

Changes in frequency of Baltic Sea cyclones and their relationships with NAO and climate in Estonia

Mait Sepp

Department of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia

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An increase in cyclone activity and the frequency of westerlies was observed over the Baltic Sea region during the 20th century. The Baltic Sea region itself is a relatively active area of cyclogenesis. Long-term changes in the frequency and mean sea-level pressure (SLP) of cyclones formed over the Baltic Sea region were analysed in the present study using the database of cyclones from literature. Relationships between the variables of the Baltic cyclones with the NAO index and some meteorological time series in Estonia were analysed. Results showed that the total number of cyclones did not change but the number and percentage of deep cyclones increased during 1948–2002. In general, the SLP of all cyclones and SLP in tracking points decreased. Correlation analysis showed that in case of the positive phase of the NAO, less but stronger cyclones form over the Baltic region. The Baltic Sea cyclones cause milder and moister weather conditions in Estonia in winter.

Introduction

The Arctic and northern Europe are the regions where an increase in surface air temperature was remarkable during the 20th century. Many studies (e.g. Gulev *et al.* 2001, McCabe *et al.* 2001, Bengtsson *et al.* 2004, Zhang *et al.* 2004) demonstrated that the Arctic warming is caused by changes in atmospheric circulation, especially in cyclonic activity. The number and intensity of cyclones entering the Arctic from the mid-latitudes increased during the second half of the century.

Changes in atmospheric circulation over northern Europe occurred during the 20th century as well. Numerous studies demonstrated an increase in cyclone activity and frequency of westerlies over the Baltic Sea region. These changes are generally related to the North Atlantic Oscillation, i.e. changes in the Icelandic low

(Alexandersson *et al.* 1998, Omstedt *et al.* 2004, Pryor and Barthelmie 2003, Sepp *et al.* 2005a). However, not all cyclones moving in northern Europe are related to the Icelandic minimum. A significant amount of them are formed over the North Sea. Cyclones from the Mediterranean, the Black Sea and even the Caspian Sea also have an effect on the weather in the Baltic Sea region (Sepp *et al.* 2005b). According to previous studies, the Baltic Sea region itself is also a relatively active area of cyclogenesis (Sepp *et al.* 2005a, 2005b, Link and Post 2007).

The aim of the present study is to analyse long-term changes in the frequency and mean sea-level pressure (SLP) of cyclones formed over the Baltic Sea region. Relationships between variables of the Baltic Sea cyclones and the NAO index, and some meteorological time series in Estonia are also analysed.

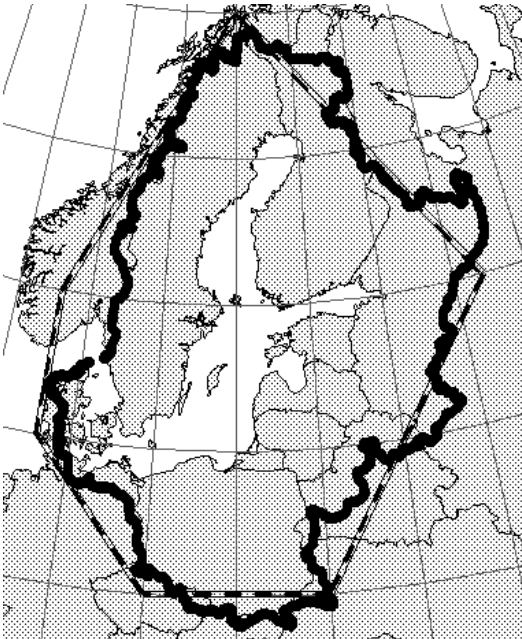


Fig. 1. Study area. Dashed line: border of the Baltic Sea region as it is defined and used in the present study. Solid line: border of the Baltic Sea catchment area.

Data and methods

The database of cyclones described by Gulev *et al.* (2001) was used in the present study. The database consists of the cyclone tracking output of the 6-hourly NCEP/NCAR reanalysis (Kalnay *et al.* 1996) of SLP fields using the software developed by Grigoriev *et al.* (2000). Cyclones are presented by the geographical coordinates of their centres (with the accuracy of 0.1°) and SLP at these points. The Baltic cyclones, formed within the Baltic Sea region (presently the territory restricted by the lines with coordinates 70°N , 20°E – 60°N , 37°E – 50°N , 25°E – 50°N , 15°E – 55°N , 8°E – 60°N , 8°E – 70°N , 20°E) during 1948–2002, were analysed. In general, the territory of the Baltic Sea region presented here is close to the territory of the Baltic Sea catchment area (Fig. 1).

The following variables were determined and studied: the total number of cyclones, the duration of cyclones expressed in the number of tracking points with the interval of six hours, the mean sea-level pressure of cyclones and

sea-level pressure at the first, last, deepest and northernmost points of cyclones.

The linear regression analysis was applied for detecting long-term changes. A linear trend was calculated for every time series and their significance level was found using Student's *t*-test. Trends were considered statistically significant at $p < 0.05$. Time series of annual and seasonal mean values were formed.

Seasons were defined by grouping three months: winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Deep cyclones with the minimum sea-level pressure of < 1000 hPa and shallow cyclones were selected. In order to determine changes in relations between deep and shallow cyclones, the percentage of deep cyclones in all cyclones was calculated.

Default settings of ArcView 3.1 were applied in the interpolation of the spatial distribution of the first tracking points. In order to avoid deformities near the border of the studied area, the first tracking points of cyclones that occurred over the territory with coordinates 5 – 40°E and 50 – 70°N were used in the interpolation process.

Two NAO indices were used to study the connections between the Baltic cyclones and general atmospheric circulation. The first index was calculated from the air pressure differences between Stykkisholmur/Reykjavik and Gibraltar (Jones *et al.* 1997), whereas the second index used the data between Stykkisholmur/Reykjavik and Ponta Delgada (Rogers 1997, Hurrell and van Loon 1997).

Meteorological variables for Estonia were taken from the monthly air temperature and precipitation data from the Tartu Meteorological Station.

Results

Results of the regression analysis

The total number of cyclones formed over the Baltic Sea region during 1948–2002 was 2372. It amounts to 1.8% of the total number of cyclones over the northern hemisphere available in the database of cyclones (Gulev *et al.* 2001). The mean annual number of the Baltic cyclones was 43.1 (SD = 8.3). The minimum number of

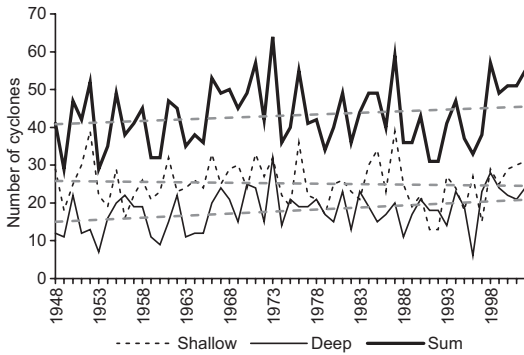


Fig. 2. Time series and trend line of the number of deep (with minimum sea-level pressure below 1000 hPa), and shallow cyclones formed over the Baltic Sea region and their sum. Only the trend of deep cyclones is statistically significant at $p < 0.05$.

cyclones (29) was observed in 1949 and 1953, while the maximum (64) was recorded in 1973. The total number of the Baltic cyclones had an increasing but insignificant trend.

After dividing the cyclones into two groups, deep (mean pressure < 1000 hPa) and shallow (> 1000 hPa), significant changes and differences appeared in the time series of these cyclones. The frequency of deep cyclones increased significantly (by 4.3 cyclones) during 1948–2002 (Fig. 2). This change is remarkable when taking into account that the mean annual number of deep cyclones was 17.9 (SD = 5.3) and that their percentage in the total number of cyclones was 41.4%, having increased by 10.3%. The frequency and percentage of shallow Baltic cyclones decreased correspondingly by 1.3 cyclones. However, the change was not as fast as the increase in deep cyclones, in addition to which this change was not statistically significant.

The mean duration of the Baltic cyclones was 12.7 tracking points (SD = 1.4), i.e. about 76 hours. On average, deep cyclones existed by 2.9 tracking points (17.4 hours) longer. There were no statistically significant changes in the time series of cyclone duration.

The mean sea-level pressure of all the Baltic cyclones was 1000.7 hPa (SD = 1.5 hPa), having decreased significantly (by 2.1 hPa) during the 55-year period. The mean pressure of the deep Baltic cyclones was 993 hPa (SD = 1.8 hPa). It had a statistically significant decreasing trend by 2.2 hPa. There were no changes in the time series

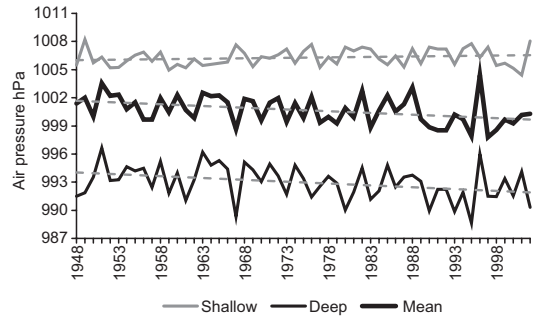


Fig. 3. Time series and trend line of the air pressure in the centre of shallow and deep Baltic Sea cyclones and their average. The trend of shallow cyclones is statistically insignificant.

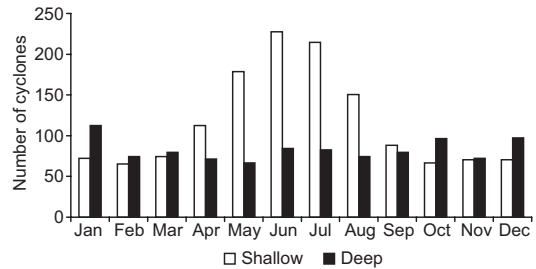


Fig. 4. The annual course in the number of shallow and deep cyclones that formed over the Baltic Sea during the period 1948–2002.

of the air pressure of shallow cyclones (mean pressure = 1006.3, SD = 0.9 hPa) (Fig. 3).

The seasonal maximum in the frequency of Baltic cyclones appeared in summer. However, most of the summer cyclones were shallow. The maximum frequency of deep cyclones occurred in winter (Fig. 4). Seasonal changes in the frequency of cyclones and mean SLP were in line with general changes. Still, statistically significant changes occurred mostly in winter and spring.

In winter, the total number of cyclones did not change, but an important decreasing trend of the mean SLP was detected. The mean SLP decreased by 5.7 hPa (average 996.7 hPa, SD = 4.5 hPa). Similar to the general tendencies, the number and percentage of deep cyclones increased significantly. The mean number of deep winter cyclones during 1948–2002 was 5.2 and their frequency increased by three cyclones. The percentage increased from 46.5% in the beginning of the period (late 1940s) to 68% at the present day. No statistically significant

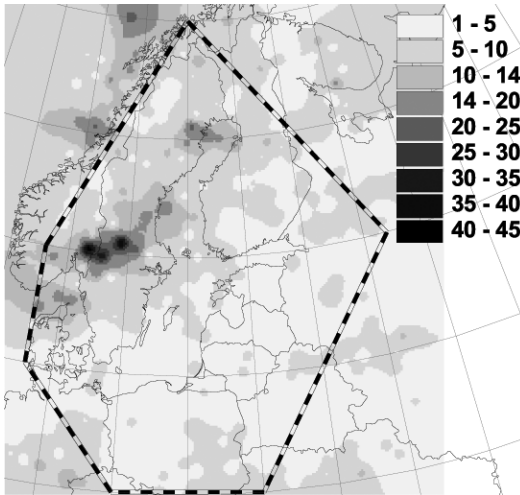


Fig. 5. Spatial distribution of the frequency in the position of the first tracing points of the Baltic Sea cyclones over the period 1948–2002.

changes were detected in the SLP of deep winter cyclones.

The mean SLP of all and deep cyclones decreased statistically significantly in spring (mean SLP of all cyclones: 1001.5 hPa and decreasing by 3.2 hPa, the mean SLP of deep cyclones: 993.4 hPa and decreasing by 4.2 hPa). Since the number of deep cyclones increased and that of shallow ones decreased (both by about 1.5 cyclones, but the changes were statistically not significant), the percentage of deep cyclones increased significantly by 15.6% (mean of the period 37.4%).

As mentioned above, most of the Baltic cyclones appear in summer. However, no significant trends occurred in that season. Only two statistically significant changes were noticed in autumn: the total number of cyclones increased by 3.1 cyclones (mean of the period 8.6 cyclones) and the duration of shallow cyclones increased by 21 hours (mean 60.6 hours).

First tracking point

The spatial distribution of the first tracking points (forming points) of the Baltic cyclones is presented in Fig. 5. As can be seen, cyclones were formed mostly on the eastern slope of the Scandinavian Mountains. The most distinguished area

of cyclone genesis was near Oslo: a total of 43 cyclones had formed at the point with coordinates 11.6°E, 60.1°N during the 55-year period.

The mean SLP in the first tracking point was 1001 hPa; it significantly decreased by 2 hPa. A decreasing trend (by 7 hPa) of the first tracking point SLP of all cyclones also occurred in winter (mean SLP 993.3 hPa, SD = 5.6). No other changes were recorded in the time series of the forming points, even if we study deep and shallow cyclones separately.

In the given case, cyclones can be divided into two groups according to SLP at the first tracking point: cyclones with a deep forming point (pressure in the first tracking point is below 1000 hPa) and shallow cyclones; 38% of Baltic cyclones were deep considering the SLP of the forming point. That percentage did not change during 1948–2002.

Certainly, most of the cyclones that are deep by the forming point are also deep by the mean pressure. Altogether, 986 cyclones were deep by mean pressure and 904 were deep by the forming point. The number of cyclones that are deep by both the SLP of the first tracking point and mean pressure was 719. This makes 30.3% of the total number of Baltic cyclones, 72.9% of deep cyclones by the mean pressure and 79.5% of deep cyclones by the forming point.

Despite the fact that there were no general disagreements between these two types of deep cyclones, some small differences could still be noticed. Only one statistically significant trend in case of deep cyclones by the SPL of the first tracking point occurred: the mean SLP of the forming point decreased by 3.3 hPa (mean of the period 993.8 hPa). There were no changes in the time series of shallow cyclones.

Deepest, northernmost and last tracking points of the Baltic cyclones

The mean SLP of the tracking point with the deepest air pressure of the Baltic cyclones was 995.5 hPa (SD = 2). It had a statistically significant decreasing trend by 2.9 hPa. This general change was mostly caused by a deepening trend in time series of deep cyclones. In case of deep cyclones by the mean SLP, the air pressure

at the deepest tracking point decreased by 2.7 hPa (mean 986 hPa). An even steeper deepening trend (by 4.3 hPa) occurred in case of deep cyclones by the forming point (mean 987 hPa). 60.8% of the cyclones formed in the Baltic Sea region had their minimum pressure < 1000 hPa.

Steeper deepening trends of the SLP appear when we studied the time series of the northernmost tracking point. The mean sea-level pressure at the northernmost tracking points of the Baltic cyclones was 1001.3 hPa (SD = 2 hPa). The deepening trend existed for all cyclones (by -3 hPa), as well as for deep cyclones by the mean SLP (mean 994.3 hPa, change by -4.2 hPa) and deep cyclones by the forming point (mean 995 hPa, change by -4.5 hPa).

The mean sea-level pressure at the last tracking point of the Baltic cyclones was 1004.1 hPa (SD = 1.2 hPa). It had a significantly decreasing trend (1.5 hPa) as well. As usual, changes could be noticed in the time series of deep cyclones. But in the present case, only deep cyclones by the mean pressure showed significantly decreasing trends (mean 998.8 hPa, change by -2 hPa). The SLP of all three tracking points had significant decreasing trends in winter (by 4–6 hPa), but the SLP of the deepest and the last tracking points decreased also in spring (accordingly by 4.7 and 2.7 hPa).

It has already been mentioned that most of the Baltic cyclones had been formed in a relatively small area. We should also note that the other examined tracking points had quite a small divergence as well; 70.1% of the deepest, 60% of the northernmost and 42.5% of the last tracking points remained in the area with coordinates 10–40°E and 50–70°N. In 899 cyclones (37.9%), all four tracking points were located in this area. Still, the immobility of Baltic cyclones was deceptive because in many occasions the tracking points just coincided; 543 forming points were at the same time the deepest points. In case of 619 cyclones, the forming point was also the northernmost tracking point.

Relationship between the NAO indexes and variables of the Baltic cyclones

A relationship between the frequency of Baltic

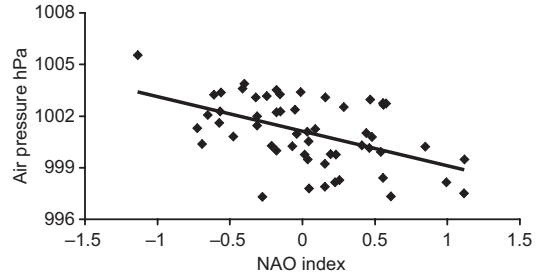


Fig. 6. Scatter plot of the NAO index and the annual mean air pressure of the first tracking points of the Baltic Sea cyclones; $r = -0.50$.

cyclones and the annual value of the NAO index (here and later, the NAO Gibraltar) was negative ($r = -0.27$) and statistically significant at $p < 0.05$. In general, connections with the number of cyclones are usually insignificant and practically absent in case of deep cyclones.

There were relatively strong correlations between the NAO index and variables of the air pressure. Statistically significant negative correlations appeared with mean SLP and the SLP of the deepest tracking point. The above-mentioned correlations occurred with deep cyclones as well as with the time series of all cyclones.

The highest values of correlation coefficients were found between the NAO index and SLP of the first tracking point. The correlation with the annual time series of all cyclones were $r = -0.50$ (Fig. 6) and with deep cyclones (deep by mean SLP): $r = -0.46$. Changes in the NAO index seemed to have no effect on the SLP of the northernmost and the last tracking point. Also, no influence on changes in the percentage of deep cyclones or the duration of cyclones occurred.

The relationships with the NAO indexes were very weak during spring, summer and autumn. Only one statistically significant correlation coefficient appeared throughout those seasons: a negative correlation with a number of weak cyclones in autumn ($r = -0.35$).

As expected, the most significant correlations occurred in winter, when some values of the coefficients even exceeded the annual ones. For example, correlation coefficients (r) with the SLP in the forming point were greater than -0.60 in case of time series of all and only of deep cyclones. Noticeable are also the positive correla-

tions between the NAO indexes and the number and percentage of deep cyclones in winter.

As mentioned before, all correlation coefficients presented before were calculated using the so-called NAO Gibraltar index. The index NAO Ponta Delgada was also applied in a calculation process, but it became evident during the analysis that almost all correlation coefficients of both indexes coincide with each other. The only significant exception was the negative correlation between the NAO Ponta Delgada and SLP of the first tracking point of all cyclones in autumn.

Relationship between the variability of the Baltic cyclones and weather in Estonia

Weather variability in Estonia is strongly influenced by atmospheric circulation processes, i.e. the NAO phenomena (Jaagus 2006). It was explained in the previous subchapter that some variables of the Baltic cyclones are closely related with the NAO index. So, as expected, statistically significant correlations also occurred between some variables of the Baltic cyclones and air temperature in Estonia (Tartu Meteorological Station).

Relatively strong correlation appeared between the annual air temperature and SLP of the first tracking point of all cyclones ($r = -0.50$). Not so strong but still statistically significant negative correlations occurred also with SLP of other three tracking points. In addition, a positive correlation between the annual air temperature and percentage of deep cyclones could be noticed. Consequently, the more deep cyclones form over the Baltic region, the higher is the annual temperature in Estonia.

The same conclusion can be made for the winter and spring data. There were statistically significant negative correlations between the air temperature and SLP of the first and deepest tracking point in winter. The air temperature in spring and SLP variables of the Baltic cyclones seemed to be even more closely related: the time series of SLP of all tracking points had statistically significant negative correlations with the air temperature in Tartu. Again, as it was the case of the NAO, there were no significant correla-

tions in summer and autumn.

The relationship with precipitation was not as strong as it was with air temperature and different variables were important. Again, a statistically significant negative correlation occurred between the annual sum of precipitation and SLP of the first tracking point (both, in case of all and also deep cyclones). Also, a significant negative correlation appeared with the mean SLP of all cyclones.

Relatively strong positive correlations occurred between the frequency of cyclones and the sum of precipitation in winter and spring. The correlation coefficients had an even higher value in case of deep cyclones. (Relation between the number of deep cyclones and the sum of precipitation in spring had the highest value of $r = 0.43$). Negative correlations with the SLP of the deepest point and mean SLP of all cyclones were also statistically significant in spring.

Exceptionally, there were significant relations with precipitation also in summer. Positive correlations occurred with the frequency of all cyclones and SLP of the last tracking point of deep cyclones. Negative correlation appeared with the percentage of deep cyclones. The most exceptional relation that occurred in summer was a positive correlation between the sum of precipitation and the number of shallow cyclones ($r = 0.31$). Only one statistically significant correlation occurred in autumn: between the sum of precipitation and the number of deep cyclones ($r = 0.33$).

Discussion

A cyclone forms over the Baltic Sea region almost every week. Most of them start on the eastern slope of the Scandinavian Mountains. A distinguished cyclone-forming area is near Oslo and also some points east of that area (Fig. 5). But significant differences occur if we compare Fig. 5 with figures published by Link and Post (2007) and Post and Link (2007), who presented cyclone forming areas using the database of Gulev *et al.* (2001). In the figures of the above-mentioned articles, no outstandingly active cyclone-forming area appeared in the region near Oslo.

The visual divergence of the figures presented here and in the refereed work (Link and Post 2007) is natural, because different spatial interpolation methods were used. In the given case, the iso-lines of the number of cyclones were generated by using the weight of the neighbouring points. As relatively few (up to 10) cyclones had formed at the eight points around the Oslo point (11.6°E, 60.1°N) during the 55-year period, the central point demonstrated a deep contrast. Link and Post (2007) normalised cyclone numbers for 100 000 km² areas and the annual numbers were shown in their figures. Also, shorter time series (1948–2000) were used and only cyclones whose minimum pressure dipped at least once below 1000 hPa were analysed.

Despite the differences in the spatial interpolation methods, the general results of both works are similar. Here, the mean annual number of cyclones formed in the Baltic Sea region was 43. Link and Post (2007) reported the annual number of cyclones — formed in five circles with a radius of 1000 km in the Baltic Sea region — to be 30–50. Forty percent of cyclones that appeared in the region had formed inside it (Link and Post 2007, Post and Link 2007).

Unfortunately, when using the database of Gulev *et al.* (2001), it is impossible to say which of the Baltic cyclones were “original” and which of them were actually secondary cyclones, i.e. an echo of the depression that moves over the North Sea. Based on the forming point distribution (as mentioned, most cyclones formed on the eastern slope of the Scandinavian Mountains) and the relative shallowness of the Baltic cyclones, we can assume that the majority of them were secondary cyclones. However, we can also assume that the influence of secondary cyclones on the local climate was similar to the “original” ones.

Significant changes occurred in the number of some types of Baltic cyclones and their air pressure variables during the last 55 years. The number and percentage of deep cyclones increased but, at the same time, the total number of lows did not change significantly. Also, the mean air pressure at tracking points generally decreased. A similar pattern of changes was reported by Sepp and Jaagus (2007), who analysed the Arctic cyclones using the same database of cyclones and the same methodology for the same period. No changes

in the total number of Arctic cyclones, defined as lows that formed north of 68°N, could be observed. But again, the number and percentage of deep cyclones significantly increased. Also, a decreasing trend of air pressure was significant in tracking points. Cyclones that enter the Arctic basin (i.e. crossing 68°N from the south to the north) were also analysed by Sepp and Jaagus (2007). The total amount of these entering cyclones increased during 1948–2002. The increase was caused by an almost equal increase of deep and shallow cyclones. But since an entering cyclone is, relatively, a rare cyclone type, very few lows drift so far in meridional direction, no conclusions can be drawn about the frequency dynamics, etc. of local mid-latitudinal cyclones (i.e. the Baltic Sea cyclones).

Results of correlation analysis between the variables of the Baltic Sea cyclones and the variables of local climate and the NAO indexes were mostly expectable. It is known that the NAO positive phase means that the gradient between the air pressure of Icelandic minimum and Azorean maximum is high. That causes a strong air flow from the Atlantic to northern Europe. A higher annual air temperature, as well as higher values of precipitation, concurs with those in Estonia (Jaagus *et al.* 2001, Jaagus 2006).

Fewer but stronger cyclones form over the Baltic Sea region in case of the positive phase of the NAO. Stronger lows from the Atlantic probably move directly over the Scandinavian Mountains to the Baltic region and local secondary cyclones cannot be formed. If a secondary cyclone is still formed, then it is significantly stronger because of the influence of a stronger original low. Those scenarios are more relevant in winter, when the weather in the Baltic Sea region is mostly driven by depressions formed in the area of Icelandic minimum.

The NAO indexes “work” better in winter, i.e. the correlation between the local climate variables and the NAO indexes is stronger in winter. But the earlier analyses (Jaagus *et al.* 2001, Jaagus 2006) showed that the relationship between different NAO indexes and the Estonian climate variables is slightly different. The index, calculated using the air pressure data of Gibraltar, gives higher values of correlation coefficients with winter data but almost no correlation

in summer. Lower correlations in winter, but significant ones in the warm half-year, occurred in the case of the NAO Ponta Delgada. No seasonal differences between the two mentioned NAO indexes were revealed in the present study. Both indexes acted similarly: a clear relationship with the Baltic Sea cyclones occurred only in winter.

In general, correlations between general atmospheric circulation and local climate variables are stronger in winter. A number of local micro-scale disturbances influence weather variables in summer and the signal of general atmospheric circulation is weakening in meteorological data series. The same tendency could be noticed in the relationship between the Baltic cyclones and air temperature and precipitation in Tartu: correlation coefficients were relatively strong and significant in winter, but not in summer and autumn. The annual means of meteorological variables in mid-latitudes are often dependent on the signals of the winter season. This tendency was also evident in the present study: correlation coefficients of the annual and winter means usually coincided.

Correlations between the air pressure variables of the Baltic cyclones and annual and winter mean air temperatures in Tartu were negative. The same direction of correlation occurred with the annual and winter sum of precipitation. This means that the stronger are the Baltic cyclones, the milder and moister is the weather in winter (cold half year) in Tartu. From the point of view of general atmospheric circulation, this means that mild and moist maritime air masses are transported over Estonia.

Relationships in summer or in a warm half-year in general were not so clear and directly explainable. The positive correlation between precipitation and the number of shallow cyclones occurred in summer. It means that precipitation in Estonia in summer is closely related to small lows that formed in close areas.

Conclusions

The average of 43 low pressure formations per year formed in the Baltic Sea region during 1948–2002. However, the percentage of cyclones with the minimum sea-level pressure < 1000 hPa

increased by 10%. While at the beginning of the period the percentage of deep cyclones was approximately 36%, it is nowadays 47%.

A decreasing trend in air pressure occurred in case of all, and especially in case of deep cyclones. In general, the cyclones that were formed at the end of the period were deeper by 2 hPa than the cyclones formed at the beginning of the period. Besides the decrease in the mean air pressure of cyclones, a deepening tendency was also noticeable in the forming, the deepest, the northernmost, and the last tracking point.

Statistically significant changes occurred mostly in winter: trends were obvious and changes much larger than during other seasons.

Results of the correlation analysis showed that the Baltic cyclones are dependent on the general atmospheric circulation. Again, most prominent correlations between the NAO indexes and variables of local cyclones could be found in winter. It can be concluded on the basis of the analysis that in case of strengthening westerlies, i.e. the positive phase of the NAO, less but stronger cyclones are formed over the Baltic region. An especially strong negative correlation occurred between the NAO indexes and the air pressure of the first tracking point of the Baltic Sea cyclones.

It can also be concluded, based on the relationship between the variables of the Baltic Sea cyclones and meteorological data of the Tartu station, that a larger number and greater depth of cyclones cause milder and moister weather conditions in winter. Again, the most distinguished correlations occurred with the air pressure data of the first tracking point.

Finally, the analysis of the changes in frequency, mean SLP, and the variables of the life cycle of cyclones, is one of the possible ways to understand climate changes. As it was revealed by the present study, the time series of the cyclones reflect changes in both the general atmospheric circulation and the local climate.

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