A wind proxy based on migrating dunes at the Baltic Coast: statistical analysis of the link between wind conditions and sand movement.

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Abstract. We statistically analyse the relationship between the structure of migrating dunes in the Southern Baltic and the driving wind conditions over the past 26 years, with the long-term aim of using migrating dunes as proxy for past wind conditions at interannual resolution.

The present analysis is based on the dune record derived from geo-radar measurements by (Ludwig et al., 2017). The dune system is located at the Baltic Sea coast of Poland and is migrating from west to east along the coast. The dunes present layers with different thickness that can be absoluted dates at interannual timescales and whose thickness can be put in relation to seasonal wind conditions. To statistically analyse this record and calibrate it as a wind proxy we used a gridded regional meteorological reanalysis data set (coastDat2) covering the recent decades. Furthermore, the identified link between the dune annual layers and wind conditions was additionally supported by the co-variability between dune layers and observed sea-level variations in the Southern Baltic Sea.

We include precipitation and temperature into our analysis, in addition to wind, to learn more about the dependency between these three atmospheric factors and their common influence on the dune system. We set up a statistical linear model based on the correlation between the frequency of days with specific wind conditions in a given season and dune migration velocities derived for that season. To some extent, the dune records can be seen analogous to tree ring width record, and hence we used a proxy-validation method usually applied in dendrochronology, namely the cross-validation with the leave-one-out-method, when the observational record is short. The revealed correlations between the wind record from the reanalysis and the wind record derived from the dune structure is in the range between 0.28 and 0.63 yielding similar statistical validation skill, as dendroclimatological records.

1 Introduction

Climate change may induce changes in wind conditions at all time scales, ranging from multi-decadal trends to changes in the daily and seasonal variability including wind extremes (see Christensen et al., 2015). For the Baltic Sea region wind poses the natural hazard with the highest damage potential, causing high economic or human losses. Furthermore it can lead to storm surges and high Baltic Sea levels, which can increase the damage potential (Rutgersson et al., 2015; Hünicke et al., 2015). To estimate future wind changes it is essential to understand how changes in the external forcing influenced wind conditions in the past (Feser et al., 2015; Rutgersson et al., 2015).

Many studies have addressed past changes in wind climate (see review by Feser et al., 2015, and references therein) based on different approaches. Some analyse wind speed changes (among others Alexandersson et al., 2000; Gulev et al., 2001; Wang et al., 2006; Matulla et al., 2007; Krueger et al., 2013) and some wind direction changes (e.g. Jaagus and Kull, 2011; Lehmann et al., 2011), both on different time scales and with different data sets. These studies include analyses of observations derived from instrumental records (Franzén, 1991; Chaverot et al., 2008), which are likely not totally consistent due to instrumental changes or relocations. Other studies have used meteorological reanalysis, which should in principle be less strongly affected by the potential inhomogeneity problem of pure observations (e.g. Gulev et al., 2001; Wang et al., 2006). These studies have come to different conclusions about past wind changes, depending on the analysed time span they report negative or positive trends in storm activity. To verify model results or to cover a longer time span than available with observations, proxy data may be a reasonable alternative. Proxy-based reconstructions of wind conditions may offer the advantage of a better temporal homogeneity over long-periods compared to observational records, for which e.g. changes in the location of the measuring device may result in very large abrupt artificial changes in the mean wind and wind variability (Krueger, 2014). There already exist wind analyses using pressure measurements as wind proxy, to take advantage of the more homogeneous properties of pressure readings over time (e.g. Alexandersson et al., 2000; Krueger et al., 2013). Other studies try to infer information of past wind events from documented damages on dikes (De Kraker, 1999) or forests (Nilsson et al., 2004). In addition, dune-based records may help to fill spatial gaps in observational data sets, which might be of special interest for analyses of a changing wind climate.

In contrast to other meteorological parameters like temperature or precipitation, there is a dearth of wind proxy records capable of reflecting changes in past wind regimes. Any new proxies, albeit imperfect, can be very useful in this regard.

Coastal dunes are affected by several meteorological parameters, including wind, temperature and precipitation and therefore their structure may contain information about changes of these atmospheric parameters (Lancaster, 1994). Recently, Ludwig (2017) presented a new proxy for annual wind-field variations based on a composite bar code of a dune system alongshore the Polish Baltic Sea close to Łeba. This bar code reflects the width of different dune layers that are annually formed. These dunes migrate by the action of wind and in the processes of migration alternating layers with varying sediment and grain-size properties are formed. These layers, therefore, contain information about how the dune structure responded to past wind conditions. Since wind conditions present an annual cycle, the dune layers can be annually dated. These varying sediment properties can be seen as an analogous to tree-ring-width records, which also may include information about changing climate conditions (Girardi, 2005). Comparable dune systems can also be found at other coasts e.g. at the Curonian spit (Lithuania) where the alternating dune structure was also interpreted as a result of winnowing of lighter quartz grains due to higher wind speeds (see Sect. 2.1.2) (Buynevich et al., 2007).

The potential of dunes to provide information about storminess has already been demonstrated (Clemmensen et al., 2014; Costas, 2013), but existing studies have used the connection between dune structure and wind only on decadal or millennial temporal resolution. The reconstruction by Ludwig (2017) is the first attempt to use dunes as wind proxies on seasonal to annual resolution.

This present study statistically analyzes in more detail the link between this new proxy record and wind conditions, in order to evaluate and calibrate the potential to reconstruct past wind conditions by comparing the new proxy record with meteorological reanalysis data. Meteorological reanalysis is a data product constructed by combining weather information (e.g. surface weather stations, satellites, etc.) of past weather observations, and a meteorological forecast model. These simulations obtained with data-assimilation assimilate the available observational records to produce a gridded, spatially and temporally complete model data set of many atmospheric and oceanic variables with a temporal resolution of a few hours (Dee et al., 2015). Due to their use of observations, the time span covered by reanalysis is also limited. On the other hand, the connection to observations may be advantageous because meteorological reanalysis data aim to track real observational data, in contrast to free-running model simulations that do not include data assimilation. However, even long-term reanalysis data e.g. 20CR (Compo et al., 2011) were shown to be difficult regarding long-term trend analysis (Krueger et al., 2013) due to the different observational data sets that are continuously included through the simulation period. Dune records may therefore pose a good opportunity to obtain homogeneous wind records spanning longer periods.

Here, we study the statistical relationship at interannual time scales between mean seasonal wind conditions in different seasons and the annual dune layers, and assess the relationships between the reconstructed and actual wind characteristics, derived from the reanalysis, with a focus on wind direction and speed. We include precipitation and temperature into our analysis to learn more about the dependencies of these three atmospheric factors and their influence on the dune system. Unfortunately, the period covered by this dune system is rather short, from 1987 to 2012. We consider this analysis relevant for the paleoclimate community as a proof-of concept to derive wind proxies once longer dune records with annual resolution become available. Hence, this analysis could be applied to other dune systems which are bigger and or move more slowly, e.g. at the Curonian spit.

This paper is structured as follows: Chapter 2 describes the analysed reanalysis data and the Łeba dunes. Chapter 3 explains the used statistical methods. Chapter 4 presents the results. A discussion of the results and a conclusion closes the manuscript.

2 Data and area

Here, the investigation area Łeba and its climatological and dune characteristics are described. An elaborated description about the analysed dune data can be found in Ludwig et al. (2017). In the following the reanalysis product coastDat2, used in this study, is introduced and briefly discussed.

2.1 Łeba dunes

The active dune system in Łeba (Poland) covers an area of 5,5 km^2 and is situated on top of a barrier that separates the Lake Lebsko from the Baltic Sea. To the north, pine trees and foredunes prevent sediment supply from the beach to reach the proper dune system; hence, the material that forms the dune is self-contained with little contamination from outside the system. Public entering is prohibited since 1967.

The barchanoid dunes are up to 600 m long and 27 m high. The sands are fine-grained (with a diameter of 0.2 to 0.3 mm (Ludwig et al., 2017)) and well-sorted and the dunes attain an average migration velocity of around 10 m/yr. This dune system has been analysed before by Borówka (1979, 1980, 1995); Borówka and Rotnicki (1995). These authors also mentioned some climatological characteristics of this area, which will be briefly recapped and compared to our own results in the following subsection. Additionally, an overview about their results and results from Ludwig et al. (2017) regarding the relation of wind and this dune structure will follow.

2.1.1 Climatological characteristics

Due to its west-east alignment, the dune migration is strongly connected to westerly winds (Borówka, 1980), which are most frequent and are strongest during winter and autumn. Westerly winds transport the sand from the luv side (west) of the dune to the lee side (east) of the dune and so contribute to the eastward movement of the dune (Fig. 1). Hence, the stronger or more frequent westerly winds are, the more sand is transported to the lee side of the dunes, which also results in a higher dune migration velocity.

Additionally to wind, temperature and precipitation have an influence on the Łeba dune migration, e.g. frost and precipitation might stabilise the dune and hinder the sand transport. Borówka (1980) reported the mean annual total precipitation in the research area to be about 700 mm with a maximum occurring in summer and autumn. Furthermore, he stated that the area undergoes only small annual temperature variations. From coastDat2, within the period 1948-2012, we calculated a mean annual precipitation amount of about 630 mm and seasonal mean (standard deviation) temperatures for winter=-1.6°C (1.7°C), spring=5.4°C (0.9°C), summer=15.7°C (0.7°C), autumn=7.9°C (1.2°C) averaged over the area shown in the right panel of Figure 2. Regarding wind direction, the Baltic Sea area shows a predominance of westerly and southwesterly winds for all seasons with a second maximum for north-easterly winds during spring for mean and for extreme wind speeds (Bierstedt, 2015). Similar wind climatology was obtained by Ludwig (2017) and Ludwig et al. (2017) with observational data of one station located close to the dunes.

2.1.2 Coastal dunes as archive of seasonal wind intensity

The dune sands are characterised by alternating changes in the sediment composition. The dune structure shows layers dominated by light quartz grains and layers with interspersed deposits of heavy minerals. Both layers are caused by seasonally changing wind conditions (Borówka, 1980). The quartz layer consists predominately of quartz grains with dispersed heavy minerals. Quartz grains as well as heavy minerals are mobilized along the luv-side of the dune and transported to the east by westerly winds, which are stronger and occur more frequently during autumn and winter. In contrast, winds from the east winnow quartz grains, as unveiled by Borowka's observations of the Łeba dunes, leaving enriched heavy minerals behind. This gives rise to an alternating structure of layers that can be investigated with the help of ground-penetrating radar (GPR).

Ludwig et al. (2017) showed that a quartz-dominated layer and a layer enriched in heavy minerals represent a whole year. This alternating pattern is termed sedimentary bar code (Fig. 1). The thickness of the individual bars varies from year to year. The link between layer thickness and wind is not linear, as the grain mobilization requires wind speed to surpass a certain threshold. Ludwig et al. (2017) estimated this threshold to be 4.4 m/s for the finest dry sands and 10 m/s for moist material. Also, the effect of the winds on a particular dune may depend on local and individual characteristics of the dune. As in the case of other proxy records, and in order to overcome dune-to-dune variations and gaps in the sedimentary record Ludwig et al. (2017) analysed a cluster of five dunes, providing individual bar codes that were later compiled into one composite bar code for the entire dune-field, and applying two dendrochronological methods, namely replication and cross-dating.

Annual variations in the bar code thickness, and hence in the migration rates, correlate with changing west wind intensities. A comparison between observational wind data, from a station located near the sample side, and the bar code thickness showed that during years with strong west winds the net dune progradation to the east is faster than during years with weaker west wind intensities. The bar code record covers a time period of 26 years from 1987 to 2012.

In this study, we provide a more detailed statistical analysis of the link between dune structure and wind conditions by investigating the seasons and wind directions for which the dune structure can be considered more representative of the wind conditions, estimate optimal wind thresholds from the data, provide an amount of wind variance that can be derived from the dune records and provide uncertainty ranges if the dune records were used to reconstruct past wind variability.

2.2 Meteorological data

For the main investigation, wind data from the regional meteorological reanalysis data set coastDat2 (Geyer, 2014) was used. The coastDat2 data set covers the period from 1948 onwards, and thus spans a period with an almost stable number of observations. Hence, it can be considered to be largely homogeneous.

CoastDat2 is a result of a regional climate simulation with the non-hydrostatic operational weather prediction model COSMO-CLM in CLimate Mode (Rockel and Hense, 2008) driven by meteorological initial and boundary conditions from the global low-resolution NCEP/NCAR Reanalysis 1 data (1948-present; T62 ($1.875° \approx 210km$), 28 levels, (Kalnay et al., 1996; Kistler et al., 2001)). The regional simulation covers Europe and was conducted applying spectral nudging (after von Storch et al., 2000). It has a spatial resolution of $0.22°$ and the output is available hourly. However, the information derived from the dunes cannot provide such high temporal resolutions, hence, we decided that daily averaged data is sufficient.

Weidemann (2014) compared the measured wind conditions at three German coastal stations (Kiel, Warnemünde, Kap Arkona) with the COSMO-CLM model output. He reported a slight systematic overestimation of wind speed, but a good agreement regarding daily mean wind speeds, and generally acceptable results regarding the daily wind speed variability. However, high wind speeds tend to be underestimated. He stated that some discrepancies might be introduced by the model COSMO-CLM, but that other differences between model and observations might be due to in-situ measurement errors. Other errors may occur due to the imperfect forcing data set NCEP and its coarse spatial resolution.

Although meteorological reanalysis track observations, it can be argued that they are still a model product. Unfortunately, the joint analysis of the dune layers and observed winds is hampered by the lack of direct nearby observations in this area. Although there exists a weather station close to the analysed dunes this station is located in the woods, which compromises especially north-western wind information (Ludwig et al., 2017). To verify our reanalysis-based results with real observations, we resort to other observations that are known to be related to seasonal wind conditions in the Baltic Sea, and compared observed coastal sea level data from various stations across the Baltic Sea with dune layer thickness. Baltic Sea level variations are strongly driven by surface winds (Hünicke et al., 2015), especially in autumn and winter, and hence can be also seen as a good proxy regarding wind in this region.

The relationship between wind and sand migration may additionally be dependent on other atmospheric parameters, like precipitation and temperature. We used the daily mean 2-meter temperature from coastDat2 and also the daily sum of total precipitation from coastDat2, which includes convective and large-scale precipitation as well as snow. The results were also confirmed with precipitation data provided by the Climate Research Unit (CRU; Mitchell and Jones, 2005). This latter gridded data set is the result of a spatial interpolation of station data. The obtained results were found to be similar (not shown).

3 Statistical methods

This study mainly focuses on the relationship between sand movement and wind conditions during different seasons: Winter (December to February; DJF), Spring (March to May; MAM), Summer (June to August; JJA) and Autumn (September to November; SON). However, we also include a short comparison with results for the windy season (September to March; SONDJFM). The analysed wind conditions are defined based on wind speed thresholds. The thresholds relevant for sand movement at the investigation side are unknown, so that different thresholds have been considered as a free parameter to find an optimal relationship between wind conditions and the dune bar code. We also use eight different wind direction subdivisions (North=N, North-East=NE, East=E, South-East=SE, South=S, South-West=SW, West=W, North-West=NW), 360 degrees are divided into eight equal sectors of 45 degrees each to derive conclusions on the dune driving wind directions. A finer division is not advisable to the limited length of the records to avoid a too small sample size

We set up a linear regression model in which the independent variable is the migration velocity of white, black and both combined layers derived from the layer thickness and the dependent variable is the number of days with daily wind means from a certain direction and above a predefined wind speed threshold. In this way we identified the leading relationships between the white and black bars (predictor–y) and different combinations of wind direction and wind speed (predictand–$\tilde{y}$). This model is tested and statistically validated with the help of cross-validation, namely the leave-one-out-method (Michaelsen, 1987; Birks, 1995). This statistical validation technique is commonly used for dendrochronological analysis to investigate the linear relation between tree ring width and temperature when the temperature record is short.

The leave-one-out-method addresses the problem of a too short record of observations that does not leave enough unused independent data for statistical validation, once all data have been used to calibrate the statistical model. In the leave-one-out validation method, all observations except one are used to estimate the free statistical parameters. The calibrated statistical model is then used to estimate the value of the predictand for the left-out observation, which is then compared to that real observation. A complete loop over all observations is then conducted in which at each step only one observation is not included in the calibration of the statistical model. In the end, a measure of the statistical skill is obtained as an average of the mismatch between estimated and observed values of the predictand at each ’left-out’ time step. In our case, this means that successively one of the available 26 predictor values (bar thickness) is left out and the remaining 25 values are used to “predict” the corresponding days per wind direction over a pre-defined wind speed threshold (predictand). In the end we have got 26 predicted wind condition values (ỹ), which can be compared to the actual values (act(y)) derived from coastDat2. We assess the statistical skill with the help of both the root-mean-square-error (rmse–Eq. 2), which can be used to determine the explained variance ($rmse^2$), and the correlation coefficient between predictand and actual values.

Due to the described winnowing effect of easterly winds (see Sect. 2.1.2), we additionally investigated the idea of an optimal ratio between the number of westerly and easterly winds which promotes the thickness of black layers. The idea is that a smaller or a larger ratio would produce thinner or thicker black layers. For this, we need to identify a nonlinear link between this ratio and the layer thickness. Thereby, we use a local regression (loess regression) - where local means here that the regression is based only on a set of observational data points (x,y) - that lie within a certain limited region in a x-y plot. The value of the parameters of the statistical model thus depends on the value of predictor and predictand x,y. The statistical models that we have used in this analysis are weighted linear least squares and a 2nd degree polynomial model. This local regression is equivalent to finding a local and second-degree polynomial that better fit the (x-y) data points. The width of the loess window is optimized with the lowest root-mean-square-error after the leave-one-out-method.

$$\tilde{y}_i = p1_i * y_i + p2_i \tag{1}$$

$$rmse = \sqrt{\frac{\sum\limits_{i=1}^{n}(act_i(y) - \tilde{y}_i)^2}{n}} \tag{2}$$

4 Results

Before we applied the linear regression model to identify a relationship between dune migration and wind conditions, we analysed the connection between the dune movement and other atmospheric parameters. The following section is devoted to the correlation between the migration velocities of the white and black layers and temperature, precipitation and wind. Later, we explain the results concerning the linear regression model between the migration velocity and wind for a specified direction and speed threshold.

4.1 Dune migration velocity and meteorological forcing

The dunes in the study area consist of alternating layers with different sedimentary characteristics which are termed “bar-code”. Quartz-dominated layers are imaged by white bars and have a mean thickness of 6.37 m. The black bars (layers) are characterised by heavy minerals and show an averaged thickness of 6.15 m. The dune migrates by the action of the wind as material from the luv-side of the dune is transported over the dune all the way forward to the lee-side of the dune. The succession of white and black layers corresponds to the annual cycle in the meteorological characteristics and this allows for the dating of each pair of layers. In the study area, the time period covered by the layers formed in the dunes span the period 1987-2012. The thickness of both type of layers varies from year to year, but not independently of each other. The thickness of the black and white layers correlates with r=0.63. The whole dune system migrates 12.52 m per year on average. This dune migration is influenced by atmospheric parameters. These parameters are temperature, precipitation and wind. The most important parameter is obviously the wind as it transports the sand. Nevertheless the other factors may have some influence. We investigated the relationship between bar thickness and seasonal precipitation. The amount of soil wetness influences the compactness of the top layers of the dune and their sensitivity to the wind drag. The colder seasons winter (DJF) and spring (MAM) show slight, albeit not significant at the 95% level, positive correlations for both layers (DJF; r=0.17-0.23 and MAM; r=0.19-0.24), which indicates an increasing bar thickness during wetter periods. The temperature also shows relations to the dune layer thickness. Autumn is the only season showing a non-negligible, albeit not significant correlation for black layers (r=0.33; p=0.09). Hence, in autumn, sand movement has a slight tendency to be faster with higher temperatures. The other seasons reveal no correlation between temperature and bar thickness.

The two meteorological parameters temperature and precipitation combined might play a role, especially during winter season. It is assumed that low temperatures, below zero, together with precipitation stabilise the dunes and thus hinder the sand transport. To consider this effect, we analysed the correlation between wind conditions (number of days per wind direction) and sand movement by excluding or including days with frost and precipitation. The biggest differences can be seen in winter (compare Fig. 4a and 3a), some differences in spring (compare Fig. 4b and 3b) and none in summer and autumn (not shown). Winter and spring show with and without frost days the same correlation sign, but some correlations are higher for days without frost and precipitation. In spring higher correlations can be seen for northern and eastern winds, but changes are still quite small. For winter, the correlation coefficients get lower (higher) without frost and precipitation, especially for white (black) bars and E (SE) winds. Nevertheless, autumn still has the highest correlations between wind and bar thickness. Therefore, conditional on the shortness of the record, temperature and precipitation may have a small additional effect on the link between wind and the dune bar code.

Wind

The analysis regarding the relationship between wind conditions and layers is based on wind intensity per wind direction. The latter is divided into eight subdivisions (N, NE, E, SE, S, SW, W, NW). The wind condition is defined by applying two measures. One measure is the mean wind speed per wind direction calculated only in the days with mean wind from that particular wind direction. The second measure is the number of days per wind direction. The correlations between white, black and combined bar thicknesses and these two wind condition measures for the eight predefined wind directions are shown in Fig. 5 and Fig. 4, respectively. Comparing the results for both measures for the windy season SONDJFM (see Fig. 4c and Fig. 5c) showed no strong correlations except for S winds with the number of days measure. Because one goal of our analysis was to statistically validate the proxy on a seasonal time scale the following results are focused on the four seasons defined above. The correlation coefficients reveal summer as the least effective season for sand transport regardless of the definition of wind condition. For the other seasons there are some differences depending on the definition of wind conditions used: In spring we only see noticeable correlations for E winds for the black layer using the mean wind speed definition (r≈0.3). The mean wind speed from E apparently has an influence on the thickness of the black layer. The number of days from a particular wind direction seems to be less effective in spring. This is an interesting result, as it is an indication for the winnowing of white and black grains as already mentioned by Borówka (1979). In winter, the link between dune layers and wind clearly depends on the definition of wind condition. The layer thickness is positively correlated with mean wind speed for almost all wind directions and layers. However, the correlation between layer thickness and the number of days from particular directions displays opposite correlation, with eastern and northern wind directions showing negative and western and southern wind directions showing positive correlations. These opposite correlations can also be seen for autumn, especially for the black layer. Hence, in autumn and winter the strong winds prevent the winnowing effect described in the introduction. In these seasons the wind speed of easterly winds seems to be high enough to erode not only the lighter white material but also the black heavy minerals. Autumn is the season with highest correlations for both measures and both bars, pointing at this season as the most important for sand transport.

As a next step, we analyse days per wind direction with wind speeds over a predefined wind speed threshold to connect the two measures based on wind speed and based on days per wind direction. The wind speed is binned into 10 groups ranging from 0 to >10 m/s. The wind directions with non-negligible correlation coefficients are E and NE during spring (Fig. 6c+d), W and SE during winter (Fig. 6a+b) and W, SW, NE during autumn (Fig. 7). The correlation coefficients in summer and in the other wind directions are predominantly low (not shown).

In spring we see a difference in the sign of the correlation coefficients between dune layers and E and NE winds. For E winds the correlation is positive especially for the white layer. NE winds show negative correlations for all layers. Winter also shows contradicting signs in the correlations to SE and W winds, although with smaller correlation differences between white and black layer.

Concerning the variations in the wind threshold, both winter and spring show higher correlations for wind speeds above 4 m/s. In autumn the correlations are highest for a threshold of 8m/s of NE winds for the black layer, with a negative sign, and for a threshold between 3m/s and 5m/s of SW winds and for a threshold of 5 m/s of W winds, both with a positive sign.

4.2 Linear regression

The highest correlation between wind and the thickness of the white and black layer can be seen in autumn for SW wind direction, thus we use this season and direction to set up a linear regression model with the layer thickness as predictor and wind speed as predictand. For SW winds correlations are highest for wind speeds from 3 to 5 m/s (see Fig. 7b). The linear relationship between days per wind direction and within this wind speed band and the migration velocity of black and white layer is tested with the leave-one-out-method (Sect. 3). We use the migration velocity (predictor), and its linear relation to the number of days with SW wind with the above mentioned wind speed (predictand). The leave-one-out-method allows for the statistical validation of this relation by comparing the predictand with the actual number of days per wind direction. Table 1 shows the correlation coefficients between the predicted and actual values, the root-mean-square-error and the explained variance of this analysis are shown.

The best results are obtained for SW winds, which is likely due to the wind speed threshold being more strictly defined e.g. compared to W winds (>5 m/s). With these threshold values the correlation between migration velocity and number of days per wind direction are higher (compare e.g. Fig. 7a,b). However, one has to keep in mind that a higher wind speed threshold (3-5 m/s) excludes many observations. This validation of the regression model to predict SW winds from the dune layers shows results that are similar to accepted validation values in dendrochronological analyses.

We see a strong positive (negative) connection between the migration velocity of the black layer and the number of days with W/SW (E/NE) winds. We assume that white and black sands are transported together eastwards by westerly winds and this explains the positive correlation between the black layers and the number of days with W and SW winds. In days with easterly winds, which are usually weaker than westerly winds, only the white lighter particles are transported to the back of the dune, enriching the black layer. This explains the negative correlation between the number of days with E and NE winds and the black layer.

This idea of winnowing was already explained by Borówka (1979) for the Łeba dunes. Easterly winds winnow only the lighter white grains and transport them backwards to the west, hence a black layer forms. This effect suggests that there might be an optimal ratio of days with west and east winds per year that results into a thicker black layer. The presence of such optimal ratio implies a non-linear relationship between this ratio and the thickness of the black layer.

To test this hypothesis we use a scatter plot between the difference in the number of days with west (W, SW, NW) and east (E, SE, NE) winds during all seasons and the black layer thickness per year (see Fig. 8). The data points are smoothed with a loess filter (red line in Fig. 8). If an optimal ratio between east and west would exist, the smoothed curve would show a clear maximum. Our result does not show this maximum and therefore no clear optimal ratio can be derived from these results. Nevertheless, there seems to be a minimum value of this ratio (≈ 4500) under which the black layer tends to be small.

4.3 Baltic Sea level and dune layers

Our results so far are based on wind data from reanalysis data. These are derived data produced by a combination of a numerical model and observations (see Sect. 2.2). The reason for not using station data for the calibration and verification of our analysis are the mentioned potential inhomogeneities of such data sets especially with regard to wind information. In particular, the closest meteorological station in this region is located close to a forest

To ascertain here the correlation between the dune layer thickness and wind, we used - as an indirect wind measure - Baltic Sea level data. Coastal Sea level interannual variations in the Baltic Sea in autumn and winter are strongly driven by the intensity of the westerly winds, so that there exists a well known and strong correlation between seasonal mean sea-level at many tide-gauges in the Baltic Sea and many indices of westerly wind intensity, such as the North Atlantic Oscillation (e.g. Andersson, 2002). Baltic Sea level variations and its forcing factors are described in detail by Hünicke et al. (2015). Not all Baltic tide-gauges display the same correlation strength to the large-scale wind, but the overall picture is that winds play a major role for Baltic Sea level, where persistent winds from SW (NE) drive the water into (out of) the Baltic Sea basin and short wind events distribute the water within the basin resulting in high or low sea level values depending on the wind directions (Ekman, 2007).

Figure 9 shows the correlation pattern between the total thickness of the dune layer and mean winter sea-level in the tide-gauges provided by the Permanent Service for Mean Sea Level (PSMSL). Since we are investigating the correlations at interannual time scales and sea-level records, which are affected by the long-term sea-level rise and long-term crust movement, the sea-level time series have been linearly detrended prior to the calculation of the correlations. Positive correlations between autumn (SON) Baltic Sea level and dune layer thickness are found for most tide-gauges. The sign of this correlation is also consistent with the idea that strong westerly winds generally cause thicker dune layers. In addition, the correlation patterns display higher correlations at tide-gauges that are located closer to the dune site and lower correlations for tide-gauges located further apart. The only plausible explanation that may explain this spatial pattern of correlations between coastal sea-level variations and the thickness of dune layers is that both variables, sea-level and dune thickness, are partially driven by the common wind forcing described above. Therefore, this strengthens our results derived from the reanalysis data set coastDat2.

5 Discussion and conclusion

Our analysis provides a more quantitative support of the migrating coastal dunes, identified by a geological analysis of Ludwig et al. (2017), as a wind proxy at interannual time scales. To statistically validate this wind proxy against wind observations we chose to use a reanalysis data set, instead of data from a meteorological station. There are two main reasons for this choice. One is that the main application of our study is the reconstruction of wind conditions that may have a wider spatial representativity than station data. Climate reconstructions will eventually be compared with climate model simulations, which have a spatial resolution similar to reanalysis, and therefore it is more convenient for this purpose to assure the statistical link between the proxy record and regional, as opposed to pointwise, wind data. This allows for a larger scale reconstruction than the observational data from one station, used by Ludwig et al. (2017) to identify the wind proxy. A second reason is that we consider that data from only one station can be affected by inhomogeneities in time, and also by local conditions like the presence of forest and hence maybe not representative of the wind conditions forming the dunes, e.g. Ludwig et al. (2017) also state that some wind directions seem to be under-represented in the station data due to the station position located behind trees.

Nevertheless, in order to demonstrate the credibility of our results compared to observations, we additionally calculated correlations between observed Baltic Sea level data and dune layer thickness during autumn (SON). Hünicke et al. (2008) stated that wind is the main driver of interannual Baltic Sea level variations, hence there should be a direct link between both parameters. Therefore, Baltic Sea level can be seen as a good proxy for wind variability in the Baltic Sea region. The derived correlation values showed a clear positive link between dune layer thickness and Baltic Sea level across the whole Baltic regions and thus a clear positive link to wind as well. On the one hand, this positive link to sea-level can be very useful as sea-level data goes further back in time than e.g. reanalysis data. On the other hand, it confirms the relationship between wind and dunes identified in our study derived with the reanalysis coastDat2, which makes the results more robust.

The analysed dunes at the Polish Baltic Sea coast are characterised by alternating white and black bars representing light quartz grains and heavy minerals. These bars might be regarded as analogous to tree ring width records. The analysis of the dune records composite was conducted similarly as with dendrochronological methods. Hence, the chosen statistical validation technique is also a common tool to verify the relation between tree-ring width and temperature when the instrumental records are to short.

We investigated the relationship between bar thickness and the atmospheric parameters: precipitation, temperature and wind. The focus lies on the relation to wind conditions because wind is assumed to actually transport the sand grains. However, precipitation and temperature also have an influence on dune migration:

Regarding precipitation, the results showed positive signs for the white and black bars for winter (DJF) and spring (MAM). Borówka (1980) stated that some rain might improve the transport due to turbulence, which makes more sand grains available. We argue that the influence of precipitation on sand transport, and hence on the dune processes, depends on the seasonal wind conditions. For example it might be possible that precipitation and wind co-vary, which is especially likely during winter and spring when stronger cyclones come into the Baltic Sea region. Ludwig et al. (2017) describe a secondary dune on top of the primary dune consisting of the white and black layer. These secondary dunes seem to be affected by precipitation due to erosion. This idea is supported by our results and shows that in wetter seasons the secondary dunes might be eroded into the primary dune and hence results in thicker dune layers.

Due to its west-east alignment the dune is most sensitive to westerly (W, SW) and easterly (E, NE) winds. This relationship with wind depends on season and on direction. During winter and autumn, westerly winds correlate positively with dune layer thickness, whereas the easterly winds correlate negatively, more or less independently from wind speed. In spring there are positive correlations for eastern wind direction for the white layer.

After analysing the influence of meteorological parameters on dune migration, we focused on the linear relationship of the migration velocity and the frequency of days with SW winds surpassing a specific wind speed threshold. The derived linear relationships were validated with the leave-one-out method due to the limited length of the observational record. This linear model allowed to hindcast the wind speed from the migration of the dunes over the past decades. The correlations between the observed and reconstructed wind speeds lie between 0.28 and 0.63 and are similar to the correlations typically obtained for other climatic proxies e.g. tree rings. As an example, Bräuning and Mantwill (2004) derived correlation values with leave-one-out validation of 0.41 to 0.78. This results lead us to the conclusion that alternating dune structures can be used as wind proxies also on annual time scales.

Dunes as wind proxies had already been used before (e.g. Clemmensen et al., 2014), but only on decadal or millennial temporal resolution. Our study therefore, statistically validates the interpretation by Ludwig et al. (2017) of the dune layers and dune migration velocities as indicators of annual and even seasonal wind conditions. Although, the dune system analysed here covers only a period of 26 years, we suggest that the analysis is of relevance for paleoclimate studies since it can be applied to other dune systems covering longer time periods.

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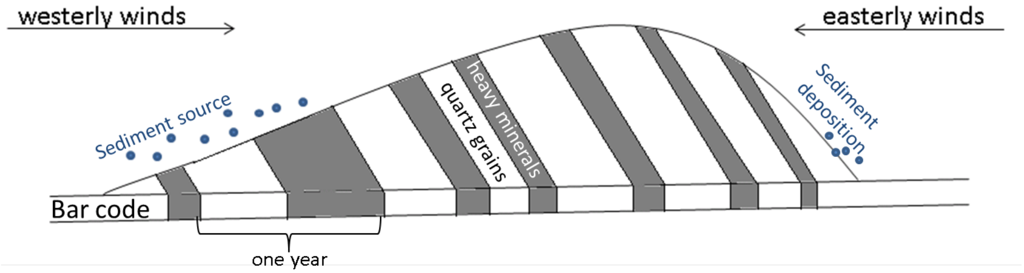


Figure 1. Schematic representation of of the Łeba dune structure (adapted from Ludwig et al. (2017)).

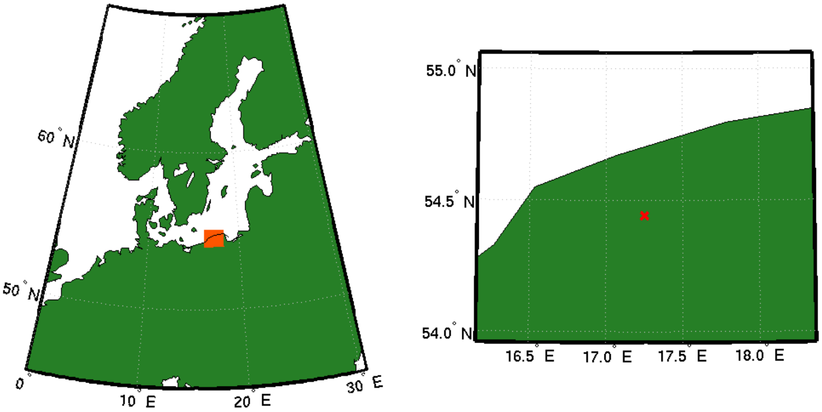
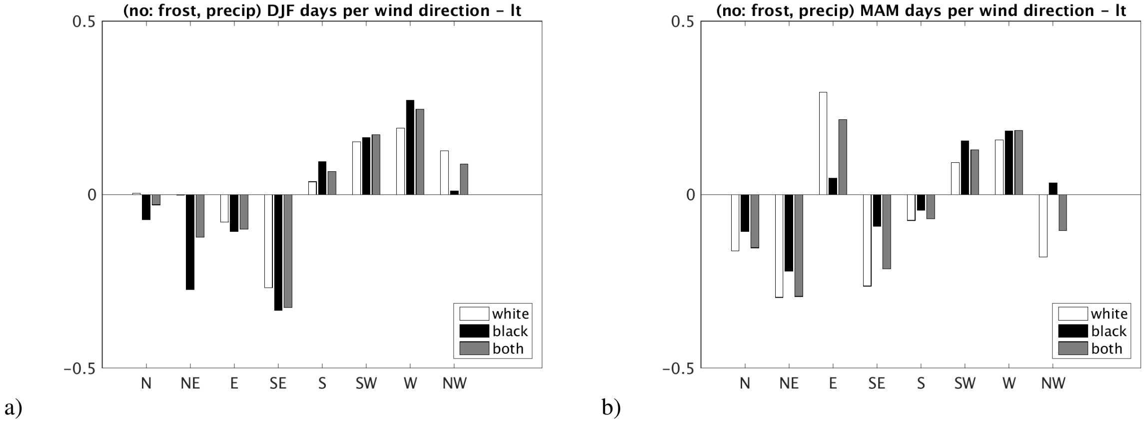


Figure 2. Location of investigation area. Left: Red box marks analysed gridded wind information from coastDat2 (1987-2012). Right: Analysed area with dune location (red dot) close to Łeba, Poland.


(no: frost, precip) DJF days per wind direction – lt

(no: frost, precip) MAM days per wind direction – lt

Figure 3. Correlation between the number of days per wind direction without frost and precipitation days and dune thickness (lt-layer thickness) of the white layer (yellow), black layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF), spring (MAM) and for eight wind directions.

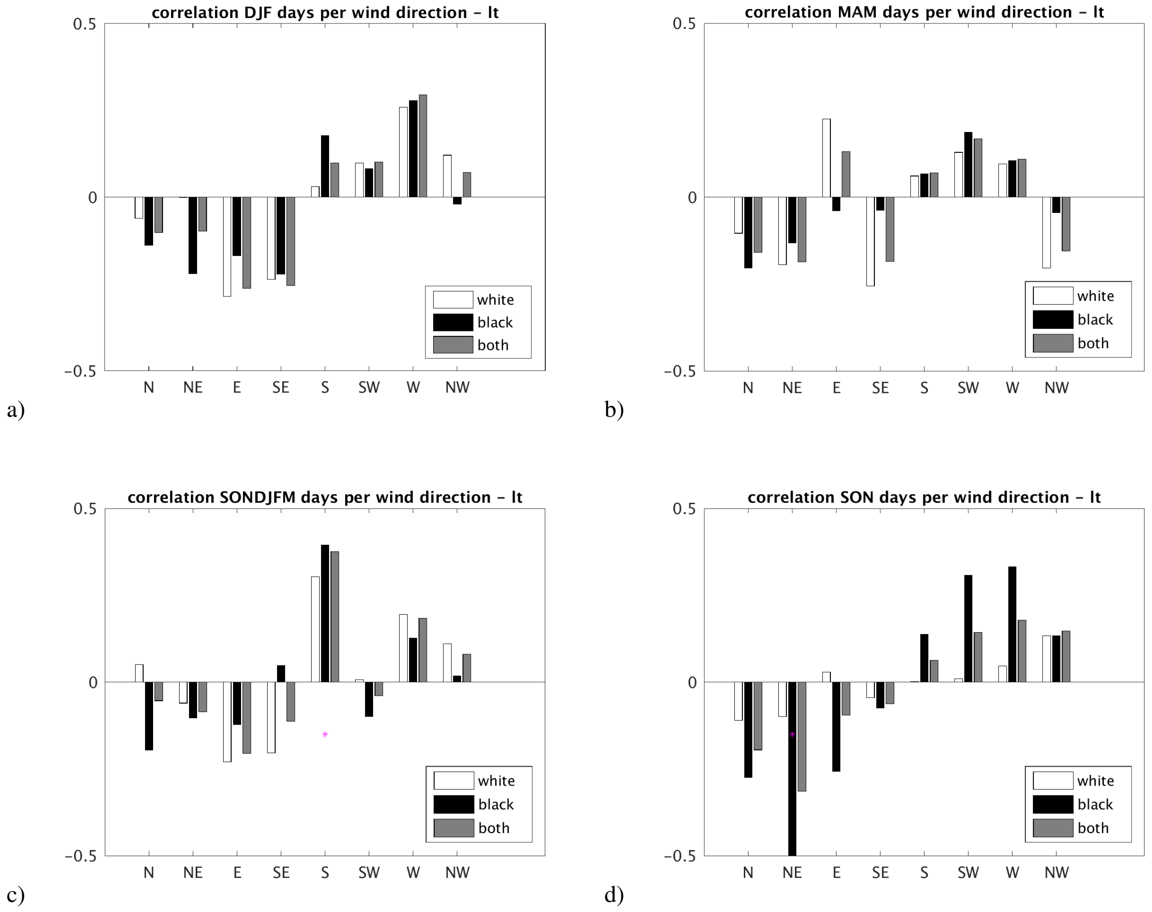
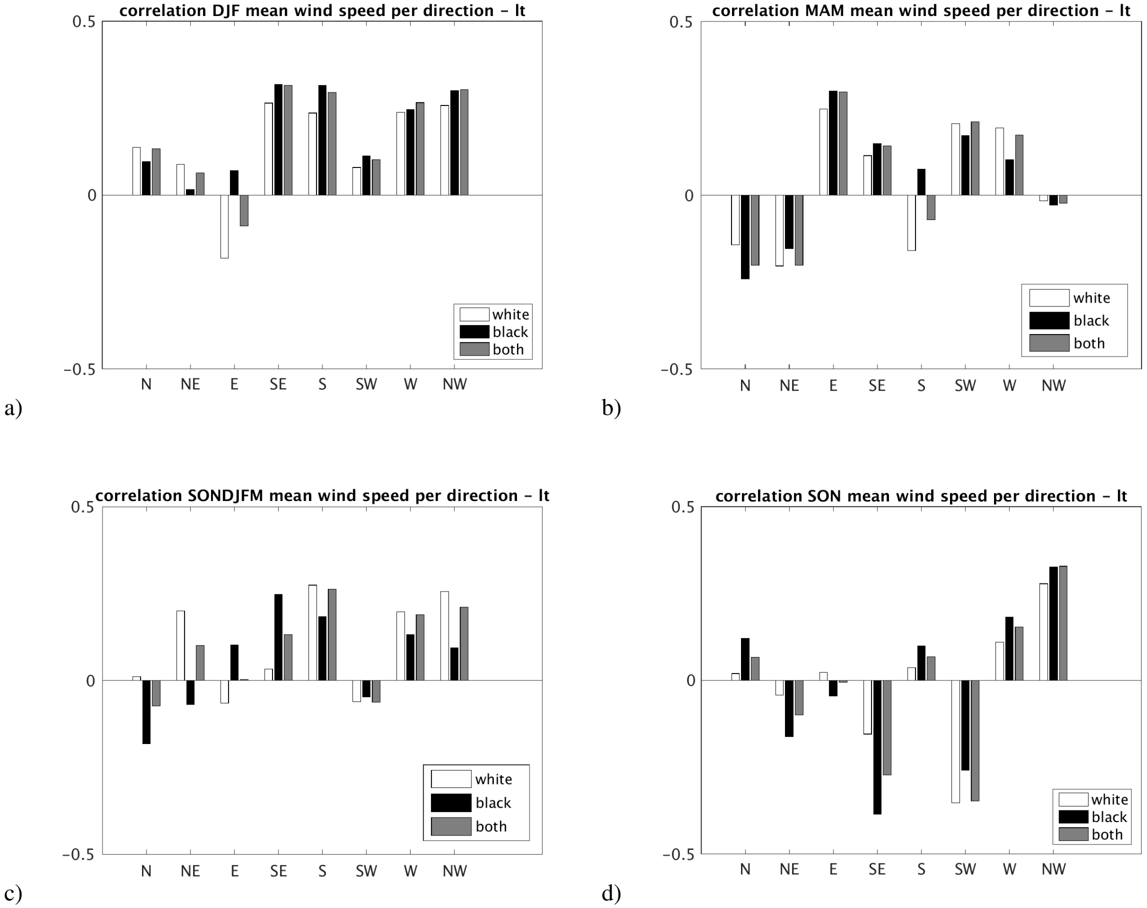


Figure 4. Correlation between the number of days per wind direction and dune thickness (lt-layer thickness) of the white layer (yellow), black layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF), spring (MAM), wind season (SONDJFM) and autumn (SON) and for eight wind directions. Correlation values marked with * are significant for the 0.05 significance level.



a)

b)

c)

d)

Figure 5. Correlation between mean wind speed and dune thickness (lt-layer thickness) of the white layer (yellow), black layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF), spring (MAM), wind season (SONDJFM) and autumn (SON) and for eight wind directions.

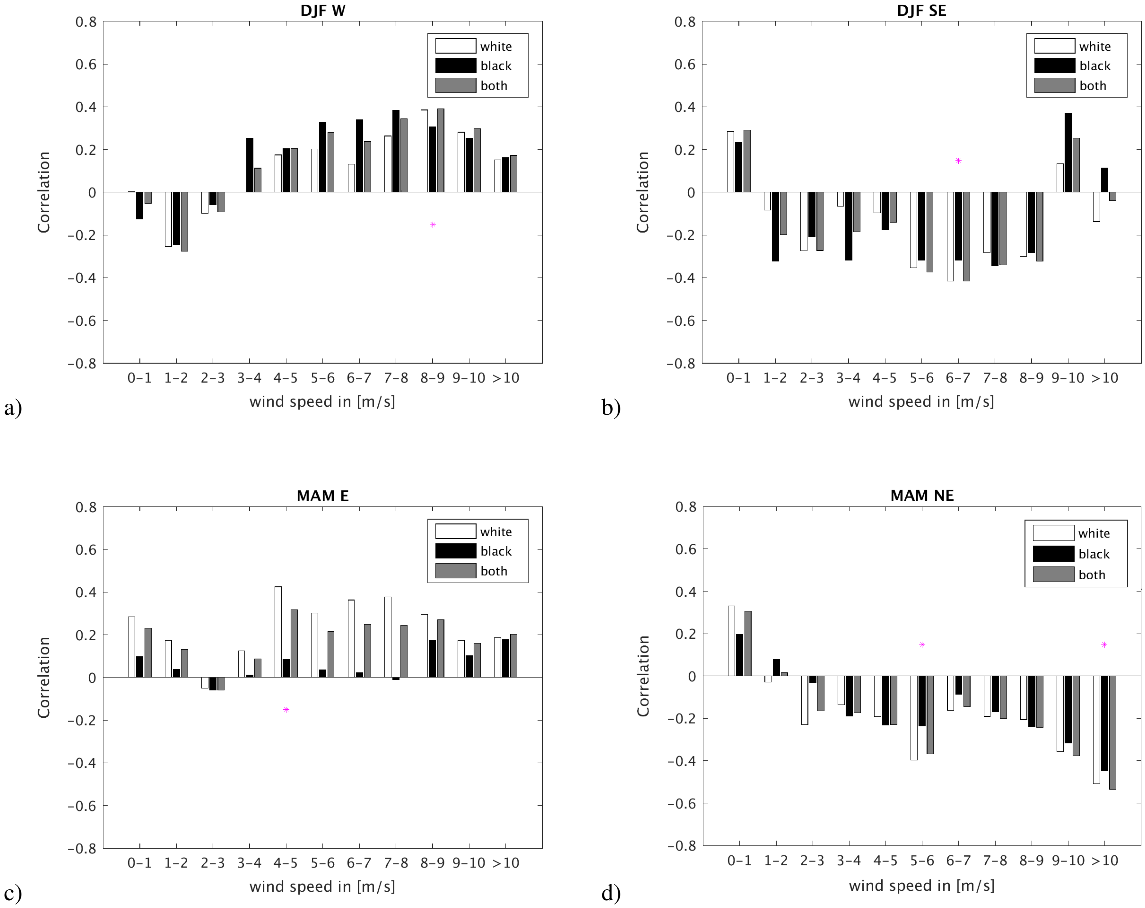
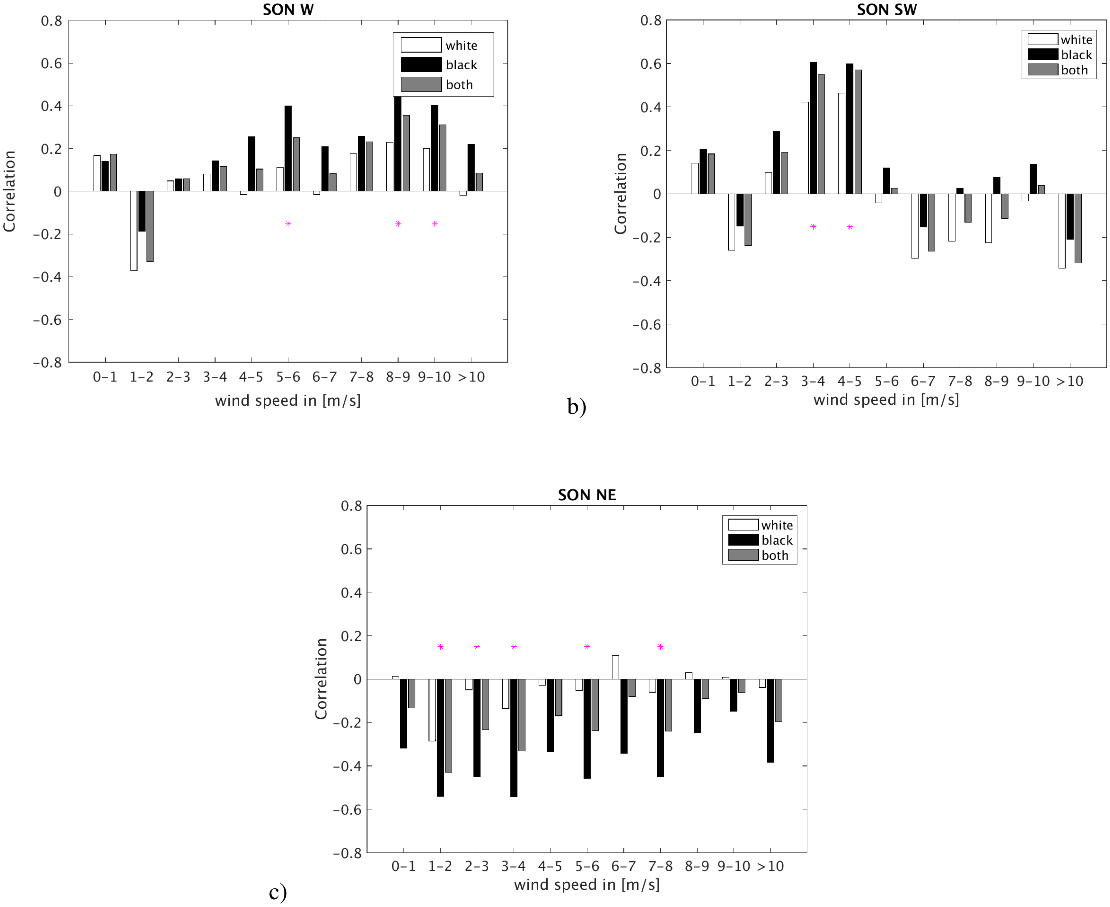


Figure 6. Correlation between the number of days per wind direction in a specified range of wind speeds and dune thickness of the white layer (yellow), black layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF; a+b) and spring (MAM; c+d) for W (a), SE (b), E (c) and NE (d) wind directions. Correlation values marked with * are significant for the 0.05 significance level.



a)

b)

c)

Figure 7. Correlation between the number of days per wind direction in a specified range of wind speeds and dune thickness of the white layer (yellow), black layer (blue) and both together (red). The correlations are shown for the seasons autumn (SON) for W (a), SW (b) and NE (c) wind directions. Correlation values marked with * are significant for the 0.05 significance level.

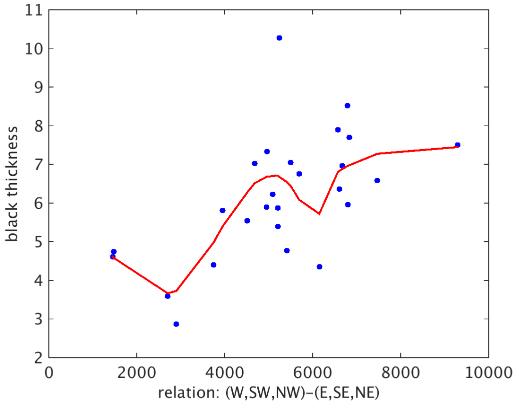


Figure 8. Scatter plot of the difference between the number of westerly (W, SW, NW) and easterly (E, SE, NE) winds and the black layer thickness. The red line shows the smoothing with a loess filtering (see Sect. 3).

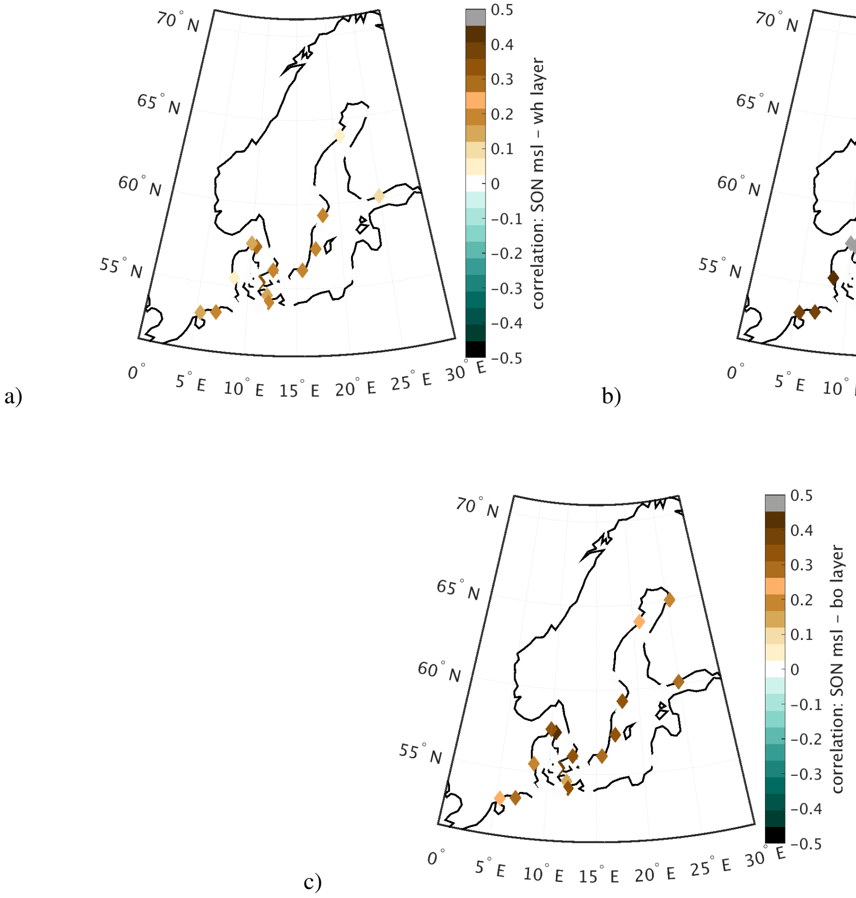


Figure 9. Correlation between mean sea level data from Baltic coastal stations and the dune layer thickness values during autumn (SON) for a) the white layer, b) the black layer and c) both layers combined.

Table 1. Correlation, root-mean-square-error and explained variance values (obtained with leave-one-out validation) used to compare predicted and actual number of days per wind direction. The prediction is based on dune thickness, which is identified to have a linear relation with SW winds between 3 and 5 m/s. Correlation values marked with * are significant for the 0.05 significance level. The last two columns show slope and intersect of the linear regression between SW winds and layer thickness if no LOOM is applied.

		correlation	rmse	exp. variance	slope	intersect
SW	white	0.28	1.93	8.07	0.37	4.22%
	black	0.63*	1.56	39.21	0.86	1.26%
	both	0.52*	1.70	27.16	0.33	2.44%