The Monsoon Monograph (Volume 1 and 2), *India Meteorological Department, Report.*

Walker, G. T. (1924) Correlation in seasonal variations of weather, IV, a further study of world weather, *Memoirs of the India Meteorolical Department, 24*, 275–332

Wang, C. Z., S. F. Dong, A. T. Evan, G. R. Foltz, and S. K. Lee (2012), Multidecadal Covariability of North Atlantic Sea Surface Temperature, African Dust, Sahel Rainfall, and Atlantic Hurricanes, *Journal of Climate*, *25*(15), 5404-5415.

Wang, C., L. Zhang, S. K. Lee, L. Wu, and C. R. Mechoso (2014), A global perspective on CMIP5 climate model biases, *Nature Climate Change*, *4*(3), 201-205.

Wang, Y. M., S. L. Li and D. H. Luo (2009), Seasonal response of Asian monsoonal climate to the Atlantic Multidecadal Oscillation, *Journal of Geophysical Research-Atmosph*eres, 114.

Webster, P. J., V. O. Magana, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai and T. Yasunari (1998), Monsoons: Processes, predictability, and the prospects for prediction, *Journal of Geophysical Research-Oceans, 103*(C7), 14451-14510.

Wittenberg, A. T. (2009), Are historical records sufficient to constrain ENSO simulations?, *Geophysical Research Letters*, *36*(12), L12702.

Wittenberg, A. T., A. Rosati, T. L. Delworth, G. A. Vecchi, and F. Zeng (2014), ENSO Modulation: Is It Decadally Predictable?, *Journal of Climate*, *27*(7), 2667-2681.

Wyatt, M. G., S. Kravtsov, and A. A. Tsonis (2012), Atlantic Multidecadal Oscillation and Northern Hemisphere's climate variability, *Climate Dynamics*, *38*(5-6), 929-949.

Yadava, M. G., R. Ramesh and G. B. Pant (2004), Past monsoon rainfall variations in peninsular India recorded in a 331-year-old speleothem, *The Holocene,* 14(4), 517-524.

Zebiak, S. E. (1993), Air–Sea Interaction in the Equatorial Atlantic Region, *Journal of Climate*, *6*(8), 1567-1586.

Zhang, R., and T. L. Delworth (2005), Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation, *Journal of Climate*, *18*(12), 1853-1860.

Zhang, R. and T. L. Delworth (2006), Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, *Geophysical Research Letters,* 33(17).

Zhang, R., T. L. Delworth, and I. M. Held (2007), Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature?, *Geophysical Research Letters*, *34*(L02709).

Zhang, R., T. L. Delworth, R. Sutton, D. L. R. Hodson, K. W. Dixon, I. M. Held, Y. Kushnir, J. Marshall, Y. Ming, R. Msadek, J. Robson, A. J. Rosati, M. Ting and G. A. Vecchi (2013), Have Aerosols Caused the Observed Atlantic Multidecadal Variability?, *Journal of the Atmospheric Sciences*, *70*(4), 1135-1144.

Paper I

Marine-based multiproxy reconstruction of Atlantic multidecadal variability

Svendsen, L., S. Hetzinger, N. Keenlyside, and Y. Gao (2014)

Geophysical Research Letters, 41(4), 2013GL059076.

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2013GL059076

Key Points:
- A new multiproxy reconstruction for AMV based only on marine proxies
- AMV persists at least back to 1780
- There is a need for more marine-based proxy records

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Table S1
- Table S2

Correspondence to:
L. Svendsen,
lea.svendsen@nersc.no

Citation:
Svendsen, L., S. Hetzinger, N. Keenlyside, and Y. Gao (2014), Marine-based multiproxy reconstruction of Atlantic multidecadal variability, *Geophys. Res. Lett.*, *41*, doi:10.1002/2013GL059076.

Received 18 DEC 2013
Accepted 3 FEB 2014
Accepted article online 6 FEB 2014

Marine-based multiproxy reconstruction of Atlantic multidecadal variability

Lea Svendsen[1], Steffen Hetzinger[2], Noel Keenlyside[3], and Yongqi Gao[1,4]

[1]Nansen Environmental and Remote Sensing Center and Bjerknes Centre for Climate Research, Bergen, Norway, [2]GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, Germany, [3]Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway, [4]Nansen-Zhu International Research Center, Institute of Atmospheric Physics, Beijing, China

Abstract Atlantic multidecadal variability (AMV) is known to impact climate globally, and knowledge about the persistence of AMV is important for understanding past and future climate variability, as well as modeling and assessing climate impacts. The short observational data do not significantly resolve multidecadal variability, but recent paleoproxy reconstructions show multidecadal variability in North Atlantic temperature prior to the instrumental record. However, most of these reconstructions are land-based, not necessarily representing sea surface temperature. Proxy records are also subject to dating errors and microenvironmental effects. We extend the record of AMV 90 years past the instrumental record using principle component analysis of five marine-based proxy records to identify the leading mode of variability. The first principal component is consistent with the observed AMV, and multidecadal variability seems to persist prior to the instrumental record. Thus, we demonstrate that reconstructions of past Atlantic low-frequency variability can be improved by combining marine-based proxies.

1. Introduction

In this study we reconstruct the Atlantic multidecadal variability (AMV) by combining several marine-based proxy records from the North Atlantic region. During the instrumental period, North Atlantic sea surface temperature (SST) has undergone pronounced basin-wide fluctuations, with warm and cold periods of 3–4 decades each. These variations are referred to as AMV or the Atlantic Multidecadal Oscillation [e.g., *Enfield et al.*, 2001]. Studies suggest that the AMV is important for climate variability globally and has been connected to several regional climate signals. The AMV can, for instance, affect European and North American climate [e.g., *Sutton and Hodson*, 2005; *Wyatt et al.*, 2012], the frequency of Atlantic hurricanes [e.g., *Goldenberg et al.*, 2001], and Arctic sea ice cover [e.g., *Kinnard et al.*, 2011; *Miles et al.*, 2014]. It has also been linked to changes in rainfall in the African Sahel [e.g., *Zhang and Delworth*, 2006; *Wang et al.*, 2012], as well as the South Asian summer monsoon [e.g., *Goswami et al.*, 2006].

Whether the AMV is a persistent mode of internal variability is still disputed [*Kilbourne et al.*, 2008; *Knudsen et al.*, 2011]. Ocean temperature data are limited to the last 140 years by instrumental records, and the data are spatiotemporally lacking before 1950 [*Smith and Reynolds*, 2003]. The relatively short instrumental SST record can therefore only capture 1–2 cycles of AMV, and is too short to confidently study natural low-frequency variability.

High-resolution climate reconstructions based on long-lived marine biota, for instance, tropical corals, bivalve mollusks, and coralline algae, can help reconstruct SST prior to the instrumental era [*Jones et al.*, 2001; *Wanamaker et al.*, 2011; *Hetzinger et al.*, 2012]. With such reconstructions we can investigate whether multidecadal variability of Atlantic SST is a persistent feature of the Atlantic climate. Alternative tools for studying AMV are climate models. However, state-of-the-art climate models simulate a wide range of variability because of large uncertainties in the underlying processes [*Medhaug and Furevik*, 2011; *Ba et al.*, 2014].

While here we reconstruct the AMV using marine-based proxies, previous reconstructions of the AMV have mainly used land-based proxies, such as tree rings [e.g., *Gray et al.*, 2004; *Mann et al.*, 2009]. Many of these land-based reconstructions have also used records from regions far from the Atlantic Ocean, in noncoastal areas. How the low-frequency variability in SST is related to atmospheric temperatures is, however, not clear. The relationship between SST and tree ring proxies seems strong for the instrumental era, but this relationship may not be stable [*D'Arrigo et al.*, 2008; *Vásquez-Bedoya et al.*, 2012]. Therefore, we investigate

Table 1. Loadings on PC1 for the Proxy Records and the Correlation With the AMV-Index[a]

Reference	Loadings on PC1	Correlation at Zero Lag	Maximum Correlation	Lag Year
Goodkin et al. [2005]	0.48	0.31	0.31	0
Kilbourne et al. [2008]	0.05	0.07	0.15	−9
Saenger et al. [2009]	0.45	0.30	0.43	7
Swart et al. [1996]	−0.28	0.07	0.21	−9
Vásquez-Bedoya et al. [2012]	0.70	0.56	0.57	3
Composite		0.52	0.52	0
AMV from *Gray et al.* [2004]		0.57	0.61	−3
AMV from *Mann et al.* [2009]		0.57	0.59	−2
PC1		0.53	0.57	3

[a]The correlation with the AMV-index is calculated for the included proxy records, the composite of the proxy records, the AMV reconstruction from *Gray et al.* [2004] and *Mann et al.* [2009], and PC1, for the period 1871–1986.

low-frequency variability of North Atlantic SST using marine-based proxies, as these are a more direct measure of SST compared to land-based proxies.

There are several annual-resolution marine-based proxy records that capture the AMV signal [e.g., *Hetzinger et al.*, 2008; *Kilbourne et al.*, 2008; *Saenger et al.*, 2009; *Halfar et al.*, 2011]. Many of these proxy records are relatively short, not extending past the instrumental era, but their consistency with the instrumental record indicates that these types of records can be used to reconstruct past SST. However, individual records will be subject to sampling and dating errors as well as microenvironmental effects. Principle component analysis (PCA) can be used to reduce these uncertainties by extracting the leading patterns of variability [*Storch and Zwiers*, 2002]. While this method is common for land-based proxies, its application to marine-based proxies has been limited [*Ault et al.*, 2009]. Here we successfully apply this method to reconstruct AMV 90 years past the instrumental data period.

2. Data and Method

We analyze five published marine-based proxy records from the North Atlantic sector (Table 1). These records are chosen on the basis that they all have annual resolution, are longer than the instrumental record, and are proxies for SST. The proxy records stem from massive-growing tropical coral colonies. Two of the records are based on growth [*Saenger et al.*, 2009; *Vásquez-Bedoya et al.*, 2012], two are based on the Sr/Ca ratios [*Goodkin et al.*, 2005; *Kilbourne et al.*, 2008], and one is based on the skeletal $\delta^{18}O$ composition [*Swart et al.*, 1996]. The locations of these proxy records are illustrated in Figure 1a, and their properties are summarized in Table S1. The records used in the analysis are all from the western tropical Atlantic. Cooler temperatures in the eastern Atlantic lead to slower coral growth rates, hampering the formation of large and long-lived colonies of massive growing coral. Thus, no long-term coral-based proxies exist at the moment from the eastern Atlantic, as well as at higher latitudes.

The five coral records from the tropical Atlantic are combined with PCA, where the individual records have been detrended and normalized prior to the analysis. Combining these records gives us an overlapping time span of 206 years from 1781 to 1986. For validation of our AMV reconstruction we compare our results with the SST data from Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) [*Rayner et al.*, 2003]. We also compare our results with two other AMV reconstructions [*Gray et al.*, 2004; *Mann et al.*, 2009]. Both these records are multiproxy reconstructions, but neither focuses on marine proxies. The reconstruction from *Gray et al.* [2004] is composed of 12 tree ring chronologies located in North America, Europe, and the Middle East between 30°N and 70°N [*Gray et al.*, 2004]. Although the reconstruction from *Mann et al.* [2009], which is composed of several different types of records, includes some marine records from the North Atlantic, none of them has continuous annual resolution [*Mann et al.*, 2009].

3. Results and Discussion

The first principal component (PC1) from the PCA explains 32% of the variance in the records and exhibits a close correspondence to the observed AMV-index (Figure 1b). The AMV-index is defined as the detrended and normalized annual averaged low-frequency (11 year running mean) Atlantic SST averaged over the region 0–60°N and 75°W–7.5°W [*Enfield et al.*, 2001; *Wyatt et al.*, 2012]. The time series of PC1 is consistent with

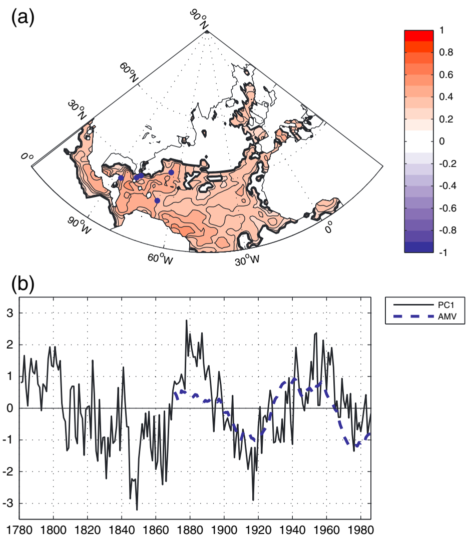

Figure 1. (a) Correlation between PC1 and annually averaged observed SST (HadISST), showing only values at a 95% confidence level for the effective degrees of freedom. Blue dots indicate the sampling sites. (b) PC1 (solid black line) and the AMV-index from HadISST data (dashed blue line).

the instrumental SST record from the Atlantic with warm periods from 1860 to 1890 and 1940 to 1970, and a cold period from 1900 to 1930. The time series have a correlation of 0.53 at a zero lag. This and other correlations discussed below are summarized in Table 1. PC1 captures an additional cold period in the 1930s that is not present in the observed AMV-index. This cooling is present in four out of the five proxy records included in our analysis, suggesting that this cold period is a tropical signal. However, this cooling is not present in the observed records for the western tropical Atlantic. Prior to the instrumental record, PC1 has a cold period from 1820 to 1860 and a warm period from the beginning of the record (1781) to 1820. When we repeat the PCA for the five coral records without detrending the records first, PC1, now explaining 35% of the variability, captures the same periodicity and timing of warm and cold periods as for the detrended records (not shown). In addition, there is a positive linear trend. PC1 provides evidence that the multidecadal variability in Atlantic SSTs may have persisted prior to the instrumental record.

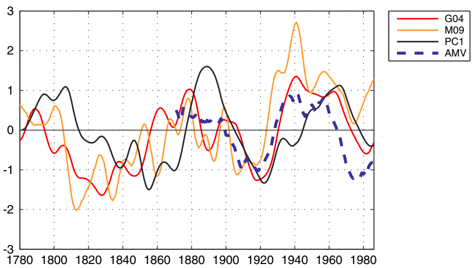

Figure 2. Normalized decadally filtered PC1 (solid black line), AMV reconstructions from *Gray et al.* [2004] (G04, red line) and *Mann et al.* [2009] (M09, orange line), and the AMV-index from HadISST data (dashed blue line).

PC1 is also comparable to the AMV reconstruction from both *Gray et al.* [2004] (G04) and *Mann et al.* [2009] (M09), but the reconstructions are somewhat displaced in time (Figure 2). For instance, the first warm period in the beginning of PC1 ends later than the corresponding warm period in the land-based reconstructions; hence, the cold period that lasts until about 1860 starts later in PC1 (Figure 1b). The cross correlation between PC1 and the AMV reconstruction from *Gray et al.* [2004] has a maximum value of 0.44 when PC1 lags the reconstruction by 11 years. At a zero lag the correlation is 0.26. The cross correlation between PC1 and the AMV reconstruction from *Mann et al.* [2009] has a maximum value of 0.39 when PC1 lags the reconstruction by 12 years. At a zero lag the correlation between PC1 and the reconstruction from *Mann et al.* [2009] is 0.33, slightly higher than that for the reconstruction from *Gray et al.* [2004]. The lags are similar when the reconstructions are 10 year low-pass filtered, as seen in Figure 2.

A significant positive correlation between PC1 and the observed SST is found for the whole tropical North Atlantic (Figure 1a). The same correlation pattern is found for PC1 with the records not detrended prior to the analysis (not shown). The highest correlations are found in the tropics in the region where the corals are situated. This bias in the location of the coral records may distort our results, with PC1 capturing a tropical rather than an extratropical North Atlantic signal. The correlation of PC1 with observed North Atlantic SSTs averaged over the tropics (0–30°N, 75°W–7.5°W) and the subtropics (30–60°N, 75°W–7.5°W) are 0.59 and 0.47, respectively. The correlation of PC1 with observed North Atlantic SSTs averaged over western (0–60°N, 75°W–45°W) and eastern (0–60°N, 45°W–7.5°W) North Atlantic are 0.53 and 0.52, respectively. The correlation between the 10 year low-pass filtered PC1 and observed SSTs show a similar pattern; however, the correlations are lower (see Figure S1 in the supporting information). We do not see such a strong tropical bias in the correlation pattern between the other two land-based multiproxy AMV reconstructions and observed Atlantic SST (Figure S1). For the observed SSTs, correlations are also high in the tropics; however, there are also high correlations in the subtropics that are not visible in the correlation with PC1 (Figure S2). The observed SST pattern is also subject to uncertainty [*Alexander et al.*, 2013], and in particular the patterns for the period prior to and following the 1940s differ markedly (Figure S2). Interestingly, the pattern prior to the 1940s resembles that associated with PC1.

Correlations between the observed AMV-index from HadISST with each individual proxy record, the composite of the records, the two land-based AMV reconstructions [*Gray et al.*, 2004; *Mann et al.*, 2009], and PC1 is given in Table 1. The correlation with PC1 is 0.57 and is higher than the correlation with any of the individual proxy records alone, except for the record from *Vásquez-Bedoya et al.* [2012]. This gives indications that PC1 is an improved reconstruction of AMV compared to individual proxy records. The correlations for the observed AMV-index with the two AMV reconstructions from *Gray et al.* [2004] and *Mann et al.* [2009] are slightly higher than for the correlation with PC1. This might be because these reconstructions have been calibrated to the observed SST field [*Gray et al.*, 2004; *Mann et al.*, 2009]. In addition, the 12 tree ring chronologies used in the reconstruction from *Gray et al.* [2004] have been chosen due to their strong link to Atlantic SSTs in the observational record.

PC1 is the optimally weighted average of the records, with loadings given in Table 1, while a composite is a simple average of the proxy records. Thus, PCA extracts the common variability in the proxy records, and can act as a filter to eliminate higher frequencies of variability. The correlation of the observed AMV-index with PC1 is equal to the correlation of the observed index with the composite (unweighted average) of the proxy records, and PC1 is not necessarily an improved AMV reconstruction compared to the composite. Nevertheless, PCA may give more reliable results than an unweighted average because PCA allows some records to be lightly weighted or even negatively weighted.

When working with proxy records, there is always the possibility that the proxy may not actually be reflecting the variable of interest. In our study we are interested in temperature, but the marine-based proxies may also be influenced by, for instance, salinity. However, we find that our reconstruction is able to successfully reproduce the variability seen in the instrumental SST record, and also by combining several records using PCA we may be able to extract the SST signal as a dominant mode of low-frequency variability.

4. Conclusion

Here we propose a different method for reconstructing low-frequency variability in North Atlantic SST based on records from long-lived marine biota. We combine several annual resolution marine-based proxy records, extending 90 years further back in time than the instrumental record, with PCA to extract the low-frequency variability and limit microenvironmental effects and sampling errors. We find that PC1 is consistent with the observed AMV, and that the AMV persists throughout the record. This suggests that our method is able to capture the Atlantic low-frequency variability, and we conclude that this method is adequate for reconstructing SST on multidecadal timescales.

We find a discrepancy in the timing of the variability between our marine-based reconstruction and other land-based multiproxy AMV reconstructions, with the land-based AMV reconstructions leading 11–12 years to the marine-based reconstruction, indicating that we have to be careful about using proxies for reconstructing multidecadal SST variability in the Atlantic. There are also discrepancies related to the location of the proxies used. For our marine-based reconstruction we find higher correlations in the tropics and an additional cold period in the late 1930s. These discrepancies reflect differences in using proxies from high and low latitudes and of various types, as well as errors and uncertainties in the records. However, there are at present relatively few high-resolution long marine proxy records from the Atlantic sector, and the existing records are mainly from the tropics. Longer marine records, including records from the subtropics, are needed to reconstruct the AMV even further back in time. Additional high-resolution marine-based proxy records will also improve the confidence in AMV reconstructions, and will help constrain climate models and in turn predictions. Such reconstructions can also be used to investigate the persistence of observed AMV teleconnections. This record is freely available for use.

Acknowledgments
The Research Council of Norway has supported this study through the IndiaClim project (no. 216554). N. K. and S. H. acknowledge support from Deutscher Akademischer Austauschdienst (DAAD). The research was also supported by the EUFP7/2007–2013 under grant agreement no. 603521, project PREFACE. We also thank the NOAA Paleoclimatology database (http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets) and all researchers who contributed the data.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Alexander, M. A., K. H. Kilbourne, and J. A. Nye (2013), Climate variability during warm and cold phases of the Atlantic Multidecadal Oscillation (AMO), 1871–2008, *J. Mar. Syst.*, doi:10.1016/j.jmarsys.2013.07.017.

Ault, T. R., J. E. Cole, M. N. Evans, H. Barnett, N. J. Abram, A. W. Tudhope, and B. K. Linsley (2009), Intensified decadal variability in tropical climate during the late 19th century, *Geophys. Res. Lett.*, *36*, L08602, doi:10.1029/2008GL036924.

Ba, J., et al. (2014), A multi-model comparison for Atlantic multidecadal variability, *Clim. Dyn.*, doi:10.1007/s00382-014-2056-1.

D'Arrigo, R., R. Wilson, B. Liepert, and P. Cherubini (2008), On the 'Divergence Problem' in Northern Forests: A review of the tree-ring evidence and possible causes, *Global Planet. Change*, *60*(3-4), 289–305, doi:10.1016/j.gloplacha.2007.03.004.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US, *Geophys. Res. Lett.*, *28*(10), 2077–2080.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nunez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science*, *293*(5529), 474–479, doi:10.1126/science.1060040.

Goodkin, N. F., K. A. Hughen, A. L. Cohen, and S. R. Smith (2005), Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca, *Paleoceanography*, *20*, PA4016, doi:10.1029/2005PA001140.

Goswami, B. N., M. S. Madhusoodanan, C. P. Neema, and D. Sengupta (2006), A physical mechanism for North Atlantic SST influence on the Indian summer monsoon, *Geophys. Res. Lett.*, *33*, L02706, doi:10.1029/2005GL024803.

Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson (2004), A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD, *Geophys. Res. Lett.*, *31*, L12205, doi:10.1029/2004GL019932.

Halfar, J., S. Hetzinger, W. Adey, T. Zack, G. Gamboa, B. Kunz, B. Williams, and D. E. Jacob (2011), Coralline algal growth-increment widths archive North Atlantic climate variability, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *302*(1-2), 71–80, doi:10.1016/j.palaeo.2010.04.009.

Hetzinger, S., M. Pfeiffer, W. C. Dullo, N. Keenlyside, M. Latif, and J. Zinke (2008), Caribbean coral tracks Atlantic Multidecadal Oscillation and past hurricane activity, *Geology*, *36*(1), 11–14, doi:10.1016/j.palaeo.2010.06.019.

Hetzinger, S., J. Halfar, J. V. Mecking, N. S. Keenlyside, A. Kronz, R. S. Steneck, W. Adey, and P. A. Lebednik (2012), Marine proxy evidence linking decadal North Pacific and Atlantic climate, *Clim. Dyn.*, *39*(6), 1447–1455, doi:10.1007/s00382-011-1229-4.

Jones, P. D., T. J. Osborn, and K. R. Briffa (2001), The evolution of climate over the last millennium, *Science*, *292*(5517), 662–667, doi:10.1126/science.1059126.

Kilbourne, K. H., T. M. Quinn, R. Webb, T. Guilderson, J. Nyberg, and A. Winter (2008), Paleoclimate proxy perspective on Caribbean climate since the year 1751: Evidence of cooler temperatures and multidecadal variability, *Paleoceanography*, *23*, PA3220, doi:10.1029/2008PA001598.

Kinnard, C., C. M. Zdanowicz, D. A. Fisher, E. Isaksson, A. Vernad, and L. G. Thompson (2011), Reconstructed changes in Arctic sea ice over the past 1,450 years, *Nature*, *479*, 509–512.

Knudsen, M. F., M. S. Seidenkrantz, B. H. Jacobsen, and A. Kuijpers (2011), Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years, *Nat. Commun.*, *2*, 178, doi:10.1038/ncomms1186.

Mann, M. E., Z. H. Zhang, S. Rutherford, R. S. Bradley, M. K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. B. Ni (2009), Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, *Science*, *326*(5957), 1256–1260, doi:10.1126/science.1177303.

Medhaug, I., and T. Furevik (2011), North Atlantic 20th century multidecadal variability in coupled climate models: Sea surface temperature and ocean overturning circulation, *Ocean Sci.*, *7*(3), 389–404, doi:10.5194/os-7-389-2011.

Miles, M. W., D. V. Divine, T. Furevik, E. Jansen, M. Moros, and A. E. J. Ogilvie (2014), A signal of persistent Atlantic multidecadal variability in Arctic sea ice, *Geophys. Res. Lett.*, *41*, doi:10.1002/2013GL058084.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Saenger, C., A. L. Cohen, D. W. Oppo, R. B. Halley, and J. E. Carilli (2009), Surface-temperature trends and variability in the low-latitude North Atlantic since 1552, *Nat. Geosci.*, *2*(7), 492–495, doi:10.1038/NGEO552.

Smith, T. M., and R. W. Reynolds (2003), Extended reconstruction of global sea surface temperatures based on COADS data (1854-1997), *J. Clim.*, *16*(10), 1495–1510, doi:10.1175/1520-0442-16.10.1495.

Storch, H. V., and F. W. Zwiers (2002), *Statistical Analysis in Climate Research*, pp. 494 , Cambridge Univ. Press, Cambridge.

Sutton, R. T., and D. L. R. Hodson (2005), Atlantic Ocean forcing of North American and European summer climate, *Science*, *309*(5731), 115–118, doi:10.1126/science.1109496.

Swart, P. K., R. E. Dodge, and H. J. Hudson (1996), A 240-year stable oxygen and carbon isotopic record in a coral from South Florida: Implications for the prediction of precipitation in Southern Florida, *Palaios*, *11*(4), 362–375.

Vásquez-Bedoya, L. F., A. L. Cohen, D. W. Oppo, and P. Blanchon (2012), Corals record persistent multidecadal SST variability in the Atlantic Warm Pool since 1775 AD, *Paleoceanography*, *27*, PA3231, doi:10.1029/2012PA002313.

Wanamaker, A. D., S. Hetzinger, and J. Halfar (2011), Reconstructing mid- to high-latitude marine climate and ocean variability using bivalves, coralline algae, and marine sediment cores from the Northern Hemisphere, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *302*(1-2), 1–9, doi:10.1016/j.palaeo.2010.12.024.

Wang, C. Z., S. F. Dong, A. T. Evan, G. R. Foltz, and S. K. Lee (2012), Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall, and Atlantic hurricanes, *J. Clim.*, *25*(15), 5404–5415, doi:10.1175/jcli-d-11-00413.1.

Wyatt, M. G., S. Kravtsov, and A. A. Tsonis (2012), Atlantic Multidecadal Oscillation and Northern Hemisphere's climate variability, *Clim. Dyn.*, *38*(5-6), 929–949, doi:10.1007/s00382-011-1071-8.

Zhang, R., and T. L. Delworth (2006), Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, *Geophys. Res. Lett.*, *33*, L17712, doi:10.1029/2006GL026267.

Auxiliary material

Table S1. Proxies used in the analysis

Reference	Location	Species	Proxy
Goodkin et al., 2005	32°N, 64°W	Diploria labyrinthiformis	Sr/Ca
Kilbourne et al., 2008	17°N, 67°W	Montastraea faveolata	Sr/Ca
Saenger et al., 2009	26°N, 79°W	Siderastrea siderea	growth
Swart et al., 1996	25°N, 80°W	Montastraea faveolata	$\delta^{18}O$
Vásquez-Bedoya et al., 2012	21°N, 87°W	Siderastrea siderea	growth

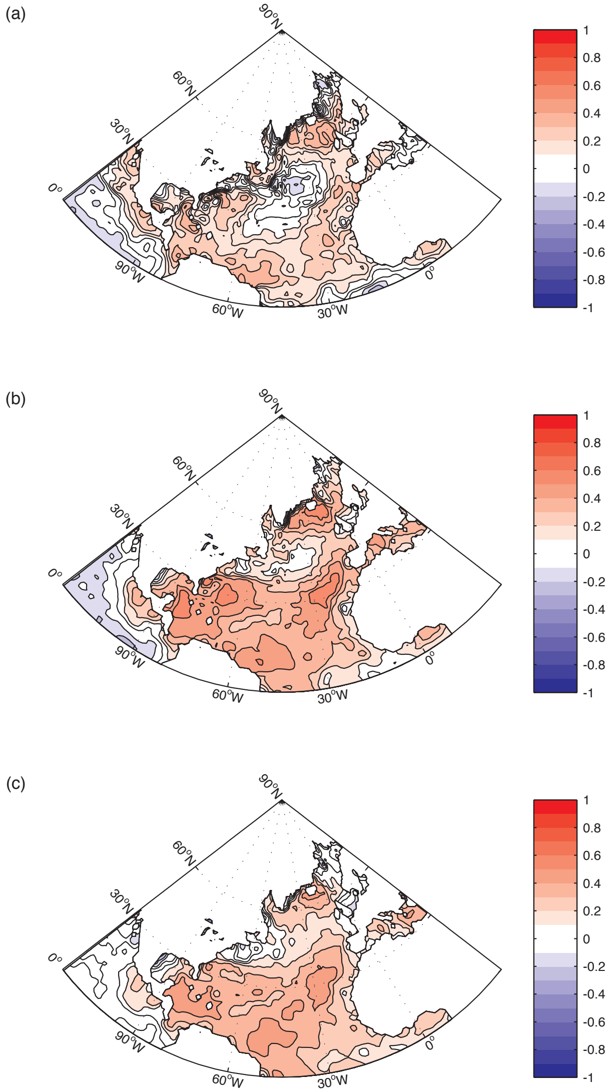

Figure S1. Correlation between the annually averaged observed SST (HadISST) and the decadally filtered (a) PC1 and AMV-reconstructions from (b) *Gray et al.* [2004] and (c) *Mann et al.* [2009] for the period 1871-1986.

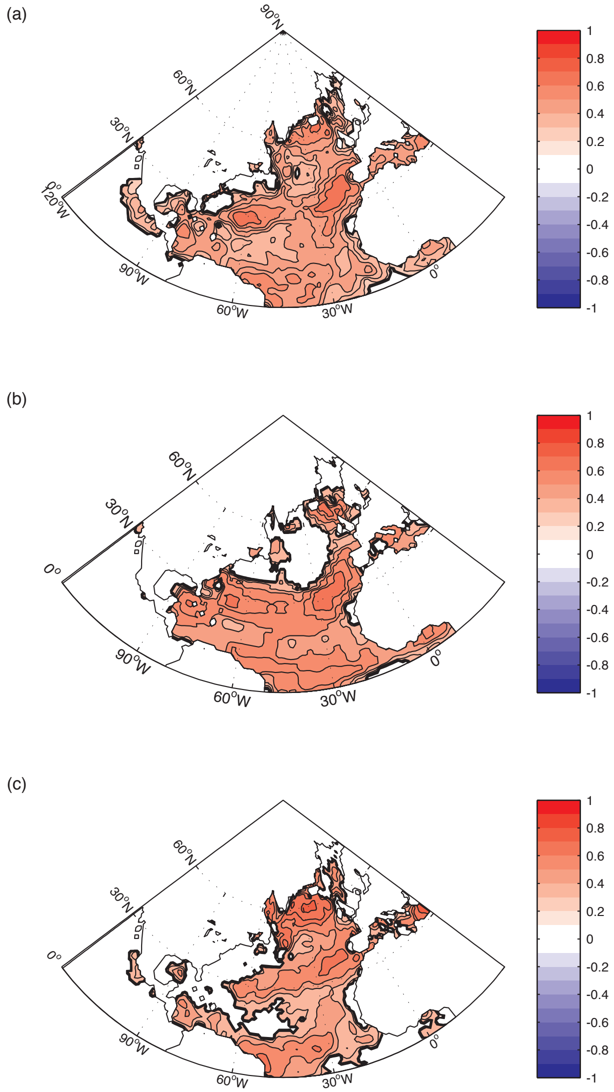

Figure S2. Correlation between the observed AMV-index and annually averaged observed SST (HadISST) for the period (a) 1871-1986, (b) 1871-1940 and (c) 1941-2012, showing only values at a 95% confidence level for the effective degrees of freedom.