On cyclones entering the Baltic Sea region

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Trends in the frequencies, durations, mean and minimum sea level pressures, and cyclone formation point sea level pressures of relatively strong (mean sea level pressure < 1000 hPa) cyclones entering the Baltic Sea region between 1948 and 2010 were subject to analysis. Incoming cyclones were divided into ten clusters based on their formation points using the *k*-means clustering method. Changes in cyclone activity were compared with the North Atlantic Oscillation index. Although the incoming cyclone frequency did not change over the study period, over time the incoming cyclones became significantly stronger as they approached the region. There is no reason at present to assume that more cyclones have begun to form in some clusters. Only weak correlations were found between the number of incoming cyclones and the North Atlantic Oscillation index. Nevertheless, the overall tendency was for fewer but stronger incoming cyclones when the North Atlantic Oscillation index was positive.

Introduction

A large part of the climate change observed in the Baltic region in recent decades is thought to be linked to changes in atmospheric circulation (BACC (Author Team) 2008, BACC (Author Team II) 2015, Lehmann *et al.* 2011). It has been suggested that intensified western flow and more active cyclonic circulation have caused the warmer winters seen in the Baltic region (Busuioc *et al.* 2001, Keevallik 2003, Pryor and Barthelmie 2003, Degirmendžić *et al.* 2004, Jaagus 2006, Jaagus and Suursaar 2013). This interpretation was based on studies of large-scale atmospheric circulation in the Atlantic-European sector. Jevrejeva (2002) and Jaagus (2006) found strong correlations between the North Atlantic Oscillation (NAO) index and various climate

variables in the Baltic Sea region, especially in the winter. Lehmann *et al.* (2011) found that the frequency of deep cyclones forming over the North Atlantic in winter increased from the 1960s onwards, and that the cyclone tracks extended further northeast into the Arctic over time. They concluded that the influence of Atlantic cyclones on northern Europe and the Baltic Sea area has increased over time.

Changes in the air pressure fields indicating a poleward shift in the tracks of northern hemisphere winter storms have been found in several reanalysis data sets (Serreze *et al.* 1997, Geng and Sugi 2001, Gulev *et al.* 2001, McCabe *et al.* 2001, Bartholy *et al.* 2006). Similar shifts have been detected in multimean ensemble projections of climate models forced by increased greenhouse gas concentrations (Bengtsson *et al.*

2006, Ulbrich *et al.* 2008, Bengtsson *et al.* 2009). Several mechanisms have been proposed to explain these poleward shifts in storm tracks, including changes in the meridional location of maximum baroclinicity, increased static stability in the subtropics and mid-latitudes, increased tropical convective stability, and changes in eddy characteristics (Tamarin and Kaspi 2017).

Understanding how the poleward shifts in storm tracks are expressed at the regional scale is very important because atmospheric circulation influences local climate and weather. Variations in atmospheric circulation at the regional scale can be expressed through fluctuations in the characteristics of cyclones, these being the most important constituents of atmospheric circulation in the mid-latitudes. It is natural to assume that variations in cyclone properties may be associated with large-scale atmospheric circulation phenomena, such as the NAO. However, the question remains whether variations in NAO cause or are caused by storm track variations (Bengtsson *et al.* 2006). Data on temporal changes in the areas in which cyclones are generated and prevailing cyclone tracks can provide information on changes in highly baroclinic regions and on large-scale atmospheric circulation conditions that favour cyclone propagation.

At the global scale, northern hemisphere cyclones form mostly near the east coasts of the continents, and propagate with general westerly flow over the Pacific or the Atlantic (Whittaker and Horn 1984, Hoskins and Hodges 2002). Most North Atlantic cyclones do not migrate over the European continent, moving either towards the Arctic or dissipating over the ocean. There are four major European domains of cyclogenesis, namely west of Iceland, west of Ireland, over the Gulf of Genoa, and in the Black Sea region (Trigo 2006). Northern European cyclones have mostly been investigated in the context of extreme events (Fink *et al.* 2009, Nesterov 2010, Post and Kõuts, 2014, Lehmann *et al.* 2017), but some statistical studies of Baltic Sea region lows have also been published (Sepp *et al.* 2005, Link and Post 2007, Feistel *et al.* 2008, Sepp 2009).

Most cyclones approaching the Baltic Sea region come from westerly directions, but some approach from other directions as well (Link and Post 2007). Skagerrak cyclones and cyclones developing in the lee of the Scandinavian mountains, often initiated by lows to the west of the mountains, are the most common in the Baltic Sea region. There is active cyclogenesis in the Baltic area itself, with about 40% of Baltic cyclones generated within the Baltic Sea region (Link and Post 2007, Sepp 2009). Sepp (2009) studied these cyclones in detail and found that while the number of cyclones generated within the Baltic Sea region did not change between 1948 and 2002, the cyclones became deeper. Using correlation analysis it was found that fewer but stronger cyclones form over the Baltic Sea area when the NAO index is positive, especially in winter. The shift in Atlantic storm tracks mentioned above is supported by Sepp *et al.* (2005), who found that the tendency of cyclones in northern Europe to follow more northerly trajectories has increased over time.

The present study builds on previous work (Sepp *et al.* 2005, Link and Post 2007, Sepp 2009, Mändla, *et al.* 2012) by quantifying changes in Baltic Sea area cyclone properties using a northern hemisphere cyclone database (Tilinina *et al.* 2013). It is an extension of a previous study by Sepp (2009) of changes in the properties of cyclones generated within the Baltic Sea basin in that the same cyclone parameters are analysed. Here we examine only those cyclones generated outside the Baltic Sea region.

Migrating low-pressures redistribute energy on their way, so any systematic changes in cyclone intensity, frequency, or position will affect the local climate. The first aim of this study was to evaluate changes in the characteristics of cyclones entering the Baltic Sea region, which can be interpreted through shifts in North Atlantic storm tracks. The second aim was to determine whether changes in cyclone properties are related to variations in large-scale atmospheric circulation phenomena such as the North Atlantic Oscillation. The incoming cyclones were placed in clusters based on their cyclogenesis points to provide a useful regional representation of the cyclones. Only relatively strong cyclones (lows with average pressures < 1000 hPa and lasting at least 24 h) are considered.

The cyclone database and clustering algorithm are described and their quality and limita-

tions assessed. Changes in cyclone frequency and intensity are then described separately for ordinary and deep cyclones. Correlations between the NAO index and cyclone parameters are then discussed, before some further general discussion and conclusions are presented.

Data and methods

Cyclone database

The Shirshov Institute of Oceanology Northern Hemisphere cyclone database was compiled using a cyclone tracking algorithm described in detail by Tilinina *et al.* (2013), Zolina and Gulev (2002, 2003), and Rudeva and Gulev (2007), based on NCEP/NCAR reanalysis (Kalnay *et al.* 1996) of sea level pressure (SLP) fields using a 2.5° × 2.5° grid. The database contains information on the geographical locations and SLPs for tracking points of every cyclone at six-hour intervals. Only areas of low pressure lasting at least 24 h are included in the database. The study period was 1948–2010.

The quality of the primary data was of the utmost importance to the study. The NCEP/NCAR reanalysis (Kalnay *et al.* 1996) output has been studied in detail and widely criticized, the main criticisms being the quality of the pre-satellite data, and particularly the polar region data from the viewpoint of temporal homogeneity (Chelliah and Ropelewski 2000, Sturaro 2003, Bromwich and Fogt 2004, Dee *et al.* 2014) because the amount and nature of the assimilated data have changed over the reanalysis period. The relatively low spatial resolutions of older reanalyses (such as the NCEP/NCAR reanalysis) yield lower cyclone counts before 1979, and exclude weak lows (Neu *et al.* 2013, Tilinina *et al.* 2013). However, Tilinina *et al.* (2013) showed that, for stronger cyclones in the northern Europe region, the NCEP time-series data are reliable and comparable with modern reanalyses. The 1000-hPa-mean SLP threshold was used in this study to ensure that only reliable data were used. This threshold retained the data for only about half (51%) of the incoming cyclones.

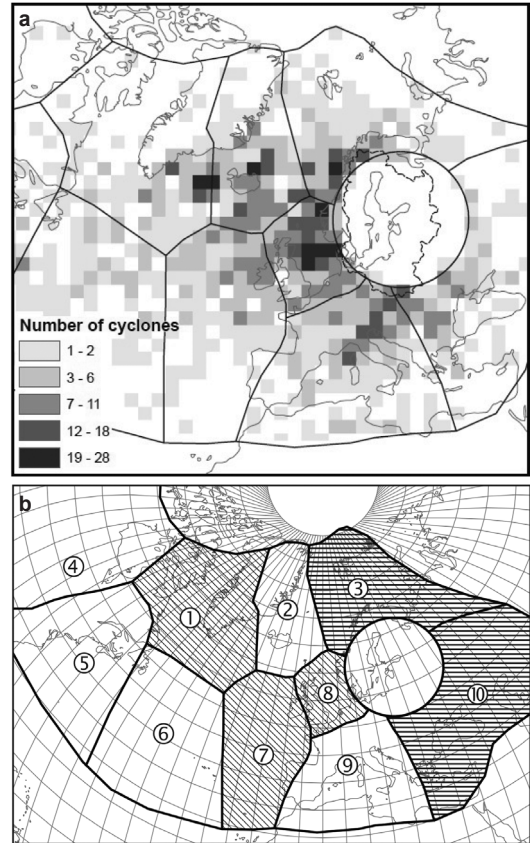We defined the Baltic Sea region using a radius of 1000 km around 58.75°N, 25.5°E, and

Fig. 1. Cyclogenesis areas of incoming cyclones in the period 1948–2010. The circle has a radius of 1000 km (the 1-K circle) and is centred on the Baltic Sea area. (**a**) The cyclone density calculated using a 200 km × 200 km grid. The bold lines are the borders between the clusters and the dashed line shows the Baltic Sea catchment. (**b**) Separation of the incoming cyclone formation points into ten clusters. Hatching indicates the clusters in which the yearly minimum central cyclone pressure (diagonal hatching) or mean central cyclone pressure (horizontal hatching) decreased significantly ($p < 0.05$).

we refer to this as the 1-K circle (Fig. 1). The same area has been used to study cyclones influencing Estonian weather (Link and Post 2007, Mändla *et al.* 2012, 2014) and it includes most of the Baltic Sea catchment (Fig. 1a). Changes within this circle should reflect changes over the whole region.

As a first step, cyclones formed outside the Baltic region and entering the 1-K circle were identified. There were 4347 such cyclones in the study period. A subset of lows with mean SLPs

< 1000 hPa was then selected. There were 2218 such cyclones (later called incoming cyclones) in the period 1948–2010, averaging about 35 cyclones per year.

The mean SLP of a cyclone used here is the arithmetic mean of the SLP at all of the tracking points (centres) of the cyclone, and the minimum SLP of the cyclone is the lowest SLP out of all the tracking points. We will refer to the mean and minimum SLPs as the central mean and central minimum of the cyclone. The interval between tracking points was 6 h, so the cyclone lifetime (in hours) is the number of tracking points multiplied by six. Formally, this method will give a lifetime 6 h longer than the lifetime given in the database, but a cyclone could emerge 5 h before the start time in the database. A cyclone can move quite far (up to 500 km) from its actual formation point in 5 h (Lukin and Nesterov 2011, Vyazilova 2012, Post and Kõuts 2014). It can be assumed, however, that this will not strongly influence the results of this study because it is unlikely that a large number of cyclones will form in one but be identified in another cluster.

The territorial distributions of the incoming cyclone cyclogenesis areas were then generated. Regions in which the most incoming cyclones per unit area (on a 200 km × 200 km grid) formed were identified using ArcGIS software. Distortions caused by the convergence of meridians were decreased by using ArcGIS tools to recalculate the geographical coordinates of the cyclogenesis points into a Bonne equal-area pseudo-conical projection, using 55°N as the standard parallel and 0° as the central meridian.

A simple directional distribution of the cyclogenesis points was then plotted as a rose diagram to identify the main general directions from which the cyclones approached the Baltic Sea region. All the cyclogenesis points were divided between 16 sectors, and the distance to the central point of the area was taken into account (Fig. 2). Most cyclones emerged in a roughly 90° sector between 210° and 300° because the general westward flow in northerly latitudes controls cyclone propagation. The distance distribution was uneven, suggesting that the cyclogenesis areas for the Baltic Sea area needed to be examined in more detail. This was achieved using a cluster analysis.

Clustering of the cyclogenesis points using *k*-means

The *k*-means cluster analysis method (MacQueen 1967) was used to identify domains in which cyclogenesis converged for incoming cyclones.

The *k*-means method clusters groups of objects with attributes as similar as possible or, in other words, as spatially close as possible to each other in a given space. In this study, the attributes were the geographic coordinates of the cyclogenesis (cyclone formation) points. The number of clusters *k* into which the algorithm mathematically divides the *n* objects is selected, then the objects are divided into clusters with the objects in a given cluster being as similar as possible and the clusters being as dissimilar as possible. The similarity between objects within a cluster is measured using the distance of each object from the cluster centroid. The *k*-means method yields good results if the clusters are spherical and quite well separated. The strength of the method lies in its simplicity, making it effective and easy to use, even with large quantities of data (Jain 2010, Linoff and Berry 2011). The weakness of the *k*-means method is that it is sensitive to outliers, i.e., single values significantly different from the others affect the location of the cluster centroid and therefore the whole cluster structure.

The most critical and most criticized problem is the determination of the number of clusters. Several tests have been developed to determine the number of clusters (Steinley 2006, Jain 2010, Linoff and Berry 2011), but determining the number of clusters remains a subjective decision determined by the study aims (Jain 2010). For example, a rule of thumb for determining the number of groups for the *k*-means method involves using the equation

$$k = \sqrt{\frac{n}{2}} \qquad (1)$$

where *n* is the number of members. For this study, *n* = 2218, so 33 clusters is recommended. This is clearly too many; most groups have too few members for reliable trend analysis. Our tests indicate that more than 12 clusters is unreasonable for this study. Using too few clusters is also problematic because although cyclones in the same cluster may be quite close to each other
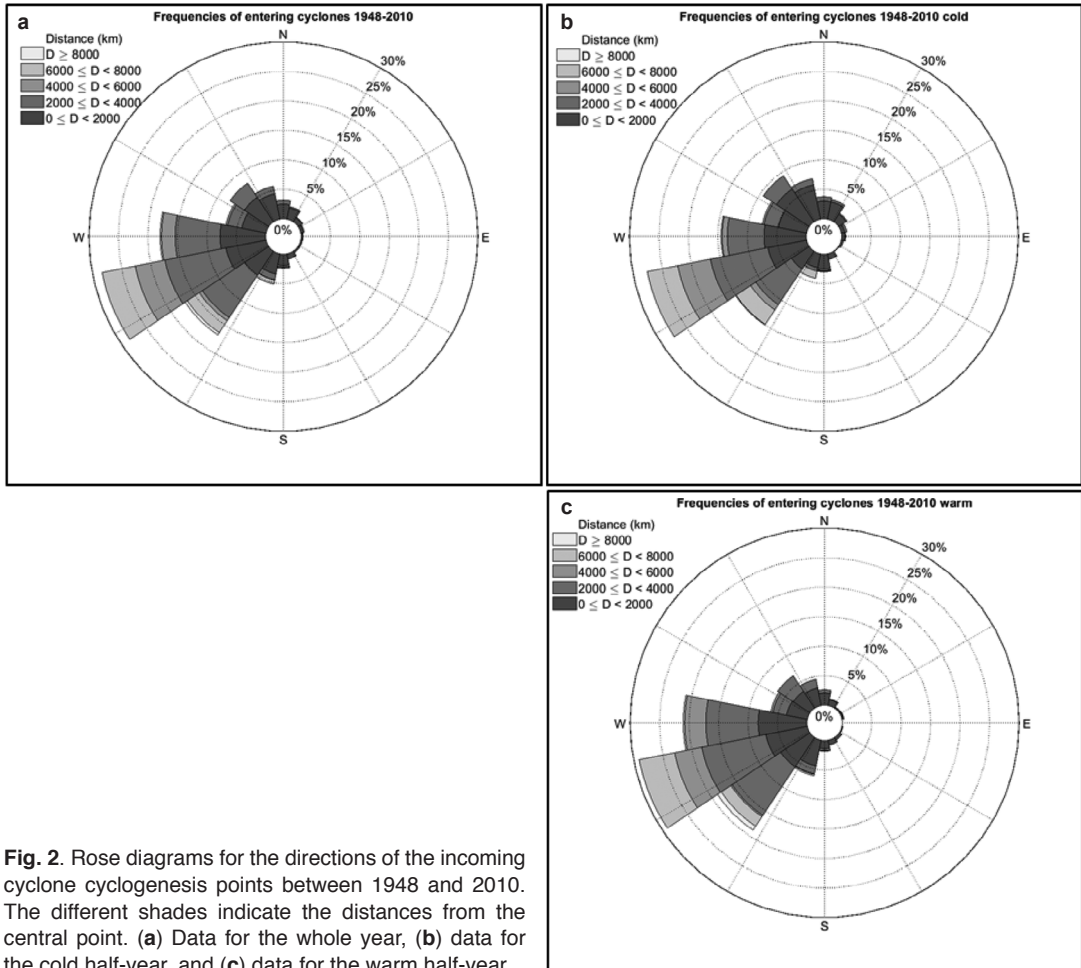
Fig. 2. Rose diagrams for the directions of the incoming cyclone cyclogenesis points between 1948 and 2010. The different shades indicate the distances from the central point. (**a**) Data for the whole year, (**b**) data for the cold half-year, and (**c**) data for the warm half-year.

geographically, they may bring completely different weather conditions to the Baltic region. For this study, fewer than ten clusters causes cyclones formed northeast of the 1-K circle to be grouped with cyclones formed west of the 1-K circle. Lows from the west bring relatively warm air masses in winter, but lows from the north or northeast bring cold Arctic air masses. Nevertheless, in terms of the sensitivity of the system, the number of clusters used needs to be investigated separately in future. After several trials, we concluded that the most appropriate number of clusters for this study is ten (Fig. 1b).

Attempts to identify correlations between the numbers of cyclones formed in different clusters each year indicate that the clusters identified using the *k*-means method are generally independent.

The only exceptions are cyclones formed over the central (CL6) and eastern parts of the North Atlantic (CL7), for which a weak statistically significant positive correlation was found ($r = 0.32$, $p < 0.01$). This implies that different clusters represent different aspects of cyclogenesis.

The clustering process was performed using the Excel macro XLSTATPro (www.xlstat.com) toolkit for *k*-means.

Statistical analysis

The study period 1948–2010 was divided into three 21-year periods, and the incoming cyclone frequencies during these periods were compared (Table 1).
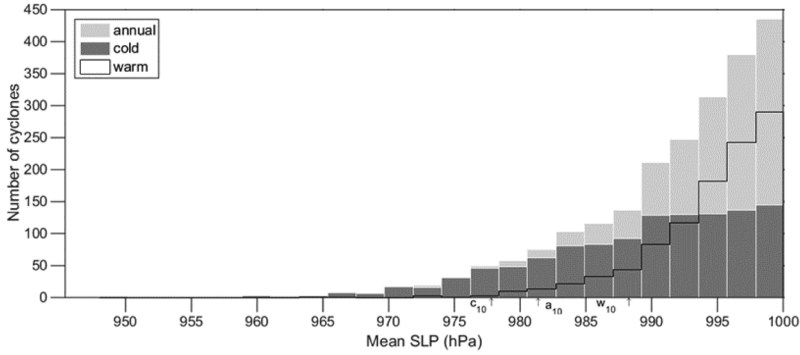
Fig. 3. Histograms of the mean sea level pressures (SLPs) of the incoming cyclones for the whole year and for the cold and warm half-years (indicated by the black stepped line). The 10th percentiles for the whole year, cold half-year, and warm half-year are labelled as a_{10}, c_{10} and w_{10}, respectively.

Next, temporal changes in the incoming cyclone characteristics were studied using linear regression analyses. Trends in the characteristics for whole years and separately for the warm half-year (April–October) and cold half-year (November–March) were analysed. These unequal half-years, seven and five months long, are traditionally used in precipitation studies at high latitudes because during the five-month cold half-year precipitation may fall in solid form. In the Baltic Sea region, these half-years also reflect generally different circulation conditions (Jaagus 2006, Jaagus *et al.* 2010) and cyclonality conditions (Sepp *et al.* 2005).

Regression parameters were calculated for the time series for the incoming cyclone numbers, lifetimes, mean and minimum SLPs, and SLPs at the cyclogenesis points, first for all cyclones and then for the separate clusters (classes). The 95% level was used to identify statistically significant results. SLP distributions have a relatively long tail towards low pressure values whereas cyclones are associated with pressure field minima (Fig. 3). This may cause trend analyses to be influenced by exceptionally strong storms that are outliers to the general SLP distribution. Thus, cyclones with minimum pressures in the lower 10th percentile (deep cyclones) were analysed separately from the ordinary (residual) cyclones. The threshold between deep and ordinary cyclones over a whole year was 981.2 hPa. The mean SLPs for the warm and cold half-year cyclones were rather different, and the thresholds for the warm and cold half-years were 988.1 and 977.6 hPa, respectively. A histogram of the mean SLPs for incoming cyclones for whole years and for the warm and cold half-years and the thresholds separating deep and ordinary cyclones are shown in Fig. 3.

Dividing the mean SLP data into two groups decreased the likelihood of false linear analysis outcomes caused by features of the data distributions. We analysed deviations (residuals) from

Table 1. Numbers of incoming cyclones from the ten cyclogenesis clusters in the three 21 y periods and the whole study period

Cluster	Region	1948–1968	1969–1989	1990–2010	Total
CL1	S Greenland	61	62	52	175
CL2	Iceland	100	107	96	303
CL3	Norwegian Sea	82	72	81	235
CL4	Central N America	22	25	24	71
CL5	Eastern N America	59	56	65	180
CL6	Central N Atlantic	52	45	42	139
CL7	Ireland	78	84	77	239
CL8	North Sea	114	130	147	391
CL9	Mediterranean	117	88	95	300
CL10	Black Sea	60	63	62	185
Total		745	732	741	2218

a linear model in the mean SLP data for both data groups. The residuals followed a normal distribution, which justified the use of linear models. All other time series analysed here also correspond to the assumptions made in the use of linear methods.

We calculated linear correlation coefficients for the relationships between the NAO index and the characteristics of cyclones entering the Baltic Sea region in order to gain an understanding of the connections between general atmospheric circulation and incoming cyclones. There are several different NAO indices. We used the NAO index introduced by Li and Wang (2003), based on standardized differences between the zonal mean pressure between 65°N and 35°N in the North Atlantic sector. It has been shown in several studies (Jaagus and Kull 2011, Hoy *et al.* 2013, 2014) that this index represents, somewhat better than other zonal circulation indices, the spatial–temporal variability associated with the NAO phenomenon and westerlies that typically cause the inflow of maritime air masses to eastern Europe, including the Baltic Sea region.

Results

Changes in the cyclone counts

Analysis of the formation regions of the incoming cyclones showed that most lows reaching the Baltic Sea formed in the typical cyclogenesis areas near Iceland, over the North Sea, over the Norwegian Sea, over the Gulf of Genoa, and over the Adriatic Sea (Fig. 1 and Table 1). Most cyclones arrived from regions < 1000 km from the study area and from directions backed by large-scale atmospheric circulation (Fig. 2). More than 300 cyclones, equivalent to almost five cyclones per year, arrived from CL2, CL8, and CL9, and about half of all cyclones were propagated in these regions. However, roughly one low pressure system from CL4, three systems from CL5, and two systems from CL6 each year came from > 4000 km from the study area.

The main cyclogenesis areas for the cold and warm half-years were slightly different, as shown in Fig. 2 and Table 2, the cyclogenesis areas being CL2, CL7 and CL8 for the cold half-year and CL8, CL 9, and CL10 for the warm half-year. It can also be seen that stronger zonal circulation in the cold half-year played a role in the cyclone origins, with all winter cyclone formation areas being located to the west of the study area. The roles of the cyclogenesis areas to the south and east of the study area were more important in the warm half-year. For most of the clusters, more cyclones were propagated towards the Baltic Sea in the cold half-year, but CL4, CL9 and CL10 were more prominent in the warm half-year.

Table 2. Mean numbers and lifetimes and the mean and minimum central pressures for the cyclones in each cluster. The first number in each group is for the whole year data, the second for the cold half-year data, and the third for the warm half-year data. The whole year means for the incoming cyclones are not the sums for cyclones in the cold and warm half-years because each cold half-year began in November of the previous year. Parameters with statistically significant trends (*p* < 0.05) are shown in italics and bold. All the trends were negative.

| Cluster	Number of cyclones in the cluster	Lifetime (h)	Mean SLP (hPa)	Minimum SLP (hPa)
CL1	175/87/***87***	152.2/136.5/171.2	989.6/987.5/993.6	***976.6***/973.0/982.5
CL2	303/186/***114***	115.4/109.0/124.8	989.7/986.3/993.7	979.4/975.3/984.9
CL3	235/137/98	105.7/94.8/112.9	***992.8***/990.9/***994.9***	984.8/***982.6***/***987.7***
CL4	71/29/41	250.2/225.9/271.4	991.8/986.4/995.5	974.7/965.4/981.6
CL5	180/95/83	202.1/***184.9***/232.9	990.4/987.6/994.3	972.3/968.2/978.1
CL6	139/84/53	172.1/157.6/196.3	991.3/989.7/994.7	976.8/974.7/981.5
CL7	239/144/89	126.4/128.1/***137.9***	988.7/987.4/991.9	***977.9***/***975.9***/982.7
CL8	391/202/186	97.7/85.4/111.7	991.0/989.1/993.4	***983.0***/980.6/986.1
CL9	300/***123***/168	129.2/112.8/142.6	995.9/994.7/996.7	987.3/986.4/987.8
CL10	185/59/126	139.9/105.9/156.0	***996.1***/995.1/***996.4***	987.7/987.1/987.9
Total	2218/1146/1045	134.2/120.5/149.4	***991.6***/***989.2***/***994.5***	***981.0***/977.7/***985.0***
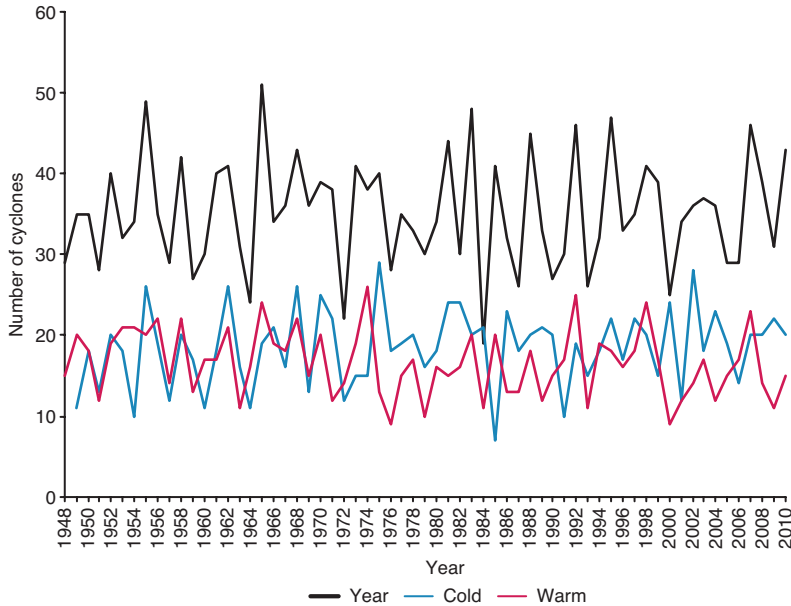
Fig. 4. Numbers of incoming cyclones per year and for the cold half-year and the warm half-year. Each cold half-year began in November the previous year, so a whole year value is not the sum of the cold and warm half-year values.

In total, there were 35 incoming cyclones per year in the Baltic Sea area, and this did not change over the 63-year study period (Fig. 4). Even when dividing the study period into three 21-year sub-periods, the number of cyclones per year remained 35. However, a certain amount of redistribution of the cyclones between the clusters was found in these sub-periods. The most prominent was a drop in the number of cyclones coming from the Mediterranean cluster (CL9), from 117 in the first sub-period to 88 in the second. This change was confirmed by a significant decreasing trend in the cold half-year (Table 2). The number of Norwegian Sea cyclones also decreased between the first and second sub-periods, leading us to suggest that this decrease was caused by stronger zonal circulation in the 1970s and 1980s inhibiting the propagation of cyclones from the north and south. The number of cyclones from the western clusters CL2, CL7, and CL8 increased at the same time.

The second significant decrease in the number of cyclones was for CL1 and CL2 in the warm half-year. This decrease was between the second and third sub-periods (Table 1), leading us to suggest that the decrease could have been caused by warmer Arctic summers and shallower temperature gradients near the Greenland and Iceland coasts.

Changes in cyclone intensity

Cyclone intensity is most often described using the minimum or mean SLP at the cyclone mid-point. The central pressure of a cyclone depends on the latitude, and therefore the pressures were less than 991.6 hPa (the overall mean) for the cluster CL1 and CL2 cyclones and higher than 991.6 hPa for the CL8, CL9, and CL10 cyclones (Table 2). The CL3 cyclones were exceptions in terms of both the mean and minimum SLPs. The cyclones with the lowest minimum SLPs covered the longest distances, coming from the central and eastern parts of North America (CL4 and CL5). These cyclones also had the longest lifetimes, generally > 200 h. Cyclones emerging over the North Sea (CL8) were easily carried by westward flow to the Baltic Sea region and had a mean lifetime of only 97.7 h. The typical cyclone lifetimes were 100–150 h (4–6 d).

The incoming cyclone intensity increased between 1948 and 2010, as shown by several statistically significant trends. The mean and minimum central cyclone pressures decreased in general over the study period (Table 2 and Fig. 5). The mean central pressure decreased in the whole year and both half-year data, and the minimum pressure decreased in the whole year and warm half-year data. Similar mean pressure

Fig. 5. Temporal changes in the annual time series of the central mean sea level pressures (SLPs) and central minimum SLPs for all incoming cyclones, with linear trends shown. Both trends were statistically significant ($p < 0.05$). The changes indicated by the trend lines were –2.7 hPa and –3.9 hPa for the central mean SLP and central minimum SLP, respectively.
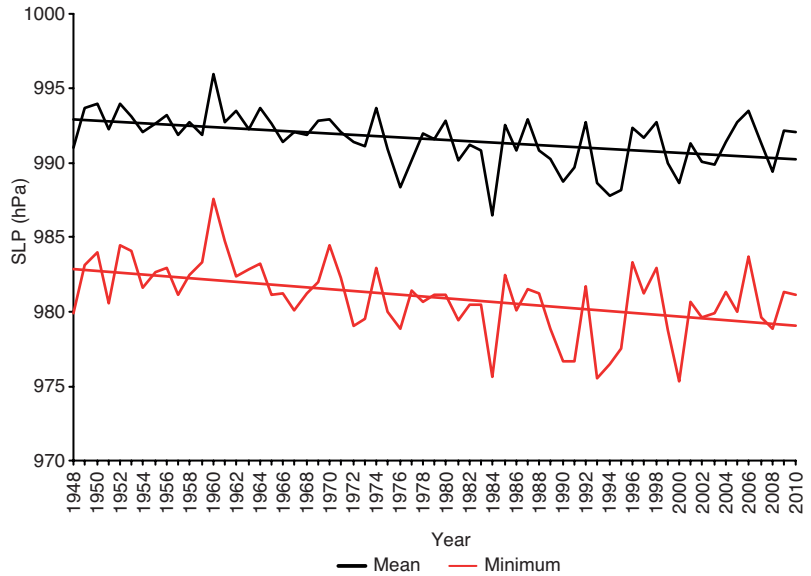
decreasing tendencies were found for cyclones from both CL3 and CL10, clusters associated with meridional circulation. The minimum pressure also decreased significantly in the CL3 cyclones and in cyclones from other clusters (CL1, CL7, and CL8) in the whole year data.

These declines in pressure over the whole study period were mostly in the range 2–5 hPa. The largest decreases, of 7.5 hPa and 5.4 hPa, were in the whole year and cold half-year minimum pressures, respectively, for lows formed near the west coast of Europe (CL7). The central pressure for cyclones formed in CL3 decreased by an average of 3.8 hPa.
It should also be mentioned that no statistically significant trends were found in the SLP time series for the cyclogenesis points.

Ordinary and deep cyclones

Cyclones with the lowest 10% mean pressures, i.e., deep cyclones, were eliminated from subsequent analyses in order to assist our understanding of why the cyclones' pressure decreased over time. The aim was to determine whether a few very deep cyclones occurred, or whether the pressure of most of the cyclones decreased. The remaining cyclones were ordinary cyclones, and the characteristics of these cyclones are shown in

Table 3. Using only one threshold of 981.2 hPa for the whole year yielded most cyclones from the cold half-year (201 out of 223), thus the threshold between deep and ordinary cyclones was dependent on the season. The distributions of the deep and ordinary cyclones in the different clusters are shown in Fig. 6. More deep cyclones were in the clusters to the west of the Baltic Sea region (CL2, CL7, and CL8) than in the other clusters. The clusters that were more important in the warm half-year (CL9 and CL10) supplied almost no deep cyclones. An additional reason for the higher pressures of the cyclones generated in CL9 and CL10 is their southward genesis.

Changes in the cyclone lifetimes were rare (Tables 2 and 3). The lifetimes of all the cyclones and of the ordinary cyclones in the cold half-year formed to the east of America (CL5) decreased by 49.3 and 45.5 h, respectively. The lifetimes of all cyclones formed near the west coast of Europe (CL7) in the warm half-year decreased by 41.1 h.

It can be concluded from Tables 2 and 3 that the significant strengthening of cyclones and decreases in the cyclone frequencies were caused by changes in most of the cyclones rather than by a few extreme lows: the significant trends in the same characteristics are shown in both tables.
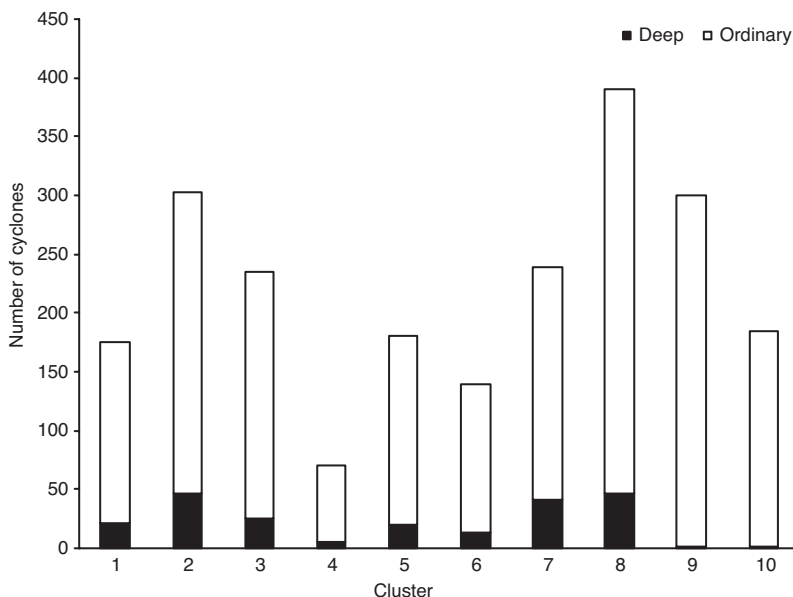
Fig. 6. Numbers of incoming cyclones divided into deep and ordinary cyclones for the ten clusters.

Correlations between the NAO index and cyclone parameters

We calculated linear correlations between the NAO index (Li and Wang 2003) and the characteristics of cyclones entering the Baltic Sea region. The results for the whole year and the cold half-year are shown in Table 4. No significant correlations were found for the warm half-year data. The significant correlations for the whole year data were mostly negative, meaning that fewer cyclones entered the Baltic Sea region as the NAO index increased, but the cyclones were stronger as all three SLP characteristics were lower. The correlations between the NAO index and SLP were stronger for the cold half-year data than for the whole year data, but no correlation was found between the NAO index and the cyclone count. However, the correlations between the NAO index and the cyclone parameters were not constant over time, and sometimes opposing relationships occurred (*see* Table 4).

Table 3. Mean numbers and durations and mean and minimum sea level pressures (SLPs, in hPa) for ordinary cyclones in the cold half-year (the first number in each pair) and warm half-year (the second number). Parameters with statistically significant trends ($p < 0.05$) are shown in italics and bold. All the trends were negative.

Cluster	Number of cyclones in the cluster	Lifetime (h)	Mean SLP (hPa)	Minimum SPL (hPa)
CL1	74/***71***	137.1/171.6	989.1/995.5	975.0/984.9
CL2	159/***98***	112.1/126.8	989.1/995.1	978.0/986.4
CL3	125/92	95.2/112.6	992.3/***995.7***	***984.1***/***988.6***
CL4	27/39	228.2/270.0	987.4/996.0	966.3/982.4
CL5	84/77	***189.5***/232.7	989.0/994.9	969.7/979.2
CL6	78/50	158.5/195.6	990.9/995.5	975.8/982.4
CL7	124/66	132.9/138.5	989.8/994.7	***978.5***/986.6
CL8	180/157	87.6/116.0	990.7/995.8	982.2/***988.8***
CL9	***122***/165	112.8/144.4	998.9/996.9	986.5/988.0
CL10	58/124	105.8/156.7	995.3/***996.5***	987.4/988.1
Total	1031/***939***	123.1/151.9	***991***/***995.7***	979.5/***986.4***

A few statistically significant but weak correlations were found between the NAO index and clustering variables, and these results are not presented here. The correlation coefficients for the significant correlations were relatively low, thus we refer only to general tendencies. For example, the long-distance cyclones from CL4 and CL5 emerging over the American continent were positively correlated with the NAO index in the cold half-year. More of these cyclones occurred when the NAO index was higher, and the cyclones had higher SLPs. This may have been due to favourable western flow when the NAO index was positive, meaning also that cyclones that were not very deep were able to travel long distances to reach the Baltic Sea. Fewer cyclones from the Mediterranean (CL9) tended to reach the Baltic Sea region when the NAO index was positive.

There was a strong linear trend in the NAO index for the cold half-year, so we also examined correlations with the detrended NAO time series, but the same significant correlations were found, although the correlation coefficients were somewhat lower.

Discussion and conclusions

Variability in the properties of incoming cyclones in the Baltic Sea region and the correlations between these properties and the NAO index between 1948 and 2010 were studied using a data set based on SLP minima for cyclones in the northern hemisphere. Only cyclones with mean central SLPs < 1000 hPa were included. These cyclones were split into ten clusters based on their cyclogenesis areas using the *k*-means clustering method. Cyclones from all the main cyclogenesis regions were found, and most cyclones came from the Iceland, North Sea, and Mediterranean regions. The trends in the numbers of cyclones, central minimum and mean SLPs, lifetimes, and SLPs at the cyclogenesis points were calculated for the whole year and for the cold and warm half-years.

The number of cyclones entering the Baltic region remained the same throughout the period 1948–2010. No significant increases in the number of cyclones in general or the number of cyclones from different cyclogenesis areas were found. This means that the warming in the winter that has occurred in the Baltic Sea region cannot be explained by increases in the numbers of cyclones arriving.

This contradicts the conclusions of several previous studies (e.g., Gulev *et al.* 2001, Neu *et al.* 2013, Tilinina *et al.* 2013) in which increased numbers of cyclones, especially deep lows, were observed over the North Atlantic cyclone track. This discrepancy could be explained by first remembering that not all cyclones from that track will have reached the Baltic Sea region. The other cyclones could propagate either north or south of the Baltic Sea region. The number of lows moving from mid-latitudes to the Arctic has increased in recent decades (Sepp and Jaagus 2011, Stroeve *et al.* 2011). Second, cyclones travelling the entire length of the storm track were not counted in most previous studies. Whittaker and Horn (1984) pointed out that relatively few systems ever travel the entire length of the North Atlantic storm track, most dissipating before the end of the track and others forming along the track and travelling to the end of it. Dacre and Gray (2009) identified five genesis areas for cyclones that reach western Europe, and they found that the so-called North Atlantic storm track is composed of many shorter tracks.

Table 4. Correlations between the North Atlantic Oscillation (NAO) index (Li and Wang 2003) and the cyclone characteristics for the whole year data and the cold half-year data. Linear correlation coefficients indicating significant correlations ($p < 0.05$) between the NAO index and the cyclone characteristics are shown in bold. SLP = sea level pressure.

Years	1948–1968	1969–1989	1990–2010	Total
Whole year				
Count	–0.39	0.34	–0.23	**–0.25**
SLP				
Initial	0.08	0.22	–0.31	**–0.26**
Mean	–0.19	**0.50**	–0.46	**–0.47**
Min	–0.21	**0.58**	–0.48	**–0.48**
Duration	–0.21	–0.11	0.14	–0.08
Cold				Total
Count	–0.25	0.24	0.21	0.15
SLP				
Initial	–0.08	–0.33	–0.32	**–0.33**
Mean	–0.29	**–0.62**	**–0.74**	**–0.64**
Min	–0.26	**–0.65**	**–0.81**	**–0.68**
Duration	**–0.51**	–0.08	–0.05	–0.23

Therefore, the Atlantic storm track covers both cyclones from CL4 and CL5 that travel along the whole track and cyclones from other genesis areas (CL1, CL2, CL6, and CL7) that are on the storm track.

The increasing winter temperatures in the Baltic Sea region in recent decades has been reported to match the observed shifts in storm tracks at a large scale (BACC (Author Team II) 2015), but our results did not validate a possible relationship between these observations. Our hypothesis that the cyclogenesis area determines the storm track was not supported because no clear redistribution of cyclones between clusters over time was found. However, only stronger cyclones were included in this study, meaning that substantially fewer cyclones were analysed than in modern-era reanalyses (Tilinina *et al.* 2013). The characteristics of weaker cyclones and deeper cyclones are substantially different, as shown in several studies (Rudeva and Gulev 2007, Sepp 2009, Campins *et al.* 2011, Sepp and Jaagus 2011), but weaker cyclones may influence the local climate significantly. Further analyses of regional cyclones based on modern reanalysis databases in which weaker cyclones are better identified than in earlier reanalysis databases are therefore required. A study using a database with a higher spatial resolution is also required, because the exact trajectory of a cyclone determines local temperature advection.

The most important changes characterizing the incoming cyclones were the decreasing mean and minimum SLP trends, with cyclones entering the Baltic region generally becoming deeper and therefore more intense over the 63 y of the study period. Separating the incoming cyclones into ten cyclogenesis area clusters allowed statistically significant negative trends in the SLP parameters to be found for only a few clusters, but the decreasing SLP tendency appeared in almost all of the clusters.

The cyclones became deeper over time, and this was not caused by extreme cyclone outliers but rather by most cyclones becoming deeper and more intense. The increase in the cyclone intensity may also have been related to the field used to identify the cyclones, the trends in the storm intensities reflecting changes in the large-scale background field. Bengtsson *et al.* (2006)

stated that identifying cyclones using the raw SLPs (as pressure minima) in particular could be influenced by trends in the background mean SLPs. We also assessed the monthly mean SLP time series in the cluster domains but found no significant trends. Unlike for the mean and minimum SLPs for incoming cyclones, no decreasing trend was found in the SLPs of the cyclogenesis points. This means that the incoming cyclones were not more intense when they formed but became stronger along their tracks to the Baltic Sea region. However, we followed only cyclones that propagated to the Baltic Sea region, so we cannot draw conclusions about the overall activities of the cyclogenesis regions.

Weak, but significant correlations were found between the incoming cyclone characteristics and the NAO index. The overall tendency for cyclones to be deeper when the NAO index was positive has also been observed by other researchers (Serreze *et al.* 1997, Jung *et al.* 2003, Sepp 2009). However, the number of cyclones entering the Baltic Sea region was anticorrelated with the NAO index on a whole year basis and no significant correlation was found on a cold half-year basis. As an exception, we found a positive correlation between the NAO index and the number of winter cyclones that formed over the North American continent, the so-called North American/North Atlantic cyclones (Gulev *et al.* 2002), and the same tendency was found by Pinto *et al.* (2009). Nevertheless, it should be kept in mind that the strengths of the correlations between the NAO index and some of the environmental parameters for the Baltic Sea region were not consistent but depended on the study period used (Jevrejeva 2002, Jevrejeva *et al.* 2003, Omstedt and Chen 2001, Lehmann *et al.* 2017). The same non-stationary connection between the NAO index and explosive cyclone development was found by Gómara *et al.* (2016). Both they and Jung *et al.* (2003) explained this in terms of different spatial structures in NAO-related patterns in independent 20–25 year-long periods. Therefore, it is unreasonable to make conclusions about the long-term properties of NAO-related climate variations from the use of short-period observations.

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