Storm frequency in the Northern Baltic Sea Region and its Association to the North Atlantic Oscillation

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Abstract

Storms can be both destructive and valuable at the same time. They expose coastal areas to various risks but can also enhance the supply of wind energy and provide marine ecosystems with oxygen rich water. As the North Atlantic Oscillation (NAO) is known to have a significant impact on the wind climate in Europe, investigating its interconnection to storm frequency and intensity under global warming circumstances in the Northern Baltic Sea region was of interest in this study. Wind speed data series of annual storm counts were obtained from five meteorological stations along with PC-based NAO values over the period 1960-2017. The data series were analysed in Microsoft Excel and modelled using a Poisson regression or negative binomial regression model in SPSS Statistics. The results display an unsystematic spatial pattern both in the association to the NAO as well as in the overall storm frequency. However, storm (≥ 21 m s⁻¹) frequency has generally been decreasing, whereas the proportion of severe storms (≥ 24 m s⁻¹) has slightly been increasing, suggesting a tendency toward stronger but fewer storms. Even though only certain data series display statistically significant findings (p ≤ .05), a majority of the winter storms and severe winter storms display a positive association, indicating that a higher NAOI is related to a greater number of winter storms. The spatial and temporal variability in the obtained results can partially be explained by storm tracks and prevalent wind directions. Nevertheless, inhomogeneities do presumably affect the wind speed observations through internal and external influences and changes related to the meteorological stations. Future research should, therefore, also consider integrating other storm related parameters, such as direct air pressure measurements, wave heights and storm surges, as well as implement different data homogenization methods and techniques.

Key words

Storm frequency, wind speed, NAO, atmospheric circulation, Poisson regression, Negative binomial regression, Northern Baltic Sea region
Glossary

AO – Arctic Oscillation
FMI – Finnish Meteorological Institute
GHG – Greenhouse Gas
GLM – Generalised Linear Model
MR – Mediterranean Region
NAM – Northern Annular Mode
NAO – North Atlantic Oscillation
NAOI – North Atlantic Oscillation Index
NB – Negative Binomial regression
NH – Northern Hemisphere
PO – Poisson regression
SCAND – Scandinavian Blocking
SMHI – Swedish Meteorological and Hydrological Institute
SSP – Sea Surface Pressure
SST – Sea Surface Temperature
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1. Introduction

Storms are characterized by a variety of disturbances that modify normal atmospheric conditions. They occur when barometric pressures drop, which in combination with high pressure centres create stormy weather conditions such as cloud formation, heavy winds and abundant precipitation. In Europe, hazardous weather events, including strong wind gusts, storm surges and heavy precipitation, are often associated with the advancement of strong extra-tropical cyclones originating in the subtropical North Atlantic (Gómara et al., 2014). These severe weather events can rupture normal human activity, impact ecosystems, cause disruptions to transport systems, endanger human life, damage infrastructure and buildings and, consequently, impact the economic stability of a whole country or a region (Pardowitz, 2014).

As atmospheric circulation and pressure systems drive the surface wind climate, storm development is dependent on changes and disturbances in these large-scale atmospheric patterns. One such circulation pattern is the North Atlantic Oscillation (NAO), which is considered one of the most prominent atmospheric circulation patterns impacting climate variability in the Northern Hemisphere (Hurrell et al., 2003). Driven by differing sea surface pressure (SSP) values between the Icelandic low and the Azores high pressure systems, the NAO has a significant impact on local weather patterns in Europe. Since the 1980s, both the NAO and the large-scale hemispheric mode of variability, the Arctic Oscillation (AO), have primarily been displaying higher index values (Ostermeier and Wallace, 2003), in parallel with unprecedented global warming. However, the variability in these circulation systems can be related to several different mechanisms, and a full consensus on whether the variability is caused by purely atmospheric processes, other climatic mechanisms or by anthropogenic climate change has not been reached.

Several studies have acknowledged the link between a positive NAO index, an enhanced zonal circulation and a northeastward tilt in the passage of extratropical cyclones towards Northern Europe (Gómara et al., 2014; Domeisen et al., 2018; Rogers, 1997; Sepp et al., 2018; Marshall et al., 2001; Rutgersson et al., 2015). When the NAO was primarily displaying positive values between the 1980s until the mid-1990s, an increase in storminess was simultaneously reported by several studies. Furthermore, most climate models predict a northeastward tilt in the storm track in addition to fewer but stronger extra-tropical cyclones in Europe and the North Atlantic (Rutgersson et al., 2015; Donat et al., 2011a), which would impact the Baltic Sea region. Since the region is already influenced by volatile weather conditions, with westerly winds predominating throughout the year (Rutgersson et
al., 2015), several urban areas located along the low-lying coastline of Sweden and Finland facing
the Gulf of Bothnia, the Archipelago Sea and the Sea of Åland, are impacted.

More intense storms and stronger wind speeds have many different consequences on society. They
expose coastal cities as well as the agricultural and forestry sectors to various risks with potentially
large economic losses but can also have positive effects on the supply of wind energy and provide
the Baltic Sea with salt and oxygen rich inflow from the North Sea (Rutgersson et al., 2015).
Investigating the frequency and intensity of storms in association to the variability of the NAO is,
consequently, of societal interest in many different aspects.

1.1 Aims and objectives

Results from several previous studies indicate that storm frequency is linked to the different phases
of the NAO, particularly in the winter period. Accordingly, the main assumption in this study is that
storm frequency and the NAOI interact in the study region. The aim is, therefore, to investigate storm
frequency and intensity in the northern section of the Baltic Sea region between 1960 and 2017, and
to examine if the obtained results relate to variations in the NAO. Furthermore, seasonal and bidecadal
(20-year-period) fluctuations will be investigated in addition to regional variations both on a north-
south and east-west axis, in order to display potential geographical differences as well as to reveal a
potential correlation in the winter period. To reach this aim, near-surface wind speed measurements
from five meteorological stations along the coastline of Sweden and Finland will be examined along
with NAOI values from the National Center for Atmospheric Research (NCAR). Data analysis will
be performed in Microsoft Excel and statistical modelling in SPSS Statistics to create data sets on
storm frequency and to reveal the potential association between the storminess and the NAO.
Consequently, the research questions are as follows:

1. Is there an association between the NAO and storm frequency in the northern section of the Baltic
Sea Region?
2. Are there inter-seasonal and inter-bidecadal variability patterns in storm frequency and storm
intensity?
3. Are there any regional differences in storm frequency and storm intensity in the study region?
2. Background

2.1 The North Atlantic Oscillation

The NAO can be described as a variability mode within the atmosphere that redistributes atmospheric mass between the subtropical Atlantic and the Arctic region (Hurrell et al., 2003). Even though there are many different ways in which the NAO can be defined, it is usually described as an atmospheric teleconnection pattern characterized by variations in near-surface pressure anomalies between the Icelandic Low and the Azores high pressure systems (Rutgersson et al., 2015). The variations in these pressure fields cause a pressure gradient to develop between the two areas, which in turn generates westerly winds (Hurrell et al., 2003). When defining the NAO, a link to climatic circumstances in Europe and the Atlantic is usually made. It is important to point out, however, that the NAO is part of a much larger extratropical hemispheric circulation pattern, namely the Arctic Oscillation (AO), also called the Northern Annular Mode (NAM) (Domeisen et al., 2018).

The NAO can be measured through either station-based or pattern-based indices (Cohen & Barlow, 2005). Traditionally, the pressure difference between meteorological stations both on the Azores and on Iceland have been used to define the NAO index. These station-based indices can date as long as back to the late 17th century, giving the advantage of observing long-term changes in the NAO (Hurrell et al., 2003). However, as the stations are in fixed locations, they can only give an approximation of the annual NAO variability since the centre moves throughout the annual cycle. The more sophisticated pattern-based index derived from a principal component (PC) analysis on sea level pressure anomalies, gives a more adequate representation of the large-scale spatial pattern of the NAO (ibid.).

The climatic circumstances vary in the Atlantic and the surrounding continents, depending on how enhanced or diminished the pressure systems are in comparison to each other (ibid.). The NAO is, therefore, said to be either in a negative or positive phase (Fig. 1). During a positive phase (NAO+), the pressure gradient is greater, which in turn causes more mild, humid and stormy winters in northern Europe and, conversely, more dry and cold winter conditions in southern Europe (Met Office, 2016). Reversed circumstances occur during a negative phase (NAO-), when a less developed pressure gradient prevails. The variability of the NAO is not, however, confined to these opposite phases, since a variety of phases of different strength can occur (Wanner et al., 2001).
Whether the NAO is entirely governed by processes internal to the atmosphere, or whether external forcing mechanisms such as anthropogenic climate change, volcanic aerosols, changes in solar activity or land- and ocean-atmosphere coupling processes are influencing the different phases of the NAO, is still a matter of conjecture (Hurrell et al., 2003). However, several studies point to the potential influence of various external mechanisms that might, consequently, render light on the predictability of the NAO (ibid.). Since the NAO has a large-scale impact on the climatic circumstances and, therefore, on human societies and ecosystems in the Northern Hemisphere, its potential interdecadal and interseasonal predictability is of interest for both the current discussions on climate change (ibid.), as well as for the development of mitigation and adaptation strategies for human societies.

![Figure 1](image.png)

**Figure 1.** a) The positive NAO phase (NAO+) and b) the negative NAO phase (NAO−) – MetOffice, 2016.

### 2.2 Surface Wind Climate and its Association to the North Atlantic Oscillation

The surface wind climate is driven by differences in air pressure fields that create pressure gradient forces between different regions around the world. Since the large-scale atmospheric circulation system, the NAO, impacts climatic conditions and extratropical storm tracks in Europe, the spatial and temporal variability of the wind climate is seemingly influenced (Rutgersson et al., 2015). Hence, interannual and interdecadal variability in the state of the NAO play a significant role for large-scale changes in the surface wind climate (ibid.) and, therefore, on the occurrence of wind storms. Several studies have been conducted as to how synoptic and regional storm events are changing in respect to
frequency and intensity, and what role the NAO plays in these changes in the Northern Hemisphere (NH).

A linkage between a positive NAO phase and storminess has been reported by several studies across Europe. Donat et al. (2009) found that storm events in Central Europe mainly take place during fairly positive NAO phases, whereas up to 20% of all storms occur during strongly positive NAO phases. Furthermore, Wang et al. (2009) found a significant correlation between the NAOI and storminess conditions in the Northeast Atlantic region between 1874 and 2007. In their study, especially spring and winter storminess displayed a substantial correlation with higher NAO indices, whereas the correlation with autumn storminess was rather insignificant. Lastly, Nissen et al. (2010) found an increase (decrease) in strong wind events in the eastern Mediterranean Region (MR) (the western MR) during a positive NAO phase. The decrease of wind events in the western MR, also noted by Kyselý and Huth (2005), can be explained by the north-eastern shift in the storm track during a positive NAO phase, leading to increased (decreased) storminess in northern Europe (southern Europe). Presumably, a negative NAO phase give rise to an enhanced storm frequency and intensity in the western MR (Cid et al., 2015).

Cid et al. (2015), Walz et al. (2018) and Villarini et al. (2010; 2012) use statistical models such as the Poisson Regression model to examine the interdependence between storm counts and different climate indices such as the NAO. Villarini et al. (2010) model tropical storm frequency by using either Poisson regression or negative binomial regression depending on the dispersion of the data set. Even though clear distinctions can be made between the impact of a positive NAOI versus a negative NAOI on storminess, some studies report only weak and variable correlations between the variables (Sepp et al., 2018; Burningham & French, 2012; Pirazzoli et al., 2010). Burningham & French (2012) conclude that the weak association reported in northwestern Europe can be explained by temporal variations in storm frequency that the NAO does not account for.

Many studies have pointed to an apparent trend in the increasing number of storms in the last decades of the 20th century, whereas others claim that there is no evidence to support this alleged trend, and that the increased storminess in the 1990s only is part of decadal variability. Donat et al. (2011) point to a clear upward trend in storminess in northern, central and western Europe during the last decades of the 20th century by using the 20th Century Reanalysis (20CR). They noted that decadal variability has been persistent since 1871 but found particularly high storminess values in the Baltic Sea region and the North Sea during the last decades of the 20th century. Wang et al. (2009) found that the high
wind storm values in the 1990s mainly occurred during the winter period, whereas Kyselý and Huth (2005) noted an apparent increase in the persistence of atmospheric circulation types in the 1990s. Furthermore, an upward trend in the maximum and mean intensities of the Atlantic storm-track has been observed by Luo et al. (2011) between 1978 and 2009. However, other long-term analysis studies (100-150 years) on the wind climate have indicated that the alleged interdecadal positive trend only displays multidecadal variability, and that the upswing in the 1990s can be attributed to changes in the NAO (Rutgersson et al., 2015). Feser et al. (2014) and Bärring & Krzysztof (2009) imply that the results obtained on trendiness in storm activity notably depend on the chosen time period for the study - studies focusing on relatively recent decades tend to showcase an increasing storminess rate, whereas long-term studies display slight interdecadal variability.

Irregularity characterises the variability of the NAO when observing its long-term behaviour (Rutgersson et al., 2015). Substantial variations can occur both within seasons, from year to year as well as from decade to decade, indicating that the NAO does not display variations on specific time scales (Hurrell et al., 2003). However, periods with NAO anomalies persisting for several winters in a row or even consecutive decades, have been observed. In the early 20th century, a positive NAOI persisted for several decades, whereas a negative NAOI prevailed during the 1960s (ibid.). Since the 1980s, and especially since the beginning of the 1990s, the NAOI was again displaying strongly positive values throughout the respective decades (Hurrell et al., 2003; Marshall et al., 2001; Ostermeier & Wallace, 2003). This interdecadal variability can be attributed to several different forcing mechanisms, which makes the variability of the NAO rather unpredictable (Hurrell et al., 2003). However, several studies have been trying to reveal potential predictability of this large-scale atmospheric circulation by investigating the role of external factors. In addition to processes internal to the atmosphere driving the majority of the variability, a deeper knowledge on ocean-atmosphere-sea-ice interactions as well as on external forcing mechanisms, such as the increasing amount of GHG in the atmosphere, could contribute to enhanced predictability of the NAO (Wanner et al., 2001; Hurrell et al., 2003).

2.3 Extratropical cyclone activity in the Baltic Sea Region

The Baltic Sea Region is influenced by a large variety of atmospheric masses from the subtropics and the Arctic region (Rutgersson et al., 2015). Two large-scale pressure systems display the greatest influence on the region, namely the NAO and the thermally induced Eurasian pressure system (ibid.). The predominating wind directions stem, in accordance with the zonal circulation, from the
southwest, although other wind directions are regularly observed. Therefore, a great number of the extratropical cyclones, originating in the North Atlantic, are the foundation of wind storms in the Baltic Sea region (ibid.).

Strong wind gusts, potentially causing harm to societies, usually occur in association with cold fronts and occluded fronts of synoptic extratropical low-pressure systems (Gregow et al., 2008). Particularly, explosive cyclones are considered dangerous because of their unpredictability, intensity and rapid development (ibid.). Nonetheless, extratropical transition, originating from tropical cyclones, cyclones developing along the Scandinavian mountains and cyclogenesis developing in the Baltic Sea itself are also potential causes to severe wind storms in the study region (Sepp et al., 2018; Gregow et al., 2008). Some of the strongest storms causing damage to societies in Northern Europe, such as Gudrun/Erwin in January 2005 and Kyrill in January 2007, took place in the winter (Rutgersson et al., 2015). Both of these severe winter storms, causing high economic loss in the Baltic Sea region, originated from the North Atlantic (ibid.).

Surkova et al. (2015) studied the different atmospheric circulation patterns for storm events in the Baltic Sea region between 1948 and 2011. The authors found a significant increase in winter storm activity by the end of the 20th century with an apparent connection to three circulation types: namely, the NAO, the AO and the Scandinavian Blocking (SCAND). Also, Lehmann et al. (2011) and Getzlaff et al. (2011) discuss the intensified zonal circulation in combination with stronger cyclonic circulation during the 1990s and 2000s in comparison to the 1970s and 80s for the whole Baltic Sea region. Generally, an increasing number of deep cyclones have been forming in the subtropical North Atlantic in the winter (DJFM) since the 1960s in addition to a north-eastward tilt in the North Atlantic storm track, leading to an increased cyclone influence on the Baltic Sea region (Lehmann et al. 2011).

On the Estonian coast, Jaagus and Suursaar (2013) investigated long-term storminess and found a significant correlation between the increased storminess during the winter period (NDJFM) and the NAO/AO in 1950-2011. However, Sepp et al. (2018) found no increase in the frequency of storminess but observed a tendency toward stronger but fewer cyclones during a positive NAO phase. Overall, the correlation between the cyclone frequency and the NAOI was relatively weak in their study.

Gregow et al. (2008) studied storminess along the Finnish coast by investigating surface wind speeds above 21 ms\(^{-1}\) on offshore weather stations between 1960 and 2007. According to the obtained results, the 1970s and the 1990s were the stormiest decades on record. Furthermore, storm winds originating
from vast low-pressure systems have increased especially in the 1990s, whereas a reduction in northerly winds has occurred between 1960 and 1990. Both Keevallik (2010), Jaagus and Kull (2011) and Khokhlova and Timofeev (2011) have found a general shift towards an enhanced zonal circulation and stronger westerly winds in Finland, Estonia and the easternmost section of the Baltic Sea region in Russia.

Lehmann et al. (2011) found regional variations in the surface wind climate along the Swedish coastline. In the central and southernmost sections of the Baltic Sea region, the mean geostrophic wind speed increased in the winter period (DJF) between 1970 and 2007, which coincides with the enhanced number of deep cyclones. A weaker increase rate was observed in the Bothnia Bay region in the same season, whereas an overall increase in westerly storm wind speeds was recorded in the spring season (MAM) over a large part of the study area (ibid.). Alexandersson (2006) found a general decrease in storm frequency in his study on the wind statistics in Sweden between 1961 and 2004.

Altogether, there has been significant multi-decadal variation in the surface wind climate in the Baltic Sea region, and several studies have noted an overall increase in storminess during the latter part of the 20th century. Most climate scenario simulations project an increase in cyclone intensity and surface wind speeds in the Baltic Sea region (Pinto et al., 2007), with the severity depending on which emission scenario is selected.

3. Methodology

3.1 Study Area

The Northern Baltic Sea region is located in Northern Europe and is part of the Baltic Sea that qualifies as a brackish sea of estuarine character (Lehmann et al., 2011) (Fig. 2). The sea has experienced wide-ranging changes since the last glacial period that ended approximately 10 000 years ago (HELCOM, 2013). The melting glaciers caused the sea level to rise, whereas the disappearance of the Fennoscandian ice sheet resulted in gradual isostatic uplift, thus countering the sea level rise (ibid.). The geomorphologic changes have resulted in a low-lying coastline and several small islands along the Northern Baltic Sea region, which are vulnerable to various natural hazards such as storms.

Large-scale atmospheric circulation plays a considerable role for the climatic circumstances in the region. The influence of both continental subarctic and maritime temperate climate result in greatly
varying year-round weather conditions (Lehmann et al., 2011). Furthermore, the Baltic Sea region has experienced a more intense warming trend (0.4°C decade⁻¹) than the global average (0.17°C decade⁻¹) since the 1980s (ibid.). Consequently, the region is highly sensitive to global atmospheric changes.

Furthermore, urban areas are located on both the eastern and western coastline in the study region. Hence, a large proportion of the population as well as industries and services are threatened by extreme weather events such as storms. However, the distinctive characteristics of the semi-enclosed Baltic Sea region, with both bays and gulfs that alter wind intensities and directions, result in regionally differing impacts (Surkova et al., 2015). The southern section is more exposed to the incoming westerlies than the northern section of the study region, which under stormy circumstances results in a higher level of vulnerability for the southernmost cities and regions (ibid.).

Figure 2. Map of the study area with the meteorological stations.*
3.2 Collected data

3.2.1 Meteorological stations

The near-surface wind speed data used in this study were obtained from the Swedish Meteorological and Hydrological Institute (SMHI, 2018) and the Finnish Meteorological Institute (FMI). Wind speed observations above 21 meters per second (~ 9 on the Beaufort wind force scale) were selected using datasets by five offshore meteorological stations, adjacent to the coastline of Sweden and Finland. The selected stations are: Utö, Söderarm, Valassaaret, Hailuoto and Rödkallen (Table 1; Figure 2).

Table 1. The meteorological stations used in this study.

<table>
<thead>
<tr>
<th>Station</th>
<th>Name</th>
<th>Location</th>
<th>Measurement period</th>
<th>Height above sea level</th>
<th>Measurement accuracy change*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31 m (1998-2005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25 m (2005 →)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 m (1995 →)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Valassaaret</td>
<td>63°26’60N, 21°04’05E</td>
<td>1960-2017</td>
<td>22 m (1960-2016)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26 m (2016 →)</td>
<td></td>
</tr>
</tbody>
</table>

* One decimal point was added to the wind speed observations resulting in more accurate measurements.

3.2.1.1 Utö

The Utö meteorological station is part of the Utö Atmospheric and Marine Research Station of the Finnish meteorological Institute. It is located near the outer edge of the Archipelago Sea on a lighthouse in the southeastern part of the Utö Island (FMI, n.d.). The elevation above sea level is 25 meters and except for minor alteration on the wind speed from islands and headlands in the north and northwest, no other major obstacles affect the wind direction and strength (Table 1). The surrounding offshore environment is characterised by bare rocky grounds, scrublands and juniper forests.

Weather observations began already in 1881 at the Utö meteorological station, but accurate wind...
speed observations are available from 1960 onwards (FMI, n.d.). Wind speed observations have only been measured around four times a day during the 1960s, but more frequent measurements are available in later decades. The station is still active today and is considered one of the main weather stations in Finland (ibid.).

3.2.1.2 Valassaaret
The island Mustasaari is a part of the island group Valassaaret situated in the narrow section of the Gulf of Bothania, namely Kvarken. The island is located approximately 50 km from the Swedish coastline and 46 km from the Finnish city of Vaasa, with the meteorological station located in the northern part of the island at an elevation of 26 meters above sea level since 2016 (Table 1). The topography of the island is relatively flat, and the surroundings are covered by sparse and low-lying deciduous forests and bare rocky ground. The direct wind speed measurements, available from the year 1960 onward, are slightly influenced since the prevalent south and southwestern winds are altered by other islands in the island group, in addition to the alteration of eastern winds cause by the tower on which the weather radar is located.³

3.2.1.3 Hailuoto
The meteorological station in the village of Marjaniemi is located on the westernmost part of the Hailuoto island in the Bothania Bay. The island, covered mostly by boreal forests of pine trees, is relatively flat, with the highest elevation reaching 20 meters above sea level. Although southern, western and northern winds are accurately measured, the eastern wind speed observations are altered by the island itself. Direct wind speed observations are only available from 1984 onwards, resulting in 24 years of observational data missing for this study.³

3.2.1.4 Söderarm
The meteorological station is situated on the small island of Torskär in the island group of Söderarm in the western part of the Sea of Åland. The station is located on a deactivated lighthouse at an elevation of 15 meters above sea level since 1995. Its location close to the highest elevation in the central parts of the island gives the station good conditions for measuring direct wind speeds. However, southeastern winds might be altered because of the location on the lee side of the lighthouse facing the north.⁴

³ FMI, personal e-mail communication, 15 March 2018
⁴ SMHI, personal e-mail communication, 19 April 2018
3.2.1.5 Rödkallen
Located approximately 30 kilometres southeast of the coastal city of Luleå in the Bothania Bay, the meteorological station of Rödkallen has been measuring wind speed observations since 1965, missing five years of measurement data in the beginning of the study period. The station is located on the southernmost cape of the treeless island of Rödkallen at an elevation of only 1 meter above sea level since 1996. The location of the station is suitable to accurately depict direct wind speed observations. However, some northerly winds might be altered by the northern sections of the island. Between 1981 and 1996 the station was out of service, which has led to a gap in direct wind speed measurements for 25 years.4

3.2.2 NAO index
The NAOI values used in this study were retrieved from the National Center for Atmospheric Research Staff (NCAR, 2018) for the time period 1960-2017 (Fig. 3). Both annual and monthly values were obtained and analysed together with the direct wind speed measurement observations from the meteorological stations in the study area. The monthly values were selected in order to examine intra-annual variations as well as seasonality in the study region (Fig. 4).

![Figure 3. The PC-based NAOI between 1960-2017.](image-url)
3.3 Data analysis and statistical methods

3.3.1 Data analysis in Microsoft Excel 2013

The data processing and the spatial wind storm analysis were executed in Microsoft Excel 2013. In order to identify storms, the obtained near-surface wind speed observations were filtered to only display wind speeds over 21 meters per second (~9 on the Beaufort wind scale). Furthermore, the dates were filtered only to include measurements from January the 1st 1960 (if applicable for the station). The annual storm counting was performed manually for each station, with at least 24 hours between two separate storms. Additionally, the monthly storm distribution was manually counted for each station in order to get an overview of the seasonal storminess in the study region. The months were thereafter clustered into a winter and a summer period, namely: ONDJFM and AMJJAS.

Additional filters were added in order to display the variation in storm wind intensity across the study region. The storm intensities were grouped into two different classes, namely: moderate storm (~9 on the Beaufort wind scale, 21-23,9 m s\(^{-1}\)) and severe storm (~10 on the Beaufort wind scale, \(\geq 24\) m s\(^{-1}\)). In addition to analysing the number of severe storms in relation to overall storms, the seasonal distribution was investigated in order to see if a seasonal pattern prevails.

The annual and monthly NAOI values were displayed and analysed in Microsoft Excel 2013. Together with the obtained results on the storm frequency and intensity in the study area, the monthly NAOI values were also clustered in order to display the intra-annual variation. Hence, the months were divided into a winter period (ONDJFM) and a summer period (AMJJAS) (Fig. 4). Since the winter period always spans two separate years, the first three months (OND) will represent the preceding year, whereas the following three months (JFM) represent the subsequent year (e.g. ONDJFM 1960/61).
3.3.2 Statistical models in SPSS Statistics

After the data processing, the relationship between the annual and monthly storm frequencies and NAOI values were analysed using either a Poisson regression (PO) or a Negative Binomial (NB) regression analysis in SPSS Statistics depending on the goodness of fit of the selected dataset (Hilbe, 2014). These generalised linear models (GLMs) are suitable when analysing count data in relation to continuous data (i.e. values for storm frequency and the NAOI in this study). By carrying out these regression analyses, interpretation of the potential association between the NAO and storm frequency in the selected locations will be possible. Hence, the statistical analysis will determine if the independent variable (NAO) has a statistically significant impact on the dependent variable (storm frequency).

The number of storms (\(N\)) per unit of time (\(i\)) can be expressed as \(N_i\) (Villarini et al., 2012). In a Poisson distributed data set the mean equals the variance, meaning that both represent \(\mu\) (\(\lambda\) in Fig. 5a). The parameter \(\mu\) represents the mean storm frequency during a specified time interval \(i\) (ibid.). The variable \(i\) represents, therefore, the unit of exposure for the dependent variable, which in this study represents one year or one winter season (ONDJFM). However, the variance is usually higher or lower than the mean, meaning that the data is either overdispersed or underdispersed (Villarini et al., 2010) (Fig. 5b). For this reason, the Negative Binomial regression analysis was used in addition...
to the Poisson regression analysis because of its suitability to accurately model overdispersed datasets (ibid.).

![Figure 5.](image)

**Figure 5.** The graphics of a) a Poisson distributed dataset with the rate of occurrence on the x-axis and the relative expected frequency on the y-axis (Brooks, 2005) and b) a “Two Crossing Theorem: Negative binomial compared with the Poisson.” (Cameron & Trivedi, 2013, p. 117).

In order to determine if a storm count dataset with a particular distribution of storm events \(k\) follows a Poisson distribution, a set of tests need to be run to evaluate the distributional adequacy (Walz et al., 2018). The one-sample Poisson-Kolmogorov-Smirnov (PKS) test, fitted for discrete values, was used to identify Poisson distributed data sets at a 5 % significance level (Antoneli et al., 2018). The results determine if the dependent variable appears to follow a Poisson distribution and is, thus, applicable to be used in a Poisson regression model.

Furthermore, in order to select the most suitable model, different goodness-of-fit tests were applied. First, a stepwise AIC (Akaike Information Criterion) estimation was applied. The AIC estimates the amount of lost information in a statistical model compared to the actual physical relation (Walz et al., 2018), and can, therefore, indicate which model is more suitable for a particular dataset. The lower the AIC value the better the fit (ibid.). Additionally, a Pearson chi-squared test \(\chi^2\), indicating if the used model displays excess or lack in variability, was used as a means of indicating the best fitted model (Hilbe, 2014). The model that presented the value closest to 1 in the dispersion statistic of the \(\chi^2\)-test was selected (ibid.). Hence, based on the values obtained from the AIC and the dispersion statistic of the \(\chi^2\)-test, either a Poisson regression model or a Negative binomial model was applied. Second, once the statistical model had been chosen and run in SPSS statistics, an Omnibus Test, representing a likelihood-ratio chi-squared test, was applied (Laerd Statistics, n.d.). This test reveals if the predictor model is a significant improvement over the equiprobable model (null hypothesis) at
a 5% significance level (ibid.). Lastly, the Incidence Rate Ratio (IRR) demonstrates how the dependent and independent variables are associated to one another. Values less than one (IRR < 1) indicate an inverse association between the variables, i.e. a negative correlation, the value one (IRR = 1) indicates no significant association, and values over one (IRR > 1) indicate a positive association, i.e. a positive correlation (IDRE, n.d.).

The full Poisson regression model for a year or a winter period \( (i) \) can be expressed as

\[
P(N_i = k | \mu_i) = \frac{e^{-\mu_i} \mu_i^k}{k!} \quad (k = 0,1,2,...),
\]

where

\[
\mu_i = \exp(\beta_1 X_{1i} + \cdots + \beta_k X_{ki}) \quad (\text{Cameron & Trivedi, 2013; Villarini et al., 2010}).
\]

The variable \( \mu \) is determined by \( X \)'s that represent \( k \) predictor variables and \( \beta \)'s that represent unspecified regression coefficients for the \( X \)'s that will be revealed once the model has been run (Hilbe, 2014).

The full Negative binomial regression model for the year or the winter period \( (i) \) is expressed as

\[
P(N_i = k | \mu_i, \alpha) = \frac{\Gamma(k+\alpha^{-1})}{\Gamma(\alpha^{-1})\Gamma(k+1)} \left( \frac{\alpha^{-1}}{\alpha^{-1}+\mu_i} \right)^{\alpha^{-1}} \left( \frac{\mu_i}{\mu_i+\alpha^{-1}} \right)^k \quad (k = 0,1,2,..., (\alpha \geq 0)
\]

where

\[
\mu_i = \exp(\ln(i) + \beta_1 X_{1i} + \cdots + \beta_k X_{ki})
\]

\[
\alpha = \frac{1}{v} \quad \text{(Cameron & Trivedi, 2013; NCSS, n.d.).}
\]

The \( \alpha \) represents the “dispersion parameter” (Hilbe, 2014, p. 126) where 1 is the mean and \( v \) is the scale parameter (NCSS, n.d.), whereas \( \Gamma \) represents the gamma function (Villarini et al., 2010). When the \( \alpha = 0 \) the model reduces to a Poisson model (Cameron & Trivedi, 2013). As illustrated in figure 4b, both the negative binomial and the Poisson regression have the same value for the mean (10) but whilst the variance equals the mean in the Poisson distribution, the variance is higher than the mean.
in the negative binomial distribution (Cameron & Trivedi, 2013). The variables $X$ and $\beta$ represent the same parameters as in the equation for the rate of occurrence $\mu$ in the Poisson regression model (Cameron & Trivedi, 2013; NCSS, n.d.). As stated by Hilbe (2014) and Villarini et al. (2010) the Negative Binomial distribution is a generalised model of the Poisson Regression model, also called a Poisson-gamma mixture, where the gamma function allows for accurate modelling of overdispersed data. For a more elaborated discussion on the statistical modelling of count data see Cameron and Trivedi (2013) and Hilbe (2014).

3.4 Delimitations and data quality

3.4.1 Delimitations

Several urban areas are located along the low-lying coastline of Sweden and Finland, making them vulnerable to various storm related impacts such as storm surges, high waves and wind gusts. In the study region the two coastlines are separated by approximately 200 km and 70 km in the widest and narrowest section respectively, whereas the latitudinal length measures around 700 km. Hence, the distinctive geographical characteristics of the region in addition to the risks that storms impose on societies, motivated the investigation of the spatial and temporal variability of storminess in the region in association to the NAO.

The time period, 1960-2017, was chosen since the earliest wind speed observations on the Finnish coastline started measuring near-surface wind speeds in the year 1960. Large-scale variations in the NAO were also recorded during the latter part of the 20th century along with unprecedented global warming, giving the time period further significance. Moreover, the five meteorological stations were selected to display the regional variation and the temporal aspect in storm frequency and intensity as comprehensively as possible. Comparison is possible both on a north-south axis and an east-west axis as a result of the distribution of the stations. Two stations were selected in the southern and the northern part respectively, in addition to one station located in the narrowest section of the Gulf of Bothania. An additional station was sought in the central section of the study area to enable an east-west comparison, but no station with sufficient historical metadata was found. Moreover, all the selected stations are located relatively close to cities namely: Uppsala and Turku in the south, Vaasa in the central section and Luleå and Oulu in the north. When viewing and analysing the measured averages for the whole study region, the data gaps at Hailuoto and Rödkallen need to be taken into account.
Since Sea Surface Pressure (SSP) values were only available for short time periods in the SMHI database, 10-minute-average near-surface wind speed measurements were used to identify storms in the study region. Furthermore, Burningham and French (2012, p. 2037) found it “surprising” that few studies have focused on the relationship between direct instrumental wind speed measurements and the NAOI, considering the substantial impact that strong wind gusts have on coastal areas. Hence, the impact-related character of direct wind speed was a further motivator to choosing wind speed measurements. The threshold of 21 m s⁻¹ was selected since storm warnings are issued at this speed on the Finnish coastline (FMI) as well as severe gale warnings on the Swedish coastline (SMHI). Furthermore, two separate storms were identified when at least 24 hours of wind speeds under 21 m s⁻¹ were recorded in between two stormy events. This threshold was motivated by the average speed at which extratropical low-pressure systems travel (Weisse et al., 2005).

In addition to investigating annual storm characteristics, bidecadal trends and seasonal variability was of interest. The reason for studying bidecadal trends was motivated by the 20-25 year-long structural patterns related to the NAO, resulting in differing correlation levels (Sepp et al., 2018). The last time period, 2000-2017, will be analysed as a full bidecade although three years are missing. Since the NAOI and storminess have been shown to display an interlink during the winter period, “the full boreal winter season” covering the six winter months (ONDJFM), was chosen for this study (Burningham & French, 2012, p. 2037). The summer months (AMJJAS) were also investigated to be able to examine the variability between the half-year-periods. Lastly, the annual and monthly PC-based NAO indices were chosen since the large-scale atmospheric pattern is considered to be more accurately represented through the pattern-based measurements, than through the station-based observations (Hurrell et al., 2003).

3.4.2 Data quality
Extratropical storms are inherently complex and multifaceted phenomena, which complicate their investigation in many different aspects. Depending on the objective of the study, various different analysis techniques can be used. For instance, when investigating the dynamical features of extratropical storms, eddy growth rates and bandpass-filtered variabilities are often investigated, whereas risk analysis and impact-related studies are more concerned with storm surges and wave heights (Weisse et al., 2005). Studies investigating storm frequency and intensity tend to focus on near-surface wind speed observations, direct SLP measurements or different reanalysis, and reconstruction projects using data assimilation techniques and various numerical models (ibid.).
Near-surface wind speed observations are often viewed as objective measures when studying impact-related storminess (Pardowitz, 2014). According to Fischer-Bruns et al. (2005) and Weisse et al. (2005), assumptions that are commonly made when using different tracking algorithms can be avoided when using accessible and temporally comprehensive wind speed data series. Nonetheless, using near-surface wind speed observations comes with limitations. Most long-time series of wind speed data suffer from inhomogeneities, data gaps and sparse observations as a result of changes in the surrounding environment, methodology, station location and in differing numbers of measurements per day (Rutgersson et al., 2015; Jaagus & Suursaar, 2013). Hence, the wind speed data series used in this study, along with most other weather station measurements globally, display a great variability in data quality.

The station-related metadata obtained for all five meteorological stations reveal both internal and external changes that do alter near-surface wind speeds to some extent. The Utö and Söderarm meteorological stations have the longest and most comprehensive data series out of the selected stations. Both stations have uninterrupted observations that span over the whole study period and are located on relatively undisturbed areas considering physical, wind altering obstacles. However, both stations, together with the three other stations, have undergone positional changes in terms of elevation and horizontal location (Table 1). The horizontal changes are relatively minor and do not seemingly cause changes to wind speed measurements, but the changes in the elevation above sea level do have an effect and need to be taken into consideration when analysing the results.

The metadata for Valassaaret in the central section of the study region show that near-surface wind speed measurements are altered because of physical obstacles in the environment and are thus not entirely reliable. However, uninterrupted observations are provided for the whole study period. The northernmost stations, Rödkallen and Hailuoto, display the sparsest data series, with neither of the stations covering wind speed data over the whole study period. The measurement series at Rödkallen started in 1965, after which uninterrupted observations were recorded until 1980. Subsequently, the station was out of service for 15 years before it was reinstated in 1996 and uninterrupted wind speed measurements were obtained again. Furthermore, Hailuoto only provides wind speed measurements from year 1984 forward, thus lacking 24 years of observations for this study.

Because of these inhomogeneities in the data series, it is important to keep in mind that the results will be somewhat affected and should, therefore, be analysed with caution. The differing
measurement periods, positional changes and the physical obstacles in the surroundings reduce the capability of accurately comparing the wind speed measurements in the study area. However, since wind speed measurements are the only long-term data series suitable for this study, their usage is motivated.

4. Results

4.1 Temporal variations and trends in local and regional storm frequency
The temporal storm frequency displays a wide-ranging variability both on a north-south as well as on an east-west axis in the Northern Baltic Sea region. The greatest average number of storms occurs at Söderarm with 4.7 storms year\(^{-1}\) followed by Hailuoto with 4.2 storms year\(^{-1}\), whereas Utö and Valassaaret measure 2.1 storms\(^{-1}\) and 2.0 storms year\(^{-1}\) respectively (Table 2). Rödkallen represents, therefore, the calmest region in the study area with 1.1 storms year\(^{-1}\). Moreover, the bidecadal trends shift between positive and negative phases throughout the study region, but the overall trend for the whole time period is negative (Appendix A; Fig. 6f). The first bidecade experienced an overall upward trend in storminess and is also classified as the stormiest subperiod in the study region (Table 2; Appendix B). During the same time period the NAOI started shifting mainly from negative to slightly positive values. More specifically the 1970s was the stormiest decade on record followed by the 1960s and the 1990s. The second bidecade (1980-1999) is the calmest one on record with a negative trend in storm counts, whereas the NAOI displayed mainly positive values with an increasing trend throughout the time period. During the current bidecade (2000-2017) a higher average storm count has been witnessed, yet with a slightly negative trend similarly to the preceding period (Table 2; Appendix B). The NAOI has been experiencing only a marginal increase with one drastic drop in the year 2010.

On a local scale, the observations at the southernmost stations, Utö and Söderarm, show differing results. Whilst near-surface wind speed measurements at Utö indicate a positive trend in annual storm counts, a slightly negative trend can be observed at Söderarm (Fig. 6a, Fig. 6b). When comparing inter-bidecadal variations between the two stations the storm frequency declined at Utö, whereas it increased at Söderarm between 1960 and 1979. Moreover, between 1980 and 1999 storm frequency declined rather drastically during the 1980s at Utö compared to the preceding two decades, including several years without any recorded storms. However, a slight increase was witnessed in the end of the 20-year-period. Simultaneously, despite the relatively high number of storms compared to Utö,
an overall decrease in storm frequency was witnessed at Söderarm during the time period. During the most recent decades, 2000-2017, storm frequency at Utö has been declining, whereas a slight increase has been witnessed at Söderarm (Appendix A).

When observing storm frequency at Valassaaret, an evident overall negative trend in storm counts can be observed (Fig. 6c). Between 1960 and 1979 a steady increase rate in storm counts can be witnessed. Also, a slight visual association can be observed between the storm counts and the NAOI up until 1975. Between 1980 and 1999 the storm frequency decreased compared to the previous decades, but a modest upward trend can be observed throughout the period. Since the year 2000 a decreasing trend can be observed, with few or no storms recorded throughout the time period (2000-2017) (Appendix A).

In the northern section of the study area, Hailuoto and Rödkallen, display differing results (Fig. 6d, Fig. 6e). The observations are only comparable from 1996 onward since this is the only period where measurements were recorded at both stations. Hailuoto displays an overall negative trend in storm counts between the measurement period: 1984-2017. When observing the time period 1984-1999, a negative trend was prevalent, whereas a modest positive trend was observed between 2000 and 2017. Rödkallen has also experienced a negative trend when comparing the measurement periods, 1965-1980 and 1996-2017. During the first measurement period, 1965-1980, a positive trend was observed, whereas only five storms were recorded during the second measurement period: 1996-2017 (Appendix A). Hence, when comparing the two stations, the storm count is significantly higher on the Finnish coastline compared to the Swedish coastline between 1996 and 2017.

Table 2. Average number of storms per year at each meteorological station and for all stations during the study period and during the three bidecadal time periods. The arrows indicate whether the general trend was positive or negative throughout the selected time period. See Appendix A and Appendix B for figures.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Utö</td>
<td>1,60 ↓</td>
<td>1,30 ↑</td>
<td>3,61 ↓</td>
<td>2,12 ↑</td>
</tr>
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<td>1,98 ↓</td>
</tr>
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<td>3,78 ↑</td>
<td>4,21c ↓</td>
</tr>
<tr>
<td>Rödkallen</td>
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<td>-</td>
<td>0,23e ↑</td>
<td>1,11e ↓</td>
</tr>
<tr>
<td><strong>All stations</strong></td>
<td><strong>3,20 ↑</strong></td>
<td><strong>2,15 ↓</strong></td>
<td><strong>2,51 ↓</strong></td>
<td><strong>2,82 ↓</strong></td>
</tr>
</tbody>
</table>

Figure 6. Annual storm frequency and the NAOI at a) Utö, b) Söderarm, c) Valassaaret, d) Hailuoto, e) Rödkallen and the average storm frequency for f) all stations.

4.2 Temporal variability in local and regional storm intensity

Expectedly, severe storms (≥24 m s⁻¹) do not occur as frequently as moderate storms (21-23.9 m s⁻¹) (Fig. 7a-f). Both regional and temporal variations can be discerned in the study region between the five meteorological stations. When observing the overall division between storms and severe storms, some regions experience proportionally more severe storms than others. However, the overall trend indicates that a slight increase in severe storms has occurred in whole study region, with the highest relative value being recorded during 1980-1999 (Table 3).

Söderarm has experienced an average decrease in severe storms in parallel with the overall storm count. Out of all the storms recorded at the station during the study period, 23.6 % were classified as severe (Table 3). When observing the whole study period, the relative number of severe storms has
diminished. However, during the bidecade 1960-1979, the relative number of severe storms was increasing, whereas a decreasing trend was observed during the bidecades 1980-1999 and 2000-2017. At the southeastern station, Utö, 15.4% of the recorded storms were classified as severe. Altogether, severe storms have been increasing throughout the study period alongside a moderate decrease in the proportion of severe storms (Table 3).

The severe storms at Valassaaret account for 16.5% out of the recorded storms during the study period (Table 3). An increase in the relative number of severe storms can be witnessed when investigating variations in severe storms throughout the study period. During the bidecadal time periods 1960-1979 and 1980-1999, the proportion of severe storms has remained rather invariable, whereas during the recent years (2000-2017), severe storms have accounted for up to 40% of all the recorded storms (Table 3). It is important to note, however, that the overall number of storms has been evidently lower than during the preceding decades, giving severe storms a proportionally higher percentage during the most recent time period.

The greatest relative number of severe storms can be observed at Hailuoto (Fig. 7d). During the time period 1984-1999, as many as 25 out of the 75 recorded storms were classified as severe, resulting in a 33.3% severe storm rate (Table 3). During the most recent time period, 2000-2017, the corresponding number was 26.50%. Therefore, an overall severe storm rate of 30.1% was recorded in the northeastern section of the study region. However, a negative trend has been recorded in both the actual and relative numbers of severe storms. On the opposite coastline, storm counts at Rödkallen display the lowest relative number of severe storms. Only 4.8% out of all the recorded storms were classified as severe. During the time period 1965-1980 only 2 out of the 37 (5.4%) observed storms were classified as severe, whereas the same number was zero out of the 5 storms recorded during 1996-2017.
Table 3. The proportion (%) of severe storms out of all recorded storms. The arrows indicate whether the general trend in absolute severe storm frequency was positive or negative throughout the selected time period.

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<tr>
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<tbody>
<tr>
<td>Utö</td>
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<td>11.5 % ▲</td>
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<td>15.4 % ▲</td>
</tr>
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</tr>
<tr>
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<td>40.0 % ▼</td>
<td>16.5 % ▼</td>
</tr>
<tr>
<td>Hailuoto</td>
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<td>26.5 % ▼</td>
<td>30.1 % a ▼</td>
</tr>
<tr>
<td>Rödkallen</td>
<td>5.4 % c ▲</td>
<td>-</td>
<td>0 % e ▼</td>
<td>4.8 % c ▼</td>
</tr>
<tr>
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<td>21.7% ▼</td>
<td>21.2% ▼</td>
</tr>
</tbody>
</table>


Figure 7. The distribution of severe storms and all recorded storms at a) Utö, b) Söderarm, c) Valassaaret, d) Hailuoto, e) Rödkallen.
4.3 Seasonal and spatial variations in storminess

Large-scale variations between the winter period (ONDJFM) and the summer period (AMJJAS) can be discerned in the study region (Appendix C). When observing the overall seasonal distribution of storm frequency, the majority of storms seem to occur during the winter period (Fig. 8 and Fig. 9). Approximately 8 out of 10 storms and 9 out of 10 severe storms seem occur during the full boreal winter period (ONDJFM) (Fig. 10). Moreover, the seasonal distribution varies according to the station, but when observing the overall trend, December and January appear to be the stormiest months in the study region followed by November and October, whereas May classifies as the calmest month followed by June, July and August (Fig. 8 and Fig. 9).

In the southern section of the study region, where one the highest numbers of storms was recorded, the monthly distribution seems to follow a pattern. January is the stormiest month at Söderarm, followed by December and November, whereas May is the calmest month of the year followed by June and July (Fig. 8). The contrast between the winter period and the summer period is significant at Söderarm with an 82,5/17,5 % ratio between the periods. The corresponding ratio for severe storms is 90,8/9,2 % (Fig. 10). The seasonal distribution is rather even at Söderarm with the subsequent month generally having a greater (a lower) average number of storms than the preceding one from May to January (January to May). At Utö, the seasonal storm frequency pattern follows a similar trend, but here December is the stormiest month followed by January and November (Fig. 8). Equally to Söderarm, May, June as well as July are the calmest months at Utö, but as a result of the low number of storms, the average number for May and June is zero. Out of the recorded storms 83,8 % occur during the winter period, whereas 16,2 % occur during the summer period. The corresponding ratio for severe storms is 95,0/5,0 % (Fig. 10).

In the narrowest section of the study region, at Valassaaret, October is the stormiest month of the year followed by November and February (Fig. 8). Hence, the seasonal distribution does not follow a similar consistent trend compared to the southernmost stations. May, June and July display the lowest average number of storms, which parallels the results obtained at the southernmost stations. 81,8 % out of all the storms occur during the winter period, whereas 18,2 % occur during the summer period whereas 78,9 % and 21,1 % out of the severe storms occur during the winter and summer period respectively (Fig. 10).
At Hailuoto in the northernmost section of the study region, the average seasonal distribution follows a regular pattern. Only one exception occurs as October has a higher average number of storms than November. The stormiest month is December followed by January and October, whereas the calmest months are May, June and July (Fig. 8). Most of the storms occur during the winter period with a ratio of 77,5/22,5% between the winter and summer period respectively, whereas the corresponding ratio for severe storms is 82,2/17,8% (Fig. 10). At Rödkallen on the opposite coastline, the seasonal storm frequency does not follow a regular pattern. February and March are the stormiest months followed by November, whereas May, June and August have an average storm frequency value of zero (Fig. 8). When comparing the winter and summer period to each other, the distribution is relatively similar to the rest of the study area with a ratio of 78,9% (ONDJFM) and 20,1% (AMJJAS) (Fig. 10), whereas all of the severe storms occur during the winter period (Fig. 10).

Figure 8. The seasonal distribution of the average number of storms at each meteorological station in the study region.
4.4 The association to the NAOI

The results obtained from the statistical analysis display a variety of different outcomes. No statistically significant (p ≤ 0.05) associations were found between the annual NAOI values and the annual storm frequency at the chosen meteorological stations (Table 4a). The values obtained in the Omnibus tests all signify statistically insignificant results, meaning that the predictor model does not provide a significant improvement over the intercept-only model (a model with no predictors, i.e. the null hypothesis). Additionally, the Incidence Rate Ratios (IRRs) display values relatively close to one, further confirming the insignificant relationship between the NAO and annual storm frequency in the study region. A visual representation of all associations can be found in the Appendix D.

However, statistical significance was found between the winter NAOI and both storm and severe storm frequency (Table 4b and 4d) as well as between the annual NAOI and severe winter storm observations (Table 4c) at certain stations in the study region. In table 4b statistically significant results can be observed between the winter NAOI values and winter storminess at Söderarm and Hailuoto. According to the PKS test, both data sets follow a Poisson distribution since p > 0.05. Furthermore, the Omnibus tests display statistically significant results (p ≤ .05), meaning that the Poisson Regression model is a significant improvement over the null hypothesis. Hence, the IRRs, indicating the rate at which the dependent variable changes in conjunction with a one-point increase in the independent variable, can be examined. A one-point increase in the winter NAOI is thus associated with a 1,233-point increase (i.e. 23.3 % increase) and an 1,859-point increase (i.e. 85.9 % increase) in annual storm counts at Söderarm and Hailuoto respectively (Table 4b). Visual representations of the statistically significant results are illustrated in figure 11a and 11b. Both the
IRR values and the visual representations reveal a tendency toward higher winter storm counts that can be related to higher winter NAOI values at all stations.

Furthermore, statistically significant results were found between the annual NAOI values and severe storm counts as well as between winter NAOI values and severe winter storm counts (Table 4c and 4d). At Hailuoto, the severe annual and winter storm counts appear to be following a Poisson distribution and the Omnibus Tests display statistically significant results, indicating that the Poisson regression model is a significant improvement over the null hypothesis (Table 4c, 4d). Thus, a one-point increase in the annual NAOI denote a 1,369-point increase in severe storm counts (i.e. 36.9 % increase), whereas a one-point increase in the winter NAOI denote a 2,638-point increase in severe storm counts (i.e. 163.8 % increase). In figure 11c and 11d the statistically significant results display a positive linear trend indicating that a higher NAOI value is related to a higher number of storms.

![Figure 11](image1.png)

**Figure 11.** The statistically significant associations (p ≤ .05) between a) the winter NAOI and winter storm frequency at Söderarm, b) the winter NAOI and winter storm frequency at Hailuoto, c) the annual NAOI and severe storm frequency at Hailuoto and d) the winter NAOI and severe winter storm frequency at Hailuoto. The statistically insignificant associations can be found in Appendix D.
Table 4. The goodness-of-fit tests for the datasets (see PKS), the tested models (see AIC, $\chi^2$ test), the selected model (see Omnibus Test) and for the independent variable (see Wald $\chi^2$ test) as well as the obtained association between the independent (NAO) and dependent (storm frequency) variables (see IRR) for a) annual storms, b) winter storms, c) severe storms and d) severe winter storms. Bold text indicates the lowest value obtained in the tests (see AIC, $\chi^2$ test) between PO and NB, and thus the chosen model for the respective station. Underlined values indicate the statistically significant results with a 95 % confidence.

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<th>Dispersion statistic (Value/df in the $\chi^2$ test)</th>
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<th>Wald Chi-Square - p value</th>
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*statistically significant at 5 % level
5. Discussion

5.1 Variations in the association between the NAOI and storminess

Results indicate that the association between the NAOI and storminess does not follow a regionally systematic distribution. While annual storm counts display a statistically insignificant association to the NAO in the whole study region, the results for the winter half-year show two statistically significant results and an overall positive association between the NAO and storm frequency. When observing only severe storms, an enhanced association can be observed when comparing the two statistically significant results obtained at Hailuoto during the full-year period and the winter period. These findings indicate that at least some of the datasets allow us to conclude that some regions experience an interconnection between the storminess and the NAO.

A tendency toward a higher storm frequency during a positive NAOI in the winter period has been observed by Donat et al. (2009), Wang et al. (2009), Surkova et al. (2015), Walz et al. (2018) and Jaagus and Suursaar (2013). All these studies found significant correlations in their respective study regions, indicating that all datasets displayed positive correlations with the winter NAOI. Results obtained in this study indicate that an overall weak positive correlation between the NAO and the storm frequency in the winter period exists, implying that a higher NAOI would be associated with higher storm counts. However, statistically significant results were only obtained at certain meteorological stations, suggesting regional variability in the association within the study area. Similar results were reported by Burningham and French (2012), Sepp (2009) and Sepp et al. (2018) where only certain statistically significant correlations were found in their respective study regions, implying that both the choice of study period, the thresholds for both speed and duration in addition to other constraints play an exceedingly important role when investigating the association between the NAO and storminess (Burningham & French, 2012).

Burningham and French (2012) conclude that although they discovered linkages between the winter wind climate and the NAO, the character of the connection is more complex than generally understood. Even though there is strong evidence that the large-scale atmospheric pressure gradient is connected to the Atlantic storm track, and thus to the wind climate (Rogers, 1997), it is not regionally apparent in the results obtained in this study. This could be explained by a variety of delimiting method-based choices (discussed in 5.3), but also by the fact that not all cyclones travel the full length of the storm track in the North Atlantic (Sepp et al., 2018). Hence, not all cyclones reach the Baltic Sea region, or more specifically the selected meteorological stations, and might divert
in a direction north or south of the study region (ibid.). Even though the enhanced winter temperatures recorded in the Baltic Sea region have been shown to be related to the shifts in the storm tracks (ibid.), the results obtained in this study on the changes in the storm frequency, similarly to Sepp et al. (2018), cannot explain this warming trend.

5.2 Trends in storm frequency, intensity and seasonality

A wide-ranging negative trend in storm frequency was found in the study area, with only one station (Utö) displaying an upward trend in storm counts. However, when observing the bidecadal time periods, clear shifts from positive to negative trends can be observed at all five stations (Appendix A). The first bidecade (1960-1979) appears to be the stormiest in the study region, displaying on average an upward trend in storm frequency, whereas the second bidecade (1980-1999) has a balanced distribution of both increasing and decreasing storm frequency trends. The last subperiod (2000-2017) has the lowest overall storm count in the study region with an even distribution of both increasing and decreasing trends. When examining each station separately, Söderarm and Hailuoto display the highest average storm counts, whereas Rödkallen displays the lowest. Hence, the storm frequency does not seem to follow an apparent regional east-west or north-south pattern in the study region.

A potential explanation to the unsystematic regional pattern could be attributed to differing wind directions and storm tracks. During the time period 1972-1995, a calm season can be witnessed at Utö, whereas the storm frequency stays relatively high at Söderarm (Fig. 12a). When comparing the predominating wind directions between the calm season (1972-1995) and the stormier season (1999-2011) at Utö, there is a much wider dispersion in wind directions during the calm period (Fig. 13). Southwestern winds predominate during the stormy period, whereas southern, western and eastern winds are all common wind directions during the calm period. Söderarm, on the other hand, experiences mainly southern winds followed by southwestern and northern winds throughout its measurement period (Alexandersson, 2006, p. 11). Hence, one possible explanation to the differences in storm frequency could be Söderarm’s adjacent position to the coastline and landmass of Sweden, creating a slight leeward position to southwesterly winds in 1999-2011. Also, Utö appears to be slightly protected by the landmass of Finland, potentially influencing the impact of northerly winds. Moreover, as suggested by Sepp et al. (2018), when certain wind directions are prevalent, others are weakened, altering the dominant cyclone characteristics.
Furthermore, in the northern section of the study area Hailuoto displays a significantly higher storm frequency compared to Rödkallen during the comparable time period: 1996-2017 (Fig. 12b). This could also partially be explained by prevalent wind directions. Since the northern section of the Baltic Sea is relatively narrow, the winds are generally directed toward the northeast. Hailuoto is located in the pathway of southwesterly winds, whereas Rödkallen is somewhat protected by the bay formation in the northwestern part of the Baltic Sea region. In addition, the prevalent pathways for strong storms, presented by Gregow et al. (2008), could also partially explain some of the regional variations (Fig. 14). Both the south and southwesterly storm tracks appear to divert north and northeastward after reaching the Baltic Sea, which could explain the high storm frequency and intensity at Hailuoto. Moreover, the variations in the position of the storm track when reaching the Baltic Sea, could also partially explain the variation between Söderarm and Utö.

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5 Personal e-mail communication with FMI, 11 May 2018
Even though Hailuoto experiences on average a higher storm frequency than Utö, the overall trend is negative, as is the case for Valassaaret. At Utö, however, a positive trend in storminess can be observed. Similar findings have been reported by Gregow et al. (2008), where windiness has been decreasing (slightly increasing or remaining the same) in the northern (southern) part of Finland. At Söderarm, the average storm count is the highest in the whole study region, whereas Rödkallen has the lowest average storm count. Even though both stations display a decrease in storminess, the
negative trend is significantly steeper at Rödkallen compared to Söderarm, where the decrease is rather insignificant. As Surkova et al. (2015) stated, the strongest winds in the Baltic Sea occur in its wide, central part (the Baltic Proper) which boarders the southernmost stations in the study region. This region is more exposed to the zonal circulation than the northern parts of the study region, which could partly explain some of the obtained results.

Several studies have reported an increase in storm frequency during the last two decades of the 20th century alongside a predominantly positive trend in the NAO (Donat et al., 2011; Surkova et al., 2015; Lehmann et al., 2011; Getzlaff et al., 2011). Even though the obtained results do not unambiguously affirm these findings, some similarities can be found. When observing the bidecadal time period 1980-1999 in the study region some differing trends can be discerned (Rödkallen excluded because of the lack of coherent measurements). A slight increase in storm counts can be observed at Utö and Valassaaret, although the average storm count is relatively low, whereas a decreasing trend can be observed at Söderarm and Hailuoto. It is important to note, however, that a slight average increase can be witnessed between 1984 and 1988 at both Söderarm and Hailuoto stations as well as in the beginning of the 1990s after which the storm frequency started to decrease (Appendix A). Previous studies have concluded that the positive trend started decreasing after the mid-1990s (Bärring et al., 2008). Overall, the 1970s was the stormiest decade in the study region, which coincides with findings by Gregow et al. (2008) stating that the 1970s was one of the stormiest decades in Finland.

In accordance with previous studies (Rutgersson et al., 2015; Surkova et al., 2015; Lehmann et al., 2011; Jaagus & Suursaar, 2013; Gregow et al., 2008), most storms occur during the winter season. Around 8 out of 10 storms and 9 out of 10 severe storms occur during the full boreal winter period (ONDJFM) in the study region, with December and January (May and June) being the stormiest (calmest) months. Similar findings were reported by Surkova et al. (2015) in their study on storm events and atmospheric circulation in the Baltic Sea, where December was presented as the stormiest month and May and June as the calmest months. Nevertheless, the general increase in winter storminess, reported by the above-mentioned studies, was not found in this study. At four out of five stations the winter storminess decreased during the study period, which contradicts a vast majority of previous studies. However, Sepp et al. (2018) did not find an increase in storm counts in the Baltic Sea region, and Alexandersson (2006) reported, similarly to this study, a general decrease in storm frequency in Sweden.
Alongside the average decrease in storm frequency, a slight increasing trend in the proportion of severe storm counts can be witnessed in the study region. These findings coincide with Sepp et al. (2018) findings on a tendency toward stronger but fewer cyclones with no increase in storm counts in their study on the Estonian coastline. Also, Luo et al. (2011) found an upward trend in maximum and mean intensities of extratropical cyclones between 1978 and 2009. These findings could be explained by Kyselý and Huth’s (2005) findings on the increase in the persistence of atmospheric circulation types. If the persistence of stormy weather has increased by 2-4 days, this could partially explain the modest increase in the proportion of severe storms witnessed in the study area (Rutgersson et al., 2015).

The results obtained on slightly stronger, but fewer extratropical cyclones could potentially be explained by the intensified latent heat release caused by a warmer and more humid atmosphere alongside global warming (Bärring et al., 2008). However, as the overall storm counts have decreased in the study region, the warming trend in the Baltic Sea region cannot be explained by an increased storminess (Sepp et al., 2018). Furthermore, it is important to note that the positive trend in the proportion of severe storm counts is not coherent, and that the highest relative number of severe storms actually occurred during 1980-1999. The variability of contradicting results in the study region may be explained by altering choices of method to study storm frequency. As a matter of fact, there is no standard method of investigating cyclone activity, owing to the variability and complexity of the phenomena (Bärring et al., 2008).

5.3 Methods, data quality and recommendations for future research

As stated by Sepp et al. (2018), Burningham and French (2012) and Bärring et al. (2008), the choice of method used in studies on storm frequency and climate indices plays a significant role on the outcome. Since no common or standard method exists for measuring changes in these complex variables, shortcomings and varying results commonly occur (Bärring et al., 2008).

The time period used in this study was motivated by the availability of direct near-surface wind speed measurements and could therefore not have been longer considering the selected method. Sepp et al. (2018) argue that the strength of the association between the NAOI and storminess relies on the chosen time period. In this study the correlation analysis was performed on the full time period (1960-2017) in order to have as comprehensive a dataset as possible for the statistical analysis. If bidecadal analysis would have been performed, stronger association levels could have potentially been
obtained, but the smaller dataset would have presented a less statistically reliable and comprehensive result (Burningham & French, 2012). Also, the low number of observations, especially in severe winter storms, does generally result in somewhat biased results and should, therefore, be analysed with caution.

Furthermore, the choice of regional coverage also impacts the outcome due to various factors - one of them being the relative location(s) of the meteorological station(s). As found in this study, the spatial location within the study area does significantly alter both the storm frequency and its association to the NAO. Therefore, for a more spatially comprehensive study, a higher number of stations should have been selected in the study region. Hence, both temporal and spatial aspects, which are often the origin to discrepancies between different studies (Bärring et al., 2008) impact the association between the NAO and storminess (Pirazzoli et al., 2010).

The datasets on near-surface wind speed measurements used in this study span time periods of variable durations and completeness’s, thus suffering from inhomogeneities. Various changes not only on the stations themselves but also in the surroundings alter the measurements of the local wind climate. Differences in measurement instruments can impact the recorded wind speeds with wind vanes recording higher mean wind intensities (~2 m s⁻¹) than anemorumbometers (Jaagus & Suursaar, 2013, p. 76). Also, the measurement accuracy changed at all five stations around the 1990s, resulting in more exact observations. Furthermore, the observation frequency has changed at all stations throughout the time period with approximately four measurements per day in the 1960s to hourly measurements towards the end of the study period. Hence, more frequent measurements would commonly result in a higher probability of detecting stormy weather (ibid.). However, as a result of the lower measurement accuracy and different measurement techniques in the early periods, the wind speeds could have been over- or underestimated.

Another source of inhomogeneity is the station height above sea level. As noted earlier, all the five stations used in this study have experienced positional changes which could greatly impact measured wind speeds. Hence, the results obtained can only give an estimation of storminess in the study region and need to be interpreted with caution. Lastly, changes in the surrounding environment may influence the direction and strength of the measured wind, potentially giving a distorted image of the actual wind climate circumstances (ibid.). Nonetheless, since all the selected stations are located offshore on islands in the open sea, changes in the surroundings can be considered rather minimal. As Li-Juan and Zhong-Wei (2012) state, different homogenization techniques are essential for raising
the quality in data obtained from meteorological stations, as well as studies focusing on the effects that changing station-related circumstances induce (Lindenberg et al., 2011).

The selection of a threshold for identifying storms and the selection of seasonality differs between studies. In this study winds classified as storm according to FMI (FMI, n.d.b) or severe gale according to SMHI (SMHI, 2017) were selected. According to Sepp et al. (2018) the nature of cyclones of varying strengths are inherently different and could, therefore, result in different association levels when related to the NAO. Stronger storms occur less frequently, resulting in a less comprehensive dataset for the statistical analysis. Thus, lowering the threshold to include gale days (17 m s⁻¹) could be of interest for further studies on the association between the NAO and storm frequency for a more comprehensive statistical analysis. Sepp et al. (2018) also found differences in correlation when investigating winter periods of varying durations. They found a reduction in both the strength and number of significant and strong correlations during longer winter periods (e.g. ONDJFM) compared to shorter periods (e.g. DJF). Hence, examination of shorter winter periods could be of interest for further studies. Lastly, also the PC-based NAO indices appear to show fewer and weaker correlations compared to the station-based indices during the winter period in addition to regional differences in the correlations (Sepp et al., 2018). Therefore, different NAO indices should be tested, and the obtained results compared in order to get as comprehensive a result as possible.

Different method-based choices could have resulted in varying results. Therefore, future research should focus on a variety of different storm-related variables for a more comprehensive understanding of storminess in the study region, including wave heights (Surkova et al., 2015), storm surges and sea-level rise (Jaagus and Suursaar, 2013; Yan et al., 2004), forest loss (Gregow et al., 2017) direct air pressure measurements and different reanalysis projects and multi-model simulations (Donat et al., 2011a, 2011b). The understanding of spatial and temporal storminess requires further investigation on both wind directions and extratropical storm tracks as a complement to the inhomogeneous datasets obtained from meteorological stations. The problems with inhomogeneity are not exclusive to this study as climate change research is often dependent on data acquired from ground surface meteorological stations (Li-Juan & Zhong-Wei, 2012). Consequently, data homogenization, using different methods and techniques, is crucial for enhancing the quality of studies (ibid.) and should, therefore, be taken into account in future research on storminess in the Northern Baltic Sea region.
For a more comprehensive study on storm frequency and its predictability, other variables such as the Arctic Oscillation (AO), sea surface temperature (SST) and the meridional overturning circulation (MOC) in the North Atlantic could be included as covariates in the statistical modelling (Walz et al., 2018). Even though studies focusing on 21st century storminess in Europe have depicted deviating results, a vast majority suggest an increase in intense storminess in Central, Western and Northern Europe along with a northeastward tilt in the North Atlantic storm track toward Scandinavia (Mölter et al., 2016; Donat et al., 2011a; Pardowitz, 2014). Together with enhanced predictability of the NAO and other climate indices, improved forecasting of storminess in Northern Europe could be achieved and thus improved adaptation and mitigation strategies developed (Burningham & French, 2012).

6. Conclusion

The association between the NAO and storminess has been investigated along with spatial and temporal variability patterns in storm frequency and intensity in the Northern Baltic Sea region. Statistically significant ($p \leq .05$) associations were only found at the northeastern and southwestern stations in the study region, thus demonstrating an unsystematic spatial association pattern. Winter storminess displays almost uniformly a positive association with the winter NAOI, indicating that higher values of the NAO correspond to a greater number of storms in the winter period. Also, a vast majority of storms were found to occur during the cold half-year in the study region. These results coincide with the findings of a positive NAO phase resulting in an enhanced zonal circulation and, therefore, an increased storminess in Northern Europe during the winter period.

Nonetheless, when investigating storm frequency, an overall decrease both in storms and severe storms was found in the study region, which contradicts a vast majority of studies. Large-scale inter-bidecadal variability patterns were found both in storm frequency and in the ratio between severe storms and storms. Generally, the proportion of severe storms increased slightly throughout the study period alongside the general decrease in storm counts. Hence, a tendency toward stronger but fewer storms could, according to these findings, potentially be expected.

Moreover, wide-ranging differences were observed in the near-surface wind speed observations, expectedly owing to the different geographical locations of the weather stations, and thus to differences in prevalent wind directions and storm tracks. The highest numbers of storms were recorded at the stations in the southwest and northeast, both located in the pathway of southern and southwestern storms. Since storminess in these regions also display significant associations to the
NAO, a connection between southern and southwestern cyclones and the NAO can be made in the Northern Baltic Sea region.

The observed frequency and intensity of storminess as well as the measured averages in the study region are greatly altered by inhomogeneities in the data series. Near-surface wind speeds are not only altered by station-related changes but also by changes in the surroundings. Hence, future studies should not only rely on wind speed measurements, but also take into account other parameters such as air pressure measurements, wave heights and preferably use different multi-model simulations. As many climate models predict an increase in storm intensity in Northern Europe, further studies on the wind climate and its relationship to the NAO could potentially shed light on future storminess and its associated threats.

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8. Appendices

Appendix C: Seasonal distribution between the winter (ONDJFM) and summer (AMJJAS) period at a) Utö, b) Söderarm, c) Valassaaret, d) Hailuoto and at e) Rödkallen.
Appendix D: The association between the annual NAOI and the (a-e) annual storm frequency and (f-j) annual severe storm frequency. The association between the winter NAOI and the (k-o) winter storm frequency and (p-t) severe winter storm frequency.

\begin{align*}
\text{UTO Storm Frequency} & \quad y = -0.0024x - 0.006 \\
R^2 &= 3E-05 \\
\text{SÖDERARM Storm Frequency} & \quad y = 0.037x - 0.184 \\
R^2 &= 0.006 \\
\text{VALASSAARET Storm Frequency} & \quad y = -0.036x + 0.0603 \\
R^2 &= 0.0055 \\
\text{HAILUOTO Storm Frequency} & \quad y = 0.1317x - 0.3362 \\
R^2 &= 0.0454 \\
\text{RÖDKALLEN Storm Frequency} & \quad y = -0.2213x + 0.0615 \\
R^2 &= 0.0157 \\
\text{UTO Severe Storm Frequency} & \quad y = -0.0575x + 0.0524 \\
R^2 &= 0.0024 \\
\text{SÖDERARM Severe Storm Frequency} & \quad y = -0.1679x + 0.044 \\
R^2 &= 0.0098 \\
\text{VALASSAARET Severe Storm Frequency} & \quad y = -0.0575x + 0.0524 \\
R^2 &= 0.0024
\end{align*}
$y = 0.493x - 0.2766$
$R^2 = 0.3672$

$y = -0.0433x - 0.0359$
$R^2 = 0.0002$

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