Past climate variability: model analysis and proxy intercomparison

Francesco S.R. Pausata

Dissertation for the degree philosophiae doctor
(Ph.D.)
University of Bergen

July 22nd, 2010

Past climate variability: model analysis and proxy intercomparison

Francesco S.R. Pausata

Dissertation for the degree philosophiae doctor
(Ph.D.)
University of Bergen
Bjerknes Centre for Climate Research
Geophysical Insitute

“ The weather is always changing...
Always inventing new scenarios
And trying them on people
To see how they will react”

Mark Twain (1835-1910)

Preface

After three long years, this great experience at the Bjerknes Centre is about to come to an end. When I started I thought it was a quest not possible to be made "on schedule", but instead I somehow managed. This accomplishment has been possible thanks to the constant availability of my advisors who amazingly guided me on this adventure. Hence, my first thank you goes to Kerim who has been not only a nicely strict advisor (he *made* me *understand* that I had 3 years – no extensions allowed! – to finish the Ph.D.) but also a friend. His positive attitude and constant availability for discussions made possible overcome several obstacles as well as made working at the Bjerknes Centre a really pleasant experience. The UW-advisors gang (advisors linked to the University of Washington, ed.) has been invaluable for my growth as a scientist. I will always be thankful to Camille with her charismatic personality, and Justin with his politeness and propensity to help (after all he is originally from Minnesota!), who have been my mentors especially when it came to fix my rusty English. Finally David, who hosted me in Seattle at the UW and whose passionate attitude (must be related to his Italian roots: the blood will out!), has been an inspiration for me.

I am also grateful to Carin who made me discover a completely new world: the ocean "bugs". I would also like to thank Jürgen for all the interesting and valuable scientific discussions (but not for the ones related to sport events: he always jinx them – e.g., Italy at the world cup). Also thanks to Michel for his help in the last months.

All my colleagues and friends at the Geophysical Institute and Bjerknes Centre have provided a nice way for relaxing now and then in the institute, especially the "klokka-3 kaffe pause" and the important Norsk lessons (e.g., "Du ser ut som et takras", it is a pick up line (?), right Marius?). I especially feel sorry for Andreas, who I shared the office with and thereby had to cope with all my colorful expressions (e.g., "mamma mia!" just to name the tamest one). Finally I would like to mention Birgitte who constantly sent "positive vibes" in my office.

I would also like to thank the Bjerkens Centre and GFI administration folks; especially Connie for invaluable help and her kindness.

During my second year, I cannot forget my friends Jenny and Mymy who went through some of my manuscripts and kept telling me that they were in good shape. This made me see the light at the end of the tunnel. However, it turns out that light was just a mirage! The last but not least, I would like to thank all my friends who encouraged me as well as dealt with my "ravings" in the last part of my Ph.D.

Bergen, July 22nd, 2010

Francesco S.R. Pausata

Abstract

This thesis investigates the climate variability of the late Quaternary (21 000 yrs BP to present day) using model simulations and proxy data. The thesis consists of four manuscripts and one appendix.

In the first two manuscripts and the appendix I, the extratropical Northern Hemisphere atmospheric circulation in different Quaternary time slices (pre-industrial, PI, 1750 AD; Mid Holocene, MH, 6 kyrs BP; Last Glacial Maximum, LGM, 21 kyrs BP) is investigated using different climate models. The contributions of greenhouse gases, ice-sheet topography and albedo on the atmospheric mean climate and its variability are analyzed. In general, the models show no major changes in atmospheric circulation nor in its interannual variability in a climate slightly warmer (MH) than the PI one. In the LGM simulations, the models show decreased sea level pressure interannual variability relative to PI; on the other hand, the interannual variability of surface temperature is increased. The leading mode of sea level pressure variability in the North Atlantic is characterized by a NAO-like behavior in all climate states; however, it represents less total variance and the centers of action are weaker at the LGM. The presence of the Laurentide ice-sheet over North America during the LGM accounts for most of the changes observed in the LGM climate. Finally, the models show that the link between atmospheric and surface climate (temperature and precipitation) variability is altered in a glacial climate compared to the PI. Therefore, assuming present-day climate-proxy relationships when interpreting proxy records may well lead to a misinterpretation of past climates.

The results of the first manuscript point out that certain proxies may record seasonal rather than annual climate changes or that they could be tape recorders for climate changes far afield rather than local. These issues are tackled in the second and third manuscripts. In paper III, various marine proxy records from the North Atlantic Ocean that spann the Holocene (10-0 kyrs BP) are compared with each other and with a model simulation of the MH. Sea-surface temperature records based on

phytoplankton generally show the existence of a warm early to mid Holocene (9-6 kyrs BP) optimum. In contrast, zooplankton-based temperature records from the North Atlantic and Norwegian Sea show a cool mid Holocene anomaly and a trend towards warmer temperatures in the late Holocene. Model results indicate that while the warming of the sea surface was stronger in summer during the MH compared to the PI due to higher solar radiation at the high latitudes, sub-surface depths experienced a cooling, mirroring the winter sea surface temperatures. These physical changes in the surface and sub-surface characteristics of the water column can explain the discrepancies between the Holocene trends exhibited by phytoplankton- and zooplankton- based temperature proxy records.

Paper III addresses the possibility that cave deposits, specifically in South Asia, record non-local rather than local climate changes. Using an atmospheric climate model with embedded stable water-isotope tracers, we propose a novel conceptual model to explain the oxygen isotopic changes recorded in Asian caves during abrupt climate changes (such as Heinrich events). We show the key role of the Indian Ocean in driving $\delta^{18}O$ variations in both Indian and Chinese cave deposits: changes of the Indian Ocean surface temperature affects the Indian summer monsoon, which in turn leads to a change in the $\delta^{18}O$ signature of the precipitation falling over the Indian subcontinent. This signal is eventually transferred from the Indian Ocean to Chinese caves via recycling of continental precipitation. Therefore, caves in eastern China (e.g., Hulu) do not record changes in the East Asian summer monsoon, as previously thought, but rather changes in the Indian summer monsoon.

List of papers

I) Pausata, F. S. R., Li, C., Wettstein, J. J., Nisancioglu, K. H., and Battisti, D. S.: Changes in atmospheric variability in a glacial climate and the impacts on proxy data: a model intercomparison. *Clim. Past,* 5, 489-502 (2009).

II) Pausata, F. S. R., Li, C., Wettstein, J. J., Nisancioglu, K. H., Kageyama, M.: The key role of topography in altering North Atlantic atmospheric circulation during the last glacial period. *Manuscript*.

III) Andersson, C., Pausata, F. S. R., Jansen, E., Risebrobakken, B., and Telford, R. J.: Holocene trends in the foraminifer record from the Norwegian Sea and the North Atlantic Ocean. *Clim. Past,* 6, 179-193 (2010).

IV) Pausata, F. S. R., Battisti D. S., Nisancioglu, K. H., Bitz C.: Eastern Chinese stalagmites: proxies for Indian Summer Monsoon during abrupt climate changes. *Science*, (submitted).

Contents

1. Introduction

Understanding the natural variability of past climates is an important step in our goal to understand present and future climate changes and to discriminate between natural and man-made changes. To understand how sensitive the climate system is to changes in solar radiation, greenhouse gases, aerosols and other forcings, it is essential to quantify the extent of natural fluctuations due to these forcings in the past. Furthermore, natural variability has to be well represented in climate models if we are to detect potential anthropogenic impacts on the climate system. Any anthropogenic influence on climate will be superimposed on the underlying background of "natural" climate variability, which may vary on different timescales in response to different forcings.

Instrumental records span only a tiny fraction of the Earth's climatic history, and therefore do not encompass the full range of climate variability. Given the shortness of instrumental records, the possibility of identifying causes and mechanisms of climate variations relies on the use of proxy data as well as model simulations.

Most of our knowledge about past climate change comes from natural archives such as ocean sediments, ice cores, cave deposits, pollen and tree rings. Many organisms such as corals, trees and insects alter their growth in response to climate changes. For example, tree ring width and density chronologies have been used to infer changes in past temperature and precipitation (e.g., Briffa et al., 1998; Cook et al., 2010). However, high quality, high resolution proxy records that consistently span a wide range of time periods are scarce. The most notable records are the Greenland and Antarctica ice cores, and Chinese cave deposits. As a consequence, data from single locations has often been used to infer past climate changes not only on regional but also on global spatial scales (Dansgaard et al., 1993; Jouzel et al., 1994; Shackleton, 2001). Several major problems arise when dealing with a limited number of patchy proxy records, some of which are:

1) Climate-proxy relationship that hold true in the present climate may not be valid in a different climate (e.g., the modern temperature-isotope relationship for the ice cores may be different during the last glacial period).
2) Proxies often record only seasonal changes, and a shift in seasonality of the recorded climate variable may lead to a flawed comparison between seasons (e.g., the isotopic composition of a given planktonic species reflects the temperature of sea water during that part of the year for which environmental conditions are most favorable for blooming. Therefore, in a different climate state the blooming month could be different and consequently the comparison would be between two different times of the year).
3) The signal recorded by proxies may represent local climate changes rather than regional or global changes.

Combining proxy records with climate model studies can help to resolve some of these problems. Models can be useful tools to help understand the mechanisms of past climate changes and how external forcings can alter internal atmospheric variability and consequently, affect the signal recorded by proxies. Moreover, climate models can fill the paleoclimatic information gap between local and global scales.

Similarly, paleoclimate reconstructions offer the possibility of testing climate models. A model might be able to reproduce current climate, but this is not conclusive evidence it is a reliable model for representing different climate states. Climate models have many parameterizations that have been developed using present-day observations. Simulating different climate states provides a good opportunity to test the validity of these parameterizations . If models prove to be reliable in such tests, more confidence can be placed in their ability to predict future climatic changes in response to anthropogenic forcing (Rind, 1993). However, developing a quantitative understanding of the underlying physical mechanisms is the only way to be able to learn from the past for the future, as there might not be direct analogues of the future in the past.

2. Background

Climate variability is usually characterized in terms of "anomalies", where anomalies are the differences between the instantaneous value of a particular climate variable and its long term mean.

The main focus of this thesis is the climate variability in the North Atlantic and its teleconnection during the late Quaternary (~ 20 000 to 0 yr BP).

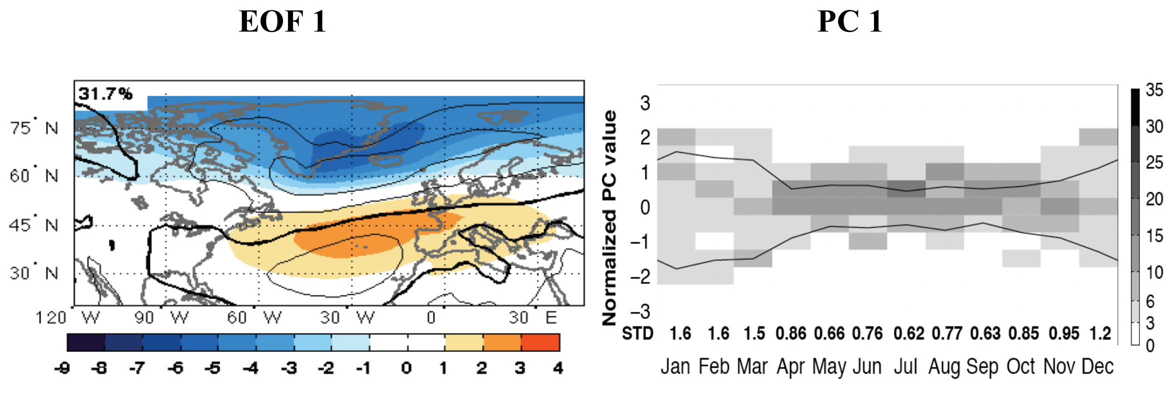
One of the most important and best-known climate variability patterns is the North Atlantic Oscillation (NAO), defined as anomalies in the pressure difference between the Icelandic Low and the Azores High pressure. Even though the NAO is fundamentally an atmospheric phenomenon, it also affects the North Atlantic Ocean via changes in heat content, gyre circulations, mixed layer depth, salinity, high latitude deep water formation and sea ice cover (e.g., Hurrell and Deser, 2009). In turn, the North Atlantic Ocean can alter the NAO via changes in the northward heat transport and sea ice extent (e.g., Rhines et al., 2008) connected to the Meridional Overturning Circulation (MOC). The influence of past changes in the MOC are not restricted to the North Atlantic basin, but affects large parts of the globe (Overpeck et al., 1996, Ganopolski et al., 2001) via changes in atmospheric and ocean circulation. Several studies (e.g., Wang et al., 2001, Yuan et al., 2004) have shown that past changes in the North Atlantic climate have lead to changes in the climate far afield influencing for example, the intensity of the South Asian monsoon system.

The following sections will present an overview on (i) the atmospheric variability - focusing on the North Atlantic sector; (ii) the key role of the North Atlantic in the past and its teleconnection with South Asia; (iii) the south Asian climate.

2.1 Atmospheric Variability

The variability in the atmosphere is controlled by different sources depending on the timescales considered. In addition to daily and seasonal variations in solar radiation, the main source of variability is baroclinic instability on short timescales. On longer timescales (from interannual to millennial) the boundary conditions (e.g., topography and greenhouse gas concentrations) become dominant in setting the patterns of atmospheric variability.

Using statistical techniques, the extratropical tropospheric variability can be represented by a limited set of variability patterns. A broadly used technique is the so-called Empirical Orthogonal Function (EOF) analysis. The EOF method provides a set of orthogonal basis functions, whose variability is represented by a set of spatial patterns and timeseries (the principal components, PC) that describes the temporal evolution of the spatial pattern. This statistical method can be applied to data set with different temporal resolution (daily, monthly, seasonal, etc.) and spatial domains. It should be kept in mind that the patterns of variability identified using the EOF technique could be merely statistical modes that do not reflect any physical process.



EOF 1

PC 1

Fig. 1: Leading EOF (left) of monthly sea level pressure anomalies (colored shading: hPa/standard deviation of PC) and sea level pressure climatology (contours: 4 hPa intervals; the bold contour denotes 1016 hPa) in the North Atlantic sector (all months). Number shows the amount of variance explained by the first EOF1. Right panel shows the histogram of the normalized leading principal component (PC1) of sea level pressure (right) as a function of month. The standard deviations of the PC are indicated along the *x*-axis. ERA-40 reanalysis data for the period 1957–2002 has been used.

However, when EOF analysis is applied to the North Atlantic domain, the leading pattern of variability (Fig. 3) is associated with a highly dynamical process and represents the North Atlantic Oscillation (NAO) and the principal component is associated with the NAO-index timeseries (Fig. 1).

The NAO was introduced for the first time in 1924 by Sir Gilbert Walker and is defined as the normalized pressure difference between a station on the Azores and one on Iceland. The positive phase of the NAO corresponds to a lower than normal sea level pressure in the northern North Atlantic and an extension of the Azores high pressure towards the Mediterranean Sea. Positive anomalies in the NAO therefore lead to wet and mild conditions over Northern Europe, drier conditions over Southern Europe and colder than average conditions over Greenland and Eastern Canada (Fig. 2). The NAO is normally considered as a winter phenomenon (see Fig. 1); however, it does have a significant influence on summer circulation as well (Folland et al., 2009).

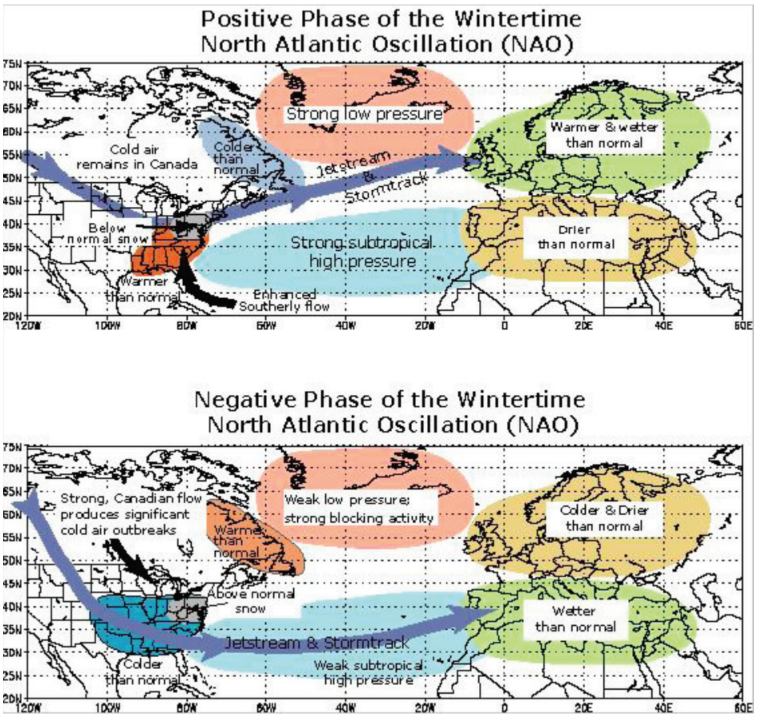


Fig. 2: The positive (top) and negative (bottom) phase of the NAO (Images from NOAA, Lamont-Doherty Earth Observatory).

2.2 Role of the Atlantic Ocean in the past and its teleconnections

The North Atlantic Ocean has been centre of several abrupt climate changes during the last glacial period, such as Dansgaard-Oeschger (D-O) and Heinrich (H) events (Fig. 3). The D-O events are rapid warming episodes in Greenland that occur in a matter of few decades, followed by a gradual cooling (Dansgaard et al., 1993). The Heinrich events are large freshwater discharges from the ice sheet over North America into the North Atlantic that occurred irregularly throughout the ice age: 6 events during the last ice age (Heinrich, 1998; Bond et al., 1992).

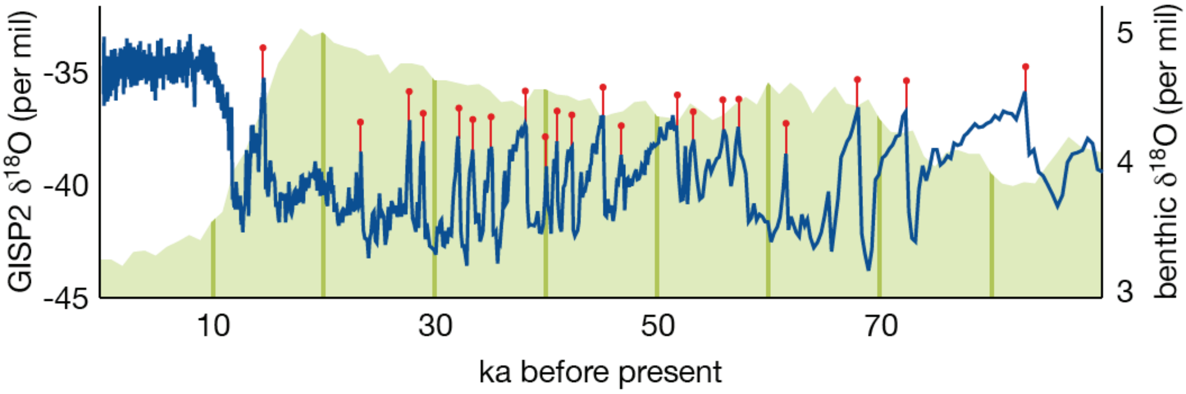


Fig. 3: Global ice volume and D-O events during the last glacial period. The blue curve (left axis) represents the $\delta^{18}O$ from GISP2 ice core (Grootes et al., 1993) with the red pins marking the D-O events. The filled green curve (right axis) represent global ice volume inferred using the $\delta^{18}O$ stack from marine sediment cores (Lisiecki and Raymo, 2005) — from Camille Li (2007).

The climate changes related with these events are not confined to the North Atlantic sector, but are communicated over a large part of the globe (Overpeck et al., 1996; Ganopolski et al., 2001) through changes in atmospheric circulation (Chiang et al., 2003; Jin et al., 2007; Li et al., 2010) as well as in ocean currents and the MOC (e.g., Vellinga and Wood, 2002) in response to rapid changes in Nordic Seas sea-ice extent. The rapid climate changes associated with D-O and Heinrich events are faithfully recorded in the isotopic records in Greenland ice cores (e.g., Grootes et al., 1993) as well as in cave deposits throughout Southeast Asia (e.g., Hulu cave; Wang et al.,

2001) and ocean sediments in the Cariaco basin off the coast of Venezuela (Haug et al., 2001). Therefore, the abrupt warming or cooling in the North Atlantic and the consequent reorganization of atmospheric and ocean circulation has an impact on the Asian monsoon system (Hulu cave) and on the location and strength of the Intertropical Convergence Zone (Cariaco basin).

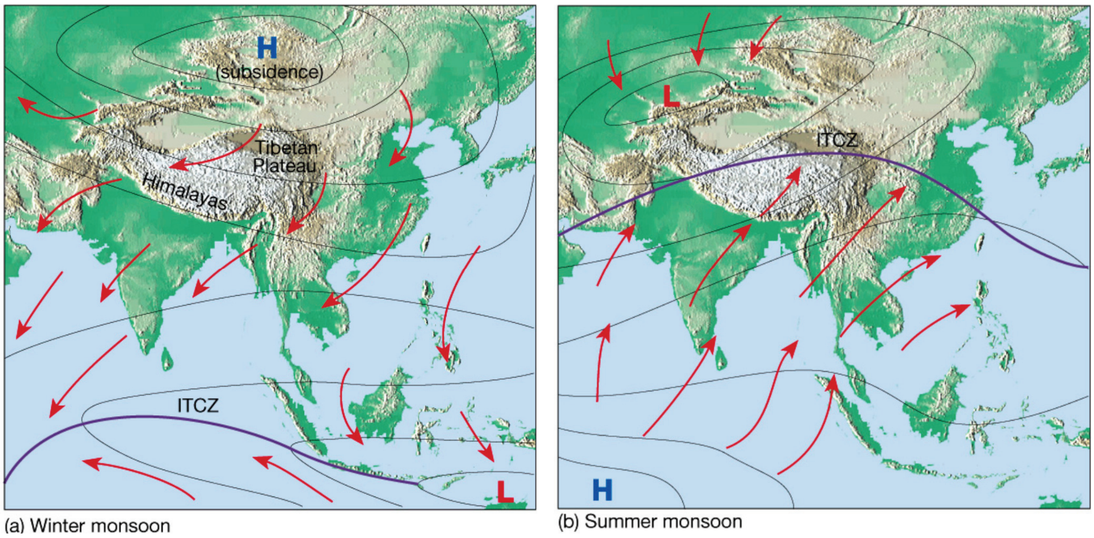
2.3 South Asian monsoon system

A monsoon is traditionally defined as a seasonally reversing wind accompanied by seasonal changes in rainfall (Ramage, 1971), but the term is now used to describe seasonal changes in atmospheric circulation and precipitation due to asymmetric heating of land and sea (Trenberth et al., 2000). The major monsoon systems of the world include the West African and Asian monsoons.

The Asian monsoon system affects the entire eastern hemisphere tropics and subtropics. During winter, the Eurasian land mass cools off rapidly compared to the Indian and Pacific and a vast thermal high pressure system extends over Siberia and the Tibetan Plateau. This anticyclone directs air masses across the Himalaya and the Indo-Gangetic Plain towards the Indian Ocean and the equator, causing heavy rains over Indonesia, northern Australia and the South Pacific Convergence Zone (Fig. 4a). During summer, the Indian subcontinent as well as the Asian continent heat up considerably, which cause a low pressure system to develop over these regions. This low pressure draws moisture-laden winds from the Indian Ocean toward the Himalayas, which acts as a barrier to the low-level atmospheric flow and causes substantial orographic precipitation (Fig. 4b).

The Asian monsoon can be divided in two sub-systems: the South Asian monsoon and the East Asian monsoon.

The **South Asian monsoon** includes the regional monsoons that occur over India, the Indochina Peninsula, and the South China Sea. The South Asian monsoon can be seen



(a) Winter monsoon

(b) Summer monsoon

Fig. 4: (a) Winter Asian monsoon; (b) Summer Asian monsoon. The red arrows show the prevalent wind direction; the purple line the approximate position of the Intertropical Convergence Zone (ITCZ). www.atmos.umd.edu – University of Maryland.

as classical tropical monsoon circulations in which rain falls almost entirely in an Intertropical Convergence Zone (ITCZ) displaced from the equator. The onset of the summer monsoon is linked to a clear change in the wind shear as a consequence of the thermally driven nature of the monsoon: westerlies at the surface and easterlies aloft. Accordingly, Webster and Yang (1992) suggested that the strength of that zonal wind shear provides a good measure of the strength of the South Asian summer monsoon. Goswami et al. (1999) modified Webster&Yang's index considering the vertical shear of meridional winds that measures the overturning over south Asia and the Indian Ocean associated with the local Hadley cell (SAM index, Table 1) They found that this modified monsoon index correlated better with monsoon rainfall on India than did the original.

The **East Asian monsoon**, which affects the climates of China, the Korean Peninsula, and Japan, is instead extratropical in nature, since precipitation and winds are associated with frontal systems and the jet stream. During winter, precipitation is confined to southern China and associated with convergent frontal circulation (e.g., Y.-S. Zhou et al., 2004). During spring, precipitation remains organized in a band

(Meiyu Front) and migrates northward, reaching a maximum in mid-June over the Yangtze River basin of central China and eastward over Japan. The abovementioned front breaks down during a relatively rapid transition to summer circulation, and rainfall becomes highly irregular. The migration and evolution of these fronts are closely associated with seasonal changes in the East Asian jet stream (Liang and Wang, 1998). The index to measure the strength of the East Asian monsoon (Lau et al., 2000) is linked to wavetrains associated with the subtropical jet (Table 1). Thereby, its dynamics seems to be affected more by Tibet's lying in the path of the subtropical jet stream rather than a land-sea contrast. It follows that the use of the term "monsoon" to define it is somehow a misnomer (Molnar et al., 2010).

Table 1: Asian monsoon indeces.

Name of the index	Type of index	Domain of application	Definition	References
AIMR (All-India Monsoon Rainfall)	Precipitation	India	Rainfall over India	Parthasarathy et al. (1992)
W-Y (Webster&Yang)	Circulation	Tropical Asia	U850-U200 0°-20°N, 40°-110°E	Webster and Yan (1992)
SAM (South Asian Monsoon)	Circulation	South Asia	V850-V200 10°-30°N, 70°-110°E	Goswami et al. (1999)
EAM (East Asian Monsoon)	Circulation	East Asia	U200 (40°-50°N, 110°-150°E) - U200 (25°-35°N, 110°-150°E)	Lau et al. (2000)

The Asian monsoon fluctuates with large amplitude on various timescales from interannual to orbital timescales. The interannual variability of the Asian monsoon is associated with the yearly deviation from the climatological annual mean and is affected by many large-scale phenomena, such as the El Niño-Southern Oscillation (ENSO). On longer timescales, the Asian monsoon can vary its amplitude due to abrupt climate changes (millennial timescales) or changes in the solar radiation (orbital timescales). As an example, sudden increases in the sea ice extent in the North Atlantic during Heinrich events cause changes in atmospheric and ocean circulation that impact the strength and the variability of the Asian monsoon (e.g., Schulz et al., 1998).

3. Motivation

The broad aim of this thesis is to provide insights into past climate variability, comparing climate model simulations with proxy data for different climate states, in order to understand what signals proxies record and the physical mechanisms behind what is recorded. Specifically, the present thesis will tackle the following questions:

1) What is the range of past atmospheric variability in the North Atlantic region?

2) What is the main driver of past atmospheric variability in the North Atlantic region?

3) What temperature signal (seasonal or annual) do different marine proxies record in the North Atlantic?

4) What is the impact of abrupt climate changes in North Atlantic on the monsoon signal in Asian cave deposits during abrupt climate changes?

1) In studying past climate variability, the focus is primarily on the comparison between a glacial climate and the pre-industrial one, but we also look at a warm state (the mid Holocene, MH; 6 kyr BP). Different climate models are used in order to evaluate whether or not there is general agreement in simulating these different climates. Using different models also provides insights into whether the parameterizations used are good, not only in representing the modern climate but also in representing different climate states. The aim is to understand how the atmospheric circulation and the dominant mode of variability might have changed, and the causes behind their changes in a completely different climate state. How changes in atmospheric variability might have affected the signal recorded by climate proxies is another aspect of this study.

2) Various forcings, such as greenhouse gases and topography, are responsible for altering the atmospheric circulation during a glacial state. To help understand the influence of each forcing in affecting atmospheric variability, a suite of sensitivity

studies is analyzed. Determining what effect each forcing exerts on atmospheric variability can also help to understand the anthropogenic impacts on climate: climatic variations may be characterized by an increase in variability without a change in the mean state. This aspect is a crucial characteristic of climate: if climate variability increases, extreme weather events become more probable and the strain on social and political systems increases.

Tackling the third and the fourth issue, we directly compare model simulations with proxy data in order to resolve some apparent contradictions among different proxies.

3) It has been shown that different plankton species record different signals for the same time period (e.g., Jansen et al., 2008): phytoplankton- (such as alkenones) based temperature records show a cooling trend from the early-mid Holocene to present day, whereas zooplankton (such as foraminifera) proxies exhibit a warming. It has been hypothesized that the two species record different seasons, or that the surface ocean temperature and waters close to the thermocline evolved differently (Jansen et al., 2008). To help resolve this issue, a model study comparing the seasonal response of temperature at different depths has been performed.

4) Another apparent contradiction between different proxies is related to changes in the millennial and orbital time scale variability of the Asian monsoon systems. Past regional climate changes in South Asia have been inferred using Asian cave deposits and they appear to be related to climate changes in the North Atlantic basin (e.g., Wang et al., 2001; Yuan et al., 2004). To date it has been widely accepted that Indian caves record changes in the Indian summer monsoon, whereas eastern Chinese caves record changes in the East Asian summer monsoon. Moreover, because the chronology of Indian caves and eastern Chinese caves are nearly identical, it has been assumed that the intensity of the Indian and East Asian summer monsoons vary in phase (Cai et al., 2006). However, independent proxy studies (peat bogs and pollen), recording mainly local climate (precipitation and temperature) changes cast some doubts on the interpretation of the in-phase relationship between the two monsoon

systems (Hong et al., 2005; Nakagawa et al., 2006). Asian cave deposits are unique proxies because the oxygen isotopic composition of the calcite forming the stalagmites in the caves can be dated precisely with a high resolution and over a long time span. It is therefore compelling to clearly understand the climatological significance of the signals recorded in the Asian cave deposits.

4. Summary of the papers

The first part of the thesis (Papers I and II, and appendix I) investigates past atmospheric variability in the extra-tropical North Atlantic in different climate states: pre-industrial climate (PI, 1750 AD), mid Holocene (MH, 6 kyrs before present) and Last Glacial Maximum (LGM, 21 kyrs before present). The analyses have been carried out using four different climate models. The models generally agree on representing the mean climate state and its variability during both the PI and MH, whereas they show different behaviors at the LGM. At the MH, the models exhibit no changes in the interannual variance of sea level pressure (SLP) compared to the PI, whereas the LGM simulations show a significant reduction in SLP variance. The North Atlantic Oscillation (NAO) is the leading mode of SLP variability in the PI climate simulations. NAO-like behavior (similar to the PI) is shown at MH, whereas the leading mode during the LGM is model dependent, but in each model differ from that in the PI climate. The pattern and the amplitude of the leading mode, the SLP variability and the mean circulation are largely determined by the topography. Finally, the models show that when the boundary conditions such as topography are remarkably different (i.e. LGM), the relationship between atmospheric variability and surface climate (temperature and precipitation) changes and proxy signals could be misinterpreted if changes in the spatial pattern and seasonality of surface climate variability are not well understood and taken into account.

The second part of the thesis (Papers III and IV) addresses the issue that different proxy records appear to show different climate histories for the same time period.

Paper III attempts to explain what temperature signal (seasonal or annual) alkenones and diatoms (phytoplankton) record compared to foraminifera and radiolarian (zooplankton) in the North Atlantic in the Holocene. Phytoplankton record sea surface temperature (SST) and show a warm early to mid Holocene optimum. On the other hand, zooplankton record temperature close to the thermocline and show a cool mid Holocene anomaly with a trend towards warmer temperature in the late

Holocene. A coupled climate model (CCSM3) has been used to test the hypothesis that thermocline temperature closely follows winter SST. If so, it would follow that the alkenones and diatoms living close to the surface record summer SST, whereas foraminifer and radiolarian species that live close to the thermocline record winter SST. Model results show a strong summer warming of the SST during mid Holocene, whereas sub-surface depth experiences a cooling. These physical changes in the surface and sub-surface characteristics of the water mass (hydrography) corroborate the above-mentioned hypothesis and explain the discrepancies between the Holocene trends shown by the different plankton-based temperature records.

Paper IV tackles two issues: (i) what is the nature of the oxygen composition signal recorded in the calcite of Asian cave deposits during abrupt climate changes? and (ii) why do independent proxies apparently exhibit a different behavior regarding the variability of the Asian monsoons? This study shows how the North Atlantic might have affected monsoon variability during Heinrich events. Changes in the $\delta^{18}O$ in stalagmites could be due to local changes in the $\delta^{18}O$ of the precipitation (Dansgaard et al., 1964; Wang et al., 2001; Cheng et al., 2006; Cheng et al., 2009) reflecting for example, changes the seasonality of precipitation; or to non-local changes (Rozanski et al., 1993, LeGrande et al., 2009) such as variation in the origin of the water vapor delivered or in the processing of the vapor during transport. However, the importance of non-local changes in $\delta^{18}O$ of precipitation is unknown. Our model study shows that changes in $\delta^{18}O$ of the precipitation at Asian cave locations during abrupt cooling such as Heinrich events are mainly due to changes in the Indian Ocean surface temperatures, which decrease the intensity of the precipitation of the Indian summer monsoon. On the other hand, no changes in the East Asian summer monsoon are shown. Our study points out that caves in Eastern China (e.g., Hulu) record non-local changes in precipitation. Furthermore, they are not proxies for changes in the East Asian summer monsoon, as previously thought (Yuan et al., 2004, Wang et al., 2008), but rather changes in the Indian Ocean temperature, and as a consequence, in the

Indian summer monsoon. We suggest that Asian caves may record Indian Ocean temperature changes not only on millennial timescales but also on orbital timescales.

5. Conclusions and outlook

This thesis has focused on various features related to climate variability in the North Atlantic from both a model and a proxy prospective.

The first part of the thesis (Paper I, II and Appendix I) tries to identify the key drivers of atmospheric variability in the Northern Hemisphere. It also provides insights into the potential effects of changes in atmospheric variability and the climatological significance of signals recorded by proxies in the North Atlantic.

The general findings can be summarized in three points:

1) Whereas models show a fair agreement in simulating atmospheric variability in a warmer climate, they fail to depict a consistent spatial pattern of surface climate and sea level pressure variability in a glacial state.

2) Present-day climate parameterizations and approximations work properly for climate states with boundary conditions similar to today, especially topography. In a glacial state, the differences among the models can be either due to the fact that present-day climate parameterizations do not work correctly in an extremely different climate state, or to the model-dependent treatment of topography, which is shown to be really important in altering atmospheric variability.

3) Improved understanding of the link between surface climate and atmospheric variability in the North Atlantic during a glacial climate state and its potential impact on terrestrial proxies.

The importance of topography in setting the position and behavior of the jet stream in the North Atlantic in a glacial climate has been shown in earlier studies (Justino et al., 2005; Li and Battisti, 2008). This work provides a step forward in understanding the changes in atmospheric variability between glacial and modern by demonstrating that changes in ocean surface temperature matter relatively little in term of their influence on atmospheric circulation on interannual timescales.

The second part of the thesis (Papers III and IV) shows how climate models can be an useful tool in investigating apparent controversies among different proxy records. When model simulations produce a climate response that is spatially and temporally consistent with paleoclimate records, climate models can be successfully used in order to interpret and understand the physical mechanisms driving the changes in the proxy data. However, in both Paper III and IV, more extensive data-model comparisons are needed to test further hypotheses.

In paper III, the explanation regarding differences in plankton temperature trends (phytoplankton record summer temperature, zooplankton annual/winter temperature) does not exclude the possibility of shifts in productivity season or changes in depth habitat of the species in a different climate state. Furthermore, changes in the ocean dynamics linked to the inflow of Atlantic water could potentially be the common source of temperature trends seen in the foraminifer records. However, the impact of a changed Atlantic inflow has only been examined for the instrumental period (Hàtùn et al., 2005), i.e. on decadal timescales. Therefore, a combined model-proxy study where both high-temporal resolution records are compared with coupled ocean-atmosphere climate models would be necessary to test the previous hypotheses on longer timescales.

In paper IV, it is hypothesized that Indian Ocean temperature plays a crucial role in setting the monsoon variability and consequently the $\delta^{18}O$ signal recorded throughout south Asia on millennial and possibly on orbital timescales. In order to test this assumption, further experiments are needed using, for example, early-mid Holocene (9-6 kyrs before present) sea surface temperature to force an atmosphere-only climate model. During early-mid Holocene the orbital configuration and insolation were substantially different to today’s and the surface ocean was in general warmer at mid-to-high latitudes. These experiments will allow us to test the response of $\delta^{18}O$ of precipitation in Asian cave deposits to insolation (orbital forcing).

References

Bond, G. et al.: Evidence for massive discharges of icebergs into the North-Atlantic Ocean during the last glacial perirod. *Nature* 360, 245–249 (1992).

Briffa, K. R., Jones, P. D., Schweingruber, F. H. and Osborn, T. J.: Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. *Nature* 393, 450-455 (1998).

Cai, Y. et al.: High-resolution absolute-dated Indian Monsoon record between 53 and 36 ka from Xiaobailong Cave, southwestern China. *Geology* 34, 621–624 (2006).

Cheng, H. et al.: A penultimate glacial monsoon record from Hulu Cave and two-phase glacial terminations. *Geology* 34, 217–220 (2006).

Cheng, H. et al.: Ice Age Terminations. *Science* 326, 248–252 (2009).

Chiang, J. C. H., Biasutti, M. and Battisti, D. S.: Sensitivity of the Atlantic Intertropical Convergence Zone to Last Glacial Maximum boundary conditions. *Paleoceanography* (2003).

Cook, E. R. et al.: Asian Monsoon Failure and Megadrought During the Last Millennium. *Science* 328, 486-489 (2010).

Dansgaard, W.: Stable isotopes in precipitation. *Tellus* 16, 436–468 (1964).

Dansgaard, W. et al.: Evidence for General Instability of Past Climate from a 250-Kyr Ice-core Record. *Nature* 364, 218–220 (1993).

Folland, C. K., Knight, J., Linderholm, H. W., Fereday, D., Ineson, S. and Hurrell, J. W.: The summer North Atlantic Oscillation: Past, present, and future. *Journal of Climate* 22, 1082–1103 (2009).

Ganopolski, A. and Rahmstorf, S.: Rapid changes of glacial climate simulated in a coupled climate model. *Nature* 409, 153–158 (2001).

Goswami, B. N., Krishnamurthy, V. and Annamalai, H.: A broad-scale circulation index for the interannual variability of the Indian summer monsoon. *Q. J. R. Meteorol. Soc.* 125, 611–633 (1999).

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. and Jouzel, J.: Comparison of oxygen-isotopes records from the GISP2 and GRIP Greenland ice cores. *Nature* 366, 552-554 (1993).

Hàtùn, H., Sandø, A. B., Drange, H., Hansen, B., and Valdimarsson, H.: Influence of the Atlantic Subpolar Gyre on the Thermohaline Circulation. *Science* 309, 1841–1844 (2005).

Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C. and Rohl, U.: Southward migration of the Intertropical Convergence Zone through the Holocene. *Science* 293, 1304-1308 (2001).

Heinrich, H.: Origin and consequences of cyclic ice rafting in the Northeast Atlantic-Ocean during the past 130,000 years. *Quat. Res.* 29, 142–152 (1988).

Hong, Y. T. et al.: Correlation between Indian Ocean summer monsoon and North Atlantic climate during the Holocene (vol 211, pg 371, 2003). *Earth Planet. Sci. Lett.* 215, 317–318 (2003).

Hong, Y. T. et al.: Inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the last 12,000 years and paleo-El Nino. *Earth Planet. Sci. Lett.* 231, 337–346 (2005).

Hurrell, J. W. and Deser, C.: North Atlantic climate variability: The role of the North Atlantic Oscillation. *J. Mar. Sys.* 78, 28-41 (2009).

Jansen, E., Andersson, C., Moros, M., Nisancioglu, K. H., Nyland, B. F., and Telford, R. J.: The early to mid Holocene thermal optimum in the North Atlantic, in: Natural Climate Variability and Global Warming – A Holocene Perspective, edited by: Battarbee, R. W. and Binney, H. A., Wiley-Blackwell, Chichester, 123-137 (2008).

Jin, L., Chen, F., Ganopolski, A. and Claussen, M.: Response of East Asian climate to Dansgaard/Oeschger and Heinrich events in a coupled model of intermediate complexity. J. *Geophys. Res.-Atmos.* 112 (2007).

Jouzel, J., Lourius, C., Johnsen, S., and Grootes, P.: Climate Instabilities – Greenland and Antarctic Records. *Comptes Rendus De l'Academie Des Sciences* Serie II, 319, 65–77 (1994).

Lau, K. M., Kim, K. M. and Yang, S.: Dynamical and boundary forcing characteristics of regional components of the Asian summer monsoon. *J. Climate*, 13, 2461-2482 (2000).

Justino, F., Timmermann, A., Merkel, U. and Souza, E. P.: Synoptic reorganization of atmospheric flow during the last glacial maximum. J. Climate, 18, 2826-2846 (2005).

LeGrande, A. N. and Schmidt, G. A.: Sources of Holocene variability of oxygen isotopes in paleoclimate archives. *Clim. Past* 5, 441–455 (2009).

Li, C.: A general circulation modelling perspective on abrupt climate change during glacial times, Ph.D. thesis, University of Washington (2007).

Li, C. and Battisti, D. S.: Reduced Atlantic storminess during Last Glacial Maximum: Evidence from a coupled climate model. *J. Climate*, 21, 3561-3579 (2008).

Li, C., Battisti, D. S. and Bitz, C. M.: Can North Atlantic sea ice anomalies account for Dansgaard-Oeschger climate signals? *J. Climate,* In press (2010).

Liang, X.-Z. and Wang, W.-C.: Associations between China monsoon rainfall and tropospheric jets. *Q. J. R. Meteorol. Soc.* 124, 2597–623 (1998).

Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic delta O-18 records. *Paleoceanography* 20 (2005).

Molnar, P., Boos, W. R. and Battisti, D. S.: Orographic Controls on Climate and Paleoclimate of Asia: Thermal and Mechanical Roles for the Tibetan Plateau, *Annu. Rev. Earth Planet. Sci.*, Vol. 38, 77-102 (2010).

Nakagawa, T., Tarasov, P. E., Kitagawa, H., Yasuda, Y. & Gotanda, K.: Seasonally specific responses of the East Asian monsoon to deglacial climate changes. *Geology* 34, 521–524 (2006).

Noone, D. and Sturm, C.: Comprehensive dynamical models of global and regional water isotope distribution. *Springer Verlag* (2009).

Overpeck, J., Anderson, D., Trumbore, S. and Warren, P.: The southwest Indian Monsoon over the last 18000 years. *Clim. Dynam.* 12, 213–224 (1996).

Parthasarathy, B., Kumar, K. R. and Kothawale, D. R.: Indian summer monsoon rainfall indices: 1987-1990. *Meteor. Mag.* 121, 174-186 (1992).

Ramage, C.: Monsoon Meteorology. *International Geophysics Series*, Vol. 15, 296 pp., Academic Press, San Diego, Calif. (1971).

Rhines, P., Häkkinen, S. and Josey, S. A.: Is oceanic heat transport significant in the climate system? - Springer Eds., Ch. 4 (2008).

Rind, D. and Overpeck, J.: Hypothesized causes of decadel-to-century climate variability: climate model results. *Quat. Sci. Rev.* 12, 357-374 (1993).

Rosanski, K., Araguas-Araguas, L. and Gonfiantini, R.: Isotopic patterns in modern global precipitation. AGU monograph, Pp. 1-36 (1993).

Shackleton, N.: Paleoclimate – Climate change across the hemispheres. *Science* 291, 58–59 (2001).

Schulz, H., von Rad, U. and Erlenkeuser, H.: Correlation between Arabian Sea and Greenland climate oscillations of the past 110,000 years. *Nature* 393, 54-57 (1998).

Trenberth, K. E., Stepaniak, D. P., Caron, J. M.: The global monsoon as seen through the divergent atmospheric circulation, *Journal of Climate*, 13, 3969-3993 (2000).

Vellinga, M. and Wood, R. A.: Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change* 54, 251-267 (2002).

Wang, Y. J. et al.: A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. *Science* 294, 2345–2348 (2001).

Wang, Y. J. et al.: Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years. *Nature* 451, 1090–1093 (2008).

Webster, P.J. and Yang, S.: Monsoon and ENSO: selectively interactive systems. *Q. J. R. Meteorol. Soc.* 118, 877–926 (1992).

Yuan, D. X. et al.: Timing, duration, and transitions of the Last Interglacial Asian Monsoon. *Science* 304, 575–578 (2004).

Zhou, Y.-S., Gao, S.-T. and Shen, S. S. P.: A diagnostic study of formation and structures of theMeiyu front system over East Asia. *J. Meteorol. Soc. Jpn.* 82, 1565–1576 (2004).