Is there an influence of solar activity on the North Atlantic Oscillation? A literature study of the forcing factors behind the North Atlantic Oscillation

Ida Johansson

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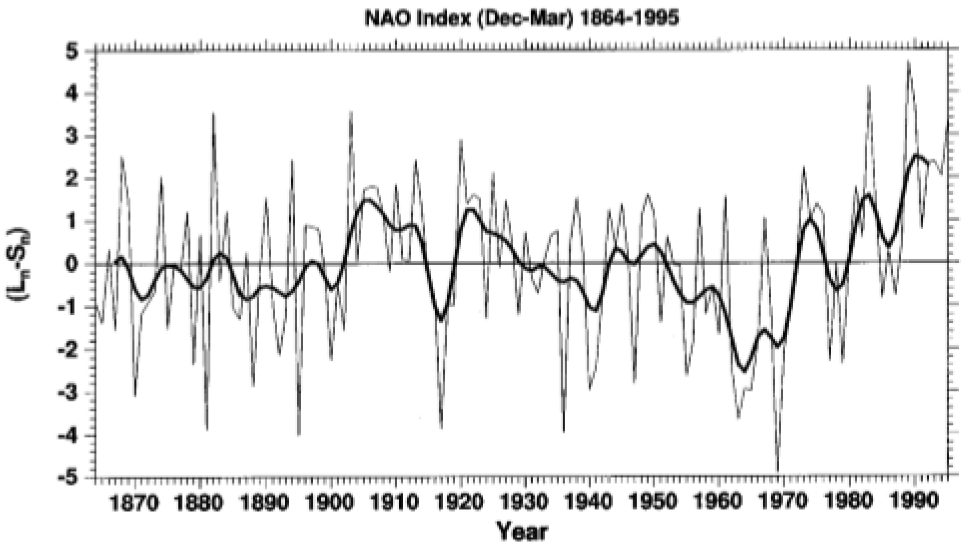

Department of Geology
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Cover Picture: Mean DJFM NAO-index from 1864 —1995 Source: Hurrell 1997

Abstract

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Johansson, I., 2015: Is there an influence of solar activity on the North Atlantic Oscillation?: A literature study of the forcing factors behind the North Atlantic Oscillation *Dissertations in Geology at Lund University*, No. 447, 18 pp. 15 hp (15 ECTS credits)

Abstract: The North Atlantic Oscillation (NAO) is an atmospheric circulation phenomenon, characterized by differences in sea level pressure between the Azores high- and the Icelandic low pressure systems. The NAO fluctuates between a positive and a negative phase depending on how well developed these pressure systems are. The NAO has a great impact on northern hemisphere winter climate since it affects temperatures, storms and precipitation over the Atlantic area. In recent years various studies have investigated the underlying mechanisms which cause the NAO to oscillate. This paper is a literature study with the aim to summarize the most prominent theories of the forcing mechanisms behind the NAO, with a main focus on the effects of variations in solar activity. Different studies disagree on whether the NAO is forced by solar activity variations or not. While the NAO has been shown to correlate with variations in solar activity in the second half of the 20th century, this correlation is less clear during the first half of the 20th century. Several studies indicate that variations in solar activity might affect the NAO by inducing stratospheric circulation changes which are propagated down on the troposphere. During high solar activity years this enhances the westerly winds and causes a positive NAO. It is also suggested that the variations in solar irradiance cause atmospheric blockings to occur. These blockings, that interrupt winds and storm tracks over the Atlantic, is more persistent during low solar activity years and is associated with a negative NAO. Except variations in solar activity, it has been suggested that the NAO varies due to variations in sea surface temperatures, sea ice and volcanic activity.

Keywords: The North Atlantic Oscillation, solar activiy, stratospheric-tropospheric couplings, blockings

Supervisor(s): Florian Adolphi & Raimund Muscheler

Subject: Quaternary Geology

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Sammanfattning

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Johansson, I., 2015: Påverkas den Nordatlantiska Oscillationen av variationer i solaktivitet? En litteraturstudie om de drivande faktorerna bakom den Nordatlantiska Oscillationen. *Examensarbeten i geologi vid Lunds universitet*, Nr. 447, 18 sid.

Sammanfattning: Nordatlantiska Oscillationen (NAO) är ett atmosfäriskt cirkulationsfenomen som kännetecknas av skillnader i havsnivåtryck mellan högtrycksområdet vid Azorerna och lågtrycksområdet över Island. NAO varierar mellan en positiv och negativ fas beroende på hur väl utvecklade dessa högtrycksområden är. NAO har visat sig ha stor påverkan på vinterklimatet på norra halvklotet eftersom den påverkar temperaturer, stormar och nederbörd över Atlantområdet. På senare år har flera studier publicerats med teorier angående vilka bakomliggande faktorer som driver NAO. Denna kandidatuppsats är en litteraturstudie med syfte att sammanfatta de mest framstående teorierna kring de pådrivande mekanismerna bakom NAO, med främsta fokus inriktat på effekterna av variationer i solaktivitet. Det är debatterat huruvida NAO drivs av variationer i solaktivitet. NAO har visat sig korrelera med variationer i solaktivitet under den senare halvan av 1900-talet men under första halvan av 1900-talet syns ingen korrelation. Studier visar att variationer i solaktivitet kan leda till uppvärmning av stratosfären. På grund av ökade temperaturer i stratosfären förstärks de stratosfäriska vindar vilka sedan kan spridas ner till troposfären. Detta leder till ökade västvindar och en positiv NAO-fas. Forskning visar även att variationer i solinstrålning leder till blockerande högtryck. Dessa förändrar vind- och stormriktningen över Atlanten, vilket leder till en negativ NAO-fas. Förutom variationer i solaktivitet har det föreslagits att NAO drivs av skillnader i havsytetemperaturer, havsis och vulkanisk aktivitet.

Nyckelord: Nordatlantiska Oscillationen, solaktivitet, stratosfär — troposfär koppling, blockerande högtryck

Handledare: Florian Adolphi & Raimund Muscheler

Ämnesinriktning: Kvartärgeologi

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1. Introduction

The North Atlantic Oscillation (NAO) is an atmospheric circulation pattern affecting mainly winter weather and climate over large areas in the North Atlantic region. The NAO is characterized by differences in sea surface pressure between the Azores high- and Icelandic low pressure systems. Variations in climate dependent on fluctuations of the NAO is seen from eastern North America to Siberia, and from the Arctic to the subtropical Atlantic (Hurrell et al. 2003).

Climatic effects associated with the NAO have been recognised by mankind for several centuries, but it is not until recently that a larger focus has been put on the subject of the NAO. Since the NAO has a strong impact on the northern hemisphere climate, it is of great importance for people living in this area. The weather variations related to the NAO have an impact on agriculture, water and energy supplies etc. (Hurrell et al. 2003). Hence, numerous detailed studies have been carried out investigating the dynamics, triggers and impacts of the NAO. Furthermore it is important to understand how the NAO reacts to global warming since this could lead to improved predictions of regional climate change (Hurrell et al. 2003).

The mechanisms driving the NAO are under constant debate. It has been debated whether the NAO is a purely atmospherically driven phenomenon or not (Wanner et al. 2001). However, while it has been suggested that the NAO on shorter time scales is driven mainly by internal atmospheric variations, it has been proposed that the NAO on longer time scales is most likely forced by other climatic mechanisms (Magnusdottir et al. 2004). Several theories of these forcing mechanisms behind the NAO have been presented. Among others, suggestions have been made that the NAO fluctuates due to variations in sea surface temperatures, sea ice, volcanic activity and solar activity (Wanner et al. 2001).

The effects of variations in solar activity on the North Atlantic Oscillation are discussed in several studies with various sometimes contradicting conclusions (e.g. Ineson et al. 2011, Brugnara et al. 2013). The solar irradiance reaching earth varies on different time scales. Among these are the 27-day variation as a result of solar rotation, annual variations caused by the orbit of the Earth, the 11-year sun spot cycle and variations over centuries between grand solar maxima and minima (Lockwood 2012).

It has been proposed that the NAO fluctuates in connection to changes in the 11-year solar cycle, however when comparing the NAO index with variations in solar activity it was shown that during some time periods the NAO index correlates more with solar variations than during others (Kodera 2002). The later part of the 20th century is characterized by a positive relationship between the NAO index and solar irradiance. Opposed to this is the earlier part of the 20th century when this connection instead was relatively weak (Kodera 2002). Several studies covering the last 50 years have shown a correlation between solar activity variations and fluctuations of the NAO (Ineson et al. 2011, Lockwood et al. 2010). However, records covering a 250-year time period did not to show a significant relationship between solar activity and the NAO (Brugnara et al. 2013). It is therefore discussed how important variations in solar activity are for the development of the NAO. It has been debated whether recent correlations really just occurred by chance (Oldenborg et al. 2013). Another suggested explanation for recent correlations is that physical changes somewhere in the climate system have caused climatic coupling to occur or made an already existing coupling apparent (Oldenborgh et al. 2013). One difficulty which makes signals between solar activity and the NAO more or less apparent is that different data sets and statistical methods are used in different studies. Depending on the chosen length of the analysed records, different results can be obtained. This means that just a small change in the observed time period can lead to very different outcomes, making the importance of solar activity as a driving factor on the NAO difficult to assess (Brugnara et al. 2013).

1.1 Aim of the paper

As mentioned, one of the biggest question marks concerning the NAO are the forcing factors behind it. Because of the effects on climate in the Atlantic region it is of great importance to understand what is causing the NAO to fluctuate. Different views of the matter have been presented but no final conclusions have been made. The aim of this paper is to conclude and summarize some of the more prominent theories behind the mechanisms forcing the North Atlantic Oscillation. The main focus will be on the theories of variations in solar activity as a forcing factor on the North Atlantic Oscillation.

2. Background

2.1 What is the NAO?

The North Atlantic Oscillation is usually described as a movement of atmospheric mass between the Arctic and the subtropical Atlantic (Wanner et al. 2001). There is no unique way to define the NAO. However, there are two pressure areas often used when describing the phenomenon, the Icelandic low- and the Azores high-pressure systems. The variations in sea level pressure between these two areas generate a pressure gradient. Because of this pressure gradient, westerly winds over the North Atlantic are generated (Wanner et al. 2001). The westerly winds, also known as "jets", reach their maximum speed of 40 m/s at about 12 km up in the troposphere (Hurrell et al. 2003).

When measuring the NAO different statistical methods can be used, either station-based or pattern-based (Wanner et al. 2001). A station-based index is measured as the normalized sea level pressure differences between two monitoring stations in the vicinity of the Icelandic low and Azores high. Alternatively, a spatial-based index, or a principal component based index, can be calculated from performing principle component analysis on the mean sea level pressure anomalies over the North Atlantic sector (usually between 20-80^{o}N and 90^{o}W-40^{o}E) (Wanner et al. 2001)

The NAO is described as being in an either positive or negative phase (see Figure 1). These phases are describing the strength of the circulation pattern. In a positive (NAO+) state the Icelandic low and the Azores high are well developed, resulting in a greater pressure gradient between these two areas. A greater pressure gradient causes stronger and more northern westerly winds. In a negative (NAO-) phase the pressure anomalies at the nodes of the NAO are less developed than normal and as a result the westerly winds get weaker and are positioned further south. However it is important to point out, is that there is not only a confined positive and negative phase of the NAO, but also everything in between (Wanner 2001). The NAO affects the climate mainly during wintertime when the NAO accounts for more than one-third of the total sea level pressure variance over the North Atlantic Ocean (Hurrell et al. 2003). During summertime the spatial extent of the NAO and the sea level pressure variance are smaller than during winter. Atmospheric variations are lager during wintertime which makes the effect of the NAO on surface climate bigger than during summertime. Because of this, most research on the NAO is restricted to wintertime, however the NAO is still noticeable all year around (Hurrell et al. 2003).

There have been periods when the NAO persisted in an either positive or negative phase. During the beginning of the last century until approximately 1930 the NAO winters were characterized by a positive phase. During the 1960s the NAO winters instead showed persistent negative NAO anomalies (Hurrell et al. 2003). Although decadal NAO trends is shown, it is observed that variations in the NAO can occur on very different timescales, making it hard to assess any preferred timescale of the NAO variability (Hurrell et al. 2003).

2.2 The climatic effect of the NAO

The different wind patterns as a result of the various phases of the NAO are accompanied by different patterns of temperature and precipitation over the North Atlantic area. It has been shown that there are statistically significant correlations between sea level pressure anomalies and air temperature anomalies over a wide region in the northern hemisphere (Van Loon & Rogers 1978). Normally during strong positive NAO phases, warm maritime air is moved over the North Atlantic ocean because of the enhanced westerly winds (Hurrell et al. 2003). This makes winter temperatures higher than normal in eastern United States and over northern Europe. Simultaneously in Greenland and the Mediterranean area temperatures are normally below average. During strong negative NAO phases the temperature pattern is opposite (Wanner et al. 2001). This reversing temperature pattern is often referred to as the Greenland seesaw (Van Loon & Rogers 1978).

The positive and negative NAO phases are also connected to different patterns of precipitation as a result of variations in the strength and paths of storms generated over the Atlantic. During a positive NAO the North Atlantic storm track is usually directed more north-eastward over northern Europe than during negative NAO winters (Hurrell et al. 2003). This makes positive NAO phases associated to precipitation anomalies above normal in northern Europe and Scandinavia, while the precipitation levels over southern and central Europe are below average. The opposite precipitation pattern is notable during negative NAO phases (Wanner et al. 2001).

It is seen that the ocean and the atmosphere interact, which makes variations in the ocean affect the NAO (Visbeck et al. 2013). The NAO is also known to force responses in different layers of the ocean (Visbeck et al. 2013). It is shown that NAO variations cause responses in the ocean on multiple time scales. Fluctuations in the NAO seems to be synchronized with interdecadal changes in convection triggering the renewal of intermediate and deep water in the Labrador Sea. On a decadal time scale this has been shown to affect the thermohaline circulation and thereby also of sea surface temperatures (Hurrell et al. 2003).

2.3 Method

This bachelor thesis is a literature study where different views and theories of the forcing mechanisms behind the North Atlantic Oscillation have been studied. The most prominent theories of these suggested forcing factors have been summarized and compiled into the following chapters of this paper.

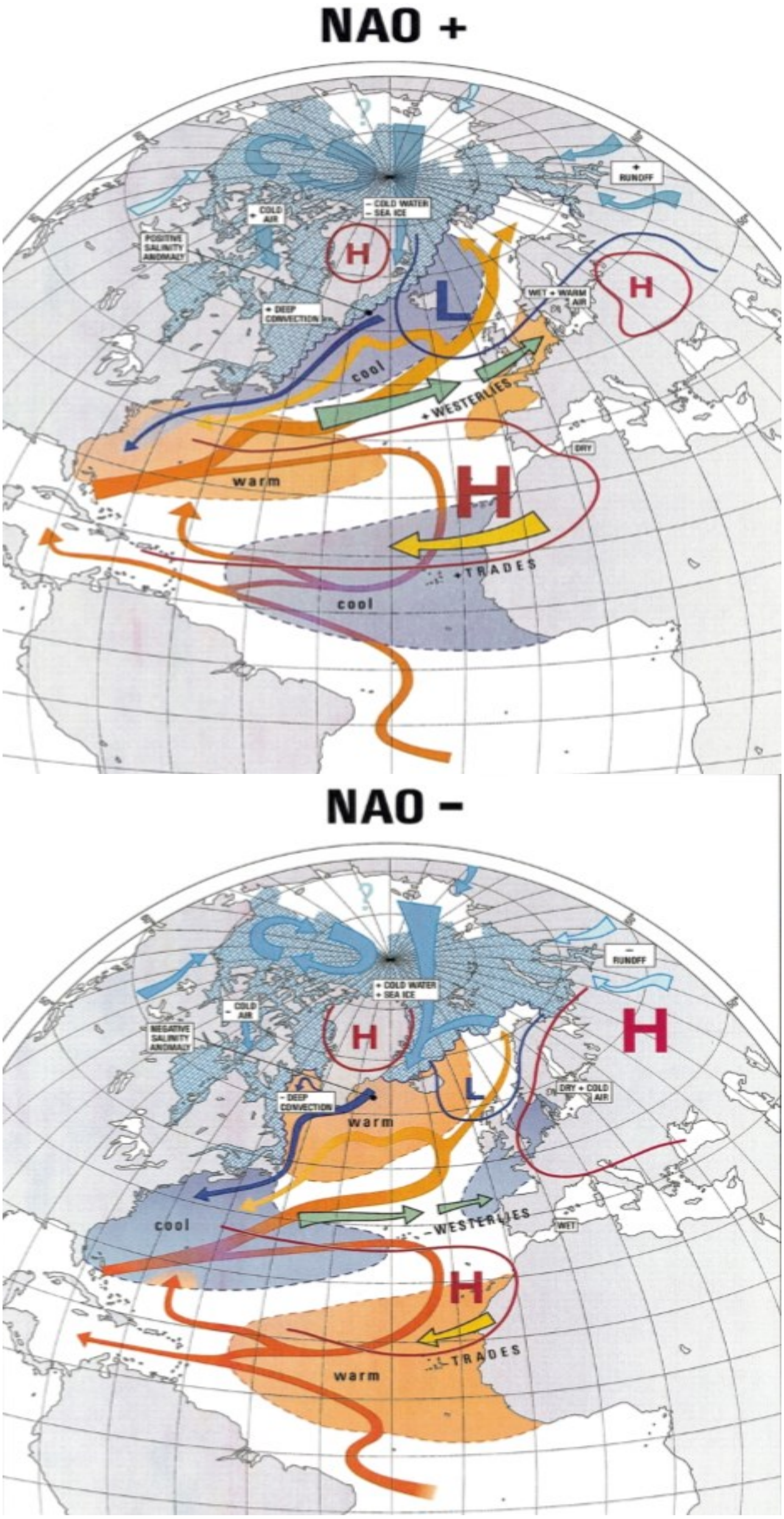

Figure 1. How the different phases of the NAO affects currents (blue and orange arrows), winds (green and yellow arrows) and sea surface temperatures over the Atlantic area. Source: Wanner et al. 2001

3. Results

3.1 The NAO response to variations in solar activity

3.1.1 Stratospheric – Tropospheric couplings

Both the lower troposphere and the stratosphere is known to be sensitive to changes in solar radiation. The lower troposphere is heated due to adsorption of visible light, while heating of the stratosphere is caused by ozone adsorbing ultraviolet radiation (Kodera & Kuroda 2002). Variations in the spectral solar irradiance affects the production and destruction of ozone. Studies show that spectral changes may result in increased or decreased ozone in the atmosphere (Haigh et al. 2010). Ozone production in the stratosphere increases during solar maximum and decreases during solar minimum (Rind et al. 2008). The variation in total solar irradiance during the 11 year cycle is approximately 0.1 %. The variations of solar irradiance in the ultraviolet wavelength (200 – 250 nm) are considerably larger, with a range from 4 – 8 % between solar minimum and solar maximum (Chiodo et al. 2012).

In 2011, using satellite observations of spectral solar irradiance variations, Ineson et al. (2011), modelled the atmospheric response to changes between solar maximum and solar minimum in the 11-year solar cycle. The radiation observations were used to force a climate model, with the purpose to demonstrate responses in surface climate to changes in ultraviolet radiation. The results showed that sea-level pressure over the northern hemisphere responds to solar activity variations mainly in wintertime. The model showed an increasing sea-level pressure at high northern latitudes and a decreasing sea-level pressure at mid-latitudes during low solar activity winters. This pattern corresponds well with a negative NAO-phase in the North Atlantic sector. The modelling result showed that responses to declining ultra violet irradiance begin in the upper stratosphere. As mentioned above, this is associated with the decrease of UV-adsorption by ozone during solar minima. Stratosphere temperatures show a change of 1 – 2 K between solar maximum and solar minimum. This temperature change causes a relative change in the temperature gradient from the North Pole to the equator. This decreased temperature gradient during low solar activity changes the strength and the latitudinal position of the stratospheric jet, resulting in a relatively weak and southward shifted stratospheric jet stream (Kodera 2002). According to Ineson et al. (2011), the wind patterns in the stratosphere as a result of solar irradiance variations are propagated downwards affecting tropospheric circulations. This theory of so called "top-down" propagation of anomalous flow from the stratosphere to the troposphere is confirmed in several other studies (e.g. Matthes et al. 2006). Opposed to the "top-down" mechanism, driven by UV-variations, is the "bottom-up" mechanism, driven by changes in total solar irradiance. The "bottom-up" mechanism is a result of solar heat adsorption by the ocean and land-surfaces. When the ocean adsorbs solar radiation evaporation increases (Engels & Van Geel 2012, Meehl et al. 2003, 2008). It has been suggested that these two mechanisms together increases sea surface temperatures and precipitation over the Pacific (Gray et al. 2010). Furthermore, variations in tropical sea surface temperatures might have an effect on NAO (see Chapter 3.2) (Hoerling et al. 2001).

Recent winters from 2008 – 2011 showed low temperatures over Northern Europe and United States, and milder conditions over the Mediterranean area. During this period the NAO also showed low values (Ineson et al. 2011). Observations also showed easterly wind anomalies in the stratosphere (Ineson et al. 2011). According to Ineson et al. (2011) these cold winters could be a result of a lower solar activity. Chiodo et al. (2012) conducted similar climate model runs. The simulations confirmed the results given by Ineson et al. (2011). According to the Chiodo et al. (2012) simulation, high solar activity lead to stronger westerly winds on the Northern hemisphere, similar to the positive phase of the NAO.

Using climate models, Scaife et al. (2005) showed that the stratospheric impact on the troposphere accounts for a majority of the observed low frequency changes of the North Atlantic oscillation from 1965-1995. During this period when the NAO was increasing, stratospheric winds were also increasing in speed. A correlation coefficient of 0.8 is seen between the NAO and stratospheric winds during this period (Scaife et al. 2005). Although the climate model showed that the NAO was strongly influenced by changes in the stratosphere during this time, it does not automatically mean that the stratospheric changes control surface temperature. It might as well be that stratospheric changes were driven by changes in the troposphere (Scaife et al. 2005).

3.1.2 Variations in spatial extent of the NAO pattern

According to observations of the spatial structures of the NAO, they vary during the different phases of the 11-year solar cycle (Kodera 2002). These observations show that the NAO has a larger hemispherical structure, extending to the stratosphere during solar maximum. During solar minimum the spatial structure is instead restricted to the eastern Atlantic and the troposphere (Kodera 2002). In 2003, Kodera used winter mean sea-level pressures, surface temperatures and sunspot numbers from 1900 through 1999 to investigate how well they correlate to the spatial patterns of the NAO. Sunspot numbers above and below average were used to define high and low solar activity years, respectively. Low solar activity winters showed the typical sea-level pressure seesaw between Icelandic low and Azores high, while high solar activity years showed a more hemispherical NAO pattern, as shown in Figure 2 (Kodera 2003).

The late 20th century experienced a longer positive NAO phase. Throughout this phase solar activity was high. During the beginning of the 20th century a long positive NAO phase also occurred. At this time, however, solar activity was rather low. By comparing mean winter sea-level pressure for both periods differences in NAO spatial patterns were revealed (Kodera 2003). Both periods showed low- and high pressure anomalies over the Icelandic low and the Azores high. However, the late 20th century positive NAO phase showed a greater area with positive and negative pressure anomalies, extending over Europe and the Mediterranean, and the North Pole, respectively. In comparison, at the beginning of the 20th century positive sea-level pressure anomalies never occurred over Europe and negative anomalies only covered parts of the polar region (Kodera 2003). Kodera (2003) draws the conclusion that differences in solar activity between early and late 20th century are correlated to the different spatial patterns of the two time periods. However, Kodera suggests that not only solar activity variations could have had an effect on the spatial variations of the NAO. Kodera also points out that other decadal changes in the Pacific sector could have had an influence on the NAO, and that it is important to keep investigating the causes of the different spatial patterns of the NAO.

3.1.3 Blocking events

Another debated possible effect of solar activity variations is the influence on the occurrence of so-called atmospheric blocking events or “Blockings”. Blockings are described as persistent anticyclones that interrupt the pattern of the westerly winds and form an integral part of the North Atlantic Oscillation occurring more often during negative phases of the NAO (Woollings et al. 2008). They can persist for several weeks, mainly during northern hemisphere winters, and are related to large anomalies in temperature and precipitation (Barriopedro et al. 2008). Studies show that blocking events on the Northern hemisphere in general are not significantly responding to solar activity, however the biggest response is noticed over the Atlantic Ocean where a significant response in blocking persistence is seen. (Barriopedro et al. 2008).

Persistent, long lasting blocking events over the Atlantic area are more common during low solar activity winters (Lockwood et al. 2010, Barriopedro et al. 2008). The blocking persistence over the Atlantic is on average three days longer in low solar activity years (LS years) than during high solar activity years (HS years), while short-lived blockings are more frequent

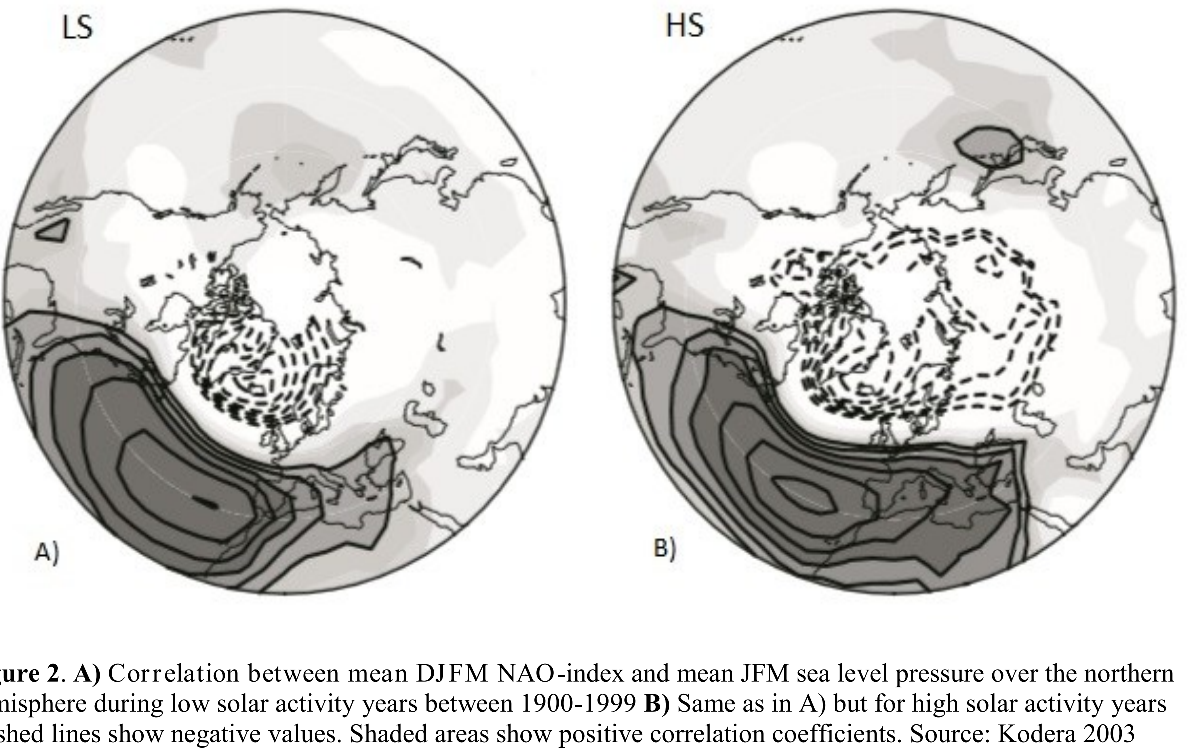

Figure 2. **A)** Correlation between mean DJFM NAO-index and mean JFM sea level pressure over the northern hemisphere during low solar activity years between 1900-1999 **B)** Same as in A) but for high solar activity years Dashed lines show negative values. Shaded areas show positive correlation coefficients. Source: Kodera 2003

during HS years (Barriopedro et al. 2008). Also the spatial blocking patterns between HS and LS winters differ. During HS blockings have a more westward location than during LS years. These blocking patterns resemble those spatial patterns shown by Kodera in 2003 (see Chapter 3.1.2), especially during HS winters when the blocking pattern covers a larger area and a larger NAO pattern is shown (Barriopedro et al. 2008). Atlantic blockings during HS and LS years have a different impact on the climate. Blockings during LS years result in cold European winters, while blockings during HS years do not affect European winters as much because of the more westward location of the blocking centre (Barriopedro et al. 2008).

In the Atlantic area blockings usually occur in the area of southern Greenland leading to that wind flow anomalies in this area which resemble the negative phase of the NAO (Woollings et al. 2008). From around 1960 to 1990 when the NAO went from a negative to a positive state, the frequency of blockings over Greenland was decreasing (Woollings et al. 2008). In addition, it has been suggested that the negative NAO phase in the early 1960s was associated with cold winters in Europe due to prolonged blocking events during this time period (Woollings et al. 2008).

The possible mechanisms behind blockings are debated. Blockings might be a result of stratospheric-tropospheric coupling, as mentioned in previous chapter, which could explain the NAO extension into the stratosphere, shown by Kodera in 2003, during HS winters (Barriopedro et al. 2008). The question remains whether the different phases of the NAO lead to blockings or blockings lead to variations in the NAO (Barriopedro et al. 2008). Different studies have shown contradicting results. Shabbar et al. (2001) proposed that the NAO forces blockings since it largely controls temperatures over ocean and landmasses in the Atlantic area. During a negative NAO temperature are warmer over the ocean and colder over land than during the positive phase. According to Shabbar et al. (2001) negative NAO conditions make it more favourable for persistent blockings to occur. Croci-Maspoli et al. (2007) instead stated that blockings might force variations in the NAO. Opposed to Shabbar et al. (2001) they proposed that persistent blockings could be causing the establishment of a negative NAO and also extend the occurrence of a negative NAO phase. According to Croci-Maspoli et al. (2007) blockings evolved during a positive NAO, dependent on their location, might also help sustain a positive NAO.

3.2 The NAO response to variations in sea surface temperatures

Several observations show that the NAO causes variations in the ocean circulation (e.g. Visbeck et al. 2013). It has been shown that the NAO strongly affects the Atlantic Ocean through changes in the westerly winds, modifying ocean-atmosphere heat exchange (Czaja et al. 2013). Regarding currents, density variations and water masses, the NAO causes large-scale anomalies over the Atlantic Ocean (Czaja et al. 2013). Sea surface temperatures (SST) over the Atlantic show a tripole pattern during winters driven by the NAO. This pattern is characterized by cold SST anomalies in the subpolar and subtropical regions, and warm SST anomalies in the mid latitudes during a positive NAO (Visbeck et al. 2001) (see Figure 1 & 3). The ocean is seen to lose energy to the atmosphere in the subpolar and subtropical Atlantic due to strong westerlies, however it gains energy in the midlatitudes because of a decrease in wind speed. Therefore it is proposed that the large SST tripole is driven by the turbulent energy flux connected to the NAO (Deser et al. 2010). It is indicated that the SST tripole responds to variations in the NAO on a monthly timescale (Bader e al. 2011) However, on a longer, decadal to multidecadal timescale it is instead suggested that the NAO responds to variations in the SST tripole (Bader et al. 2011).

Since the atmosphere exchanges heat and moisture with the land and ocean beneath it, it is not an isolated system. It is therefore possible that the NAO fluctuates as a result of changes in the ocean, just as the ocean changes due to NAO variations (Rodwell et al. 1999). In a study from 1999, Rodwell et al. simulated December to February NAO and sea surface temperatures over northern Europe index from 1947 – 1997, showing a strong significant correlation between both variables. This could indicate, that if sea surface temperatures are known, it might be possible to predict whether the NAO is positive or negative in two out of three years (Rodwell et al. 1999). The same study showed that evaporation increases over areas with positive SST anomalies and decreases in areas with negative SST anomalies. According to Rodwell et al (1999), this means that sea surface temperatures can modulate the structure of the NAO as a result of changes in evaporation, atmospheric heating and precipitation.

Czaja & Frankignoul (2001) suggested that the NAO could be driven by a positive feedback between the SST tripole and the NAO as a result of a direct interaction with the ocean, similar to what Rodwell et al. (1999) suggested. They proposed that this might affect the NAO on longer timescales. However, Czaja & Frankignoul (2001) also suggested that the NAO might vary because of a different SST pattern, called the North Atlantic Horseshoe (NAH). This SST pattern is generated during summertime, by ocean-atmospheric interactions, and lasts through early winter. The summertime NAH is shown to correlate with a positive NAO during winter. It has been hypothesized that the NAH generates a response in the NAO and that this response then generates the SST tripole in wintertime. However, it appears that the NAH cannot generate a NAO pattern during summertime because of unidentified, most likely, dynamical reasons (Czaja & Frankignoul 2001). Yet, since the NAH is persistent through fall and early winter it has an impact on the

NAO in wintertime because of a then more active atmospheric flow over the North Atlantic area. Different to the suggestion that there is a positive feedback between the NAO and the SST tripole because of a direct interaction between the atmosphere and the ocean, the idea that the summertime NAH generates a positive winter NAO instead proposes that NAO variations are caused by an external forcing. By observing summer sea surface temperatures Czaja & Frankignoul (2001) have been able to predict up to 15 % of the monthly NAO variations during winter.

It has also been suggested that the NAO varies not only because of changes in the Atlantic Ocean but also from variations in tropical sea surface temperatures. Hoerling et al (2001) proposed that the NAO might vary in response to atmospheric heating and tropical precipitation over equatorial oceans. Czaja & Frankignoul (2001) also investigated the NAO response to tropical SSTs and found a small significant influence, however smaller than the response to midlatitude SSTs.

According to Czaja et al. (2013) observations are still too limited in time to conclude the significant impact of the Atlantic Ocean on the NAO. In addition, it is difficult to determine the impact of the ocean on the NAO, since the NAO show an impact on the ocean (Czaja & Frankignoul 2001).

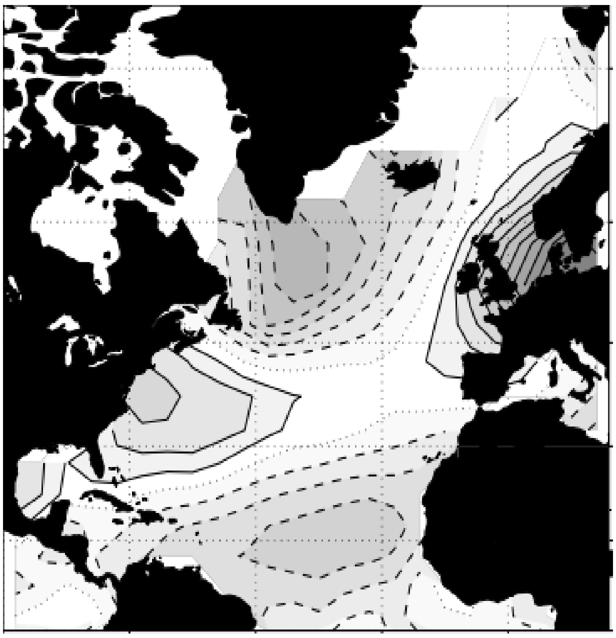

Figure 3. Covariance map between mean DJFM sea surface temperatures and NAO-index from 1900 – 2000. The map show the SST tripole. Dashed/solid lines show negative/positive values. Source: Visbeck et al. 2013

3.3 The NAO response to variations in sea ice

It has been suggested that the atmospheric circulation might be affected by sea ice (e.g. Alexander et al 2003, Deser et al. 1999). Variations in sea ice extent can modulate the climate by changing the surface albedo as well as heat and moisture exchange between the ocean and the atmosphere (Deser et al. 1999).

An observational study by Honda et al. in 2009 showed that a low sea ice minima corresponded to a negative NAO in wintertime. Due to ice loss in the coastal area of Siberia during summer the ice cover in Barents sea is reduced in autumn. Honda et al. (2009) proposed that the ice loss intensifies the strength of the cold northerlies and causes temperature anomalies over Eurasia associated with a negative NAO. Francis et al. (2009) focused on sea ice losses in summertime and the effects on the NAO in the following months. This study showed that after summers with less ice than average, more heat and moisture extended from the surface to the lower stratosphere mainly in areas where sea ice was retreating. This heating of the stratosphere combined with more solar energy adsorbed by the ocean as a result of the decreasing albedo diminishes the regrowth of sea ice in autumn. In consequence the pressure gradient between the Azores high and the Icelandic low is reduced by up to 20% after summers with low ice cover, resembling NAO- conditions, which in turn reduces the speed of the westerly jets during winter (Francis et al. 2009).

Simulations made by Seierstad & Bader in 2008, showed that a future reduced sea ice cover would reduce storminess in the middle latitudes and towards the Arctic. According to Seierstad & Bader this result is associated with a negative phase of the NAO during late winters. .

Magnusdottir et al. 2004, performed simulations investigating the effect of SST and sea ice variations on northern hemisphere teleconnections. These simulations showed that sea ice variations induce a greater atmospheric response associated with the NAO than variations in SSTs does. Model simulations with different sea ice extent showed large variations in surface energy flux. Simulations where sea ice was removed from the area around eastern Greenland showed similarities with the negative phase of the NAO. Areas with decreased sea ice were characterized by an increasing latent and sensible surface flux. This demonstrates the isolation between the ocean and the atmosphere by sea ice. Furthermore, the decreasing sea ice also led to increasing precipitation over this area. Similarly, Magnusdottir et al (2004), suggested that there is a negative feedback between the NAO and sea ice variations, resulting in a negative NAO when sea ice is decreasing.

Alexander et al. (2004) suggested that the retreat of sea ice forces a direct atmospheric response in a relatively small spatial area, mainly were the ice is retreating. Alexander et al (2004) stated that evaporation and precipitation increases just in the area of ice loss. However, if this area is in the vicinity of the local storm tracks, sea ice loss can then impact on the paths and strength of storms. Hence, the findings of Alexander et al (2004), support the idea by Magnusdottir et al. 2004, that ice loss in eastern Greenland weakens the North Atlantic storm track and is therefore strongly associated with the negative phase of the NAO.

3.4 The NAO response to volcanic eruptions

Volcanic aerosols are emitted during volcanic eruptions. While aerosols from smaller eruptions usually remain in the troposphere where they persists only for a couple of weeks, larger eruptions inject aerosols up to the stratosphere where they can remain for several years (Muscheler & Fischer 2012). The climatic effect of volcanic forcing, caused by large volcanic eruptions, is well observed. In general, the climatic effect is large but short-lived (Fischer et al. 2007). It has also been shown that large volcanic eruptions can affect atmospheric circulation patterns as the NAO, but to what extent is still under debate (e.g. Fischer et al. 2007, Shindell et al. 2004).

Fischer et al. (2007) studied the effect of 15 major volcanic eruptions onto northern hemisphere climate during the last 500 years. Observations indicate that volcanic eruptions are followed by a positive NAO, resulting in warm and wet winters over Northern Europe. According to Fischer et al. (2007) northern hemisphere winters show strong warm anomalies about two years after a large volcanic eruption. This result was confirmed by Ottera et al. in 2010. In this study volcanic eruptions were modelled by simulating an injection of volcanic aerosols into the stratosphere, resulting in heating of the lower stratosphere. The results imply a two year positive NAO phase after a volcanic eruption associated with warm temperatures over northern Europe, as shown in Figure 4. Similar results were obtained by Shindell et al. (2004). Using climate model simulations, Shindell et al. (2004) showed that volcanic aerosols heat the stratosphere by absorbing longwave radiation. This heating enhances westerly winds which in turn are projected down to the troposphere resulting in stronger tropospheric westerlies, showing great similarity to the solar driven “top-down” mechanism. Shindell et al. (2004) suggested that volcanic eruptions show a pronounced effect on the NAO during wintertime because of enhanced stratosphere-troposphere coupling. During summertime volcanic aerosols instead show a cooling effect on the northern hemisphere as a result of radiative cooling. It is therefore suggested that the effect of volcanic eruptions onto the NAO is seasonally dependent (Shindell et al. 2004).

It has been suggested that during the Little ice age (~ 1300 – 1900) volcanic eruptions triggered sea ice – ocean feedbacks (Schleussner & Feulner 2013). When volcanic aerosols scatter solar irradiance back to space this might lead to an expansion of sea ice on the northern hemisphere because of surface cooling. When sea ice is extended in the North Atlantic Ocean it affects ocean dynamics and reduces the possibility for sea ice to melt (Zong et al. 2011). In this climate modelling study

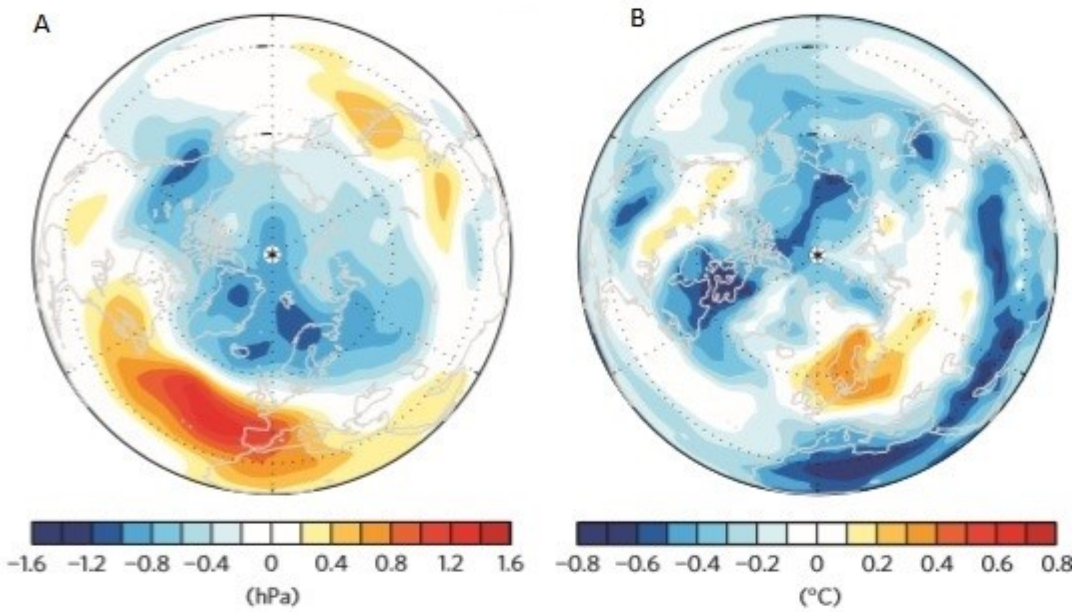

Figure 4. The response to volcanic forcing
A) Sea level pressure anomalies over the northern hemisphere two years after a simulated volcanic eruption. The pressure anomalies show a positive NAO phase.
B) Same as in **A** but showing temperature anomalies over the northern hemisphere.
Source: Ottera et al. 2010

the NAO went from a persistent positive phase to a more fluctuating state when transitioning from the medieval warm period into the little ice age. It has therefore been suggested that this sea ice – ocean feedback as a result of volcanic eruptions might have affected the NAO (Schleussner & Feulner 2013).

4. Discussion

4.1 Summary

The North Atlantic Oscillation is likely driven by several different forcing factors, but to what extent is not yet established. It has been suggested that the NAO might be driven by variations in 11-year solar cycle. Observations show that the spatial extent of the NAO varies due to variations in solar activity, with a large hemispherical structure extending to the stratosphere during high solar activity years and a smaller spatial structure confined to the troposphere during low solar activity years (Kodera 2002). The spatial variations of the NAO might be caused by couplings between the stratosphere and the troposphere. Increased irradiance in the UV spectrum causes stratospheric heating which in turn generates stratospheric winds (Ineson et al. 2011). This stratospheric wind anoaly can be propagated downwards into the troposphere, generating a positive NAO with increased westerly winds during high solar activity ("top-down" mechanism). Stratospheric-tropospheric couplings might also cause atmospheric blockings to occur. Studies show that the frequency of long lasting blockings increases during low solar activity (Barriopedro et al. 2008). These blockings tend to interrupt the paths of the westerly winds and are shown to correlate with a negative NAO, although, it is not unequivocal whether blockings lead to variations in the NAO or the NAO leads to blockings. Besides the "top-down" influence on climate, changes in solar activity may also trigger "bottom-up" mechanisms causing changes in ocean temperatres via adsorption of solar radiation. This mechanism is heating the ocean mainly in tropical waters which is suggested to show an effect on the NAO as a result of increasing precipitation and evaporation (Meehl et al. 2003, 2008). The NAO during wintertime is associated with a SST tripole over the Atlantic that is responding to variations in the NAO on shorter time scales. On longer decadal time scales however, the NAO is suggested to be forced by variations in this SST tripole. Variations in the SST tripole may also cause the spatial structure of the NAO to vary due to atmospheric heating, evaporation and precipitation (Rodwell et al. 1999). It is also suggested that the winter NAO varies due to another SST pattern called the North Atlantic Horseshoe. This pattern is seen during summertime but is believed to show a delayed effect on the following winter NAO (Czaja & Frankignoul 2001) .

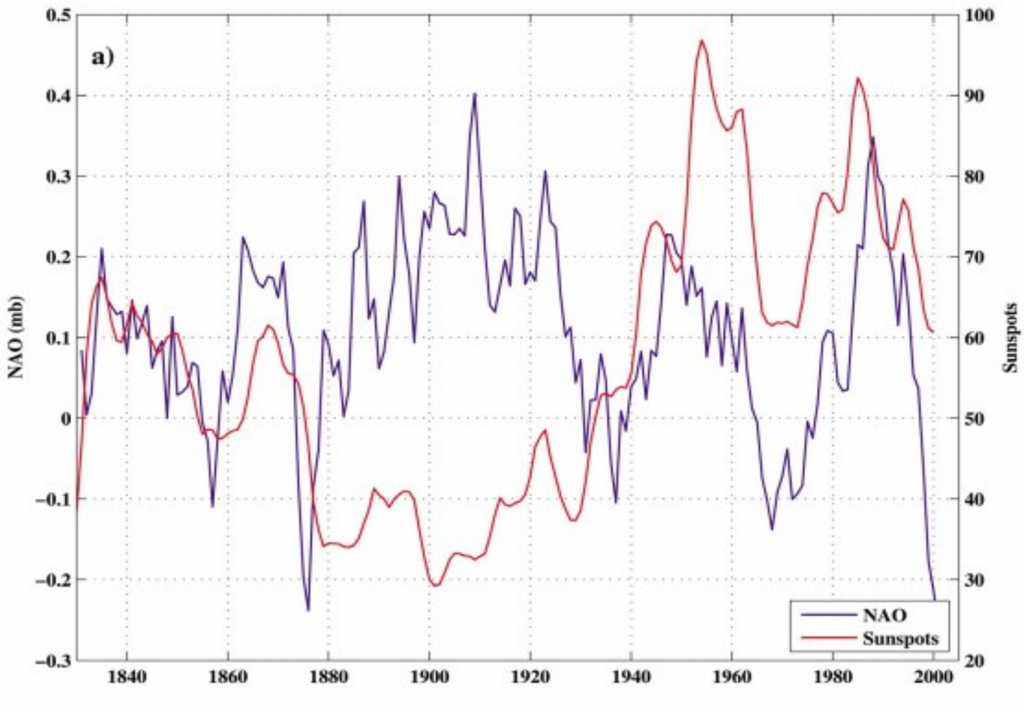

Figure 5. The correlation between the mean NAO index and the mean number of sunspots during December to February 1830 – 2000.

The ocean is suggested to force the NAO not only through variations in sea surface temperatures but also by the increase or decrease of sea ice. It is shown that the decrease of sea ice is corresponding to a negative NAO, which might be a result of a negative feedback (Magnusdottir et al. 2004). When sea ice decreases, heat and moisture are released in to the atmosphere. Depending on where the ice is retreating this might show an effect on the atmospheric storm paths. When sea ice is decreasing in the area east of Greenland this may interrupt the Atlantic storm path and cause the NAO to respond with a negative phase (Alexander et al. 2003). In addition, the NAO can be affected by large volcanic eruptions. Volcanic eruptions release aerosols into the stratosphere in which they can remain for several years. Observations show that the winter NAO responds with at positive phase for about two years after a large volcanic eruption (Ottera et al. 2010). The release of aerosols into the stratosphere causes stratospheric heating and enhances the westerly winds. Opposite to this, volcanic aerosols can cause a cooling in the northern hemisphere during summertime. It is therefore possible that the NAO response to volcanic eruptions is seasonally dependent (Shindell et al. 2004).

4.2 Is there an influence of solar activity on the NAO?

As shown in Figure 5, there is a similar trend between the NAO and the amount of sunspots in the 11 -year sunspot cycle during the second half of the 20th century. However, it is obvious when studying Figure 5 that this correlation is not always showing. The relationship shown between sunspots and the NAO index in the latter part of the 20th century is not seen in the beginning of the century. Many of the studies presented on the subject of solar activity as a forcing factor on the NAO only covers the last part of the 20th century, since there is more reliable data covering this period. However, by only focusing on recent years, this though might result in a fabricated picture of the relationship between solar activity and the NAO. A change in the analysed period can change the strength of this relationship significantly. Why this obvious correlation is shown in the later 20th century and not earlier is the main question to be answered. Could it be, as mentioned in the introduction of this paper, that the dynamics of other factors in the climate system have made this correlation apparent? Or did this correlation occur just by chance?

Even though the forcing of solar activity is not apparent all the time, it might not necessarily mean that the sun is not affecting the NAO. It could be that other mechanisms are more strongly affecting the NAO during certain time periods instead. It is made clear that there are various climatic factors such as sea surface temperatures, sea ice variations and volcanic eruptions that might be forcing the NAO. It is seen that variations in some climatic component might cause a response somewhere else in the climatic system. For instance, it is suggested that solar irradiance affects sea surface temperatures by bottom-up mechanisms or that sea ice variations be might be affected by volcanic activity. Hence, it is important to see these factors as parts of a coherent system, instead of as isolated factors. It could be that a series of mechanisms are causing the fluctuations of the NAO rather than one single forcing. One difficulty is therefore that most studies and simulations presented on the subject of the NAO only focus on one possible mechanism.

It is also important to consider that there are other factors that are not discussed in this paper which could be affecting the NAO. The climatic effect of anthropogenic activity and the increase of greenhouse gasses in the atmosphere during the latter half of the 20th century is one of these factors that should be further investigated (Shindell et al. 2001).

5. Conclusions

In this paper several proposed forcing mechanisms behind the variations of the North Atlantic Oscillation are summarized. It is suggested that the NAO might be forced by variations in sea surface temperatures, sea ice, volcanic eruptions and solar activity etc. It is shown that the NAO in recent decades correlates with solar activity variations, yet this correlation is not apparent in earlier decades. This makes it hard to determine the solar impact on the NAO. To be able to define the forcing mechanisms behind the NAO further investigations, which combine the different suggested mechanisms together, need to be done. As for the future, it is important to investigate the impact of anthropogenic releases of greenhouse gasses into the atmosphere since this might show an impact on the development of the NAO.

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