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HOW FAST IS ABRUPT CLIMATE CHANGE? PUTTING EVIDENCE FROM ICE CORES INTO CONTEXT WITH OTHER PALEOCLIMATE ARCHIVES

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ABSTRACT

The abrupt climate change events that happened during the Last Glacial Period, are the most remarkable variations of the climate in the past. These events are characterized with very rapid temperature, accumulation rate and atmospheric circulation variations over short time, sometimes happening only in a few decades, with temperature shifts as large as 16 °C. The changes that are characterizing the abrupt climate change events, are recorded in the proxies of the paleoclimate archives. The primary purpose of the paleoclimatology is the analysis of the archives that preserve the information of the climate changes in the past, and translating of the measured variables present in encrypted form, into useful data. This is of crucial importance not only for obtaining information about the principle of functioning of the climate system, but also for learning about similar changes that are happening today, or might happen in the future. The recent global warming phenomenon might be considered as an abrupt climate change event as well, due to its short time-scale. The study of the abrupt climate change events that happened in the past, might provide the necessary knowledge for this phenomenon, and the risks related to it.

The exact processes that are responsible for the occurrence of the events are still not revealed completely. The most symbolic feature of the events is their abruptness, in comparison to the gradual changes that are happening in the climate system as a result of the different forcing factors. According to this, the reasons behind their occurrence, must be looked for into the internal mechanisms of the climate system, such as the feedback processes, that might be responsible for enhancing of the small perturbations, and leading to the noticeable abruptness.

This research will try to provide answers about the time-scale of the abrupt climate change events, and the required resolution necessary for their analysis. There are many paleoclimate archives that have recorded the abrupt climate change events, among which the ocean sediments, the speleothems and the ice cores provide good resolution needed for capturing the variations related to the events that occur very rapidly. From these, the ice cores are the most outstanding records, due to the ultra-high-resolution that they can offer. The represented features of the events and the results of the analysis of the ocean sediments and the speleothems in this research, should provide the necessary knowledge about the time-scale and the characteristics of the events. Then, that information should be used for posing a hypothesis of what evidence of the abrupt climate change events should be found in the ice core records, in terms of the proxies and the depth versus time-scale profile. Finally, the hypothesis should be tested against the evidence obtained with analysis of the ice cores with LA-ICP-MS.

The main objective of this research is to represent that studying of the abrupt climate change events is of high importance. Moreover, it should show that the analysis of the ice core records with LA-ICP-MS technique, due to the high-resolution, offers the most desirable and precise information about the features that mark the events.

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1. INTRODUCTION

1.1 - Studying the climate of the past

Paleoclimatology is the study of the climate on the planet Earth before the appearance of the instrumental measurements, that occupy very small portion of the climatic history. Analysis of the climate of the past is founded on examining variables that depend on the climate, a dependency that can be measured. These phenomena show a change in a particular feature, that is related to the change in the climate. The phenomena are called climatic archives (Bradley, 2015). The archives are environmental systems that usually contain a material that is deposited in a continuous way (Stocker, 1999). The indicators of the climate in the past, included in the climate archives are known as climate proxies. The information that can be obtained from these indicators cannot be directly related to the climate conditions at the particular period in the past. That is why analyses of the processes that allow recording of the climatic signals in these indicators is necessary (Ruddiman, 2013). It can be concluded that the data recorded in the archives, is used to reconstruct climatic changes in the past (Bradley, 2015). This information is typically present in an encrypted form. Hence, special techniques are required for allowing translation of the measured variables into data that is desired (Stocker, 1999). Studying the proxy data provided by the archives is the primary objective of the paleoclimatology. This can be used for understanding of the reasons for the variations and draw conclusions about the principle of working of the climatic system (Bradley, 2015).

1.2 - Components of the climate system and their response time

The climate system consists of five elements: ocean, atmosphere, cryosphere, lithosphere and biosphere. The changes in the climate system are occurring as a result of the climate forcings, to which the different compartments of the climate system respond. The three primary climate forcings, are the tectonic processes, the orbital changes and the changes in the strength of the sun. Some include the anthropogenic forcing as well. The different components of the climatic system, after being influenced by the forcing factors, respond with different response times. A response time is the time necessary for the complete reaction to the imposed change. In particular, the atmosphere responds to changes within hours, and it is probably the fastest responding component of the climate system. The lithosphere responds slower, with changes occurring from hours to days, even weeks. The water has a response time that is even slower, because of its bigger heat capacity. Namely, the upper layers of the water body respond within weeks or months, while the deeper parts have response time ranging from decades to many centuries. Then, the cryosphere, such as the mountain glaciers, respond within decades, while the ice sheets represent the parts of the climatic system that have the slowest response, many thousands of years. Finally, the vegetation might have short response times, and respond within hours, or longer seasonal changes that might occur within weeks to months. A comparison between the duration of the forcing and the response, represents that the forcing can be substantially slower compared to the response, both can occur with similar time-scale and the forcing can be faster compared to the response of the climate system. Usually the changes in the nature occur in continuous cycles, with continuously changing forcings. In addition, the frequency of the forcings influences the amplitude of the responses, and a slower occurring forcing causes larger response, while forcings with shorter cycles lead to smaller responses. An example of forcings that occur within longer time-scale, are the orbital changes that happen over tens of thousands of years, leading to large time-scale responses of the ice sheets, that grow and melt in a cycle with similar time-scale as the forcing (Ruddiman, 2013).

Importantly, following this explanation and the analysis of the orbital forcings, it can be concluded that such forcings cause gradual, and not abrupt climate changes. So, more abrupt changes in the climate system, probably occur due to internal mechanisms and feedback processes. The ice albedo is an example of a positive feedback mechanism, that causes higher reflection of the solar energy, with increasing of the ice cover, and vice versa. As a consequence, when the ice cover is increased during colder periods, the ice albedo feedback causes further cooling with the reflection of the incoming insulation (Ruddiman, 2013).

1.3 - Abrupt climate change events and period of occurrence

During the Last Glacial Period, from about 90 to 13 kyr Before Present, climatic oscillations that were large in amplitude over intervals significantly shorter that the orbital cycles, took place (Ruddiman, 2013). These events, that marked the Last Glacial Period are called Abrupt climate change events (Broecker, 2003). Abrupt climate change events are oscillations in the temperature and the other weather conditions, that occur very rapidly and with large amplitudes. During the abrupt climate change events, the climate system suddenly shifts from one equilibrium state to another, and the meteorological variables drastically change (Easterbrook, 2019).

An abrupt climate change event happens at a particular time when the climate system is forced to cross a threshold, this causing transition to another condition at a rate that depends on the climate system itself, and happens with higher velocity than the cause. Due to the internal variability of the climate system, sometimes the cause is so small, that it is difficult to be detected (Abrupt Climate Change, 2002). The climate changes during the abrupt climate change events are discovered to be up to half as large as the difference between the ice age and the modern climate. The abrupt climate change episodes are representing the rapid changes in the atmosphere-ocean-cryosphere-biosphere system (Rashid, Polyak, & Mosley-Thompson, 2011).

In addition to the Last Glacial Period, the abrupt climate changes were a characteristic of the climatic system before that period as well, such as the Paleocene-Eocene Thermal Maximum that occurred 55.8 million years ago, or the fast occurring cooling episodes at the boundaries between the Eocene and Oligocene and Oligocene and Miocene epochs, and similar changes are persisting even in the current warm period, the Holocene (Easterbrook, 2019). For example, a change in the El Niño behavior in 1976 towards wetter and warmer conditions might be considered as an abrupt climate change event, even though this event had a regional scale. Furthermore, extreme events such as abrupt droughts have been found in historical records from the Mayan and Mesopotamian culture. Also, the recent global warming phenomena can be interpreted as an abrupt climate change event. According to this, the abrupt climate change events cannot be considered to be a characteristic only of the glacial periods, but also of the warm phases (Abrupt Climate Change, 2002).

Even though the abrupt climate change events have been studied deeply, an understandable explanation of the main causes and mechanisms behind the events is still lacking. The analysis of the paleoclimate archives and modeling simulations are used for obtaining the answers that are missing. The biggest efforts are put on the study of the ice core records, because of the numerus and precise evidence and information that can be derived from them (Li & Born, 2019).

1.4 - Importance of the analysis of the abrupt climate change events

Understanding the reason and the pathway of the abrupt climate changes that happened during the Last Glacial Period, is of crucial importance. This is because today's civilization is facing similar events, such as the global warming phenomenon (Abrupt Climate Change, 2002). Understanding how the Earth system functions and how the human actions can influence its functioning, is essential in order to provide the necessary knowledge for the transition that we are facing, and how to reduce the risks and the impact of the changes to the economic development (Reid, et al., 2010). Also, this is important because we should be able to manage the climate conditions that may appear as a response not only to large perturbations, but also small perturbations enhanced with feedback mechanisms (Stocker, 1999). In particular, the abrupt climate change events show that a small and gradual change in one of the climatic system components, might result in large changes in the entire system (Easterbrook, 2019). The relation between the global warming and the abrupt climate change events lies in the short time-scale. Similarly to the time-scale of the abrupt climate change events, the global warming phenomenon, that covers the increase of both, the surface air and the sea surface temperature, has happened in the last 200 years (Allen, et al., 2018). The main reason for the global warming phenomenon is considered to be the increase of the greenhouse gases in the atmosphere. Even though that the changes that result from the increase of the greenhouse gas concentrations might take more than a few decades to happen, the feedback mechanisms related to them might trigger more abrupt climate jump. In order to be prepared for such abrupt changes, it is necessary to analyze the abrupt climate changes from the past, and understand the reasons for the occurrence, the mechanism and the spatial and temporal scale (Alley, The Younger Dryas cold interval as viewed from central Greenland, 2000).

Also, an important aspect for studying of the abrupt climate change events, is the possibility that they might result in big and adverse socio-economic and ecology effects. The effects become more significant not only when the temporal and spatial scale of the events are bigger, but also when the variability in the climate is bigger. Having sub-continental or global scale, is an often feature of such events (Abrupt Climate Change, 2002). It is crucial to understand where such changes could have the largest impacts, depending on the population (Alley, The Younger Dryas cold interval as viewed from central Greenland, 2000). Moreover, it is necessary to be capable to predict these events, because their fast occurrence without warning, makes the adaptation and resilience maintenance difficult. Researches have shown that the human population, as well as flora and fauna are more capable to adjust to the changes in the climatic conditions if that changes happen gradually, and not abruptly. Furthermore, it is believed that abrupt climate changes might have strong negative consequences, such as redistribution, and even extinction of the marine and terrestrial species and depletion of the non-renewable resources (Abrupt Climate Change, 2002).

So, in order to reach the sustainability goals, and prevent the negative consequences of the climate changes, we need to improve our knowledge with scientific research and better comprehend how the Earth system functions and which are its critical thresholds. Moreover, research for analyzing the potential impacts of the climate changes on the human health, food security, biodiversity, non-renewable resources, economy, energy, and population response, is necessary as well. Finally, understanding the link between the social and natural systems is crucial for finding the most appropriate way for responding to the threads such as the abrupt non-linear dynamics of the climate system. According to this, we should completely understand the characteristics of the abrupt climate changes that happened in the past with short time-scale, and be prepared for a proper response, ways of adaptation and influence, on similar changes that are happening now, or might occur in the future (Reid, et al., 2010).

1.5 - Main objectives of the research

The primary purpose of this research is to represent the necessity of existence of a high-resolution paleoclimate archive and a high-resolution method for analysis, for the investigation of the abrupt climate change events. The main questions that need to be answered are: “How fast are the abrupt climate change events?” and “What kind of archive and which technique are the most appropriate for the analysis of short time-scale events from the distant past, such as the abrupt climate change events, and what are the main essentialities that the archive and the technique should offer?”. For providing the answers of these questions, it should be determined what is the characteristic time-scale of the changes that mark the abrupt climate change events.

So, for comprehensive understanding of the abrupt climate change events, first their main features are represented. Then, the possible mechanisms that can be responsible for their occurrence, are explained. Also, it is important to represent the numerus archives from all around the world, that contain evidence of the abrupt climate changes that occurred during the Last Glacial Period. A detailed description of the archives that offer the most valuable evidence of the events, follows. Such archives are the ocean sediments and the speleothems. According to the imprints found in these paleoclimate archives, it should be discussed what should be found in the ice cores, in terms not only of the proxies, but also of the time-scale translated into depth of the ice core records. The ice cores are selected because they represent the leading and the most fitting paleoclimate archive capable for capturing and preserving the variations characterizing the abrupt climate change events. Finally, after the discussion about the necessary resolution for studying the abrupt climate change events, an explanation of the most proper technique for the analysis of the ice core records and the results of some performed studies, follows. The most important criterion in determining the most suitable technique, is the sampling resolution that it offers, whether it is high enough in order to reveal the information about the abrupt climate change events preserved in the ice core records.

2. ABRUPT CLIMATE CHANGE EVENTS

The Last Glacial Period, during which the abrupt climate change events occurred, took place from the end of the Eemian (127000-106000 years ago) until the end of the Younger Dryas (115000-11700 years ago). During this period, large ice sheets covered Canada, the northern parts of North America, northernmost Europe and parts of Euroasia. In the remaining parts of the planet, that have not been covered by the ice sheets, the temperatures were low, it was windy, the dust was blown to a large distance, the sea level was considerably lower than today, the vegetation distribution was different and the concentrations of the GHG were lower (Ruddiman, 2013). During the period known as the Last Glacial Maximum, the ice sheets that covered Euroasia, North America, Antarctica and Greenland reached their maximum size. At that time, the global ice volume was equivalent to 110-130 m of sea level. The temperatures were probably 3 °C-8 °C lower than the temperatures during the preindustrial time, and the temperatures were lower over the land compared to the ocean (Li & Born, 2019).

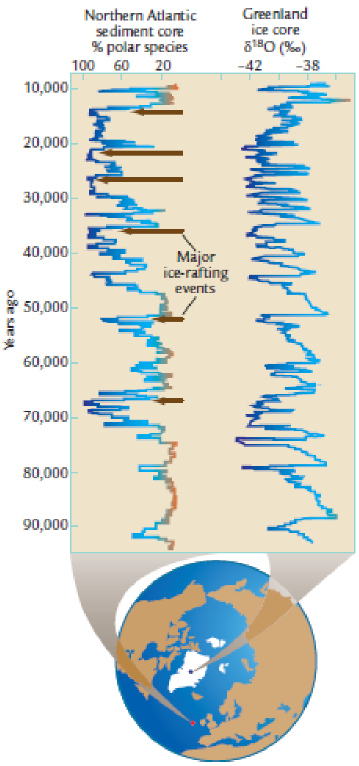
The three groups of abrupt climate change events are: abrupt changes associated with the Dansgaard-Oeschger (DO) events, abrupt changes associated with the Heinrich (H) events and in a separate category, the Younger Dryas (YD), that often is considered as a large Dansgaard-Oeschger event (Broecker, 2003). In the group of abrupt climate changes events, the Bond events, or Bond cycles can be included as well. The Bond cycles are represented by nine ice-rafting events and each one includes three or four Dansgaard-Oeschger events, that are terminated with a Heinrich event (Easterbrook, 2019).

The events are characterized by abrupt temperature changes, up to 16°C and a factor of 2 in precipitation (Abrupt Climate Change, 2002). The analysis of many paleoclimate records has shown that the millennial-scale abrupt climate changes tend to be a typical feature of glacial periods, rather than interglacial ones. This finding suggests that an important role in the mechanism that caused the appearance of these events, is played by the ice sheets, that might act as a barrier for the winds, sink for huge amount of freshwater and have an influence of the local climate (Alvarez-Solas, Montoya, & Robinson, 2019). However, the recent global warming phenomenon, that might be considered as an abrupt climate change event, happens during a warm Holocene period (Abrupt Climate Change, 2002).

Figure 1 shows the millennial climate scale oscillations recorded in the North Atlantic Ocean sediments and Greenland ice cores, in order to achieve better representation of the abrupt climate change events (Ruddiman, 2013).

Figure 1

Visual Representation of the Millennial-Scale Oscillations



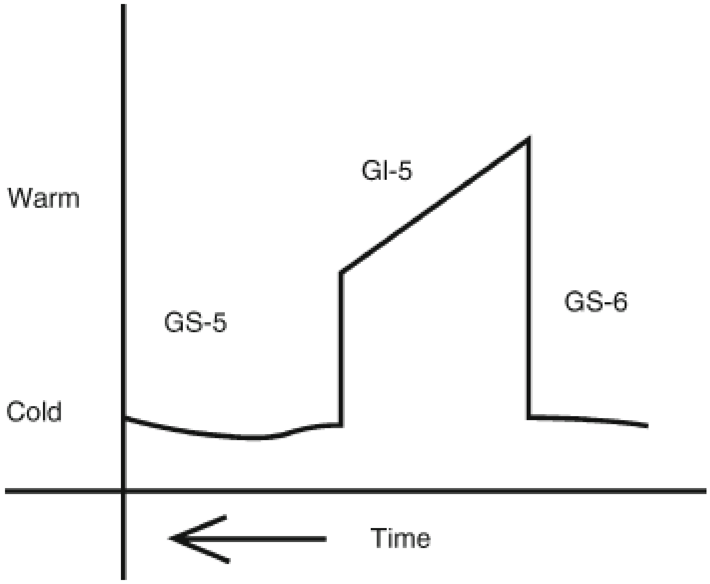
Note. This Figure represents the North Atlantic sediment and Greenland ice core records of abrupt climate change events. It can be seen that there is a correspondence between the data from the sediments (foraminifera and ice-rafting influxes) and the $\delta^{18}O$ records from the ice cores. Reprinted from *Earth's Climate: Past and Future* (p. 298) by W. F. Ruddiman 2013.

2.1 - Dansgaard-Oeschger events

Dansgaard-Oeschger events are the millennial-scale episodes of warming, from cold full-glacial stadial, to warm interstadial conditions, that occurred in the time interval (60000-35000) years ago (Peltier & Vettoretti, 2014). During these events, the average temperature change was 8-16 °C within a time interval of a few decades (Erhardt, et al., 2019; Ruddiman, 2013). Dansgaard-Oeschger events are one of the most examined examples of abrupt climate change events that involve a wide range of time-scales (Li & Born, 2019). To be more specific, the majority of the Dansgaard-Oeschger events happen every 1470 years, with a warming onset of the oscillation that can last as short as 20 years, accompanied by a few centuries cooling phase and a recognizable cold phase that lasts from a few centuries to a millennium (Easterbrook, 2019; Stocker, 1999). This cyclical behavior that is characterizing the Dansgaard-Oeschger events is found to have a sawtooth shape, represented on Figure 2 (Gornitz, 2008).

Figure 2

Schematic Representation of the Temperature Change During Dansgaard-Oeschger Events Showing the Characteristic Sawtooth Shape

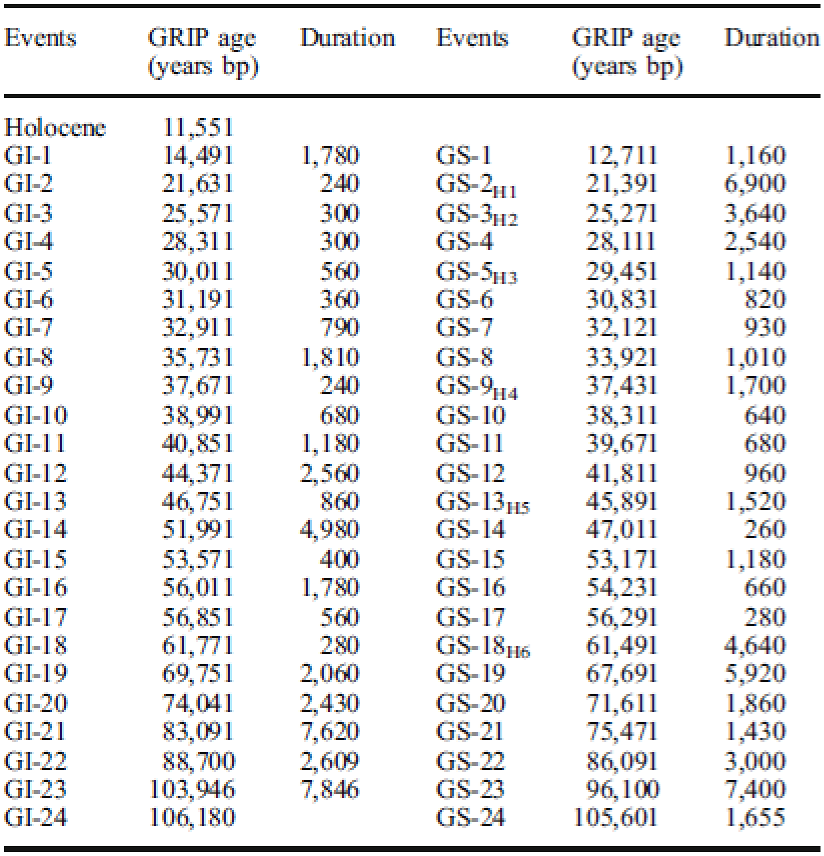


Note. GS is the Greenland stadial, while GI is the Greenland interstadial. Reprinted from *Encyclopedia of Paleoclimatology and Ancient Environments*, (p. 230), by V. Gornitz, 2008, Springer.

These events are known as Millennial climate oscillations because the time period between the events is on the order of a thousand years (Easterbrook, 2019). It is important to mention that not all of the records show the 1470-year periodicity very regularly. More precisely, the intervals spacing these events ranged from 1000 to 9000 years in length (Ruddiman, 2013). The occurrence of the Dansgaard-Oeschger events is reported to be mostly concentrated in the period (57-29) kyr before present, known as Marine Isotope Stage 3, the period before the Last Glacial Maximum (Li & Born, 2019). Table 1 represents a list of the 24 Greenland stadials and interstadials, the period when they occurred according to GRIP (Greenland Ice Core Project) time-scale and their duration (Gornitz, 2008).

Table 1

List of the 24 Dansgaard-Oeschger Stadials and Interstadials, GRIP Age and Duration



Events	GRIP age (years bp)	Duration	Events	GRIP age (years bp)	Duration
Holocene	11,551				
GI-1	14,491	1,780	GS-1	12,711	1,160
GI-2	21,631	240	GS-2$_{\mathrm{H1}}$	21,391	6,900
GI-3	25,571	300	GS-3$_{\mathrm{H2}}$	25,271	3,640
GI-4	28,311	300	GS-4	28,111	2,540
GI-5	30,011	560	GS-5$_{\mathrm{H3}}$	29,451	1,140
GI-6	31,191	360	GS-6	30,831	820
GI-7	32,911	790	GS-7	32,121	930
GI-8	35,731	1,810	GS-8	33,921	1,010
GI-9	37,671	240	GS-9$_{\mathrm{H4}}$	37,431	1,700
GI-10	38,991	680	GS-10	38,311	640
GI-11	40,851	1,180	GS-11	39,671	680
GI-12	44,371	2,560	GS-12	41,811	960
GI-13	46,751	860	GS-13$_{\mathrm{H5}}$	45,891	1,520
GI-14	51,991	4,980	GS-14	47,011	260
GI-15	53,571	400	GS-15	53,171	1,180
GI-16	56,011	1,780	GS-16	54,231	660
GI-17	56,851	560	GS-17	56,291	280
GI-18	61,771	280	GS-18$_{\mathrm{H6}}$	61,491	4,640
GI-19	69,751	2,060	GS-19	67,691	5,920
GI-20	74,041	2,430	GS-20	71,611	1,860
GI-21	83,091	7,620	GS-21	75,471	1,430
GI-22	88,700	2,609	GS-22	86,091	3,000
GI-23	103,946	7,846	GS-23	96,100	7,400
GI-24	106,180		GS-24	105,601	1,655

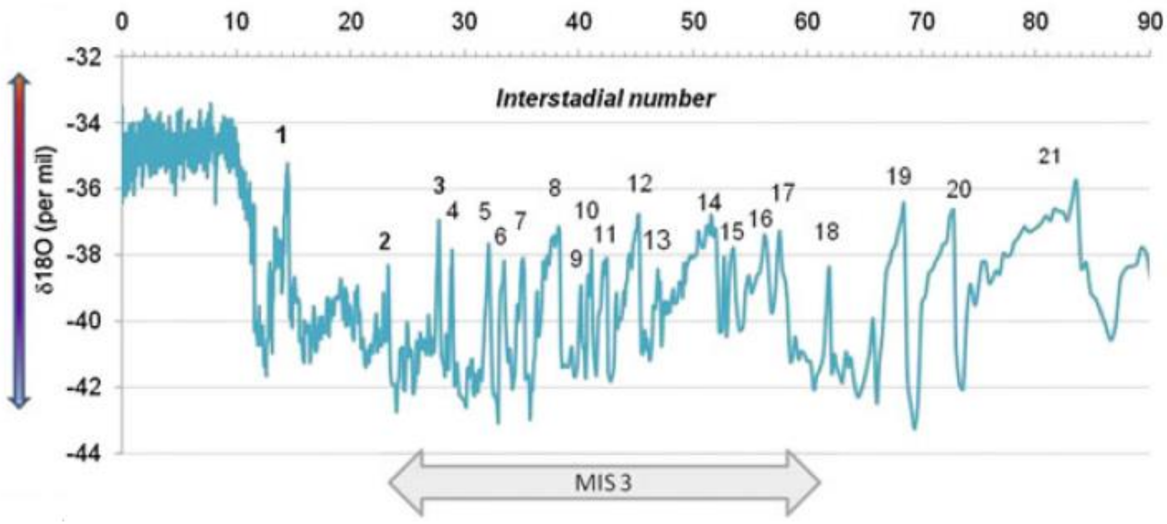
Note. Reprinted from *Encyclopedia of Paleoclimatology and Ancient Environments,* (p. 230), by V. Gornitz, 2008, Springer.

The Dansgaard-Oeschger events were first discovered in Greenland ice cores by Willi Dansgaard and Hans Oeschger. The δ^{18}O and dust concentration signal patterns from the ice core record, were the first indicators of these events. Positive δ^{18}O value and low dust concentration represented the warm, interstadial phase, after which followed the stadial phase characterized with more negative δ^{18}O value and higher dust concentration. δ^{18}O values of the ice are representing the composition of the water vapor that falls as snow and forms the ice, that depends on the local temperature of the surrounding air mass. Higher air temperature at the time of the snow accumulation corresponds to higher level of the heavy oxygen isotope and higher δ^{18}O value in the ice cores, and vice versa. The analysis of the Greenland ice cores showed that the measured dust during the Dansgaard-Oeschger events originated from northern Asia. Its concentration and the size of the particles changes in relation to the strength of the winds (Ruddiman, 2013). In particular, stadial periods are marked with cold, dry and windy conditions. There were strong winds capable to transport more dust from the source to the ice sheets. During the stadials, the Asian and West African monsoons were weakened in the Northern Hemisphere. Also, the tropical Atlantic rain belt was moved southward (Ruddiman, 2013; Li & Born, 2019). In addition to the dust concentration and the δ^{18}O value change, it has been found that the sea aerosol concentration in the ice cores also varied in relation to the phases of the Dansgaard-Oeschger events. More precisely, stadial periods are marked by higher Na^+ and Cl^- concentration in the ice cores due to stronger winds and more turbulent ocean, and the opposite applies to interstadial periods (Ruddiman, 2013). Additionally, at the time of the interstadials there was almost a doubling in the local snow accumulation compared to the stadials, with proportionally more snow accumulating in winter (Erhardt, et al., 2019; Li & Born, 2019). Moreover, the interstadials are characterized with increased levels of nitrous oxide and methane as a result of the positive feedback mechanisms, and reduced dust and sea salt levels. Such indications testify the bigger spatial scale of the events (Li & Born, 2019).

Although the best paleoclimate record that contains evidence of the Dansgaard Oeschger events are the Greenland ice core records, the analysis of the North Atlantic sediments that have high accumulation rate and the proxy records for sea surface temperature, match them closely. The correlation indicated a strong relation between the cryosphere and the ocean at the time of the events in the region (Clement & Peterson, 2008). The overall number of the Dansgaard Oeschger events is reported to be 25, with 13 Dansgaard-Oeschger events in the interval (11600-45000) years ago (Easterbrook, 2019). The Dansgaard-Oeschger abrupt climate change events, that happened during the Marine Isotope Stage 3 (80000-20000) years before present, as the Greenland $\delta^{18}O$ record shows, are represented on Figure 3 (Agosta & Compagnucci, 2016).

Figure 3

Representation of the Dansgaard-Oeschger Events in Greenland Ice Core Record During the MIS 3

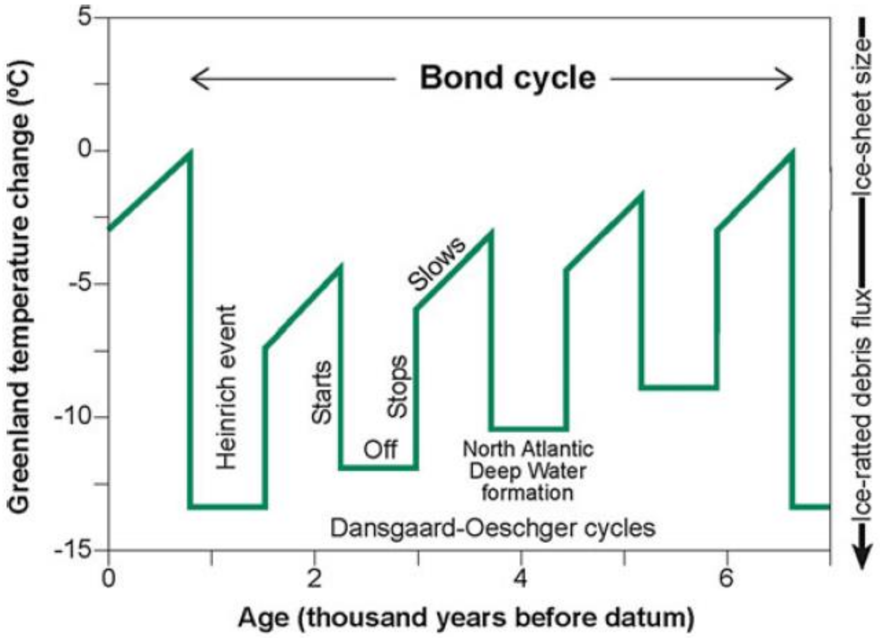


Note. The $\delta^{18}O$ record is expressed in ‰ and it represents 20 of the 25 Dansgaard-Oeschger events. Reprinted from “Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3)” by E. A. Agosta & R. H. Compagnucci, 2016, *Springer Earth System Sciences*, (p. 83).

An important finding is that three to four Dansgaard Oeschger events group into long-term cooling trends, and then are interrupted by abrupt warming. These cycles, known as Bond cycles, represent a link between the millennial-scale Dansgaard-Oeschger events, and slower time-changing Heinrich events (Agosta & Compagnucci, 2016). The Bond cycles in which the Dansgaard Oeschger events are bundled, last about (5-10) kyr, and then are terminated by Heinrich events (Rashid, Polyak, & Mosley-Thompson, 2011). These cycles are reported to have sawtoothed shape as well, and every next interstadial is shown to be cooler than the previous (Bond, et al., 1993). Such evolution of the Bond cycles represents incrementally cooler interstadials up to the Holocene warm period (Agosta & Compagnucci, 2016). The Bond cycles have first been discovered in three sediment cores from the North Atlantic, that represent the shifts in the ocean currents and the winds (Bond, et al., 1993). A schematic representation of the Bond cycles is shown on Figure 4 (Agosta & Compagnucci, 2016).

Figure 4

Schematic Idealized Representation of the Temperature and Ice Sheet Changes During a Bond cycle in the North Atlantic



Note. The consecutive Dansgaard-Oeschger become colder and after a few of them, follows one Heinrich event. Reprinted from “Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3)” by E. A. Agosta & R.H. Compagnucci 2016 (p. 85).

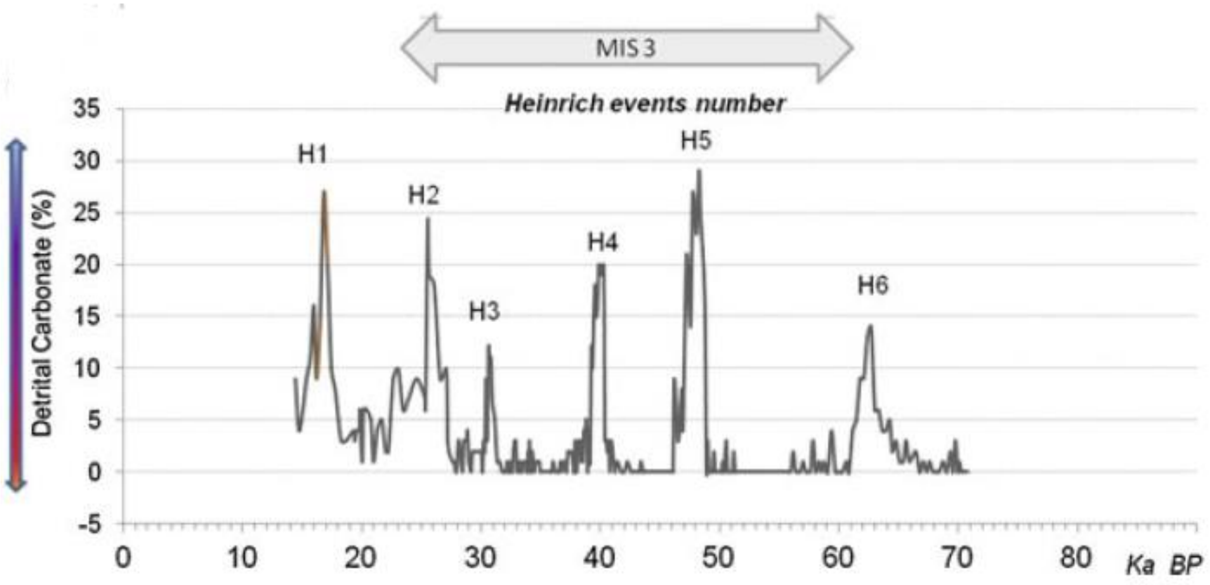
2.2 - Heinrich events

The Heinrich events are episodes of warming spaced at (7000-12000)-year intervals, that appear in the Northern Atlantic sediment records. These events have been described using the sediments that contain ice-rafted debris, that originates from the melting of the icebergs from North America (Broecker, 2003). Scientists have been focused in interpretation of these events because the concentration of the ice-rafted debris that has been found in the sediments, is unusually high (Banderas, Alvarez-Solas, Robinson, & Montoya, 2014). Six such sediment layers have been discovered in sediment cores located from the Hudson Straits over the northern Atlantic to the coast of France (Broecker, 2003). Ruddiman (2013) includes even shorter-term oscillations (2000-3000) years in the Heinrich events, related to the abundance of polar species of foraminifera and the amounts of the shells of foraminifera relative to the size of the ice-rafted grains. The cold and the warm phases of the Heinrich events, represented with the different concentration of the polar foraminifera species in the sediments, have later been confirmed with data from the Greenland ice cores (Ruddiman, 2013).

Similar to the Dansgaard-Oeschger events, the Heinrich events show sawtoothed pattern with slower gradual cooling phase followed by ice-rafted debris influx, after that the abrupt warming phase takes place. The major source of the ice rafted debris was the Laurentide ice sheet that covered North America at the time of the Last Glacial Period (Ruddiman, 2013). Clarke & Marshall (1999) believe that also the Fennoscandian ice sheets played an important role. There were at least 6 Heinrich events and each one of them lasted from 200 to 2300 years. Differences in the grain type and composition of the ice-rafted debris, suggest that probably for some of the events, the debris originated from Europe as well (Easterbrook, 2019). The six Heinrich events, represented in the North Atlantic sediment core record, that happened during the MIS 3 are shown on Figure 5 (Agosta & Compagnucci, 2016).

Figure 5

North Atlantic Sediment Core Ice-rafted Debris Record as a Representation of the Heinrich Events During the Marine Isotope Stage 3



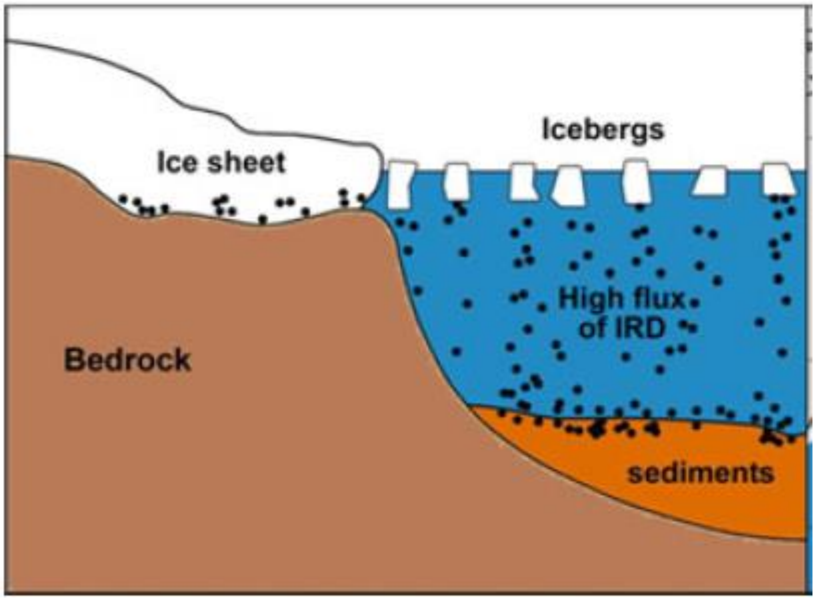
Note. Heinrich events marked with increased percentage of detrital carbonate. Reprinted from "Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3)" by E. A. Agosta & R. H. Compagnucci, 2016, *Springer Earth System Sciences,* (p. 83).

It is still not clear whether the cooling, or the warming phase of the Heinrich events is responsible for the releasing of the debris in the ocean. In the first possible explanation, the cooling phase caused increasing of the mass of the glaciers and due to the higher pressure on the ground, calving of the icebergs occurred and the calved bergs brought the debris into the ocean. In the second case, the warming phase led to melting of the ice, and the released fresh water increased the sea level and influenced the connection between the continental ice and the ice shelves (Easterbrook, 2019). More clearly, the material is believed to have been discharged from eastern Canada during the melting of ice, as a result of the large advancements of the Hudson Bay lobe of the Laurentide ice sheet. Another hypothesis suggests that the material originates from shattered ice shelves and Jökulhlaups (glacial outburst flow). However, both of the hypotheses agree in the fact that the melting of the icebergs led to decreased salinity of the surface waters of the North Atlantic, that probably influenced the circulation patterns (Broecker, 2003). Bassis, Petersen, & Mac Cathles (2017) suggest that the massive discharge Heinrich events can be explained with the processes that are responsible for the retreat of the modern marine-terminating glaciers. In particular, they indicate that the warming of the surface ocean waters that probably occurred due to changes in the Atlantic Meridional Overturning Circulation, led to increased underwater melting, further causing quick margin retreat, and increased release of icebergs. In the remaining part of the cycle, they explain that there is an uplift of the bed due to isostatic adjustment, eliminating the contact with the warmed water layers and causing an ice sheet advancement. The most advanced position allows occurrence of another Heinrich event. Bassis, Petersen, & Mac Cathles (2017) state that this mechanism marks the timing and amplitude of the Heinrich events. The iceberg discharge into the

North Atlantic, that led to increased deposition of ice-rafted debris layers in the ocean sediments, is represented on Figure 6 (Agosta & Compagnucci, 2016).

Figure 6

Schematic Representation of the Iceberg Discharge and Deposition of the Ice-rafted Debris in the North Atlantic Sediments at the Time of the Heinrich Events

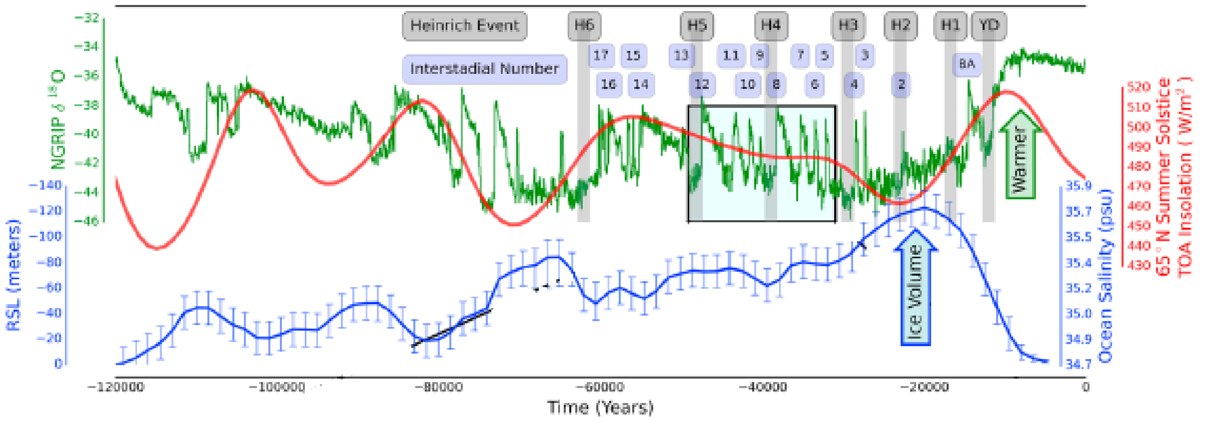


Note. The icebergs that were broken-off from the glaciers and released into the North Atlantic included rock mass that was eroded by the glaciers. After the icebergs melted, the material was accumulated on the sea floor. Reprinted from "Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3)" by E. A. Agosta & R. H. Compagnucci, 2016, *Springer Earth System Sciences,* (p. 84).

For better understanding of the Heinrich events, it is essential to study their relationship to other climate oscillations. In this regard, it is believed that the Bond cycles are being terminated by the Heinrich events (Clarke & Marshall, 1999). Bond, et al., (1993) using a correlation of ice and ocean records, suggest that the release of the icebergs and the resultant decrease in the ocean salinity, must have had occurred during the cold stadial periods. They add that the unclear part is the mechanism, whether the cycles of cooling were induced by internal variability of the ice sheets, or by a climate forcing that resulted in ice sheet growth, with a culmination reached during the cold stadials when the ice sheets became unstable and this led to massive calving. Furthermore, they indicate that the Younger Dryas correlates with a prominent stadial without a doubt, and have similar features with the Heinrich events. This opinion is based on the recorded decrease of the temperature and salinity, and advancement of the Laurentide ice sheet that caused the deposition of debris in the sediments located in the Labrador Sea during the Younger Dryas event. However, they also point out that at the time of the Heinrich events only, the icebergs moved far into the North Atlantic from the Labrador Sea. Another important finding from Bond, et al., (1993) indicates that the Heinrich events (except H1) and the Younger Dryas ice rafting event, happened near the end of the bundled Dansgaard Oeschger events. The finding that the Heinrich events are correlated with the more frequent Dansgaard Oeschger events is an important step towards the understanding of the complex interactions between the components of the climatic system (Bond, et al., 1993). Peltier & Vittoretti (2014) indicate that the Dansgaard-Oeschger events are probably triggered by the Heinrich events, because from the NGRIP δ^{18}O record represented on Figure 7, it can clearly be seen that they are following the individual Heinrich events. They explain this possible relation with a kicked oscillator model, in which every Dansgaard-Oeschger oscillation, or a cluster of oscillations, is induced by a Heinrich event that plays the role of a kick (Peltier & Vettoretti, 2014).

Figure 7

NGRIP δ^{18}O Record Representing the Dansgaard-Oeschger and the Heinrich Events, Versus the Insolation at 65°N Compared with the Relative Sea Level



Note. The δ^{18}O is expressed in ‰ with a green curve, the insolation is expressed in Wm^{-2} with red curve, and the RLS is expressed in meters with a blue curve and it correlates with changes in the salinity (the increase of the ice volume is associated with the increase in the salinity). Reprinted from "Dansgaard-Oeschger oscillations predicted in a comprehensive model of glacial climate: A "kicked" salt oscillator in the Atlantic" by W. R. Peltier & G. Vittoretti, 2014, *Geophysical Research Letters* (p. 7307).

2.3 - Younger Dryas

The Younger Dryas represents a sudden cooling phase at the time of an abrupt increase of the temperature, that lasted approximately a millennium, and it marks the transition to the Holocene (Broecker, 2003; Clement & Peterson, 2008). This event, that happened between 12,900 and 11,600 years ago, interrupted the period of warming that took place at the end of the Last Glacial Period. It is the most studied abrupt climate change period, because of the high-resolution and quality of the records available. However, the exact mechanism that is responsible for the occurrence of this event, is still unknown (Easterbrook, Younger Dryas, 2019).

To explain the conditions more specifically, due to the change in the orbital parameters among the other possible mechanisms, summer insolation maximum was reached in the Northern Hemisphere, that resulted in melting of the northern ice sheets. The positive feedbacks of the ice sheet melting and the increased concentration of the greenhouse gasses, are believed to have produced a warming trend. Many records confirm the melting of the ice sheets during this period, with the coral reefs being the most proper one in representing the rise of the sea level. An interesting finding, is that the coral reefs and other records show different rates of sea level increase. In particular, the sea level increased gradually at first, then the rise was abrupt, and finally, it slowed down (Ruddiman, 2013). This abrupt warm interstadial period that happened prior to the Younger Dryas is known as the Bølling/Allerød (Clement & Peterson, 2008). The slowing down phase, that happened 13000 years ago, resulted of a cold climatic oscillation that caused the return of even full glacial conditions, the Younger Dryas (Ruddiman, 2013).

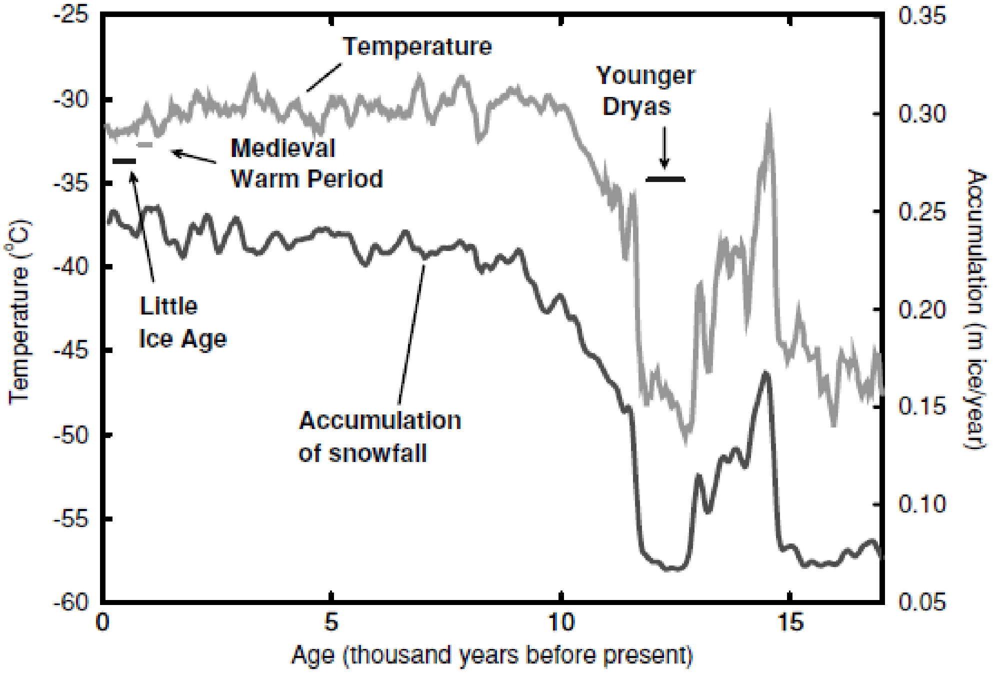
After the Younger Dryas event, around 11700 years ago, the warming phase took place again, and led to retreat of the polar front to the north (Ruddiman, 2013). The onset of this event lasted less than 100 years and the cold phase lasted around 1300 years. After the Younger Dryas event, the Holocene Epoch began, with an abrupt warming of 10 degrees in a few decades (Easterbrook, Younger Dryas, 2019). It is suggested that the Younger Dryas cooling episode has been associated with a fast movement of the North Atlantic polar front towards south, by even more than 20° latitude (Stocker, 1999).

The most commonly accepted mechanism responsible for the sudden cold Younger Dryas episode, is the shutdown of the Atlantic Meridional Overturning Circulation as a result of the discharge of meltwater from the ice sheets. Additional proposals include the changes in the radiation and atmospheric circulation, and the combination of these three (Renssen, et al., 2015). Renssen, et al., (2015) state that the mechanism responsible for this cold episode is not simple and probably cannot be ascribed to only one process.

The first evidence of the Younger Dryas stadial and the Bølling/Allerød interstadial were found in the Greenland Ice Core records. The oxygen isotope ratio clearly represents the temperature increase, followed by its abrupt decrease during the Younger Dryas, when the Greenland temperatures were around 15 °C colder than today's. This abrupt temperature and snow accumulation variation is represented on Figure 8 (Easterbrook, Younger Dryas, 2019; Abrupt Climate Change, 2002).

Figure 8

Variation in the Temperature and the Snow Accumulation in Central Greenland over the Last 17,000 Years



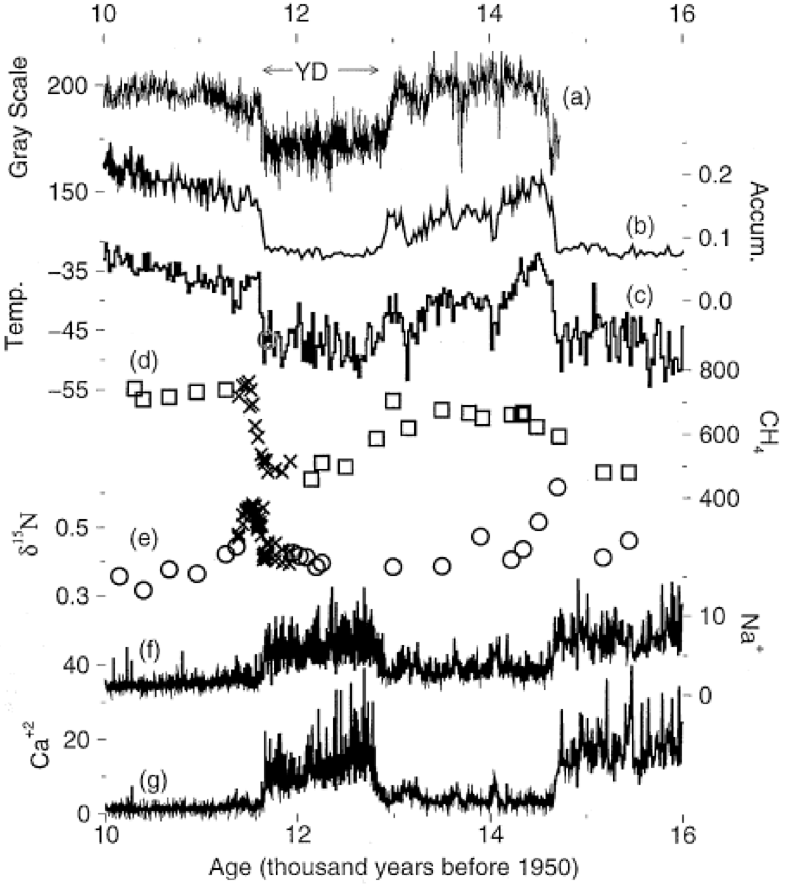
Note. The abrupt shift in the snow accumulation and temperature clearly represents the Younger Dryas cold event approximately 12000 years ago. Reprinted from *Abrupt Climate Change: Inevitable Surprises*, (p. 15), 2002, The National Academies Press.

The GRIP and GISP2 ice cores were studied in detail in order to determine the changes that were characteristic for the Younger Dryas event. The analysis has shown that the accumulation rate doubled at the end of the Younger Dryas, from 0.7 m to 0.14 m of ice per year. Such change happened very abruptly, in one to a few years. After the Younger Dryas episode, the accumulation rate increased even more, up to 0.24 m of ice per year. Furthermore, the analysis shows that at the end of the Younger Dryas episode, there was a decrease in the sea salt, dust and Ca concentration, that were reduced even more during the Holocene. The larger sea salt concentration during the Younger Dryas event, indicates that the winds were stronger, even by 70 % than the following periods, and made possible the transport and the production of the sea salt. Also, the stronger winds were the reason for the bigger dust transport and the dry conditions without precipitation, decreased the possibility for scavenging. Moreover, the isotopic paleothermometer, through the analysis of the isotopic composition of the water molecules, reveals the decrease in the temperature during the Younger Dryas event, and an abrupt increase at the end of it. Other indications, such as the thickness of the layers, the different chemical impurities, the dust, the isotopes, including argon and nitrogen, the depth-density profile, the borehole temperature and its calibration, confirm the abrupt changes of temperature decrease at the beginning, and increase at the end of the episode. These proxies show that during the Younger Dryas, the temperature was around 15 °C lower than the modern one, and one half of the change occurred very abruptly, while the other half during one millennium. At the end of the episode, the increase of the temperature was 5-10 °C, that occurred over a period of a few decades. In addition, among the changes characteristic for the Younger Dryas event, was also the change in the atmospheric composition and the greenhouse gasses, determined through analysis of the air bubbles in the ice cores. The largest change was found to be related to the concentration of methane, with its strong reduce during the Younger Dryas, from 700 ppbv before the event, to 475 ppbv during the event. After the Younger Dryas, the concentrations of methane increased even to 750 ppbv (Alley, The Younger Dryas cold interval as viewed from central Greenland, 2000).

Figure 9 represents the changes characteristic for the Younger Dryas episode, the the Bølling/Allerød interstadial and the beginning of the Holocene (Alley, The Younger Dryas cold interval as viewed from central Greenland, 2000).

Figure 9

Climate Changes at the Time of the Bølling/Allerød Interstadial, the Younger Dryas and the Beginning of the Holocene



Note. The data comes from the GISP2 ice core and from sediment cores from Cariaco Basin. Reprinted from "The Younger Dryas cold interval as viewed from central Greenland" by R. B. Alley, 2000, *Quaternary Science Reviews 19*, (p. 214).

It is important to mention that probably there was another Younger Dryas-type event during the Marine Isotope Stage 7e (MIS 7e). Evidence of this event were discovered in the stalagmite records from two high-altitude caves in Shennongjia area, Swan and Yongxing cave, that represent likely changes in the strength of circulation and the precipitation of the Asian Monsoon. The data is very similar to the findings about the Younger Dryas in the stalagmite records from Nanjing. The $\delta^{18}O$ records indicate that there was a millennial dry reversal, that matches the pattern of the Younger Dryas $\delta^{18}O$ stalagmite record. According to this, it can be concluded that the Younger Dryas event probably was not a one-time event and that maybe there were other similar episodes during the previous periods (Chen, et al., 2006).

3. PROPOSED MECHANISMS

The analysis of the abrupt climate change events during the Last Glacial Period shows that these events happened within decades. However, the studying of the climatic system has shown that there is no such rapid climate forcing. That is why, it is suggested that these events must have happened as a result of the internal processes of the climatic system, such as the feedback mechanisms related to the ice sheets and the sea ice. Another proposal indicates the possibility that the events happened as a result of a rapid response, to an external forcing that increased gradually (Clement, Cane, & Seager, An Orbitally Driven Tropical Source for Abrupt Climate Change, 2001). Very important point is that during the analysis of the paleoclimate archives and the determination of the processes behind the abrupt climate change events, it is often difficult to distinguish whether the changes that are found are a cause or a consequence of the events. Such uncertainties are often an issue of chronological control and temporal resolution in the archive (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Even though the magnitude and the scale of the abrupt climate change events are best explained using the ice cores as a record, many other records from different locations, such as the sediment cores from the North Atlantic, or the speleothems from the Hulu Cave, show indication of abrupt climate change events with a similar temporal behavior, and confirm the evidence found in the ice cores. A number of paleoclimate scientists have tried to explain why the abrupt climate changes happened. They posed the question whether there are physical mechanisms that allow establishing relation between the different regions with evidence of abrupt climate change events, and what can drive such mechanisms to produce the abrupt climate changes (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

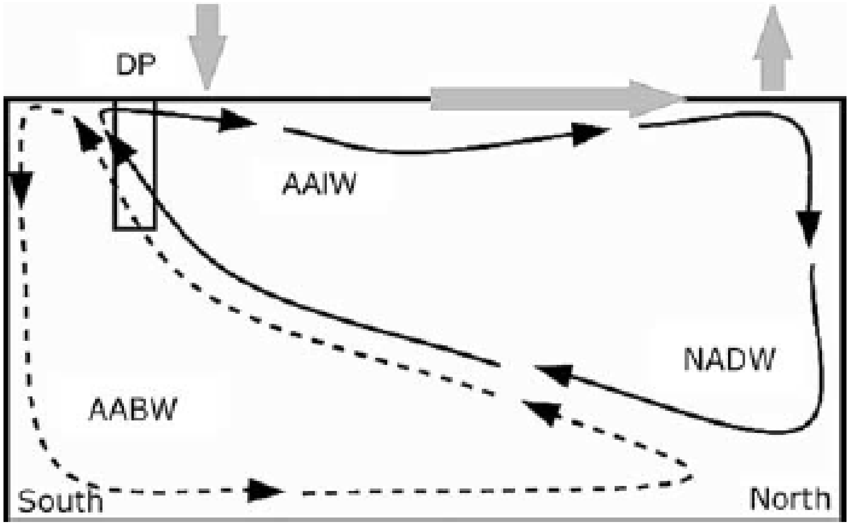
There are a few mechanisms that have been proposed to be responsible for the abrupt climate change events during the Last Glacial Period. One such mechanism, that is widely accepted to be a good explanation of the occurrence and the spread of the events, is the input of fresh water in the North Atlantic and the effect of this freshwater input on the heat transport. It is believed that this fresh water can cause disruption of the MOC (meridional overturning circulation) of the Atlantic Ocean (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008). The Atlantic Meridional Overturning Circulation is a mechanism for allowing transport of the heat from the tropics towards the higher latitudes. Indeed, due to the shape of the planet Earth, the solar radiation causes higher amount of heating of the tropics, compared to the remaining parts. As a result, the atmosphere and the ocean are responsible for redistribution of this heat to the poles, with the poleward heat flux. More specifically, the heat transport in the Atlantic Ocean is northward. Actually, the Atlantic Meridional Overturning Circulation connects the northward flow of warm waters, and the southward flow of cold waters across all latitudes (Frajka-Williams, Ansorge, Baehr, & Bryden, 2019).

Due to the higher density, the southward flowing cold waters are deep, without direct contact to the atmosphere and hence, reduced ventilation. The AMOC allows capturing of carbon from the atmosphere and its storage in the deep ocean. An appealing feature is that the AMOC strength is continuously varying, thus influencing the climate system with different time-scales (Frajka-Williams, Ansorge, Baehr, & Bryden, 2019). For instance, strengthened Meridional Overturning

Circulation causes increased poleward transport of heat in the ocean, that should be balanced with bigger heat loss to the atmosphere in the same regions, and higher heat uptake from the atmosphere in the regions from where the heat is being transported. This is represented on Figure 10, that shows the two main cells of the MOC: the AMOC cell, related to the formation of the North Atlantic Deep Water, its Southern Ocean upwelling and the returning as lighter Antarctic Intermediate Water, and the other related to the Antarctic Bottom Water, that is formed at high southern latitudes, its spread towards the North, its mixing with the North Atlantic Deep Water and its return in the Southern Ocean (Gornitz, 2008).

Figure 10

Two Main Cells of the MOC



Note. The arrows show that a change in the strength in the AMO cell, would affect the oceanic transport of heat towards the North Atlantic, that has to be balanced by the heat exchange with the atmosphere. For instance, intensified AMO cell, would cause stronger oceanic heat transport, stronger heat loss in the North, and weaker heat uptake in the South. Reprinted from *Encyclopedia of Paleoclimatology and Ancient Environments,* (p. 943), by V. Gornitz, 2008, Springer.

Alvarez-Solas, Montoya, & Robinson, (2019) indicate that even climate models show that the changes in the freshwater flux in the North Atlantic can drastically cause rearrangements of the Atlantic Meridional Overturning Circulation. This allows using different model simulations in order to analyze what are the consequences of such changes in the AMOC on a global scale (Alvarez-Solas, Montoya, & Robinson, 2019). Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, (2008) state that it is accepted that the fresh water discharge from melting of the ice sheets located on the landmasses surrounding the Atlantic Ocean, can lead to abrupt weakening of the ocean thermohaline circulation (THC).

Thermohaline circulation represents the deep ocean currents that are induced by the differences in the density of the water, these being regulated by the temperature and the salinity (Thermohaline Circulation, 2013). It is substantial to clarify that even though the terms Atlantic Meridional Overturning Circulation (AMOC) and thermohaline circulation (THC) are defined similarly, it is important to distinguish their meaning. Namely, the AMOC is defined as the total circulation in the latitude depth plan, and it does not contain information about the exact driver of the circulation. On the other side, thermohaline circulation (THC) is a specific driving mechanism that is connected to the formation or the loss of the buoyancy (Delworth, 2008).

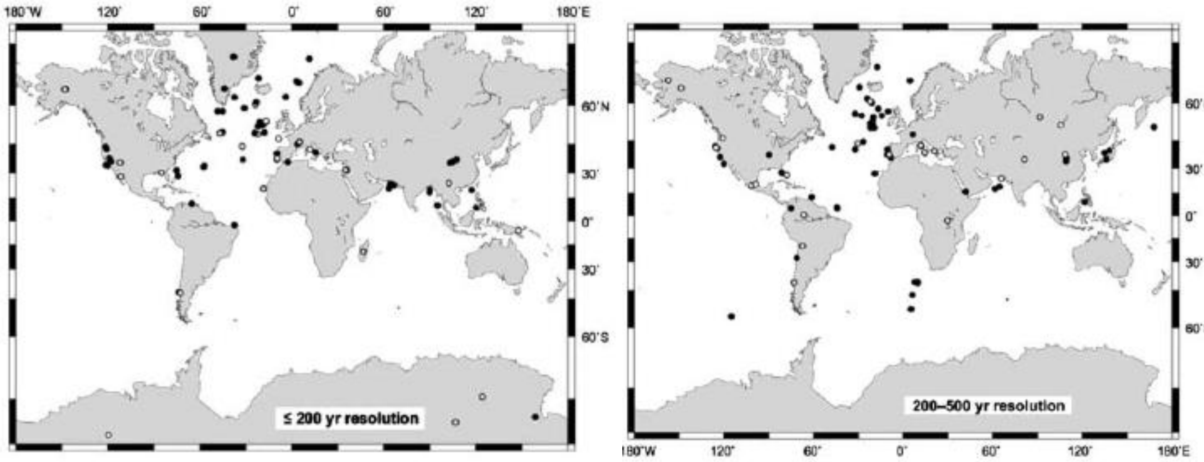
The AMOC at some particular location includes contributions from the THC, and wind-driven overturning cells. According to this, the changes in the thermohaline forcing of the AMOC are the changes that might be responsible for the abrupt climate change events (Delworth, 2008). Changes in the intensity of the thermohaline circulation at the time of the abrupt climate changes during the Last Glacial Period have been confirmed by the paleoclimate archives. The controversy related to this issue is whether these changes in the thermohaline circulation were a cause or a consequence of the events. Moreover, these changes in the Atlantic Ocean thermohaline circulation are probably not an adequate mechanism for describing the abrupt climate changes that according to the paleoclimate data, were present worldwide (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Other proposed engine that may be responsible for the occurrence of the abrupt climate changes includes the feedback mechanisms of the sea ice located in the North Atlantic, such as an albedo and air-sea heat exchange. The sea ice has a high albedo value, meaning that it reflects a high percentage of the incoming solar radiation, thus making possible to keep the low temperatures and prevent melting. In addition, sea ice plays an important role in the gasses and energy interchange between the air and the sea. Furthermore, the sea ice has an ability to rapidly change its own distribution. The last point additionally supports the idea that this might be a driver for fast climatic changes, such as the abrupt climate changes during the Last Glacial Period. Moreover, the processes of formation and melting of the sea ice, affect the salinity because the sea ice is made of freshwater, and its release with melting causes decrease of the salinity in the ocean, and hence, the stratification and convection and ventilation processes in the ocean waters. A third proposed mechanism that might have caused the abrupt climate changes is related to the processes happening in the tropics, due to their significant inter-annual changes and their characteristic feature to be the main source of heat and water vapor for the global climate (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

In order to analyze the possible mechanisms that caused the abrupt climate change events, it is important to understand where other evidence of such events can be found as a means to determine the spatial scale. In this regard, two maps of distribution of the existing paleoclimate records, in the period of marine isotope stage 3 (MIS 3-time-scale that refers to the Last Glacial Period) are represented on Figure 11. The maps are created by *Voelker and Workshop Participants* [2002] and refer only to the Dansgaard-Oeschger events (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Figure 11

Distribution Map of Paleoclimate Records (Solid Circles-Clear Evidence, Open Circles-Unclear or Absent Oscillations Typical for the Dansgaard-Oeschger Events) that Contain Evidence of the Occurrence of the Dansgaard-Oeschger Events During MIS 3 (Last Glacial Period).



Note. Resolution 1-200 year (left) and resolution 200-500 year (right). The criteria for the resolution were that the record must contain 7 points per cycle (≤ 200-year resolution), or 5-7 points per cycle (200-500-year resolution), throughout the 1500-year period of a Dansgaard-Oeschger cycle. Reprinted from “Mechanisms of Abrupt Climate Change of the Last Glacial Period” by A. C. Clement & L.C. Peterson, 2008, *Reviews of Geophysics 46.4,* (p. 3).

The noteworthy feature of the maps represented on Figure 11, is that the records that contain evidence about the Dansgaard-Oeschger events are not uniformly distributed, with the most of them located in the North Atlantic, while there are huge breaks around the rest, even though the records can be found all over the planet (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

3.1 - Evidence of the abrupt climate changes that can be related to the proposed mechanisms

3.1.1 - Northern Hemisphere

The paleoclimate records in the Northern Hemisphere that contain clear evidence of the abrupt climate change events are the Greenland Ice Sheet and the North Atlantic sediments. An important point concerning the different drilling sites of the Greenland Ice Core record, is that the analysis of the ice cores obtained with the Greenland Ice Core Project (GRIP) and the Greenland Ice Sheet Project 2 (GISP2) show basically identical signals at the time of the abrupt climate change events, thus confirming the obtained results. The findings about the abrupt climate change events are further confirmed by other paleoclimate records in the Northern Hemisphere, such as the sediment cores in the North Atlantic that have high-accumulation rate. The temperature-dependent foraminifera species, show that the SST of the North Atlantic changed for at least 5 °C at the time of the abrupt climate change events. Moreover, the abrupt climate change events are additionally validated by the sediment ice cores in the subtropical North Atlantic and in the western Mediterranean, that also show temperature changes of 4-5 °C and 6 °C respectively (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Because the Northern Atlantic and Greenland are the locations where the clearest evidence of the abrupt climate change events have been found, it might be proposed that the mechanisms behind the events include local changes that happened there. Moreover, the best chronological record of the Younger Dryas episode comes from the ice sheets. For example, Clement & Peterson (2008) believe that the Younger Dryas event was produced as a result of the meltwater discharge in the North Atlantic that originated from the melting of the ice sheets at the time of the deglaciation period. This is because the meltwater could have caused decrease of the salinity of the ocean and disruption of the thermohaline circulation (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

In addition, there are a few records, such as the Cd/Ca ratio from the shells, representing a sediment proxy for nutrient content, that confirm that the thermohaline circulation can be modified. Such records show that at the time of the Younger Dryas cold episode, an older water mass originating from the southern parts and rich with nutrients, replaced the North Atlantic Deep Water and caused weakening of the deep currents. It was suggested by Clarke & Marshall (1999) that the operation trend of the thermohaline circulation changed throughout the history: weak and shallow overturning during the glacial period, a shutdown phase at the time of the Heinrich events and strong overturning in the modern periods. This opinion is supported by evidence that confirm that the meridional overturning of the Atlantic Ocean did not exist at the time Heinrich 1 event (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

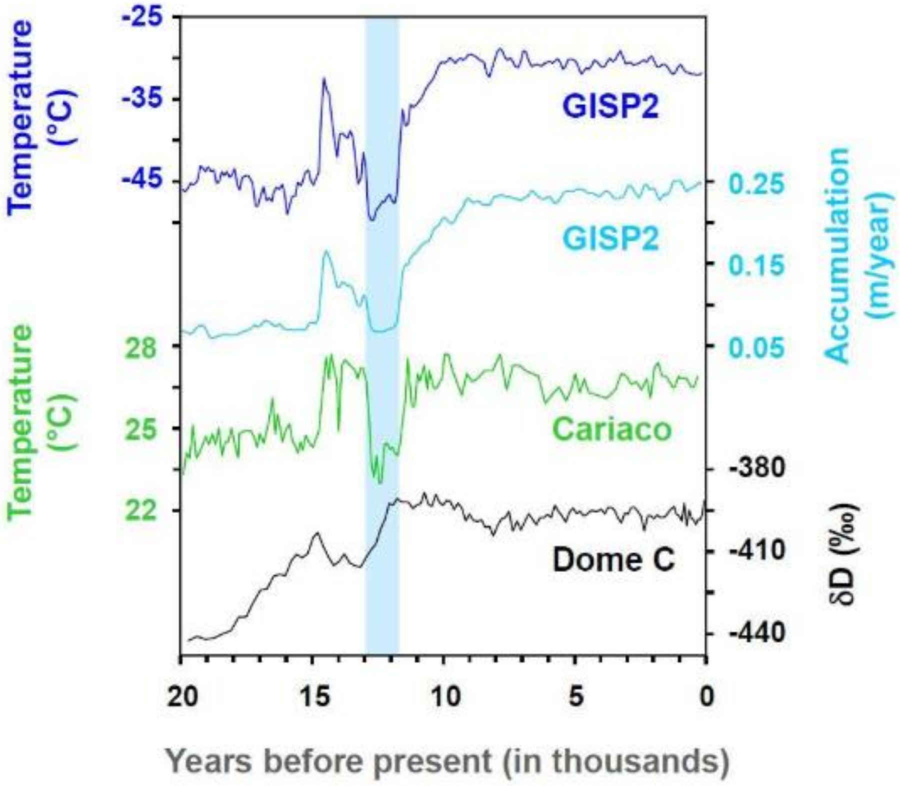
Evidence of freshwater release, such as the sediment record proxies δMg/Ca, U/Ca, and $^{87}Sr/^{86}Sr$, show that the meridional overturning circulation strongly decreased at the time of the Younger Dryas event. The hypothesis that the meltwater and the resulted ocean stratification of the North Atlantic led to changes in the thermohaline circulation, that served as a driver of the abrupt climate changes, is further confirmed by the evidence of the freshwater input from the Lake Agassiz. At the time of the Younger Dryas onset, there was a sudden diversion towards the east of freshwater originating from this lake into the North Atlantic, through the Great Lakes–St. Lawrence River system. Clement & Peterson (2008) state that probably there was a release of fresh meltwater from the Lake Agassiz that was put in place with opening of a lower outlet as a result of the retreating margin of the Laurentide Ice Sheet.

Broecker er al., (2003) consider that approximately 9500 km^3 of water was discharged during the Younger Dryas event. Modeling results have shown that the release of such a big amount of melt water should result in strongly reduced formation of North Atlantic Deep Water. This is confirmed by proxy data that show that at this time, there was a steep increase in the ratio ^{14}C to ^{12}C in the surface ocean. The increase in the ratio represents a shutdown of the deep water production, because that process should balance the radiodecay in the deep sea. In particular, after the Younger Dryas onset, the ratio began to increase and after 200 years it reached a value that is 5% higher than the period before the onset. The Greenland ice core record, offering the best chronological record and important evidence for studying of the Younger Dryas event, clearly shows an increase of the dust content and the NaCl concentration during the Younger Dryas onset. Other proxy records, such as δ^{18}O, prove that there were colder temperatures and lower accumulation rate. Furthermore, there was a drop in the methane content at the onset of the Younger Dryas, measured from the air bubbles in the ice. Broecker (2003) suggests that this drop is due to the decreased extent of the wetlands in the tropics. Furthermore, Melton, Schaefer, & Whiticar (2012) indicate that other sinks of methane, such as the thermokarst lakes and the marine gas hydrates, contributed in the change. According to this, it can be concluded that the changes in the tropics match the timing of the changes at higher latitudes. To add, Antarctica ice core records of methane are correspondent to the Greenland ones. At the time of the Younger Dryas onset, the Antarctica warming and the atmospheric CO_2 rise specific for the Bolling-Allerød continued after the pause, throughout the entire Younger Dryas event. This indicates that the timing of the Younger Dryas onset also matches the Antarctica records with the Greenland ones, even though the change was opposite (Broecker, 2003).

Figure 12 shows that the climate changes related to the Younger Dryas stadial were recorded in the Greenland Ice Core, Cariaco Basin sediment core and the out-of-phase warming in Antarctica, representing its global footprint (The Younger Dryas, n.d.).

Figure 12

Climate Changes Related to the Younger Dryas Stadial in Greenland, Cariaco Basin and Antarctica



Note. There are decreased temperatures and snow accumulation in Greenland at the time of the Younger Dryas. The proxy record also shows decreased temperatures in the tropical Cariaco Basin sediment core. On the other side, there is a warming in Antarctica, representing the out-of-phase relationship between the hemispheres. Reprinted from *NOAA,* https://www.ncdc.noaa.gov/abrupt-climate-change/The%20Younger%20Dryas.

Opposite to the Younger Dryas event, the best evidences of the Heinrich events were found in the North Atlantic sediment record. These events, marked by the ice-rafted debris, regardless of the origin of the ice armadas that melted into the North Atlantic, have been recorded in the $\delta^{18}O$ foraminifera records that show reduced salinity in the surface waters, that further influences the circulation. Evidence from other regions of the world have been found to match the time-scale of the changes, such as the cooling phase in the Mediterranean Sea, records of sediment discharge off Eastern Brazil, pine records from Central Florida, Chinese Hulu Cave records, etc. These indications of the existence of the Heinrich events on global scale, similarly to the Younger Dryas event records, show that probably the events triggered by disruptions in the thermohaline circulation in the North Atlantic, were affecting the global climatic system (Broecker, 2003).

To conclude, there are indications that confirm the changes of the thermohaline circulations at the time of the Younger Dryas and the Heinrich abrupt climate change events. However, it is not comprehensible enough whether the thermohaline circulation variations are associated with the

Dansgaard-Oeschger events in a similar way. As a result, it cannot be stated that there is a specific paleoclimate record that directly connects the abrupt climate change events and the thermohaline circulation variations (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

3.1.2 - Southern Hemisphere

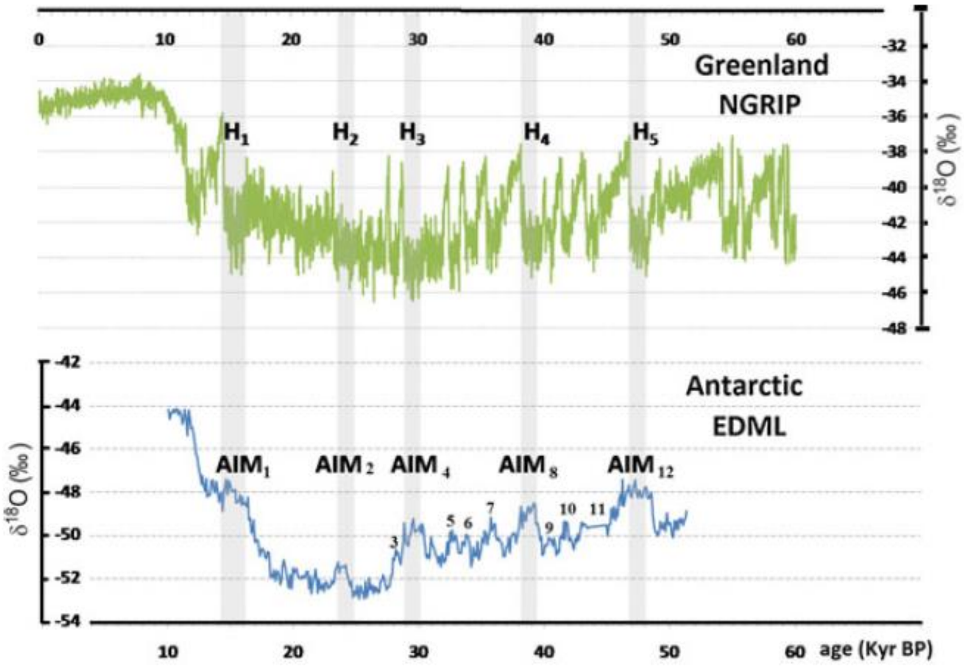
The most thorough evidence of the abrupt climate changes in the Southern Hemisphere are contained in the Antarctica ice cores. Still, the lower accumulation rate compared to the Greenland ice sheets, makes the records less resolved and it is difficult to determine their timing relative to the Northern Hemisphere records. Changes in the proxy data represent changes in the temperature, such as $\delta^{18}O$ and δD, at the time of the recorded abrupt climate change events, although the warming and cooling trends are more gradual and less pronounced. The most intriguing part, is that the temperature changes between the Antarctica and Greenland ice cores are out-of-phase at the time of several interstadials that lasted longer (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Clement & Peterson (2008) have suggested that this interhemispheric coupling is a result of the changes in the thermohaline circulation. In particular, strong changes in the thermohaline circulation gather heat from the Southern Ocean. Moreover, weakening or elimination of the Meridional Overturning Circulation causes cooling of the North Atlantic, that is associated with warming of the Antarctic region. This is known as the bipolar seesaw. Additional studying if the Antarctica ice cores has shown that no less than seven of the Atlantic warming events happen at the same time with the Greenland cooling events. Further drilling projects resulted in obtaining of an Antarctica ice core record with improved resolution, that confirms the coupling between the Antarctica warm events and the stadial cold events in Greenland, and vice versa. An interesting feature that was discovered in the Antarctica record, was that the amplitude of the warm events there, was linearly related to the length of the stadial event in the Greenland records. This shows that probably all of the events originate from a similar decrease in the Atlantic meridional overturning, and that the deep ocean circulation played an important role in the abrupt climate change events (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Thus, Antarctica records also show evidence that the deglaciation was interrupted at the time of the Younger Dryas cooling event. Due to the relatively small number of records in the Antarctic Continent, with proper temporal resolution, length and timing relative to the North Hemisphere changes, that are necessary for comparison, the evidence of the climate change events reveal complicated regional patterns. An exception of this is the ice core from the EDML site, that contains indications of dampened, but out-of-phase oscillations of the temperature change characteristic for the Dansgaard-Oeschger events, thus being consistent with the bipolar seesaw hypothesis. Still, other Antarctica ice cores (Law Dome and EPICA Dome C) do not confirm the concept of the bipolar seesaw, because there is not an exact match between the time of the abrupt warming in the beginning of the Bølling/Allerød transition that happened 14,500 years ago, and the cooling phase in the Antarctic. Moreover, some of the Antarctica records show rapid climate changes that are not confirmed by Greenland or other records, such as the 22000 years ago increase of the temperatures of 6 °C. Considering then the whole Southern Hemisphere, the records such as the glacial deposits, pollen records, speleothems and marine sediments that are located on land, cannot be used for the analysis of the abrupt climate changes due to the low resolution (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008). Figure 13 represents the asynchronous relationship between the temperature variations with millennial time-scale in Greenland and Antarctica EDML Ice Core (Agosta & Compagnucci, 2016).

Figure 13

δ^{18}O Records of Greenland (NGRIP) and Antarctica (EDML) as a Representation of the Asynchronous Change in the Temperature in Both Hemispheres



Note. δ^{18}O are expressed in ‰. Greenland NGRIP record is represented with green line, while Antarctica EDML is represented with blue line. The bipolar seesaw pattern can clearly be seen through the δ^{18}O record that represents the temperature change. The Greenland interstadials are associated with the beginning in the cooling of the Antarctic Isotopic Maximum. Reprinted from "Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3)" by E. A. Agosta & R. H. Compagnucci, 2016, *Springer Earth System Sciences*, (p. 90).

3.1.3 - Tropics

A complete high-resolution record of the abrupt climate change events in the tropics, is the laminated sediment record, located at the Santa Barbara Basin. It shows a strong correlation between the proxy data of sea surface temperature and basin ventilation, and the ice core records from Greenland, for all of the Dansgaard-Oeschger events and the Younger Dryas. Other records, such as pollen records of lake sediments and other marine sediments located at the tropical region, confirm the occurrence of the three types of the abrupt climate changes in the tropics. For example, a high-resolution marine sediment record in the Cariaco Basin in the tropical Atlantic confirmed climate changes not only at the time of the Dansgaard-Oeschger events, but also the warming phase at the time of the Bølling and the cooling phase during the Younger Dryas. The last two were synchronous within ±30–90 years of their correspondent changes in the air temperature in Greenland. The same record reveals that there was reduced river runoff from northern South America and it was dry at the time of the Younger Dryas and the other stadials, and the opposite conditions existed during the warm phases. Also, the proxy records show that there was a change in the hydrological conditions at the time of the abrupt climate change events, and the position of the Intertropical Convergence Zone (ITCZ) in the Atlantic was shifted by latitude (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

This and other records, such as the sediment cores from the Caribbean region, reveal that the Intertropical Convergence Zone was shifted southward at the time of the Younger Dryas. Furthermore, the records show that there was an increased salinity during the Last Glacial Period as a whole. Other records, even the ones located in tropical zones outside of the Atlantic, later reveal that the salinity was higher during the stadials and lower during the interstadials. Although these patterns of salinity change are analogous to the ones caused by the El Niño–Southern Oscillation, the evidence show that the productivity variations do not match (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Clement & Peterson (2008) proposed that the millennial-scale oscillations such as the Dansgaard-Oeschger events and the Younger Dryas, might have appeared as a result of the surface water salinity changes due to the changes in the east Asian monsoon. This opinion is supported by records from the western Pacific, the Hulu Cave from China and South China Sea sediment records. Speleothems and other land-based records, in regions that were affected by the Indian/Asian summer monsoon, show a correlation between the dry conditions and the stadials or other cold episodes (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Moreover, the variations in the monsoon strength within decades or centuries, have been found to be in phase with the abrupt temperature changes found in Greenland, this suggesting a strong connection. Also, records from India reveal that there was an increase of the summer Indian monsoon precipitation at the time of the Bølling/Allerød warm period, and its decrease during the Younger Dryas, supporting the previously mentioned correlation. Such correlations between the cold and warm phases recorded in the Greenland ice cores and the variation in the strength of the monsoons, are documented in the speleothems from the Hulu and Dongge Cave as well, that were affected by the east Asian monsoon (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Further support comes from the cave deposits of Socotra Island, located off South Yemen, high-resolution records that show evidence of Intertropical Convergence Zone shifts over the Arabian Sea, with southward shifts at the time of the stadials, that led to decreased monsoon precipitation. Marine sediments in the Arabian Sea hold up the mentioned correlation, because these records show evidence of increased ventilation, upwelling and surface productivity at the time of the strong Indian monsoon during the interstadials (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

In addition, tropical records, such as the mountain glaciers in the Ands, show decreased temperature during the Younger Dryas event. Also, the changes in the tropical region include not only the water vapor concentration, as a greenhouse gas with high potential, but also methane concentration. To be more clear, at the time of the Last Glacial Period, the northern boreal regions, a methane source, were covered with ice. As a result, the main methane source at that time were low-latitude wetlands. So, the mentioned monsoon strength and other tropical convection systems changes, might have affected the emitted methane levels, that could have led to conservation or even amplification of the abrupt climate changes through many feedback mechanisms (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

3.2 - Mechanisms

The proposed mechanisms responsible for the abrupt climate changes during the Last Glacial Period, should be able to fulfill a few requirements. First, a mechanism must identify the conditions between which the climatic system has passed over and what triggered the jumping among the states. Second, it has to be related to some telecommunication system that will allow global transmission of the signal. Finally, it has to be able to maintain the system in the particular climatic state for a given time, that matches the time-scale of the abrupt climate change events (Broecker, 2003).

3.2.1 - Thermohaline circulation change and AMOC reorganization

The first episode of warming present globally, is quickly interrupted in the North with an abrupt cooling episode, while it is still present in the South. The North soon experiences warming phase again, while the first warming episode is still persisting in the South. In order to explain this, Stocker, (1999) proposed that probably this was linked to an abrupt beginning of deep water formation. Namely, a vigorous thermohaline circulation in the Atlantic that draws heat from the Southern Ocean, should cause a cooling in the South, something that has been confirmed with the proxy data from the Antarctica Ice Sheet. In particular, these records show that the warming phase is interrupted and the Antarctic cold reversal begins (Stocker, 1999).

As a result of the abrupt warming in the South, the melting of the ice sheet and the enhanced hydrological cycle occurs, leading to an intensified supply of freshwater into the North Atlantic. The consequences of this interhemispheric seesaw, would cause weakening of the thermohaline circulation in the Atlantic, further causing gradual cooling during the Bølling/Allerød phase. After it, the Younger Dryas, an abrupt cold period, starts in the North, while the warming still continues in the South. Evidence suggest that this cold phase maybe occurred because of a complete shutdown of the thermohaline circulation in the North Atlantic, and after the event the thermohaline circulation probably resumed again with the drawing of heat from the Southern Ocean. The long warming phase in the South comes to an and approximately at the same time. According to this, it can be concluded that there were three occasions when the two hemispheres experienced a strong coupling. In all of these, the change in the thermohaline circulation has been suggested to be the main reason (Stocker, 1999).

The thermohaline circulation itself, or the AMOC, should be able to undergo abrupt changes in order to produce the abrupt climate change events. First, the abrupt change in the thermohaline circulation can be caused by meltwater event, that can lead to reduced salinity and hence, reduced sinking of the dense water. The resultant drop of the deep ocean water, could lead to changes in the upwelling and diffusion processes and thus, the thermohaline circulation would be altered. The abrupt flow of meltwater could occur at the time of the Younger Dryas, from the melting of the Laurentide Ice Sheet directly into the North Atlantic, and at the time of the Heinrich events, that were marked by ice-rafted debris in the North Atlantic sediments, transferred with iceberg melting. The melted icebergs during the Heinrich events, might have originated from the Laurentide Ice Sheet, jokulhlaup activity from Hudson Bay lake, or enlarging or breakdown of the ice shelfs (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Secondly, the abrupt variability of the thermohaline circulation can be explained by the existence of thermohaline circulation (or AMOC) modes, and the possibility to change the mode with slight forcing. This second option requires further analysis and determination whether it is a real characteristic of the climatic system. Important questions regarding the two mentioned alternatives are whether the meltwater delivery should be happening over a longer time-scale in order to cause more mixing, and whether it depends on the location and the different mean climatic conditions (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008). The two possible mechanisms that can explain the existence of AMOC modes are the freshwater flow and the combined effects of the change in the CO_2 concentration and wind-stress variations in the Southern Hemisphere (Alvarez-Solas, Montoya, & Robinson, 2019).

Since it is widely believed that the freshwater flow could have caused reorganizations in the Atlantic Meridional Overturning Circulation, many modeling simulations have been using this occurrence in order to try to explain the abrupt climate change events, with a millennial time-scale. Such examinations have been used for gaining a clearer perception of many processes related to the abrupt climate change events, such as: how the AMOC variations can affect the hydro-climatic response in the regions close to the equator, sea surface temperature changes in the North Atlantic, the phasing of atmospheric CO_2, Antarctica and global temperatures and why the Southern Hemisphere is leading the Northern one at the time of the deglaciation, the changes in the mass-balance of the Laurentide Ice Sheet and the found phasing difference of the oxygen isotope records in the deep waters at the time of the deglaciation (Alvarez-Solas, Montoya, & Robinson, 2019).

Banderas, Alvarez-Solas, Robinson, & Montoya (2014) state that there are models show that the negative flux of freshwater in the Northern Ocean induces increased salinity and strong convection. The denser waters contribute to North Atlantic deep water formation and strengthening of the AMOC. As a consequence of the bipolar seesaw effect, a cooling of the Southern Hemisphere occurs, followed by density increase in the South Atlantic. Increased salinity in the Northern Atlantic is maintained for a longer period because of the AMOC strengthening, which allows keeping of the system in the interstadial conditions. This phase of the cycle ends when there is a positive freshwater flux that causes AMOC weakening in the North Atlantic, while the density in the South Atlantic is reduced as a result of the consequent warming of the bipolar seesaw effect. When the density of the North Atlantic decreases enough so it can prevent the North Atlantic Deep Water formation, it reduces the AMOC and the system shifts into stadial state (Banderas, Alvarez-Solas, Robinson, & Montoya, 2014).

Still, there are many uncertainties, mostly related with the argument that the freshwater flow was responsible for the mentioned occurrences. In these terms, it is important to understand the timing and the sources of some of the strongest meltwater pulses such as the MWP-1a, that according to the proxy data, caused the most notable increase of the sea level for a short period of (340-500) years. Analysis of this event has been done using many models. Following the first preposition, that this event happened at the time of the Older Dryas, a cooling event that ended the Bølling/Allerød warm period, it matches the time of AMOC weakening. The second possible timing of this event coincides with the Bølling/Allerød warm period, when there was AMOC intensification. Moreover, Alvarez-Solas, Montoya, & Robinson, (2019) believe that a large part of the melt water pulse originated from the Antarctica Ice Sheet. The most important point regarding this meltwater pulse is that it had a multi-centennial to millennial time-scale. However, it is not yet clearly determined what explains the MWP-1a. The important issue is whether the freshwater flow in the North Atlantic can cause the abrupt climate change events. The models show that probably there was a decrease in the AMOC followed by a complete shutdown, and then AMOC recovery, as a response to the changes in the freshwater flow forcing, its sudden and gradual shutdown, or its strong increase. Some modeling results suggest that at the time of the Heinrich event 1, the decrease of the AMOC happened, while others suggest that it was the time of the recovery. Also, regarding the Bølling/Allerød, some models suggest that it matches the time of the AMOC recovery, while others point out that it matches the second shutdown phase. If there was an abrupt recovery of the AMOC during that period, it is implied that it probably occurred as a result of a sudden termination of the fresh water injection. Still, evidence of other climatic changes that resulted from these happenings are missing, and modeling results are often not successful. Nevertheless, the important aspect is that the models show that probably there was a change in the AMOC modes as a result of the variation in the freshwater forcing. However, the complete understanding of these occurrences requires a further modeling analysis and existence of more evidence (Alvarez-Solas, Montoya, & Robinson, 2019).

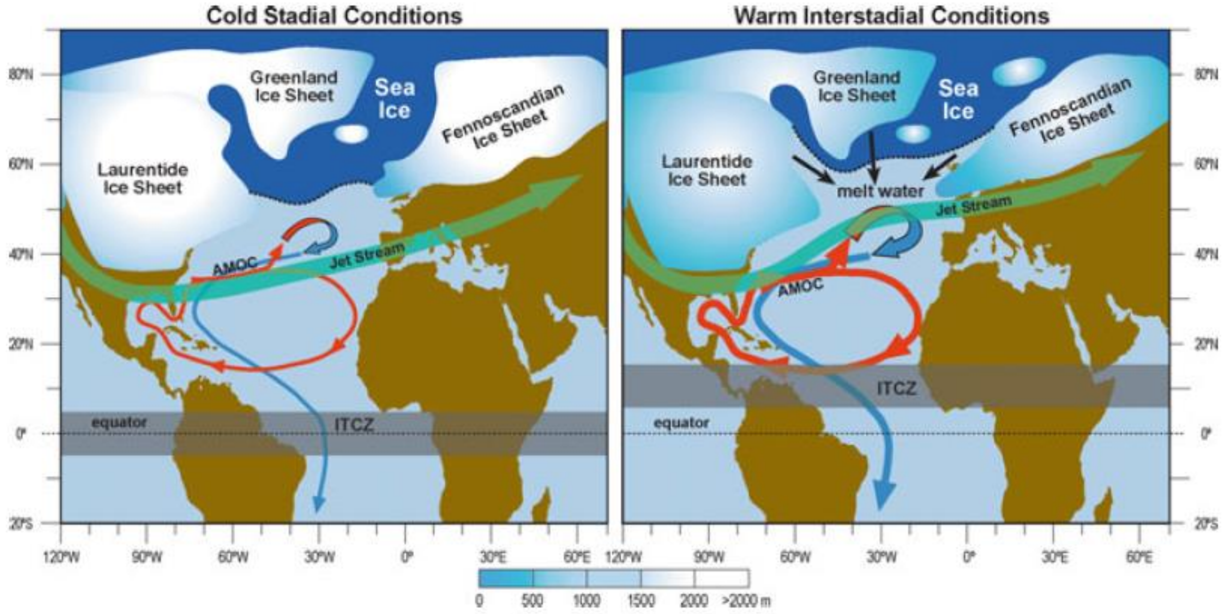
Another possible mechanism that might have caused variations in the AMOC is related to the interhemispheric climatic link, an opinion that comes from the existence of strong coupling between the Dansgaard-Oeschger events and Antarctica warm events. Banderas, Alvarez-Solas, Robinson, & Montoya, (2014) believe that the link between the hemispheres might have been enabled via variation in the ocean heat transport through the bipolar seesaw mechanism. Also, they suggest that abrupt warming events in the North Atlantic might have originated from the southern latitudes, and being enabled through the imposed changes in the AMOC, something that has been shown with modeling results. Moreover, gradual climate changes on a global scale have been indicated as a way to cause AMOC reorganizations, that might have originated from changes in the atmospheric CO_2 concentration. To add, a possible close correlation between the changes in the CO_2 concentration and the temperatures in the Antarctic at the time of the Heinrich stadials might exist. The increased CO_2 concentrations might have originated from the increased ventilation and upwelling in the Southern Hemisphere oceans, that might have caused the cooling in the North Atlantic during stadials. At the times of the cooling episodes in the North Atlantic, a weak overturning is believed to have led to decreased northward heat transport through the ocean. During these cold phases in the Northern Hemisphere, the Southern Hemisphere experiences warming periods, according to the bipolar seesaw effect. All these processes have probably been accompanied by migrations of the intertropical convergence zone and the Southern Hemisphere mid-latitude jet. To summarize, the winds in the Southern Hemisphere and the increased CO_2 concentration are expected to have led to AMOC strengthening, thus causing an abrupt transition of stadial to interstadial stages. The cycle would have changed due to northward shift of the intertropical convergence zone that would have led to weaker winds in the Southern Hemisphere and hence, decreased CO_2 concentration. Banderas, Alvarez-Solas, Robinson, & Montoya, (2014) show that the modeling results confirm that the AMOC changes between weak and strong circulation state, as a response to the changes in the CO_2 concentration and wind variations. The modeling results further show that the switch from stadials to interstadial conditions is possible to have occurred as a result of both, AMOC intensification and freshwater flux in the North Atlantic, that cause North Atlantic deep water formation and further recovery of the AMOC. Strong AMOC is expected to cause loss of heat in the Southern Hemisphere Ocean and increased salt transportation into the north, leading to a density increase in the entire Atlantic Ocean. The modeling results also represent that AMOC reactivation is expected to have led to reduced wind-driven upwelling and resultant decreased CO_2 levels, that lead to global cooling. At times like this, in the North Atlantic, this cooling is neutralized through increased oceanic heat transport, while in the South Atlantic, there is a further cooling associated with the bipolar seesaw effect. All these processes are shown to cause increasing of the density in the Atlantic, that is more enhanced in the Southern Hemisphere. This leads to a gradual AMOC shutdown, that gives rise to the sea ice growth in the north. The outcome is a reduced North Atlantic deep water formation and returning of the AMOC at stadial conditions. The models show that this cycle is then being repeated. Therefore, this is one possibility for explaining the transition between stadial and interstadial phases. The timescale of the changes in the AMOC as a result of all of the mentioned processes, is determined by the necessary time for the meridional density gradient to trigger AMOC reorganizations. The introduced changes in the density are more abrupt in the North Atlantic, compared to the South Atlantic where they are found to be more gradual, something that is consistent with the proxy records found worldwide. The couplings between the CO_2, Southern Hemisphere winds and AMOC strength are proposed to be able to cause the internal mechanisms of the climate system that allow interhemispheric oscillations, that are able to produce abrupt climate change events. Finally, these proposed mechanisms are not yet proven to be the exact reason for the abrupt climate change events, even though the modeling results are satisfactory (Banderas, Alvarez-Solas, Robinson, & Montoya, 2014).

A third possible explanation for the changes in the thermohaline circulation is the variation in the distribution of the surface winds, that can be caused by the presence of the large ice sheets (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

The time-scale of the changes in the thermohaline circulation should be more or less the same with the time-scale of the abrupt climate change events. The problem regarding this matter is the lack of knowledge about the period of lasting of the pulses of meltwater during the Heinrich events. For example, if the pulses of meltwater lasted over several centuries, they might have come from ice sheet collapse due to glaciological instability, because of their large mass and pressure over the bedrock. The collapse and the buildup probably occur repeatedly, and the time-scale of this cycle might be millennial. If it is approximately 7000 years, this matches the time-scale of the Heinrich events. Additional information is necessary in order to determine whether the time-scale of this process might be smaller, and match the Dansgaard-Oeschger events (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008). A schematic representation of the processes that might have occurred and generated Dansgaard-Oeschger events, with a change in the strength of the Atlantic Meridional Overturning Circulation is represented on Figure 14 (Agosta & Compagnucci, 2016).

Figure 14

Schematic Representation of the Ocean, Atmosphere and Ice Mechanisms that Together Might Generate Millennial-scale Dansgaard-Oeschger Events



Note. The melting of the massive ice sheets surrounding the North Atlantic during the Last Glacial Period, provided freshwater, that could have changed the surface salinity of the North Atlantic in the locations where deep water was formed, that could have caused change in the intensity of the AMOC, shift of the ITCZ and change in the pathway of the subtropical jet stream (represented with green arrow). Such changes could have caused switch between stadials and interstadials. Reprinted from "Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3)" by E. A. Agosta & R. H. Compagnucci, 2016, *Springer Earth System Sciences,* (p. 86).

The third condition that the change in the thermohaline circulation has to meet in order to represent a possible mechanism that causes the abrupt climate changes, is to affect many regions of the world. Namely, the ocean is responsible for net import of heat from the south towards the north because the warm water that flows into the North Atlantic, exits the basin as deep cold water. If this water transfer ceases, the decreased heat transfer from the south towards the north would lead to cooling of the Northern and warming of the Southern Hemisphere. The concept of this bipolar seesaw, is that every change of the strength of the thermohaline circulation that results in abrupt temperature change in the north, will generate more or less equal change in the temperature with an opposite sign in the south. However, the changes in the thermohaline circulation might not be able to affect regions outside of the Atlantic Ocean, due to the small heat transfer towards the North Pole. Although the first models used to test this support the latest point, other more precise models that have been developed later, demonstrate that the consequences of the change in the thermohaline circulation can be felt in other regions of the world, such as the precipitation change and the strength of the monsoon in the tropics, change in the strength of the winds over the Arabian Sea and the Atlantic as a result of the increased ice sheets and atmospheric and oceanic heat transfer towards the tropics and cooler Hemisphere. Still, the changes suggested by the models do not completely match the evidence found in the paleoclimate archives (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

3.2.2 - Sea ice

There are two major ways in which the sea ice can influence the climate. One is related to the albedo positive feedback mechanism, that can affect the overall energy budget. The other is related with the possibility of the sea ice to act as a barrier and insulate the ocean from the atmosphere, thus resulting in interruption of the moisture and heat exchange, and impacting the local climate (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Abrupt changes in the sea ice should be possible, in order to be able to influence the abrupt climate change events. The abrupt changes in the sea ice can be possibly related to the temperature threshold for its emergence and melting, and rapid advancement or melting due to the strong albedo feedback. A third possible option is associated with the ceasing of the sea ice growth that comes from the disrupted transfer of heat from the ocean to the atmosphere as the ice grows, this limiting the cooling down of the ocean that is necessary for the ice growth. An important point is that due to the third option mentioned and the possible shift in the state, the sea ice can be very sensitive to the changes in the thermohaline circulation and behave as an amplifier of the caused changes in the climate locally and globally. A probable interaction between the ocean, atmosphere, sea ice and the ice sheets might lead to the appearance of the Heinrich events. Therefore, Clement & Peterson (2008) propose that the meltwater released from the ice sheets could reduce the thermohaline circulation and the sea ice would extend more, towards the equator, while the temperatures at high latitudes are strongly reduced. After these conditions, when the meltwater event ceases, the thermohaline circulation comes back to the previous state and leads to melting of the extended sea ice, but the reduced sea ice through the albedo feedback and the insulating effects, acts as an amplifier and causes even further melting of the ice sheets present everywhere. The resultant minimum of the sea ice extend provokes the decrease of the ocean temperatures due to possible heat transfer to the atmosphere, this leading to bigger advancement of the sea ice and return to the starting levels. Clement & Peterson (2008) believe that these oscillations of the sea ice and feedback mechanisms are capable to produce the sawtooth pattern, although the possible time-scale has not been found to be millennial. According to this option, although the ice sheets are the main trigger, making this mechanism to be able to explain why the abrupt climate changes are mostly occurring during glacial periods, the main role in the creation of the abrupt changes is played by the sea ice feedback mechanisms, while the system is trying to come back at the previous condition. Also, Clement & Peterson (2008) state that there are models that show that the changes in the sea ice can give rise to temperature variations up to 10 °C in the North Atlantic. However, the precise quantification of the climatic changes due to the sea ice and thermohaline circulation interactions, are not yet available. In addition, the possible feedback mechanisms between the sea ice and the CO_2 concentration, might also play an important role (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

One of the main issues related with the sea ice variations as a possible mechanism responsible for the abrupt climate changes, is the lack of millennial time-scale behavior. In particular, the time-scale of their changes is much shorter, though it can evolve in longer-term oscillations through an interaction with the ice sheets. Still, this interaction might cause the required longer-term oscillations, but on a 100 kyr time-scale and not a millennial time-scale. As a consequence, it has been acknowledged that the only way for achieving the millennial time-scale, is through a mechanism in which the sea ice only plays a role of an amplifier (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

The models used to determine whether the sea ice mechanisms fulfill the requirement to allow global linkages, reveal that the strong warming phase during the Dansgaard-Oeschger events, can be clarified by the removal of the sea ice in the North Atlantic. They show that the reduced winter sea ice and the feedback mechanisms related to it, can explain the amplitude in the temperature and accumulation changes in the Greenland Ice Sheet during the interstadials. Furthermore, the sea ice is required to explain the pattern of the moraines in the North Atlantic region. Regarding the Younger Dryas event, if there was an advance in the sea ice during winter, it would have caused considerably lower winter temperatures, thus making possible the explanation of the strong seasonality recorded in the proxy data (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

It is logical to believe that the freshwater flow in the North Atlantic can cause variation in the AMOC, and the termination of such forcing would cause AMOC strengthening and temperature increase, as recorded in the Greenland ice cores. Probably the reduction in the sea ice in the North Atlantic is playing an important role in this processes, acting as a driving or amplifying force. Erhardt, et al., (2019) suggest that modeling results support this, and show that if the sea ice in the North Atlantic and Nordic Seas is completely removed, the Greenland temperatures and the snow accumulation are increased. The used models further suggest that this sea ice reduction can be caused with some variations in the wind stress over the sea ice either spontaneously, or affected by elevation alteration of the Laurentide Ice Sheet. Another possible mechanism for sea ice reduction is related to the accumulation of heat underneath it, at the time of the cold stadials. In particular, the accumulated heat can lead to destabilization of the stratified water column, this causing collapse of the stratification and sea ice melting from below. Erhardt, et al., (2019) believe that the Dansgaard-Oeschger and similar oscillations can be explained by the development and the disintegration of a meridional salinity gradient, between the North Atlantic covered by sea ice and the open ocean. If there is a breakdown in this gradient, it causes collapse of the sea ice cover and AMOC recovery. In a nutshell, the sea ice cover is a critical factor that is included in determining the climatic changes at the time of the Dansgaard-Oeschger events. To add, it is very difficult to distinguish the effects of the different processes that can be involved in the production of the Dansgaard-Oeschger events, and their interactions as well. That is why it is not easy to determine the validity of all the proposed mechanisms that might take part (Erhardt, et al., 2019).

3.2.3 - Tropical ocean-atmosphere processes

The first requirement that needs to be fulfilled for a mechanism to be considered as a possible one for causing the abrupt climate changes, is its abruptness. In this case, the tropics are considered to be capable to undergo abrupt changes, something that can be confirmed even from nowadays occurrences. According to the results of many models, Clement & Peterson (2008) suggest that the abrupt changes in the tropical oceans might be explained by the changes in the winds blowing over the equatorial region, regardless of the origin of their change. They propose that the changes in the tropics might arise from a small change in the orbital forcing. Also, the changes might originate from the nonlinear response of the tropical convection to a surface temperature due to a smoothly varying forcing, such as the gradually increased concentration of the CO_2. This nonlinear response of the convection, can sometimes lead to an abrupt behavior of the tropics, because of the feedback mechanisms that include the cloud cover and the water vapor as a greenhouse gas. This behavior can even have a larger scale. Still, it is not clear enough what is the exact smoothly varying forcing that can produce the abrupt climate changes during the Last Glacial Period. Clement & Peterson (2008) also propose that an important influence in the regional and global climate might originate from the change of the state of the jets in the tropics. Or, that freshwater fluxes in the ocean can affect the structure of the thermocline, that has a serious influence on the tropical climate. Also, it is important to mention that for the tropical climate, the connection and the feedback mechanisms between the ocean and the atmosphere are crucial. For instance, if there was an increase in the sea surface temperature in the tropics, the resultant enhanced atmospheric circulation would cause stronger meridional overturning circulation and increased heat transfer from the tropics, which would eventually lead to a decrease in the sea surface temperature (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

In the case of the tropical ocean-atmosphere processes as a possible mechanism for inducing the abrupt climate change events during the Last Glacial Period, the main issue is related to the millennial time-scale of the changes. In other words, in the tropics the dynamics of the climatic components do not have a long time-scale, such as in the higher latitudes. Still, there are some possibilities of millennial variability in the tropics, mostly related to the internal mechanisms (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

An important aspect is that there are evidences that the variability in the tropics can influence the climate globally, such as the sea surface temperature changes associated with ENSO, or sea surface temperature changes that can affect the high latitude regions. Moreover, the tropics affect the global climate with the energy budget. To be more clear, because of the large solar radiation and energy gain in the tropics, a balance should be reached through local radiation and heat export towards the poles. The local radiation is mostly done through the released water vapor in the atmosphere, that is an example of positive feedback mechanism because the water vapor is a strong greenhouse gas. According to this, its high atmospheric concentration, resulting from strong warming of the tropics, can further increase the temperatures. So, it is possible that some perturbations to the tropical climate and the content of water vapor in the atmosphere, can amplify the changes and affect the climate globally. However, the role of the clouds in the tropics should be considered as well. The cloud cover often can be considered as a negative feedback mechanism, since they can reduce the heating in the tropics because of their high albedo. So, if there is a perturbation that can lead to increased amount or spatial extent of the clouds, this can also cause a global effect. However, there are different types of clouds that can have different feedback mechanisms and it is not simple to determine their role in the climatic system and the spatial range affected by the consequences. Clement & Peterson (2008) suggest another mechanism at the tropics that can impact the climate globally, and is related to the influence of the tropical sea surface temperature to the large ice sheets present during the glacial periods, such as the Laurentide Ice Sheet. The Laurentide Ice Sheet is presumed to affect the North Atlantic deep water formation through the meltwater, and the tropical sea surface temperatures might have a large impact because the ice sheets can be very sensitive to their changes. However, more information and data about the spatial extent of this influence are necessary. There is another possible teleconnection, that links the wind patterns in the tropical Pacific and the North Atlantic. More clearly, modeling results support that these winds are able to affect the abrupt climate changes, such as the ENSO system. In the glacial periods, the winds might have driven the sea ice from the Arctic and caused sediment deposition in the North Atlantic, such as the observed data from the archives for the Last Glacial Period abrupt changes show. According to this, the tropics can influence the climate in the North Atlantic through the atmosphere, as addition to the already mentioned oceanic pathways. There is another option for the tropical Pacific to influence the North Atlantic, that is via transport of fresh water into the atmosphere. The water vapor released in the atmosphere in the tropics, can be carried by easterly airflow. In situations when high amounts of water vapor from the atmosphere, that originated from the tropical Atlantic, are exported, the tropical Atlantic becomes saltier, and this causes stronger deep water formation in the North Atlantic (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

3.2.4 - Interactions between the tropics and higher latitudes

Since the evidences of abrupt climate changes are present everywhere across the globe, one possible approach for understanding the reasons of their occurrence, is looking at the feedbacks and interactions between the high and the low latitudes. Such interaction is the one between the salinity of the tropical Atlantic and the thermohaline circulation. High salinity in the tropical Atlantic causes sinking of the surface waters in the North Atlantic, while the thermohaline circulation has a strong influence on the rainfall patterns in the tropics. A thermohaline circulation cessation causes change in the balance between evaporation and precipitation, with more net evaporation that leads to increased ocean salinity in the northern subtropics. This is followed by transfer of the signal in the North Atlantic that promotes the recovery of the thermohaline circulation. Hence, this interaction is an example of a negative feedback mechanism between the tropics and the higher latitudes. However, the time-scale of this mechanism is within centuries, and it should be overcome for affecting the abrupt climate change events that have a millennial time-scale. In this case, positive feedbacks that will cause a transition into a different state are required. One such positive feedback in the atmosphere, is the shift of the intertropical convergence zone towards the south that could modify the trajectory of the mid-latitude storm tracks in the North Atlantic. This can further affect the formation of the deep water, with the reduction of the salty and warm water that flows into the North Atlantic. If the jet is more zonal, it can cause decrease of the temperatures in Europe, and cause expansion of the ice cover towards the equator, something that can be linked with the evidence of the abrupt climate change events found in that region. Still, it is not clear how this mechanism might affect global regions, and reduce the precipitation in the regions influenced by the Asian monsoon. Another possible mechanism is related to the thermohaline mean depth. Clement & Peterson (2008) explain that the thermohaline in the tropics adjusts, in order to satisfy the balanced energy budget between the ocean and the atmosphere. To be more clear, in terms of decreased heat loss at high latitudes, the equatorial thermohaline becomes deeper in order to prevent the ocean to gain a lot of heat in the tropics. It is proposed that this occurred during the Pliocene, and it led to permanent El Niño state. These conditions are further expected to cause increased atmospheric concentrations of water vapor and reduced stratus decks that will lead to warming of the climate and allowing for the feedback mechanism to take place. Or, the tropical thermohaline can be modified with freshening of the surface waters at high latitudes that can lead to a decrease of the meridional density gradient between the subtropics and the equator, thus causing a change in the wind-driven circulation. The result will be deepening on the tropical thermocline and reduced east-west sea surface gradient throughout the length of the equator. However, these proposed feedback mechanisms have not been deeply analyzed and it is not certain if the suggested interactions between the tropics and the higher latitudes truly exist (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

3.2.5 - Spontaneous oscillations of the coupled atmosphere-ice-ocean system in the North Atlantic, Nordic Seas and Arctic

Even though the most often suggested hypothesis for explaining the Dansgaard-Oeschger events, and the other abrupt climate change events during the Last Glacial Period, includes the changes in the AMOC, these events could be better explained if they are considered to be a result of the interactions between the different components of the climatic system. Li, et al., (2019) state that until recently, the AMOC hypothesis has been considered as the best one not only because the abrupt change in the AMOC modes can explain the abrupt temperature changes at high latitudes, but also because it could explain the antiphase expression of the Dansgaard-Oeschger events in the Southern Hemisphere. This hypothesis has been improved over the years in order to fit better with the proxy data. In these terms, the hypothesis suggests that there have been three circulation modes: warm/cold/off, strong/weak/off or interstadial/stadial/Heinrich. The trigger for the mode switching has probably been the freshwater input from the continental ice sheets. However, there are some uncertainties related to this hypothesis, such as the ones related to the freshwater perturbations. Namely, freshwater fluxes are necessary for the AMOC change of modes, but it is not yet clear whether these events occurred before or after the abrupt climate change events. Moreover, there is an absence in the ocean signals for the shortest events. Another uncertainty is related to the fact that the AMOC modes probably exist during interglacial periods without abrupt climate change events. To add, there is an unexplained lag phase between the ocean heat transport change as a result of the AMOC mode changes, and the surface climate change, such as the temperature variation in Greenland (Li & Born, 2019).

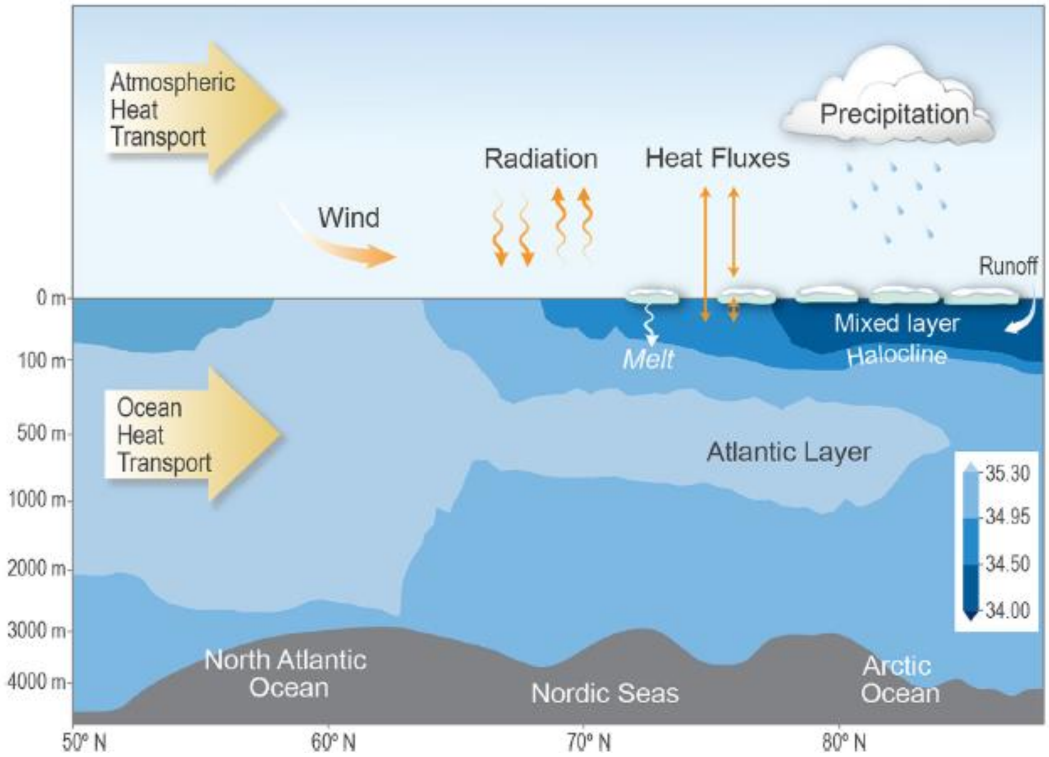
Due to these uncertainties, Li, et al., (2019) propose another mechanism for explaining the Dansgaard-Oeschger events, based on the internal dynamics of the climatic system, that suggest that these events are spontaneous climate oscillations and originate from atmosphere-ice-ocean interactions that alter poleward energy transport. In this case, similarly to the AMOC mode change hypothesis, the alternating phases of strong and weak poleward energy transport could cause the swings between stadials and interstadials. More specifically, there is a cyclonic circulation system known as a subpolar gyre, consisting of the Labrador Current (fresh surface water from the Arctic to the East Greenland Current, and then into the Labrador Current to the south), the North Atlantic Current (warm salty waters that lose heat travelling towards the North Pole) and the Irminger Current (warm and saline waters from the Eastern North Atlantic towards west). This circulation is determined with the atmospheric winds, surface heat exchange, freshwater balance, and finally, the sea ice cover, with its variability well documented in the records (Li & Born, 2019).

The Greenland climate seems to be most sensitive to the change in the sea ice cover in the North Atlantic, and probably this is the reason why the Heinrich events appear as regular Dansgaard-Oeschger stadials in the Greenland ice core records. So, it can be concluded that the sea ice cover plays a major role in the abrupt climate changes and it is important to determine how it can undergo variations. In this terms, a fundamental assumption is that the sea ice can be changed from above or below. This change of the sea ice cover cannot cause the abrupt climate changes itself, and it needs to be accompanied with changes in the heat transport with the ocean, that should be substantially decreased in order to cause sea ice cover expansion and millennial sea ice variability. This conclusion already establishes connection between two components of the climate system, the sea ice cover and the oceanic heat transport (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

The third component in the proposed coupled interaction is the atmosphere. Namely, the atmospheric wind patterns are crucial in determining the surface ocean circulation and the gyre position and strength. Moreover, the interactions between the atmosphere and the sea is necessary for regulation of the buoyancy. For instance, the ocean can lose heat or freshwater to the atmosphere and become denser, that would result in increased oceanic heat transport towards the north with the stronger gyres, and vice versa. To add, there is an interaction between the atmosphere and the sea ice as well. In particular, the sea ice might experience fast changes as a result of wind forcing, and slower one due to variability in gyres or ocean advection. Furthermore, the sea ice influences the interaction between the atmosphere and the ocean, because it acts as a barrier for the energy exchange. The suggested interactions between the atmosphere, ocean and sea ice are also represented in Figure 4 (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Figure 15

Schematic Representation of the Interactions between the Atmosphere, Ocean and Sea Ice in the North Atlantic Ocean, Nordic Seas and Arctic Ocean



Note. The interactions include exchange processes of heat, freshwater and momentum. Also, the salinity profile that determines the density of the ocean is represented. Reprinted from "Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events" by C. Li & A. Born, 2019, *Quaternary Science Reviews 203,* (p. 5).

A mechanism that includes atmosphere-ocean-sea ice interaction, that might be responsible for the abrupt climate change events, starts with a cooling phase as a result of the atmospheric blocking over the eastern subpolar gyre. This promotes expansion of the sea ice cover and produces a high sea level pressure anomaly. Further sea ice expansion initiates a freshwater perturbation that causes weakening of the deep ocean convection, the longer exposure of the surface waters to low temperatures leads to their freezing, that reinforces the previous sea ice changes. If instead the deep ocean convection weakening, there was a weakening of the subpolar gyre that is also possible, it causes reduced heat and salt transport to the western North Atlantic with the Irminger Current, this leading to stronger positive sea ice anomaly. The positive feedback mechanisms allow persistence of these conditions for several decades. The reversed conditions and mechanisms should cause the subsequent abrupt warming. Li, et al., (2019) state that similar mechanisms to the proposed one, have been tested with models, and the modeling results show match in the time-scale and the abruptness of the abrupt climate change events. This confirms that such interactions are extremely important and might be the exact cause of the abrupt climate change events. In addition, the ice sheets also play a role in these interactions, because their increased height can cause shifts in the wind patterns. Furthermore, the greenhouse gases, such as the CO_2

concentrations are essential as well, because they influence the ice sheet topography. Due to the fact that the abrupt climate change events appear during glacial periods, it is important to determine what are the glacial characteristics that assist the occurrence of these oscillations. Probably, the winds are the most important one, because their patterns are highly affected by the presence of the high-elevated ice sheets, and the large-scale winds difference represent the most noteworthy inequality between the glacial and interglacial phases. During glacial periods, these winds cause stronger wind-stress over the North Atlantic, thus resulting in strengthening of the subpolar gyre. Hence, it can be concluded that the wind-driven circulation is an important interaction that obviously takes place in the production of the abrupt climate change events. In summary, the atmosphere-ocean-sea ice interaction might be the right mechanism for explaining the abrupt climate change events, particularly the Dansgaard-Oeschger events. Moreover, the used models managed to create oscillations similar to the Dansgaard-Oeschger ones, using these coupled interactions. Still, this potential mechanism requires further analysis (Li & Born, 2019).

Thus, it can be concluded that all the mechanisms that have been proposed to explain the onset of abrupt climate changes occurred during the Last Glacial Period, might have played very important role in inducing and causing global extent of the abrupt climate changes. The evidence of the abrupt climate change events during the Last Glacial Period can be found everywhere on the globe, from the Northern Hemisphere, through the tropics and in the Southern Hemisphere. This can be also concluded with observation of the Figure 11 that represents the map of the records with imprint of the Dansgaard-Oeschger events. Determining the exact reason how the abrupt climate change evets happened, and how their impact was spread all over the globe is extremely important because in that way we will be able to learn more about the principle of functioning of the components of the climate system and their interactions. Also, we will be able to predict the occurrence of similar events in the future (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Probably a major task was performed by the thermohaline circulation, that most possibly was generated through meltwater input in the North Atlantic. Moreover, the expected spatial extend from the modeling results matches the evidence from the tropical and North Atlantic. However, there are some uncertainties related to this mechanism, such as the unresolved method that causes the meltwater pulses, that is most probably related to the internal mechanisms of the ice sheets. Then, the lack of knowledge for the capability of this mechanism to explain the Dansgaard-Oeschger events, while it is more suitable in the case of the Heinrich events and the Younger Dryas. Further disadvantage is the absence of enough evidence about the effect in the Southern Hemisphere. To add, there is a mismatch between the evidences and the changes in the thermohaline circulation regarding the regions affected by the Asian monsoon, because the shutdown of the thermohaline circulation does not exactly cause its weakening. Moreover, the relation between the thermohaline circulation and the monsoon strength is still not well resolved. Also, the thermohaline changes cannot explain the abrupt warmings well enough, because the modeling results show that after the meltwater events, the thermohaline circulation simply recovers and there is no an abrupt behavior. Nonetheless, Clement & Peterson (2008) believe some of these issues can be resolved if there were modes in the thermohaline circulation changes. The suggested AMOC modes, such as weakening, intensifying, or a shutdown, are proposed to happen due to freshwater forcing, or CO_2 concentration and wind-stress variations in the Southern Hemisphere. Yet, the most important problem related to the AMOC, regardless if it is referring to the mode swings or not, is the fact that we are not sure whether the AMOC changes appeared before the abrupt climate change events, or as a result of them (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

The second possible mechanism for explaining the abrupt climate changes is related to the sea ice feedbacks. Such feedbacks are the albedo, the high impact on the sea-atmosphere heat and moisture exchange and the probable on and off switches. Still, the sea ice needs some forcing in order to be able to change and make these feedbacks relevant. Such forcings might be the thermohaline and the atmospheric circulation variations. A major issue related to this mechanism in order to be able to link it with the abrupt climate changes, is the absence of direct proxy for the sea ice (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

The third proposed mechanism, the tropical processes, might be a good option for explaining of the abrupt climate change events because of their capability to influence the climate globally. This is possible through the direct influence to the radiation budget on the planet, the hydrological cycle and the atmospheric and the thermohaline circulation. However, Clement at al., (2008) explain that it is still not certain what is the exact forcing (orbital changes, CO_2 concentration, etc.) that can cause the millennial-scale changes in the tropics, and there is a lack of evidence for coupled interactions in the region of the tropical Pacific Ocean with a resolution that is high. Anyway, an important point is that the changes in the tropics can cause further variability in the strength of the monsoons, something that was missing in the other options (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

Finally, in determining the exact reason for the occurrence of the abrupt climate changes during the Last Glacial Period, some crucial aspects are the global-scale coupled feedbacks that will allow the climate change across the planet, such as the atmosphere-ocean-sea ice system explained in the fourth proposed mechanism. The atmospheric and oceanic circulation are crucial for the heat transport from the tropics to the poles, and this transport is strongly influenced by the sea ice cover. These three components of the climatic system are possible to have experienced changes as a result of a small perturbation, that through the feedback mechanisms could have been substantially amplified. The final result might have been the abrupt climate change events. Still, this possible mechanism that includes interaction of the internal climatic components requires further analysis (Li & Born, 2019).

In summary, all the above proposed mechanisms can be the reason for the occurrence of the abrupt climate change events. However, the exact mechanism has not been described yet. In order to be able to do that, we should continue with the analysis of the evidence and develop more sophisticated climate models (Clement & Peterson, Mechanisms of abrupt climate change of the last glacial period, 2008).

4. COMPARISON BETWEEN THE ABRUPT CLIMATE CHANGE EVENTS

In order to better describe the abrupt climate change events, it is important to illustrate the similarities and differences between them. Therefore, the comparison between the three types of abrupt climate change events is represented in Table 2.

Table 2

Abrupt climate change events

Abrupt climate change events	**Dansgaard-Oeschger events**	**Heinrich events**	**Younger Dryas event**
Number of events	25	6	Not certain if it was only 1 event, or there were more
Duration of the separate events/years	260-7400	200-2300	1300
Time interval between the separate events/years	1000-9000 Most often every 1470 years	7000-12000	
Period of occurrence	Last Glacial Period 57000-29000 years	Last Glacial Period 60000-16800 years	Last Glacial Period 12,900-11,600 years
Main characteristics	A few decade warm interstadial conditions, a few centuries cooling phase and a cold stadial period that lasts from a few centuries to a millennium	A slower gradual cooling phase followed by ice-rafted debris influx, and abrupt warming phase	Abrupt cooling onset that lasted 100 years, cold phase lasting 1150-1300 years and abrupt warming phase that lasted 40 to 50 years in three 5-year steps
Temperature change/°C	8-16	3-6	4-10
Shape of the curve that shows the temperature variation	Sawtooth shape	Sawtooth shape	

Other changes in the climatic conditions	Twice bigger accumulation rate during interstadials compared to the stadials, expansion of the polar front and meltwater influx during stadials	Increased ice volume, decreased ocean salinity and SST, bigger distribution of cold-loving vegetation, increased runoff, stronger winds, changes in ocean current velocity and meltwater influx	Change in vegetation cover with expansion of cold climate vegetation, advance of the continental ice sheets, drier conditions, expansion of the mountain glaciers, stronger winds and more dust, and decreased sea level
Occurrence during glacial periods	Yes	Yes	Yes
Evidence of meltwater events in the North Atlantic	No	Yes	Yes
Spatial cover	Global	Global	Global
Paleoclimate archive with the main evidence	Greenland ice cores	North Atlantic sediments	Greenland ice cores
Proxy data from the main archive	δ^{18}O, dust and aerosol concentration	Ice-rafted debris concentration, different foraminifera species	δ^{18}O, pollen, dust and aerosol concentration
Evidence distribution	Global	Global	Northern Hemisphere, tropics and part of the Southern Hemisphere. Evidence of the cooling are missing in Antarctica, New Zealand and Oceania
Other cycles in which the events take part	Bond cycles	Bond cycles that are terminated by the Heinrich events, near the end of the D/O events (except H1)	Marks the termination of the Pleistocene epoch and the beginning of the Holocene
Mechanism related to the existence of AMOC modes	Maybe: Change in modes triggered with freshwater flow. AMOC mode shift allow antiphased expression in the SH	Yes: Shutdown of the AMOC due to ice armadas melting in the ocean	Yes: Reduced strength of the AMOC as a result of the melting of the ice sheets

Mechanism related to tropical ocean-atmosphere processes	Yes: Surface water salinity change due to east Asian monsoon variations	No: The most noteworthy occurrences and biggest changes are in the North Atlantic	Yes: Surface water salinity change due to east Asian monsoon variations
Mechanism related to the bipolar seesaw	Yes	Yes	No: The Antarctic cold period started longer before the YD and does not have clear beginning and end
Mechanism related to the internal characteristics of the ice sheets	No: Bigger time-scale than the D/O changes	Yes	Yes
Mechanism related to the change in the sea ice cover, or its role as an amplifier	Yes	Yes	Yes
Mechanism related to the coupled atmosphere-ice-ocean system in the North	Yes	Yes	Yes

Note. Comparison between the main characteristics of the three types of abrupt climate change events, and the possible mechanisms that can explain the occurrence of each type. Data obtained with using: "Correlations between climate records from North Atlantic sediments and Greenland ice" by G. Bond, 1993, *Nature 365.6442*; *Earth's Climate: Past and Future* (p. 298) by W. F. Ruddiman; *Heinrich Event* by D. Easterbrook, 2019, https://www.britannica.com/science/Heinrich-event.

5. EVIDENCE OF ABRUPT CLIMATE CHANGE EVENTS

Paleoclimate archives are chemical, physical and biological materials that can be used for determining the climate in the past, through the analysis of the parameters (proxies) that these records contain. The abrupt climate change events during the Last Glacial Period had a global impact, and there are many evidence for these occurrences present worldwide (Bradley, 2015). The mechanism behind the abrupt climate change events remain uncertain, as explained in the previous section. An important point in the process of determining the correct mechanism, is the development of precisely-dated paleoclimate records, with temporal resolution essential for establishing the amplitude and the phasing of the variations that occurred in the different components of the climate system at the time of the abrupt climate change events (Vacco, Clark, Mix, Cheng, & Edwards, 2005).

The proxy records can be separated in few groups: geologic, glaciological, biological and instrumental. The geologic records can be marine and terrestrial, and the marine sediments might contain biogenic and inorganic material. The biogenic material is represented through the planktic and benthic foraminifera fossils, and some of the measured values that can represent the past climate conditions can be: oxygen isotopic composition, species abundances, trace elements and organic biomarkers. On the other side, the analyzed properties of the inorganic material might be the dust, the ice-rafted debris, the grain size and ratios of the present elements (Bradley, 2015). One of the many advantages of the sediments as an archive, is the fact that they can be used for continuous study of the past climate throughout most of the Planet's history, because the oldest sediment record is even 3.9 billion years old. Moreover, an important feature is that a single archive as the sediment cores, contains lots of information about the past climate conditions. In addition, the sediments can be correlated with other records. Finally, they are present in 70 % of the Earth's surface, making them able to represent the changes that happened worldwide. The negative sides of the sediments, is that they are difficult to be dated accurately and often do not provide the proper resolution for analyzing abrupt climate changes, because they have generally low sedimentation rates and the sedimentation process is often disrupted. An exception are the areas with high sedimentation rate (Paleoclimate Research, n.d.; Bradley, 2015).

Geologic terrestrial archives are the speleothems, the glacial deposits and features of glacial erosion, the lacustrine sediments and erosional features, the periglacial characteristics, the aeolian deposits such as loesses and send dunes, some pedological features, etc. The speleothems can be used for obtaining important information, but they cannot always provide annual resolution. The loesses contain information on long time-scales, but they do not provide proper resolution and it decreases with going further into the past (Bradley, 2015).

The following group of proxy records are the glaciological records, such as the ice cores. Some of the features of the ice cores that can represent the climate of the past are: the geochemical features like the oxygen and hydrogen isotopic composition and presence of different ions, the air bubble composition and pressure, concentration of microparticles, physical properties of the ice cores, etc. The ice cores are considered to be the best paleoclimate archive, not only because they can provide long spanning records (up to 800000 years), but also because they provide annual or even seasonal resolution, with using the clearly visible annual layers. Furthermore, they contain important information about many parameters, such as the temperature, precipitation, wind patterns, volcanic activity and atmospheric composition in the past. Moreover, their spatial coverage is complementary to the tree rings and corrals, even though they occupy small surface. To add, they can also be correlated with other records (Bradley, 2015; Paleoclimate Research, n.d.; Mann, 2002).

The next group, the biological records, covers: tree rings, corals, pollen, lake sediment biota, insects, plant microfossils and modern species distribution. The tree rings represent an archive that can be very accurately dated and might provide continuous record of more than a thousand years. Their high-resolution allows analysis of fast occurring changes. In addition to the data about the temperature and precipitation, they contain information about local changes such as fires and earthquakes. However, they provide very short time-span and not enough accurate information of the climate changes on multicentennial time-scales. Also, they can be used for obtaining information only for the subpolar terrestrial regions. Similarly, the corals represent an archive with high-resolution, able to preserve ever monthly changes, but the time-span is relatively short. They contain information about the temperature, salinity and sea level change. However, they provide information only about the tropical and sub-tropical regions. The lake sediments provide annual resolution and contain many important information about the climate conditions of the past: temperature, biomass, magnetic field changes, precipitation, volcanic eruptions and chemical composition of the water in the lake (Bradley, 2015; Paleoclimate Research, n.d.; Mann, 2002).

Finally, the historical records include the phenological records and the written records of some environmental indicators. They can provide annual or even intra-annual data, but they existed only in the last few centuries and were not present everywhere (Bradley, 2015).

Some of the records do not provide enough temporal resolution for capturing the abrupt climate change events, while others do not provide precise dating, that is necessary for the correlation between the different records (Vacco, Clark, Mix, Cheng, & Edwards, 2005). The correlation between the different records is called multi-proxy approach, and it aims to use the advantages of the different records in order to obtain the necessary information about the climate changes in the past, with a large spatial cover that allows reconstruction of hemispheric or global composite. Such multi-proxy approach requires possibility for precise dating of the records (Mann, 2002). High-resolution records mean that the records should be able to preserve detailed information about the climatic changes that happened very quickly. Resolution of the signal varies from archive to archive, and the perfect archive for the analysis of the abrupt climate change events is the one that preserves annual changes and allows dating even beyond the Last Glacial Period. Table 3 represents some of the most commonly used proxy records, the time-span they cover, their temporal resolution and the climate variables that they contain information about (Bradley, 2015; Ruddiman, 2013).

Table 3

List of the most commonly used paleoclimate archives, the time-span of the record, their temporal resolution and the climate variables that can be described with the archives

Archive	Time-span of record/years	Temporal resolution	Climatic variables that can be described with the archive
Historical records	~10^3	1 month-100 years	Temperature, precipitation, vegetation, volcanic eruptions, sea level, solar activity
Three rings	~10^4	1 month-100 years	Temperature, precipitation, vegetation, volcanic eruptions, solar activity
Lake sediments	~10^4-10^6	1-10^4 years	Temperature, vegetation, geomagnetic field variations, precipitation, volcanic eruptions, chemical composition of water
Corals	~10^4	1 month-10^5 years	Chemical composition of water, sea level, temperature, precipitation
Ice cores	~$8*10^5$	1 month-10^4 years	Temperature, precipitation, chemical composition of air, vegetation, volcanic eruptions, geomagnetic field variations, solar activity
Speleothems	~$5 * 10^5$	10^2-10^4 years	Chemical composition of water, temperature, precipitation, volcanic eruptions, vegetation
Ocean sediments	~10^7	10^2-10^7 years	Temperature, chemical composition of water, vegetation, geomagnetic field variations, sea level, precipitation, solar activity

Data obtained from: *Earth's Climate: Past and Future* (p. 298) by W. F. Ruddiman; *Paleoclimatology* by R. S. Bradley, 2015.

The archives that preserve the changes at a resolution of tens to hundreds of years are not appropriate, because they allow only detection of the millennial-scale changes, without a possibility for defining their amplitudes. According to this, there are only a few high-resolution records capable to store enough information about the abrupt climate change events. In the next sections, the detailed description of two such records, the ocean sediments and the speleothems found in the Hulu Cave in China, follows.

5.1 - Ocean sediments

Ocean sediments originate from the eroded continental rocks that are transported into the ocean in granular or dissolved form, and are deposited there. The depositions are able to persist on the ocean floor for a very long time, after what they are destroyed by tectonic processes. The high-resolution sediments that preserve the most information are deposited continuously. However, during the process of sediment formation, the deposition can be disturbed by strong waves produced by storms, earthquakes, currents, dissolution by corrosive water, sea level change and most importantly, the movements of the deep-dwelling ocean organisms. Stronger disturbance by organisms, and hence poorer resolution, is present in the areas with higher productivity because of the many burrowing organisms. Still, the deep ocean quiet environment allows good preservation of the sediments, where the sediments are preserved for tens of millions of years. It is important to mention that the sediment deposition in the oceans is substantially slower compared to the other environments. That is why, the ocean sediments are not considered as a proper archive for examining short term climatic changes. Most often, the deposition rates are not exceeding 1 or 2 cm per 1000 years. An exception are the regions that receive eroded influxes from the surrounding continents. Such sediments located in the North Atlantic, might have deposition rates of 10-20 cm per 1000 years. Also, the ocean currents might play a role in the deposition with transport of the fine sediments in the locations where the currents become slow. However, some materials, such as the foraminifera and the ice-rafted debris, are not sensitive to the movements with the ocean currents, and tend to stay in their locations, representing a reliable record of climate changes (Ruddiman, 2013).

5.1.1 - Dating of the sediment records

The dating of the sediment records can be done with radiometric dating (through the decay of radioactive isotopes) and counting annual layers (varve couplets related to the seasonal alternations of deposition of mineral-rich and organic matter-rich material) (Ruddiman, 2013). Radiocarbon ^{14}C dating is most often used dating technique for the last 50000 years, because it allows precise dating, compared to the annual layer counting. In particular, every organism contains carbon that can be dated and there are many techniques that can provide quick results with analysis of a small sample. Moreover, radioactive intermediates generated during the decay of uranium and thorium and the potassium-argon system, are techniques that are used as well. Other techniques include determination of accumulated damages to rocks, mineral grains and chemicals. In addition, the reference horizons and the possibility for correlation with other records, play an important role in the dating (Abrupt Climate Change, 2002).

5.1.2 - Commonly used proxy records from the sediment cores

Some of the proxy data deposited in the sediments that can contain information about the climate in the past are: pollen assemblages, planktic species (foraminifera, coccoliths, radiolaria and SiO_2 diatom shells), type of the debris and grain size and isotopic composition (Ruddiman, 2013). The species assemblages, isotopic composition, shell geochemistry and alkenone ($U_{37}^{K'}$) thermometry, represent paleoclimate proxies of temperature and vegetation cover. The presence of Mg or Sr ions, or stiffer molecules in calcium carbonate shells, can be used as a proxy for precipitation or warming. The shell isotopic composition, after correction for temperature and ice volume, represents a proxy for salinity. Furthermore, the isotopic composition of pore waters and shell isotopes, after correction for temperature and salinity, can be used for ice volume determination. The oxygen isotopic ratio in carbonate shells can be used as an indicator of presence of large ice sheets. The boron isotopes in shells are used for pH value calculations. Cd/Ca in shells and carbon-isotopic data values can be used as a proxy of ocean circulation. In addition, the shell dissolution can be used for determining the corrosiveness of the waters. Moreover, the carbon isotope ratio can be used as a proxy of ocean productivity. Finally, the isotopic values in organic matter can give information about the photosynthesis pathways (Abrupt Climate Change, 2002).

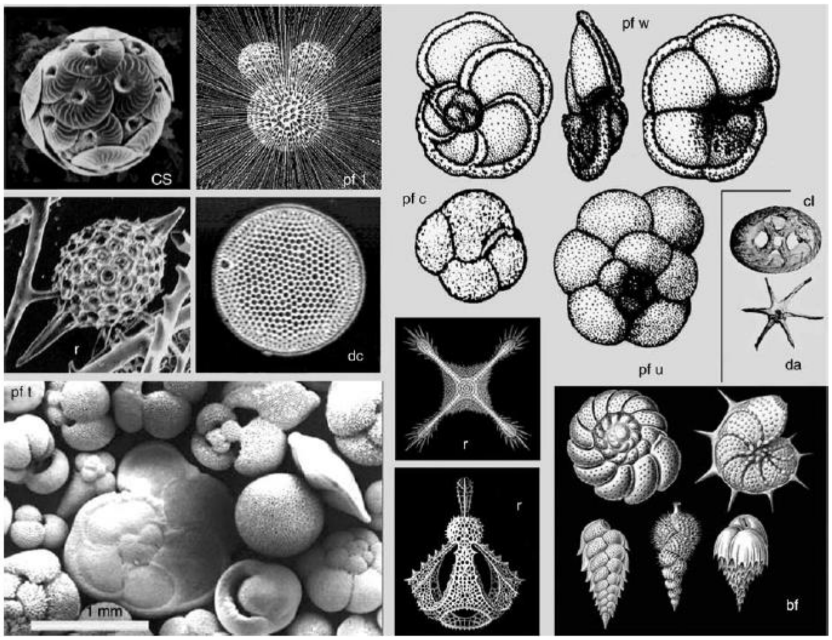
For example, colder periods can be related to isotopically heavier water in the oceans and heavier isotopes in the shells, because the lighter isotopes have been incorporated in the large ice sheets (Abrupt Climate Change, 2002). To be more clear, the foraminifera species are build up from calcium carbonate shells, and for their formation, they use the dissolved HCO_3^- ions from the water. The planktic foraminifera live in the surface waters, more precisely in the first 100 m, while benthic foraminifera live on the ocean floor. The oxygen in these shells is incorporated directly from the water, and it can be either ^{18}O or ^{16}O. As a result, the shells of the foraminifera species, that later become part of the ocean sediments, represent the relative abundance of the two oxygen isotopes in the ocean waters. The $\delta^{18}O$ value, which represents the ratio between ^{18}O and ^{16}O, is directly related to the ocean temperature, because for every increase in the temperature of 4.2 °C, there is a decrease in the $\delta^{18}O$ value of 0.1 %. This shows that when the water temperature increases, the ^{18}O isotope becomes less abundant than the ^{16}O isotope. The 0.1 % value refers to the planktic foraminifera, while for the benthic foraminifera the change is +0.35 %. However, this change in the isotopic composition does not concern only the change in the temperature of the waters, but also the amount of water that is stored in the continental ice sheets. This is because the lighter, ^{16}O isotope is stored in the ice sheets, thus leaving the ocean depleted in ^{16}O. As a consequence, times with large mass of ice sheets corresponds to larger $\delta^{18}O$ value. The opposite, or smaller $\delta^{18}O$ value is consistent with periods of melting of the ice sheets (Ruddiman, 2013).

To add, $\delta^{13}C$ value of the foraminifera species is another important indicator of the temperatures. This is because, when the organic carbon is transferred into the ocean during glacial periods, it is quickly converted into inorganic carbon. The organic carbon from the land is present in the form of ^{12}C. When this organic ^{12}C is being converted into inorganic form, it causes the ^{13}C isotope to be less abundant in the oceans and hence, the $\delta^{13}C$ value becomes lower. According to this, it can be concluded that lower $\delta^{13}C$ values correlate with bigger $\delta^{18}O$ values at the time of periods with colder temperatures of the ocean waters and larger glacial ice sheets (Ruddiman, 2013). The temperature changes can also be determined from abundance of cold-loving or warm-loving shells in sediments and the stiff diatom cell-wall molecules in sediments. Moreover, information can also be obtained from the concentrations of non-carbonate ions substituted into the calcium carbonate shells (Abrupt Climate Change, 2002). In this term, the ratio Mg/Ca is another valuable indicator of the past climate. To be more specific, Mg can replace Ca in the $CaCO_3$ of the foraminifera shells, and the process of substitution is dependent on the temperature of the ocean water. The ratio Mg/Ca increase with the increasing of the temperature of the ocean water (Barker, Cacho, Benway,

& Tachikawa, 2005). Some of the biogenic proxies in the sediment cores that provide information about the past climate are represented on Figure 16 (Gornitz, 2008).

Figure 16

Biogenic Material in the Ocean Sediments



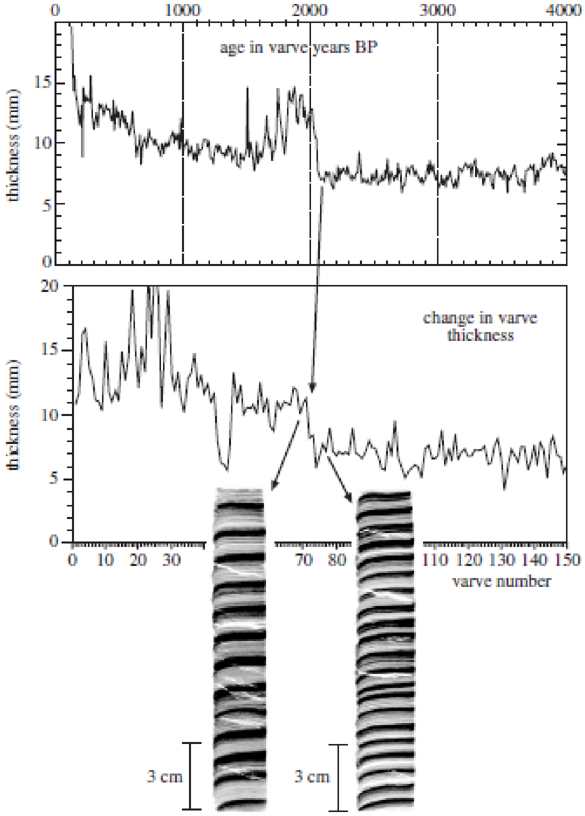
Note. Cs: cococlithophorid, pf: planktic foraminifera, r: radiolarian, dc: centric diatom, pf t: tropical assemblage of planktic foraminifera, pf w: planktic foraminifera characteristic for warm water, pf c: planktic foraminifera characteristic for cold water, pf u: planktic foraminifera characteristic for upwelling, cl: coccolith, da: discoaster, r: radiolarians, bf: benthic foraminifera. Reprinted from *Encyclopedia of Paleoclimatology and Ancient Environments,* (p. 526), by V. Gornitz, 2008, Springer.

5.1.3 - Annually-laminated ocean sediments as high-resolution records capable to capture the abrupt climate change events

The annually-laminated ocean sediments represent beneficial high-resolution records capable to capture abrupt climate changes. Moreover, the high-resolution comparable to the ice cores and coral reefs, allows correlation with the other archives that contain evidence of the abrupt climate change events and making assumptions about their global imprint. The seasonal cycle forcing is responsible for the formation of these laminated sediments, and the formation requires enough material influx. Furthermore, less disruption with biological activity is essential in order to preserve the laminae, and it is achieved in regions with anoxic conditions. These conditions can be achieved in areas with reduced levels of dissolved oxygen and in basins that block direct communication with the open sea. The laminae can be created with terrigenous sediment transported with winter rainfall, spring meltwater input, summer thunderstorm sediment input, rainfall controlled by the migration of the ITCZ in the tropics, lamina formed during periods of largest run-off, lamina rich with clay created by background settling from the water column, lamina formed during different phases of the reproduction cycles of the diatom species in relation with upwelling processes, gyres, disrupted stratification of the water column, etc. The climate changes preserved in the laminated sediments can be quantified with measurements of the thickness and the composition of the laminae. Such change in the laminae thickness that can illustrate an abrupt climate change event, is represented on Figure 17 (Kemp, 2003).

Figure 17

Representation of Abrupt climate change events in the Thickness of the Sediment Laminae as a Consequence of the Increase of the Sediment Input to the Basin in Saanich Inlet



Note. Reprinted from “Evidence for Abrupt Climate Changes in Annually-laminated Marine Sediments” by A. E. S. Kemp, 2003, *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences 361.1810,* (p. 1859).

In addition, an important point is the determination to which extent the bioturbation (mixing of sediments by the organisms) can attenuate the millennial-scale oscillations preserved in the record.

The mixing process can cause homogenization of the sediment, and reduction of the gradients in the particle concentration and oxygen isotope ratio in the foraminifera shells. An interesting finding is that the attenuation is proportional to the gradient in particle concentration, meaning that a larger rate of concentration variation with respect to the depth, corresponds to bigger mixing of that particular event. Also, bigger smoothing occurs in more slowly accumulating sediments. The bioturbation has been found in sediment cores with accumulation rates of 5-15 cm/kyr and this process can cause errors in the determination of the amplitude of the abrupt climate change events. As a result, the exact amplitude of the variations can be determined with using sediment cores that experience less mixing, or have a sedimentation rate of more than 25 cm/kyr, or even 50 cm/kyr, values that have been determined with usage of attenuation models. The annually-laminated ocean sediments that represent adequate archive for the abrupt climate change events have been found in the Santa Barbara Basin, Cariaco Basin, Hudson Strait, Florida Strait, Northeastern Arabian Sea/Pakistan Margin, and many other locations (Anderson, 2001).

5.1.4 - Imprints of the abrupt climate change events in the sediment cores

5.1.4.1 - Sediment core evidence of the Dansgaard-Oeschger events

Although the Dansgaard-Oeschger events are most prominent in the Greenland Ice Cores, and in the Antarctica Ice Cores with smaller amplitudes and more gradual warmings, imprints of these events have also been found in the ocean sediments all over the world (Rasmussen, Thomsen, & Moros, 2016). Indication of the Dansgaard-Oeschger events in the sediment cores can be the imprinted changes in the surface water temperatures, patterns of oxygenation of the bottom waters, patterns of wind-blown dust supply, ice-rafted debris, etc (Abrupt Climate Change, 2002).

Even though the ice-rafted debris found in the ocean sediments is a major characteristic of the Heinrich events, it is also an indication of the Dansgaard-Oeschger events, and in this case these ice-rafted pulses are lower. In addition, the percentage of polar species of foraminifera and the concentration and the size of the grains of the ice-rafted debris are also important marks. Higher concentration of the ice-rafted debris and bigger percentage of polar foraminifera species suggest that there were colder periods with a lot of icebergs in the ocean waters, and vice versa. Moreover, the relative quantities of the foraminifera shells compared to the size of the grains and the amount of one polar foraminifera species as a fraction of the total population, represent some of the major signs of the temperatures during the phases of the events (Ruddiman, 2013). So, the stadial periods of the Dansgaard-Oeschger events were marked by increased ice-rafting debris into the North Atlantic waters that were fresher and colder, and decreased strength of North Atlantic Deep Water formation, while the interstadials were characterized with the opposite conditions (Abrupt Climate Change, 2002).

In addition to the most commonly used indicators of the millennial-scale Dansgaard-Oeschger events in the sediment cores, the variations in the red-green color intensity of the material that is ice-rafted in the sediments, can be useful as well. Such analysis of this indicator has been performed on the 500,000-yr-long sediment core M23414 in the Northeast Atlantic by Helmke, et al., (2002). The possibility to use these values as a proxy of temperature, has been confirmed by the matching with the data obtained by the planktic oxygen isotope values and the concentrations of the ice-rafted debris. The variations in the color have been considered to depend on the changes in the deposition of iron- and manganese-bearing components in the sediments. More precisely, the change in the color is due to variations in the concentration of red-colored, iron-bearing minerals, that on the other side, depend on the millennial-scale climate variations and the ice-rafted debris transport. It has been discovered that higher iron levels correlate to higher red-green values. Also, this proxy allows a possibility to take part in the determining or confirming of the origin of the ice-rafted debris. The average resolution of the centimeter-sampled colored data has been determined to be around 360 years, and this allows the proxy values to be used in the analysis of the millennial-scale oscillations, such as the Dansgaard-Oeschger events. The results of the examining of the variations in the red-green color intensity in the sediment core, show that the climate variations with large amplitudes, occur at periods with a large continental ice volume, indicated by using the sea level as a proxy data for the mass of the continental ice. Furthermore, the analysis has shown that when the mass of the continental ice exceeds a specific threshold value, the biggest millennial-scale climate changes occur at the same time with the changes in the ice mass. The climate changes are absent at times when the ice volume is more or less stable (Helmke, Schulz, & Bauch, 2002).

As indicated by Bond, et al. (1993) the Dansgaard-Oeschger cycles are bundled between the Heinrich events, that have geographical occurrence in the North Atlantic and are marked with ice-rafted debris originating from the Hudson Strait. So, in the analysis of the imprint of the higher-frequency Dansgaard-Oeschger events in the North Atlantic, it is necessary to distinguish the signals of the Heinrich events that are better recognizable with more massive proxies in scale in the sediments, from the ones that can be related to the Dansgaard-Oeschger events. This has been done by Andrews & Barber, (2002) during the analysis of sediment cores from the Labrador Sea, where the signals of the Heinrich events have been removed. These sediments cores have been reported to have distinctive color lithofacies (physical and organic characteristics of the rock record of a sediment, and a mappable subdivision of stratigraphic unit, which is differentiated from other subdivisions on the basis of lithology). Such lithofacies are the light cream facies rich in detrital carbonate and the black facies, that is rich in total organic carbon and kaolinite. This allows correlation to the sources of origin. For instance, the black facies has been found to originate from glacial erosion of the Cretaceous outcrop on the floor of Cumberland Sound, while the light cream facies were found to originate from erosion of Paleozoic limestone on the floor of Hudson Strait, Hudson Bay, and Ungava Bay. The time-scale of the Labrador Sea sediment records has been determined with radiocarbon dating. The sampling interval was ranging between 3 and 10 cm, corresponding to 210–700 years, showing that these high-resolution records can be used for the analysis of the Dansgaard-Oeschger events. The analysis has shown that there is an increase in the $\delta^{18}O$ values and the $\delta^{13}C$ values of the planktic foraminifera *N. pachyderma* at the time of the Dansgaard-Oeschger stadials, indicating low temperature of the surface waters. The removal of the sediments that are linked to the Heinrich events, allows better observation of the proxy data for the Dansgaard-Oeschger events with lower amplitudes in the sediment cores. The results show that these sediments located in the Labrador Sea can represent an adequate archive for abrupt millennial-scale oscillations such as the Dansgaard-Oeschger events (Andrews & Barber, 2002).

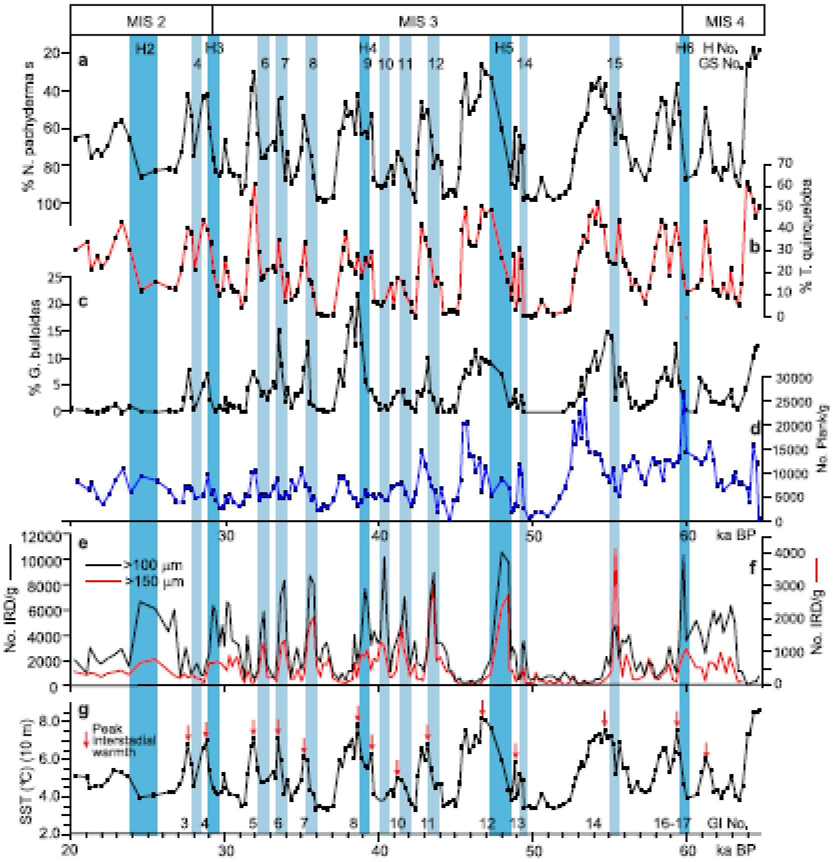
The out-of-phase relationship between the temperature changes in the two hemispheres, at the time of the different phases of the Dansgaard-Oeschger events, can be studied using the sediment core records. The archive analysis shows that the pattern of changes in the Antarctica Ice cores is followed by the Southern and Central Atlantic sea surface temperatures, all the way to the ice-rafted debris (IRD) belt (characterized by sediment cores that contain layers with ice-rafted debris), while the Greenland pattern is followed by the North Atlantic and Nordic Seas. The sediment records located at the Greenland-Scotland Ridge, can represent the changes in the open Atlantic. There, the meltwater and the ice do not strongly impact the characteristics of the cores (Rasmussen, Thomsen, & Moros, 2016).

Rasmussen, et al., (2016) analyzed the SO2 sediment core from that area, and they have found that it contains alternating layers of light grey, clayey silt and dark grey, sandy clay. The proxy for the sea surface temperature from the sediment core used in this study is the percent of polar planktic foraminiferal species *N. pachyderma s*, present with a low percentage at the time of the interstadials, and the subpolar species *Globigerina bulloides* and *Turborotalita quinqueloba*, present with high percentage at the time of the interstadials. The analysis has shown that the sea surface temperature during the interstadials was varying in the interval 7–8.5 °C, and 3–3.5 °C during stadials. On the other side, the temperature of the bottom waters, was between 3 °C and 3.5 °C colder than the surface ones. Furthermore, the analysis has shown that the stadial-interstadial transition and vice versa was mostly gradual, and the warming periods lasted approximately 800 years in average. A noteworthy finding is that the temperature peak during the interstadials occurs in the beginning of the warming phase, and it is marked not only by low percentage of *Neogloboquadrina pachyderma s* and high percentage of *Globigerina bulloides* and *Turborotalita quinqueloba*, but also high abundance of the planktic foraminifera. The analysis of the Mg/Ca ratios of other sediment cores in the same area, coincides with the temperature change found in this core. Also, the study of the core has shown that there is a very low concentration of ice-rafted debris, that confirms that in that specific area, there was an absence of sea ice and icebergs. In the middle of the interstadial phase, the foraminifera species start to change quickly, this representing a decrease in the temperature. In the parts of the sediments cores that represent the interstadial cooling phase, there is a substantial decrease of the abundance of the planktic foraminifera. After this phase, a cooling stadial period starts, represented by the increasing values of the $\delta^{18}O$ and the abrupt increase of the ice-rafted debris, representing an expansion of the sea ice cover and increased iceberg melting. The analysis of the ice-rafted debris has shown that it originates from Eastern Greenland and that it has been brought by the East Greenland Current. The foraminifera species show that there were low temperatures of the waters during the stadials, with the minimum values often reached at the interstadial-stadial transition. Then, a decrease of the *Neogloboquadrina pachyderma s* foraminifera species and an increase of the *Globigerina bulloides* and *Turborotalita quinqueloba* follows, representing the beginning of the warming phase marked by increase of the surface water temperatures. Calculations have shown that the summer sea surface temperatures increased from 3.4 °C (beginning of the stadials) to a value of 7.0 °C at the time of the transition to the next interstadial. Moreover, there was a decrease in the concentration of the ice-rafted debris, related to the drop in the sea ice cover and the icebergs. The changes in the deep water temperatures are following almost the same cycle as the surface waters (Rasmussen, Thomsen, & Moros, 2016).

The comparison between the results from the analysis from this core, located over the Reykjanes Ridge, and other sediment cores the North Atlantic and Nordic seas, shows a gradual warming of the intermediate water during the stadials and the Heinrich events, and differences between the warming of the surface and subsurface waters. The gradual warming has been found to be a characteristic of the central part of the northern Atlantic between the IRD-belt and the Greenland-Scotland Ridge, that represent areas with low influx of meltwater and small amounts of sea ice and icebergs. On the other side, an abrupt warming is a characteristic of the waters in the Nordic seas, the IRD-belt and land-near areas farthest to the northeast and northwest, areas with a large influx of meltwaters, large ice cover and many icebergs. The line that separates these two regions was actually displaced far to the north close to the Greenland-Scotland Ridge. According to this, it can be concluded that the term bipolar seesaw cannot be used in the same sense when it refers to the marine conditions. Some of the obtained results with the analysis of the paleoclimatological proxies from this sediment core are represented on Figure 18 (Rasmussen, Thomsen, & Moros, 2016).

Figure 18

Selected Proxies for the Sediment Core SO82-02GGC Located on the Reykjanes Ridge



Note. a. percentage of the polar foraminifera species *Neogloboquadrina pachyderma s*, b. percentage of the subpolar foraminifera species *Turborotalita quinqueloba*, c. percentage of the subpolar foraminifera species *Globigerina bulloides*, d. number of total planktic foraminifera per gram of sediment dry weight, e. concentration of ice-rafted debris bigger than 100 µm per gram of sediment dry weight, f. concentration of ice-rafted debris bigger than 150 µm per gram of sediment dry weight, g. sea surface temperature at depth of 10 m determined with usage of planktic foraminifera bigger than 100 µm. On the top, the marine isotope stages are represented. The red arrows show the positions of the maximum temperatures during interstadials. Also, the Greenland stadials (GS), Greenland interstadials (GI) and Heinrich events (H) are specified. Reprinted from "North Atlantic warming during Dansgaard-Oeschger events synchronous with Antarctic warming and out-of-phase with Greenland climate" by T. L. Rasmussen, 2016, *Scientific reports* 6, (p. 5).

One of the possible mechanisms for explaining of the Dansgaard-Oeschger events, is associated to the changes in the Atlantic Meridional Overturning Circulation. Gottschalk, et al., (2015) analyzed these changes at the time of the Dansgaard-Oeschger events, in the sediment core MD07-3076Q. In this core, the changes in the export of the North Atlantic Deep Water to the sub-Antarctic Atlantic were analyzed, using [CO_3^{2-}] as an indicator of the bottom water variations. The planktonic cold-water foraminifera *Neogloboquadrina pachyderma sinistral* were used in this study as well, as an indicator of the water temperatures. The analysis has shown that in this core, like in the others that represent the Last Glacial Period, the average sedimentation rates were 15 cm kyr^{-1}, making the bioturbation insignificant. The area where the core is located, represents a transition zone between the southern-sourced Antarctic Bottom Water characterized with low [CO_3^{2-}], and the northern-sourced North Atlantic Deep Water, characterized with high [CO_3^{2-}]. The core is sensitive to the changes in the NADW/AABW boundary, because the [CO_3^{2-}] gradient between NADW and AABW is increased during glacial periods such as the Last Glacial Period. This causes the core to be more sensitive to the presence of northern- versus southern-sourced water masses as well. The variations in the bottom water [CO_3^{2-}] are determined with using B/Ca ratios of the epibenthic foraminifera species *Cibicides kullenbergi* and additional sedimentary partial dissolution proxies. To add, the variations in the degree of foraminifera shell fragmentation, the ratio of benthic to planktic (Be/Pl) foraminifera species and the abundance of planktic foraminifera in MD07-3076Q, are also used as a proxy for changes in carbonate saturation in the area. This is possible because the exposure to corrosive low [CO_3^{2-}] water, has a stronger impact on the thin-walled and fragile shells of planktic foraminifera, compared to the more robust shells of benthic foraminifera, resulting in chemical destruction of the planktic foraminifera shells. Gottschalk, et al., (2015) through analysis of the carbonate saturation and the sedimentary partial dissolution proxies, show an existence of millennial-scale changes in the corrosiveness of the bottom water. After the comparison with other sediment cores in the North Atlantic, it has been shown that the Dansgaard-Oeschger interstadials were characterized with lower dissolution events and enhanced carbonate preservation, while the stadials were marked with stronger dissolution events. The B/Ca ratios show a variation of the [CO_3^{2-}] from values that are commonly observed in the modern deep Southern Ocean at the time of the Dansgaard-Oeschger stadials, to values that are observed in the modern deep North Atlantic, at the time of the interstadials. This finding indicates a strong coupling between the North Atlantic Dansgaard-Oeschger climate variability and deep sub-Antarctic Atlantic [CO_3^{2-}] during the Last Glacial Period. The observed carbonate saturation changes might have been related to abrupt shifts of water mass boundaries. Evidence for increased carbonate dissolution during the Dansgaard-Oeschger stadials have also been found in the deep sub-Antarctic. According to this, it can be concluded that all of the North Atlantic stadials were related to reduced flow of North Atlantic Deep Water into the sub-Antarctic Atlantic. The evidence for abrupt and repeatedly occurring changes in the deep water mass structure in the sub-Antarctic Atlantic, support the suggestion for perturbations of the AMOC, occurring at the same time with the Dansgaard-Oeschger oscillations in the Northern Hemisphere. Furthermore, Gottschalk, et al., (2015) suggest that a role in the abrupt climate changes might have been played by the carbon cycle feedbacks. Still, the exact mechanism remains to be determined, as argued in the previous section (Gottschalk, et al., 2015).

Thus, as the reported studies shown, the sediment cores may represent a proper archive for the analysis of the Dansgaard-Oeschger abrupt climate changes. There are numerus proxies that can be used as indicators of the imprint of these events in the sediment cores, allowing more precise analysis and several intercomparisons. In addition, the possibility to remove larger-amplitude oscillations imprinted in the sediment cores such as the Heinrich events, permits more precise study of the faster occurring Dansgaard-Oeschger climatic oscillations (Andrews & Barber, 2002; Gottschalk, et al., 2015; Helmke, Schulz, & Bauch, 2002; Rasmussen, Thomsen, & Moros, 2016).

5.1.4.2 - Sediment core evidence of the Heinrich events

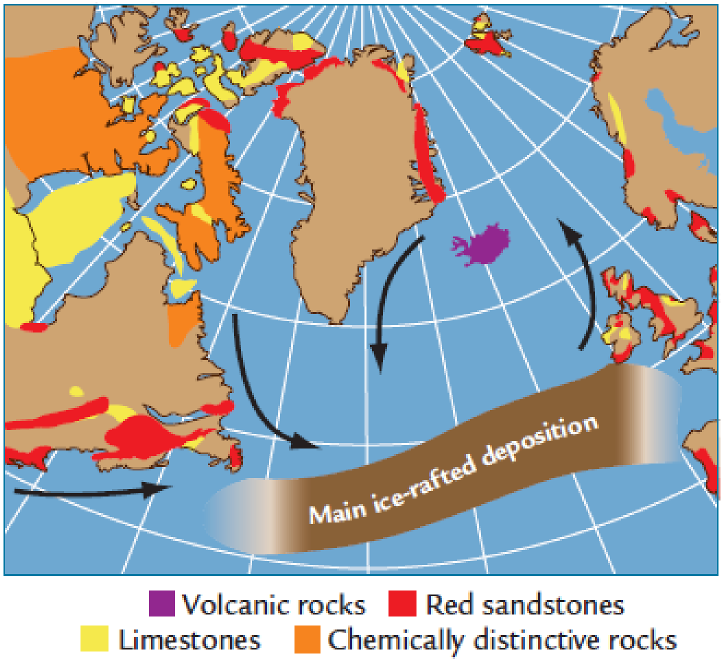
Heinrich discovered unusual variations in the relative concentrations of the foraminifera and lithic grains in sediment cores, expanding from My Dryzack Seamount, to the west of the Iberian Peninsula. Such changes were found to be important not only for explaining the interactions between the ice sheets and the ocean, but also the ice sheet behavior itself (Andrews & Barber, 2002). Bond, et al., (1993) show that the bundled Dansgaard-Oeschger events in the Bond cycles, are being terminated by Heinrich events. More specifically, the Heinrich events are following after the cold stadial intervals and are represented by the ice-rafted debris layers into the North Atlantic Ocean sediments. These so called Heinrich layers, are actually deposits of coarse-grained sediment layers (Abrupt Climate Change, 2002). These layers were particularly appealing because the material was unusually abundant (Ruddiman, 2013). Also, the abundant coarse material suggests that it must had been transported by icebergs (Abrupt Climate Change, 2002). So, the Heinrich events are representing the past occurrences when great armadas of icebergs were discharged into the North Atlantic. The imprint of these events was global (Hemming, et al., 1998). The highest deposition was located near the Hudson Strait, where each Heinrich layer in the sediments was approximately 0.5 m thick. From the Hudson Strait, to the east side of the Atlantic Ocean, the layer thickness was reduced, and the thickest layers were even less than 1 cm (Abrupt Climate Change, 2002). The sediments that contained the Heinrich layers that were the richest with ice-rafted debris, were located in the North Atlantic ice rafted detritus belt (IRD belt). Even though there have been at least six Heinrich events, the events H1 (16.8 kyr ago), H2 (24 kyr ago), H4 (38 kyr ago) and H5 (45 kyr ago) are the most notable features of the ocean sediments at the time of the Last Glacial Period. H1, H2, H4 and H5 were mostly marked by high percentage of the ice-rafted debris and a large presence of lithic grains, detrital carbonate and pronounced changes in the isotopic compositions. The high percentage of the coarse debris in these layers, might be due to low abundance of foraminifera, likely related to decreased productivity or sediment dilution. On the other side, H3 (~31 kyr ago) and H6 (~60 kyr ago), are characterized with high percentage of the ice-rafted debris, but not so abundant lithic grains and sediment flux. Moreover, Hemming, et al., (1998) indicate that during H3 and H6, there were not notable increase in detrital carbonate and strongly marked isotopic changes. The Heinrich layers have been found to have sharp bases, indicating that the onsets of the events were substantially abrupt (Hemming, et al., 1998). However, this seems to be not the case at sites close to the former ice front, where the Heinrich layers are characterized with 20-50 cm laminated clayey layers, with low concentrations of ice-rafted debris (Andrews & Barber, 2002).

5.1.4.2.1 - Origin of the sediment material in the Heinrich layers

Identifying the source of the sediment material is an important step in the analysis of the Heinrich layers, and can provide valuable information for the processes behind the Heinrich events (Hemming, et al., 1998). The origin of the debris can be determined through the analysis of the material that composes the Heinrich layers (Abrupt Climate Change, 2002). Such analysis includes studying of the limestone fragments and isotopic analysis of the mineral grains (Ruddiman, 2013). Bond, et al., (1993) proposed determination of sources of origin based on the pattern of Heinrich layers thinning. Such analysis has shown that most of the material was originating from Hudson Bay. On the other side, the study of the debris located in the thin edges of the Heinrich layers, or between them, has shown that it can be related to multiple sources of origin (Abrupt Climate Change, 2002). In addition, the mineral debris as a part of the influxes, was originating from the ice-rafting with the majority of the ice sheets surrounding the North Atlantic. Still, there was a part that can be related to a deposition with the northeastern margin of the Laurentide ice sheet, a large ice sheet that during the Last Glacial Period was covering North America. To add, Ruddiman, (2013) state that among the material deposited, fragments of volcanic glass were found, originating mostly from the volcanic eruptions on Iceland. Also, the discovered iron-stained quartz grains were related with sources where outcrops of Pangaean-age sandstone have been found to contain quartz grains stained red because of iron oxidation, at times of monsoonal climate in the ancient history (Ruddiman, 2013). Furthermore, the sedimentation process of the thicker parts of the Heinrich layers, compared to other sediments, occurred substantially faster, and during periods of cold and fresh ocean surface water. Moreover, the comparison between the indications of these events in the ocean sediments, and the Dansgaard-Oeschger events, represents that the Heinrich events were very similar to them, but had substantially larger amplitudes (Abrupt Climate Change, 2002). The main sources of the deposited ice-rafted debris in the Heinrich layers of the ocean sediment cores are represented on Figure 19.

Figure 19

Deposition and Main Sources of the Ice-rafted Debris during the Heinrich Events



Note. Biggest deposition rates of the ice-rafted debris are found between 458 and 508N in the Atlantic Ocean. At the time of the smaller ice-rafting pulses, the debris contains volcanic rocks from Iceland and red sandstone rocks from a few coastal margins. On the other side, during large and massive influx of ice-rafted debris, the material consists mainly of limestone from Hudson Bay, debris from eastern North America and fragments from other regions with distinctive chemical impressions. Reprinted from *Earth's Climate: Past and Future* (p. 298) by W. F. Ruddiman 2013.

Andrews & Barber, (2002) state that the majority of the material that represent the Heinrich layers, was found to originate from Hudson Strait, a conclusion obtained with using of the detrital carbonate as a main tracer, and the distribution and thickness of the Heinrich layers. More specifically, this material was probably brought into the ocean as a result of the erosion of Palaeozoic limestones on the floor of Hudson Strait and Hudson Bay. An important finding is that the Hudson Strait was the main source for the H1, H2 and H4. The estimated average rate of sediment accumulation at the time of the Heinrich events H1 and H2, was 0.4-0.04 mm/year. This suggests that there was probably an erosion of the floor outcrop from the Hudson Strait and Hudson Bay, with rates double from the accumulation ones. In addition, the found carbonate rock can be correlated with other sources, such as the southeast Baffin Shelf, the High Canadian Arctic channels, Baffin Bay. A noticeable feature before the discovery of the Heinrich events, were the lithofacies with high amount of detrital carbonate, in sediment cores located at Baffin Island Shelf and the floor of the northwest Labrador Sea. These layers are related to the Heinrich events, even though it should be clarified that the sediments on these locations do not contain good record of the H3 events. In order to explain this, Andrews & Barber, (2002) proposed that the H4 deglaciation of the Hudson Strait, happened in a way that at the time of H3, the ice stream in Hudson Strait was analogous to the one described for H0, characterized with an ice flow across the Hudson Strait, to the Baffin Island. The indication that the Hudson Strait was the major source of the ice-rafted debris during the Heinrich events that occurred on 5-7 kyr interval, and that the debris from other sources probably led or lagged, can be explained with a possible instability due to the great depth of the shelf break off Hudson Strait and the deep basin on the shelf (Andrews & Barber, 2002).

5.1.4.2.2 - Indications of the Heinrich events in the sediment cores

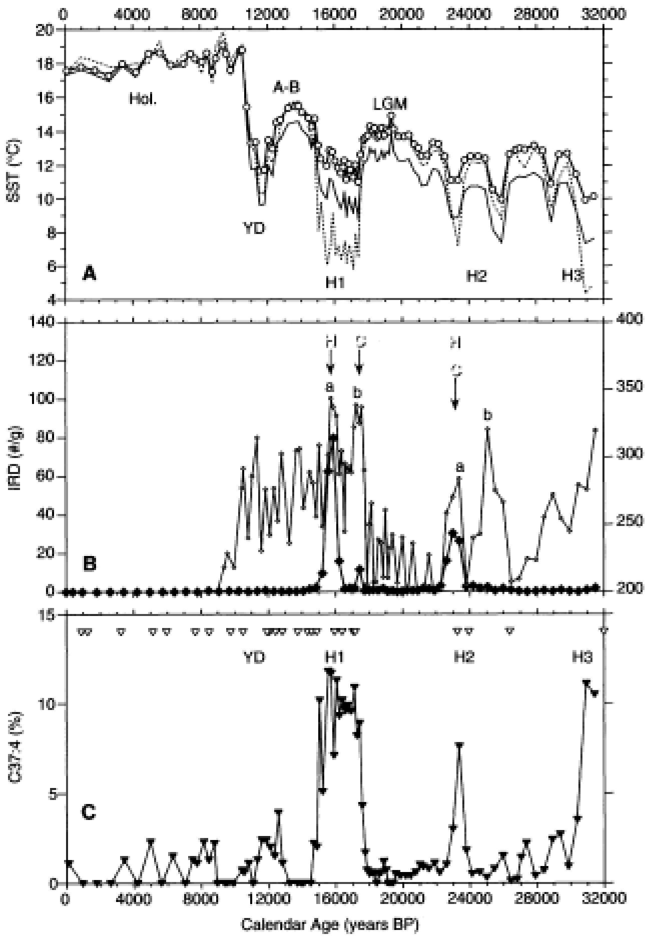
Two important indications of the imprint of the Heinrich events in the sediments are the abundance of one polar foraminifera species, as a fraction the total population, and the relative amounts of the shells of foraminifera compared to the sand-sized grains that were ice-rafted. Ruddiman, (2013) explains that there was an uncertainty related to the secondly mentioned proxy, because the increase of the ice-rafted debris concentration compared to the quantity of foraminifera shells might be not only because of more ice-rafted debris, but also because of drop in the rate of depositonon of foraminifera. However, the analysis has shown that there was an increase in the ice-rafted debris deposition and in the rate of deposition of foraminifera as well, but the first rate was substantially bigger, causing the final indication of increased concentration of the ice-rafted debris. The increase in the rate was even larger than tenfold. In particular, the bigger concentration of the ice-rafted debris and the bigger percentage of the polar foraminifera species, are related to the colder periods, characterized with colder ocean water and a lot of icebergs present (Ruddiman, 2013). In addition, the $\delta^{18}O$ values of planktic foraminifera, show that at the time of the Heinrich events, there was a decrease in the salinity of the ocean waters, probably related to ice melting. This is supported by the fine-grained and laminated nature of the Heinrich layers in the sediments, that can be related to deposition with vigorous supplies of meltwater. According to these indications, Andrews & Barber, (2002) conclude that the Heinrich events were related to generation of huge quantities of meltwater at the bed of the ice stream. In addition, they state that the Heinrich events were probably also associated to outburst floods of large subglacial lakes, or formation of large glacial lakes in Hudson Strait because of south-north flow from eastern Ungava across the Hudson Strait (Andrews & Barber, 2002).

To add, some studies correlate the reduction of the North Atlantic Deep Water formation and the occurrence of the Heinrich events (Abrupt Climate Change, 2002). This is supported by evidence obtained from the measurements of the isotopic values, as indicated by Ruddiman, (2013). Namely, the isotopic composition of the $CaCO_3$ shells of the benthic foraminifera characteristic for the bottom waters, can be used as an indicator of the changes in the deep water formation. In these terms, more negative $\delta^{13}C$ values, correlate with times when the deep water from the North Atlantic was replaced with bottom water originating from the Southern Ocean. Moreover, the possibility to determine the changes in the surface waters through $\delta^{13}C$ values of the planktic foraminifera, allows determination of the relative time of the changes. Finally, the indications obtained with the analysis of the carbon isotopes, show that the North Atlantic deep water formation was quick at the time of the warm interglacial periods, slower during glacial phases, and exceptionally slow at the time of the ice-rafting pulses (Ruddiman, 2013).

The sediments that have the highest amount of the ice-rafted debris are located in the North Atlantic IRD belt. However, in order to better understand the mechanisms behind these events, it is important to reconstruct the changes outside this region as well. Such study of a sediment core from the Iberian margin, carried out by Bard, et al., (2000) report that this area was also impacted by the cooling episodes and the transport of low-salinity water masses, probably resulting from the melting of ice armadas. Evidence of abrupt drop of the water temperatures that occurred in phase with the Heinrich events, were found in sediments located at the Bermuda Rise and the Mediterranean Sea. An analysis has been done using the SU8118 core, one of the best dated sediment cores from the Iberian margin. Its sedimentation rate was found to be more than 20 cm/1000 years. The changes in the sea surface temperatures were determined using the alkenone unsaturation ratios and the ice-rafted debris concentration was used for analyzing of the sediment transportation (Bard, Rostek, Turon, & Cendreau, 2000). Alkenone unsaturation ratio is a technique for analysis of the sea surface temperature founded on measuring of the unsaturation ratio, U_{37}^{k}, of long chain C_{37} methyl alkenones produced by the phytoplankton *Prymnesiophyceae*. Sikes, et al., (1991) state that this technique is more sensitive for the determination of the small changes in the temperature, compared to paleontological faunal assemblages and foraminiferal oxygen isotopes. The unsaturated alkenones are a class of long-chain lipids (C_{37}) produced by Prymnesiophyceae algae and used for regulation of the membrane fluidity, with changing of the unsaturation levels in accordance with the temperature. As a result, these compounds, that can be well preserved in the sediment records, can be used as a proxy of the sea surface temperature changes (Sikes, Farrington, & Keigwin, 1991). The average sampling resolution of the sediment core with using of the aleknone sea surface temperature records, is approximately 250 years, thus making possible the analysis of the abrupt climate change events. The performed analysis of the ice-rafted debris from this core by Bard et al., (2000) shows that the last two Heinrich events occurred 18,000-15,500 cal yr B.P. for H1, and 26,000-23,000 cal yr B.P. for H2, both consisting of two depositional phases. The last point, that can be supported also from the alkenone record, can probably be due to the smaller millennial-scale oscillation between the Heinrich events, such as the Dansgaard-Oeschger events. In addition, this core does not contain well enough evidence for the H3 event, because the oldest sediments in the core are originating from the period of the occurrence of the H3. Moreover, other sediment records show that the H3 event was not characterized with so large increase of the ice-rafted debris concentration, even though changes in the sea surface temperature have been imprinted. Figure 20 represents the results obtained with alkenone unsaturation ratio analysis and ice-rafted debris concentration for the Heinrich events H1, H2 and H3, the Younger Dryas event and the Holocene period (Bard, Rostek, Turon, & Cendreau, 2000).

Figure 20

Results from the Analysis of the SU8118 Sediment Core on the Iberian Margin (Age Calendar was obtained with Radiocarbon Dating)



Note. a. SST changes obtained from alkenone unsaturation data; b. ice-rafted debris concentration expressed in number per gram, for the size fraction bigger than 150 µm; c. abundance of $C_{37:4}$ in the total C_{37} alkenones in percent. The marked peaks represent the H1, H2, H3 and the Younger Dryas abrupt climate change events. Reprinted from "Hydrological impact of Heinrich events in the subtropical northeast Atlantic" by E. Bard, 2000, *Science 289.5483,* (p. 3).

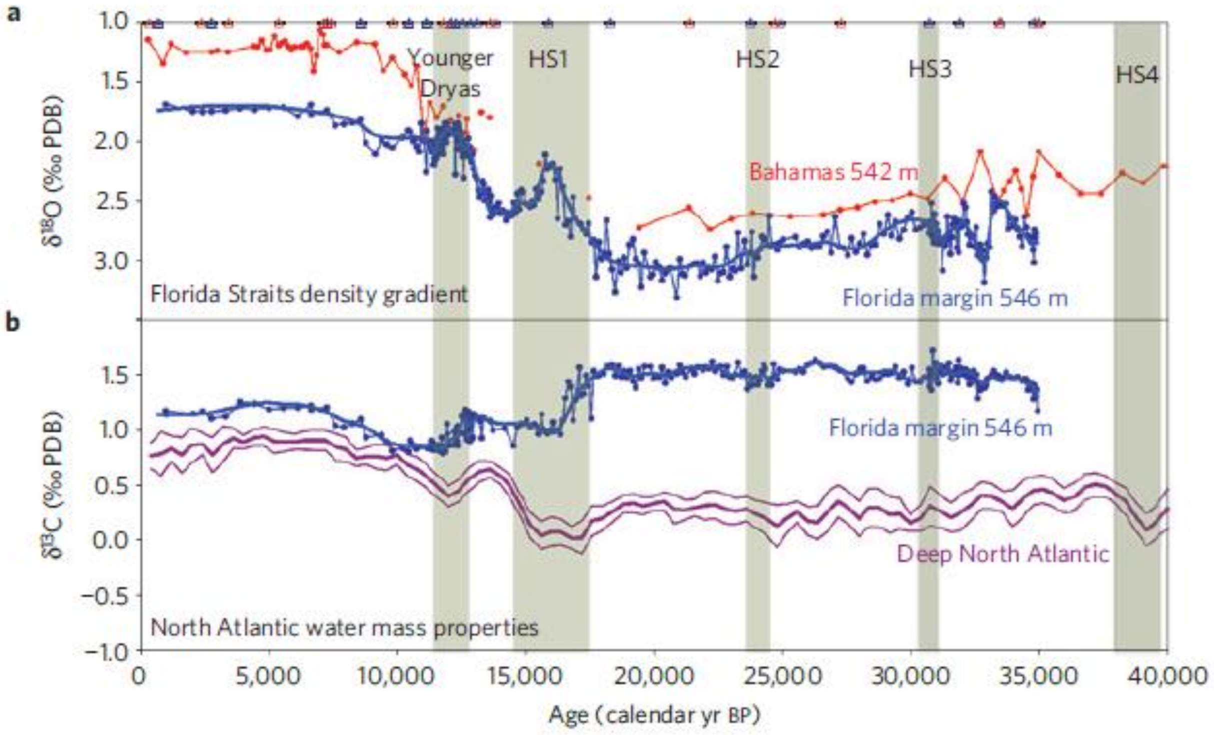
It can be seen that strong cooling episodes occurred at the time of the last three Heinrich events, and the well-dated alkenone record shows that all latitudes of the eastern North Atlantic were experiencing these changes in the temperature. In particular, the alkenone record shows that at the time of all of the Heinrich events, there was a serious drop in the sea surface temperatures in the eastern North Atlantic, while on the contrary, in the western low-latitude Atlantic, during the last Heinrich event and the Younger Dryas, there was increase in the sea surface temperature of +3 °C in the east-west gradient. In addition, Bard, et al., (2000) explain that the abundance of tetra-unsaturated C_{37} alkenones $C_{37:4}$, or the percentage of the tetra-unsaturated alkenones in the total C_{37} alkenones, can be used as a sensitive indication of the changes in the sea surface temperature and low-salinity water masses. Namely, the periods related to the percentage of these alkenones that is higher than 5 %, are at the same time with the occurrence of the Heinrich events. Moreover, the percentage of $C_{37:4}$ between 5 and 10, is found to correspond to a freshening of one practical salinity unit. It is not yet clear enough how the salinity affects the biosynthesis of $C_{37:4.}$ The analysis of this proxy shows that there was a decrease in the salinity of 1 to 2 PSU at the time of the last three Heinrich events. The overall results of the study of the core SU8118, indicate that there were icebergs that melted and released fine-grained material in the Iberian margin, being transported there with water (Bard, Rostek, Turon, & Cendreau, 2000).

More information about the Heinrich events can be retrieved from the distribution of biomarkers, that represent another proxy of the climate changes during these events. In the analysis performed by Rosell, et al., (1997) the sediment core BOFS 5K was used, where the distribution of the biomarkers C_{37} alkenones, tetrapyrrole pigments and aromatic hydrocarbons, were studied. The age model of the core was constructed using radiocarbon dating on foraminifera species *Globigerina bulloides* and *Neogloboquadrina pachyderma s.* The abrupt change in the samples (spaced at 1 cm) color after the extraction, from colorless to green to orange, resulted in further analysis of the pigments and their relation to the Heinrich events. Their study has shown that indeed there were chlorins and vanadyl porphyrins present. Furthermore, the samples with the highest porphyrin concentration, had also the highest concentration of ice-rafted debris, a known feature of the Heinrich events. More specifically, the chlorins and porphyrins are diagenetic products of the chlorophyll of phytoplankton, with formation of the chlorins in earlier, and porphyrins in later stages of the diagenesis. Even though porphyrins in other cores had been found, the vanadyl porphyrins have not been determined previously, something that can be related with the possibility that these compounds have an allochthonous origin by way of erosion and advection of much older, organic-rich sedimentary material. This opinion has been confirmed by the finding by Rosell, et al., (1997) that the maximum in the vanadyl porphyrins concentration and the ice-rafted debris concentration were matching. Furthermore, the aromatic hydrocarbons in the Heinrich layers, have homologous series of aryl isoprenoids, triaromatic isoprenoids and C_{40} diaromatic components with a carotenoid-derived carbon skeleton found, all of them being diagenetic products of aromatic carotenoid pigments, a feature of green photosynthetic bacteria. These bacteria type are obligate anaerobes, and probably inactive if there is a photic zone anoxia in the water column of the depositional setting. Still, there is no possibility of occurrence of anoxygenic photosynthesis in the North Atlantic. As a result, Rosell, et al., (1997) also considered that the carotenoid-derived hydrocarbons present in the Heinrich layers, are originating from the continents. However, the distributional characteristics of the two types of compounds found to originate from the continents, can be used for analysis of the deposition of the Heinrich layers and the origin of the debris. For the BOFS 5K core, the determined place of origin is North America. In addition, the chlorines have also been found only when the ice-rafted debris concentration was high and their concentration was changing abruptly in the Heinrich layers. These variations can be related to changes in oceanographic conditions that affected the accumulation of the chlorines, via changes in the primary productivity, or enhanced preservation. One preposition relates the productivity and the nutrients obtained from iceberg melting, that could be obtained as a result of the caused upwelling, or their release from the icebergs where they were trapped. Due to the fact that the primary productivity was low at this period, it is also proposed that the changes in the chlorines might have been a result of the sealing effect in the sediments, something that can be considered after understanding that the sedimentation rates were high at the time of the Heinrich events (10-200 cm/kyr). This hypothesis has been rejected after understanding the chlorine accumulation was the highest before and after the increased presence of the ice-rafted debris, and sealing without ice-rafted debris would have been impossible. So, the probable reason for the accumulation of the chlorines was the high amount of meltwater, that is considered to be the main reason of the strong decrease, or even cessation, of the North Atlantic Deep Water formation. The chlorines had to be preserved in order to be found in such amounts, and the preservation is proposed to have occurred because of the changes of the Deep Water Formation in the North Atlantic, because it resulted in decreased oxygen levels and favorable oxic conditions. As a result of these findings about the chlorines, it can be summarized that the data supports the previously suggested reduction of the thermohaline circulation and the abrupt switch between on and off states in the deep circulation at the time of the Heinrich events. Also, it can be concluded that the presence and absence of the pigments in the core, represent the quick oceanographic conditions that have been caused by the Heinrich events (Rosell-Mele, Maslin, Maxwell, & Schaeffer, 1997).

The Heinrich events have been marked by release of freshwater from the melting of the icebergs into the Atlantic Ocean, something that is believed to have caused interruption of the Atlantic Meridional Overturning Circulation and reducing of the heat transport into the northern North Atlantic. The indications of such changes are related to the nutrient values in the deep waters, from low during glacial times, to high at the time of the Heinrich event 1. The weakened, or complete shutdown of the overturning during the H1, was supported by Lynch-Stieglitz, et al., (2014) with the evidence from the preserved values of the ratio of the particle reactive decay products of U, ^{231}Pa and ^{230}Th in the water column. However, these indications are not the same for the H2 and H3 events. Moreover, for only some of the Heinrich stadials (H4 and H5), there are indications of nutrient-rich waters. Still, it has to be cleared out that sometimes there cannot be found a direct relationship between the changes in the nutrients and the changes in the circulation. The warm water that flows towards the north, passes through the Florida Straits, and therefore, the changes in the sea water properties in this region should be preserved in the sediment cores located there. An analysis of the oxygen isotopic ratios of benthic foraminifera from two sediment cores located on both sides of the Florida Straits has been performed by Lynch-Stieglitz, et al., (2014). The oxygen isotopic composition of benthic foraminifera from this region, is sensitive to the AMOC changes, while the carbon isotopic composition of the benthic foraminifera, is sensitive to the changes in the nutrient concentrations of the intermediate waters. The oxygen isotopic composition of the calcite of the benthic foraminifera from both sides of the current that flows through the Florida Straits, can be used for determining of the density gradient, because it can express the changes in both, the temperature and the salinity. Lynch-Stieglitz, et al., (2014) explain that the reduced gradient is related to the reduction in the strength of the AMOC. The sediments represent climatic oscillations 36 kyr old at most, and the sedimentation rates have been shown to be 15-35 cm kyr^{-1}, making the analysis of the abrupt climate events, in particular Heinrich events, possible. The analysis of the isotopic composition has shown that the H1 event was marked by lower δ^{18}O values, that can be correlated to warmer temperatures and less saline and dense waters. A reduction in the cross-strait δ^{18}O gradient was determined to be a case for the Younger Dryas period. Even though this was not proved for the H1 event because of the low sedimentation rates during this period, it is expected to be a characteristic as well, representing the AMOC reduction. Still, this was not the case for the H2 and H3 events, as shown from the $\delta^{18}O$ record. Such indication might be related to the low resolution of the records, or to other processes that result in opposing changes in the water characteristics. Nevertheless, Lynch-Stieglitz et al., (2014) conclude that the magnitude of the changes in AMOC for those two events, was substantially lower than the ones characteristic for the H1 event. In addition, $\delta^{13}C$ records confirm the previous findings, because $\delta^{13}C$ deviations can be related to the H1 events, and not to the H2 and H3 events. One possible explanation might be that the proxy values did not respond to very short changes in the ocean circulation. Also, the H3 event might not have exactly been associated with ocean circulation changes. Still, this is not the case for H2. The changes in the $\delta^{13}C$ records for the H4 and H5 reflect switches from weaker stratification in the geochemical water mass properties (strong AMOC), to the more strongly stratified water mass and weaker AMOC during the Last Glacial Maximum. The possible explanation for the observations for the H2 and H3 events, is that the AMOC was already in the weakened state and it could not become further weakened due to the freshwater influx. On the other side, the H1 event was so intense and long, because it lasted for many thousands of years, that the changes of AMOC were more intense. Furthermore, the starting of the decay of the ice sheets and the huge amount of meltwater, intensified the observed changes. In conclusion, it is not yet determined what was the exact reason for the differences in the AMOC changes between the Heinrich events. The results of the analysis of the proxy records $\delta^{18}O$ and $\delta^{13}C$ in benthic foraminifera in the two cores located on both sides of the Florida Strait are represented on Figure 21 (Lynch-Stieglitz, et al., 2014).

Figure 21

$\delta^{18}O$ and $\delta^{13}C$ Records from Benthic Foraminifera from Sediment Cores from the Florida Strait



Note. a. oxygen isotope ratio of the calcite from benthic foraminifera from two sediment cores located on both sides of the Florida Current; b. carbon isotope ratio of the calcite of the benthic foraminifera *P. ariminensis*, from one of the two cores on the Florida side of the Strait and average δ^{13}C records from the deep Atlantic for comparison. The last four Heinrich stadials and the Younger Dryas are indicated. Reprinted from "Muted change in Atlantic overturning circulation over some glacial-aged Heinrich events" by J. Lynch-Stieglitz, 2014, *Nature Geoscience 7.2*, (p. 146).

From the explanation about the evidence of the Heinrich events in the ocean sediment cores, it can be concluded that this paleoclimate archive can be used for detailed study of the events. The analysis of the ice-rafted material, characteristic for the Heinrich events, has shown that the majority of the debris originates from Hudson Bay and from melting of the Laurentide Ice Sheet. Many proxy records, including the polar foraminifera species, the relative abundances of different foraminifera species, alekenone unsaturation ratios and biomarkers, can be used for studying of the mechanisms behind the events and the comparison between the different events (Bard, Rostek, Turon, & Cendreau, 2000; Lynch-Stieglitz, et al., 2014; Rosell-Mele, Maslin, Maxwell, & Schaeffer, 1997).

5.1.4.3 - Sediment core evidence of the Younger Dryas and the Bølling/Allerød

The last type of abrupt climate change events, with an imprint in the ocean sediments, includes the Younger Dryas stadial and the Bølling/Allerød interstadial. Evidence of the Younger Dryas cold interval are well preserved in the sediment cores (Abrupt Climate Change, 2002).

One of the first manifestations of the Younger Dryas event, is related to the abrupt return of the high amount of the of the polar planktic foraminiferal species *Neogloboquadrina pachyderma* in the North Atlantic (Abrupt Climate Change, 2002). Right before the occurrence of the Younger Dryas event, there was an episode of warming, the Bølling/Allerød, that caused melting of the ice sheets. The evidence of pulses of meltwater have been found in the $\delta^{18}O$ records of the shells of planktic foraminifera. Such pulses of unusually negative $\delta^{18}O$ values early in the deglaciation, have been discovered from the planktic foraminifera in sediment cores located at the Norwegian Sea. It should be explained that $\delta^{18}O$ records can represent a proxy of both, changes in the temperature and occurrence of meltwater pulses. From the fact that the low $\delta^{18}O$ value cannot be attributed to major temperature fluctuations because of the species composition of surface-dwelling microfossils from the same sediment cores, it can be concluded that it indicates an episode of early melting of the Barents ice sheet, located north of Scandinavia. The melting of this ice sheet was explained with using of the sediment records, that suggested that the ice sheet had a base lying below sea level, making its collapse possible with the rise of the summer insulation. Other records confirm the occurrence of pulses of meltwater from the ice sheets in the Bølling/Allerød period, such as the cores from the Gulf of Mexico, that with the low $\delta^{18}O$ record, show that there was an increase of the meltwater flow from the North American Ice Sheet through the Mississippi River. Furthermore, this warming phase was also marked with higher concentration of deposited sediments, rich with ice-rafted debris and poor with the usually present planktic foraminifera and coccoliths, in the sediment cores. The Bølling/Allerød warming phase was ended by the Younger Dryas cold episode, that was mostly preserved in records near the subpolar North Atlantic Ocean. The Younger Dryas event was also marked by the readvance of the polar front (a zone of rapid transition of the water temperature) to the south, that represents an important change in the Atlantic circulation, recorded in the sediments (Ruddiman, 2013). Another important proxy that can represent the change in the nutrient concentrations during the Younger Dryas event, is the Cd/Ca ratio from the shells, that clearly represents an increased nutrient concentration at the time of the cold episode. Moreover, the amount of nutrients and the primary productivity can also be illustrated by the changes in the sediment color, such as the changes in the color of the cores located at the Cariaco Basin (Hughen, Southon, Lehman, & Overpeck, 2000).

The probable reasons for the change in the nutrients and the upwelling, are the increased strength of the trade winds and the decreased river runoff. In addition, the changes related to the Younger Dryas were recorded even in ocean sediments located in the North Pacific, such as the ones found in the Santa Barbara Basin and the Gulf of California. Interesting features of these records are the ones that represent that these sediments, that have usually been anoxic, became oxic at the time of the Younger Dryas. Furthermore, other evidence of this event exist, such as the $\delta^{18}O$ and $\delta^{13}C$ records in the Pacific Ocean, located in the equatorial Pacific. One very appealing finding, is the discovery of the evidence of the Younger Dryas event in the North Arabian Sea and Indian Ocean. Here, alkenone paleothermometry records represent the cooling Younger Dryas phase. Moreover, bottom-dwelling foraminiferal shell proxies, show that the export of Deep North Atlantic Waters was reduced at the time of the Younger Dryas. Finally, records of this abrupt climate change event were found in the southern Atlantic and Indian Oceans, showing that there the event was marked by increase of the temperatures, this being in tune with the Antarctica changes (Abrupt Climate Change, 2002).

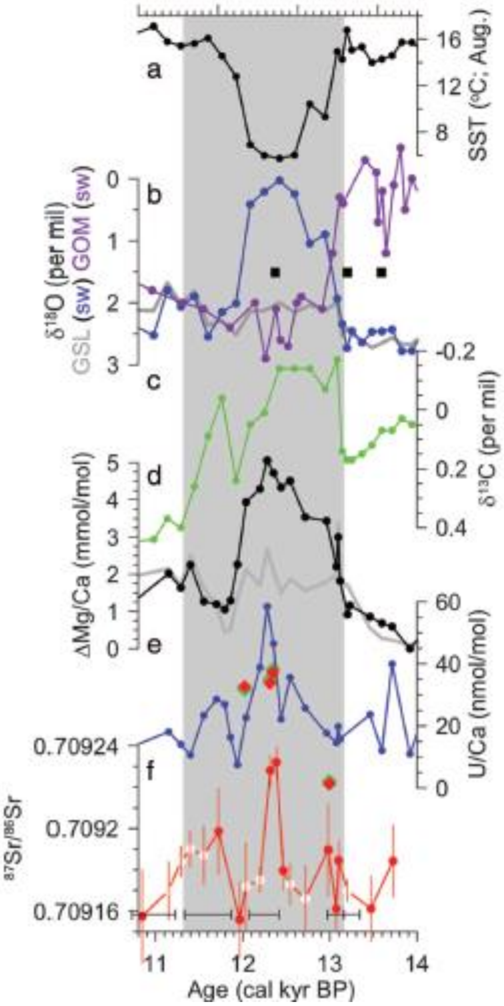
It is crucial to understand the exact mechanism behind the Younger Dryas event. The results of the analyzed proxy records. agree that in the beginning of the Younger Dryas episode, there was a strong reduction of the Atlantic Meridional Overturning Circulation. This can be related to one of the proposed mechanisms responsible for the event: the loss of ocean heat transport towards the North Atlantic. This probably occurred due to the routing of freshwater to the St. Lawrence River. Rosell, et al., (1997) state that the AMOC rate was changing during the Younger Dryas event. Analysis of the paleoclimate proxies $^{87}Sr/^{86}Sr$, U/Ca, and Mg/Ca from planktic foraminifera and their changes, can be used to comprehend what exactly occurred, because these ratios can be used as indicators of the routing of continental runoff derived from distinct geological areas. The most widely accepted mechanism for the Younger Dryas episode, is related to the opening of the eastern Lake Agassiz outlet and the Straits of Mackinaw, with the retreat of the southern Laurentide Ice Sheet margin, that led to almost doubling of the size of the St. Lawrence River drainage basin. Interestingly, the new basin contained different bedrock lithologies compared to the previous one, consequently leading to changed water geochemistry. The changes should have been imprinted in the planktonic foraminifera, this stimulating the analysis of two sediment cores in the outer St. Lawrence estuary (Rosell-Mele, Maslin, Maxwell, & Schaeffer, 1997).

Among the studied foraminifera species, there were *Globigerina bulloides* and *Neogloboquadrina pachyderma (s)*. Changes in Mg/Ca in foraminifera represent the uptake of Mg as a function of the temperature and the salinity of the ocean water, as well as changes in the concentrations of the magnesium and calcium of the water. It is important to mention that the sea ice that covered the estuary during the Younger Dryas event, was present for nine months of the year, meaning that the foraminifera grew only in the remaining three months, and the sea surface temperature was actually reconstructed for this period. Furthermore, the salinity variations were reconstructed using the $\delta^{18}O$ record. The analysis of these indicators, shows that there is an increase in the δMg/Ca in the beginning of the Younger Dryas, that is related to a decrease in the temperature and salinity of the water. These changes can be related to the routing of western Canadian runoff to the St. Lawrence River, because of the ice retreat. Moreover, a higher concentration of Mg in rivers routed to the St. Lawrence basin during the Younger Dryas was found, compared to the concentrations before the event. In the later stage of the event, the δMg/Ca increases again, representing an increase in the freshwater flux from Canada. The second proxy record, U/Ca from the two foraminifera species, shows higher peak values at the time of the Younger Dryas, than before it. Namely, the major sources of the seawater U are the rivers rich in dissolved U, or it can originate from colloid and particulate disintegration at high salinities, and the release from ocean sediments as a result of an increase in bottom-water oxygen. Such oxygenated freshwater can be the one released into the St. Lawrence estuary at the time of the Younger Dryas event. The analysis has shown that the starting increase in the U/Ca record is gradual, contrasting the δMg/Ca record, and then it abruptly rises to its peak value. The gradual rise might be related to the carbonate ions concentration brought into the estuary from the drained carbonate terrains, that causes a reduction in the ratio U/Ca in foraminifera. On the other side, released U will increase with the river flux. The last indicator, the ratio $^{87}Sr/^{86}Sr$, shows very small change in the beginning of the event, accompanied with an abrupt increase. The increase can be related to the St. Lawrence River, because the ratio varies as a function of bedrock age and the duration of chemical weathering of granitoid sediment, while the marine ratio is not changing with time. The enlarging area of the Lake Agassiz and the exposed bedrock, are believed to have caused increase of the $^{87}Sr/^{86}Sr$ ratio, because of the release of radiogenic Sr from young granitoid soils (Carlson, et al., 2007).

The results of the analysis performed by Carlson, et al., (2007) confirm the proposed routing of surface waters from western Canada to the St. Lawrence River at the start of the Younger Dryas, and show that there was a substantial freshwater flux increase. The changes in the flux are further confirmed by the $\delta^{13}C$ record of planktic foraminifera, because this value of dissolved inorganic carbon, represents the carbon isotope ratio of soil CO_2 derived from decay of organic matter (lower values) and the one of any underlying carbonate bedrock (bigger values). The results clearly show that there was not such a small decrease in the salinity in this region during the Younger Dryas, as represented by the $\delta^{18}O$ values of the calcite of the foraminifera *N. pachyderma (s)* and dinoflagellate–cysts. However, the difference between the δMg/Ca and $\delta^{18}O$ records, are probably due to the depth–habitat difference between the dinoflagellates and *N. pachyderma (s)* used for the determination of the oxygen isotopic values for salinity calculation, and because the cooling episode causes large increase in percentage of *N. pachyderma (s)*. Moreover, increase of the values of the $\delta^{18}O$ records from the Gulf of Mexico, support the proposal that the routing of North American runoff from the Mississippi River to the St. Lawrence River, happened at the beginning of the Younger Dryas. The analyzed proxies represent clear and direct oceanographic evidence of the eastward routing of the surface waters from western Canada. In addition, the results show that the meltwater influx was not constant, but the discharge was changing, from increase in two steps in the beginning of the event, to decrease to values correspondent to the pre-Younger Dryas values, with these indications matching the proxy data for the changes in AMOC strength. Figure 22 represents the results of the analyzed proxy data for the Younger Dryas event (Carlson, et al., 2007).

Figure 22

Indications of the Climatic Changes during the Younger Dryas Cooling Phase obtained from Different Proxy Records from Sediment Cores located at the St. Lawrence Estuary



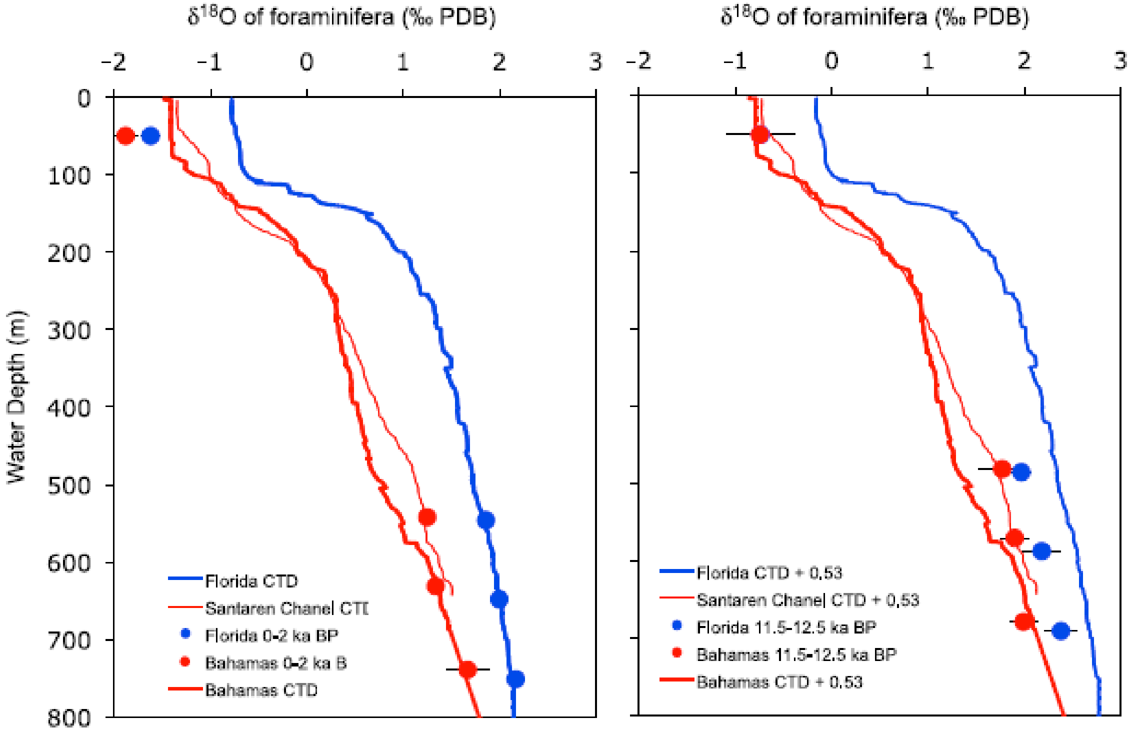
Note. a. SST reconstruction from dinoflagellate cyst; b. δ^{18}O record of *N. pachyderma (s)* from the St. Lawrence estuary (water-blue; planktic foraminifera-grey) and from the Gulf of Mexico (purple); c. δ^{13}C record of *N. pachyderma (s)* (green); d. Mg/Ca (gray) and δMg/Ca (black) of *G. bulloides*; e. U/Ca of *G. bulloides* (blue and green) and *N. pachyderma (s)* (red); f. Sr isotopes of *G. bulloides*. Reprinted from "Geochemical proxies of North American freshwater routing during the Younger Dryas cold event" by A. E. Carlson, 2007, *Proceedings of the National Academy of Sciences 104.16,* (p. 2).

Similarly to the analysis of the circulation changes during the Heinrich events in the Florida Strait, a study of the sediment cores from the same location has been done, in order to determine the changes in the circulation during the Younger Dryas event. The Florida Strait waters represented by the western portion of the wind-driven subtropical gyre and the northward flow of the upper waters which cross the equator, compensate the export of NADW, that is a part of the AMOC. At the time of the Younger Dryas, probably there was a weakening, or even shutdown of the AMOC, because of the meltwater that disrupted the NADW formation. The changes in the deep water mass properties occurred at the same time and with the same duration, to the cooling in the North

Atlantic, during the Younger Dryas event. To analyze the exact changes that occurred during the event, it is important to study the properties of the waters that are part of the Florida Current, because an important component of the current is the cross-equatorial flow of surface waters which compensate the export of NADW. The densities of the waters at the both sides of the channel are different, and they can be determined using the $\delta^{18}O$ values of benthic foraminifera calcite, that represents a record of the temperature of calcification and the changes in the water salinity. So, the $\delta^{18}O$ values from sediments located at the both sides of the Strait, can be used to determine the contrast in the $\delta^{18}O$ across the Strait, in order to represent the changes in the flow during the event. Lynch et al., (2011) analyzed the benthic foraminifera *Cibicidoides pachyderma* and *Planulina ariminensis*, and planktic foraminifera *Globogerinoides ruber*. The results of the analysis of the $\delta^{18}O$ values of benthic foraminifera, show that their contrast across the deeper part of the Strait was much smaller at the time of the Younger Dryas, compared to the warmer Holocene period later. To clarify, colder temperatures and saltier waters can be related to higher values of the $\delta^{18}O$ of the calcite. So, the contrast between the $\delta^{18}O$ value of the Bahamas side of the Strait and the Florida Margin, is a function of the temperature and the salinity of the water, and it may vary in time. The input of freshwater, that is believed to have happened during the Younger Dryas event, probably led to a drop in the contrast. Moreover, an increase in Mg/Ca in benthic foraminifera during the Younger Dryas was found, suggesting that the Florida Margin temperatures were higher than the ones in the Bahamas where no change was observed, meaning that a reduction in the temperature gradient was present. With information only for the gradient in the deeper parts, it cannot be determined how the Florida Current transport changed during the event. Lynch, et al., (2011) proposed that the current might have been weaker because of the reduced surface branch of the AMOC. So, during the Youger Dryas, probably there were a reduced ocean heat transport by the AMOC and a cooling of the gyre. The indicated ocean circulation changes happened abruptly at the onset of the Younger Dryas event, lasting even less than 70 years. The expected $\delta^{18}O$ values of *Cibicidoides* and *Planulina* foraminifera species, obtained with using the water column temperature and salinity, from the cores on both sides of the Strait, at the time of the Late Holocene and the Younger Dryas, are represented on Figure 11 (Lynch-Stieglitz, Schmidt, & Curry, 2011).

Figure 23

Expected $\delta^{18}O$ Values of Cibicidoides and Planulina Foraminifera Species, using the Water Column Temperature and Salinity



a) Late Holocene

b) Younger Dryas

Note. (a) and sea level data (b), from the cores on both sides of the Strait, at the time of the Late Holocene and the Younger Dryas. The data for the Florida Margin water column are represented with tick blue line; the data for the Bahamas water column are represented with tick red line; data for the shallowest Bahamas core are represented with a thin red line. The circles represent the average foraminiferal δ^{18}O values, for today (a) and the Younger Dryas period (b). The core depths are tuned in terms of the sea level in the two different periods. The δ^{18}O values of the subsurface are obtained with usage of the benthic species *C. pachyderma* and *P. ariminensis*, while the mixed-layer values are obtained with usage of the planktonic species *G. ruber*. Reprinted from "Evidence from the Florida Straits for Younger Dryas ocean circulation changes" by J. Lynch-Stieglitz, 2011, *Paleoceanography 26.1*, (p. 7).

Calibration of the carbon-14 time-scale can be done, in order to allow quantification of the record of changes in the past carbon-14 concentration in the atmosphere, during the Younger Dryas period. Hughen, et al., (2000) performed such analysis, using the radiocarbon data from sediment core from the Cariaco Basin. While previous studies have associated abrupt changes in the δ^{14}C to the beginning of the YD, suggesting the shutdown of the deep ocean ventilation as plausible hypothesis, Hughen et al., (2000) argued that solar variability might have been the cause of that shift. The area where the studied sediment core 58PC is located, is characterized with anoxic water column below 300 m, that appears because of the high surface productivity in the basin and the restricted deep circulation. Also, the deep waters in the basin have a short residence time. Moreover, the climate changes between a season characterized with dry and windy conditions and coastal upwelling, and subsequent non-windy and rainy season. These changes cause formation of laminated sediments that consist of light-colored, organic-rich laminae, and dark-colored mineral grains from local river runoff. The thickness of the light laminae, sediment reflectance, and abundance of the foraminifera species *Globigerina bulloides*, are sensitive proxies for surface productivity, upwelling, and trade wind strength. Comparison with results obtained from the analysis of other sediment cores located in the North Atlantic, shows that the abrupt changes in the upwelling at the Cariaco Basin, occur at the same time and with same duration with the changes in the surface temperature in the North Atlantic. The proposed relation for the synchronous changes in the both locations, is the variation in the trade winds, as a response to the temperature changes. The analysis of the core shows that the reservoir age of the Cariaco Basin does not change substantially as a response to increased local upwelling. The varve chronology of the core from Cariaco Basin allows radiocarbon calibration at high-resolution. Using this, Hughen, et al., (2000) show that in the beginning of the Younger Dryas, there was an abrupt drop in ^{14}C age, followed by a ^{14}C plateau. The oldest part of the record shows another plateau, that extends even beyond the Glacial/ Bølling boundary. Furthermore, the determined atmospheric ^{14}C concentrations from this record, represent that they experienced large variations during the deglacial period, with sharp increase of the $\delta^{14}C$ in the Younger Dryas onset, followed by centrury-scale oscillations that consist of a phase characterized with rise in the $\delta^{14}C$, a brief period of elevated $\delta^{14}C$ and its decrease. The change of the $\delta^{14}C$ record versus climate, shows that the observed change is synchronous with climatic changes during the events, and it is consisted of abrupt rise in the Younger Dryas onset, after what follows a phase of its decline, that continues through the entire event, and an abrupt drop at the end of the Younger Dryas (Hughen, Southon, Lehman, & Overpeck, 2000).

According to the lastly mentioned finding, it can be concluded that the changes in the $\delta^{14}C$ and climate, were affected by a common forcing mechanism. Probable mechanisms might be the large-scale changes in the ocean circulation, such as AMOC changes and change in the North Atlantic Deep Water formation, and the changes in the solar irradiance. The indicated circulation changes influence not only the distribution of heat and moisture on global scale, but also the sequestration of ^{14}C into the ocean. The NADW formation was reduced or absent at the time of the Younger Dryas, and the modeling results show that its shutdown might substantially influence the $\delta^{14}C$, causing its increase. If the feedback mechanisms of the sea ice are taken into consideration, this influence is even larger. On the other side, solar irradiance variations might also influence both, the climate and the $\delta^{14}C$ value, causing $\delta^{14}C$ increase during phases of reduced solar activity. The changes in the climate and the $\delta^{14}C$ due to solar forcing, in order to be with such a large magnitude as the observations at the time of the Younger Dryas, should be influenced by large-magnitude changes in the solar variation as well, yet such variations are unproven. As a conclusion, the changes in the climate and the $\delta^{14}C$ at the time of the Younger Dryas period, probably occurred due to variation in the ocean circulation (Hughen, Southon, Lehman, & Overpeck, 2000).

The results of the presented studies, show that the Younger Dryas was a strong event with a global footprint. Many evidences, such as the $\delta^{18}O$ values that indicate the changes in the water temperature and salinity, point out that this cold episode was marked by a meltwater flow into the North Atlantic, probably through routing of freshwater to the St. Lawrence River. This is believed to have led to loss of ocean heat transport towards the North Atlantic, and the consequent reduction of the AMOC. The paleoclimate proxies $^{87}Sr/^{86}Sr$, U/Ca, and Mg/Ca confirm the proposed routing and the freshwater flux that was not constant during the event. The analysis of the sediment cores from the Florida Strait represents that the contrast in the $\delta^{18}O$ across the Strait was smaller during the Younger Dryas event than during the later Holocene, indicating that there was a temperature change and probable freshwater input during the event. The changes in the ocean circulation that happened abruptly at the onset of the Younger Dryas, are believed to have originated from AMOC reduction. Finally, the analysis of the changes in the $\delta^{14}C$ and the climate during the event in the Cariaco Basin core, show that such changes occurred probably due to changes in the ocean circulation, and that they were varying during the event. In summary, the sediment core analyses show that there is a very high probability that the mechanism behind the Younger Dryas cold episode is related to the changes in the ocean circulation caused with the freshwater influx (Rosell-Mele, Maslin, Maxwell, & Schaeffer, 1997; Carlson, et al., 2007; Hughen, Southon, Lehman, & Overpeck, 2000; Lynch-Stieglitz, Schmidt, & Curry, 2011).

In conclusion, the ocean sediments are depositions on the ocean floor, that if deposited continuously with a high deposition rate, and without disturbances, can represent a high-resolution paleoclimate archive, that is tens of millions of years old. The large number of proxy records that can be analyzed from this record, make possible the determination of the past climatic conditions and the comparison of the data with other archives, allowing precise time correlation and confirmation of the obtained data. Moreover, studying the sediment material allows determination of its origin, that is essential for the analysis of the proposed mechanisms responsible for the production of climate change events. The high-resolution of the annually-laminated ocean sediments, makes the sediments an archive capable to capture abrupt changes in the climate during the history of the planet, such as the abrupt climate changes at the time of the Last Glacial Period. Many sediment cores have been used for the analysis of the three types of abrupt climate change events, located in different regions. The most noticeable feature of the abrupt climate change events in the sediment records, is the presence of ice-rafted debris, with its highest amount during the Heinrich events. Also, the preserved different species of foraminifera and the analysis of the shells and their isotopic composition, provide valuable data even for the fastest occurring changes in the temperature, salinity and other climatic conditions. These and many other indications from the sediments, make this type of archive a beneficial record of the abrupt climate change events and the processes related to them (Ruddiman, 2013; Abrupt Climate Change, 2002; Kemp, 2003).

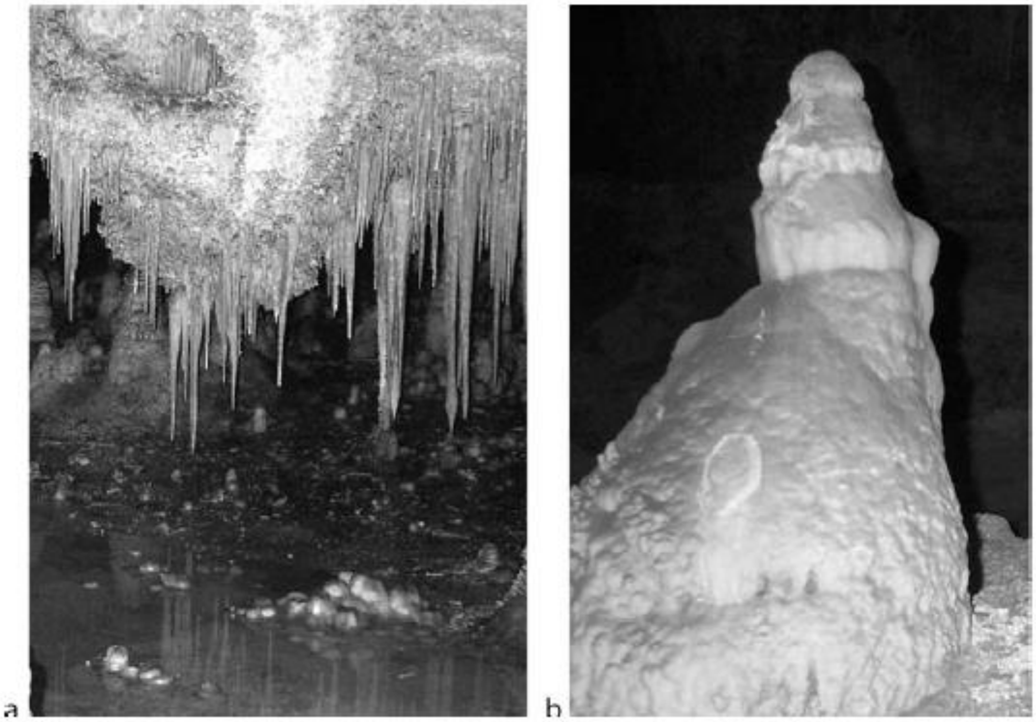
5.2 - Speleothems

The second paleoclimate archive that will be described are the speleothems, mineral deposits that grow inside the caves. Speleothems represent one of the best paleoclimate records for the analysis of the abrupt climate change events, because they provide high-resolution records and possibility for precise U-Th dating (Vacco, Clark, Mix, Cheng, & Edwards, 2005).

Each speleothem is a unique record of the climate in the past. There are two types of speleothems: stalactites and stalagmites, and the difference between the two is related to the growth. In particular, stalactites grow down from the roof, while stalagmites grow upwards from the cave floor. In addition, flowstones and crystalline deposits that form underwater can also be considered as speleothem types (Fairchild & Baker, 2012). The difference between the stalactites and stalagmites can be seen from Figure 24 (Gornitz, 2008).

Figure 24

Stalactites from the Slaughter Canyon Cave in New Mexico and Stalagmites from Carlsbad Caverns in New Mexico

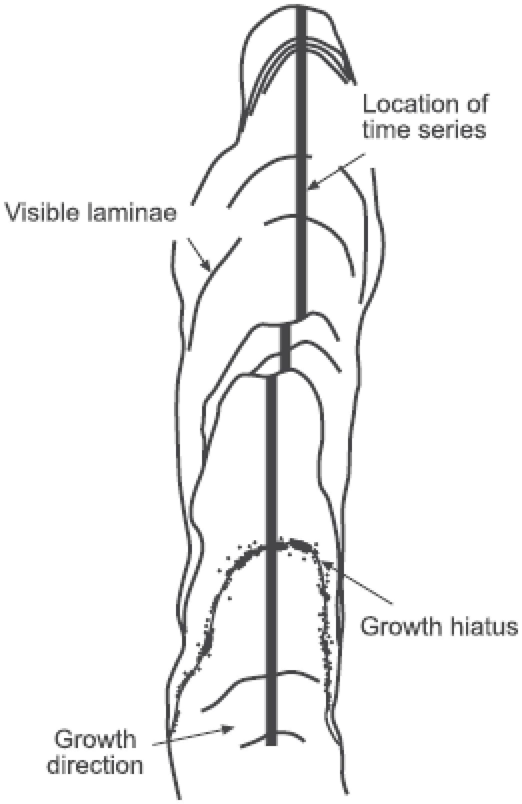


Note. a. the stalactites are hanging from the ceiling, while b. the stalagmites are growing from the floor. Reprinted from *Encyclopedia of Paleoclimatology and Ancient Environments,* (p. 916), by V. Gornitz, 2008, Springer.

In the analysis of the climate, most often the stalagmites are being used, due to their simpler internal structure. The stalagmites have internal layers, usually flat at the top of the sample, that allow the representation of the different periods in the past. A cross-section of a stalagmite is represented on Figure 25, that contains lateral shifts in the stalagmite's growth axis, due to changes in the landing position of the drops of water. An interesting feature of the stalagmites, is that their growth might pause, and then resume again, something that is related either to changes in climate, or local processes (Fairchild & Baker, 2012).

Figure 25

Cross-section of a Typical Stalagmite that Contains Growth Laminae

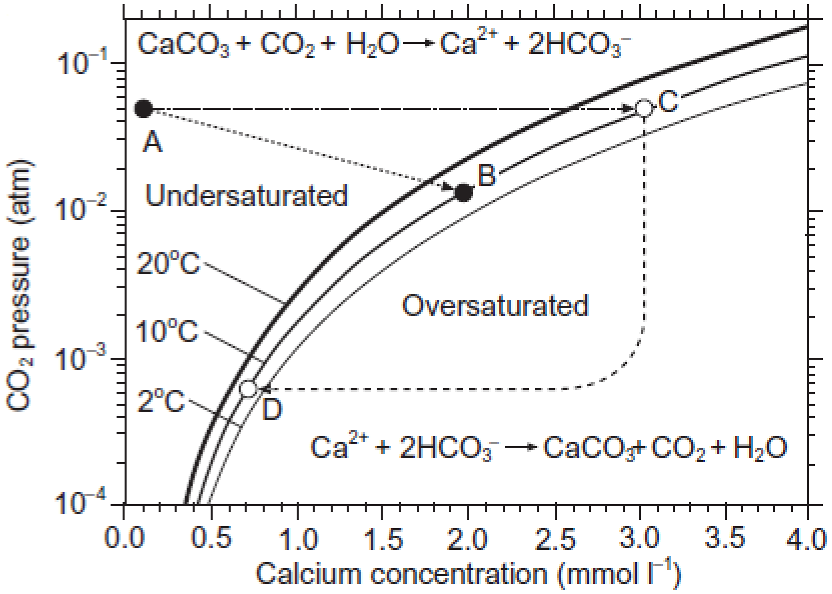


Note. A noticeable feature is the shifting position of the growth axis (makes possible the creation of the most continuous time-series). Reprinted from *Speleothem science: from process to past environments* (p. 33) by I. J. Fairchild & A. Baker, 2012, Wiley-Blackwell.

The speleothems that are being used as a paleoclimate archive, are usually calcareous, composed either of calcite or aragonite minerals, occurring within carbonate rocks, often limestones ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$). Hence, these rocks are aquifers with a specific permeability rate, that can store and transmit water, through a vertical and hypogeum drainage, with a specific permeability rate. Similarly to the sediments, the speleothem lifespan ends when they are destroyed by earthquakes, human, or are buried, flooded, dissolved and eroded. The speleothems occur very often in places where karstic host rocks and water are present. Except in the caves, they can be found in deserts, mountain tops in regions characterized by uplift, or beneath water if they are formed during periods with lower sea level. The formation of the speleothems requires presence of carbonate dissolution region (undersaturated calcium carbonate dissolution) and an underlying vadose area of $CaCO_3$ precipitation (oversaturated calcium carbonate dissolution) (Fairchild & Baker, 2012). Where vegetation covers the bedrock, the soil can absorb huge amounts of carbon dioxide, and its concentration might be significantly larger than the atmospheric one. The water that passes, is capable to dissolve the limestone in the soil and the small cracks of the bedrock. Such calcareous solution enters a cave, where by outgassing of the carbon dioxide, it becomes supersaturated, and a calcium carbonate precipitation occurs (Dreybrodt, 2008). How much calcite or dolomite will be dissolved by the precipitation, depends on its acidity, expressed as partial pressure of the carbon dioxide, with the highest acidity originating from the processes related to respiration and organic decomposition in the soils. Figure 26 represents the chemical reactions of the formation of the speleothems (Fairchild & Baker, 2012).

Figure 26

Chemical Processes Included in the Formation of the Speleothems



Note. The point A represents a situation with high partial pressure of the CO_2 in the soil, as a result of processes of respiration and organic decomposition. High amount of CO_2-containing percolating water is capable to dissolve carbonate minerals, causing a decrease of the calcium concentration in a solution.

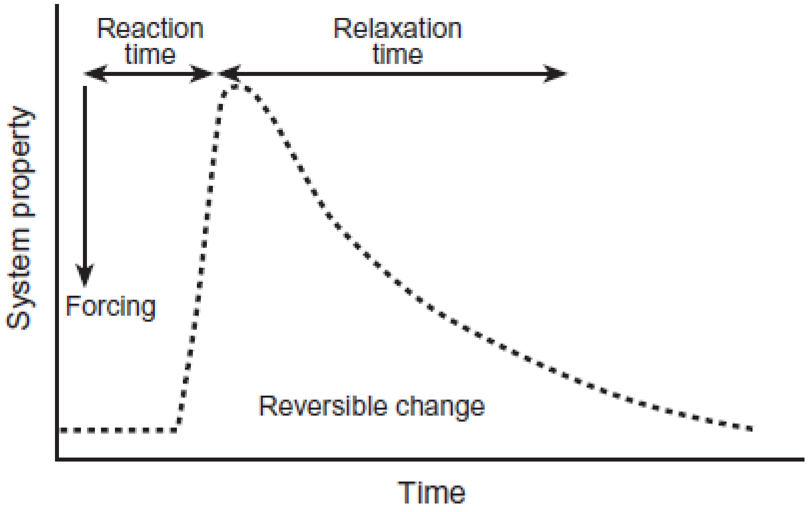
Without CO_2 renewal, the water goes to the saturation point B through a closed system path. On the other side, if the CO_2 is replenished and the water maintains a constant partial CO_2 pressure, the saturation will be reached at the point C. Reprinted from *Speleothem science: from process to past environments* (p. 34) by I. J. Fairchild & A. Baker, 2012, Wiley-Blackwell.

On the other side, the shape of the speleothem depends on the amount of the water that is supplied to them (Dreybrodt, 2008). The difference between the partial pressure of the CO_2 between the soil and the karst is the most important parameter, that determines the rate of the precipitation. The speleothem growth rate can vary between millimeter per year in warm and humid regions, and less than 100 μm per year, in the cold areas. For the growth, it is necessary to have enough water and air that is circulating, in order to remove the carbon dioxide as a waste product (Fairchild & Baker, 2012).

An important point regarding the changes in the climatic conditions and their impact to the speleothem, is that the air exchange between the cave and the outside, is influenced by the temperature. In particular, the air exchange is larger when the outside temperature is lower, than inside the cave. This usually causes lower partial pressure of the carbon dioxide inside the cave during winter. Indeed, the water degassing is limited by the partial pressure of the carbon dioxide in the cave air, and the slow drips will reach an equilibrium with the partial pressure of the carbon dioxide and the pH of the cave air, thus strengthening speleothem growth. The opposite occurs in summer. In addition, the larger degassing and the growth of calcium carbonate in winter, is related to increased $CaCO_3$ deposition, as well as $\delta^{13}C$ and Mg/Ca raise. Furthermore, the rain events are related to a lag before the water comes to a particular position in the karstic aquifer, and an exponential decrease in discharge during the relaxation time. The overall impact of rainfall and snowmelt events is smoothed due to storage in the aquifer. In addition, the average discharge of a drip, strongly depends on the flowpaths of the water. This response, characterized with an exponential decrease in the discharger over the relaxation time is represented on Figure 27 (Fairchild & Baker, 2012).

Figure 27

The Response of the Speleothem System to a Single Forcing: Rain Event



Note. Reprinted from *Speleothem science: from process to past environments* (p. 17) by I. J. Fairchild & A. Baker, 2012, Wiley-Blackwell.

The seasonal climatic changes are related to the variations in the drip water, such as the imprint of the Alpine environments snowfall and winter rain in lighter $\delta^{18}O$ values. These events can also be related to the saturation index reduction and speleothem growth rate reduction. In situations with constant saturation index, larger water flux will lead to larger growth rate of the speleothem. The caves that are permanently wet, show some characteristic features for the autumn season, such as the presence of colloids from the soil and some trace elements. On the other side, if there are strong summer droughts, there will be more intense degassing and calcite precipitation along the water flowline. If the drip water hydrology has a nonlinear behavior, it could be used for obtaining important information. Features like the reaction times and the sensitivity of the individual drips are changing, and also the change thresholds are seasonally variable, and this variability is imprinted in the speleothems (Fairchild & Baker, 2012).

5.2.1 - Dating of the speleothem records

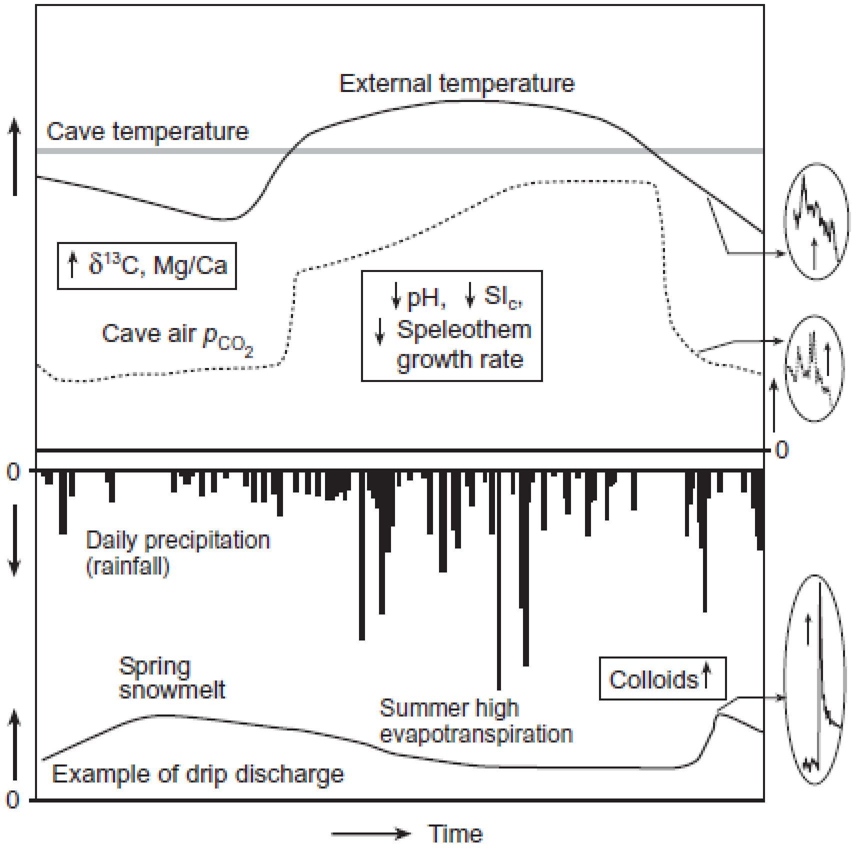
Even though it seems that the conditions in the caves are constant, changes in temperature, humidity and in the amount of carbon dioxide in the air are typically recorded. The variability of those parameters is the reason for the annual visible or chemical lamination in a speleothem. However, indications about the seasonality, may also be recorded, when their growth is fast enough to be resolved. Nevertheless, sometimes there are pauses or complete stops in the growth, thus absolute dating may result particularly helpful in resolving this issue. In particular, among the possible radiometric techniques, the uranium-thorium dating is one of the most commonly used, particularly when samples are supposed to be a few hundred, or a few thousand years old. The principle behind the uranium-thorium dating, is that during the speleothem growth, there is an incorporation of uranium from the solution, but not of thorium because it is insoluble. ^{234}U decays in time, and the main product is ^{230}Th, that accumulates over time. Hence, with usage of the half-life, dating to samples that are 500,000 years old, can be done (Fairchild & Baker, 2012). All in all, the possibility for precise radiometric dating of the speleothems, represents also an important advantage to other paleoclimate records, that might be dated only with the ^{14}C method. However, the annual changes preserved in the chemical and isotopic composition of the speleothems, indicate that the uranium-thorium dating is not preferable for the young calcium carbonate with sub-annual resolution with a usual uranium concentration of approximately 1 ppm. (Lachniet, 2009).

5.2.2 - Proxy records of the speleothems and the processes that affect their values

The most often used proxy records from the speleothems, as indications for the past climate, are δ^{18}O and δ^{13}C, the growth rate and the Mg concentration. Temperature changes and the δ^{18}O changes in precipitation, can be related to the atmospheric variability and its past composition. Moreover, changes in the δ^{13}C values and the trace elements variation in relation to Ca, can be used for quantifying processes of decomposition of the organic matter, mineral dissolution, the water flow and the mixing, and other processes occurring in the soil and upper epikarst. Epikarst is a zone located in the upper layers of the karst, that stores significant amounts of water, and feeds the speleothem growth. The same proxy values can also be used for the processes of the lower epikarst and caves, such as the degassing, evaporation, prior calcite precipitation, and how the solution saturation impacts the growth rate. Furthermore, isotopic analysis or fractionation and partitioning of elements, between the molecules of water and calcium carbonate, can be used for determining variations in the $CaCO_3$ precipitation. Finally, a secondary change, such as aragonite to calcite and calcite-water exchange of ^{18}O, can also represent a useful indicator of the climatic changes in the past. Indeed, the change in the temperature, such as the seasonal changes, can influence the composition of the rain and this can be imprinted in the speleothem proxy data. Also, there might be some specific signals that can represent the periods with high rainfall and infiltration, even though the quantification of these cannot be done, like the high amount of colloid-transported elements. To sum up, the δ^{18}O is influenced by continental, altitudinal, latitudinal and seasonal variations, that determine the isotopic fractionations in the path from the source to the sink. In the end, it is important to indicate that the changes in the growth rate that are reflected in the thickness of the annual layers, can also represent an important proxy record that can be used for the study of the climate changes in the past. More clearly, changes in the concentration of the CO_2, changes in the humidity, or the air flow, might happen in regular intervals with annual periodicity, due to climate conditions changes, such as variations in the temperature, the CO_2 concentration in the soil and the excess of water. If a speleothem is growing close to a place in the cave strongly affected by these factors, their small changes might be illustrated in changes in the growth of the speleothem, with a sensitivity that depends on the location in the cave, the cave ventilation and the possibility to preserve laminae. Such changes in the growth might be the annual changes in the fabric, annual change from calcite to aragonite, annual change in the concentrations of Sr, Ba and Mg and annual variations in the organic matter. However, the process of laminae counting is difficult and requires many person-hours for construction of the chronology. Also, trace-element laminae counting is complicated with a big amount of time series data and the required confirmation of the yearly periodicity of the element variations. Some of these problems are overcome with the appearance of the software for counting peaks, allowing precise chronology. To add, instrumental calibration of the annual thickness records, allows determination of signals that are dominated with the temperature or precipitation changes, or mixed changes. Figure 28 represents the possible annual variations in some of the parameters, that influence the speleothem growth (Fairchild & Baker, 2012).

Figure 28

Climate Conditions Changes that Lead to Annual Changes in Parameters that Impact the Speleothem Growth



Note. Reprinted from *Speleothem science: from process to past environments* (p. 23) by I. J. Fairchild & A. Baker, 2012, Wiley-Blackwell.

Lachniet, (2009) states that if an equilibrium exists, the $\delta^{18}O$ value of the speleothem $CaCO_3$, is associated with only with the $\delta^{18}O$ value of the dripwater, and the temperature of the cave. Namely, the temperature affects the value because it influences the equilibrium fractionations between the water and the $CaCO_3$. Moreover, it is manifested in the seasonal rainfall, with $\delta^{18}O$ values larger in summer and lower in winter, this depending on the equilibrium fractionation and the variations in the moisture source. The seasonal variability is a few per mille in low latitudes, and up to 15 per mille in the higher latitudes. However, the $\delta^{18}O$ value of the dripwater is more dominant in the $\delta^{18}O$ value signal (Lachniet, 2009). The change in the $\delta^{18}O$ value of the precipitation might occur as a result of local or non-local processes (Pausata, Battisti, Nisancioglu, & Bitz, 2011). The $\delta^{18}O$ signal in the speleothems is a site-specific, meaning that it is mostly related to the regional climate. Furthermore, the $\delta^{18}O$ signal decreases with increasing of the altitude, and the water $\delta^{18}O$ value decreases with increasing of the distance from the ocean (Lachniet, 2009). Also, the strength of the precipitation or the amount effect plays an important role, with its changes occurring due to changes in the intensity if the convection (Pausata, Battisti, Nisancioglu, & Bitz, 2011). In these terms, the rainfall $\delta^{18}O$ value decrease with the increase of the amount of the rainfall. Lachniet, (2009) define the $\delta^{18}O$ value of the dripwater in the cave as a function of the seasonality of recharge and the changes within the soil and epikarst. Such changes lead to attenuated variability compared to the $\delta^{18}O$ value of the precipitation because of the mixing in the soil zone and the epikarst (Lachniet, 2009). Regarding the seasonality, a change in the $\delta^{18}O$ value can happen because of a change in the ratio of summer precipitation, that is characterized with lighter (more negative) $\delta^{18}O$ value, to spring precipitation. To add, the $\delta^{18}O$ value of the precipitation changes with the origin of the water vapor in the area, and such variations occur because of the changes in the circulation. Finally, $\delta^{18}O$ value of the precipitation can change because of variation in the isotopic composition of the water vapor, that can change because of the different processing of the water vapor from the source to the precipitation site, or the change in the isotopic composition in the source because of processes such as sea surface temperature change or river runoff (Pausata, Battisti, Nisancioglu, & Bitz, 2011).

In order to make possible the usage of the $\delta^{18}O$ signal for determining the temperature in the past, information about the mean annual temperature of the site, the temperature of the cave and the $\delta^{18}O$ value of the dripwater are necessary. Lachniet, (2009) state that not all of the speleothems have annual banding, or other geochemical or physical indicators of annual layers. To be more specific, the annual changes might be preserved in the concentration of the trace elements, such as Ti, Mn, Mg and Y, the $\delta^{13}C$ and $\delta^{18}O$ values, in the annual petrographic bands, luminescence banding, etc (Lachniet, 2009).

Fairchild & Baker, (2012) indicate that an important feature of the speleothems is that they are capable to capture decadal to millennial time-scale oscillations. The steady growth of the speleothems occurs up to 10^4 years, and with rates that are strongly changing up to 10^5 years. Later, in the period between 10^5 and 10^6 years, very often some structural changes to the karst occur. Furthermore, in areas that are seismically active, there are changes in the flowrates and with that, deep water supply, after 10^3 years. The change in the atmospheric precipitation will also have an impact, and the precipitation itself will be modified by changes in the evapotranspiration. Finally, the difference between the precipitation and the evapotranspiration, will influence the average annual infiltration to the karst and the discharge from the karst. The biota overlying the karst, and with it some biomarkers and organic compounds change with the climate as well. In addition, the speleothem growth and its shape is also affected by the geometrical properties of the cave. Another important parameter is the strength of the air circulation that regulates the removal of the gasses inside the cave, such as the carbon dioxide and radon, and the aerosol introduction. If the flow is stagnant, the relative humidity might reach even 100 %, causing slower speleothem growth. Each of the measured properties of the speleothems, can be correlated to the geographical position or the properties of the bedrock, with every one of them representing more variables, with only one dominant factor. The possibility of the speleothems to preserve climatic changes with decadal and multi-millennial time-scale, can be represented by the preserved cyclicity of some parameters, that match the orbital changes (Fairchild & Baker, 2012).

5.2.3 - Evidence of abrupt climate change events in the speleothem records

The speleothems represent a valuable archive for the abrupt climate change events because of the possibility for precise dating and their widespread distribution. Moreover, an additional advantage compared to other records is that the oxygen isotope and trace element analysis, allow producing of annual to sub-annual resolution, necessary for the study of the fast occurring climate change events (Treble, et al., 2007). Also, Fairchild & Baker, (2012) indicate that not all speleothem records have the proper resolution and chronology for analyzing the abrupt climate change events, and that there should be imprints in the growth rate, $\delta^{18}O$ or $\delta^{13}C$ of the speleothems.

During the abrupt climate change events in the Last Glacial Period, changes at lower latitudes were mostly interpreted through changes in the precipitation. So, Fairchild & Baker, (2012) indicate that one of the best archives that contain evidence of these events are the speleothems, and their $\delta^{18}O$ records in the regions that were affected by monsoons. Times with stronger monsoons during the different phases of the abrupt climate change events, are being also marked with $^{87}Sr/^{86}Sr$ variations, because of the stronger leaching from silicate minerals in wind-blown sediments (Fairchild & Baker, 2012).

Probably, the clearest representation of the abrupt climate change events in the speleothem record, is the noticeable shift in the $\delta^{18}O$ records. Mg follows the trend of the $\delta^{18}O$ record, showing an increase of both records at times with drier conditions. Still, Mg does not undergo such abrupt changes as the $\delta^{18}O$ record, that probably occur due to monsoon changes that are not reflected in the amount of rainfall. Fairchild & Baker, (2012) explain that the most convenient way of determining the rainfall amount, is through a comparison of the different places along the average moisture flow direction. A significant point is that the speleothem records are capable to represent the global climate changes in the past, through the regional variability in the monsoon strength. For instance, a region impacted by the Asian Monsoon, can reflect the southward movement of the Intertropical Convergence Zone, related to stronger water vapor transport from the tropics, through the $\delta^{18}O$ record of the precipitation. The analysis of many stalagmites from the Asian Monsoon region, show that there is a doubling in the $\delta^{18}O$ values over the glacial-interglacial cycles. Also, the $\delta^{18}O$ record is correlated with the summer insulation in the Northern Hemisphere, with small-amplitude oscillations related to the decrease of the $\delta^{18}O$ when the Asian Monsoon is weaker. These small-amplitude oscillations correlate with the timing of the abrupt climate change events during the Last Glacial Period, representing a connection between the events and the strength of the Asian Monsoon (Fairchild & Baker, 2012). Clearly, the Asian Monsoon is of crucial importance because it is responsible for the transport of heat and moisture from the warmest part of the tropical ocean, through the equator, to the higher latitudes (Wang, et al., 2001).

5.2.4 - Abrupt climate change events recorded in the Hulu Cave in China

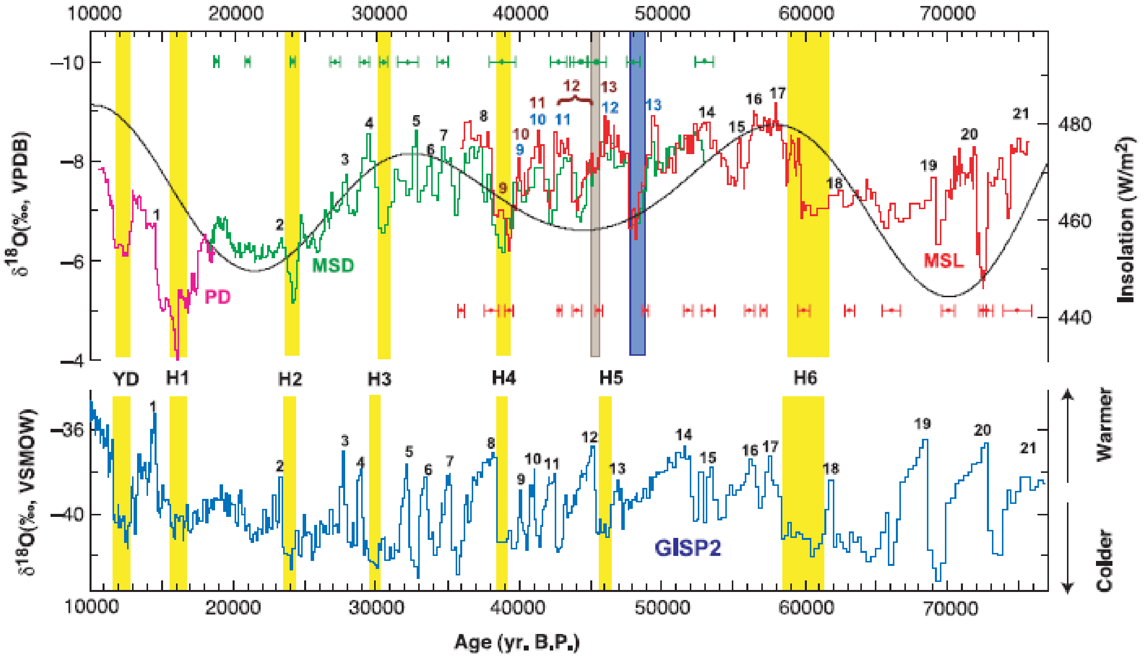
The stalagmites from the Hulu Cave, located east of Nanjing in China, from the Asian Monson region, were the first paleoclimate archive that has shown the link between the millennial-scale changes of the monsoon and the abrupt climate change events, through a climate teleconnection to the North Atlantic (Lachniet, 2009). The Hulu Cave record analyzed by Wang, et al., (2001) represents a composite of $\delta^{18}O$ values of five stalagmites, with overall time interval of the record of 75-11 kyr. The net variation of the $\delta^{18}O$ is 5 ‰, with six intervals marked by high $\delta^{18}O$ values, that coincide with H1-H6 events (Treble, et al., 2007). The east Asian Monsoon region, the region where the Hulu Cave is located, is a sub-system of the Asian Monsoon, and its intensity changes with the seasons. Namely, the summer monsoon is initiated with the spring heating of Asia, and it transports moisture and heat northward, from Australia, to places as far as northern China. On the other side, the winter monsoon brings cold and dry air from Siberia towards the south, through eastern China, and it contributes to the Australia summer monsoon (Wang, et al., 2001). The East Asian Summer Monsoon is driven by the northward shift of the intertropical convergence zone and the difference between the sea level pressure between Asia and the oceans around it (Treble, et al., 2007).

The changes in the east Asian Monsoon are reconstructed using the oxygen isotopic composition of the speleothem $CaCO_3$, and its precise dating is done using mass spectrometric ^{230}Th techniques. The high-resolution of the $\delta^{18}O$ analysis and the dating is a result of the continuous formation of the speleothems in the Hulu Cave for tens of thousands of years. The confirmation that these speleothems have annual bands, has been obtained with comparison of the number of bands and the differences in age between the sub-samples that were dated, that has shown that they are equal (Wang, et al., 2001).

The analysis of the Hulu Cave stalagmites, shows that all of the analyzed stalagmites have a similar pattern of the $\delta^{18}O$ variations. Moreover, they have also found a correlation between the $\delta^{18}O$ and the $\delta^{13}C$ records of most of the stalagmites. The ones that did not show a positive correlation, make the interpretation of the $\delta^{18}O$ of temperature and precipitation complicated. However, Wang, et al., (2001) suggest that due to the big seasonal difference (80 % precipitation with the summer monsoon with more negative $\delta^{18}O$ value compared to the winter one), the large variations in the average annual $\delta^{18}O$ of precipitation, might be because of the change in the ratio of the summer to winter precipitation amount, with small effects of the temperature. In addition, the records from the Hulu Cave follow the summer insulation, that suggests that the strong insulation in summer enhances the difference between the temperature of the ocean and the land, leading to stronger summer monsoon. This pattern is punctuated by the millennial-scale oscillations. According to this, the temperature in Greenland is correlated with the ratio of summer to winder precipitation in China, and probably the changes in the ratio originate from changes in the summer precipitation (Wang, et al., 2001). The interstadial periods of the Dansgaard-Oeschger events are related to lower values of the $\delta^{18}O$ in the stalagmite, that is associated with the amount effect and the seasonal variations of the rainfall in the monsoon climate (Lachniet, 2009). So, the interstadials correlate with stronger summer East Asian Monsoon (Wang, et al., 2001). On the other side, stadial periods and Heinrich events are related to higher δ^{18}O values due to bigger contribution of winter rainfall, also linked with the wet periods in the neo-tropics of the Southern Hemisphere. Furthermore, the change in the strength of the Asian Monsoon recorded in the Hulu Cave stalagmites, was also correlated with the Bolling-Allerød warming and Younger Dryas cooling events (Lachniet, 2009). Still, there were found some differences in the Greenland and Hulu Cave records, such as the sharp increase of the δ^{18}O at the time of the Heinrich event 1, even though similar characteristic has not been found in the ice cores. On the other side, the similarities dominate, such as the duration and abruptness of the transition of the beginning and the ending if the Younger Dryas episode. Figure 13 represents the comparison between the δ^{18}O stalagmite records from the Hulu Cave and the δ^{18}O record from the Greenland Ice Core (Wang, et al., 2001).

Figure 29

δ^{18}O Record of the Stalagmites from the Hulu Cave and the δ^{18}O Record of the Greenland Ice Core



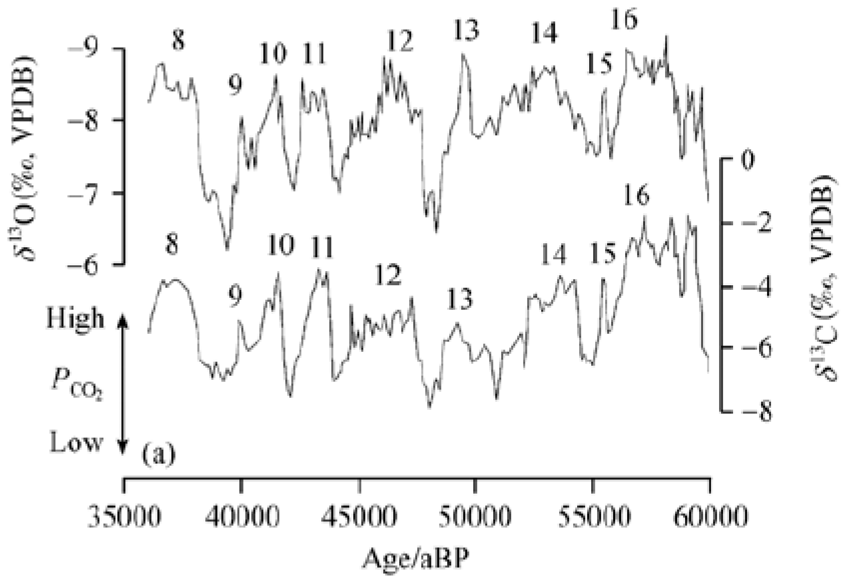
Note. The δ^{18}O record of the stalagmites from the Hulu Cave is indicated with purple, green and red lines (upper part) and the δ^{18}O record of the Greenland Ice Core is indicated with blue line (bottom). The average insulation over the summer months at 33° N versus time is indicated with black line. ^{230}Th ages and the colored error bars of the of the stalagmite record are also represented. The abrupt climate change events that are correlated between the two records are represented with numbers. In addition, the Heinrich events and the Younger Dryas are represented with vertical bars. The two possibilities that might represent the H5 event in the stalagmites are indicated with blue and brown bars. The δ^{18}O scales from the Hulu cave are reversed and they should be increasing down. Reprinted from "A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China" by Y. J. Wang, 2001, *Science 294*, (p. 2).

Treble, et al., (2007) point out that probably the best technique for the oxygen isotope analysis of the speleothems is Secondary Ionization Mass Spectrometry (SIMS), due to the increased resolution, at least tenfold, and the possibility for small-time windows investigation, characterized with large isotopic shifts. The study of the Hulu Cave speleothems with this technique, reveals an abrupt shift of the δ^{18}O value of 2 ‰, with 1.5 ‰ shift in the first 1-2 years, and the overall 2 ‰ increase in 6 years, at 16.07±0.06 kyr, that matches the timing of the H1 event. After this, the highest value of the δ^{18}O in the Hulu Cave record follows, representing the driest phase in eastern China, in the interglacial/glacial cycle. Wang, et al., (2001), managed to find the imprint of the Heinrich events in the Hulu Cave record because of their long impact on the East Asian Summer Monsoon of about 500 years, using analysis of micro-shaved intervals. On the other side, the SIMS analysis performed by Treble, et al., (2007) shows that such fluctuations in the oxygen isotopic values, but with much shorter duration, are an often feature of the Hulu Cave record, representing local rainfall changes. This further confirms the capability of the SIMS technique to achieve higher spatial and temporal resolution (Treble, et al., 2007).

In addition to the δ^{18}O record, the δ^{13}C record from the Hulu Cave in China, represents another proxy record of the link between the abrupt climate change events and the strength of the East Asian Monsoon. The variation in the δ^{13}C values usually occurs due to change in the C4 to C3 ratio in plants. That are variations related to the metabolic pathways. Other important influence on the isotopic value, comes from the variations in the hydrological activity due to changes in the rainfall. Also, there is an influence from the introduction of old and dead carbon, changing fractionations in different conditions, level of vegetation, etc. Kong, et al., (2005) found that the δ^{13}C and the δ^{18}O records vary similarly to the Dansgaard-Oeschger events in Greenland. As a result, they conclude that the changes in the δ^{13}C must be related to the precipitation, since it has been found that δ^{18}O record is controlled by the precipitation. In these terms, stronger precipitation correlates to less negative δ^{13}C values and conversely for the weaker precipitation. Also, a decline in the precipitation might be predated by a decrease in a soil humidity, and because this is related to the temperature change, probably the δ^{13}C variations might be useful in the analysis of the mechanisms responsible for the link between the Asian Monsoon and the Dansgaard-Oeschger events. Moreover, the analysis has shown that there is a negative correlation between the δ^{18}O and the δ^{13}C records on millennial time-scale. The proposed reason for this is the possible disequilibrium between the soil water and soil carbon dioxide when the water flows quickly through the soils. This negative correlation between the δ^{13}C and the δ^{18}O records on millennial time-scale is represented on Figure 30. The comparison between the δ^{18}O and the δ^{13}C records from the same stalagmites, shows that the δ^{13}C records of the Younger Dryas event and the last deglaciation, lag behind the δ^{18}O by 700 years, something that has been found in stalagmite records from other locations as well. The suggested reason for the lag is the time duration necessary for the landscape stabilization and vegetation establishment to the change in the climate. After all, the δ^{13}C represents a proxy record of vegetation changes (Kong, et al., 2005).

Figure 30

Comparison Between the $\delta^{13}C$ and the $\delta^{18}O$ Records of Stalagmites from the Hulu Cave on Millennial Time-scale



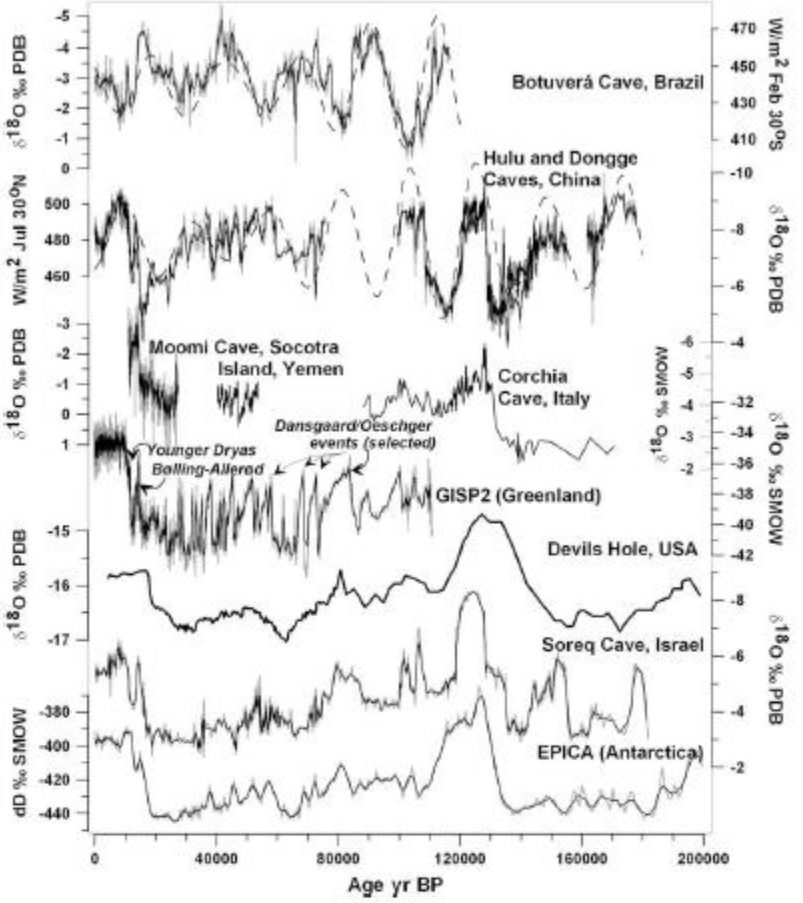
Note. $\delta^{13}C$ and the $\delta^{18}O$ show a negative correlation. Reprinted from "Complicated responses of stalagmite δ13C to climate change during the last glaciation from Hulu Cave, Nanjing, China" by X. Kong, 2005, *Science in China Ser. D Earth Sciences 48,* (p. 3).

5.2.5 - Correlation with other stalagmite records

The abrupt climate change events leave marks in the speleothem records, such as the changes in the $\delta^{18}O$ or $\delta^{13}C$, in regions all over the world (Fairchild & Baker, 2012). In addition to the stalagmite records from the Hulu Cave in China, the impact of the abrupt climate change events has been recorded in stalagmite data from other regions as well. In this terms, evidences have been found in the European Alps and the southwestern United States. To add, evidence of the impact on the monsoon rainfall by the Dansgaard-Oeschger events and the Bolling-Allerød, have been found in Socotra Island, Yemen, (Lachniet, 2009). An interesting point is that the comparison between different speleothem archives located in different places, shows that there is an agreement in the timing of the recorded abrupt climate change events (Fairchild & Baker, 2012). For example, periods of lower $\delta^{18}O$ values of the rainfall at the Socotra Island, that reflect strengthening in the precipitation in the ITCZ, are related to the interstadials in the North Atlantic. If the relation between the interstadials and the Asian Monsoon strength found in the Hulu Cave records is taken into account, it can be concluded that the strength of both, the Asian and Indian Monsoon are linked through teleconnections to the North Atlantic climate (Lachniet, 2009). In addition, regions that have vegetation cover and productivity that depend on the climate, the $\delta^{13}C$ proxy can provide well record of the abrupt climate change events (Fairchild & Baker, 2012). Wang, et al., (2001) indicate that differences between the stalagmite records from different areas exist as well, such as the ones between the Hulu Cave and the Sorrel Cave from Israel, or the Crevice Cave from Missouri. Such contrast represents the regional difference in the past climate (Wang, et al., 2001). The global climate teleconnections can be seen in Figure 15, where comparison between the results of analyzed speleothem and ice cores records is made (Lachniet, 2009).

Figure 31

Comparison Between Stalagmite and Ice Core Records Located in Different Places of the World, Representing the Global Climate Teleconnections



Note. It can be clearly seen that the Northern Hemisphere speleothem records from the Hulu Cave, Dongge Caves, Moomi Cave, Soreq Cave and the Devils Hole, contain imprints of the climate characteristic for the high latitudes, represented in the records from Greenland and Antarctica Ice Cores. The represented climate records show an atmospheric circulation response to the ocean-atmosphere cryosphere reorganizations. Moreover, the monsoon records clearly represent the antiphase relationship between the two hemispheres, due to the antisymmetric insolation changes with precessional scale. Reprinted from “Climatic and environmental controls on speleothem oxygen-isotope values” by M. S. Lachniet, 2009, *Quaternary Science Reviews 28,* (p. 427).

In conclusion, the speleothems represent a valuable paleoclimate archive that contains evidence of the climate changes in the past, and are capable to capture fast occurring changes such as the abrupt climate change events, due to the proper temporal resolution of some speleothem records. Moreover, the possibility for precise dating with U-Th radiometric method, and the possibility for counting annual layers in some of the speleothem records, represent additional advantages compared to other archives. Furthermore, they can be used for the study of the global imprint of such events because they have widespread distribution. The variation in the climate might affect the speleothems, directly and indirectly, and therefore these records can be used for analyzing the climate of the past in terms of the temperature, precipitation and vegetation changes. The most commonly used proxy records from the speleothems are the oxygen and carbon isotopic composition, the growth rate, the concentration of Mg and the presence of trace elements. The abrupt climate change events are associated with changes in the strength of the monsoons, and the resultant changes in the precipitation can be determined from the $\delta^{18}O$ value of the speleothems located in the areas affected by the monsoons. Such speleothems, influenced by the changes in the intensity of the East Asian Monsoon, that provide important indications of the abrupt changes, are located in the Hulu Cave in China. The Hulu Cave stalagmite records represent a link between the North Atlantic climate and the East Asian Monsoon, and confirm the point that the abrupt climate change events have a spatial extent that is hemispheric or larger. The most useful proxy records of the Hulu Cave stalagmites that represent the abrupt climate changes, are the $\delta^{18}O$ and $\delta^{13}C$ records, and for their study, the SIMS technique is found to be the most proper one. This is because of its good temporal resolution and possibility for small-time windows analysis. Finally, speleothem records from different locations all over the world, confirm the timing and findings of the Hulu Cave record, with small differences in the proxy records, that represent the regional climate (Vacco, Clark, Mix, Cheng, & Edwards, 2005; Lachniet, 2009; Wang, et al., 2001; Treble, et al., 2007).

6. ICE CORES

Ice cores are one of the most studied paleoclimate archives because of their high temporal resolution and because they contain valuable information about the climate of the past: the temperature, atmospheric composition, volcanic eruptions, sources of terrestrial dust, the location of the sea ice, the terrestrial and marine biological activity, the atmospheric oxidation capacity, pollution, etc. Moreover, they contain both climate proxy information and climate-forcing proxy information, they provide information on hundreds of thousands of years, at the highest latitudes (and altitudes) they are often the only proxy data archives available. They are samples that are obtained with drilling of the ice sheets and the alpine glaciers sites. The changes in patterns of the chemical species and physical properties recorded in ice cores, allow investigation of the past climate variability, and the causes-effects connection of that variability. This is because such changes over different time periods, can be quantitatively associated to climate changes, through specific transfer functions, that should provide information about the global atmosphere during the deposition time, although the dependence is nonlinear. Indeed, the ice formation processes, and the post-depositional processes, highly depend on the water accumulation, temperature and the presence of other species (Bales & Wolff, 1995).

6.1 - General properties of the ice sheets

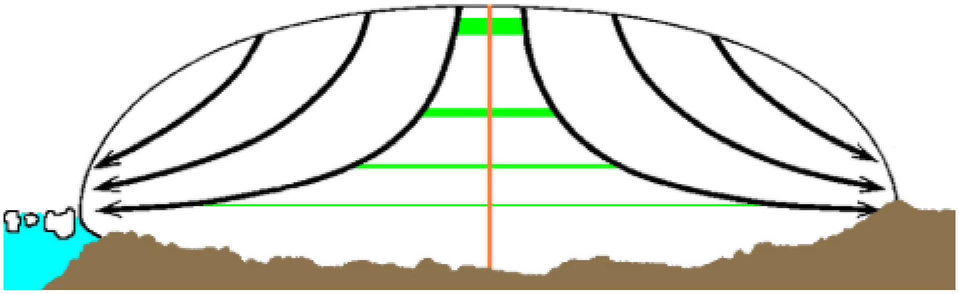
Ice sheets are typically formed through a progressive densification of the snow that is accumulated at the ice sheet surface (Gornitz, 2008). More precisely, the deposited snow is on the central part of the ice sheet, and it is compressed to ice, that moves downwards or towards the margins of the ice sheet, where it is removed either by melting or by calving (icebergs discharge in the ocean). The ice moves with high viscosity and the reason for such movements and deformation is the gravity. An important aspect is that the sinking down of the layers in the central parts, causes their thinning. On the other side, the accumulated snow at the surface, strongly depends on the temperature, and has higher amount in warmer periods, compared to colder periods. So, the thickness of the annual layers also varies with time (Research at Centre for Ice and Climate , n.d.). As a result, it can be concluded that the annual layer thickness of the ice core, is influenced by both, the changes in the surface accumulation, that is the quantity of the ice between two temporal lines in the ice core, and the flow (Alley, 2000; Research at Centre for Ice and Climate , n.d.).

So, the snow structure is changing constantly, and that process is called snow metamorphism. Such changes result in material responses that are non-liner, because the properties of the snow strongly depend on the microstructure, and thus, deriving information with studying of the snow, requires clear understanding of the metamorphism (Miller, Adams, & Brown, 2003). Among the other important physical properties of the snow affected by the metamorphism, is the albedo. Most of the variations occur due to the thermodynamic relationship between the different water phases, and the metamorphism depends on the thermal and meteorological conditions. There are two types of metamorphism, dry and wet, and this classification is determined by the presence and the absence of the liquid water phase, that influences the melting point of the ice (Climate Policy Watcher, 2020).

The flow of the ice is schematically represented on Figure 32. How the annual layer thickness in Greenland is changing with the depth, is represented on Figure 33 (Research at Centre for Ice and Climate , n.d.).

Figure 32

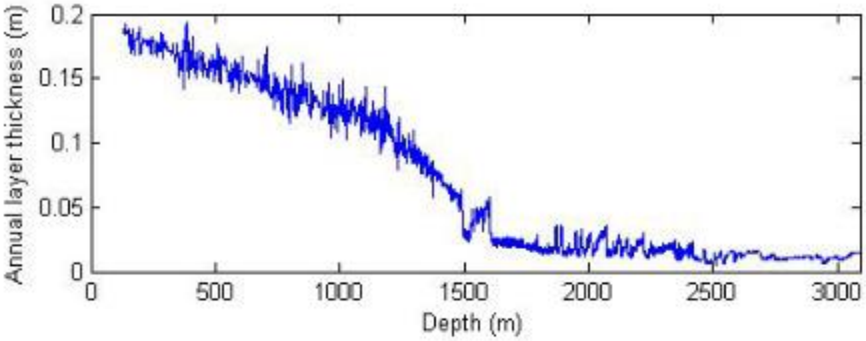
Flow of Ice on the Ice Sheet



Note. The arrows show the direction of the flow of ice. The green lines indicate that the layers in the deeper parts of the ice sheet become thinner and are stretched in the horizontal direction. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

Figure 33

Variation of the Annual Layer Thickness with the Depth in Greenland Ice Core

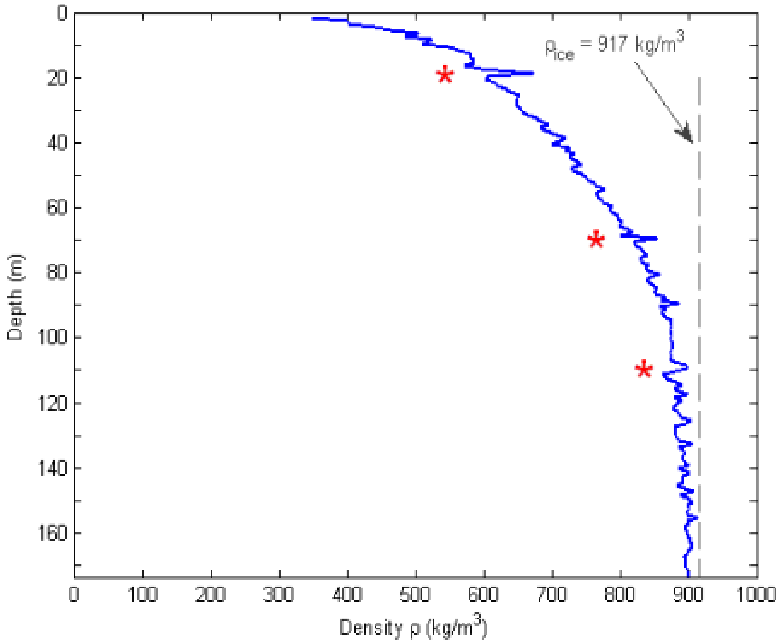


Note. It can be seen that at 1500 m depth, there is a sharp change in the curve, representing the transition glacial-interglacial climate, because the snow accumulation is lower during glacial periods. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

The new deposited snow has a density of about 50-70 kg m^{-3}, and since the temperature in the central parts of the ice sheets never becomes larger than the freezing point, the snow accumulates and gets buried by the new snow layers, and does not melt. The new layers press with their weight, compressing the layers below, and leading to their increased density (Research at Centre for Ice and Climate , n.d.). Usually, the snow-ice transformation happens within the first 100 m, and the process might last decades or even millennia, that depends on the accumulation rate and the temperature. The densification process consists of recrystallization of the snow grains until they are packed dense enough (Bales & Wolff, 1995). At a density of 830 kg m^{-3}, there is a transition from firn to ice, and the closure of the air passages restricts the motion of the air, so the air is only present in the form of closed bubbles. To clarify, firn is the porous intermediate phase between the snow and the glacial ice, formed when sintered snow has outlasted at least one ablation season, and it occupies only 70-100 m in the ice sheet (that in Greenland has a thickness of around 3000 m). Going deeper, when the density becomes 917 kg m^{-3}, the glacier ice stage is reached, and additional compressing is impossible. At greater depths, only thinning of the layers occurs, as a result of the flow of the ice. This change of the density relative to the depth of the Greenland Ice Core is represented on Figure 34 (Research at Centre for Ice and Climate , n.d.). Figure 35 represents the transitions snow-firn and firn-ice, how the density changes with the depth, and finally, it illustrates that the concentration of a particular chemical from the atmosphere, can be determined from its concentration in the ice (Bales & Wolff, 1995).

Figure 34

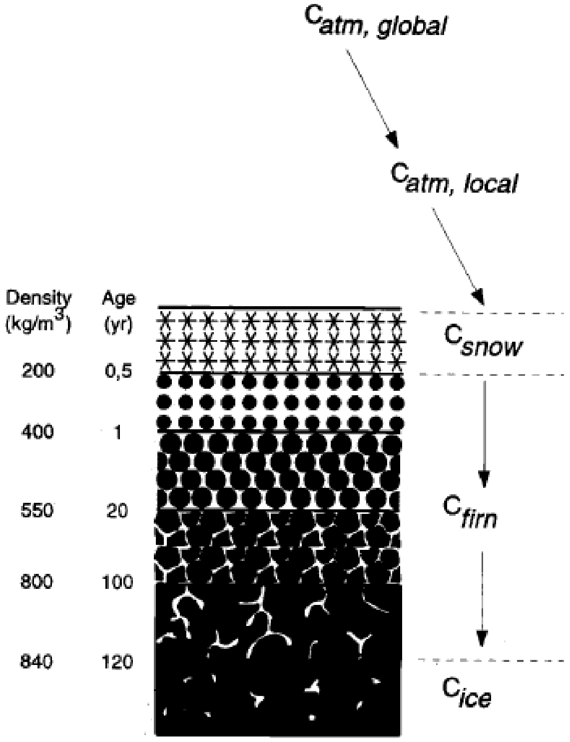
Density Change with the Depth of Greenland Ice Core



Note. The red stars indicate the melt layers because sometimes there the temperatures might increase and cause melting of the snow from the surface. The following refreezing, leads to higher density than the surrounding firn. The density is expressed in kg m^{-3}, and the depth in m. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

Figure 35

Snow-Firn and Firn-Ice Transition at a Particular Depth, how the Density Changes with the Depth in the Ice Cores and Relation Between the Atmospheric Concentration and the Concentration in the Ice Core

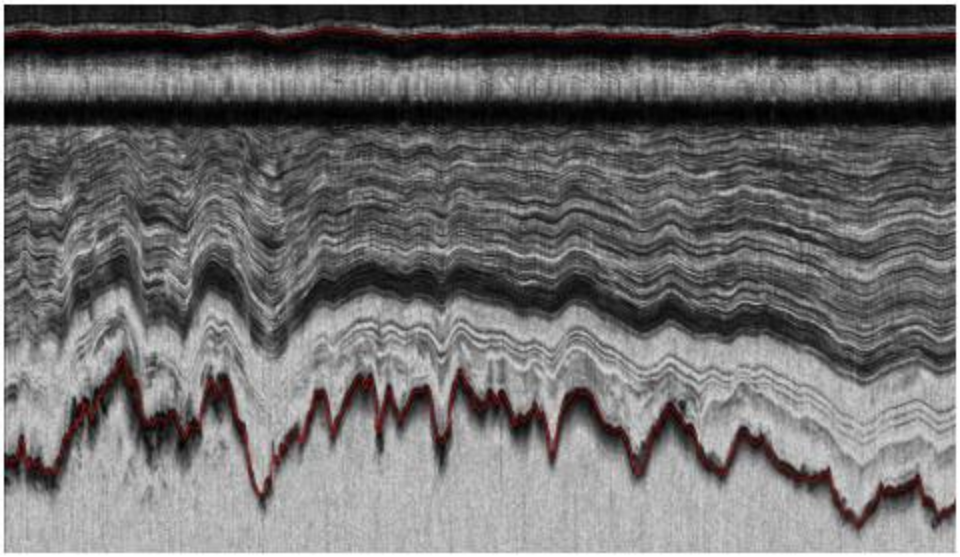


Note. The snow-firn transition is determined by the metamorphism and grain growth, while the firn-ice transition is determined by pore closure. Reprinted from Interpreting Natural Climate Signals in Ice Cores by R. C. Bales & E. W. Wolff, 1995, *Eos, Vol. 76, No. 47,* (p. 478).

The ice sheets are characterized with internal layers, and their shape depends on the accumulation rate, the history of the ice flow, the topography of the bedrock and the basal melt rate pattern. The accumulation rate influences the shape of the layers because there is bigger sinking down of the layers in areas with higher accumulation rate and vice versa, with the strongest influence at the top of the ice sheet. On the other side, the shape of the layers in the deeper parts, mostly depends on the bedrock topography. Still, the shape of the deeper layers does not depend only on the bedrock topography, because if the ice is at the melting point, the shape of the layers is different. This is due to the pulling down of the layers from below because if there is basal melting. According to this, it can be concluded that the shape of the internal layers can be used for studying the basal melt rate and accumulation patterns. Figure 36 shows how the shape of the internal layers can follow the bedrock topography (Research at Centre for Ice and Climate , n.d.).

Figure 36

Internal Layers in the Greenland Ice Sheet with a Shape that Follows the Bedrock Topography



Note. Reprinted from *Research at the Center for Ice and Climate*, http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

6.2 - Ice cores dating

The establishing of the chronology, or a time versus depth relation, is necessary to correctly interpret isotopic and chemical analysis performed on ice core records (Dansgaard & Johansen, 1969). Some of the methods used for ice cores dating include annual layer counting, synchronization to the orbital changes or other archives with using the common horizons, use of stratigraphic markers, and glaciological modeling (Gornitz, 2008).

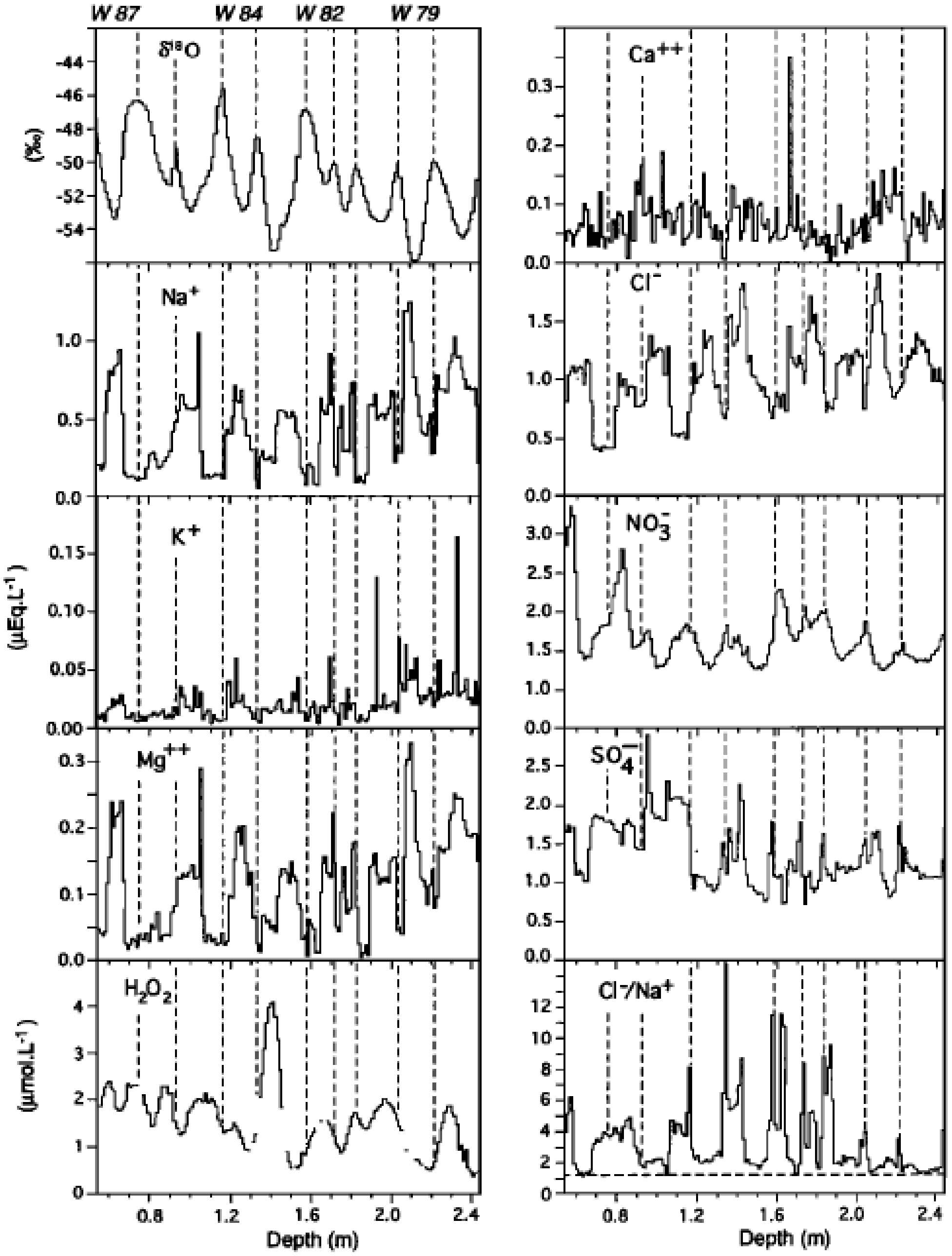
The annual layer counting can be done with determination of the seasonal changes of ice core properties, such as the isotopic composition of the ice, the chemical composition of the aerosols and the content of dust (Gornitz, 2008). Seasonal changes of other features such as the electrical and physical properties can be useful as well (Alley, 2000). The positive side of the method of counting annual layers using the seasonal change in the isotopic composition, is that no special preventive measures are essential in order to save the sample from contamination (Legrand &

Mayewski, 1997). This method has been shown to be very accurate at locations characterized with high accumulation rate, with maximum error of 2 %. On the other side, areas with low accumulation rate, such as the ones from East Antarctica, cannot be dated correctly with this method, mostly because of processes of diffusion. This especially refers to the ice cores taken from the center of the EAIS (East Antarctica Ice Sheet), because the accumulation rate varies with respect to the coastal areas (Gornitz, 2008). Legrand & Mayewski (1997) suggest that the method does not provide well dating of the records in areas with accumulation rate lower than 200 kg m^{-2} yr^{-1}. On the other side, counting annual layers through measurements of the impurities, allows better accuracy because the impurities are not affected by the diffusion, thus making the determination of the annual layers even in the old ice possible (Rasmussen, et al., 2014).

Hydrogen peroxide is considered to be a good seasonal tracer, only in areas that have high accumulation rates, due to the diffusion and the smoothening effect with depth. In such places, the ratio between the summer and winter concentration of hydrogen peroxide is bigger than 5, as a result of the stronger photochemistry in summer. Furthermore, chemical species like calcium and ammonium can also be used, because of the strong seasonal cycles. Calcium originates from the sea and the continental dust, and it experiences maximum at spring in Greenland, and at winter in Antarctica. Ammonium exhibits strong summer maximum in Greenland, associated to the emissions from the biosphere, while in Antarctica its seasonal cycle has not been identified (Legrand & Mayewski, 1997). Moreover, winter to spring maxima in nitrate and sulfate ions have been noticed in Greenland as well, mostly related to anthropogenic sources. More precisely, the sulfate ions originate from diverse sources, such as the sea salt, dust, volcanic eruptions, combustion of fossil fuels and phytoplankton production of dimethylsulfide (Kuramoto, et al., 2011). In addition, sodium as a sea salt tracer can be used as well, with the highest concentration in winter, as a result of the more often advections of the marine air masses. Also, weaker but noticeable seasonal variation experience chlorine ions, with a maximum at summer (Legrand & Mayewski, 1997). Other species, such as the methanesulfonic acid (MSA), can be used as well. MSA is an oxidization product obtained from dimethylsulfide and produced by the marine phytoplankton, that shows double maxima, in spring and in late summer-autumn (Kuramoto, et al., 2011). Figure 37 represents how the chemical species concentration changes with the depth in the Antarctica Ice Core record, for the period 1978-1987 (Legrand & Mayewski, 1997).

Figure 37

Seasonal Variation of Chemical Species in the Antarctica Ice Core Used in the Dating of the Record



Note. Reprinted from "Glaciochemistry of Polar Ice Cores: A Review" by M. Legrand & P. Mayewski, 1997, *Reviews of Geophysics, 35, 3,* (p. 224).

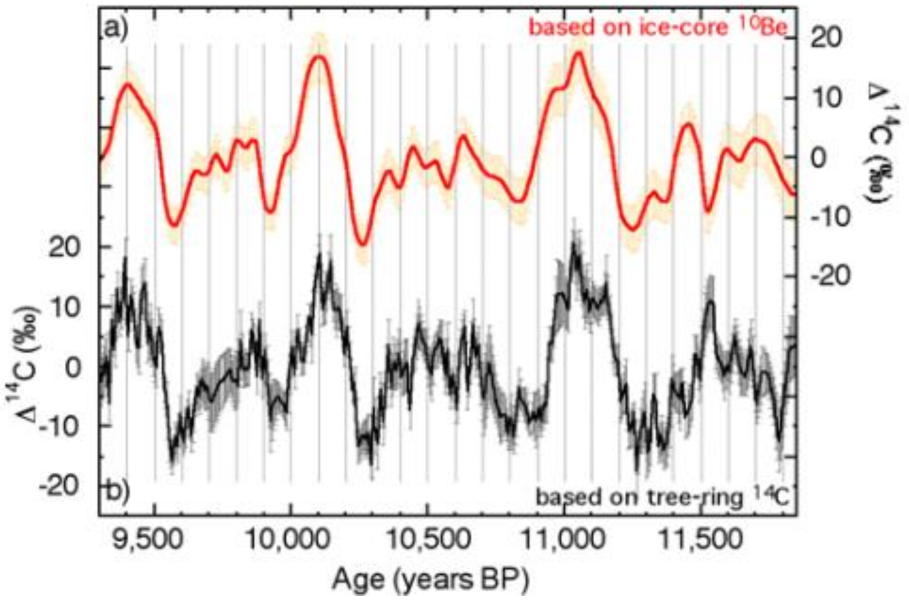
Orbital changes synchronization method is based on tuning of the ice core records to the variations in the insolation. Still, this method is limited due to the phasing between the change in the insolation and the climatic response, that is not constant, resulting in chronological uncertainty of around 5 kyr. Such uncertainty might be improved with using of the properties of the cores that reflect the local insolation directly. Synchronization between records for dating includes synchronization between different ice cores, such as Greenland ice cores with the ones taken from Antarctica, or linking with other types of paleoclimate archives (Gornitz, 2008). Also, combining of the method of synchronization with other ice cores, with the annual layer counting, allows dating with errors that are less than 1 % (Alley, 2000). For example, Antarctica and Greenland ice cores can be synchronized using the ^{10}Be, or CH_4 records, or through the well dated volcanic eruptions as reference horizons (Gornitz, 2008). The methane synchronization, done with usage of the methane variation in the global atmosphere, is extremely important for determining of the relationship between the climate changes occurring in the two hemispheres and the bipolar seesaw pattern explanation (EPICA Community Members, 2006). The volcanic eruptions are marked with high sulfur dioxide concentration, or volcanic debris for the eruptions further in the past. Furthermore, radioactive debris that was deposited in 1955 and 1963-1965 can also be used as a reference horizon (Legrand & Mayewski, 1997). However, even though combination between the annual layer counting and synchronization methods permits adequate dating, the flow of the ice might cause disruption of the layers that are close to the bed. Moreover, the layer thinning in the deeper parts, is related to some sampling limitations and processes of diffusion that make the annual layers undetectable (Alley, 2000).

To add, correlation can be done with using the gas composition of the air bubbles that are trapped in the ice. This method is based on the fact that the air bubbles inside the ice cores, reflect the composition of the global atmosphere at the time when the air was trapped, because the gasses stay in the atmosphere long enough for well mixing. So, bubbles with the same gas composition can be used for correlation of the different ice core records. The limitations of this method, are related to the diffusion of the air in the firn and snow, before the trapping of the bubbles through compression with additional snow. This results in having younger air bubbles than the surrounding ice. Still, such age difference can be calculated, thus allowing overcoming of the limitation and more accurate dating (Alley, 2000). Such computation can be done using firn model. The difference in the high accumulation and high temperature sites has been determined to be a few centuries, while the low accumulation and low temperature sites, such as the Antarctica Plateau, are characterized with difference of several thousands of years. Moreover, the difference becomes bigger under glacial conditions because of the cold temperatures and lower accumulation rate (Gornitz, 2008).

Linking with other archives for dating is necessary in order to determine whether the climate changes imprinted in the records result from regional differences, or the climate oscillations are global and in phase. However, the dating uncertainties make the correlation with other records more complicated. The uncertainties can be overcome with usage of the reference horizons, such as the chemical composition of the ash layers related to the volcanic eruptions, and the ^{10}Be peaks. Linking with the chronologies of the tree rings is possible with using ^{10}Be and ^{14}C records, because of the similar atmospheric processes for production of the two isotopes. Still, it should be taken into account that the global carbon cycle also influences the ^{14}C concentration, and for the synchronization, additional modeling step is necessary. This step includes conversion of the ^{10}Be record from the ice cores into ^{14}C record, and comparison with the ^{14}C record from the tree rings. Such comparison between the records is represented on Figure 38 (Research at Centre for Ice and Climate , n.d.).

Figure 38

Linking of the Ice Core Records with Tree Rings through ^{10}Be and ^{14}C Data



Note. The red curve represents the reconstructed ^{14}C data with using ^{10}Be data from an ice core record, while the black one represents the ^{14}C data from the tree ring record. Such similar pattern allows time linking between the two records. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

In addition to these techniques, sometimes radiometric dating might be used, if the ice core contains enough material for radiometric dating, which is not their common feature (Alley, 2000). The radiometric dating is based on the decay process of radioactive isotopes, into stable daughter isotopes. The possibility for determining of the decay products, with a known decay rate, in closed systems, allows dating of the records (Gornitz, 2008). The radioactive isotopes might be present in the air bubbles (^{86}Kr and ^{14}C), in the aerosols (^{210}Pb, ^{32}Si, ^{10}Be and ^{36}Cl), or in the water (^{3}H). The advantage of the radiometric method is that it allows determination of the absolute age of very old ice. However, the unclear changes of the initial concentrations of the compounds in the past atmosphere, complicate this method. Well radiometric dating might be done with using of ^{10}Be, cosmogenic radioisotope, because it can allow determination of the quantity of snow precipitation (Legrand & Mayewski, 1997).

For overcoming the limitations of some of the explained methods, the usage of inverse methods has been shown useful, and it is based on connecting information from the different dating techniques on one core, for getting an optimal chronology and applying it on other cores (Gornitz, 2008).

Probably, the most precise method for dating, is calculation of the annual thickness at each depth, through ice flow models and snow accumulation, and one of its advantages is that it does not depend on the orbital tuning. The disadvantages are associated with uncertainties related to the weak knowledge of the changes in the accumulation throughout the history, the sliding and melting of the ice sheets and other basal states, and the rheological conditions that are related to the flow (Gornitz, 2008). Still, this method is very useful for locations where knowledge about the accumulation rate, the topography of the bedrock and surface of the ice sheet, and the horizontal surface velocity, exists. Using these values, numerical models can be designed, with an establishment of a time-scale, through a relationship between the depth of the core and the age, as their main objective. An important aspect is that the counting of the annual layers allows precise dating in the upper parts. However, due to the fact that the annual layers are thinning out with the depth, and that their determination and counting at a particular depth becomes impossible, these models need to allow precise dating in the deeper parts (Research at Centre for Ice and Climate , n.d.). Andersen et al., (2006) believe that the relationship between the age and the depth in the ice cores, is simpler and better understood compared to other paleoclimate records. They state that the accumulation rate, that is necessary for establishing such relation between the depth and the age, is different in Antarctica and Greenland. In particular, the accumulation rate in Antarctica has been determined to be a few centimeters of ice equivalent per year, while in Greenland it has been determined to be more than half a meter of ice equivalent per year. Also, Andersen et al., (2006) explain that due to the higher temporal resolution of the Greenland ice cores compared to the ones from Antarctica, the dating is more accurate (Andersen, et al., 2006).

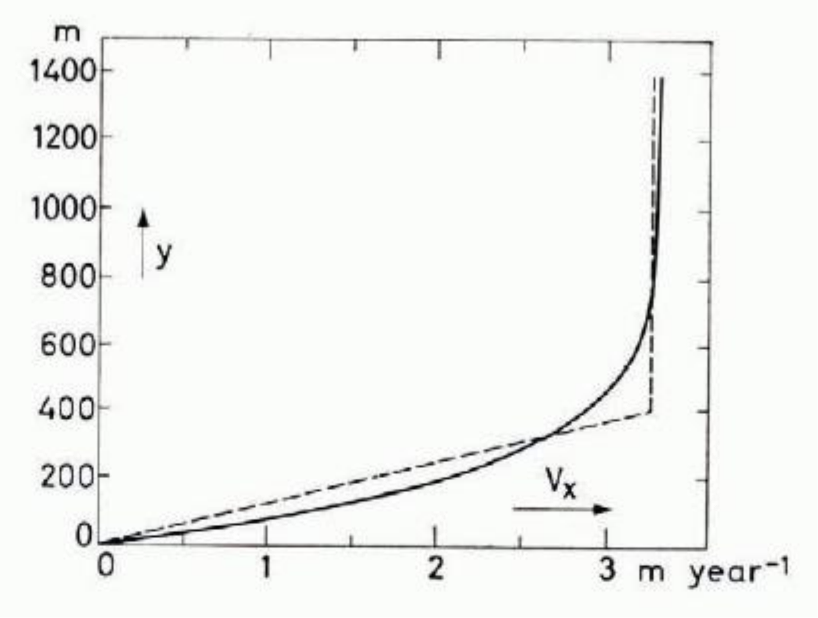
Flow models are used for establishing a relationship between the depth of the core and the age, in the deeper parts of the ice cores. Dansgaard & Johansen (1969) explain that a flow model is necessary for a time-scale establishment, due to the uncertainties related to the dating with usage of the seasonal variations of the isotopic composition and their diffusion, the radiometric dating with ^{3}H and ^{210}Pb that goes only to 100 years back in the time, or the ^{14}C and ^{32}Si radiometric dating, that requires big amounts, even several tons of ice (Dansgaard & Johansen, 1969).

For an ice sheet in a steady state, the relationship between the age and the depth, can be calculated from the balance between the processes of snow accumulation, and ice layer thinning, as a result of the flow velocity horizontal gradients. The simplest flow model for determining of the timescale, is the Nye's model. It uses constant value of the vertical strain rate, that is calculated as a ratio between the accumulation rate and the ice thickness. The constant value implies that the thinning appears as a result of the sliding velocity gradients at the bed, while the vertical column during the deformation remains vertical. On the other side, a slightly more complicated model, the Dansgaard-Johansen model, suggests that more precise results can be obtained if it is assumed that below a certain height above the bed, there is a linear decrease of the vertical strain rate, down to zero (Fahnestock, Abdalati, Joughin, Brozena, & Gogineni, 2001). So, this flow model is based on the assumption that the ice horizontal velocity is constant to a certain depth, and deeper from that point, the horizontal velocity decreases linearly with the depth (Dansgaard & Johansen, 1969). If there is no basal sliding, the two models are equivalent. Still, the Dansgaard-Johnsen model is considered to be more correct, and in that model the increase of the age with the depth near the surface, is faster than in the Nye's model, with the older ice being higher in the column. Where these models do not provide good enough results, some modifications are used. For example, a modification to the Nye's model can include melting of the basal ice (Fahnestock, Abdalati, Joughin, Brozena, & Gogineni, 2001).

The profile of the horizontal velocity in the Dansgaard-Johnsen model is represented on Figure 39 (Dansgaard & Johansen, 1969).

Figure 39

Change of the Horizontal Velocity as a Function of the Depth of the Ice Core in the Dansgaard-Johansen Model



Note. Reprinted from "A flow model and a time-scale for the ice core from Camp Century, Greenland", by W. Dansgaard & S. J. Johnsen, 1969, *Journal of Glaciology, Vol. 8, No. 53*, (p. 216).

The flow models usually rely on the reference horizons from volcanic eruptions and determine the accumulation rate through the seasonal changes in the isotopic composition of water molecules. However, due to the diffusion processes related to the water molecules, more precise dating can be obtained with usage of trace elements (Massam, et al., 2017). Precise detection of the annual layers in the deeper parts of the ice core records, characterized with substantial thinning of the layers, can be obtained with measuring of the seasonal variations of the deposited impurities with high-resolution methods. For example, in Greenland, the peak in sodium concentration has been found to be in late winter, the peak in calcium concentration has been found in spring, the sulfate, nitrate and ammonium ions peaks have been found to be in summer, etc. In addition, changes in the physical properties of the ice and the visible stratigraphy can also be used for revealing of the annual layers (Andersen, et al., 2006).

In conclusion, dating of the ice core records with less uncertainties, is necessary for the analysis of the climate changes in the past, especially the abrupt ones, and to determine their spatial extent through synchronization with other archives. The above described methods are used for dating with less errors, that is the first required step in the glaciochemical studies (Legrand & Mayewski, 1997).

6.3 - Ice core proxy records

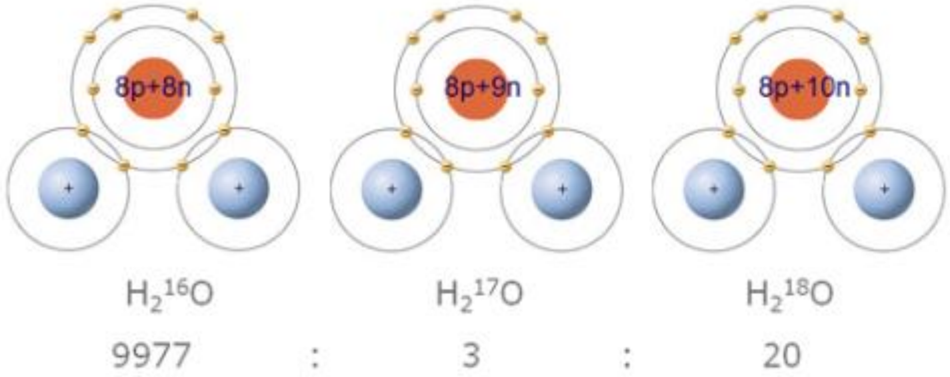
6.3.1 - Reconstructing past temperatures

The ice is built up from molecules of water, and the water molecules can have different mass, that is determined by the isotopic composition of the molecules. The isotopic composition of molecules trapped in the ice depends on climate conditions at the time of ice formation. The climate conditions might affect the processes of evaporation, transportation of the water vapor and precipitation (Research at Centre for Ice and Climate , n.d.).

The molecules of water contain two hydrogen atoms and one oxygen atom, and most commonly present isotopes are ^{1}H, that contains only one proton and no neutrons, and ^{16}O, that contains eight protons and eight neutrons. However, sometimes other isotopes might be included in the molecule of water, such as ^{2}H and ^{3}H, that have one and two neutrons in addition to the one proton respectively, and ^{17}O and ^{18}O, that have nine and ten neutrons respectively. The water molecules can be built up from different combinations of the isotopes, and the molecules have different abundance in the nature. Figure 40 shows the three water molecules that contain different oxygen isotopes and the ratio of their abundances in nature (Research at Centre for Ice and Climate , n.d.).

Figure 40

Three Water Molecules that Differ by the Oxygen Isotopes



Note. For every 10000 water molecules present in the nature, only three of them contain oxygen with nine neutrons, and twenty of them contain oxygen with ten neutrons. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

In the ice cores, the most often used water molecules for interpretation of the climate, are the ones that contain the commonly present ^{1}H and ^{16}O, and the ones that contain ^{2}H and ^{18}O (Research at Centre for Ice and Climate , n.d.). In particular, there is some percent of isotopically heavy molecules of water, and the heavy water is characterized with lower vapor pressure (Alley, 2000). The presence of the water molecules with ^{2}H and ^{18}O in the ice, depends on the temperature at the time of the formation, and because of that, they are used as temperature proxies. The relative amount of the ^{2}H and ^{18}O are represented with the $\delta^{18}O$ and δD values, usually negative values expressed in per mille. The calculation of the $\delta^{18}O$ value is represented with equation 1 (Research at Centre for Ice and Climate , n.d.).

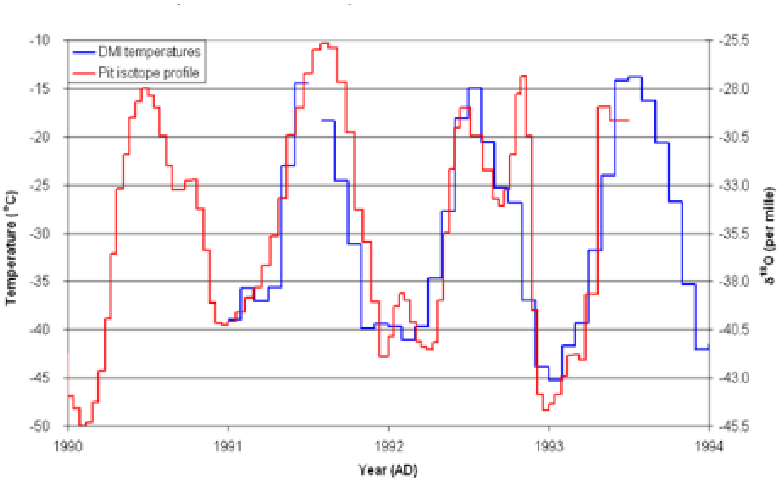
$$\delta^{18}O(‰) = \left[\frac{\left(\frac{O^{18}}{O^{16}}\right)sample - \left(\frac{O^{18}}{O^{16}}\right)standard}{\left(\frac{O^{18}}{O^{16}}\right)standard}\right] * 10^{3} \qquad (1)$$

The isotopic composition is determined in relation to a standard (Gornitz, 2008). The $\delta^{18}O$ of the ice cores, usually varies in the interval (-80-0) ‰, while δD varies in the interval (-600-0) ‰. The isotopic analysis of the ice cores, allows obtaining information about the temperature for the last 100000 years, and even further in the past. The measurements have shown that one per mille of $\delta^{18}O$ and eight per mille of the δD, are equivalent to a temperature difference of 1.5-4 °C (Research at Centre for Ice and Climate , n.d.). That is why the ice cores are also called paleothermometers (Alley, 2000). The isotopic composition can be used as a proxy for the temperature, due to the fact explained by simple physical laws (Clausius-Clapeyron law), that the highest moisture amount that a parcel of air can hold, decreases with the temperature drop. Also, the heavier isotopes have bigger tendency for condensation and precipitation, and evaporate more slowly due to their weight. Thus, the humid air masses will be depleted in water molecules that contain heavier isotopes with precipitation, in comparison to the ocean water, or a fractionation will occur (Research at Centre for Ice and Climate , n.d.). Fractionation usually occurs in the atmosphere, when the water vapor is transported from ocean to continents, from low to high latitudes, and from low to high elevation, as a consequence of successive stages of condensation and evaporation (Gornitz, 2008). So, at the time of cold periods, the air masses that bring moisture towards the ice sheets, would have cooled more on their way, this resulting in more precipitation along their route, preferentially of the heavy water molecules, and causing the remaining water vapor to contain more light isotope water molecules, and be depleted in the heavy ones (Research at Centre for Ice and Climate , n.d.). Hence, in the next condensation stage, where the ice sheets are located, the precipitation will be depleted in ^{18}O (Gornitz, 2008). This is related to lower $\delta^{18}O$ and δD values measured in the ice cores, due to the isotopically lighter precipitation (Research at Centre for Ice and Climate , n.d.; Alley, 2000).

Even though the physical relationship between the two parameters $\delta^{18}O$ and δD, is not simple, their values show strong correspondence in the change as a function of the temperature (Research at Centre for Ice and Climate , n.d.). In addition to the temperature, the paleothermometer can be influenced by other glaciological and atmospheric factors, but the existing methods for calibration, should make possible the correct interpretation of the temperatures (Alley, 2000). Moreover, the isotopic composition of the ice, especially the deuterium excess (difference between δD and 8* δ^{18}O), can be used for providing information about the climate conditions in the area of the moisture source. To add, isotope data can also be used for dating of the ice core records, because the δ^{18}O and δD values have annual cycles, due to the seasonal temperature change, and therefore can be used for counting of the annual layers. A representation of such yearly cycle of the δ^{18}O value is shown on Figure 41 (Research at Centre for Ice and Climate , n.d.).

Figure 41

Annual δ^{18}O Cycle in Greenland Ice Core as a Result of the Seasonal Temperature Change that can be used for Dating of the Records



Note. The red curve represents the change of the δ^{18}O isotope values, while the blue curve represents the temperature changes. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/.

It is important to mention that this method for dating of the ice cores, can be limited with the decreased thickness of the layers in the deeper parts of the ice cores, that on the other side depends on the accumulation rate. Furthermore, diffusion of the isotopes from the older ice layers, can cause weakening of the annual signal and less precise dating (Research at Centre for Ice and Climate , n.d.).

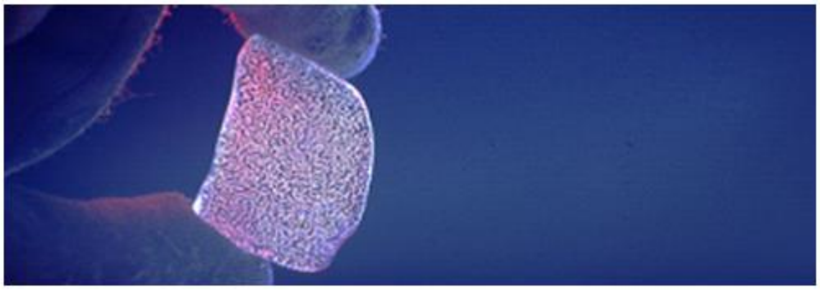
In addition to the isotopic composition of the ice, the temperature changes, especially the abrupt ones, can be determined with analysis of the isotopic composition of the Ar and N_2 in the air bubbles that are trapped in the ice (Gornitz, 2008). The advantage of these proxies compared to the δ^{18}O and δD records, is that they allow determination of temperature fluctuations over smaller time-scales, decadal or centennial. The isotopic ratios that are being measured are $^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$, and these ratios are being constant in the atmosphere for more than 100000 years. Changes in the isotopic composition in the ice cores, occur due to firn layer processes. Such processes are the isotopic separations with gravitational and thermal fractionations, as a result of the thickness of the firn layer and the temperature gradient between the upper and bottom layers of the firn, respectively. Because the separation is with known amount, measuring of the two isotopic ratios makes possible the isolation of the two effects, and determination of the thickness of the firn and the temperature gradient. From the obtained result about the temperature gradient, the surface temperature can be calculated, with using the values of accumulation rate and a firn-densification/heat diffusion model. In that way, a decadal average temperature can be obtained, without seasonal bias, and without need for calibration to instrumental records. The temporal resolution of such record is decadal to centennial (Kobashi, et al., 2010). The study of the isotopic ratios of Ar and N_2 has shown an initial positive correlation of $\delta^{15}N$ and $\delta^{40}Ar$ values with the temperature, typically followed by a decrease of the gradient and a final stabilization. In addition, the rise in temperatures also leads to firn layer thinning, causing a reduction of the isotopic fractionation due to gravitational settling (Kobashi, Severinghaus, & Kawamura, Argon and nitrogen isotopes of trapped air in the GISP2 ice core during the Holocene epoch (0–11,500 B.P.): Methodology and implications for gas loss processes, 2008).

6.3.2 - Reconstruction of the past atmospheric composition

One of the most useful information that can be obtained with the analysis of the ice cores, is the composition of the atmospheric gasses trapped in air bubbles (Alley, 2000). Indeed, during the process of ice formation, small amounts of air are being caught in ice cavities (Research at Centre for Ice and Climate , n.d.). This happens in the firn zone, at a density of 800 kg m^{-3}. Afterwards, when the firn is further compressed and the ice is created, air bubbles that contain atmospheric air, are being formed. This occurs at a close-off depth at which all pores become closed and firn transforms to bubbly ice. (Legrand & Mayewski, 1997). Figure 42 shows how the gas bubbles trapped in the ice look like (Research at Centre for Ice and Climate , n.d.).

Figure 42

Air Bubbles in the Ice Cores



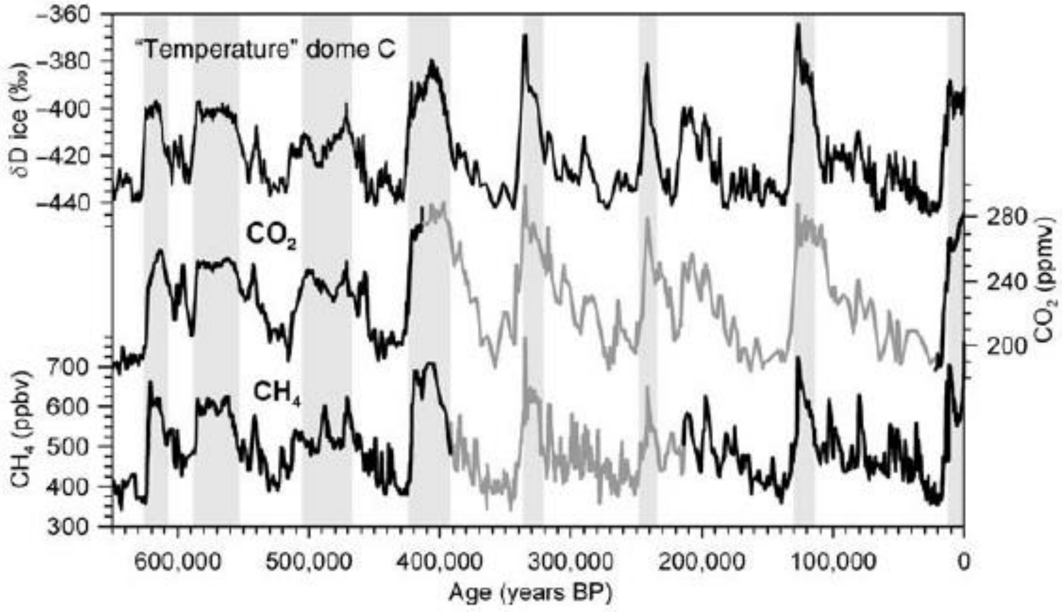
Note. Reprinted from *Research at the Center for Ice and Climate,* http://www.iceandclimate.nbi.ku.dk/research/flowofice/

However, diffusion plays an important role, particularly in the first tens of meters from the surface, leading to a delta age issue that results in younger gas bubbles than the surrounding ice. Nevertheless, the age difference can be estimated with models, fundamental for data interpretation (Alley, 2000), always bearing in mind that delta age might significantly vary from few decades for high accumulation sites, to five millennia or more, in presence of lower accumulation rates. Thus, only a specific age distribution can be prescribed, depending on the accumulation rate and temperature. This further causes lower temporal resolution of the greenhouse gas records, that is approximately a few years for the areas characterized with high accumulation, and more than a century for the low accumulation places (Gornitz, 2008).

The potential of this kind of analysis, typically applied to CH_4, CO_2, N_2O, O_2/N_2 as well as to trace gases, lies in the possibility of investigating the past atmospheric composition of hundreds of thousands of years back in time. This allows possible correlations between the change in the concentration of the greenhouse gases and variation of other climatic conditions in the past. Even though usually the concentrations of the CH_4 and CO_2 are the same all over the globe because of the quick mixing of the atmosphere, there are some differences originating from the diverse source distribution (Gornitz, 2008). In these terms, for instance the methane analysis, gives an indication of the global wetland distribution, due to the short residence time of the gas in the atmosphere. The bigger concentrations found at some periods in the past in Greenland than in the Antarctica ice cores, suggests that the most of the methane sources were located in the Northern Hemisphere. Hence, the changes in the source distribution over the history can be studied with this method (Alley, 2000). The analysis of the gasses in the bubbles requires first their extraction, without contamination, for what different analytical methods can be applied. Figure 43 represents the determined concentrations of the CH_4 and CO_2 with analysis of the air bubbles, in comparison with the δD temperature record from Antarctica, for the last 650000 years. the Figure shows that in that period, the concentrations of the greenhouse gasses were never as high as today (Gornitz, 2008).

Figure 43

Comparison Between the CH_4 and CO_2 Concentrations with the δD Record for the Last 650000 Years



Note. CH_4 record is expressed in ppbv, CO_2 record is expressed in ppmv and δD record is expressed in per mille. Reprinted from *Encyclopedia of Paleoclimatology and Ancient Environments*, (p. 119), by V. Gornitz, 2008, Springer.

Figure 43 clearly shows that the greenhouse gas concentration is closely correlated to the δD record that represents the temperature variations (Gornitz, 2008). Such correlation is a result of the positive feedback mechanisms of the greenhouse gasses. For instance, a small warming due to increased insolation related to the orbital factors, leads to the release of greenhouse gasses from oceans and continents, enhancing further the increase of temperatures due to the greenhouse effect. An important indication is that the variation in the CH_4 concentration can be associated to changes in Greenland temperature records, while the CO_2 variation can be more related to the climatic changes over Antarctica. Taking into account the distribution of land and oceans in the two hemispheres, it can be concluded that the probable reasons for such indications are the mainly continental responses of CH_4 and the coupling to the Northern Hemisphere climate changes. On the other side, there is a coupling of the CO_2 with the climate signal in the Southern Hemisphere, strongly influenced by the ocean (Research at Centre for Ice and Climate , n.d.).

6.3.3 - Impurities in the ice cores

The impurities in the ice cores can be used as indicators of the past climatic conditions. Despite their typical low concentrations due to transport and precipitation processes, they can still be detected and analyzed as past climate proxies. Such impurities are dust particles, Na^+ and Cl^- ions that provide information about the past ocean activity and the presence of sea ice, NH_4^+ ion which is an indicator of fires and biomass burning, volcanic ash and acids, and the indicators of human pollution such as SO_4^{2-}, NO_3^- and Pb (Research at Centre for Ice and Climate , n.d.).

6.3.3.1 - Dust in the ice cores

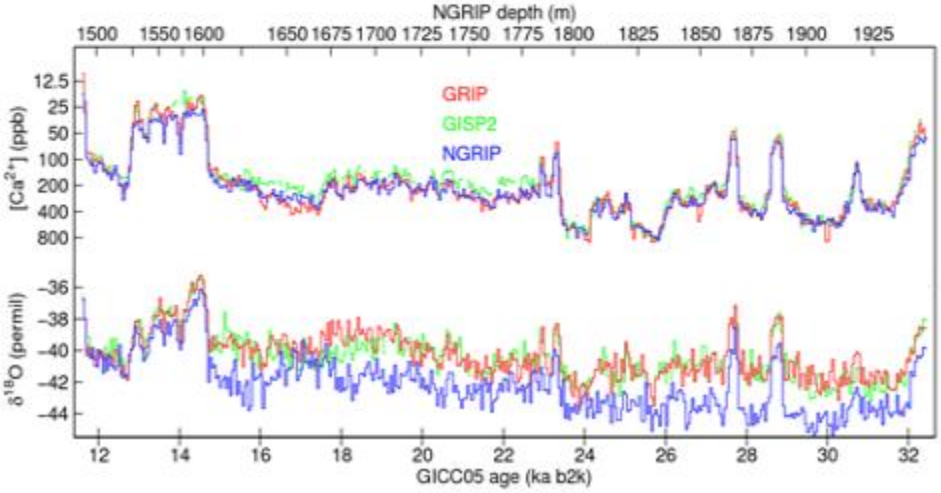
Greenland and Antarctica Ice Sheets represent important dust deposition archive (Vallelonga & Svensson, 2014). The dust in the ice cores originates from arid and semiarid regions, and it is transported with the wind (Research at Centre for Ice and Climate , n.d.). So, in order to understand the change in the pattern of the atmospheric circulation during the history, the aeolian dust flux analysis is of crucial importance. The ice cores represent a perfect archive for the dust analysis, due to their simple and clean water matrix, the possibility for precise dating and the good temporal resolution (Ruth, et al., 2008). According to this, dust can be considered as a significant tracer of the atmospheric circulation in the past (Anderse, Armengaud, & Genthon, 1998). The study of the dust composition can also lead to determination of its origin, that in several cases has been identified with Asia. An important indication is the fact that bigger amount of dust is transported to the ice sheets during glacial periods, compared to the interglacial. However, its composition was shown to be the same in the different phases, indicating that the probably the sources were not varying greatly, and the strength of the winds was the feature that was changing the most. According to this, the glacial periods were characterized not only with low temperatures, but also with stronger winds (Research at Centre for Ice and Climate , n.d.). Vallelonga and Svensson (2014), indicate that in Antarctica the dust flux dropped even by 25 times, with the transition from glacial to interglacial periods. In Greenland, the biggest dust flux happened during the MIS 2 and MIS 4. The maxima in the dust levels, were similar to the ones observed during the Last Glacial Maximum, with concentrations that were 80-100 times larger than the modern values, or other interglacial phases. According to this, there is a strong variability of the dust levels in Greenland. Vallelonga and Svensson (2014) suggest that the reasons for this might lie in the variations in the extent and productivity of the dust sources. Moreover, the changes in the processes scavenging by precipitation, that depend on the climate and the variations in the temperature gradient and strength of the winds, can cause the variability as well. Finally, the precipitation quantity in Greenland, affects the concentration of the dust in the ice sheets, making the concentration to differ even by factor of two, between colder and milder phases (Vallelonga & Svensson, 2014).

Most often, the concentration of the Ca^{2+} ions are used as a measure of the dust content, while the Nd and Sr isotopes are used for the sources identification (Research at Centre for Ice and Climate , n.d.). For example, Nd and Sr isotopes indicate that the deserts Gobi and Taklamakan, from central Asia, are the predominant source of dust in Greenland. On the other side, the main sources of dust in the Antarctica Ice Sheet, are found to be the loesses and the glacial outwash plains from South America and Australia, and some local deflation zones from Antarctica (Vallelonga & Svensson, 2014). Other used proxies for the analysis of the dust and its content in the ice cores are the concentration of insoluble particles, their mass and concentrations of Sr and Nd (Research at Centre for Ice and Climate , n.d.). Also, the insoluble particles, their mass and concentrations of Al, Fe, V, Si, can be used as well (Ruth, et al., 2008). Often, the seasonal variations of ions indicative of dust, such as Al^{3+}, Ca^{2+} and Fe^{2+} are measured, and used in determining of the annual layers, their counting and dating of the ice core records. The peaks of these ions are observed to be in spring (Della Lunga, Müller, Rasmussen, Svensson, & Vallelonga, 2017). The diameter of the dust particles has been found to be in the interval 1-10 µm, if the dust is transported from further sources, and the particles remain on their layers of deposition without diffusion during the processes of firnification and ice compaction (Della Lunga, Development and Application of Cryo-Cell –UV-Laser Ablation Mass Spectrometry (UV-LA-ICPMS) to Greenland Ice Cores: Implications for Abrupt Climate Change and Ice Physics, 2015). Such small-size particles are a characteristic of the Antarctica ice sheet, with the average size of 1-2 µm, while in cold periods such as the Last Glacial Maximum, the size increases. The small size shows that the sources of the Antarctica dust are very distant (Vallelonga & Svensson, 2014). This results in visual stratigraphy in the ice cores, that can be seen as dark and bright layers, associated to low and high dust particle concentration areas, respectively. The bright layers, that have particles with smaller diameter than the dark ones, are known as cloudy bands. Such layering can be seen to great depths of the ice cores, even down to 2800 m at NGRIP ice core record. Areas with higher concentration of particles that are observed as bright layers, are representing the stormy spring and summer periods. According to this, these layers can also be used for determining the annual layers and dating of the ice core records. Furthermore, higher particle concentration, seen as higher density of the layers that are bright in the ice core records, also represents the cold glacial periods (Della Lunga, Development and Application of Cryo-Cell –UV-Laser Ablation Mass Spectrometry (UV-LA-ICPMS) to Greenland Ice Cores: Implications for Abrupt Climate Change and Ice Physics, 2015). Interestingly, the presence of dust in the ice sheets, plays a role in the crystal structure of the ice, the processes of densification and ice formation, and the glacial dynamics, and hence, the impurities like the dust, should be taken into account in the flow models. Furthermore, it can also influence the albedo (Vallelonga & Svensson, 2014).

Figure 44 represents the variation in the concentration of Ca^{2+}, as an indicator of the dust content in the Greenland ice core record, and the $\delta^{18}O$ record, in the interval 32-12 kyr before present (Research at Centre for Ice and Climate , n.d.).

Figure 44

Variation in the Ca^{2+} Concentration and the $\delta^{18}O$ Record in the Greenland Ice Core in the Period 32-12 kyr BP



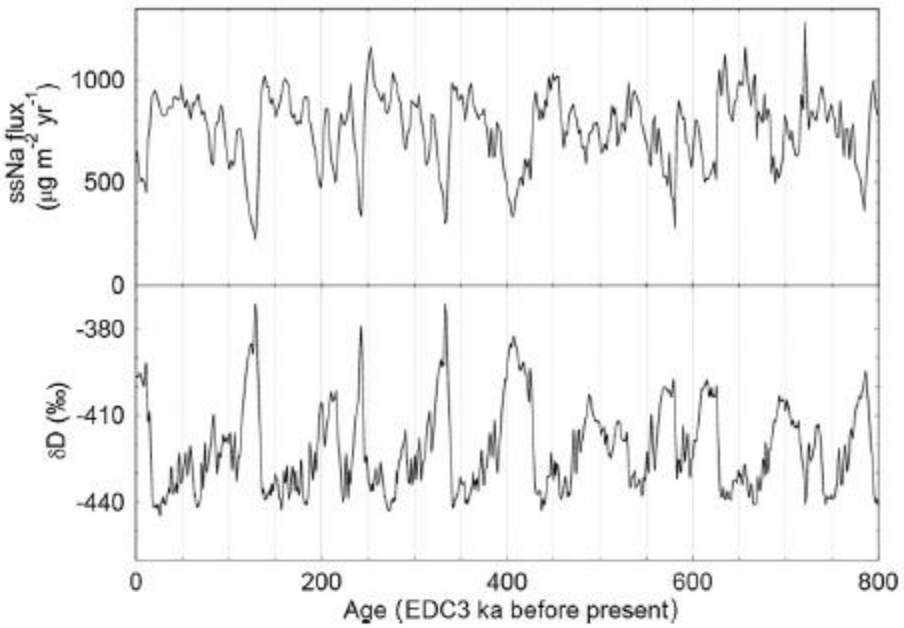
Note. The scale of the concentration of calcium ions is logarithmic and it is upside down. It can be seen that there is a good correspondence between the change in the temperature represented with the $\delta^{18}O$ record and the dust content. Reprinted from "Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimatic implications" by S. O. Rasmussen, 2008, *Quaternary Science Reviews 27,* (p. 24).

6.3.3.2 - Sea salt in the ice cores

The sea salt aerosols are formed with bubble bursting and sea spray over the open ocean, with coarser aerosol particles deposited nearby, and smaller aerosols transported towards the continents. Deposition also occurs over the ice sheets, and sea salt can be determined in ice core records through measurement of the Na^+ and Cl^- ion concentration. The most reliable marker is the Na^+, because Cl^- can undergo fractionation as a result of the reaction with acids and production of HCl. However, an additional factor is found to be the sea ice, that further increases the distance from the water source, leading to bigger loss during the transport. Therefore, the amount of the sea salt can be used as a proxy of the sea ice cover and typically shows peaks in winter season and during glacial phases (Abram, Wolff, & Curran, 2013). Thus, the salty snow lofted from the sea ice surface, represents one of the major sources of sea salt found in ice cores. This is further confirmed by the reduced ratio between sulfate anions and sodium cations in winter in the ice cores, compared to the ocean water, that on the other side matches the same reduced ratio in frost flowers from the sea ice. The larger sea ice extent in colder periods, and its surface covered with salty snow, relates with the findings of the bigger sea salt concentrations in winter in the ice core records (Rhodes, Yang, Wolff, McConnell, & Frey, 2017). Also, the difference in the sea ice extend in summer and winter can be associated to the seasonal variations found in the ice core records. Na^+, Cl^- and sea salt Mg^{2+}, indicative of the sea salt, are found to show maxima in winter, cold stadial periods and glacial phases, due to the increased storminess over the ocean, and the formation of the saline brine and fragile frost flowers, that represent additional sources of aerosols (Della Lunga, Müller, Rasmussen, Svensson, & Vallelonga, 2017). The interannual variability is determined with the atmospheric transport and deposition, that increases drastically during glacial compared to interglacial periods, due to the increased sea ice cover over the oceans and dry conditions (Erhardt, et al., Decadal-scale progression of the onset of Dansgaard–Oeschger warming events, 2019). Figure 45 represents the flux of Na^+ ions in Antarctica ice core records over the last 800 kyr, in comparison with the δD record of local temperature. It clearly represents the increased see salt concentration during cold periods (Abram, Wolff, & Curran, 2013).

Figure 45

Comparison Between the Sea Salt Flux and the δD Temperature Record in Antarctica Ice Cores Over the Last 800 kyr



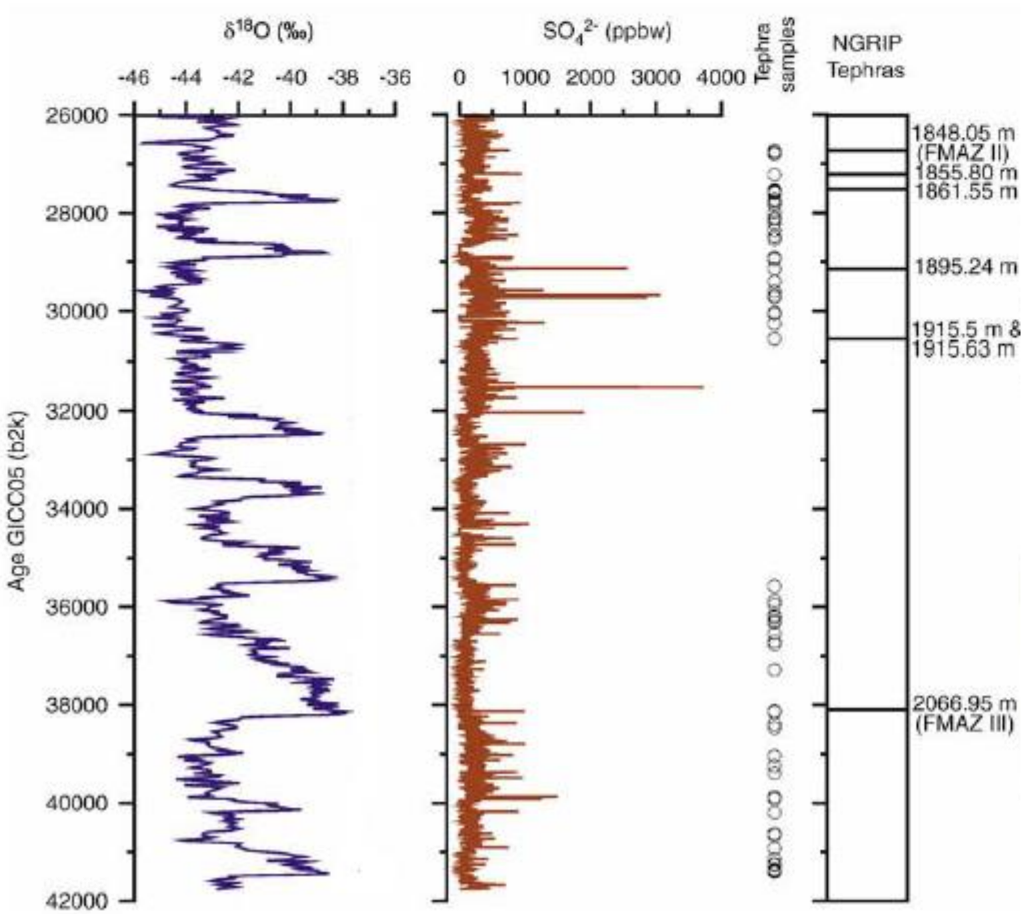
Note. The flux of the sea salt Na^+ ions is expressed in µg m^{-2} y^{-1}, while the δD record is expressed in per mille. Reprinted from "A review of sea ice proxy information from polar ice cores" by N. J. Abram, 2013, *Quaternary Science Reviews 79*, (p. 173).

6.3.3.3 - Impurities in the ice cores of volcanic origin

The ice cores are one of the best paleoclimate archives for studying the past volcanism, due to the possibility to develop continuous time series for long periods during the past, and the good temporal resolution. Furthermore, the ice core records allow measuring of both, the aerosol and the silicate component (tephra) linked to the volcanic eruptions, while other records only provide information on the climatic effect of the eruptions (Zielinski, et al., 1997). The most commonly used indicators of the volcanic eruptions in the ice cores, are the volcanic ash particles and the concentrations of acids, usually the SO_4^{2-} and F^- (Research at Centre for Ice and Climate , n.d.). The overall acidity of the sample can be measured, or more correctly, through the concentration of the anions such as SO_4^{2-}, only the acidity increase due to volcanic eruptions can be determined. However, some complications might result from the sulfates originating from biogenic production, as well as from sea salt and continental salts. Moreover, the analysis of tephra and aerosols trapped in ice cores can pinpoint the source volcano. The match is done through the chemical features of the volcanic glass that originates from an eruption, and is found in the ice cores. Therefore, associating the signal with a particular eruption becomes crucial in the ice cores dating process, particularly for the precise link detection between the age and the depth of the core, which also provides reference horizons for correlations with other archives (Zielinski, et al., 1997). Figure 46 displays such tephrochronology framework obtained with analysis of the Greenland Ice Core with sulfate records from the same core, and the $\delta^{18}O$ variations (Davies, et al., 2010).

Figure 46

Tephrochronology Framework, $\delta^{18}O$ and SO_4^{2-} Record of the Greenland Ice Core



Note. Reprinted from "Tracing volcanic events in the NGRIP ice-core and synchronising North Atlantic marine records during the last glacial period" by S. M. Davies, 2010, *Earth and Planetary Science Letters 294,* (p. 71).

An interesting aspect, is that Ca^{2+} also represents an indicator of the volcanic eruptions in addition to the dust and the sea salt aerosols, but indirect one, because it can react with the SO_4^{2-} ions and form gypsum. So, it can also be used for determining the tephra horizons (Davies, et al., 2010). More noticeable are the imprints of the volcanic eruptions that occurred close to the ice sheets, but indications of volcanic eruptions happening in the tropics, or even in the other hemisphere can be identified as well. Indeed, the volcanic eruptions affect the global climate, most often through the release of high amounts of aerosol particles in the stratosphere, causing reflection of the incoming solar radiation, that results in global cooling (Research at Centre for Ice and Climate , n.d.). The main volcanic gas that is released with the eruptions is SO_2, and its oxidation occurs in the atmosphere, resulting in formation of sulfuric acid aerosol particles. These are the aerosols that are responsible for the sunlight reflection, after their spreading in the stratosphere with atmospheric circulation, and they can remain there even for several years. The decrease of the temperatures that is related to these aerosol particles is very abrupt. For instance, Cole-Dai et al., (1997) state that the Pinatubo volcanic eruption led to decrease of 0.2-0.7 °C of the global temperatures. The sulfuric acid aerosols in the atmosphere, are then preserved in the ice core records, through the H_2SO_4 and SO_4^{2-} signals (Cole-Dai, Mosley-Thompson, & Thompson, 1997). The relation between the volcanic eruptions recorded in the ice cores, and the subsequent cooling due to the sunlight reflection effect, can be also seen in Figure 46 (Davies, et al., 2010).

6.3.3.4 - Other impurities that can be found in the ice cores

In addition to the represented impurities, others that can represent important indicators of the climate conditions, can be found as well. The oxidation capacity of the atmosphere, can be analyzed through the concentrations of species such as the hydroxyl radical, hydrogen peroxide and formaldehyde in the ice cores. The performed analysis shows that the oxidative capacity of the atmosphere, has also been changing in the past (Bales & Wolff, 1995). Furthermore, ammonium cation can be used as a proxy for biomass burning and soil and vegetation emissions, with a well-defined concentration increase during summer. So, its measurement may be used for analysis of the past fires. In addition, the analysis of the impurities induced by anthropogenic sources has become very important in recent years, due to their substantial increase. For instance, there is noticeable increase of the amount of sulfuric acid, as a result of the fossil fuels burning. Furthermore, an increase in lead concentration has been recorded during the Roman empire and particularly in recent epoch due to its usage as an anti-knocking agent. To add, nitrate concentrations have also been observed to increase, due to the nitrous oxides production in the vehicle engines (Research at Centre for Ice and Climate , n.d.). Increased presence of SO_4^{2+}, NO_3^- and NH_4^+ are found during summer (Andersen, et al., 2006).

7. EVIDENCE OF THE ABRUPT CLIMATE CHANGE EVENTS IN THE ICE CORE RECORDS

The exceptional attributes of the ice core records, such as the outstanding resolution, precise dating and the numerus proxy values, are expected to allow preservation of valuable evidence of the abrupt climate change events that happened during the Last Glacial Period. The ice core records should provide clear answers about the time-scale of the events and the patterns of change of the proxy values that mark them. The key question regarding the time-scale of the events, is related to the required resolution of an analytical technique, in order to be capable to reveal such fast-occurring changes. In an effort to make the two assumptions, that refer to the necessary resolution for analysis, and the patterns of change of the proxy values, the Dansgaard-Oeschger event 8 and the NGRIP (North Greenland Ice Core Project) will be taken as an example.

NGRIP ice core has been selected due to the precise chronology, obtained with counting annual layers in the upper part, and using flow models for the deeper part, that is characterized with annual layer thinning. One such model that is used for obtaining the time-scale, is the ss09sea model, used in the study by Svensson et al., (2006) and Andersen et al., (2006), originally constructed for the GRIP ice core, and based on the $\delta^{18}O$ changes.

The Dansgaard-Oeschger event 8 occurred 38176 kyr before present, and the corresponding depth to the beginning of the onset in the NGRIP ice core is 2070.14 m. The onset of this event lasted 21 years. In order to determine the thickness of the layers at the time of the event, the Nye's model for thinning will be used. The model can be represented with the equation 2:

$$y = A\,(1 - \frac{z}{H}) \qquad (2)$$

where y is the thickness of the layer, z is the depth in the ice core, A is the surface accumulation rate and H is the thickness of the ice (Dansgaard & Johansen, 1969).

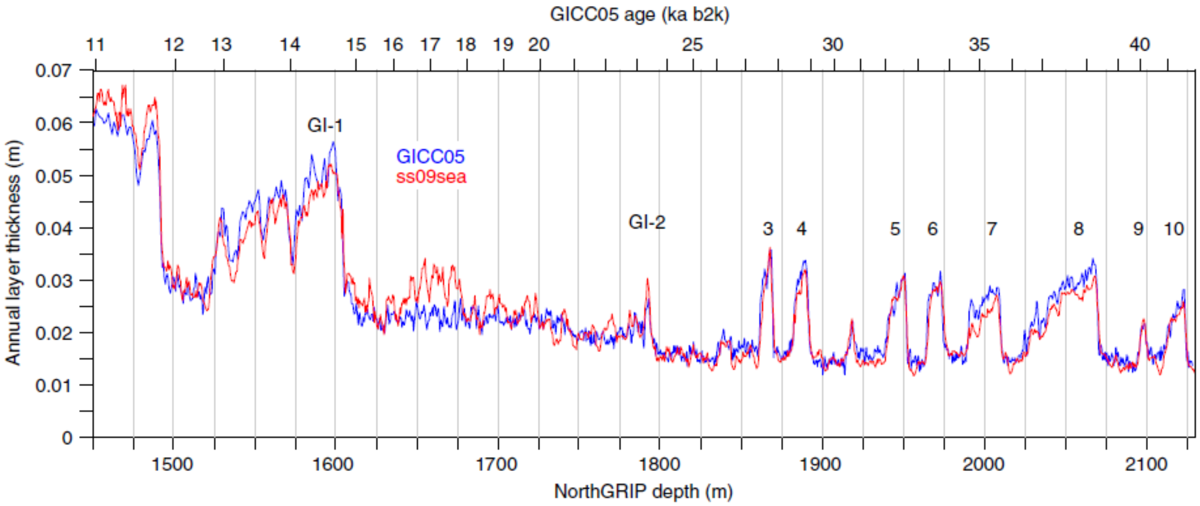
Andersen et al., (2006) give the values of the surface snow accumulation A for the NGRIP core, that is 19 cm y^{-1}, and the thickness of the NGRIP core H, and it is 3085 m. For the calculation of the annual layer thickness at the surface of the core, z is 0, while for the annual layers that correspond to the Dansgaard-Oeschger event 8, the depth is 2070.14 m. Using of the Nye's model, we obtain values for the annual layer thickness at the surface of 19 cm, and at a depth of 2070.14 m, thickness of 6.25 cm. So, the change in the annual layer thickness from the surface to the depth that corresponds to the Dansgaard-Oeschger event 8, is 12.85 cm. The changes in temperature that are observed during the onset of the Dansgaard-Oeschger events are very abrupt, and they occur within a few decades. For the Dansgaard-Oeschger event 8 in particular, such changes happen during an onset that lasts only 21 years.

However, the Nye's model is very simple and it is based on many assumptions, therefore does not provide precise information for the thinning of the layers. Here, it has been used to simply represent the large change in the thicknesses of the annual layers from the top of the ice core, related to the compression with the new accumulated snow.

In particular, the ss09sea model for layer thinning represented in Figure 47 from the study by Svensson et al., (2006) provides a different value of the annual layer thickness, that is approximately 1.5 cm during the stadial, and 3 cm during the interstadial phase of the Dansgaard-Oeschger event 8.

Figure 47

Annual Layer Thickness of the NGRIP Ice Core: Comparison Between the ss09sea model and the GICC05 time-scales



Note. Reprinted from "The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records" by A. Svensson, 2006, *Quaternary Science Reviews 25*, (p. 3261).

There are ice cores that are characterized with lower accumulation rates than the NGRIP core, and with even bigger thinning of the layers due to higher compression, such as the ones obtained from the Antarctica Ice Sheet. In these ice cores, annual layers with thickness of only 1 mm are often observed.

Therefore, in order to capture the significant variations, even at sub-annual scale, that typically characterize any abrupt climate change event, a high-resolution technique is required. This kind of technique should provide information about the transport, atmospheric circulation and sources of origin. In addition, the high-resolution analysis is essential for precise determination of the timing and the mechanisms behind the abrupt climate change events, and their synchronization to other records, in order to investigate their spatial extent. So, the first assumption is, that a few hundred micrometer resolution should be provided, in order to adequately resolve all the changes that are characterizing abrupt climate change events such as the Dansgaard-Oeschger event 8.

The second assumption is related to the proxies that are expected to represent the abrupt climate changes in the ice core records. The stadial periods are colder phases expected to be marked by lower $\delta^{18}O$ and δD values, because of the higher precipitation of the heavier isotopes during the transfer of the air masses to the ice sheets, that remain depleted in heavier isotopes. Also, the stadial periods are expected to be characterized with lower $\delta^{15}N$ and $\delta^{40}Ar$ values, due to the lower temperatures. Moreover, as a consequence of the positive feedback mechanisms related to the greenhouse gas concentration, during the stadial periods, it is expected to find lower CH_4 and CO_2 concentrations in the air bubbles from the ice cores. The impurities concentrations are expected to change as well, at the time of the oscillations between the stadials and interstadials. In particular, the colder stadial periods are expected to be marked by higher dust concentration, as a result of the stronger winds during these cold phases, represented with larger Ca^{2+} ion abundance and bright layers due to the high particle concentrations. The larger sea ice extent and the increased storminess over the ocean at colder periods like the stadials, are expected to result in larger sea salt aerosol concentrations, mostly noticeable by the larger Na^+ ions presence. On the other side, the interstadial period of the Dansgaard-Oeschger event 8 is expected to be marked by the opposite changes. Specifically, the interstadial is expected to be characterized not only with larger $\delta^{18}O$ and δD values, but also with larger $\delta^{15}N$ and $\delta^{40}Ar$ values, as a result of the higher temperatures. Also, the presence of the greenhouse gasses CH_4 and CO_2 is expected to be larger. The impurities, such as the dust, should be represented with lower Ca^{2+} ion and particle concentrations as a consequence of the weaker air circulation. The sea salt aerosol concentrations are expected to be lower as well. In addition to these changes, the annual layer thickness variations should be also observed. The colder stadial periods are expected to be marked with lower accumulation rates, while higher accumulation rates and hence, thicker layers should be related to the interstadial periods.

Precise dating is essential for the study of the time sequence of the abrupt climate change events, without usage of models. In particular, the chronology should be obtained through the annual layer counting, identified with seasonal variations of the ice core impurities, or through the seasonal variations of the stable water isotopes. More precise chronology should be achieved with usage of the seasonal variations of the impurities, because of the diffusion processes related to the water molecules. For instance, the peaks in Na^+, Cl^- and sea salt Mg^{2+} should be observed in winter, while the dust proxies Ca^{2+}, Fe^{2+} and Al^{3+} should be observed in spring. Summer peaks in SO_4^{2+}, NO_3^- and NH_4^+ should be seen as well. In addition, it is also important to determine if the variations of the impurities are in phase with the changes in temperature and other proxies. The technique that is used for the analysis of the ice cores, should allow multi-element analysis, in order to allow measurement of the variations of all these impurities. Also, low limit of detection is required, because of the low concentrations of the elements in the ice core records. Low limit of detection means that the technique is capable to distinguish the lowest amount of a substance, from its absence. Finally, high-resolution technique is necessary, for studying of the seasonal variations in very thin layers from the deepest parts of the ice cores, that are closely spaced one to another.

8. HIGH-RESOLUTION ANALYTICAL TECHNIQUE FOR ANALYSIS OF THE ABRUPT CLIMATE CHANGE EVENTS IN THE ICE CORE RECORDS

Many mass spectrometry methods, that provide adequate results, have been used for the analysis of the ice core records. Some of them are: secondary ion mass spectrometry SIMS, electron microprobe analysis EMPA, particle induced X-ray emission PIXE, micro X-ray fluorescence μXRF and laser ablation inductively coupled plasma mass spectrometry LA-ICP-MS. The LA-ICP-MS is considered to be the superior technique for paleoclimatology analyses, and can be used not only for the ice cores, but also for the other archives (Muller & Fietzke, 2016).

LA-ICP-MS is considered to be the key technology for paleoclimate studies, due to its suitability for diverse purposes. Among the other potentialities, there must be cited the easy preparation of the samples and the low limit of detection (sub-ng/g). Also, it allows precise analysis of the isotopical composition and a moderate matrix influence. Low costs and the possibility to use it as a scanning tool for obtaining laser ablation imaging and high-resolution are fundamental features as well (Muller & Fietzke, 2016).

High-resolution analytical technique with low limit of detection is essential for the study of the variations preserved in the ice core records, especially the ones characterizing the Abrupt Climate Changes. Such changes are the air circulation patterns in the past, the sea ice cover, the accumulation rates of the cryosphere, the volcanic eruptions in the past and the processes that lead to pollution. LA-ICP-MS is the perfect technique for such analyses, because of the possibility for resolution of a few hundred micrometers, allowing determination of the sub-annual patterns of these processes, with plotting the concentrations of the chemical elements against the depth or the age of the ice core. Techniques with lower resolution do not allow study of the seasonal cycles, especially if the analyzed samples are characterized with highly compressed layers from low accumulation sites. The ice core analysis with LA-ICP-MS was firstly applied in 2000 by Reinhardt, and the accomplished resolution was 300 µm (Sneed, et al., 2015).

Other advantages include the minimal sampling volume, that makes possible replicate sampling and preservation of almost the whole ice core for analysis with other methods (Sneed, et al., 2015). Moreover, LA-ICP-MS novel methods allow multielement analyses of the ice core records, with many elements measured from the same ablation spot, even though multielement measurements are usually done when the elements are present with high concentrations. This makes possible the precise study of the relative phasing of the concentration variation of the elements during the abrupt climate changes (Spaulding, et al., 2017). Also, it is possible to couple LA-ICP-MS with other techniques for more precise results, such as its coupling to accelerator mass spectrometry AMS for radiocarbon dating (Muller & Fietzke, 2016)

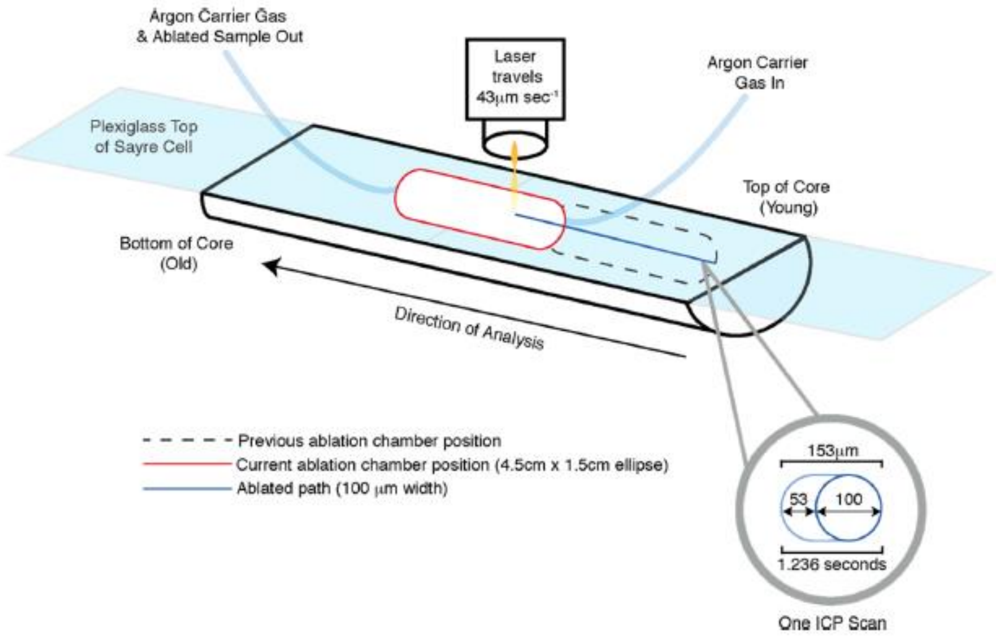
LA-ICP-MS is the preferable technique over continuous flow analysis method, used for the trace element analysis, due to the higher resolution obtained with LA-ICP-MS. Even though Continuous Flow Analysis (CFA) method, allows direct and continuous measurement of the trace elements, with extremely low levels of contamination, the analysis completely destroys the sample with melting, and the resolution is low due to the dispersion in the melting and liquid transport (Massam, et al., 2017). CFA can be used for adequately resolving annual layers only down to 10 mm thickness, because the highest resolution provided by CFA today is 1 cm (Della Lunga, Müller, Rasmussen, Svensson, & Vallelonga, 2017). Obviously, this is not enough for resolving of the seasonal patterns of the elements in the ice core records, that have substantially thin layers, and studying of the Abrupt climate change events. Electrical conductivity and laser light scattering measurements are used for annual layer counting, because of the determination of the seasonally deposited dust. Still, the resolution that these techniques provide is not as high as the on obtained with LA-ICP-MS (Sneed, et al., 2015).

The LA-ICP-MS system contains a laser with a spot size, positioning and viewing capabilities depending on the analysis requirements, an ablation chamber that has optical window with inlet and outlet ports, through which the ablated material is transported inside the Teflon tube with using He or Ar. The laser can be solid or gas-based with a wavelength that depends on the material that should be ablated, the costs and the required maintenance. The ablation chamber is either closed, with the sample being located inside it, and this is more commonly used for small-size samples, or open, for samples that are bigger or cannot be subsectioned. The time necessary for the removal of the ablated material is decided by the chamber size and the flow rate of the gas. In addition, for ice core analysis, the temperature of the sample should be kept below the freezing point. The calibration allows conversion of the ablation results to concentrations of the analyzed elements (Sneed, et al., 2015).

For the analysis of the ice core samples, often a cryocell system is used. A cryocell is a chamber that can maintain temperature of −20 °C, when holding an ice sample of 1 m. The ablation compartment has a small volume of approximately 5 cm^{-3}, and it is of open type, and permits continuous ablation at almost the original length of the ice core samples. The cryocell can move, and the controlled change of the position is necessary after the laser module had passed through the sample. It has a plexiglass window above it. Sayre Cell, an example of a cryocell chamber is represented on Figure 48 (Spaulding, et al., 2017).

Figure 48

Sayre Cell Ablation Chamber



Note. In this case, Ar is used as a carrier gas. One ICP scan lasts 1.236 s and the laser travels with a velocity of 43 µm s^{-1}. As a result, during one scan, the laser moves 53 µm, and with an addition of the 100 µm beam size to this value, the nominal resolution can be calculated, and it is 153 µm. Reprinted from "A New Multielement Method for LA-ICP-MS Data Acquisition from Glacier Ice Cores" by N. E. Spaulding, 2017, *Environmental Science and Technology 51,* (p. 13283).

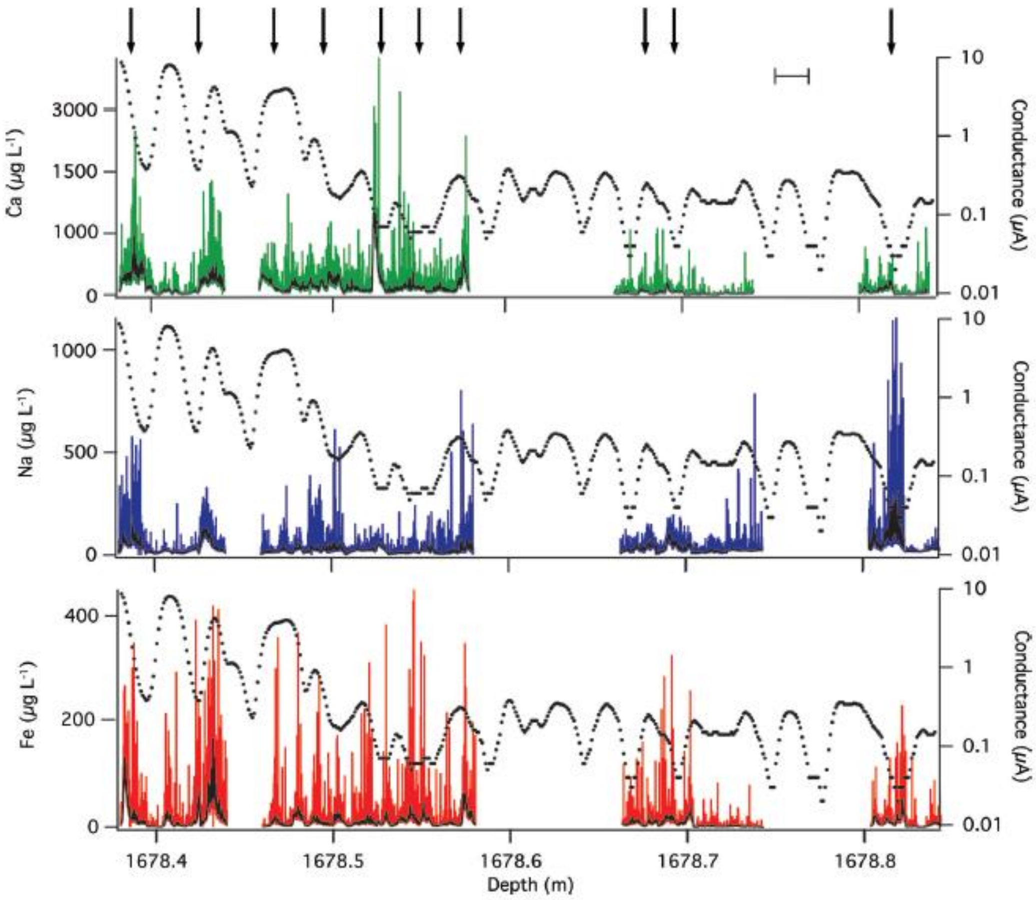
The calibration can be done with a combination of frozen reference materials and liquid standards, and it is often completed in two steps for the ice core samples. The calibration should allow calculation of the concentrations in the ice core samples, with using calibration equations and transfer functions (Sneed, et al., 2015).

8.1 - Results of the performed analyses of ice cores with the LA-ICP-MS technique

In order to determine whether the hypothesis about the patterns of the impurities change during the abrupt climate change events is correct, the results of a study of the GISP2 ice core with LA-ICP-MS, will be represented. The analyzed section was at 1678 m depth, corresponding to the transition period between the glacial and interglacial. The profiles of the measured impurities, Ca, Na and Fe, from marine and dust sources, are represented in Figure 49 (Sneed, et al., 2015).

Figure 49

LA-ICP-MS Determined Concentrations of Ca, Na and Fe from the GISP2 Core at a depth of 1678 m



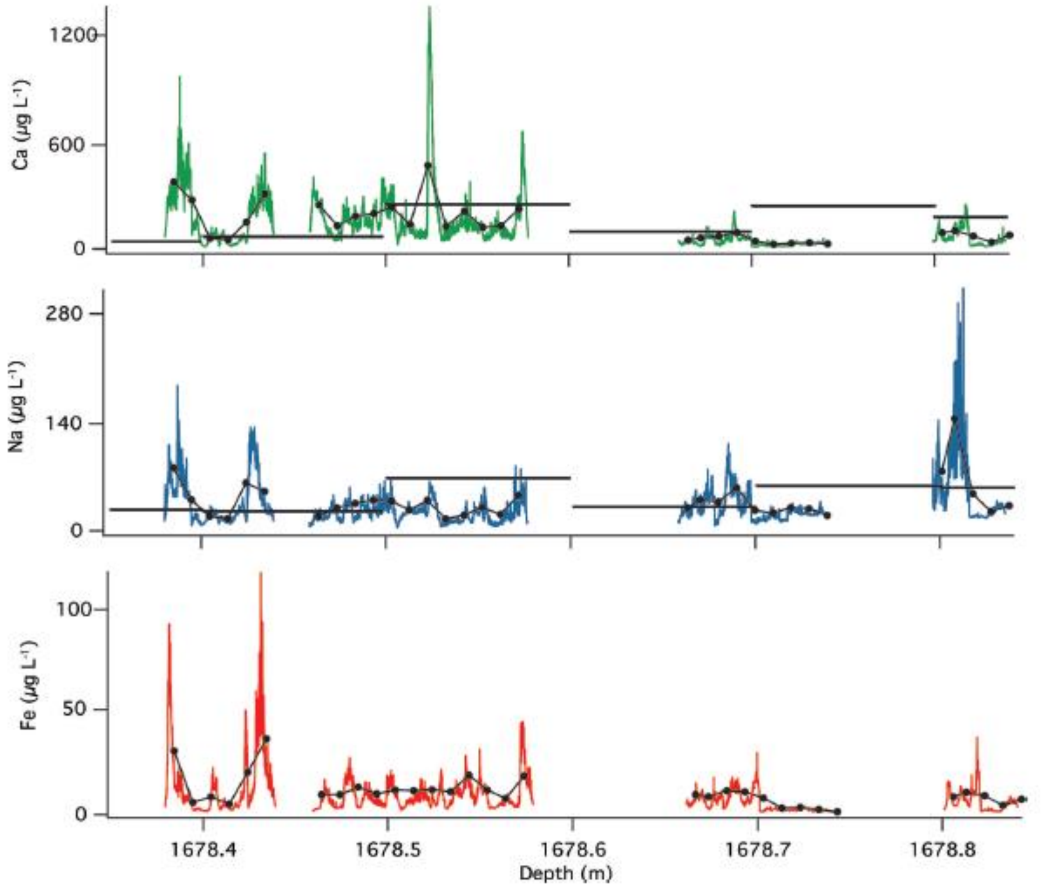
Note. Ca profile is represented with green, Na with blue and Fe with red curve. The black curve represents the smoothened profile, while the black dotted curve represents the results from the electrical conductivity measurements. The black arrows show the annual layers that are determined from the peaks in the Na concentration. The detection limits are 2.1 µg L^{-1} (Ca), 2.3 µg L^{-1} (Na) and 0.1 µg L^{-1} (Fe). Reprinted from "New LA-ICP-MS cryocell and calibration technique for sub-millimeter analysis of ice cores" by S. B. Sneed, 2015, *Journal of Glaciology, Vol. 61, No. 226,* (p. 237).

Since the peaks of the impurities can be used for determining and counting of the annual layers, this study shows that there are 33 annual layers in the 1 m depth at 1678 m. If the most continuous section is taken into account (1678.38-1678.58), the determined annual layer thickness is 3 cm. Also, in this study a deeper section was investigated, and a similar calculation shows that at 2680 m depth, there were 208 annual layers, and their thickness was around 0.5 cm. This clearly represents the reduced thickness in the deeper parts due to the compression, and the need for high-resolution technique for their determination (Sneed, et al., 2015).

Moreover, the results of this study can be used for confirmation of the advantages of the LA-ICP-MS technique, over the lower-resolution CFA. In these terms, the Figure 50 shows the comparison between the results obtained with high-resolution LA-ICP-MS (resolution of 121.25 µm sample^{-1}), and the CFA analyses (resolution of 1 cm), at a depth of 1678 m (Sneed, et al., 2015).

Figure 50

Comparison Between the CFA and LA-ICP-MS Results, Characterized with Different Sampling Resolution

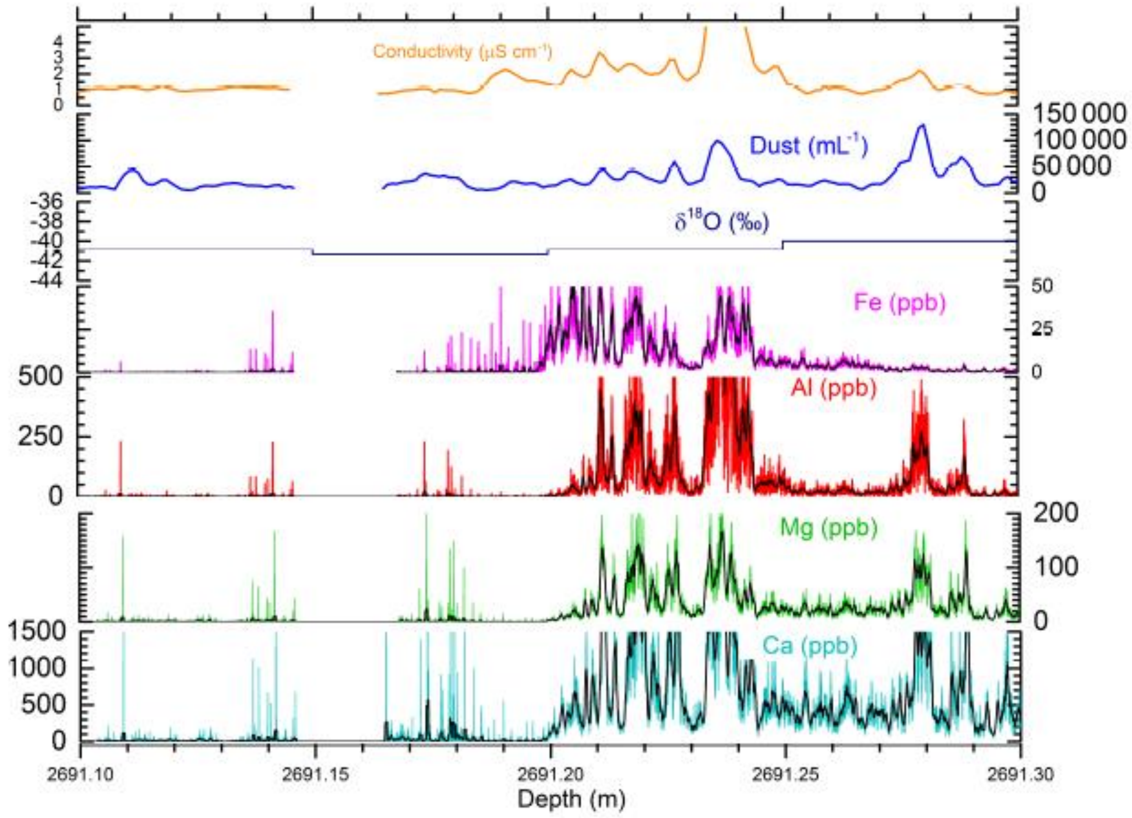


Note. Green curve for Ca, blue curve for Na and red curve for Fe, represent the smoothed ten-point running mean profiles obtained with LA-ICP-MS, while the black lines with dots represent the 1 cm resolution profiles obtained with CFA. The horizontal lines show IC results with 10 cm resolution. Reprinted from "New LA-ICP-MS cryocell and calibration technique for sub-millimeter analysis of ice cores" by S. B. Sneed, 2015, *Journal of Glaciology, Vol. 61, No. 226,* (p. 239).

The assumption about the required resolution of a few hundred micrometers for analysis of the Abrupt climate change events, can be validated with the results of the LA-ICP-MS analysis of the dust proxies, during the transition to the Greenland Interstadial 21.2. Also, the expectation that the dust level increases during stadials, and decreases during interstadials, can be supported with this study as well. The section (2691.50–2688.65) m depth of the NGRIP core was studied, and that particular depth of the sample of 2.85 m actually is a short interstadial period prior to interstadial GI-21.1. The analyzed elements are Na^+, Fe^{2+}, Al^{3+}, Ca^{2+} and Mg^{2+}, as indicators of dust and sea salt, with a sampling resolution of 200 µm, allowing obtaining around 50 data points per year. This is true because the annual layer thickness at this depth is approximately 10 mm, and the technique provides low limits of detection in the range of ppb. The analysis is useful for determining the phasing of the different changes that characterize the Dansgaard-Oeschger events. Figure 51 represents the obtained results (Della Lunga, Müller, Rasmussen, Svensson, & Vallelonga, 2017).

Figure 51

Sea Salt and Dust Indicators Profiles During Greenland Interstadial 21.2 Obtained with LA-ICP-MS Analysis



Note. 200 mm window, that corresponds to approximately 20 years, of the profiles of conductivity, dust, $\delta^{18}O$, Fe^{2+}, Al^{3+}, Ca^{2+} and Mg^{2+} at the cold-warm transition of GI 21.2. The different colored curves represent the LA-ICP-MS results, while the black curves represent the 30-point average values. At a depth of 2691.20 m, the transition that occurs over a space of 10 mm (corresponds to 1 year at this depth), can be clearly seen. The top orange and dark blue curve represent the conductivity and the CFA dust results, for a comparison with the LA-ICP-MS results. Reprinted from “Calibrated cryo-cell UV-LA-ICPMS elemental concentrations from the NGRIP ice core reveal abrupt, sub-annual variability in dust across the GI-21.2 interstadial period" by D. Della Lunga, 2017, *The Cryosphere, 11,* (p. 1302).

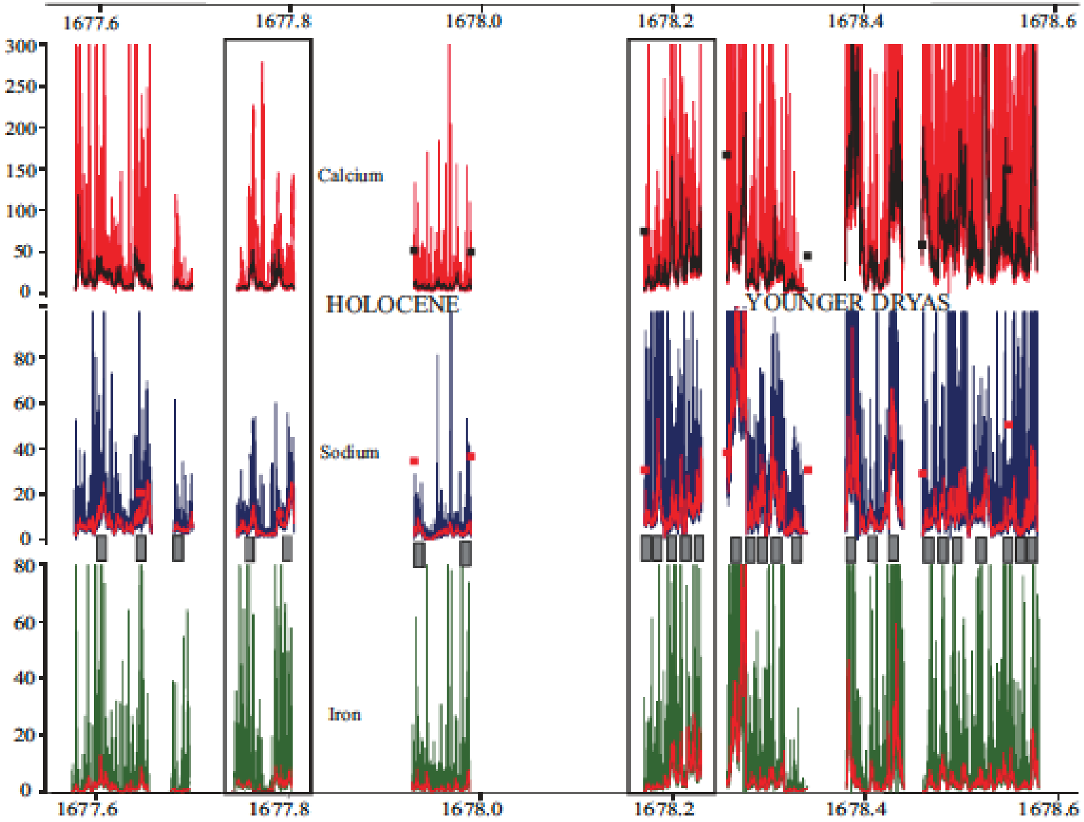
Figure 51 clearly represents the match between sea salt, dust proxy records, and the $\delta^{18}O$ variations. In the deepest part of the analyzed section, the elements are present with relatively high concentrations, indicating a cold phase. Importantly, in the interval between (2690.00-2688.65) m, the ions show millennial-time-scale oscillations characterized with 10-fold change in the concentration. These evidences mark the Dansgaard-Oeschger events. To add, Figure 51 also indicates that the LA-ICP-MS profiles have more clear and abrupt details, compared to the CFA ones, and the results from the two techniques agree for almost all of the change patterns (Della Lunga, Müller, Rasmussen, Svensson, & Vallelonga, 2017).

For some of the events, even higher-resolution should be offered, for more precise analysis. The ultra-high-resolution of 20 mμ, that can be provided by the LA-ICP-MS technique, makes possible the detailed analysis even of the abrupt Holocene onset that lasted only one year. The abrupt Holocene beginning happened right after the end of the Younger Dryas. Through the analysis of the impurities profiles (Ca, Na and Fe), Mayewski et al., (2013) tried to reveal the atmospheric circulation change preceding the variation in temperature at the onset of the Holocene. Hereafter, the total calcium, mostly transported in the form of carbonate and gypsum, has been related with a zonal atmospheric circulation, while the total sodium, seems to has been transported in the soluble form towards Greenland through the Icelandic Low. The iron, instead, has been indicated as the result of dissolution processes within the atmosphere. Also, a comparison with the results obtained from ion chromatography analyses with 10 cm sampling resolution, confirms the need of the high-resolution provided by LA-ICP-MS (Mayewski, Sneed, Birkel, Kurbatov, & Maasch, 2013).

Figure 52 represents the results of the ultra-high-resolution analysis of the Ca, Na and Fe in the GISP2 record (Mayewski, Sneed, Birkel, Kurbatov, & Maasch, 2013).

Figure 52

Ultra-high-resolution Record of Ca, Na and Fe during the Holocene Onset from the GISP2 Ice Core

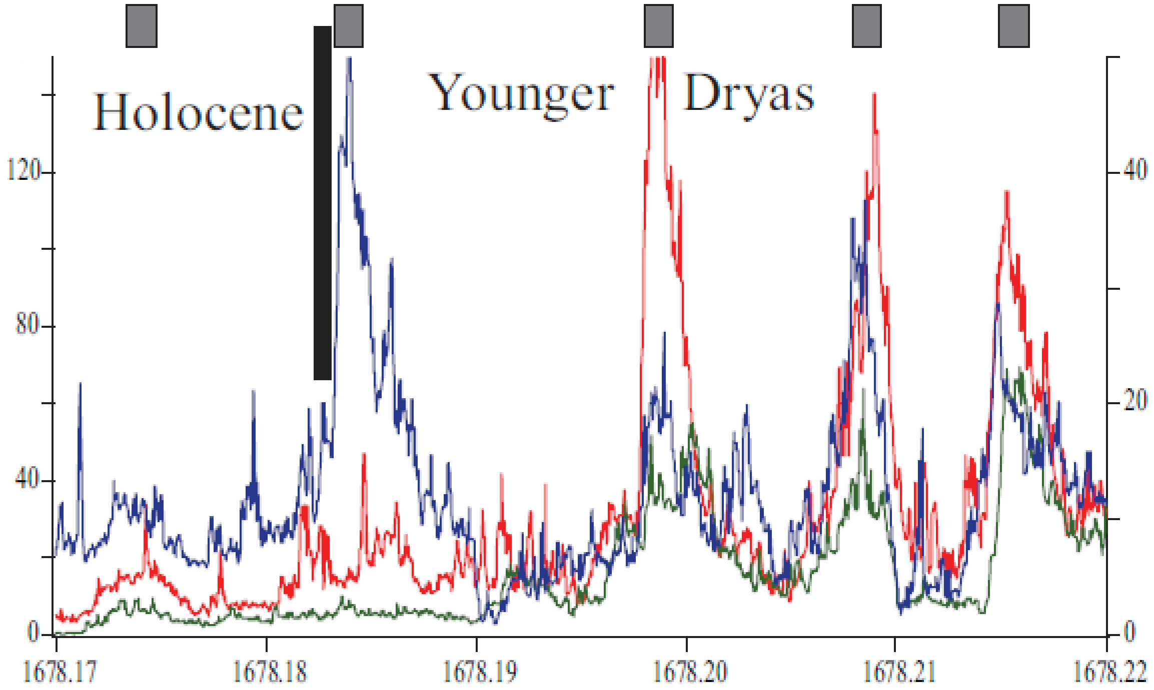


Note. Ca (red), Na (blue) and Fe (green) are represented in ppb. The 10-cm resolution results are represented with black (Ca) and red squares (Na), plotted at the midpoint of the 10-cm. Grey rectangles represent the peaks used for determining of the annual layers. Reprinted from "Holocene warming marked by abrupt onset of longer summers and reduced storm frequency around Greenland" by P. A. Mayewski, 2013, *Journal of Quaternary Science*.

Due to the high sampling resolution in this study, a storm-scale details can be captured, making the comparison between concentrations, phasing, and the length of the seasons, before and after the transition from the Younger Dryas to the Holocene, possible. In Figure 52 these differences have been represented clearly. In particular, the significant differences in concentration between Ca and Fe records considering pre- and post-Holocene onset might suggest a variation in the source region. Moreover, the Figure shows the decreased concentration variability of the ions before and after the transition, that might be related to storminess. In particular, lower concentrations of these elements in Greenland represent less stormy periods, while higher concentrations indicate increased storminess and transport of sea salt and dust. The difference in the concentrations of impurities before and after the transition, can be clearly seen in Figure 53, that includes the last three years of the Younger Dryas cold episode, the transition year, and the Holocene first year (Mayewski, Sneed, Birkel, Kurbatov, & Maasch, 2013).

Figure 53

Representation of the YD, YD-Holocene Transition and Part of the Holocene, through the Smoothened LA-ICP-MS Profiles of the Ca, Na and Fe



Note. Ca (red), Na (blue) and Fe (green) are represented as smoothened data with 10-point running median, in 5 cm section. Annual layers determined from the peaks in the chemicals are represented with grey rectangles. The transition year YD-Holocene is marked with black line. Reprinted from “Holocene warming marked by abrupt onset of longer summers and reduced storm frequency around Greenland” by P. A. Mayewski, 2013, *Journal of Quaternary Science*.

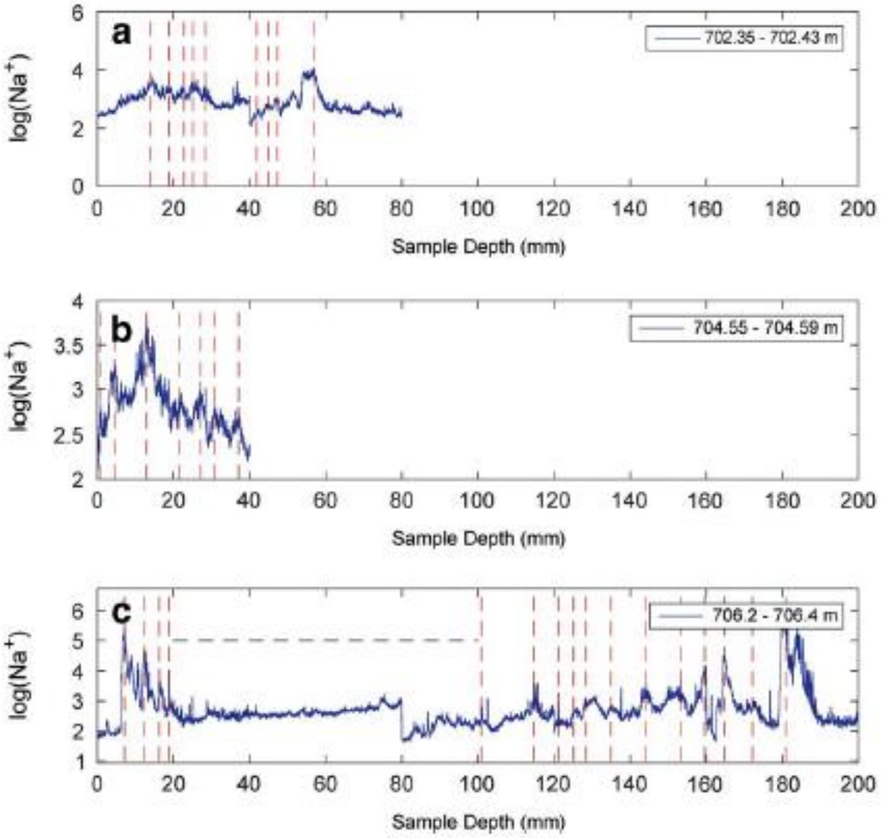
The Figures show that the analyzed elements have longer periods of low levels in the Holocene, compared to the Younger Dryas. According to this, it can be concluded that the reduced concentrations of these elements and increased precipitation, do not result only from the hampered transport vigour and rise in the moisture availability, but are related even to longer periods without storms and mild conditions. Indeed, the duration of the summer season was at least twice longer during the Holocene than before, confirmed by the decreased sea ice cover. Figure 53 shows that the transition that lasts one year is marked by decreased peak in westerly winds in winter/spring (Ca record), compared to the three previous years when it was rising gradually. On the other hand, the marine storm intrusions appear to fluctuate in the three years before the transition, hindering the transport of marine air over Greenland. The intrusion is the largest during the transition year, indicating strengthened air circulation over the ocean, also related to the reduced sea ice cover and decreased strength of the westerly winds. After the transition, in the Holocene, the incursions are less strong, as the decreased concentration peaks of sodium during summer suggest. In addition, the Fe record shows decreased concentration at the beginning of the Holocene and during the transition year, due to decreased transport, that is consistent with the weakening and migration of the westerlies and easterlies (Mayewski, Sneed, Birkel, Kurbatov, & Maasch, 2013).

Also, the change in the accumulation rate from the Younger Dryas to the Holocene, can be represented through the determined annual layer thickness. The annual layer thickness that was determined for the depth of the GISP2 ice core corresponding to the Holocene is 3 cm, while for the end of the Younger Dryas is 1-2 cm. This represents the minor accumulation rate due to lower precipitation during cold periods such as the Younger Dryas (Mayewski, Sneed, Birkel, Kurbatov, & Maasch, 2013).

However, the determination of the annual layer thickness is most challenging at sites characterized with extremely low accumulation rate and highly-compressed layers, such as the ice core from Berkner Island from the Antarctica Ice Sheet. There, the accumulation rate is reported to be 0.185 m y^{-1}, and deeper than 550 m, the reduced annual layer thickness hampered the application of any low-resolution technique. Massam et al., (2017) used the peaks in Na and Mg for determining the annual layers. Importantly, this study shows a comparison of the annual layer thickness estimated with model, and the ones determined with LA-ICP-MS using the element's peaks. Such a comparison demonstrates that the models often provide results that are not correct. The results show that for the mid-Holocene period, that corresponds to depth 454-459 m of the ice core, the annual layer thickness suggested with the model is 57 mm. On the other side, the LA-ICP-MS analysis shows that the layers are much thinner, between 5 mm and 33 mm. The differences between the thickness estimated with the model and LA-ICP-MS are much lower at depth of 694-697 m, with an annual layer thickness of 3 mm estimated by the model, and 3.4 mm determined with LA-ICP-MS. The average thickness of the layers at 702-707 m, determined with LA-ICP-MS is approximately 3.1 mm. At this depth, the annual layer thicknesses cannot be resolved with a technique that does not provide ultra-high-resolution. Going deeper within this interval, it can be seen that the frequency of the Na^+ peaks increases. Moreover, the seasonality in the analyzed profiles decreases, going deeper from 694 m. Between 695 m and 704 m, it has been observed that the annual layer thickness increases, and eventually doubles, indicating a rise in the accumulation rate during the deposition. This is opposite to the predictions by the model, because it is not capable to predict such natural variability. The results obtained with LA-ICP-MS for the depth range of 702-707 m are represented on Figure 54 (Massam, et al., 2017).

Figure 54

LA-ICP-MS Results of Three Sections of Ice in the Depth Interval 702-707 m Representing the logNa^+ for Determining of the Seasonal Peak

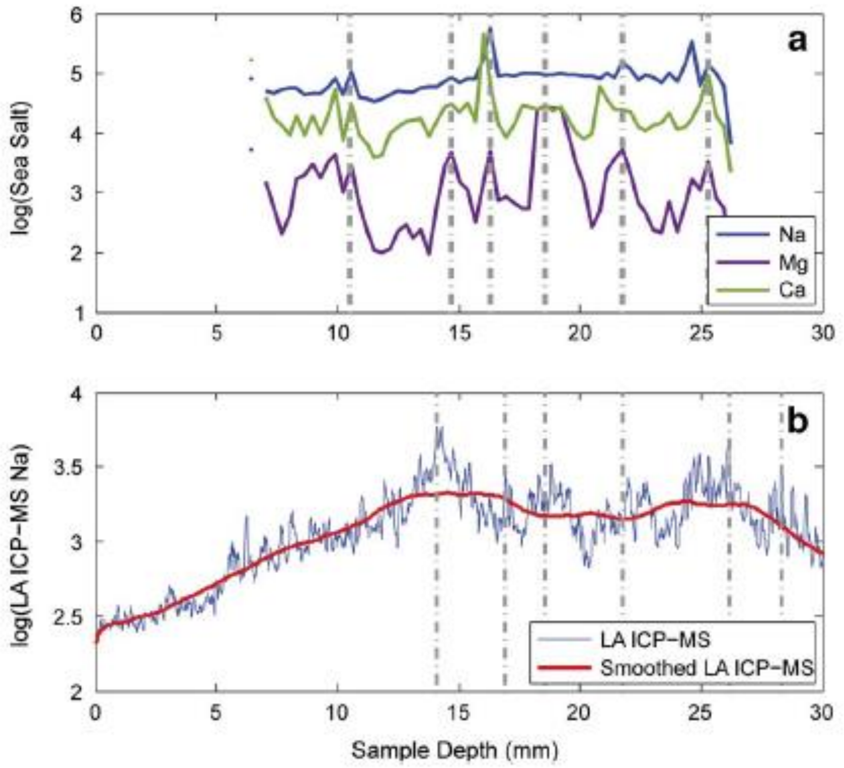


Note. The dashed lines represent the seasonal peaks in Na$^+$. Reprinted from "A comparison of annual layer thickness model estimates with observational measurements using the Berkner Island ice core, Antarctica" by A. Massam, 2017, *Antarctic Science 29(4)*, (p. 387).

In addition, this study represents a comparison between the results obtained with LA-ICP-MS and discrete sampling using ion chromatography. The results show that the annual layer thickness determined with discrete sampling, agrees with the results obtained with CFA and the modeled thickness, and the seasonality appears to be smoothened. This refers to the deeper parts, while for the upper layers, such as the ones in the depth interval 454-459 m, this technique appears not to be useful, because of the large sampling volume that is needed. This illustrates the lower resolution of the discrete sampling, compared with the LA-ICP-MS analysis. A comparison of the results of the discrete sampling, and the LA-ICP-MS results, are represented on Figure 55. The Figure shows the ion chromatography profiles of Mg^{2+}, Na$^+$ and Ca^{2+}. Interestingly, using this method, additional annual layers were found, this indicating that the LA-ICP-MS annual signals might be lost (Massam, et al., 2017).

Figure 55

Comparison of the Results of the Analyzed Ice Core Samples with Discrete Sampling and LA-ICP-MS for Determining Annual Layers



Note. The results are referring to 703.2-703.22 m depth. The black dashed lines show where the annual layers are recognizable. Reprinted from "A comparison of annual layer thickness model estimates with observational measurements using the Berkner Island ice core, Antarctica" by A. Massam, 2017, *Antarctic Science 29(4),* (p. 389).

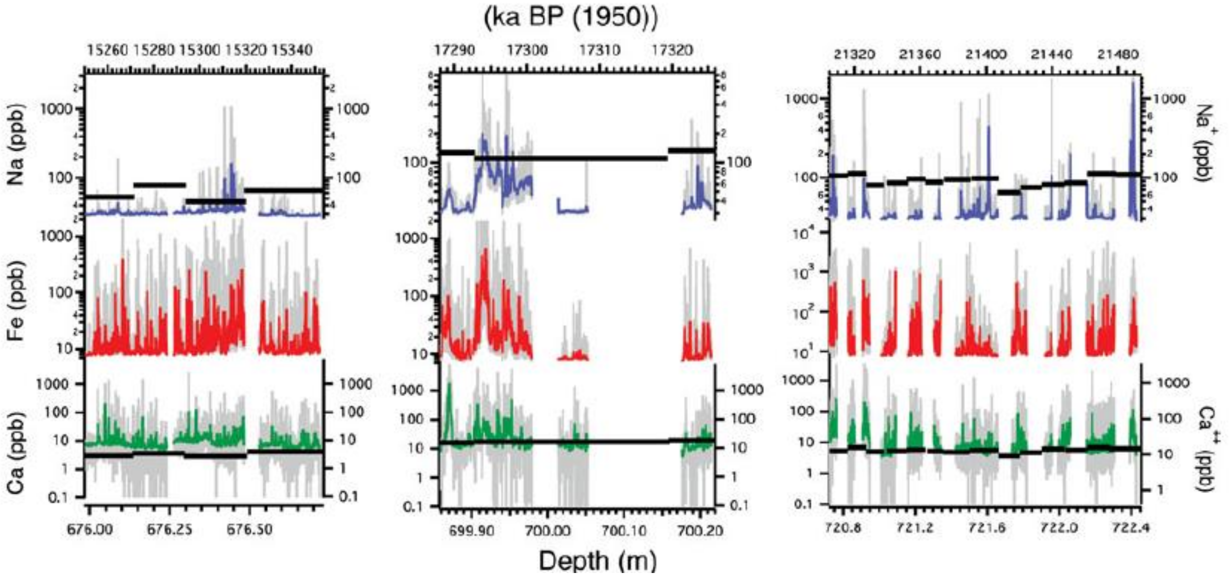
Other low-accumulation Antarctica sites, such as Siple Dome-A, have also been analyzed with high-resolution LA-ICP-MS methods, for determining annual layers and seasonal patterns of change. The highly compressed layers characterized with low accumulation rate, are able to be analyzed with LA-ICP-MS due to the resolution of 121 µm and possibility for multielement analysis of Na^+, Ca^{2+} and Fe^{2+} ions. Such high-resolution provides 62 data points per year, thus making possible the sub-seasonal analysis of the patterns of atmospheric circulation and precipitation, and separate storm events. The measured sea salt Na, is an indicator of the sea ice. The non-sea salt Ca is transported mainly in spring to the Antarctica Ice Sheet with the austral circumpolar zonal westerlies. The non-sea salt Fe originates from the arid regions, and is brought to the ocean gyres, as a nutrient necessary in phytoplankton productivity (Haines, et al., 2016).

Haines et al., (2016) analyzed three samples of the Siple Dome-A ice core, from different depths and corresponding to three late glacial periods (~15.3, 17.3, 21.4 kyr ago). For what concern the winter accumulation rate, the distance between the increase of the earliest maximum of an element and the decrease of the latest maximum has been considered and used for counting of the same year. The summer accumulation is determined in a similar way, measuring the distance between the fall of the latest local maximum of an element and the increase of its earliest maximum. This trick is used for counting the next year. The results of these measurements show that the ratios between the winter and summer precipitations in the three sections remain approximately the same, and are 1.7, 1.3, and 1.6 for section 1,2 and 3 respectively. Importantly, the winter season is longer than the summer season, a feature that is characteristic for the glaciar periods. Still, after the Younger Dryas-Holocene transition, there is a doubling of the summer season, as expected during warm periods (Haines, et al., 2016).

Figure 56 represents the differences in the results obtained with high-resolution LA-ICP-MS analysis (121 µm sampling resolution), and the ion chromatography, with a sampling resolution of 11-16 cm, for the three analyzed sections (Haines, et al., 2016).

Figure 56

Comparison Between the Results Obtained with LA-ICP-MS and IC for Na, Ca and Fe from Three Sections of the SDMA Ice Core

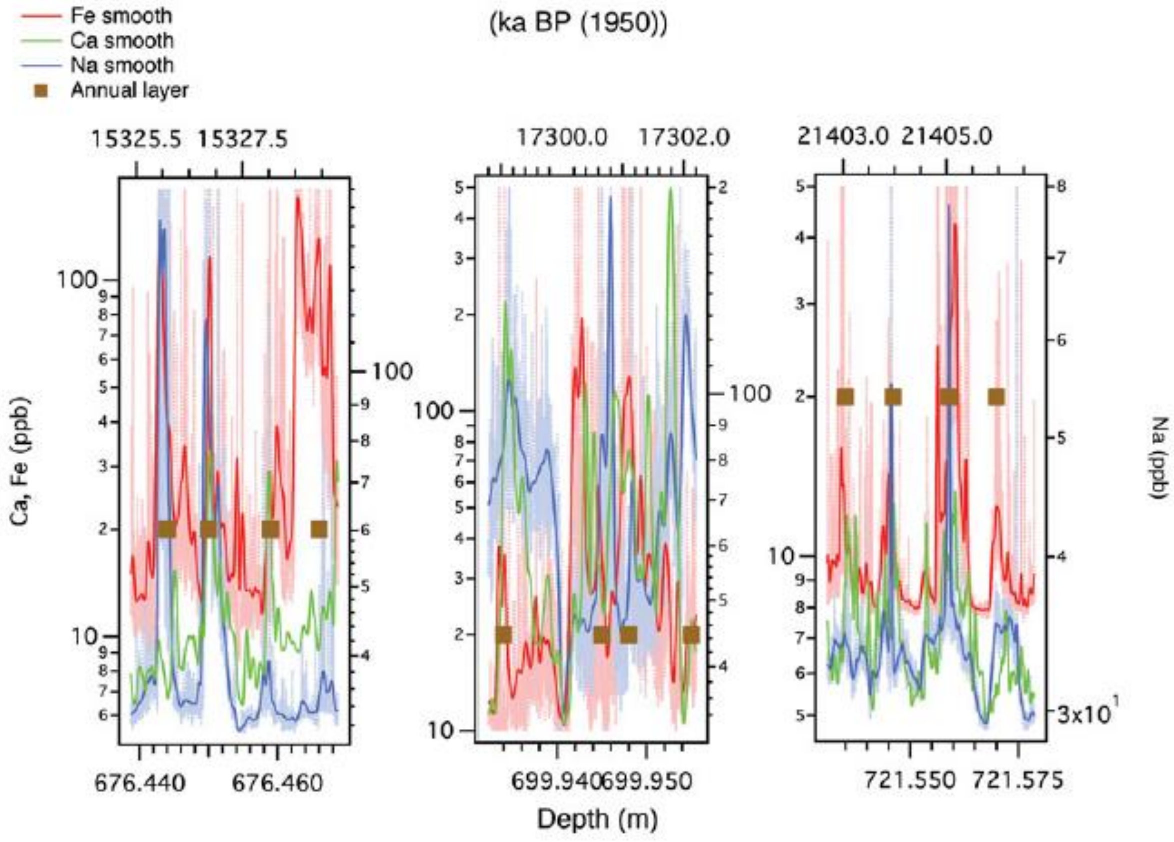


Note. Na (blue), Fe (red) and Ca (green) profiles obtained with high-resolution LA-ICP-MS for analyzed sections 1, 2 and 3. The black dots represent the results obtained with ion chromatography, with resolution of 16 cm, 16 cm and 11 cm for the different sections. Reprinted from "Ultra-high-resolution snapshots of three multi-decadal periods in an Antarctic ice core" by S. A. Haines, 2016, *Journal of Glaciology,* (p. 33).

The high-resolution of the LA-ICP-MS allows investigation of the variations in the storm features, such as the timing, amplitude and frequency. As a result of such changes, the proxy variations are often not in phase with each other. Thus, in order to determine the annual layers in the analyzed ice core sections, the winter/spring season in each annual layer is defined through a synchronous peak in the three studied elements. Quite often, some of the element's peaks are missing, or appear to be asynchronous with the others, suggesting probable changes in the pathway of transport or a block, changes in the source, or in the timing of the input of that particular element. Figure 57 represents the annual layer counting through the seasonal element peaks for each of the three sections analyzed in this study (Haines, et al., 2016).

Figure 57

Counting of the Annual Layers in Three Analyzed Sections of the SDMA Ice Core Through the Seasonal Element Peaks



Note. Na profile is represented with blue curve, Ca profile with green curve and Fe profile with red curve. The brown boxes represent the centers of the annual layers, determined with the peaks of the elements. Reprinted from "Ultra-high-resolution snapshots of three multi-decadal periods in an Antarctic ice core" by S. A. Haines, 2016, *Journal of Glaciology,* (p. 35).

8.1 – Discussion about the LA-ICP-MS analyses

The study of the impurities change patterns during an abrupt glacial-interglacial transition, clearly shows that the seasonal patterns of variation of Ca, Na and Fe are recognizable even if the layers are closely spaced. This is possible due to the high-resolution of LA-ICP-MS. Before the analysis using LA-ICP-MS, the annual layers in parts representing an abrupt transition, could not be determined. The reason is the resolution offered by other techniques, that is not good enough for identifying the patterns of the chemical signals. Figure 50 confirms this, clearly showing that the annual layers cannot be recognized at 1 cm resolution using CFA, because they are represented only with one data point. So, LA-ICP-MS allows revealing of structure that has not been previously recognized with other analytical techniques for ice core analysis (Sneed, et al., 2015).

Another example of an abrupt event and its analysis with LA-ICP-MS, is the study of the GI-21.2 interstadial period. The results of the performed analysis of the GI-21.2, show that the dust and the sea salt proxies react to the abrupt climate change events very abruptly with sub-annual scale. This is referring even to the events that last very shortly, such as the analyzed one. Also, the patterns of change correspond to the CFA profiles for the NGRIP ice core, with clearer features of the elemental proxies, probably due to an influence by single storm events. Finally, the results show that there is a small disagreement between the profiles of the analyzed elements, and the $\delta^{18}O$ value, that is an expected feature as a consequence of the different resolutions. The resolution for the $\delta^{18}O$ analysis is 50 mm, and for the elemental dust and sea salt proxies, it is 200 μm. Interestingly, the elemental proxies respond to the warming onset before the $\delta^{18}O$ values, even by 100 mm (Della Lunga, Müller, Rasmussen, Svensson, & Vallelonga, 2017). Della Lunga states that the dust proxies precede the variation of the temperature even by three to ten years. This study confirms the hypothesis that high-resolution, of at least few hundred micrometers, is essential for the study of the fast-occurring Abrupt climate change events, like the GI-21.2.

The Holocene onset is an additional example of an Abrupt Climate Change Event, and it is one of the shortest-lasting events. The study of the abrupt Younger Dryas-Holocene transition, shows that it was marked by abrupt shifts in the proxy records. The results of the analyzed impurities, suggest that during the transition, there was a change in the atmospheric circulation features, and a decrease in the sea ice cover. These variations occurred even before the change in the temperature. Also, the study shows that the Holocene onset lasted only 1-3 years, confirming its abruptness and the need of high-resolution technique for analysis of the changes with short time-scale, even the storm-scale details (Mayewski, Sneed, Birkel, Kurbatov, & Maasch, 2013).

LA-ICP-MS represents probably the most precise tool for annual layer thickness determination and their counting. The annual layer examination of the ice core from Berkner Island, shows the differences in the results of the determined annual layers thickness with models, and with LA-ICP-MS measurements of the Na peaks. The results show that the model is not exactly able to estimate the thickness of the annual layers, especially in the deeper parts. Furthermore, the study confirms the advantages of the LA-ICP-MS technique to the ion chromatography discrete sampling. The discrete sampling provides correct results only for the upper layers, while the data for the highly-compressed layers is smoothened, as a consequence of the lower resolution (Massam, et al., 2017). The abilities of the high-resolution LA-ICP-MS method are further confirmed with the results of the study of the Siple Dome-A ice core. It represents the possibility for determination of the annual layers in the deep parts of the Antarctica ice core, and the seasonal patterns of change of the proxies, despite the low accumulation and high compression of the layers. Also, the advantages of the LA-ICP-MS high-resolution, in comparison to the ion chromatography technique, are verified. Finally, the study represents the ability of LA-ICP-MS for analysis even of the storm characteristics (Haines, et al., 2016). It can be understood that detecting of the annual layers depends on how well the seasonal cycle is preserved in the ice core record, how much capable is the chosen method for extracting the seasonality and how adequate is the sampling resolution (Massam, et al., 2017).

From the presented results of the analysis of the ice core records with LA-ICP-MS, it can be concluded that the micrometer resolution provided by the technique allows studying of the characteristic changes of the proxies even with sub-annual time-scale, a feature that is essential for investigation of the rate, the timing and the typical features of fast-occurring climate variations, such as the Abrupt climate change events. Moreover, the new methods that allow multielement analysis with extremely low levels, and the possibility for preserving low temperatures of the ice sample, make the LA-ICP-MS the leading technique for precise studying of ice cores. In addition, the multielement method, can be used for studying of the elemental ratios and discovering new proxies that might explain many features of the abrupt climate change events, that are still unclear. Finally, the ultra-high-resolution provides possibilities not only for the analysis of change patterns of the impurities in the ice, but also precise dating of the ice core records with annual layer determination through the seasonal peaks of the impurities (Spaulding, et al., 2017; Massam, et al., 2017).

9. CONCLUSION

Representation of the most important features of the abrupt climate change events, and the paleoclimate archives that contain valuable evidence of their occurrence, are some of the primary objectives of this research. The Abrupt climate change events that happened during the Last Glacial Period are one of the most remarkable features of the Earth's climate, mostly because of the short time-scale of these swings. In particular, they are extraordinary phenomena because of the large-amplitude shifts (up to 16 °C temperature change) happening within a few decades.

Moreover, this research explains why the analysis of abrupt climate changes that have occurred in the past is essential. The most significant characteristic of these events is their abruptness, that makes such occurrences to be unlike the usual gradual changes in the climate system. Also, their abruptness is the attribute that makes their study so relevant, because of the complicated adaptation strategies to similar abrupt events that may occur. So, we have to try to obtain as much as possible information about the processes behind the events, and the climate changes that can appear as a result of them. Specifically, even if there are small changes, the internal mechanisms of the climate system, mostly related to the feedback processes, might increase the magnitude of the variations, and lead to large shifts. Such occurrences might be fatal, especially because the living organisms can hardly adapt to large fluctuations over short time. Knowledge about the processes that cause the events is necessary, in order to be able to prevent similar abrupt shifts that might occur. Furthermore, understanding these events might allow solving the issues related to the Global Warming phenomena, and help us to keep its consequences from continuing.

This research also shows that even though the Abrupt climate change events are one of the best studied features of the climate system, there are some uncertainties associated to them, especially related with the definitive processes responsible for their occurrence. This represents the need of further analysis of the paleoclimate archives for obtaining more useful indications. Particularly, more precise study of the paleoclimate archives with novel analytical techniques, should permit differentiation between the observed variabilities in the archives that are indications of the processes that cause the events, and the ones that appear as a consequence of them. Some of the suggested mechanisms responsible for the events include the change in the Atlantic Meridional Overturning Circulation, and the sea ice dynamics and feedback mechanisms. Others involve the ocean-atmosphere processes happening in the tropics, or the consequences of the interactions between the tropics and higher latitudes, as responsible mechanisms for the events. Another alternative is the spontaneous oscillations of the coupled atmosphere-ice-ocean system in the North Atlantic, Nordic Seas and Arctic. Still, the definitive reason remains unknown. The most intriguing aspect is that all of the proposed mechanisms agree in one feature: they do not include external forcing factor. Instead, all of them are related to the internal processes of the climate system. The main reason for this assumption is linked with the time-scale of the events. In particular, so fast forcing factors, that might lead to such abruptness, do not exist. Therefore, the answer about the reasons of the Abrupt climate change events, should be looked for in the internal principles of functioning of the climate system and the complex links between its components. This will not only allow understanding of the Abrupt climate change events, but it will also make possible further comprehension about the climate system functioning. Such knowledge might be very useful in resolving other doubts related to the climate system.

This research has also attempted to demonstrate that beneficial information about the events can be derived with the analysis of the paleoclimate archives, especially the ones capable to capture the abrupt changes, that mark the events. Here, the ocean sediments and the speleothems have been described in details, because they are considered as archives that contain valuable evidence of the events. The ocean sediment provide useful indications of the variations related to the Abrupt climate change events, especially to the Heinrich events, because their main feature is the ice-rafted debris found in the ocean sediments. The most valuable information can be derived from the annually-laminated sediments that are deposited continuously, without disturbances. Sediments that fulfill these requirements are very rare. Similarly, the speleothems that have annual banding, or other indicators of annual changes, are the most beneficial. This is because such archives can preserve the variations that occur very rapid, even with decadal to millennial time-scale.

The research further aims to illustrate how much the resolution of an archive is relevant for the study of fast-occurring variations, such as the Abrupt climate change events. The abruptness of the changes associated with the events, requires high-resolution archives that allow preservation of the evidence. Other important criteria include the time-span of the archives, the precise dating, the spatial coverage and the information that can be obtained from the proxy records. In particular, the high-resolution criterion, leads to the election of the ice cores as the most proper archive for study of the abrupt climate change events, marked with extremely short time-scale. Another advantage of the ice cores is the possibility for providing record of the Earth’s climate that is even 800000 years old. Furthermore, they offer vast amount of information about the past air temperature, atmospheric composition, accumulation rate, volcanic eruptions, processes of anthropogenic pollution, sea ice cover, atmospheric circulation, biological activity, atmospheric oxidation capacity, etc.

Still, due to the process of thinning of the annual layers characteristic for the ice cores, a technique that offers high sampling resolution is necessary, for revealing of the evidence imprinted in the ice core records. Such high-resolution should provide obtaining information not only about the seasonal patterns of change of the proxies, but also obtaining information about single storm events that occurred in the past. The resolution of a few hundred micrometers provided by the LA-ICP-MS technique, makes possible the study of the sub-annual patterns of change, even in the highly-compressed layers of the low-accumulation ice cores. Also, the LA-ISP-MS allows precise analysis with low limits of detection, simple preparation of the samples, minimal sample volume, possibility for multielement analysis and low costs. These are the reasons why the LA-ICP-MS is considered to be the principal technique for paleoclimate analysis. The represented results of the performed analyses of the ice cores with the LA-ICP-MS, clearly confirm the applicability of this technique in paleoclimate studies.

Nevertheless, the number of the ice core record investigations, accomplished with this technique, is low. The expectations for more remarkable discoveries, encourage additional studies with LA-ICP-MS. It would not be surprising if with the help of this technique, many answers about the uncertainties related not only to the Abrupt climate change events, but also to other climate variabilities of the past, are revealed. Moreover, models with improved performance that simulate the past climate conditions, are also a crucial part of the future work. What remains to be understood about the Abrupt climate change events, are the mechanisms in the climate system that trigger them. The analysis of the ice cores and other paleoclimate archives with high-resolution techniques, such as the LA-ICP-MS, will be undoubtedly beneficial for achieving the target. Nonetheless, the reoccurrence of the past climatic changes is not impossible, hence the urgent need for their investigation and better comprehension.

10. REFERENCES

Abram, N. J., Wolff, E. W., & Curran, M. A. (2013). A review of sea ice proxy information from polar ice cores. *Quaternary Science Reviews*, 168-183.

Abrupt Climate Change. (2002). National Academies Press. doi:10.17226/10136

Agosta, E. A., & Compagnucci, R. H. (2016). Abrupt Climate Changes During the Marine Isotope Stage 3 (MIS 3). *Springer Earth System Sciences*. doi:10.1007/978-3-319-40000-6_5

Allen, M. R., Dube, O. P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., . . . Zickfeld, K. (2018). *IPCC*. Retrieved from Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways: https://www.ipcc.ch/sr15/chapter/chapter-1/

Alley, R. B. (2000, 02 15). Ice-core evidence of abrupt climate changes. *Proceedings of the National Academy of Sciences* , 1331-1334. doi:10.1073/pnas.97.4.1331

Alley, R. B. (2000). The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews*, 213-226.

Alvarez-Solas, J., Montoya, M., & Robinson, A. (2019). Deglacial abrupt climate changes: not simply a freshwater problem. *Climate of the Past*. doi:10.5194/cp-2019-96

Anderse, K. K., Armengaud, A., & Genthon, C. (1998). Atmospheric dust under glacial and interglacial conditions. *Geophysical Research Letters*, 2281-2284.

Andersen, K. K., Svensson, A., Johnsen, S., Rasmussen, S., Bigler, M., Rothlisberger, R., . . . Clausen, H. (2006). The Greenland Ice Core Chronology 2005, 15–42 ka. Part 1: constructing the time scale. *Quaternary Science Reviews*, 3246–3257.

Anderson, D. M. (2001). Attenuation of millennial-scale events by bioturbation in marine sediments. *Paleocenography*, 352-357.

Andrews, J. T., & Barber, D. C. (2002). Dansgaard–Oeschger events: is there a signal off the Hudson Strait Ice Stream? *Quaternary Science Reviews*, 443–454.

Bales, R. C., & Wolff, E. W. (1995). Interpreting Natural Climate Signals in Ice Cores. *Eos*, 477-488.

Banderas, R., Alvarez-Solas, J., Robinson, A., & Montoya, M. (2014). An interhemispheric mechanism for glacial abrupt climate change. *Springer*. doi:10.1007/s00382-014-2211-8

Bard, E., Rostek, F., Turon, J.-L., & Cendreau, S. (2000). Hydrological Impact of Heinrich Events in the Subtropical Northeast Atlantic. *Science*.

Barker, S., Cacho, I., Benway, H., & Tachikawa, K. (2005). Planktonic foraminiferal Mg/Ca as a proxy for past oceanic temperatures: a methodological overview and data compilation for the Last Glacial Maximum. *Quaternary Science Reviews*, 821–834.

Bassis, J. N., Petersen, S. V., & Mac Cathles, L. (2017). Heinrich events triggered by ocean forcing and modulated by isostatic adjustment. *Nature*. doi:10.1038/nature21069

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., & Bonani, G. (1993). Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature Publishing Group*.

Bradley, R. S. (2015). Paleoclimatic Reconstruction. In R. S. Bradley, *Paleoclimatology (Third Eddition)* (pp. 1-11).

Broecker, W. S. (2003). Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere? *Science*, 1519-1522. doi:10.1126/science.1083797

Carlson, A. E., Clark, P. U., Haley, B. A., Klinkhammer, G. P., Simmons, K., Brook, E. J., & Meissner, K. J. (2007). Geochemical proxies of North American freshwater routing during the Younger Dryas cold event. *PNAS*, 6556-6561.

Chen, S., Wang, Y., Kong, X., Liu, D., Cheng, H., & Edwards, R. L. (2006). A possible Younger Dryas-type event during Asian monsoonal Termination 3. *Science in China Series D: Earth Sciences*, 982-990. doi:10.1007/s11430-006-0982-4

Clarke, G. K., & Marshall, S. J. (1999). A Glaciological Perspective on Heinrich Events. *Geophysical Monograph*.

Clement, A. C., & Peterson, L. C. (2008). Mechanisms of abrupt climate change of the last glacial period. *Rev. Geophys*. doi:10.1029/2006RG000204

Clement, A. C., Cane, M. A., & Seager, R. (2001). An Orbitally Driven Tropical Source for Abrupt Climate Change. *Journal of Climate*.

Climate Policy Watcher. (2020, 01 16). Retrieved from Snow Metamorphism: https://www.climate-policy-watcher.org/snow/snow-metamorphism.html

Cole-Dai, J., Mosley-Thompson, E., & Thompson, L. G. (1997). Annually resolved southern hemisphere volcanic history from two Antarctic ice cores. *Journal of Geophysical Research*, 16761-16771.

Dansgaard, W., & Johansen, S. J. (1969). A flow model and a time scale for the ice core from Camp Century, Greenland. *Journal of Glaciology*.

Davies, S. M., Wastegård, S., Abbott, P. M., Barbante, C., Bigler, M., Johnsen, S. J., . . . Svensson, A. (2010). Tracing volcanic events in the NGRIP ice-core and synchronising North Atlantic marine records during the last glacial period. *Earth and Planetary Science Letters*, 69-79.

Della Lunga, D. (2015, May). Development and Application of Cryo-Cell –UV-Laser Ablation Mass Spectrometry (UV-LA-ICPMS) to Greenland Ice Cores: Implications for Abrupt Climate Change and Ice Physics. London, United Kingdom.

Della Lunga, D., Müller, W., Rasmussen, S. O., Svensson, A., & Vallelonga, P. (2017). Calibrated cryo-cell UV-LA-ICPMS elemental concentrations from the NGRIP ice core reveal abrupt, sub-annual variability in dust across the GI-21.2 interstadial period. *The Cryosphere*, 1297–1309.

Delworth, T. L. (2008). The Potential for Abrupt Change in the Atlantic Meridional Overturning Circulation. *Abrupt Climate Change*, 258-359.

Dreybrodt, W. (2008). Chemical kinetics, speleothem growth and climate. *Boreas*, 347-356.

Easterbrook, D. (2019, 12 16). *Heinrich event*. Retrieved 25.05.2020, from Encyclopædia Britannica: https://www.britannica.com/science/Heinrich-event

Easterbrook, D. (2019, 07 11). *Younger Dryas*. Retrieved from Encyclopædia Britannica: https://www.britannica.com/science/Younger-Dryas-climate-interval

EPICA Community Members. (2006). One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Letters*.

Erhardt, T., Capron, E., Rasmussen, S. O., Schüpbach, S., Bigler, M., Adolphi, F., & Fischer, H. (2019). Decadal-scale progression of the onset of Dansgaard-Oeschger warming events. *Climate of the Past*, 811-825. doi:10.5194/cp-15-811-2019

Erhardt, T., Capron, E., Rasmussen, S. O., Schüpbach, S., Bigler, M., Adolphi, F., & Fischer, H. (2019). Decadal-scale progression of the onset of Dansgaard–Oeschger warming events. *Climate of the Past*, 811-825.

Fahnestock, M., Abdalati, W., Joughin, I., Brozena, J., & Gogineni, P. (2001). High Geothermal Heat Flow, Basal Melt, and the Origin of Rapid Ice Flow in Central Greenland. *Science*.

Fairchild, I. J., & Baker, A. (2012). *Speleothem Science: From Process to Past Environments*. Wiley-Blackwell.

Frajka-Williams, E., Ansorge, I. J., Baehr, J., & Bryden, H. L. (2019). Atlantic Meridional Overturning Circulation: Observed Transport and Variability. *Frontiers in Marine Science*. doi:10.3389/fmars.2019.00260

Gornitz, V. (2008). *Encyclopedia of Paleoclimatology and Ancient Environments*. New York: springer.

Gottschalk, J., Skinner, L. C., Misra, S., Waelbroeck, C., Menviel, L., & Timmermann, A. (2015). Abrupt changes in the southern extent of North Atlantic DeepWater during Dansgaard–Oeschger events. *Nature Geoscience*. doi:10.1038/NGEO2558

Haines, S. A., Mayewski, P. A., Kurbatov, A. V., Maasch, K. A., Sneed, S. B., Spaulding, N. E., . . . Bohleber, P. (2016). Ultra-high-resolution snapshots of three multi-decadal periods in an Antarctic ice core. *Journal of Glaciology*, 31–36.

Helmke, J. P., Schulz, M., & Bauch, H. A. (2002). Sediment-Color Record from the Northeast Atlantic Reveals Patterns of Millennial-Scale Climate Variability during the Past 500,000 Years. *Quaternary Research*, 49–57. doi:10.1006/qres.2001.2289

Hemming, S. R., Broecker, W. S., Sharp, W. D., Bond, G. C., Gwiazda, R. H., McManus, J. F., . . . Hajdas, I. (1998). Provenance of Heinrich layers in core V28-82, northeastern Atlantic: 40Ar/39Ar ages of ice-rafted hornblende, Pb isotopes in feldspar grains, and Nd–Sr–Pb isotopes in the fine sediment fraction. *Earth and Planetary Science Letters*, 317-333.

Hughen, K. A., Southon, J. R., Lehman, S. J., & Overpeck, J. T. (2000). Synchronous Radiocarbon and Climate Shifts During: the Last Deglaciation. *Science*.

Kemp, A. E. (2003). Evidence for abrupt climate changes in annually-laminated marine sediments. *The Royal Society*. doi:10.1098/rsta.2003.1247

Kobashi, T., Severinghaus, J. P., & Kawamura, K. (2008). Argon and nitrogen isotopes of trapped air in the GISP2 ice core during the Holocene epoch (0–11,500 B.P.): Methodology and implications for gas loss processes. *Geochimica et Cosmochimica*, 4675–4686.

Kobashi, T., Severinghaus, J. P., Barnola, J.-M., Kawamura, K., Carter, T., & Nakaegawa, T. (2010). Persistent multi-decadal Greenland temperature fluctuation through the last millennium. *Climatic Change*, 733-756. doi:10.1007/s10584-009-9689-9

Kong, X., Wang, Y., Wu, J., Cheng, H., Edwards, R. L., & Wang, X. (2005). Complicated responses of stalagmite δ 13C to climate change during the last glaciation from Hulu Cave, Nanjing, China. *Science in China Ser. D Earth Sciences*, 2174-2181. doi:10.1360/04yd0140

Kuramoto, T., Goto-Azuma, K., Hirabayashi, M., Miyake, T., Motoyama, H., Dahl-Jensen, D., & Steffensen, J. P. (2011). Seasonal variations of snow chemistry at NEEM, Greenland. *Annals of Glaciology*.

Lachniet, M. S. (2009). Climatic and environmental controls on speleothem oxygen-isotope values. *Quaternary Science Reviews*, 412-432. doi:10.1016/j.quascirev.2008.10.021

Legrand, M., & Mayewski, P. (1997). Glaciochemistry of Polar Ice Cores: a Review. *Reviews of Geophysics*, 219-243.

Li, C., & Born, A. (2019). Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger. *Quaternary Science Reviews*, 1-20. doi:10.1016/j.quascirev.2018.10.031

Lynch-Stieglitz, J., Schmidt, M. W., & Curry, W. B. (2011). Evidence from the Florida Straits for Younger Dryas ocean circulation changes. *Paleochenography*. doi:10.1029/2010PA002032

Lynch-Stieglitz, J., Schmidt, M. W., Henry, L. G., Curry, W. B., Skinner, L. C., Mulitza, S., . . . Chang, P. (2014). Muted change in Atlantic overturning circulation over some glacial-aged Heinrich events. *Nature Geoscience*. doi:10.1038/NGEO2045

Mann, M. E. (2002). The Value of Multiple Proxies. *Science*.

Massam, A., Sneed, S. B., Lee, G. P., Tuckwell, R. R., Mulvaney, R., Mayewski, P. A., & Whitehouse, P. L. (2017). A comparison of annual layer thickness model estimates with observational measurements using the Berkner Island ice core, Antarctica. *Antarctic Science*, 382–393.

Mayewski, P. A., Sneed, S. B., Birkel, S. D., Kurbatov, A. V., & Maasch, K. A. (2013). Holocene warming marked by abrupt onset of longer summers and reduced storm frequency around Greenland. *Journal of Quaternary Science*.

Melton, J. R., Schaefer, H., & Whiticar, M. J. (2012). Enrichment in 13C of atmospheric CH4 during the Younger Dryas Termination. *Climate of the Past*, 1177-1197. doi:10.5194/cp-8-1177-2012

Miller, D. A., Adams, E. E., & Brown, R. L. (2003). A microstructural approach to predict dry snow metamorphism in generalized thermal conditions. *Cold Regions Science and Technology*, 213-226.

Muller, W., & Fietzke, J. (2016). The Role of LA–ICP–MS in Palaeoclimate Research. *ELEMENTS*, 329–334.

Paleoclimate Research. (n.d.). Retrieved from USGS: https://www2.usgs.gov/landresources/lcs/paleoclimate/archives.asp

Pausata, F. S., Battisti, D. S., Nisancioglu, K. H., & Bitz, C. M. (2011). *Nature Geoscience*. doi:10.1038/NGEO1169

Peltier, W. R., & Vettoretti, G. (2014). Dansgaard-Oeschger oscillations predicted in a comprehensive model of glacial climate: A “kicked” salt oscillator in the Atlantic. *Geophysical Research Letters*, 7306-7313. doi:10.1002/2014GL061413

Rashid, H., Polyak, L., & Mosley-Thompson, E. (2011). Abrupt Climate Change Revisited. *Geophysical monograph*, 1-14. doi:10.1029/2011GM001139

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., . . . Guillevic, M. (2014). A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews*, 1-14.

Rasmussen, T. L., Thomsen, E., & Moros, M. (2016). North Atlantic warming during Dansgaard-Oeschger events synchronous with Antarctic warming and out-of-phase with Greenland climate. *Scientific Reports*. doi:10.1038/srep20535

Reid, W. V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y. T., Mokhele, K., . . . Whyte, A. (2010). Earth System Science for Global Sustainability: Grand Challenges. *Science*.

Renssen, H., Mairesse, A., Goosse, H., Mathiot, P., Heiri, O., Roche, D. M., . . . Valdes, P. J. (2015). Multiple causes of the Younger Dryas cold period. *Nature Geoscience*. doi:10.1038/NGEO2557

Research at Centre for Ice and Climate . (n.d.). Retrieved from Centre for Ice and Climate Niels Bohr Institute: http://www.iceandclimate.nbi.ku.dk/research/flowofice/

Rhodes, R. H., Yang, X., Wolff, E. W., McConnell, J. R., & Frey, M. M. (2017). Sea ice as a source of sea salt aerosol to Greenland ice cores: a model-based study. *Atmospheric Chemistry and Physics*, 9417–9433.

Rosell-Mele, A., Maslin, M. A., Maxwell, J. R., & Schaeffer, P. (1997). Biomarker evidence for "Heinrich" events. *Geochimica et Cosmochimica Acta,* 1671-1678.

Ruddiman, W. F. (2013). *Earth's Climate: Past and Future.* Jessica Fiorillo.

Ruth, U., Barbante, C., Bigler, M., Delmonte, B., Fischer, H., & Gabrielli, P. (2008). Proxies and Measurement Techniques for Mineral Dust in Antarctic Ice Cores. *Environ. Sci. Technol*, 5675–5681.

Sikes, E. L., Farrington, J. W., & Keigwin, L. D. (1991). Use of the alkenone unsaturation ratio U37k to determine past sea surface temperatures" core-top SST calibrations and methodology considerations. *Earth and Planetary Science Letters*, 36-47.

Sneed, S. B., Mayewski, P., Sayre, W. G., Handley, M. J., Taylor, K. C., Kurbatov, A. V., . . . Spaulding, N. E. (2015). New LA-ICP-MS cryocell and calibration technique for sub-millimeter analysis of ice cores. *Journal of Glaciology*.

Spaulding, N. E., Sneed, S. B., Handley, M. J., Bohleber, P., Kurbatov, A. V., Pearce, N. J., . . . Mayewski, P. A. (2017). A New Multielement Method for LA-ICP-MS Data Acquisition from Glacier Ice Cores. *Environmental Science and Technology*, 13282−13287.

Stocker, T. F. (1999). Abrupt climate changes: from the past to the future – a review. *Int Journ Earth Sciences*, 365-374. doi:https://doi.org/10.1007/s005310050271

Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., . . . Vinther, B. M. (2006). The Greenland Ice Core Chronology 2005, 15–42 ka. Part 2: comparison to other records. *Quaternary Science Reviews*, 3258–3267.

The Younger Dryas. (n.d.). Retrieved from NOAA: https://www.ncdc.noaa.gov/abrupt-climate-change/The%20Younger%20Dryas

Thermohaline Circulation. (2013, 06 01). Retrieved from Currents: NOAA's National Ocean Service Education: https://oceanservice.noaa.gov/education/tutorial_currents/05conveyor1.html

Treble, P. C., Schmitt, A. K., Edwards, R. L., McKeegan, K. D., Harrison, T. M., Grove, M., . . . Wang, Y. J. (2007). High-resolution Secondary Ionisation Mass Spectrometry (SIMS) δ18O analyses of Hulu Cave speleothem at the time of Heinrich Event 1. *Chemical Geology*, 197-212. doi:10.1016/j.chemgeo.2006.11.009

Vacco, D. A., Clark, P. U., Mix, A. C., Cheng, H., & Edwards, L. L. (2005). A speleothem record of Younger Dryas cooling, Klamath Mountains, Oregon, USA. *Quaternary Research*, 249-256. doi:10.1016/j.yqres.2005.06.008

Vallelonga, P., & Svensson, A. (2014). Ice Core Archives of Mineral Dust. In P. Knippertz, & J.-B. W. Stuut, *Mineral Dust: A Key Player in the Earth System* (pp. 463-485). Copenhagen, Denmark: Springer.

Wang, Y. J., Cheng, H., Edwards, R. L., An, Z. S., Wu, J. Y., Shen, C. C., & Dorale, J. A. (2001). A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China. *Science*.

Zielinski, G. A., Mayewski, P. A., Meeker, L. D., Gronvold, C., Germani, M. S., Whitlow, S., . . . Taylor, K. (1997). Volcanic aerosol records and tephrochronology of the Summit Greenland ice cores. *Journal of Geophysical Research*, 26625-26640.

11. TABLE OF FIGURES