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Variations in wind velocity components and average air flow properties at Estonian coastal stations in 1966–2021; Sõrve Peninsula case study

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ABSTRACT

Despite considerable differences in local conditions, the average air flow parameters at coastal stations had similar seasonal and interannual patterns. The decreasing trends in average wind speeds were not reliable due to inhomogeneity in the long-term series. Being less sensitive to inhomogeneities, both the zonal and meridional components and the average air flow estimates increased in 1966–2021. The changes in flow direction and in other wind characteristics were better described as quasi-cyclic rather than using a linear trend. In the Sõrve coastal case study, the wind velocity components were separated into opposite subsets, which were one-sidedly analysed by ignoring the other direction. Both westerly and easterly sub-components increased by 0.5 m/s in 2004–2021. Regarding wind-driven coastal processes along the peninsula, the changes in the westerly component, but not in the easterly component, are important on the western coast, and vice versa for the eastern coast. Assuming the potential impacts of winds via waves and currents, the influence of long-term changes in sea ice conditions were considered. Although the forcing load was more than twice as high on the western coast, the relative effect of the 'ice mask' was smaller, as ice conditions were milder there. Along the eastern coast of the Sõrve Peninsula, the prevalence of SW-directed forcing can be expected, because the westerly forcing is shaded there by land. The SW-directed flow has strengthened over the study period because of an increase in the easterly and northerly wind speed subset and a decrease in the ice cover on the Gulf of Riga.

Introduction

The statistical properties of near-surface wind conditions are of great scientific and practical importance. Wind speed and direction have a strong influence on human activities, such as marine navigation, aviation, electricity production in wind farms, and in fact, on the maintenance of any kind of critical infrastructure and built environment. Being first and foremost related to air mass movement in the atmosphere, winds also force up marine hydrodynamic processes, such as sea currents and waves, which, in turn, mediate various exchange and ecological processes in the sea. Furthermore, winds act directly (as aeolian processes) or indirectly (via wave action and coastal currents) on the coastal zone, either causing coastal erosion or sediment deposition – thus, constantly shaping coastlines.

Over a score of years, some specific changes in the regional wind regime in the Baltic Sea area have been revealed (Rutgersson et al. 2015). There has been a northward shift in storm tracks, as well as increased cyclonic activity over the Baltic Sea in recent decades (Orviku et al. 2003; Weisse et al. 2005; Donat et al. 2011; Sepp et al. 2018). Understandably, it is possible to study wind in many ways. Besides the most traditional one, which considers long-term variations in local wind speeds and changes in wind rose shapes (i.e., directional distributions; e.g., Soomere and Keevallik 2003; Kull 2005; Jaagus and Kull 2011), also the analysis of wind vector velocity components has been used (Keevallik 2008; Suursaar 2010; Keevallik and Soomere 2014). Some studies have been devoted to wind climatology in the free atmosphere, but those are based, e.g., on radiosoundings (Keevallik and Rajasalu 2001) or pressure-based modelling of geostrophic air flows (Weisse et al. 2005; Johansson and Kahma 2016). It has been noted that the wind regime in the northern Baltic Proper is anisotropic, meaning that the directions of the most frequent and strongest winds roughly coincide with the basin axes, but may be different from the prevailing direction of the geostrophic winds (Soomere and Keevallik 2003). Wind data characterize mainly the measurement site and are, therefore, influenced by nearby obstacles and the general orography (Keevallik et al. 2007; Žukova 2009). Still, significant alterations in wind speeds and directions have occurred, especially in winter, including increasing percentage of W and SW winds, and decreasing trends in SE, E and NW winds (Jaagus and Kull 2011). Also, some regime shifts (abrupt changes) in wind and air flow properties have occurred over the last decades (Keevallik and Soomere 2008; Keevallik 2011). It is believed that these developments are largely associated with changes in the winter NAO (North Atlantic Oscillation) (Lehmann et al. 2011; Jaagus and Suursaar 2013; Rutgersson et al. 2015).

Although all those abovementioned findings are presumably true in their respective timescales and locations, they cannot be considered definitive and terminal because lengthening of time series inevitably alters the outcome. Therefore, such analyses should be updated and reassessed from time to time. This study stems from the growing pool of in situ measurements made at selected coastal weather stations in Estonia (Fig. 1). We aim at presenting an updated (until 2021) overview of wind vector component-based statistics at coastal stations of Estonia. A development of this analysis approach is illustrated by the following Sõrve Peninsula case study. The question was how to estimate the influence of changes in wind climate on coastal processes directly, without using real hydrodynamic and wave models. There, we further split the wind velocity vector components, precisely as it was done for the Kunda–Letipea case study (Suursaar 2010). In the Kunda study we assumed that the southerly wind component was essentially 'lost' for coastal action and only the northerly subset of wind and wave data was one-sidedly analysed. Although the Sõrve weather station provides marine winds almost as a station in the middle of the sea would (Žukova 2009), it is still attached to a certain coastal section and can illustrate coastal geomorphic changes on both sides of the peninsula. It is also worth mentioning that marine areas on both sides of the Sõrve Peninsula are considered for constructing wind farms. As for 2022, the preparation of projects was underway for Saare–Liivi and Gulf of Riga offshore wind farms to the east of the Sõrve Peninsula, and by Saare Wind Energy for the Saaremaa offshore wind farm to the west.

There is no need to consider sea ice conditions when analysing wind data. However, the importance of considering ice conditions in wave climate modelling has been highlighted in many Baltic wave studies (e.g., Suursaar 2010; Tuomi et al. 2011; Najafzadeh et al. 2022). Due to variations in ice cover, considerable changes in wave statistics have occurred in the Bothnian Bay (Tuomi et al. 2011; Björkqvist et al. 2018), and they can occur in other seasonally ice-prone sub-basins as well. A similar 'ice mask' approach was used here in the Sõrve case study, while trying to link winds to the potential for coastal change. We argue that the required information for coastal inferences may already be contained in the wind data. After all, wave conditions in the Baltic Sea are strongly wind dependent, with a relatively short memory and a small swell component (Soomere et al. 2008; Tuomi et al. 2011).

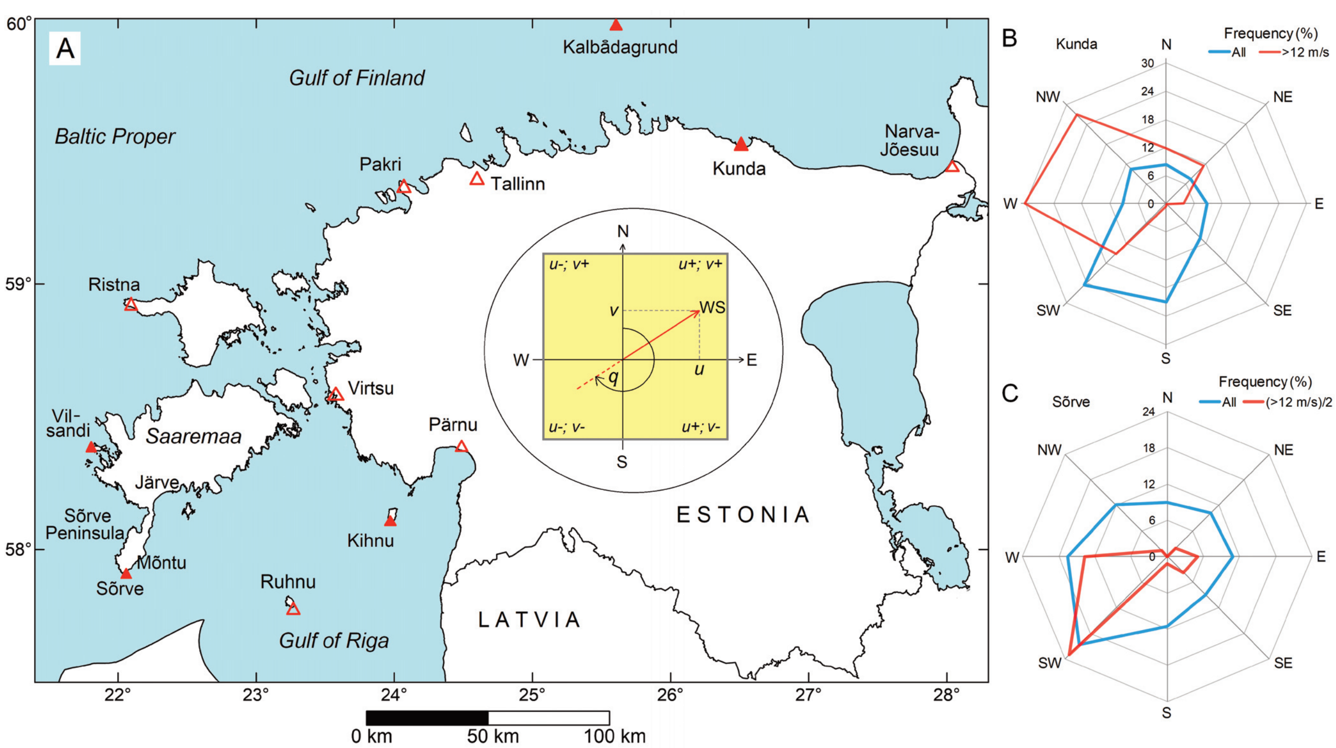

Fig. 1. Map of the study area (A). Locations of the weather stations used in the study (see also Table 1) are marked with red filled triangles. Inset sketch explains relationships between wind speed (WS), direction (q) and components (u, v). Examples of wind roses at Kunda (B) and Sõrve (C) for 2004–2021 show 8-rhumb distributions for all data as well as for strong winds (>12 m/s; accounting for 1.5% at Kunda and 5.3% at Sõrve). The frequency of strong winds at Sõrve (C) is reduced twice to better accommodate the overwhelming (46%) dominance of SW winds.

To sum up, the main objectives of this study were: (1) to present an updated, component-based analysis of Estonian coastal wind measurements; (2) to discuss possible coastal impacts of changes in wind conditions by means of selective masking of wind statistics to take into account coastline configuration and sea ice conditions.

Materials and methods

Overview of data

The study is mainly based on wind data from selected weather stations: Vilsandi, Sõrve, Kihnu and Kunda, which are operated by the Estonian Environment Agency, and Porvoo Kalbådagrund, operated by the Finnish Meteorological Institute (FMI). The detailed analysis covers the instrumentally homogeneous period from 2004 to 2021 (hourly data from the website of the Estonian Weather Service; EWS 2022), but also trends over a longer period (1966–2021) are discussed. Additionally, for the Sõrve Peninsula coastal application, some data on ice conditions in the Estonian coastal sea were used.

Wind data

The chosen weather stations (Fig. 1) were supposed to represent marine wind conditions, i.e., the winds that can freely approach across the sea from at least some directions (Table 1). However, not all stations located on the Estonian seacoast fulfil such conditions for long-term analyses (Keevallik et al. 2007; Žukova 2009; Suursaar 2013). For instance, long-standing coastal stations at Pakri, Ristna, Narva-Jõesuu, Virtsu, Ruhnu, Tallinn and Pärnu were excluded for various reasons, such as very limited openness towards the sea, influence of the Baltic Klint, changes in station locations, or large gaps in time series. Of the chosen stations, Kunda is somewhat problematic too, but it is still the best among the EWS stations located on the northern coast of Estonia to represent marine winds from NW, N and NE (Žukova 2009; Suursaar 2010).

An important aspect of long-term climatic studies is the length and temporal homogeneity of time series. Firstly, relocation of a station can compromise the usability of wind measurements. Of the chosen relatively stable stations, even the location of the Sõrve station has slightly changed since 1987 (probably without serious consequences for wind data quality) and the Kunda station was relocated seawards in March 2014. Secondly, changes in obstacles and vegetation growth around the station can have an effect, but its assessment or elimination is complicated (Jaagus and Kull 2011). Thirdly, changes in measurement equipment and routines have occurred over time (see the overviews by Keevallik et al. 2007; Žukova 2009). The digitized data has been available from the database of the EWS since 1966. Starting from that year, the frequency of observations was eight times a day. From January 1966 to November 1976, visual observations from wind vanes ('weathercocks') of Wild's design (with light and/or heavy plate) were used. Since 1976, several types of anemorhumbometers (M-63, M-63M, M63M1) have been introduced. For a few years, some parallel measurements were performed with old and new equipment to assess the differences. It became evident that the previous visual readings from the weathercocks systematically overestimated strong (>10 m/s) winds in comparison to the new anemorhumbometers. The database by the EWS does not consider that difference. However, we adjusted the strong wind data from 1966–1976 with a correction provided by a professional handbook (Gidrometeoizdat 1990). This procedure, which slightly reduces wind speeds over 10 m/s, was also briefly described by Suursaar (2013). For example, a wind speed of 11 m/s corresponds to the previous 12 m/s, and 20 m/s is equivalent to the previous 23 m/s. Further on, since autumn 2003, MILOS-520 automatic weather complexes, providing hourly (or near-continuous) data, have been in use. Hence, since 2004, we have instrumentally homogenous hourly time series in full years (Suursaar 2015). The older data with a time step of 3 h is also less accurate: the value step for the wind speed was 1 m/s in 1966–2003, but 0.1 m/s thereafter. The wind direction in 1966–1976 was originally given in the 16-rhumb system (i.e., with 22.5° step). The directional resolution for anemorhumbometers was 10° (in 1976–2003) and the currently used MILOS-520 enables 1° resolution output.

The completeness of the data series for 1966–2021 was 99%. While hardly any values were missing from the database for Kunda and Kihnu, there were some gaps for Vilsandi (in 1990, 1992, 2003 and 2005; 5 months in 1991) and Sõrve (in 1983, 1993, 2005; entire 1994). While in the detailed analysis (2004–2021) the missing values during shorter gaps (such as during the January 2005 storm) were interpolated or taken from neighbouring stations, the longer gaps in earlier subsets were left blank. Thus, the year 1991 was omitted in the Vilsandi analysis and the year 1994 in the Sõrve analysis. We only used data on sustained (i.e., not gust or maximum) wind speeds (hourly 10-minute averages since 2004). As the North Estonian coast and the Gulf of Finland area were insufficiently covered by reliable marine wind measurements, some data from the Porvoo Kalbådagrund station (Fig. 1; Table 1) were downloaded from the website of the FMI (FMI 2022). Located in a caisson lighthouse ca 37 km north of the Estonian coast, the station is open to marine winds from all directions. The data from that station has frequently been used by oceanographers and wave modellers (Myrberg 1997; Soomere et al. 2008), although with some height corrections, because the wind is measured 32 m above mean sea level (Launiainen and Laurila 1984). We did not delve into the

Table 1. Weather stations (Fig. 1) and their openness to wind directions, combining both local and geographical aspects (Žukova 2009; Suursaar 2013): + open, ~ partly obstructed/altered, – strongly obstructed/sheltered. Kalbåda refers to the Porvoo Kalbådagrund station (Launiainen and Laurila 1984)

Station	Longitude / Latitude	N	NE	E	SE	S	SW	W	NW
Vilsandi	58° 22′ 58″ 21° 48′ 51″	+	+	~	~	+	+	~	+
Sõrve	57° 54′ 49″ 22° 03′ 29″	~	~	+	+	+	+	+	~
Kihnu	58° 05′ 55″ 23° 58′ 12″	–	–	~	+	+	+	+	~
Kunda	59° 31′ 04″ 26° 32′ 43″	+	+	–	–	–	–	–	+
Kalbåda	59° 59′ 08″ 25° 35′ 56″	+	+	+	+	+	+	+	+

details of Finnish measurement routine and only used recent data to complement our analysis on seasonal variability in 2004–2021. Over that period, the time step decreased from one hour to 10 min, and the value steps (0.1 m/s, 1°) were similar to those of Estonia. However, there have been some gaps in these series too (the longer ones in 2019 and 2020).

Wind velocity components, air flow and wind stress

Traditionally, wind measurements are given by its speed (magnitude of velocity) and direction (historically, in the 32-rhumb compass rose system, later in the 360-degrees system). However, wind speed and direction when analysed separately do not give robust information on the atmospheric air flow, and analysis based on wind vector projections (orthogonal components) better characterizes dynamic processes in the atmosphere (Keevallik 2008; Keevallik and Soomere 2014). The zonal component u of the wind vector (positive to the east) and the meridional component v (positive to the north) can be expressed as:

$$u = -\mathrm{WS}\sin q;\ v = -\mathrm{WS}\cos q,$$

where WS is the wind speed (in m/s), and q is the wind direction (compass degrees recalculated into radians). One should bear in mind that the presentation of u and v vector components (see inset in Fig. 1A) applies similarly to both winds and sea currents, but there is a historical controversy regarding the directions in the compass rose system: the wind blows 'into the compass', but the sea current 'flows out of the compass'.

The u and v components can easily be averaged over certain periods of time and then turned into air flow speed (AFS) and its direction (AFD). One can also split the statistics into opposite (positive or negative) directions. For instance, we calculated the occurrences of u+, u–, v+ and v– wind episodes and the corresponding averages. The derivation of occurrence statistics separately for u+, u–, v+ and v– also enables some coastal engineering applications. For instance, differentiation between 'land' and 'marine' wind was also made by Žukova (2009) and Suursaar (2010). Indeed, regarding coastal processes, only forcing from seaward directions is relevant, while the opposite directions are essentially 'wasted'. Secondly, weak and strong winds can have very different impacts, since the kinetic energy of wind is proportional to the wind speed squared. Also, other wind-dependent forcing agents (coastal currents, waves) have non-linear relationships in their formulas. Wind stress on the sea surface is roughly proportional to the wind speed squared; in calculations of wave load and power (per unit area), the velocity is further amplified (Soomere and Eelsalu 2014; Najafzadeh et al. 2022). In this study, we used the wind speed (or wind speed component) squared as the simplest approximation to represent the wind's kinetic energy and its inter- and intra-annual variations. We called it simply 'energy', but we did not consider, for example, any specific formulas such as those used in electricity production.

In the Sõrve coastal application we also considered the direction of the local coastline. This required rotation of the Cartesian coordinates accordingly, while calculating the along- and cross-shore components from u and v. We also considered long-term changes in ice statistics, as the possible impact of wind energy on a specific coastal section is lost when the sea is covered by ice.

Sea ice data

In the application regarding the coastal process on the Sõrve Peninsula, data on temporal variations in sea ice were used. Data from several sources were combined for the Gulf of Riga. Firstly, ice charts of the entire Baltic Sea from the Swedish Meteorological and Hydrological Institute (SMHI) were studied for the period 1980–2022. This dataset (SMHI 2022) combines information from SMHI ice observations, pilot stations, icebreakers and satellite images, and its good usability for local applications was also demonstrated by Najafzadeh et al. (2022). The charts were sufficiently detailed to take readings of ice appearance and disappearance for the areas close (within ca 5 km) to Mõntu, Järve and the southern tip of Kihnu Island, as well as on the western coast of the Sõrve Peninsula (Fig. 1A). The frequency of the ice map production has increased over time from twice weekly during the winter season to daily since 2003/2004, and some inhomogeneities may, therefore, exist in such series.

To assess whether such local readings are representative, the regressions between Kihnu (visual) and Kihnu (SMHI charts) were studied, as well as the correlations of Mõntu and Järve data with the Baltic maximum ice extent. The ice statistics at the Kihnu station (Jaagus 2006; Kont et al. 2007) were based on routine visual observations made by EWS staff from a coast near the station. In recent decades, the ice cover has become more fragmented and disrupted, and it is increasingly difficult to interpret ice conditions across the entire gulf based on such isolated visual observations. The data on the maximum extent of the ice cover in the Baltic Sea in the period of 1719/20–2021/22 (EEA 2022) can be used for reconstructing local ice conditions even before the actual ice observations were available. Based on the abovementioned regressions, the time series of the duration of the Mõntu ice season were reconstructed for the years 1966–2022.

Results and discussion

Seasonal variations in wind components in 2004–2021

The seasonality of wind parameters and its relationships with atmospheric pressure and temperature fields is a well-known fact (Rutgersson et al. 2015); the annual course of wind speed (and wind waves) can be expressed by a harmonic wave (e.g., Launiainen and Laurila 1984; Suursaar 2015). At the studied coastal stations, both average and high (90%) wind speeds were 1.5–1.6 times higher from October to January than from May to July (Fig. 2A, B). The seasonal variation in the speed of the meridional wind component (Fig. 2C) was only 0–1 m/s from March to July, meaning that northerly and southerly winds almost compensated each other. In autumn, the southerly component prevailed over the northerly and v increased to 1.7–3.2 m/s. The zonal component u was positive (i.e., the westerly prevailed over the easterly) throughout the

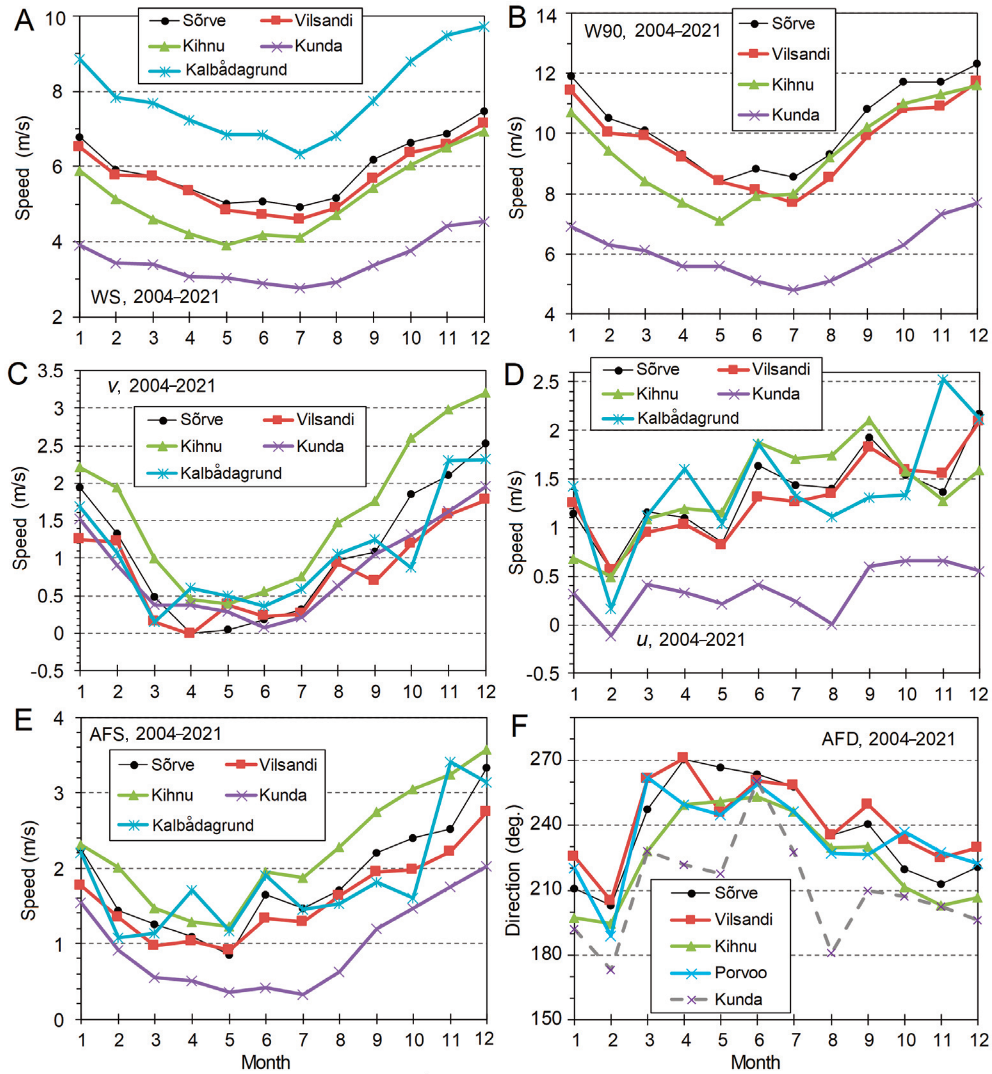

Fig. 2. Seasonal variations in average wind speed and velocity components in the selected weather stations: WS – average wind speed; W90 – 90th percentile, *u* and *v* components; AFS – average air flow speed; AFD – average air flow direction. The data cover 2004–2021, except at Kunda (2004–2013).

year (Fig. 2D), although it increased towards December. The only exception was the more sheltered Kunda, where the winds were weaker mainly because of obstruction in the zonal air flow, while the meridional air flow was well represented (Fig. 2C).

Although wind roses can reveal certain seasonal variations in prevailing wind directions too, wind roses in their simpler form do not consider different impacts of weak and strong winds. The seasonality of air flow (Fig. 2E) was even more pronounced than for average wind speeds, as seasonal minima and maxima differed from each other by a factor of 2.5–4. The air flow was strongest from October to December mainly because of the substantial input from the zonal component (Fig. 2D). This strong air flow in late autumn is related to incoming directions of cyclones, mainly from SW (210°–230°; Fig. 2D; Sepp et al. 2018), whereas the relatively weak air flow in spring comes mainly from W (250°–270°).

It is surprising that wind velocity components at Kalbådagrund did not differ much from those of the Estonian land-based stations, except for the huge difference in average wind speeds (Fig. 2A). The wind gauge at Kalbådagrund sits on the top of the lighthouse at 32 m above sea level, and undisturbed winds are naturally stronger in the middle of the sea from all directions. However, the striking similarities in air flow parameters (*u*, *v*, AFS, AFD) mean that, regardless of local land surface obstacles, data from direct wind measurements at weather stations can represent the same general air movement that occurs in the free atmosphere (Keevallik and Soomere 2014). This zonal air flow is well correlated, e.g., to the NAO and other large-scale atmospheric circulation indices over Northern Europe (Post and Tuulik 1999; Jaagus and Kull 2011) and it does not easily appear or disappear from one location to another. Its zonal representativeness was only crippled at the Kunda station (resulting in weak *u*, WS, AFS, and unsettled AFD; Fig. 2). However, the Kunda station was representative in regards of marine winds from NW and W (Suursaar 2010), which became especially evident for strong winds (Fig. 1B). Compared to the zonal component, this meridional air flow component is regionally not dominant, but can be locally important for the entire northern coast of Estonia.

Long-term variations in 1966–2021

As the long-term series (1966–2021) of wind measurements are inhomogeneous and the homogeneous subset from 2004–2021 is still too short, the trends in average and high wind speeds are generally not reliable. Even the formal tests of statistical significance do not apply, since it is difficult to take into account the influences of all data quality changes. Nevertheless, virtually all average wind speed series (Figs 3, 4) in Estonia include a formal negative trend, the occurrence of which has been tried to be explained mainly by changes in

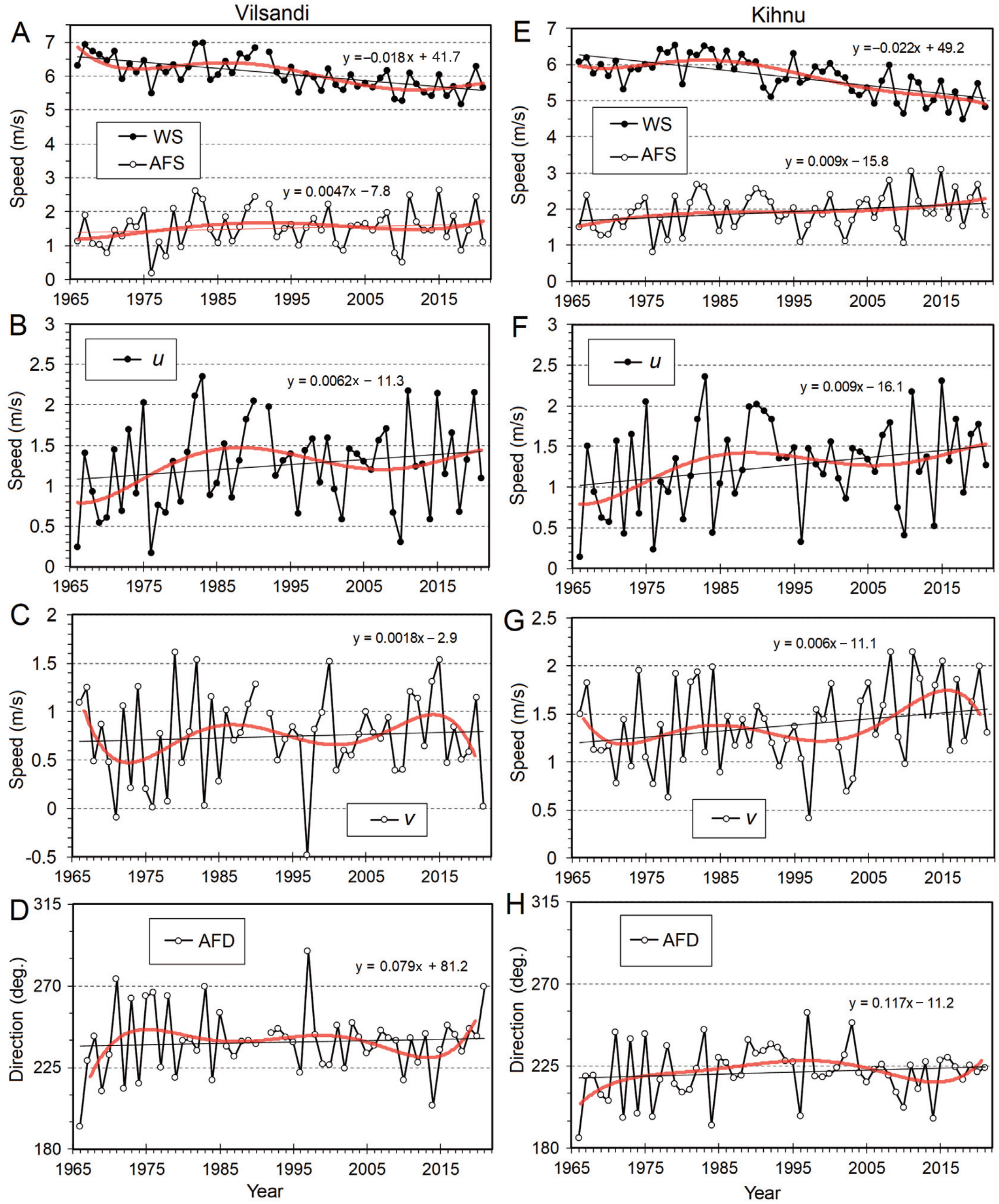

Fig. 3. Variations in annual average wind speeds (WS), air flow speeds (AFS) and directions (AFD), and *u* and *v* components at Vilsandi and Kihnu in 1966–2021. To illustrate quasi-cyclic variability, fifth- or sixth-order polynomials were added to the graphs (without any physical meaning or predictive purpose); the added linear trends are statistically not reliable.

measurement equipment and routines (Keevallik et al. 2007; Suursaar 2013), and also by vegetation growth around weather stations (Jaagus and Kull 2011). However, unlike mean wind speeds, the average AFS has slightly increased at all the stations, except at the less representative Kunda (Fig. 4). Apparently, the air flow characteristics (*u*, *v*, AFS, AFD) are less affected by localized fluctuations in the wind field and by technical inhomogeneities because those fluctuations, subjective errors, instrumental biases and noise occurring around all directions are largely cancelled out in the long run. Due to improvements in measuring equipment, the decrease in the intra-annual noise levels has led to a decrease in apparent mean wind speeds over time and an actual increase in the AFS has been revealed (Figs 3A, E, 4E).

According to the linear trend, both *u* and *v* have increased over the period of 1966–2021, and as a combination of both, the AFD has remained roughly the same (220°–240°) or slightly (by 10°–20°) turned clockwise (Figs 3D,H, 4D,H). This finding does not support the hypothesis that wind directions have significantly changed over the last decades. However, interannual changes could occur in the distribution of strong wind events (e.g., Soomere et al. 2015) or in the balance of opposite directions (discussed further below). While the exact directions of the linear trends (Figs 3, 4) can be questionable, the existence of decadal-scale cyclicity is probably truthful, as those cycles (or shifts) can be found at many stations, as well as in the indices of general circulation and storminess (Suursaar et al. 2015). Also, the assessment of the Baltic climate change (Rutgersson et al. 2015) concluded that there are no robust long-term (centennial-scale) trends in annual wind speeds, but much variation at the multidecadal timescale. When looking at increasingly longer

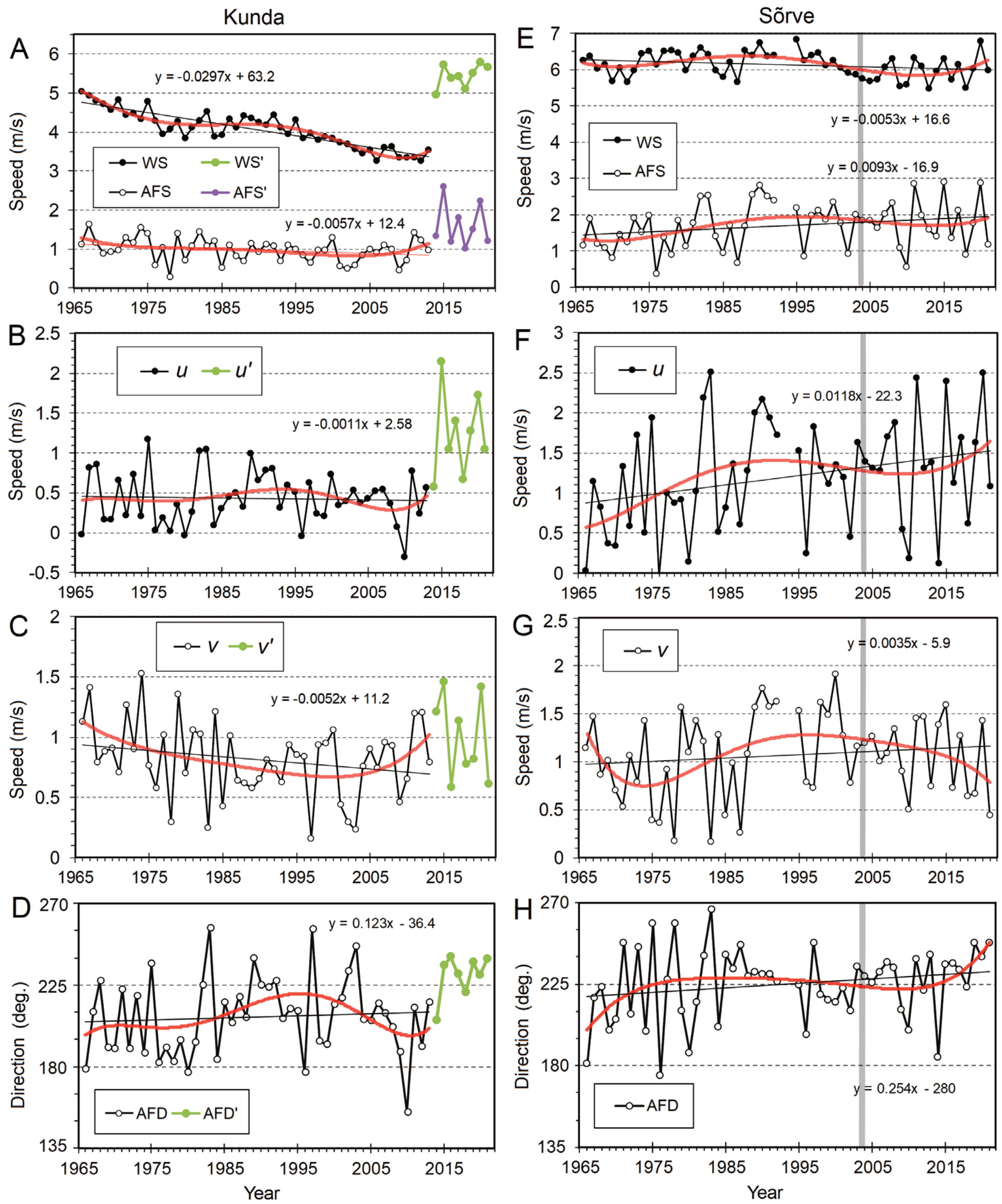

Fig. 4. Variations in annual average wind speeds (WS), air flow speeds (AFS) and directions (AFD), and *u* and *v* components at Kunda and Sõrve in 1966–2021. To illustrate quasi-cyclic variability, fifth- or sixth-order polynomials were added to the graphs; the added linear trends are statistically not reliable. Beginning of the homogeneous subset (2003/04–2021) for the Sõrve case study is indicated by vertical line (on E–H).

time spans of wind velocity characteristics, the sections of linear trends cannot continue forever. Instead, some quasi-cyclic, decadal-scale variations appear that may accommodate some shorter linear cuts between shifts and backshifts (e.g., Keevallik and Soomere 2014) and leave some room for different interpretations. It is quite possible that the same, roughly 25–35-year quasi-cyclicity in wind conditions is also reflected in elevated beach ridge systems found in the West Estonian Archipelago (Suursaar et al. 2022).

At Kunda, one can see how the (seemingly small) seaward shift in the location of the station had a vast impact on the time series (Fig. 4A–D). Secondly, the decrease in the *v* component essentially means that northerly wind episodes (*v*–) have become either stronger or more frequent at Kunda, increasingly cancelling out the southerly (also rising) subcomponent *v*+.

A case study of Sõrve Peninsula

The separation of wind data into *u*+, *u*–, *v*+, *v*– was especially fruitful for one-sided coastal engineering applications, because completely ignoring certain directions can reveal new, fascinating aspects in others (Table 2; Fig. 5). Over the instrumentally homogeneous period of 2004–2021, both the *u*+ and *u*– components increased at Sõrve in their respective directions by 0.50–0.52 m/s (Table 2). The change by linear trendline has been 11.2% for *u*+ and 13.4% for *u*–. As the frequency in *u*+ has slightly increased too (by 1.4%), the combined increase (increase in annual sums in *u*+ events) was 13.2% in 2004–2021. Since the frequency of *u*– decreased by 2.2%, the corresponding increase in annual sums was only 10.4%. The resulted *u* increased by 0.21 m/s, as *u*+ is more frequent and also slightly stronger than *u*–.

The trends for *v*+ and *v* have been decreasing, but *v*– (northerly) increased slightly in 2004–2021 (Table 2; see also Fig. 3G for the 1966–2021 timespan). Also, the average WS increased by 0.37 m/s, the average AFS was nearly stable (0.012 m/s increase), and its direction (AFD) turned slightly clockwise (from 222° to 237° according to the linear trend; Table 2). While both *u*+ and *u*– have become stronger on average (Table 2; Fig. 5A), also the maximum wind speeds from those opposite directions have increased (Fig. 5B). The simultaneous increase from both opposite directions is the first 'hidden' change.

Table 2. Statistics of wind components at the Sõrve station in 2004–2021 (given in absolute values for the opposite directions *u*+, *u*–, *v*+ and *v*–), including their frequency (%), average (av) and maxima (max; m/s); resultant values for *u* and *v*, wind speed (WS) averages and maxima, and average air flow speeds (AFS) and directions (AFD). Slopes (Slope) and changes (Ch, Ch%) by linear trend

2004–	*u*+			*u*–			*v*+			*v*–			*u*	*v*	WS		AFD	AFS
2021	%	av	max	%	av	max	%	av	max	%	av	max	av	av	av	max		
av/max	60.7	4.60	23.0	39.3	3.72	19.6	55.7	3.90	16.3	44.3	2.54	28.0	1.36	1.07	5.93	28.0	229.0	1.78
Slope	0.048	0.029	0.156	–0.047	0.028	0.076	–0.125	–0.012	–0.080	0.125	0.007	–0.380	0.012	–0.018	0.021	0.035	0.818	0.001
Ch	0.85	0.52	2.82	–0.85	0.50	1.37	–2.25	–0.22	–1.45	2.25	0.12	–6.84	0.21	–0.33	0.37	0.62	14.72	0.012
Ch%	1.4	11.2	14.8	–2.2	13.4	8.7	–4.0	–5.6	–10.0	5.1	4.7	–59.5	15.7	–30.5	6.3	2.9		0.7

Regarding coastal processes on the opposite sides of the Sõrve Peninsula, the changes in *u*+ are important for the western coast and the changes in *u*– are not, and vice versa for the eastern coast (Fig. 6A). The exception is the southern tip of the peninsula near the Sõrve weather station, which is exposed to both directions. The kinetic energies cumulated on an annual basis showed that the forcing load to the western coast of the Sõrve Peninsula has increased by 26% over the last 18 years (CE*u*+; Fig. 7A). Compared to the eastern coast, the forcing was 2–2.5 times higher on the western coast near Jämaja (Fig. 7A vs 7C). This difference partly reflects regional air flow climatology, and the different impacts of weak and strong motions in terms of kinetic energy (Soomere and Eelsalu 2014). While the increments in CE*u*+ were higher in autumn, they were more evenly distributed throughout the year in CE*u*– (Fig. 8). The most extreme year for CE*u*+ was 2020 (Figs 7A, B, 8; see also Raudsepp et al. 2022), when the difference was introduced mainly during the very warm winter in the beginning of the year (Fig. 8C).

On the eastern side, the energy has increased as well (Fig. 7C, D), but the trend was less steep than for CE*u*+. For CE*u*–, the most extreme year was 2014 (Fig. 8D). Similarly to 2020, the decisive difference was introduced from January to April.

The share of winter months (here, January to April – the months with the highest probability of sea ice near the Sõrve Peninsula) of the annual cumulated energy has varied between 17 and 50% for the westerlies (CE*u*+) and between 19 and 54% for CE*u*– (Fig. 7E). In winter, the negative trend in easterlies (Fig. 7E) and the positive trend in westerlies (Fig. 7A, B) indicate the increasing trend in general westflow (Figs 3B, F, 4F).

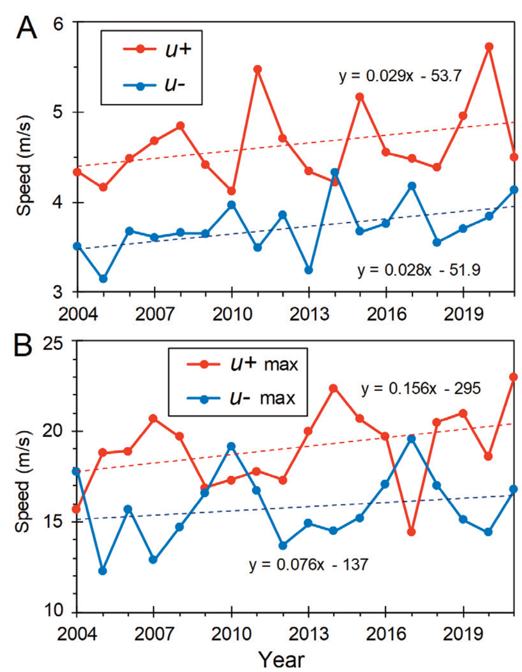

Fig. 5. Variations in annual averages (A) and maxima (B) in *u*+ and *u*– wind components (*u*– expressed as positive values) together with linear trendlines.

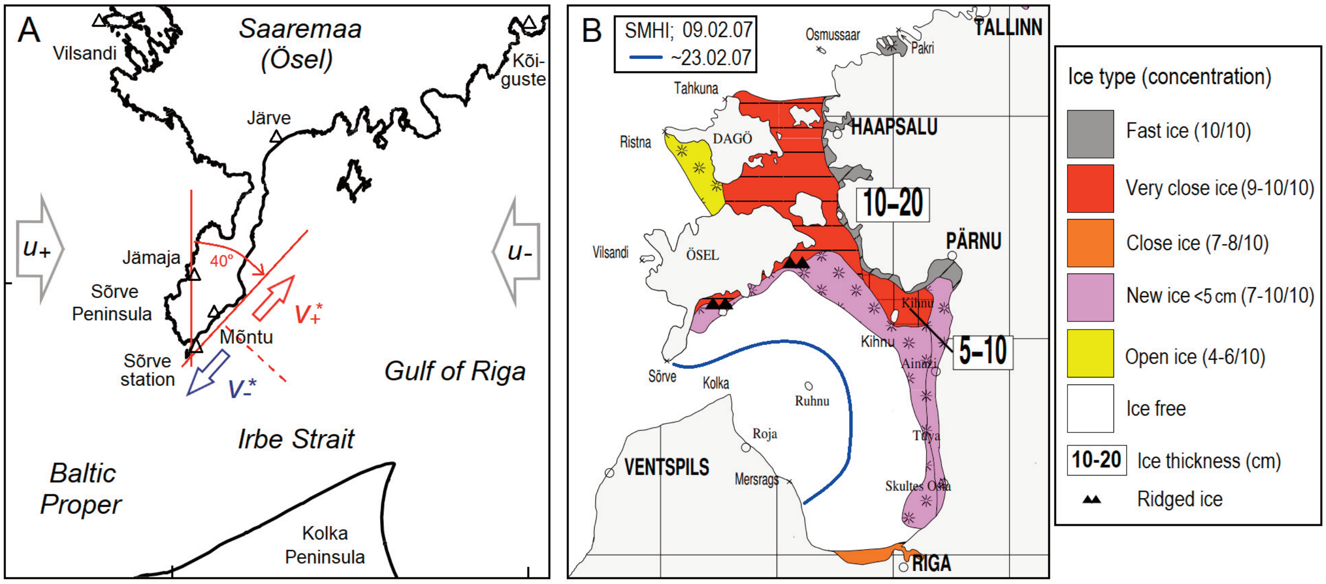

Fig. 6. Setting of the Sõrve Peninsula and its Mõntu coastal section regarding alongshore (rotated) flow components v^*+ and v^*- (A). A rather typical example fragment of the SMHI ice chart showing freezing up of the Gulf of Riga between 9 and 23 February 2007 (B). Ultimately, the entire gulf froze over and for a short time, a narrow coastal ice strip was formed along the western coast of Saaremaa as well.

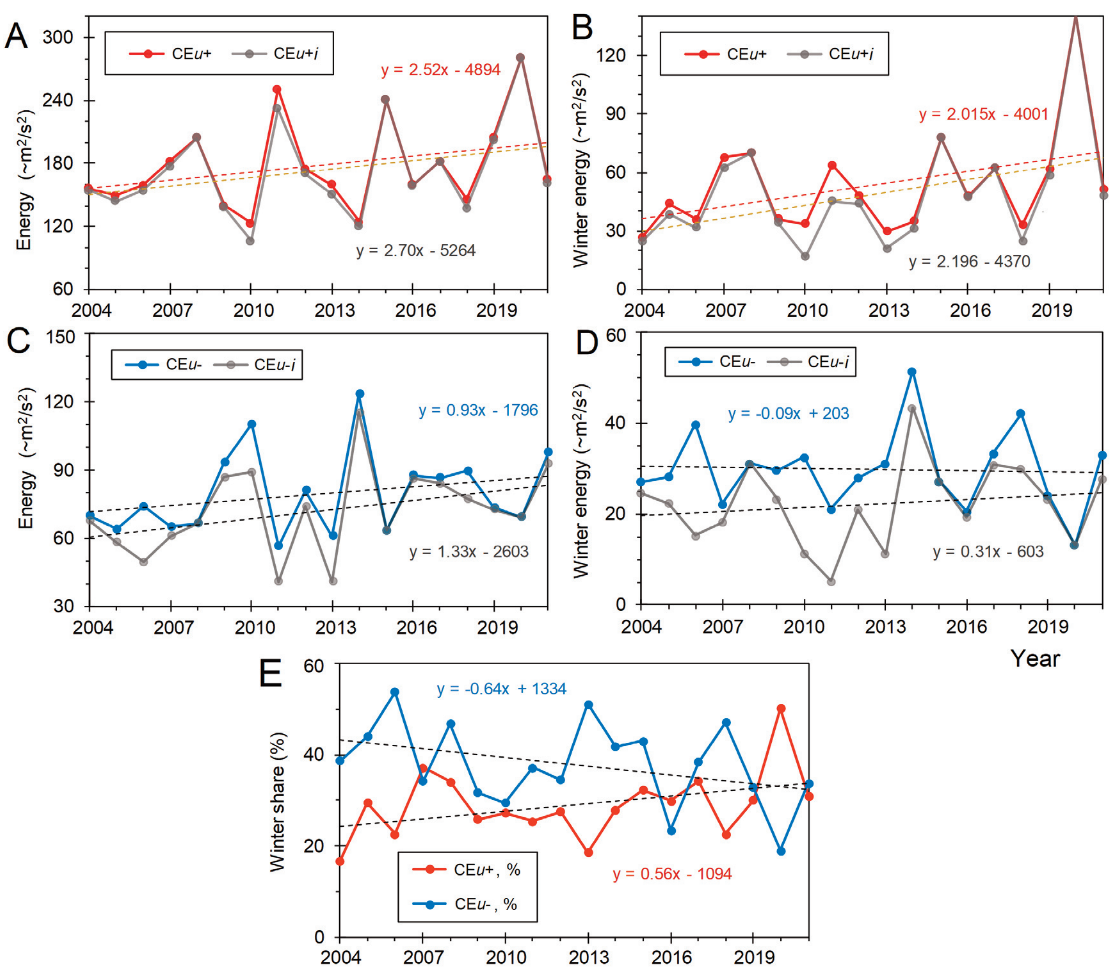

Fig. 7. Variations in annual cumulated energy (calculated as the sum of u component squares; x10^3) from both the west (CEu+, A) and east directions (CEu–, C), winter (January to April) energies (B, D) and shares (E; both % of their respective annual totals), and ice-masked winter sums (index i in A–D) together with their respective changes in linear trend.

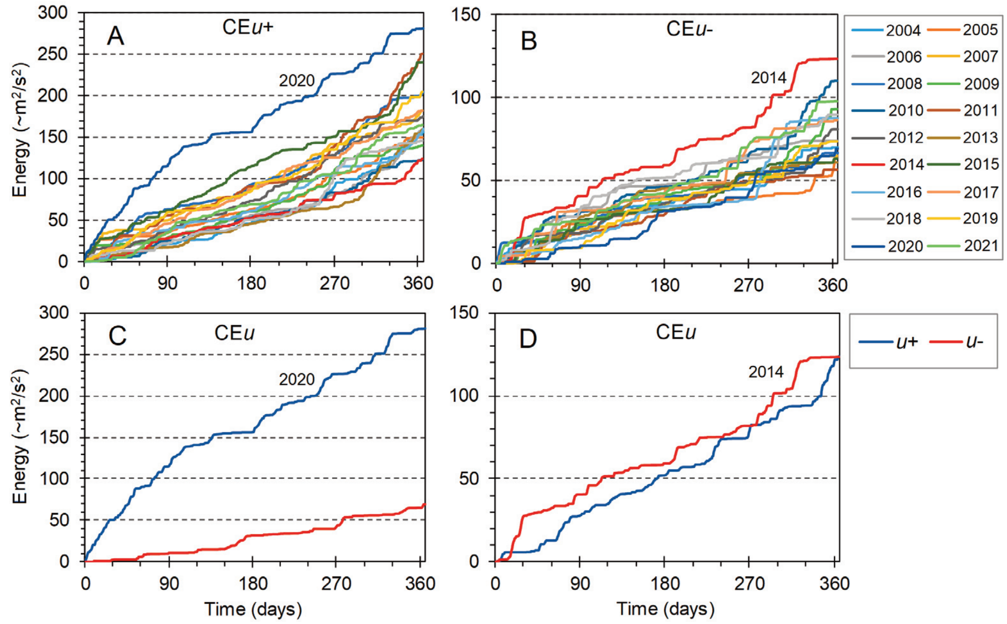

Fig. 8. Intra-annual variations in cumulated energies presented separately for the opposite directions *u*+ and *u*– (both shown as positive) in separate years at Sõrve in 2004–2021 (A, B). The courses for the most extreme years 2020 and 2014 (C, D).

Consideration of sea ice and coastline direction

The occurrence of sea ice is crucially important for coastal processes, especially in this Baltic Sea region (Orviku et al. 2011; Tuomi et al. 2011; Zaitseva-Pärnaste and Soomere 2013). Time series for local ice conditions on both sides of the Sõrve Peninsula were reconstructed on the basis of ice charts, which were available from 1980/81 to 2021/22. The readings for Mõntu were rather well correlated ($R^2 = 0.81$, $r = 0.90$) to the Baltic annual maximum ice extent (Fig. 9B). Using the same relationship, the time series were extended back to 1966 (Fig. 9A). Due to very infrequent ice on the western coast near Jämaja (Figs 6, 9A), it was not feasible to extend this series.

Within the Gulf of Riga, the correlation with the Baltic maximum ice extent was also high at Järve ($R^2 = 0.82$), but lower at Kihnu. Between Kihnu and Mõntu the R^2 was 0.86, and 0.92 between Järve and Mõntu. Indeed, the variations in ice conditions at different locations are rather synchronous with each other (Fig. 9A). With a certain degree of confidence, such relationships can be used for estimating the number of local ice days back to AD 1720, from the time when the Baltic Sea ice reconstruction has existed (Seinä and Palosuo 1996; Haapala et al. 2015). For the Baltic Sea ice extent, the change in the linear trend was from 233 to 113 days (10^3 km²) over 1966–2022 (–52%) and at Mõntu from 52 to 19 days (–63%). However, the change has not been steady. One well-known regime shift occurred around 1989 (Keevallik 2011; Haapala et al. 2015), and the second rapid decrease occurred after 2013 (Fig. 9C). There have been a number of extremely mild winters, such as 1975, 1989, 1990, 1992, 2008, 2015, and most notably, the year 2020.

Using the obtained dates, we applied an 'ice mask' on the series both at Mõntu and Jämaja coasts (Fig. 7). It involved ignoring the wind data in periods with ice, assuming that such winds are 'wasted' for coastal processes (due to protective ice cover, absence of waves and sea currents). The values with and without ice mask were equal in 2020 (Fig. 7A–D) because there was no sea ice that winter. Consideration of sea ice altered the winter energy trend direction. While the easterly energy without the ice mask has slightly decreased on the eastern coast in winter (by 5% over the studied 18 years; Fig. 7D), the easterly energy with ice mask has increased by 25% instead. The relative effect of the ice mask was much smaller on the western shore (Fig. 7A, B), which has on average 3–4 times fewer ice days than on the Mõntu side (Fig. 9C). The difference between ice conditions on the opposite sides

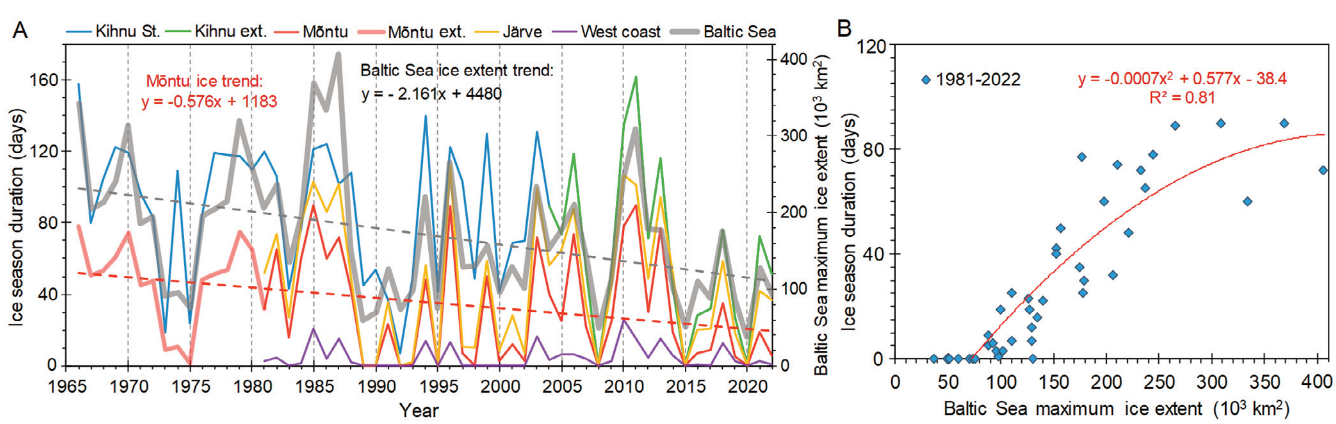

Fig. 9. Comparison of annual ice statistics in the study area (see also Fig. 6) with the Baltic Sea annual maximum ice extents over the period of 1966–2022 (A). Based on regression between the Mõntu series and the Baltic ice extent (B), the Mõntu series was extended (ext.) to cover the period 1966–2022 (on A). The Kihnu station (St.) ice duration series (1950–2003) was extended for 2004–2022 (on A).

of the peninsula occurred, firstly, because the wave climate within the Gulf of Riga is milder than in the area bordering the Baltic Proper (Soomere and Eelsalu 2014). Secondly, northerly to easterly winds, which are usually responsible for cooling and ice formation, may evoke 'warm' upwelling, which counteracts and delays freeze-up. Such a process was recently described for the shores of the Gulf of Finland (Suursaar 2021), and it can occur along the western coast of Saaremaa as well. Hence, the difference introduced by the ice mask in annual energy was only 3% on the western coast. As a result, the trend that was already steep, steepened slightly more (Fig. 7A, B).

To sum up, the kinetic energy on both sides of the peninsula has increased over the last 18 years. On the western side, it is mainly because of the increasing westerly air flow. On the eastern side, it is mainly because of the increasing average and maximum values of the easterlies (Fig. 5), and secondly, because of the gradual decrease in the sea ice cover on the Gulf of Riga (Fig. 9). In earlier times, the number of Mõntu ice days was even higher. For instance, in 1976–1987 it was on average 58 days or twice as long as in 2004–2021, and in some years it reached 90 days (Fig. 9C). Consequently, ice can occasionally be responsible for up to 25% of the variations in annual forcing on the Mõntu coast.

The above-described analysis showed that coastal erosion and coastline change could indeed have increased on the Sõrve Peninsula, as suggested by Tõnisson et al. (2008) and Kont et al. (2022). Another question was which direction is preferred for sediment transport along the eastern shore, is it to NE or SW? It is reasonable to assume that wind (and hence, waves, in wind-seas) approaching the shore at an angle evokes a corresponding alongshore flow (Fig. 6A). Regional generalization of such flows along the coasts of the eastern Baltic Sea has been presented, e.g., by Knaps (1966) and later by Viška and Soomere (2013). To consider the coastline orientation near Mõntu, we rotated the coordinate axes for *u* and *v* by 40° clockwise and completely ignored the westerly side of *u* (due to land shade; Fig. 6A): only winds between 40° and 220° were effective. It appeared that the prevailing net transport direction in the Sõrve–Mõntu coastal section was SW (Fig. 10), which suggests that elongation of the peninsula due to sediment flux is favoured on that side of the peninsula. To the north of Mõntu, the northerly wind direction becomes increasingly shaded. Since eastward (E–NE) sediment flux prevails at the coast of Järve (Tõnisson et al. 2008; Kont et al. 2022), a divergence point should occur between Mõntu and Järve. Along the southern coast of Saaremaa (between Järve and Kõiguste), eastward forcing is generally prevailing (Suursaar et al. 2012), although a very indented coastline can locally redirect wave forcing (e.g., Männikus et al. 2022).

In winter months, the SW-directed flows have considerably strengthened over the last 18 years (from –2.3 to –3.6 m/s), and from –1.6 to –3.2 m/s when considering the ice mask (Fig. 10A). In linear trend, the annual change was from –2.7 to –3.4 m/s, or from –2.4 to –3.3 m/s when considering the ice mask. The trend steepened with the applied ice mask. When looking at the period starting from 1995 (data

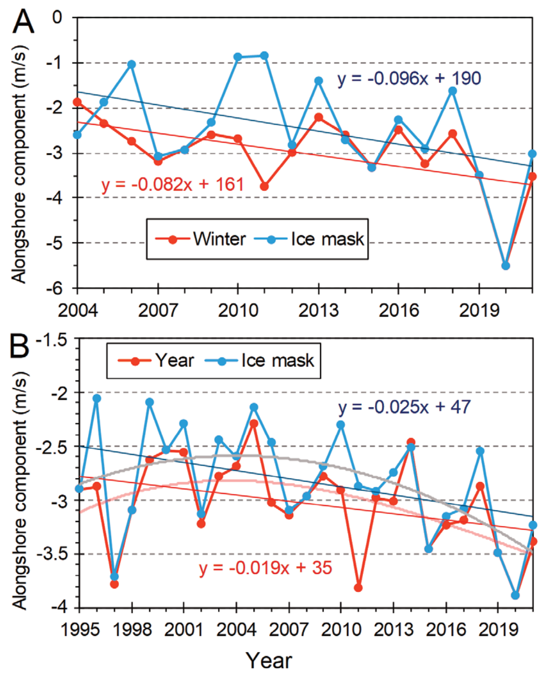

Fig. 10. Variations in the alongshore (rotated) wind velocity component v^* at Sõrve in winter (A) and over the entire year (B) with and without ice mask, together with trendlines (equations given for the linear trendlines). Negative v^* values indicate the prevalence of SW-directed flows (see Fig. 6A).

on the year 1994 was missing at Sõrve), a non-linear trend would better illustrate the variations (Fig. 10B).

These surprising results can be explained as follows: although *u*+ has increased, its influence has been cut off at Mõntu; *u*– has also increased, which has contributed to the increasing alongshore (SW-directed) flow; the wind direction change from ca 190°–220° to 220°–240° has essentially eliminated some strong SW winds, as they have turned to the 'shaded side' (Fig. 6A); although *v*+ is somewhat stronger than *v*–, the *v*+ trend has been negative and the *v*– trend has been positive in 2004–2021 (Table 2). All such features are not so obvious when looking at plain wind data. However, as it was demonstrated above, they can be revealed by splitting the wind data into specific sub-components. In fact, comparable results can be achieved by specifically using hydrodynamic and wave models (e.g., Suursaar et al. 2012; Soomere and Viška 2014), since the models inherently consider coastline configuration and land shade effect, but it is a much more laborious way.

Conclusions

1) Statistical analysis of the wind velocity components (zonal *u* and meridional *v*) and further splitting the data into opposite subsets (*u*+, *u*–, *v*+ and *v*–) revealed certain fascinating features and trends in the atmosphere, which may remain hidden when looking at plain wind speed and direction data. Such separation of wind components and one-sided ignoring of certain directions can be an especially fruitful approach in coastal applications.
2) Despite the considerable differences in local conditions between the studied coastal stations (Kihnu, Vilsandi,

Sõrve, Kunda and Kalbådagrund), the average air flow parameters were similar in their seasonal and interannual courses. Atmospheric air flow is mainly zonal in our region and this mode of motions does not appear or disappear from one location to another. The zonal representativeness is only crippled at Kunda. However, the Kunda station is representative of local marine winds and northerly air flow.

3) As the long-term series (1966–2021) of wind measurements are inhomogeneous and the homogeneous subset from 2004 to 2021 is still too short, the (mainly decreasing) trends in average and high wind speeds are generally not reliable. Being less sensitive to local fluctuations and inhomogeneity problems, the mean speed of the air flow and the u component increased over 1966–2021. The long-term changes in the air flow direction and, in fact, in any parameter, were better described as a wavy (cyclic) rather than monotonic linear trend. In the long run, the air flow parameters have probably experienced some quasi-cyclic, decadal-scale variations, which may accommodate some shorter linear cuts and leave some room for different interpretations. Over the period from 2004 to 2021, both the westerly and easterly subsets of the zonal component increased in their respective directions by ca 0.5 m/s. Regarding wind-driven coastal processes on the opposite sides of the Sõrve Peninsula, the changes in the westerly component, but not in the easterly, are important on the western coast, and vice versa for the eastern coast. The annually cumulated kinetic energy has increased by 26% on the western coast over the last 18 years. The forcing was more than twice lower on the eastern coast, yet it has increased there, too, by 21%.
4) To consider the possible influence of long-term changes in sea ice conditions, an 'ice mask' was applied on both sides of the Sõrve Peninsula. While the easterly wind energy has slightly decreased on the eastern coast in winter (by 5% over the studied 18 years) – probably because of the regionally increasing westerly air flow in winters – the easterly energy, when considering the ice mask, has increased by 25% instead. The relative effect of the ice mask was much smaller on the western coast, which has 3–4 times fewer ice days than the eastern side. The energy on the western side has mainly increased because of the increasing westerly air flow, and on the eastern side because of the increase in the easterlies and the gradual decrease in the ice cover on the Gulf of Riga. Ice can occasionally be responsible for up to 25% of change in annual forcing.
5) Along the eastern coast of the Sõrve Peninsula, the alongshore (NE to SW) flow prevailed. This flow has strengthened because the influence of the increasing westerly has been cut off on the Mõntu side. Although the southerly was somewhat stronger than the northerly, its trend was negative in 2004–2021. The SW-directed flow was enhanced by the increasing impact of the easterly and northerly.

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References

Björkqvist, J.-V., Lukas, I., Alari, V., van Vledder, G. Ph., Hulst, S., Pettersson, H. et al. 2018. Comparing a 41-year model hindcast with decades of wave measurements from the Baltic Sea. *Ocean Engineering*, **152**, 57–71. https://doi.org/10.1016/j.oceaneng.2018.01.048

Donat, M., Renggli, D., Wild, S., Alexander, L., Leckebusch, G. and Ulbrich. U. 2011. Reanalysis suggests long-term upward trends in European storminess since 1871. *Geophysical Research Letters*, **38**(14), L14703. https://doi.org/10.1029/2011GL047995

EEA (European Environment Agency). 2022. *Maps and graphs.* https://www.eea.europa.eu/data-and-maps/figures/maximum-extent-of-ice-cover-1 (accessed 2022-10-23).

EWS (Estonian Weather Service). 2022. *Ajaloolised ilmaandmed* (*Historical weather data*). https://www.ilmateenistus.ee/kliima/ajaloolised-ilmaandmed (accessed 2022-10-23).

FMI (Finnish Meteorological Institute). 2022. *Download observations.* https://en.ilmatieteenlaitos.fi/download-observations (accessed 2022-10-23).

Gidrometeoizdat. 1990. *Научно прикладной справочник по климату СССР* (*Scientific-Practical Handbook of the Climate of the USSR*). 4th ed. Series 3, Parts 1–6. Gidrometeoizdat, Leningrad.

Haapala, J. J., Ronkainen, I., Schmelzer, N. and Sztobryn, M. 2015. Recent change – sea ice. In *Second Assessment of Climate Change for the Baltic Sea Basin* (The BACC II Author Team, eds). Springer, Cham, 145–153. https://doi.org/10.1007/978-3-319-16006-1_8

Jaagus, J. 2006. Trends in sea ice conditions on the Baltic Sea near the Estonian coast during the period 1949/50–2003/04 and their relationships to large-scale atmospheric circulation. *Boreal Environment Research*, **11**(3), 169–183.

Jaagus, J. and Kull, A. 2011. Changes in surface wind directions in Estonia during 1966–2008 and their relationships with large-scale atmospheric circulation. *Estonian Journal of Earth Sciences*, **60**(4), 220–231. https://doi.org/10.3176/earth.2011.4.03

Jaagus, J. and Suursaar, Ü. 2013. Long-term storminess and sea level variations on the Estonian coast of the Baltic Sea in relation to large-scale atmospheric circulation. *Estonian Journal of Earth Sciences*, **62**(2), 73–92. http://doi.org/10.3176/earth.2013.07

Johansson, M. M. and Kahma, K. K. 2016. On the statistical relationship between the geostrophic wind and sea level variations in the Baltic Sea. *Boreal Environment Research*, **21**, 25–43.

Keevallik, S. 2008. Wind speed and velocity in three Estonian coastal stations 1969–1992. *Estonian Journal of Engineering*, **14**(3), 209–219.

Keevallik, S. 2011. Shifts in meteorological regime of the late winter and early spring in Estonia during recent decades. *Theoretical and Applied Climatology*, **105**, 209–215. https://doi.org/10.1007/s00704-010-0356-x

Keevallik, S. and Rajasalu, R. 2001. Winds on the 500 hPa isobaric level over Estonia (1953–1998). *Physics and Chemistry of the Earth*, **26**(5–6), 425–429.

Keevallik, S. and Soomere, T. 2008. Shifts in early spring wind regime in North-East Europe (1955–2007). *Climate of the Past*, **4**(3), 147–152. https://doi.org/10.5194/cp-4-147-2008

Keevallik, S. and Soomere, T. 2014. Regime shifts in the surface-level average air flow over the Gulf of Finland during 1981–2010. *Proceedings of the Estonian Academy of Sciences*, **63**(4), 428–437. https://doi.org/10.3176/proc.2014.4.08

Keevallik, S., Soomere, T., Pärg, R. and Žukova, V. 2007. Outlook for wind measurement at Estonian automatic weather stations. *Proceedings of the Estonian Academy of Sciences. Engineering*, **13**(3), 234–251.

Knaps, R. J. 1966. Перемещение наносов у берегов Восточной Балтики (Sediment transport near the coast of the Eastern Baltic). In *Развитие морских берегов в условиях колебательных движений земной коры* (*Development of Sea Shores under the Conditions of Oscillations of the Earth's Crust*). Valgus, Tallinn, 21–29.

Kont, A., Endjärv, E., Jaagus, J., Lode, E., Orviku, K., Ratas, U. et al. 2007. Impact of climate change on Estonian coastal and inland wetlands – a summary with new results. *Boreal Environment Research*, **12**, 653–671.

Kont, A., Tõnisson, H., Jaagus, J., Suursaar, Ü. and Rivis, R. 2022. Eesti randade areng viimastel aastakümnetel kliima ja rannikumere hüdrodünaamiliste muutuste tagajärjel (Evolution of the Estonian seashores in relation to climate and hydrodynamic changes over the last decades). *Tallinna Ülikooli ökoloogia instituudi/keskuse publikatsioonid*, **13**, 9–58.

Kull, A. 2005. Relationship between inter-annual variation of wind direction and wind speed. *Publicationes Instituti Geographici Universitatis Tartuensis*, **97**, 62–70.

Launiainen, J. and Laurila, T. 1984. Marine wind characteristics in the northern Baltic Sea. *Finnish Marine Research*, **250**, 52–86. https://core.ac.uk/download/pdf/33738887.pdf

Lehmann, A., Getzlaff, K. and Harlaß, J. 2011. Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Climate Research*, **46**, 185–196. https://doi.org/10.3354/cr00876

Männikus, R., Soomere, T. and Najafzadeh, F. 2022. Refraction may redirect waves from multiple directions into a harbour: a case study in the Gulf of Riga, eastern Baltic Sea. *Estonian Journal of Earth Sciences*, **71**(2), 80–88. https://doi.org/10.3176/earth.2022.06

Myrberg, K. 1997. Sensitivity tests of a two-layer hydrodynamic model in the Gulf of Finland with different atmospheric forcings. *Geophysica*, **33**(2), 69–98.

Najafzadeh, F., Kudryavtseva, N., Soomere, T. and Giudici, A. 2022. Effect of ice cover on wave statistics and wave-driven processes in the northern Baltic Sea. *Boreal Environment Research*, **27**, 97–116.

Orviku, K., Jaagus, J., Kont, A., Ratas, U. and Rivis, R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *Journal of Coastal Research*, **19**(2), 364–375.

Orviku, K., Tõnisson, H. and Jaagus, J. 2011. Sea ice shaping the shores. *Journal of Coastal Research*, Special Issue 64, 681–685.

Post, P. and Tuulik, J. 1999. About the relationships between Estonian weather elements and European circulation patterns. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, **24**(1–2), 97–102.

Raudsepp, U., Maljutenko, I., Haapala, J., Männik, A., Verjovkina, S., Uiboupin, R. et al. 2022. Record high heat content and low ice extent in the Baltic Sea during winter 2019/20. *Journal of Operational Oceanography*, **15**(1), 175–185. https://doi.org/10.1080/1755876X.2022.2095169

Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M., Bärring, L., Briede, A. et al. 2015. Recent change – atmosphere. In *Second Assessment of Climate Change for the Baltic Sea Basin* (The BACC II Author Team, eds). Springer, Cham, 69–97. https://doi.org/10.1007/978-3-319-16006-1_4

Seinä, A. and Palosuo, E. 1996. The classification of the maximum annual extent of ice cover in the Baltic Sea 1720–1992. *MERI – Report series of the Finnish Institute of Marine Research*, **27**, 79–91.

Sepp, M., Post, P., Mändla, K. and Aunap, R. 2018. On cyclones entering the Baltic Sea region. *Boreal Environment Research*, **23**, 1–14.

SMHI (Swedish Meteorological and Hydrological Institute). 2022. *Sea Ice. Archived charts and reports.* https://www.smhi.se/oceanografi/istjanst/havsis_en.php (accessed 2022-10-23).

Soomere, T. and Eelsalu, M. 2014. On the wave energy potential along the eastern Baltic Sea coast. *Renewable Energy*, **71**, 221–233. https://doi.org/10.1016/j.renene.2014.05.025

Soomere, T. and Keevallik, S. 2003. Directional and extreme wind properties in the Gulf of Finland. *Proceedings of the Estonian Academy of Sciences. Engineering*, **9**(2), 73–90.

Soomere, T. and Viška, M. 2014. Simulated wave-driven sediment transport along the eastern coast of the Baltic Sea. *Journal of Marine Systems*, **129**, 96–105. https://doi.org/10.1016/j.jmarsys.2013.02.001

Soomere, T., Myrberg, K., Leppäranta, M. and Nekrasov, A. 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia*, **50**(3), 287–362.

Soomere, T., Bishop, S. R., Viška, M. and Räämet, A. 2015. An abrupt change in winds that may radically affect the coasts and deep sections of the Baltic Sea. *Climate Research*, **62**(2), 163–171. https://doi.org/10.3354/cr01269

Suursaar, Ü. 2010. Waves, currents and sea level variations along the Letipea–Sillamäe coastal section of the southern Gulf of Finland. *Oceanologia*, **52**(3), 391–416. https://doi.org/10.5697/oc.52-3.391

Suursaar, Ü. 2013. Locally calibrated wave hindcasts in the Estonian coastal sea in 1966–2011. *Estonian Journal of Earth Sciences*, **62**(1), 42–56. https://doi.org/10.3176/earth.2013.05

Suursaar, Ü. 2015. Analysis of wave time series in the Estonian coastal sea in 2003–2014. *Estonian Journal of Earth Sciences*, **64**(4), 289–304. https://doi.org/10.3176/earth.2015.35

Suursaar, Ü. 2021. Winter upwelling in the Gulf of Finland, Baltic Sea. *Oceanologia*, **63**(3), 356–369. https://doi.org/10.1016/j.oceano.2021.04.001

Suursaar, Ü., Kullas, T. and Aps, R. 2012. Currents and waves in the northern Gulf of Riga: measurement and long-term hindcast. *Oceanologia*, **54**(3), 421–447. https://doi.org/10.5697/oc.54-3.421

Suursaar, Ü., Jaagus, J. and Tõnisson, H. 2015. How to quantify long-term changes in coastal sea storminess? *Estuarine, Coastal and Shelf Science*, **156**, 31–41. https://doi.org/10.1016/j.ecss.2014.08.001

Suursaar, Ü., Rosentau, A., Hang, T., Tõnisson, H., Tamura, T., Vaasma, T. et al. 2022. Climatically induced cyclicity recorded in the morphology of uplifting Tihu coastal ridgeplain, Hiiumaa Island, eastern Baltic Sea. *Geomorphology*, **404,** 108187. https://doi.org/10.1016/j.geomorph.2022.108187

Tõnisson, H., Orviku, K., Jaagus, J., Suursaar, Ü., Kont, A. and Rivis, R. 2008. Coastal damages on Saaremaa Island, Estonia, caused by the extreme storm and flooding on January 9, 2005. *Journal of Coastal Research*, **24**(3), 602–614.

Tuomi, L., Kahma K. K. and Pettersson, H. 2011. Wave hindcast statistics in the seasonally ice-covered Baltic Sea. *Boreal Environment Research*, **16**(6), 451–472.

Viška, M. and Soomere, T. 2013. Simulated and observed reversals of wave-driven alongshore sediment transport at the eastern Baltic Sea coast. *Baltica*, **26**(2), 145–156. https://doi.org/10.5200/baltica.2013.26.15

Weisse, R., von Storch, H. and Feser, F. 2005. Northeast Atlantic and North Sea storminess as simulated by a regional climate model during 1958–2001 and comparison with observations. *Journal of Climate*, **18**(3), 465–479.

Zaitseva-Pärnaste, I. and Soomere, T. 2013. Interannual variations of ice cover and wave energy flux in the northeastern Baltic Sea. *Annals of Glaciology*, **54**(62), 175–182. https://doi.org/10.3189/2013AoG62A228

Žukova, V. 2009. *Eesti rannikujaamade võimalused meretuule hindamisel* (*Possibilities of estimation of marine winds from Estonian coastal stations*). MSc thesis. Tallinn University of Technology, Estonia.

Muutused Eesti rannikul ajavahemikus 1966–2021 mõõdetud tuule kiiruskomponentides ja keskmises õhuvoolus; Sõrve poolsaare näide

Ülo Suursaar

Eesti rannikul mõõdetud tuuleandmete analüüsil selgus, et vaatamata kohalike tingimuste mõjule, olid tuule kiiruse komponentide ja keskmise õhuvoolu karakteristikute sesoonsed ja paljuaastased käigud vaadeldud jaamades sarnased. Kuna pikad (1966–2021) andmeread olid mittehomogeensed, siis leitud (peamiselt langevad) trendid keskmistes tuulekiirustes olid ebausaldusväärsed. Arvatavasti kasvas aga ebahomogeensuste suhtes vähemtundliku tsonaalse ja meridionaalse kiiruskomponendi, aga ka keskmise õhuvoolu kiirus. Muutusi keskmise õhuvoolu suunas ning tegelikult ka teistes õhuvoolu karakteristikutes oli parem iseloomustada mitte lineaarse trendi abil, vaid lainelisena.

Sõrve poolsaare tuuletingimuste detailsemal analüüsil jagati mõlemad tuulevektori komponendid omas sihis kaheks vastandsuunaliseks andmekogumiks. Selgus, et nii lääne- kui idakomponendi kiirus kasvas ajavahemikus 2004–2021 umbes 0,5 m/s võrra. Poolsaare lääneranniku rannaprotsesside jaoks on olulised need muutused, mis toimuvad tuule läänekomponendis ja idakomponendi muutused on ebaolulised ning vastupidi poolsaare idaranniku jaoks. Eeldades, et tuul mõjutab randu suuresti lainetuse ja hoovuste kaudu, siis võeti arvesse ka jäätingimuste pikaajalisi muutusi poolsaare mõlemal küljel. Läänerannikule langev tuulekoormus oli keskmiselt üle kahe korra suurem kui idarannikule langev koormus. Ometi oli jäätingimuste muutusi kajastava „jäämaski" mõju suurem just idarannikul, kus tavaliselt on jääd rohkem. Poolsaare idaranniku sihile kohandatud tuulevektori komponendis domineeris edelasuunaline vool, kuna tuule läänesuuna mõju on maa poolt ära lõigatud. See edelasse suunatud vool tugevnes perioodil 2004–2021, kuna samal ajal tugevnes ida- ja põhjatuul ning järk-järgult kahanes talvine jäätumus Liivi lahel.