Changes in surface wind directions in Estonia during 1966–2008 and their relationships with large-scale atmospheric circulation

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Abstract. Changes in the percentages of eight main surface wind directions at 14 meteorological stations in Estonia, Northeast Europe, were studied during 1966–2008. Long-term changes in wind directions are related to variations in the large-scale atmospheric circulation but partly also to changes in the surroundings of the stations and in wind obstacles. Significant alterations in wind directions were determined, and found to be the strongest in the winter season. The percentages of W and SW winds have clear positive trends, while SE, E and NE winds are characterized by negative tendencies in winter. In conclusion, wind directions have probably been shifted from east to west. Differences in trends between the stations are explained by changes in wind obstacles around the stations. The trends in wind roses in Estonia were caused by the intensification of the westerly circulation over the Atlantic/European sector during the winter season.

Key words: wind directions, climate change, atmospheric circulation, wind rose, Estonia.

INTRODUCTION

Near-surface wind is an important climate parameter, which has a strong influence on human activities. Wind speed and direction significantly affect transport – aviation, marine navigation, road transport, etc. Wind is an important natural factor also in other kinds of human activity, as well as in everyday life of humans.

Wind speed, and especially wind direction, determine the general character of weather conditions. In the temperate latitudes N wind is usually related to colder and drier weather, and S wind to warmer weather. Wind directions have different effects on winter weather conditions in Europe. Warmer air is coming from the western directions, from the ocean, and colder air is coming from the eastern directions. Long-term changes in wind regime might have a substantial effect on climatic conditions as a whole.

Estonia is located in the transitional zone between a maritime climate in the west and a continental climate in the east. Substantial alternations of air masses of different origin have been observed, which cause different weather conditions in different years. Atmospheric circulation is the most important climatic factor in Estonia during the cold season (Jaagus 2006). Generally, W, SW and NW winds bring warmer air from the North Atlantic, while E, NE and SE winds bring colder air from the East European Plain. During the other seasons the thermal influence of the wind directions is different.

While studying climate change, main attention has been paid to changes in the large-scale atmospheric circulation. They are induced by changes in the sea-level pressure (SLP) pattern. The most pronounced SLP change in the Northern Hemisphere has been observed in the Arctic, where mean SLP has decreased significantly during the second half of the 20th century (Serreze et al. 2000). At the same time an increase in mean SLP was observed over the subtropical North Atlantic and southern Europe. As a consequence, the air pressure gradient has increased in mid-latitudes. It has induced an intensification of westerlies, i.e. the air flow from the North Atlantic to Europe has become stronger. It is well reflected by trends in winter North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices (Hurrell 1995; Hurrell & van Loon 1997; Jones et al. 1997; Slonosky et al. 2001; Thompson et al. 2000; Feldstein 2002).

The NAO index is closely correlated with the other regional circulation indices in the Baltic Sea region like Fennoscandian and Central European zonal indices (Heino et al. 2008). The winter warming in the Baltic Sea region has been caused by the changes in large-scale atmospheric circulation (Lehmann et al. 2011).

The NAO index has started to fall during the last decade and reached its highest negative value in the winter of 2009/2010, which has caused winter cooling in Europe. Considering the variations in the NAO index and the oceanic circulation variables, prevailing of the

NAO negative phase, temperature decrease and colder winters are predicted for the next few decades (Keenlyside et al. 2008; Semenov et al. 2010).

Large-scale atmospheric circulation generally forms the character of local wind directions. Unfortunately, few studies have been centred on changes in the directions of near-surface winds. Mostly, much wider regions are studied, with a focus on changes in cyclone activity, storm tracks and storminess (Alexandersson et al. 1998, 2000; Bijl et al. 1999; Orviku et al. 2003; Bärring & von Storch 2004; Matulla et al. 2008; Bärring & Fortuniak 2009).

The first attempts to assess changes in the frequencies of wind directions were made in Estonia (Kull 2005; Keevallik 2008; Jaagus 2009), where an increase in SW winds was detected. An analysis of wind components on the 500 hPa isobaric level over Estonia during 1953–1998 revealed a significant increasing trend in the zonal component of wind velocity in winter and in its meridional component in March (Keevallik & Rajasalu 2001).

The main objectives of this study are to analyse long-term changes in the occurrence of different near-surface wind directions in homogeneous time series from 14 stations of Estonia, and relationships between the indices of large-scale atmospheric circulation and near-surface wind directions.

MATERIAL AND METHODS

Occurrences of near-surface wind directions, calculated by eight main sectors at 14 stations in Estonia (Fig. 1), were used for the analysis of long-term changes in wind roses. These stations were chosen following the criteria of data homogeneity and continuity. Measuring sites were not significantly changed at these stations. Only in Viljandi (1982) and Sõrve (1987) the observation field was shifted approximately 0.7 km within the period under study. A general tendency around the observation fields has been growth of sparse trees and nearby hedges, while suburban development has had moderate effect at Viljandi, Valga and Võru.

The effects of obstacles on wind were modelled by the WAsP program, using a standard procedure (Troen & Petersen 1989). Relative importance of the sheltering effect was modelled for all 14 meteorological stations and always independently for periods with homogeneous obstacles set up.

The WAsP model was developed for the microscale wind climate modelling, estimation of wind energy resources and for the siting of wind turbines, but has frequently been used for a variety of wind-related applications (e.g. Landberg & Watson 1994; Frank & Landberg 1997; Mortensen & Petersen 1998; Goossens & Gross 2002; Reutter et al. 2005). It is an integrated model including parameterized physical-based submodels for moderately complex topography, landscape roughness and flow around sheltering obstacles. The model transforms a wind speed and direction time series at a reference site to a regionally representative wind climatology representing a theoretical wind over a flat and featureless landscape of homogeneous roughness. Thus its calculation is based on the description of local terrain variations, sheltering obstacles and effective landscape roughness. The wind climatology is expressed as a set of sectorwise Weibull parameters describing the wind speed distribution by sectors. Detailed description

Fig. 1. Location map of the meteorological stations whose wind duration data were used in this study.

of the physical basis of WAsP is given by Troen & Petersen (1989) and Troen (1990).

In our study wind obstacles of the area surrounding the meteorological fields of the stations in a 1000 m radius were analysed retrospectively by use of plans in archives of meteorological stations (1966–1990), and large-scale maps (1 : 10 000), orthophotographs (1 : 2000 and 1 : 10 000) and tachymetrical survey data collected during field works in 1995, 2003 and 2005–2008. All obstacles were digitally mapped for the WAsP submodel in polar coordinates relative to the wind vane with angular resolution of 10″, distance and height with a resolution of 0.1 m. The porosity of the obstacles was calculated according to Perera (1981). The surroundings of the meteorological stations were mapped on the basis of large-scale topographic maps (1 : 10 000 and 1 : 25 000) in an extent of 20 km around the measurement device. According to the roughness classification proposed by Troen & Petersen (1989), the surroundings of the meteorological stations mainly belong to roughness class 2 ($z_0 = 0.05-0.2$ m, farmland with some windbreaks) and class 3 ($z_0 = 0.4-0.7$ m, forests and farmland with many windbreaks). As an exception forest and coppice near the anemometer (up to a distance of 50 times the height of the object) was handled as an obstacle instead of the usual roughness element (Troen & Petersen 1989; Taylor & Salmon 1993). While the orography model was considered as constant over the study period (1966–2008), the roughness map was updated if the surroundings of the meteorological station experienced significant land use change (e.g. suburban development at Viljandi and Valga). In these cases the first roughness map was assumed to be characteristic of the period 1966–1990 (based on topographic maps originating from 1978–1984) and the recent roughness map (period 1991–2008) was based on contemporary topographic maps and orthophotographs. However, the influence of general roughness change was clearly inferior (average wind direction turn 0.1–0.7°) to the effect of changes in obstacles as the obstacles were located close to the anemometers.

The starting year 1966 was chosen because since that time eight observations per day at 00, 03, 06, 09, 12, 15, 18 and 21 GMT have been carried out at the meteorological stations of Estonia. Three instrument changes occurred during the observation period of 1966–2008. During the first decade wind speed and direction were visually observed using Wild's wind vanes. Since November 1976 automatic anemo-rhumbometers and since September 2003 automatic weather stations have been used. It can be assumed that the change of instruments had no effect on the records of wind direction divided by the eight main directions.

At the same time the exactness of the wind direction measurements improved significantly. All the records of different exactness are calculated so that the frequencies of eight main wind directions are fully comparable during the entire study period. The wind vane allowed us to measure wind direction in the 16-rhumb scale, i.e. with the resolution of 22.5°. When converting the data from the 16-rhumb system into the 8-rhumb system, the frequencies of intermediate directions were divided equally between two neighbouring directions.

The anemo-rhumbometers measured wind direction with the exactness of 10°. The results were assigned the code numbers from 1 to 36, where number 1 denoted the wind direction of 10° and 36 denoted the wind direction of 360° (N wind). The code number 9 indicated E, 18 – S and 27 – W winds. The wind directions from the 36-rhumb scale were calculated to the 8-rhumb scale by special formulas. The principle was that the wind directions between two main wind directions were equally distributed between them. For example, the following formulas were applied:

- for SE winds

$$(\mathrm{SE}) = 0.25 \times (11) + (12) + (13) + (14) + (15) + 0.25 \times (16),$$

- for S winds

$$(\mathrm{S}) = 0.75 \times (16) + (17) + (18) + (19) + 0.75 \times (20),$$

where the frequencies of wind directions of different code numbers are indicated in brackets.

The automatic weather stations introduced in September 2003 measure wind direction hourly with the exactness of 1°. It was easy to divide the measured wind directions with the exactness of 1° between eight main directions. Although the measurements were recorded hourly, only the same eight synoptic times were used for data analysis.

Frequencies of the main wind directions are found for every month. They are divided by the number of observations. As a result, all the data are expressed in per cent, while the sum of the percentages of the eight wind directions should be 100. In addition to monthly values, annual and seasonal values are calculated, while seasons are defined be three months as usual: spring (MAM), summer (JJA), autumn (SON) and winter (DJF).

By the Lilliefors and Shapiro–Wilk tests it was determined that the data on the frequencies of wind duration were normally distributed. Therefore, linear regression analysis was applied in trend analysis. Slopes of time series and changes by trend were calculated separately for different wind directions for different months and seasons.

Long-term changes are presented in the form of wind roses where two lines indicate mean wind roses, i.e. the percentage distributions of different wind directions in case of the first (1966) and the last year (2008) of the observation period according to the linear trend. The larger the difference between the two wind roses, the greater the change. Trends are considered statistically significant on the $p < 0.05$ level.

Large-scale atmospheric circulation is characterized by various circulation indices: the Arctic Oscillation (AO) index, five teleconnection indices obtained from the NOAA CPC (http://www.cpc.noaa.gov/products/) and four different North Atlantic Oscillation (NAO) indices presented at J. Hurrell's web page http://www.cgd.ucar.edu/cas/jhurrell/indices.html and at the web page http://www.lasg.ac.cn/staff/ljp/data-NAM-SAM-NAO/NAO.htm.

Arctic Oscillation (also named Northern Annular Mode) is a dominant pattern of non-seasonal SLP variations north of 20°N latitude and is characterized by pressure anomalies of one sign in the Arctic with the opposite anomalies centred on sub-tropical latitudes about 37–45°N. The AO index describes the strength of circumpolar vortex (Thompson & Wallace 1998). The NAO indices are highly correlated with the AO index and can be observed as an AO representation over the North Atlantic/European sector. North Atlantic Oscillation is defined as SLP fluctuations between the Icelandic low and the Azores high. It controls the strength and direction of westerly winds and storm tracks across the North Atlantic.

The NAO index is calculated as a difference between the standardized SLP anomalies between the Azores high and the Icelandic low regions. It can be calculated between the station data and the more generalized regional data. Hereby, two NAO indices using the station data from Stykkisholmur/Reykjavik, Iceland, from Ponta Delgada, Azores (Hurrell & van Loon 1997) and from Gibraltar (Jones et al. 1997) were analysed. In addition, one NAO index is used, which is defined as the difference in the normalized monthly SLP regionally zonal-averaged over the North Atlantic sector from 80°W to 30°E between 35°N and 65°N (Li & Wang 2003). The fourth NAO index (PC-based) involved in this study is calculated as the leading principal component of SLP anomalies over the Atlantic sector (20–80°N, 90°W–60°E) (Hurrell et al. 2003).

The teleconnection indices were derived from the principal component analysis of the Northern Hemisphere SLP fields (Barnston & Livezey 1987). Hereby, five teleconnection indices were used, reflecting atmospheric circulation conditions over northern Europe: North Atlantic Oscillation (NAO), East Atlantic (EA), Polar/Eurasia (POL), East Atlantic/West Russia (EAWR) and Scandinavia (SCA) patterns. The corresponding pressure areas for the teleconnection patterns are the following: EA – high over the tropical Atlantic and Mediterranean, low in mid-latitudes over the Atlantic, POL – high over Eurasia and low over the Arctic Ocean, EAWR – high over the British Isles and the North Sea and low over eastern Europe, and SCA – high over northern Europe and lows over Siberia and southwestern Europe. The last two teleconnection patterns represent the meridional circulation over Estonia.

Relationships between the large-scale atmospheric circulation indices and the frequencies of wind directions in Estonia were analysed using Pearson correlation coefficients.

TRENDS IN WIND DIRECTIONS

The results of the regression analysis revealed a number of statistically significant changes in the occurrence of wind from different directions during 1966–2008. Table 1 presents the numbers of stations with a statistically significant trend (a positive as well as a negative trend) for each of the eight main wind directions, and for each month and season and for the whole year. It appeared that there had been much less changes for certain directions (N, S) and months (April, July, October, November, December), and much more changes for other directions (W, SE) and months (January, February, March, May, June). The largest changes in

Table 1. Numbers of stations with statistically significant trends on the $p < 0.05$ level in the frequencies of wind directions during 1966–2008. + Positive trend, – negative trend

	N	NE	E	SE	S	SW	W	NW
January	1–	7–	7–	8–		6+	12+	8+
February	7+		7–	12–	1+	3+		
March	4+	1+		5–	1–	1–	4+	6+
April				1–				
May		8–	8–		1+	1+	11+	4
June	2–	9–	1–		1+	1+	9+	
July	1+				1+			1–
August		1+	2+	1+	1+/2–		2–	
September		3+			2–			3–
October	1+							2–
November			1+		1–			
December							1+	1+
Year	1+	1+/4–	2–	13–	1+/1–	4+	6+	1+
Spring	1+		1–	3–	1–		8+	2+
Summer		3–	1+		2+	2+	2+	1–
Autumn	1+	6+	1+				1–	5–
Winter	3+		7–	14–	1+	9+	7+	6+

wind roses had taken place in winter. Trend characteristics are different for different stations and can partly be explained by land use changes in the vicinity of the measuring sites and by changes in wind obstacles. The occurrences of the SW and W winds show a clear increasing tendency, with the exception of the Ristna, Kunda, Valga, Vilsandi and Jõhvi stations where the surface roughness or the character of obstacles had changed significantly.

The most prominent locally induced shift in the occurrence of wind directions was observed at Ristna, which is surrounded by forest with the only open sector in the SW direction. Relative openness of the SW sector at the Ristna station increased during the study period as forest height and density in the other sectors got higher, thus enhancing wind flow along the SW–NE 'corridor'.

A similar but more complex local effect can be distinguished in Kunda where the W sector was highly sheltered throughout the study period, while the S, E and N directions were relatively open. This station is known by the most developed sea-breeze-influenced wind climate in Estonia with the typical S–N directionally elongated wind roses. Currently the N sector of the Kunda station has experienced a severe roughness increase due to the building activity in the nearby sea port. At the same time the S and SW sectors of the measuring site have been cleared for the creation of a large ground storage. As a result, the occurrence of wind has increased only in the open S and SW directions, while thermally driven sea breeze does not show up equal strength from the northern sector.

Even an individual obstacle located close to the wind vane is effective enough to neutralize a long-term regional trend in a wind direction observed at the other stations. For example, the Vilsandi station on a small island with semi-open location is often used as a reference station for marine climate (Soomere & Keevallik 2001; Soomere & Zaitseva 2007; Keevallik 2008; Räämet et al. 2009). Yet, the house of the meteorological station, situated only 20 m westwards from the wind measurement mast, blocks a significant part of the W winds. A similar effect of lower intensity can be observed in Jõhvi, where the occurrence of the W wind is also flawed in a generally open meteorological field by the aerodrome building located 49 m W from the meteorological mast. The former 1-storey building was turned into a 2-storey building in the 1990s.

Changes in the occurrence of northerly winds have been comparatively smaller than in case of the other directions. The increase was highest in February and, to a lesser extent, in March. Thereby, these trends were statistically significant in both months in Jõhvi and Viljandi. During the rest of the months mostly no trends were revealed. A weak decreasing trend prevailed in June. The annual frequency of N winds increased significantly only in Jõhvi where the slightly distant row of 20 m high trees was removed.

The frequency of NE winds can be described by a general decreasing tendency, except the autumn season when positive trends were revealed. At the majority of stations a strong negative trend was observed in January, May and June. At some stations (Tiirikoja, Kuusiku, Viljandi, Valga) the share of NE winds decreased by more than 10% during these months. In these cases the regional trend is enhanced by local effects like increased surface roughness (e.g. forest growth at Tiirikoja and settlement development in Viljandi). At the same time the annual as well as the August and September percentages of NE winds in Valga increased significantly because the NE sector is less affected by nearby settlement development in the urban fringe and acts as a small-scale wind corridor.

In 1966–2008 the part of easterly winds significantly decreased in winter and to a lesser extent in spring, first of all in January, February and May. A weak increase was detected in August and November. The decrease was strongest in Valga and Võru. An increase in the frequency of easterly winds was detected for Viljandi as the meteorological station was moved from the urban area to the northern edge of the city.

Southeasterly winds have changed most of all. Their proportion in winter considerably decreased at all stations. The mean decrease by trend was approximately 10% in winter and 3–5% for annual series. This great change was caused by the fact that the share of SE winds was extremely large during two winters at the beginning of the study period (Fig. 2). The highest decrease of 21% was observed at Nigula in January.

The percentage of S winds did not generally change during 1966–2008. A significant increase was observed only at the Kuusiku station. Some negative trends were

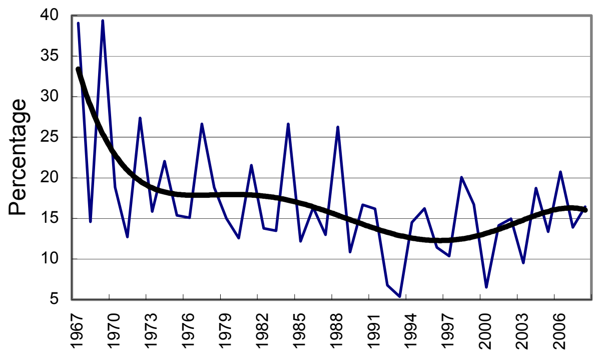

Fig. 2. Time series of the percentage of southeasterly winds at the Türi station in winter (DJF) during 1966/67–2007/08, and its generalized average shown by spline.

revealed in Võru and Väike-Maarja, which can be explained by a slight increase in the surface roughness caused by a steady growth of trees in the nearby gardens.

The share of SW winds increased significantly in winter, especially in January and February. The most substantial changes took place in the coastal stations of Vilsandi, Ristna and Sõrve where the annual values show a statistically significant increase as well. No trends were revealed during the rest of the months.

The frequency of W winds in Estonia increased most of all (Table 1). Significant increases of even more than 10% have occurred in January, March, May and June, i.e. in winter and spring. The maximum of winter westerlies was at the end of the 1980s and at the beginning of the 1990s (Fig. 3). During the period from August till November the percentage of westerlies decreased slightly. In case of the stations on the western coast, part of the increasing occurrence of SW and W winds in winter can be attributed to changes in sea surface roughness, decrease in the duration of ice cover and increase in the strength of the western cyclones over the ice-free humid relatively warm sea. Changes in thermal stratification in the atmospheric boundary layer due to relatively warm unfrozen sea and the contrasting cold land area are considered an important factor more strongly affecting the wind speed and direction in the Estonian west coast than the breeze.

The occurrence of NW winds increased in winter and spring (January, March, May) and decreased in summer and autumn (from July till October). In most cases the trends were statistically insignificant.

Analysis of changes in frequencies by single wind directions does not give a good general description. For a better understanding of changes wind roses of changes were composed. Based on linear trends of each of the eight main wind directions, the wind roses of the first and the last year of the study period were calculated.

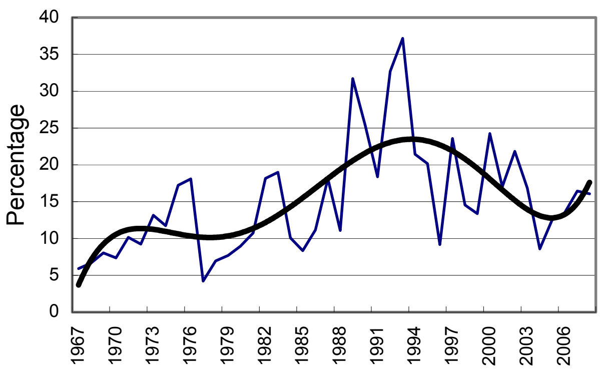

Fig. 3. Time series of the percentage of westerly winds at the Väike-Maarja station in winter (DJF) during 1966/67–2007/08, and its generalized average shown by spline.

Figure 4 presents changes in annual wind roses for all 14 stations.

Although the wind roses depend on the openness of the measuring site for different wind directions as described above, the general tendencies of changes are still clear. They are similar at the majority of stations. The frequency of E, NE and SE winds has clearly decreased, while the share of W and SW winds has increased (Fig. 4).

However, there are some single peculiarities, which can be explained by artificial changes in wind obstacles at the neighbourhood of the stations. For example, a significant increase in the frequency of NE winds in Valga was observed (Fig. 4J).

These changes appear more clearly in case of seasonal wind roses of change in Vilsandi (Fig. 5). The largest changes in wind roses occurred in winter, when the prevailing wind direction turned from the southeast to the southwest (Fig. 5D). This corresponds very well with the increase in the winter mean air temperature. Southeasterlies bring colder air and southwesterlies bring warmer air to Estonia in winter.

During the other seasons the changes occurred with a lesser intensity. It is interesting that the changes in autumn were quite opposite to winter changes. The percentage of W and NW winds decreased, while the share of E, SE and SW winds increased. However, the dynamics of changes in wind directions in autumn and winter led to a highly similar occurrence of wind from different sectors at the end of the study period both in autumn and winter despite drastic dissimilarity at the beginning of the study period (Fig. 5C, D). The summer wind rose probably elongated to the southwest, i.e., the percentage of the northern directions (N, NW, NE) decreased and that of the southern directions (SW, SE) increased.

RELATIONSHIPS BETWEEN LARGE-SCALE ATMOSPHERIC CIRCULATION AND LOCAL WIND DIRECTIONS

It is natural that large-scale atmospheric circulation has a major role in determining the directions of local winds. Circulation indices characterizing zonal circulation are highly positively correlated with the frequency of W and SW winds (Table 2). Among the different NAO indices, the PC-based NAO index (Hurrell et al. 2003) had the highest correlation with the frequencies of wind directions presented in Table 2. The NAO index elaborated by Li & Wang (2003) has a slightly lower correlation, while the station-based NAO indices have a much lower correlation.

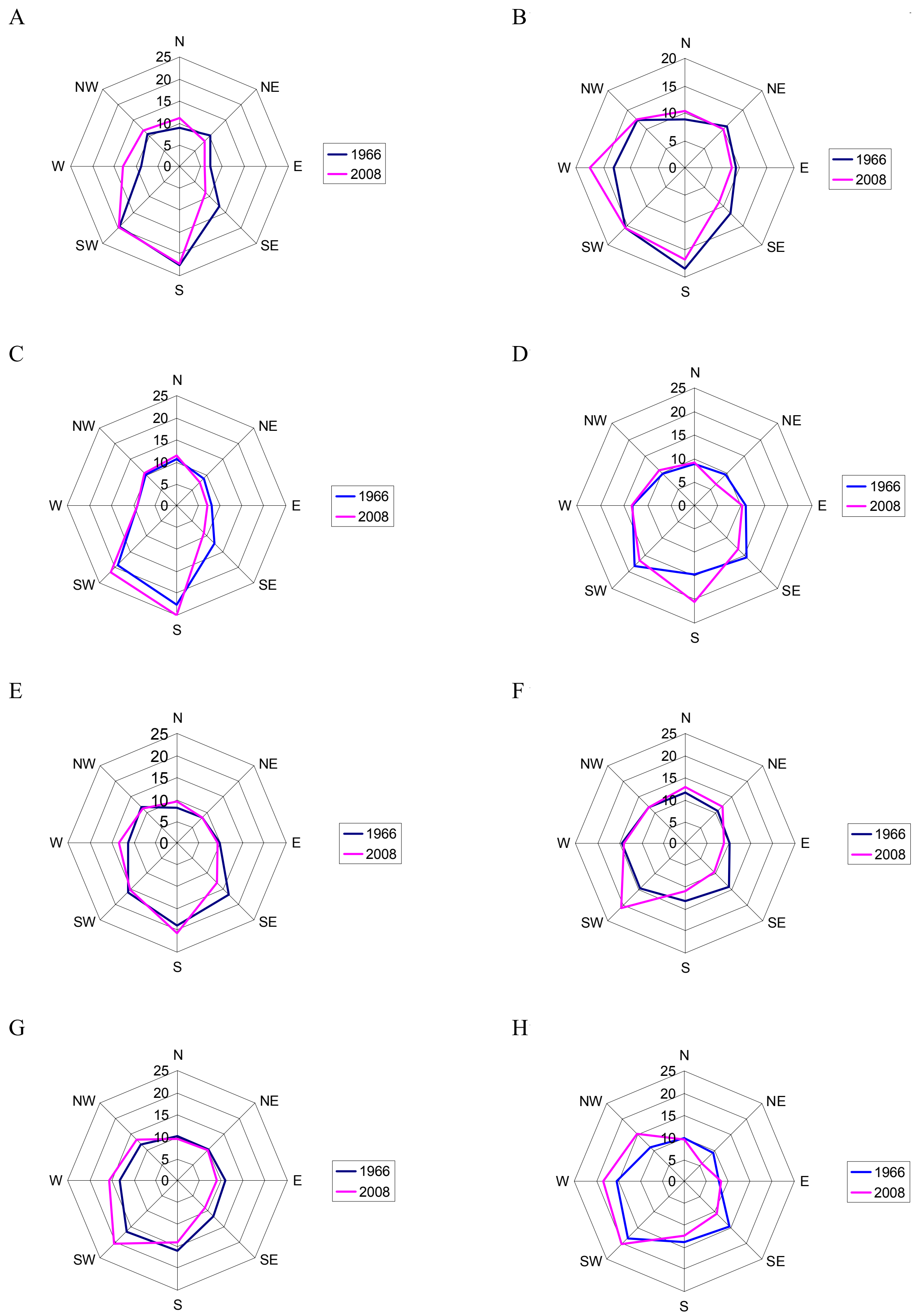

Fig. 4. Annual wind roses in the first (1966) and the last year (2008) of the study period according to the linear trend. A, Jõhvi; B, Kihnu; C, Kunda; D, Kuusiku; E, Nigula; F, Ristna; G, Sõrve; H, Tiirikoja; I, Türi; J, Valga; K, Viljandi; L, Vilsandi; M, Võru; N, Väike-Maarja.

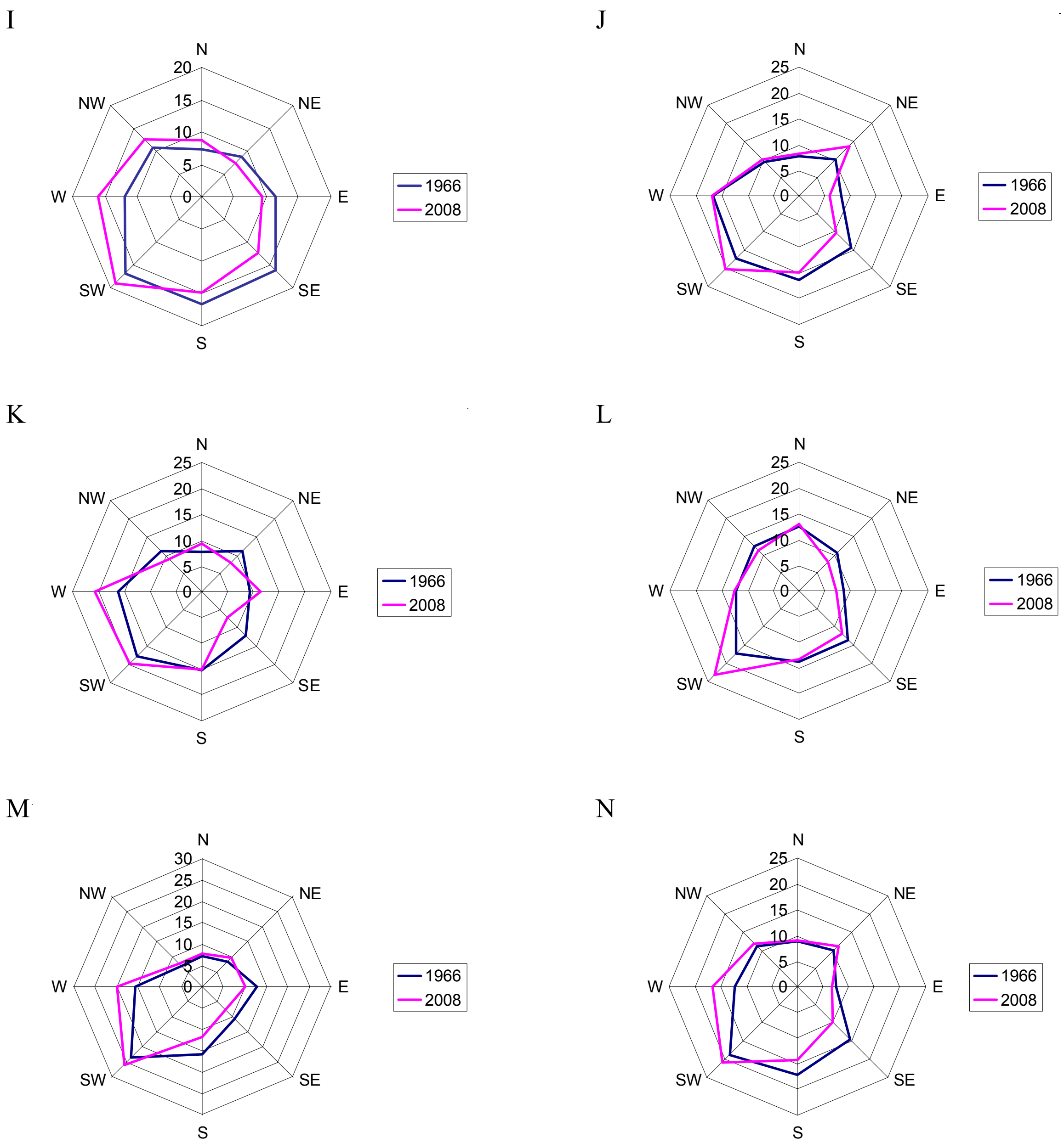

Fig. 4. *Continued.*

The frequencies of SW and W winds are positively correlated with the AO and NAO indices, while the frequency of E and NE winds is negatively correlated. The highest correlation was revealed in the winter season, especially in case of SW winds when the correlation coefficients are even higher than 0.7 (Fig. 6). The correlation is lower in spring and autumn and absolutely missing in summer. The stations located on the open western coast of the Baltic Sea (Vilsandi, Sõrve, Kihnu, Ristna) mostly have a higher correlation between the frequencies of SW and W winds, and the AO and NAO indices.

The EAWR and SCA teleconnection indices reflect the meridional circulation over Estonia. The SCA index describes SLP variations between northern Scandinavia, Siberia and southern Europe. It is positively correlated with the frequencies of E, NE and SE winds, and negatively correlated with westerlies (Table 3). Statistically

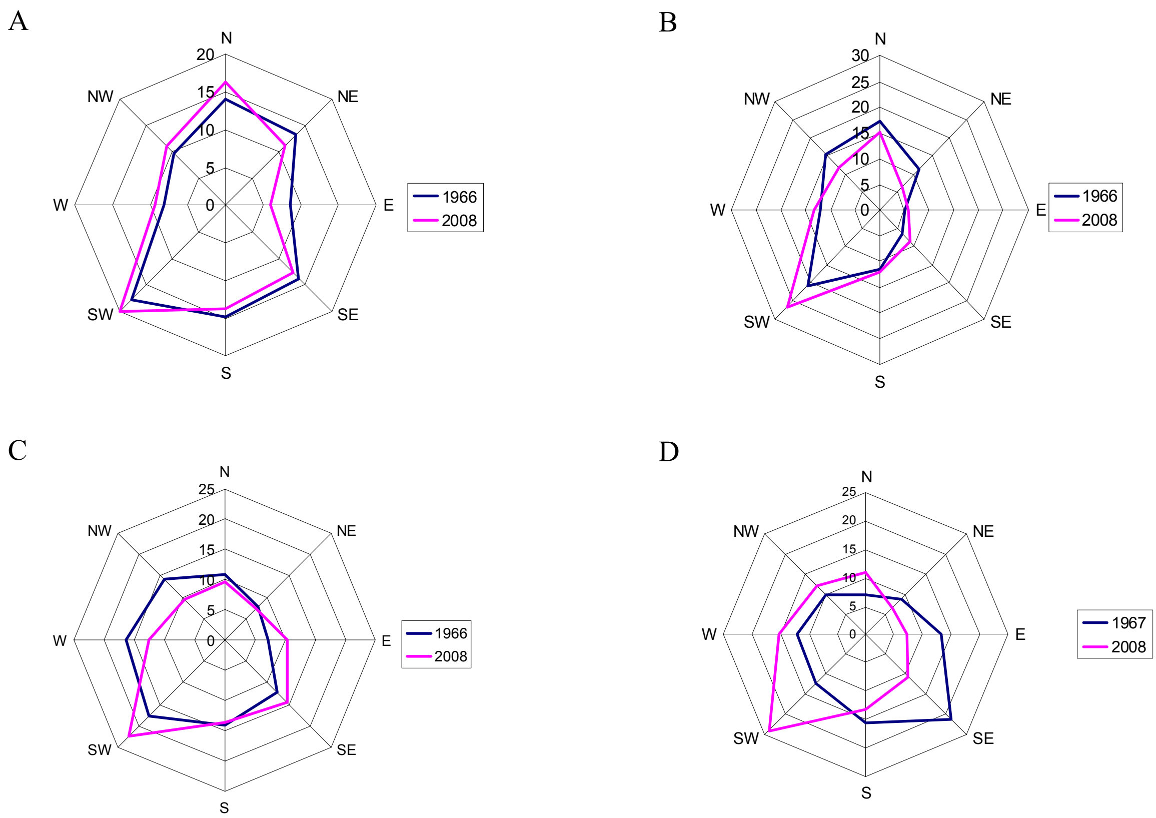

Fig. 5. Seasonal wind roses in Vilsandi in the first (1966, 1966/67 in winter) and the last year (2008, 2007/2008 in winter) of the study period according to the linear trend. A, Spring; B, summer; C, autumn; D, winter.

Table 2. Correlation coefficients between annual and seasonal values of the Arctic Oscillation (AO) and the PC-based North Atlantic Oscillation (NAO) indices and mean frequencies of wind directions in Estonia, calculated by using data from 14 stations. Statistically significant correlation coefficients on the $p < 0.05$ level are typed in bold

	N		NE		E		SE		S		SW		W		NW	
	AO	NAO	AO	NAO	AO	NAO	AO	NAO	AO	NAO	AO	NAO	AO	NAO	AO	NAO
Annual	–0.01	–0.11	**–0.44**	**–0.48**	**–0.37**	**–0.33**	**–0.43**	–0.28	0.01	0.17	**0.32**	0.23	**0.47**	**0.39**	**0.34**	0.20
Spring	–0.16	–0.16	**–0.51**	**–0.46**	**–0.48**	**–0.40**	–0.23	–0.15	0.27	0.29	**0.50**	**0.40**	**0.40**	**0.34**	0.18	0.11
Summer	0.07	0.01	–0.21	–0.30	–0.14	–0.21	–0.14	0.02	–0.09	0.01	–0.01	–0.01	0.21	0.21	0.23	0.24
Autumn	–0.13	–0.26	**–0.36**	**–0.37**	**–0.45**	**–0.40**	**–0.36**	–0.07	0.05	0.29	**0.44**	0.26	**0.44**	0.24	0.20	0.00
Winter	–0.18	–0.19	**–0.55**	**–0.57**	**–0.63**	**–0.67**	**–0.50**	**–0.50**	0.05	0.16	**0.70**	**0.72**	**0.65**	**0.59**	**0.37**	**0.32**

significant correlation with NE winds is present from April to October, with E winds at all months and with SE winds from October to June. The negative correlation between the SCA index and westerlies is significant all around the year.

The EAWR teleconnection pattern represents a different oscillation system. A high over the North Sea and the British Isles and a low over southern Russia induce NW winds in case of its positive phase. High positive correlation with the EAWR index is typical of NW, W and even SW winds in winter, while negative correlation was revealed for SE, E and S winds.

Two teleconnection indices (EA and POL) have no significant correlations with the occurrences of wind directions in Estonia. It can be supposed that these indices describe circulation conditions in more distant regions.

Table 3. Correlation coefficients between annual and seasonal values of the East Atlantic/West Russia (EAWR) and the Scandinavia (SCA) teleconnection indices and mean frequencies of wind directions in Estonia, calculated using data from 14 stations. Statistically significant correlation coefficients on the $p < 0.05$ level are typed in bold

	N		NE		E		SE		S		SW		W		NW	
	EAWR	SCA	EAWR	SCA	EAWR	SCA	EAWR	SCA	EAWR	SCA	EAWR	SCA	EAWR	SCA	EAWR	SCA
Annual	0.08	–0.17	0.05	**0.46**	0.02	**0.50**	–0.29	**0.46**	**–0.32**	–0.07	0.05	–0.28	0.27	**–0.36**	**0.30**	**–0.42**
Spring	0.09	–0.13	–0.08	**0.56**	–0.16	**0.64**	–0.24	**0.30**	–0.23	–0.18	0.16	**–0.37**	0.27	**–0.41**	0.24	**–0.48**
Summer	0.15	0.23	0.17	**0.51**	–0.07	0.27	–0.27	0.02	**–0.30**	–0.28	–0.08	–0.28	0.09	**–0.31**	0.25	–0.01
Autumn	0.10	–0.06	0.03	**0.40**	0.12	**0.56**	–0.20	**0.50**	**–0.38**	0.00	–0.14	**–0.34**	**0.35**	**–0.52**	**0.42**	**–0.50**
Winter	0.21	–0.01	–0.16	0.29	**–0.40**	**0.53**	**–0.55**	**0.60**	**–0.34**	–0.09	**0.37**	**–0.65**	**0.59**	**–0.44**	**0.60**	–0.29

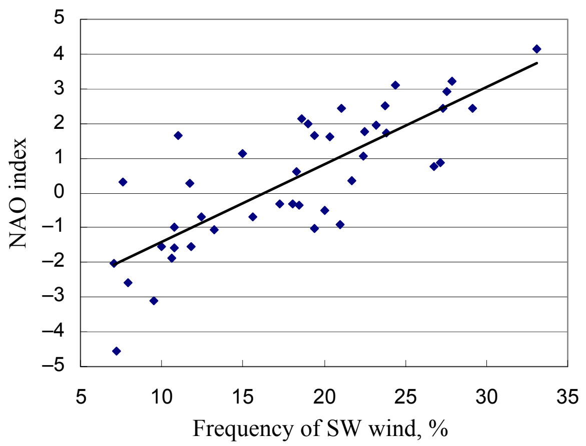

Fig. 6. Scatterplot of the frequency of SW winds in Vilsandi during winter and of the winter NAO index according to Li & Wang (2003) (correlation coefficient $r = 0.80$).

DISCUSSION AND CONCLUSIONS

Climatic conditions in any region are very complex. Single climatic variables are closely related to each other. A long-term change in one variable induces corresponding changes in other related variables. In that sense climate warming is a complex phenomenon, including changes not only in surface air temperature but also in many other climatic variables. The results of the current study clearly confirm this statement. All the major hypotheses were approved.

As for air temperature, the most significant changes in the frequency distribution of the main wind directions during 1966–2008 were observed in the winter season. Higher occurrence of W winds is illustrated by wind roses which likely shifted from east to west. The occurrence of W and SW winds causing the advection of the warm air in winter increased significantly, and the share of E, SE and NE winds related to the cold advection clearly decreased. This result is in good concordance with the previous studies.

Similar changes of a lesser magnitude are typical also of the spring season. Few trends were revealed for summer wind directions. An increase in the percentage of SW and S winds and a decrease in the percentage of NE wind in summer were detected at some stations. Changes in the autumn wind roses differ from those of the other seasons. The frequency of NE wind increased and the frequency of NW winds decreased.

There are some differences in wind rose trends between the stations. On the open coast of the Baltic Proper (Ristna, Vilsandi, Sõrve), the positive trend in the frequency of SW winds is especially strong. This can partly be explained by the increased thermal contrast between land and sea, and the different surface roughness of ice-covered and open water. Changes in thermal stratification in the atmospheric boundary layer due to unfrozen sea and cold land area are considered a more important factor affecting the wind speed and direction than the breeze. Other differences between the stations can be explained with changes in wind obstacles in the surroundings of single stations. The most pronounced effects are observed for the occurrence of wind direction by the steady growth of forest or nearby trees. Even an individual obstacle close to the wind vane is effective enough locally to neutralize a long-term regional trend in wind direction observed at other stations. It should be emphasized that not only a new emerging obstacle is capable of blocking the air flow from a single sector, leading thus to locally flawed wind direction distribution, but even the character of the existing obstacles (e.g. growth of trees and hedges) is changing over the time. Meanwhile some of the formerly existing nearby obstacles may disappear and thus restore the regionally more characteristic natural air flow, but this artificial change would still be easily notable in the long-term wind direction distribution.

It is evident that the main changes in wind roses in Estonia during 1966–2008 are related to changes in large-scale atmospheric circulation. Intensification of the westerly circulation over the Atlantic/European sector during the study period, especially in winter and also in spring, induced a westward shift of wind roses in Estonia. Variables describing the intensity of westerlies, the NAO and AO indices, are highly correlated with the frequency of W and SW winds. This relationship is most evident in winter when the correlation coefficient exceeds 0.7. The influence of large-scale westerly circulation on weather conditions in Estonia in summer is negligible.

The SCA teleconnection pattern corresponds to a synoptic situation where a wide area of high pressure is spread over Scandinavia. It causes NE and E winds in Estonia. This relationship is evident in all seasons but has some seasonal peculiarities. The highest correlation with the SCA teleconnection index in summer was revealed for NE winds, in spring and autumn for E winds, and in winter for SE winds. The EAWR teleconnection pattern is highly positively correlated with the frequencies of W and NW winds, and negatively correlated with SE, E and S winds. This relationship is significant mostly in winter.

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Muutused maapinnalähedaste tuulte suundades Eestis perioodil 1966–2008 ja nende seosed atmosfääri suuremõõtmelise tsirkulatsiooniga

Jaak Jaagus ja Ain Kull

On analüüsitud kaheksa peamise tuule suuna protsentuaalse osakaalu muutusi 14 Eesti ilmajaamas perioodil 1966–2008. Pikaajalised muutused tuule suundade korduvustes on seostatud atmosfääri suuremõõtmelise tsirkulatsiooni kõikumistega, aga osaliselt ka mõõtejaama ümbruse tuuletakistuste muutustega. Kõige tugevamad trendid tuule suundade korduvuses on aset leidnud talvel. Lääne- ja edelatuulte osakaal on selgelt suurenenud ning kagu-, ida- ja kirdetuule osakaal vähenenud. Seega on tuule suunad justkui idast läände nihkunud. Jaamade vahel esinevaid erinevusi trendides püütakse seletada muutustega üksikute jaamade tuuletakistustes. Trendid Eesti ilmajaamade tuuleroosides on seotud läänevoolu intensiivistumisega Atlandi-Euroopa sektoris talvisel aastaajal.