We would like to thank the reviewer Tarmo Soomere for his carefully reading and the very constructive criticism. We respond to all comments below.

RC1 (T. Soomere):

Specific major aspects

1. No information is presented about statistical significance of the presented correlations. Even though this way of categorisation of links between different quantities is basically formal and may provide false positive or negative conjectures, it is important to amend the material so that the strength of correlations is characterised by some other kind of measure with clear interpretation. Also, in some occasions other measures such as root mean square deviation or similar would be helpful to clarify the context.

> We included new figures where a '*' marks significant correlations.
> We use RMSE to compare the results derived from the linear regression model and the actual values from coastDat2.

2. The formulation of the main outcome (the existence of positive/negative correlations) is interpreted in a manner that is not really supported by the presented analysis. This first of all applies to wording like "validation" of the results. Even though the correlations in question are interesting and potentially valuable, essentially no validation is provided in the manuscript.

> We do not totally understand this comment. We use the term validation in the usual statistical meaning, i.e. the comparison between predicted and observed values in an independent data set. Our validation measures are included in Table 1 where the results of the linear regression model are compared with actual values from coastDat2. We acknowledge that the length of the record is short, and this is why we cannot split the data set in a calibration and independent validation period. This is the reason why we used the leave-one-out method. This comparison is to our knowledge an accepted (see tree ring record validations) validation measure. Perhaps the reviewer refers to another meaning of the term validation, including for instance a mechanistic explanation or comparison with a dynamical model. We now explain in the text more clearly our usage of the term validation.

3. It is questionable whether it is acceptable to rely so strongly on a source (Ludwig et al. 2016) that is currently not yet published and has thus not fully undergone quality control of the peer-review process. A partial solution would be to make this source available, e.g., via ArXiv.org or similar channels.

> Unfortunately, this is currently not possible. The manuscript is still under revision in Aeolian Research. This unfortunately precludes the publication in another platform, but we now refer to the PhD dissertation by Juliane Ludwig that is published and available on-line at the repository of the University of Hamburg

4. The use of English is generally fine but the use of several specialised terms is questionable and in some locations help from a native speaker might make the presentation more transparent and compact. The text contains numerous unnecessary repetitions, redundant words and phrases. The examples below highlight only a small selection of these, so the text should be thoroughly and entirely polished. The Abstract is far too long and contains several exact sentences from the body of the manuscript. The Discussion is basically a reformulation of work done, including assumptions, and contains no proper

discussion. The list of references systematically ignores capitalisation of proper names.

We carefully re-read the text and hope to make the necessary adjustments to avoid redundant repetitions. The abstract was rephrased and shortened. We reworked the discussion and changed capitalizations in the references.

Technical issues and recommendations for Sections 1 and 2 (pages 1–5)

Page 1, sentences on lines 3–4, 6–8, and 9 should not be part of Abstract and the rest of Abstract should also be compactified.

We rephrased and shortened the abstract.

Line 18: the expression "that this type of dunes can be validated with dendrochronological methods and derive acceptable validation values" requires complete rewriting.

Old version: “Thus, our study verifies that this type of dunes can be validated with dendrochronological methods and derive acceptable validation values as a wind proxy.”

New version: “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. ”

Line 20: " from the meteorological reanalysis" is redundant.

We changed this accordingly.

Lines 21–24: the two sentences are redundant (or packed into a few words) without any loss to the content.

We reworked the abstract in large parts and these sentences are no longer included.

Page 2, line 2: remove "Future" as the statement is valid also for the past and present

We changed this accordingly.

Line 13 "during migration" is redundant.

We removed "during migration".

Line 15: " This kind of dunes do not only exist at the Polish coast, but also ..." should be rephrased.

Old version: “This kind of dunes do not only exist at the Polish coast, but also e.g. ...”

New version: “Comparable dune systems can also be found at other coasts e.g. ...”

Line 20: it is questionable whether it is appropriate to appraise here a source that is not yet published.

Old version: “The novelty of the Ludwig et al. (2016) study lies in the focus on seasonal to annual resolution.”

New version: “The reconstruction by Ludwig (2017) is the first attempt to use dunes as wind proxies on seasonal to annual resolution. ”

Line 23 "measure device" should be corrected; also probably "step-like" is meant.

Old version: “...changes in the location of the measure device may result in very large stepchanges in the mean wind and wind variability.”

New version: “...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). ”

Page 3, lines 1–2: "instead of direct station observations " is redundant without any loss of content.

We deleted "instead of direct station observations"

The sentence on lines 7–9 is weakly (if at all) connected with the text and could be deleted without any harm to the core message.

Maybe we did not phrase this sentence clearly enough. This sentence is meant to be connected to the previous sentence that demonstrates the disadvantage of the reanalysis. The following sentence should, on the other hand, present the clear advantage of reanalysis data (homogeneity) compared to station data. We tried to rephrase it more clearly:

Old version: “Due to their use of observations, these kind of data may span a limited period in which the records can be considered homogeneous. However, the connection to observations is an advantage, as, in theory, meteorological reanalysis being close to the available - possibly sparse and incomplete - observation records, provide a multivariable data set that is complete in space and time.

New version: “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. ”

Line 10: "statistical link" sounds strange.

We changed “links” to “relationship”.

Line 11 and in many occasions below: the term "dune intervals" is, to my knowledge, not widely used in coastal science. Its classic (but perhaps partially outdated) notion is the distance between crests of two subsequent dunes. Its use in the context of this manuscript may collide with the use of "interval" in a completely different sense as intervals between glacial cycles. Thus, I strongly recommend to consider another term, and if "dune intervals" is generally used in this field of science, to bring a thorough explanation and references in order to avoid misinterpretation.

We changed “dune interval” to “dune layer”.

Line 11: "the relationships between the reconstructed wind and wind characteristics" is incomprehensible.

> Old version: "...the relationships between the reconstructed wind and wind characteristics..."
>
> New version: "...the relationships between the reconstructed and actual wind characteristics, derived from the reanalysis,..."

Line 12: say just "speed" instead of "wind speed".

> We changed this accordingly.

Lines 20–22: such short introductions to chapters are basically fine, but they also serve as partial repetitions of the material in Introduction and could be merged with the information on lines 17-18.

> We agree with the reviewer. This might be merged into the last part of the introduction. Nevertheless, we personally think that a short "introduction" to the second section may be helpful to lead the readers, especially as this section includes several subsections with important information.

Line 25: the sentence is pure repetition of material on lines 3-4 and should be omitted.

> We removed this sentence.

Line 29: "changes" requires "are".

> We changed this accordingly.

Lines 30–31: the length of the coastDat2 does not make it homogeneous, so please reformulate the claim.

> Old Version: "In our case, the coastDat2 data set covers the period from 1948 onwards. Thus, it can be considered to be largely homogeneous."
>
> New Version: "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."

Line 32: the text says already fourth time here that coastDat2 is used in the presented manuscript.

> Old Version: "In this study, the analysed data set is coastDat2, a result of..."
>
> New Version: "CoastDat2 is a result of..."

Page 4, line 1: "COSMO-CLM" should appear only once.

> We changed this accordingly.

Line 3: a comma before the equality sign should be deleted, and one should say "levels".

We changed this accordingly.

Line 5 " on hourly temporal resolution": say simply "hourly".

We changed this accordingly.

Line 8: delete " (used to generate coastDat2)" as this information was already provided.

We changed this accordingly.

Line 10 and several other occasions: "comparable" is not a good adjective to characterise the match of two quantities; please use some more exact quantification.

We changed “comparable” in the mentioned occasion to “equal” and in the other cases to “similar”.

The sentence on lines 18-20 seems not to carry any new information and could be deleted.

We deleted the mentioned sentence.

Line 20: consider replacing "And although there exist" by "Although there exists".

We changed this accordingly.

Line 22: consider replacing "be dependent" by "depends".

This is just personal taste. We would prefer to keep “be dependent”.

Lines 23-24: remove " Regarding temperature," and " Regarding precipitation".

We changed this accordingly.

Line 25: remove " obtained with coastDat2 data" as it is clear from the context from where the results stem.

We changed this accordingly.

Page 5, lines 5–6: consider replacing the unclear phrase " which mostly occur and are strongest" by "which are most frequent and strongest".

We changed this accordingly.

Lines 7–8: delete "due to sediment deposition on its lee side" as this is clear from the first part of the sentence.

We deleted “due to sediment deposition on its lee side”.

Lines 11–12: the claim " Nevertheless, winds are the most important drivers of aeolian processes in general" is true by definition (Aeolus was the Greek god of the winds) and should be removed from here.

The sentence was removed.

Line 12: remove "amount".

We changed this accordingly.

Line 15: please provide standard deviations of the seasonal and annual temperatures; otherwise the claim that the area undergoes only small annual temperature variations is not justified.

We included standard deviations.

Lines 18–19: as above, please consider whether "interval" is the appropriate term here; also rephrase "intervals with interspersed intervals of heavy minerals".

All "intervals" were replaced.
Old version: "...intervals with interspersed intervals of heavy minerals "

New version:"...layers with interspersed deposits of heavy minerals."

Lines 21–22: the sentence almost exactly repeats material on lines 6-7.

Yes, it is a little repetition about the sand movement direction. However, this sentence also adds two new pieces of information. One is that both sand materials are transported together. The second is that it provides the main wind directions of transport and the seasons in which they occur. Therefore we would like to keep the sentence as it is.

Lines 24–25: remove " GPR has already been used to analyse dunes by ".

We changed this accordingly.

Line 27: it is not clear what "its thickness" means (of layers, not the code?).

Old version: "This alternating pattern is termed sedimentary bar code (Fig. 1), and its thickness varies from year to year."

New version: "This alternating pattern is termed sedimentary bar code (Fig. 1), and the thickness of the individual bars varies from year to year."

Line 28: either "not linear"(without a hyphen) or "non-linear"; please notice that these categories are different.

We changed this to "not linear".

Line 29: remove "rather".

We removed "rather".

Line 31: consider saying "cluster" instead of "dune complex composed".

We changed this accordingly.

Page 6: "progradation" generally cannot be "higher" but should be faster (or its rate may be higher).

We changed “higher” to “faster”.

Sections 3–5 the manuscript contain a more or less similar proportion of small issues per page but I do hope that they will all be removed in the substantially revised version of the paper.

We re-read and reworked the manuscript and hope to have eliminated those small issues.

We would like to thank the reviewer and the editor for their carefully reading and the very constructive criticism. We respond to all comments below.

RC2:

In my opinion, the manuscript offers an interesting evaluation of such a sand layer structure as a temporally high resolution proxy for wind. With a correlation of up to 0.63, the barcode structure of the sand dunes provides a valuable wind proxy. While the novelty of using such a barcode structure as wind proxy and reasonable correlations are promising, the paper requires some significant re-work wrt. to the clarity of text, the paper’s structure and the robustness of statistical evaluation. I therefore think the manuscript may be published after major revisions.

Major comments:

Text: The structure of the manuscript, the motivation for this study and the scientific context should be improved (see below).

Statistics: The authors present an interesting evaluation but without a proper validation. Although the sample size is relatively small, significance testing (p-values) would be important to provide at least some estimate about the robustness of the results/methods. The author’s attempt to test the link between temperature or precipitation and sand mobilization/transport and hence a potential disturbance of the wind signal by other factors is, not fully convincing. The causal link remains unclear here whether temperature and precipitation simply co-vary with wind or really affect sand mobilization. This is a serious problem for most other paleo-wind proxies as well as e.g. dry periods may be confused with stormy periods or wet periods simply co-vary with windy periods etc. This aspect should be addressed or at least discussed in more detail. The use of a LOESS regression is not convincing given the low sample size and unclear relation. Correlations for the whole wind season should be added as the barcode has an annual resolution.

> Response to the general comments, further elaborated in the response to the specific comments:
> We include now the statistical significance of the correlations
> We did try to disentangle the role of temperature and precipitation from that of the wind by estimating correlations excluding or including frost days. The differences in those correlations were discussed as well.
> There seems to be a misunderstanding about the rationale of using the loess regression and we hope it is now more clear in the revised version

Specific comments:

Abstract:
One or two leading sentences, why it is important to study the wind climate in the past and why it is important to use proxies even for shorter timescales, would make the paper more appealing to read. The abstract should be improved by focusing on main aspects of your work only, without too much detail.

> We rephrased and shortened the abstract and hope it now reads more clearly and focused.

Introduction:
Generally, the structure here is a bit chaotic. I would recommend to re-write it following a clear structure like why it is important to study the wind climate, what has been done already using which data or methods (the references on page 2-3), what are the conclusions and open questions from these studies so far (see e.g. Rutgersson et al. 2015; Feser et al. 2015; Christensen et al. 2015 for reviews), the problems of the data/methods and need for using different proxies, how Aeolian transport can be used here followed by here we present...or similar.

> We have re-structured the introduction according to the suggestion of the reviewer.

Page 2, line 1-2: References needed, many studies investigated it already (e.g. Christensen et al. 2015 for references)

> We have added a reference.

Page2, line 4: References needed, this has been done already (e.g. Rutgersson et al. 2015; Feser et al. 2015)

> We have added a reference.

Page 2, line 23-24: Not only the location changes, a reference could be e.g. Lindenberg et al. 2012

> We have added a reference.

Page 2, line 29 to Page 3, line 9: This is all quite technical for an introduction. What do these studies tell us about past wind climates? What are their main conclusions so far? What are open questions a dune proxy may help to answer?

> We hope to have addressed these questions in the revised version.

Page 3, line 2-9: A detailed explanation for this data product is not really needed here. A short note might be more interesting here like e.g. that even the use of long-term reanalysis data like 20CR has been shown to be problematic regarding long-term trends (Krueger et al. 2013 etc.) and dune records may therefore help to get more consistent results.

> Since this is a quite interdisciplinary work we think it is useful to explain reanalysis data, even as early as in the introduction. The readers not used to handle model data may miss the difference between free-running climate simulations and meteorological reanalysis, and the links between the latter and observations. Hence, we would prefer to keep this explanation.
> However, we added the mentioned short note regarding 20CR.

Data and area
Acknowledging the geological context of a site-specific analysis, I would suggest a classical structure 2.1 Area/Leba Dunes, 2.2 Climatological characteristics, 2.3 Meteo data, 2.4 Dunes

We changed the order accordingly.

2.1. Meteorological data
I think it is enough to write “we use a numerically downscaled reanalysis dataset … ” with two or three sentences which reanalysis and regional model, spectral nudging and resolution used in coastdat2. For details you can refer to Geyer 2014. More relevant for this study are the properties and validation of simulated wind (Weidemann 2014).

We shortened the explanation about coastDat2.

Page 3: line 29: “usually kept to a minimum”. This is not correct, all available data is used for each time step. Reanalysis hence gives the best possible estimate for each time step which may lead to artifacts if the type, quality or number of observations changes over time. Rather a frozen data assimilation scheme is used to minimize these effects. For your region and time period, all the issues are not really relevant after ~1980.

This sentence was deleted to shorten the description of coastDat2 addressing your preceding comment.

Page 4: line 12: The imperfect NCEP forcing and its coarse resolution is another relevant source of error here

We added: “Other errors may occur due to the imperfect forcing data set NCEP and its coarse spatial resolution. ”

Page 4, line 33: Could you give the typical size here (dominant sand fraction, µ m or a range)?

We added: “The sands are fine-grained (with a diameter of 0.2 to 0.3 mm (Ludwig, 2017)) and well-sorted...”

Page 5, line 16: What about wind? Reference here to Ludwig et al. for more detailed seasonal information (Fig. 5 in that paper)

We do not want to rely solely on the weather information given by Ludwig et al. (2017) as they based their conclusions on only one station, where wind from some directions is potentially perturbed by the nearby forest.
Therefore we added: “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.”

Page 5: line 28: Is there not any experimental / theoretical range giving a rule of thumb which wind speed can mobilize which grain size or mass? If so, you could use it to physically verify the realism of your statistically estimated thresholds.

We added: “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. ”

Page 5, line 31: compiled

We changed this accordingly.

Statistical Methods

It is convincing and very nicely shown, that one barcode interval reflects one year in Ludwig et al. However, the separation into junks of three months for wind is in the end subjective and artificial wrt. to the annual dune activity. Consider e.g. that your seasonal correlation analysis may suffer from intra-seasonal changes in wind activity over time (e.g. Lehmann et al. 2011). I would hence suggest to add first a correlation analysis for the whole wind year (e.g. ONDJFM). You could then replace the JJA figures in the multi plot figures 4 and 5 with the full wind season. Then you can continue and show also whether the full wind season or rather a fraction of the season yields the highest correlation.

We also re-did the analysis for the whole wind year (SONDJFM). However, the results in this case show lower correlations and less differentiated results for the black and white layer. Because one goal was to analyze seasonal differences, the seasonal analysis was retained, although the results for the whole wind year are now discussed in the manuscript.

The same applies for the wind directions. The correlations for the wind octants in combination with the small sample size in this study may be quite sensitive to small random changes to the neighboring octant (as can be anticipated from the wind rose figures in Ludwig et al.). I think you should test in addition quadrants of 90◦(e.g. W= 225-315◦or SW=180-270◦). It is certainly interesting to make the detailed tests in this study but one aim should be to find the optimal setting with the best fit to the dune data rather than limiting it to very strict seasons and directions.

The coarser separation into wind directions was, in a similar way, already prescribed by Ludwig et al. (2017), although they used a different wind data set (observations). The suggestion by the reviewer is indeed very logical, but unfortunately we face the limitation of the short record. If the wind data are further stratified according to finer directional bin resolution, the sample size for each direction bin will become really small, compromising the statistical analysis.

Page 7: line 2: Please explain in more detail how such a ratio or difference might look like and why, I cannot follow here.

We have expanded this explanation in the new version according to following scheme:
Old version: ”In addition, we try to find an optimal ratio between the number of westerly and easterly winds that better describe the thickness of the black interval.”

New version: “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. ”

What are the x-axis units in Fig. 8?

> Old figure caption: “Scatter plot of the difference between westerly (W, SW, NW) and easterly (E, SE, NE) winds and the black interval thickness. The red line shows...”
>
> New figure caption: “Scatter plot of the difference between the number of westerly (W, SW, NW) and easterly (E, SE, NE) winds and the black interval thickness. The red line shows...”

Page 7, line 3: I see the point of exploring the outcome of a LOESS fit here. But the result does not look useful. Based on Fig. 8, a linear regression (digitizing your data in Fig. 8, I got y=0.00053x+3.388; r 2=34%; p=0.0012) looks more convincing although it remains unclear to me, what it means. With the low sample size, LOESS regression is very sensitive to outliers. As it does not yield any equation, the fit cannot be reproduced by others without having the original data. I would therefore suggest to stick to a linear fit, give confidence intervals and explain the outcome.

> Maybe the reason for the application of LOESS was not clear enough in the old version of the manuscript. Our goal was to see if there is an optimal relation between westerly and easterly winds which promotes the thickness of black layers, so that smaller or larger ratios would produce also a smaller thickness. For this, we need to identify a nonlinear link between this ratio and the layer thickness. Unfortunately the obtained results are not robust so that such an optimal relation cannot be confirmed. We try to explain this more clearly in the new version. In contrast, a linear regression would not serve our purposes in this case. This is related to the previous comment of the reviewer. A linear regression would only show the influence of the difference between westerly and easterly winds. We already know that westerly winds are the driving force as the dune is moving towards the east. Hence, this would not give us new information.

Page 8, line 3: “slight positive correlation” – Which value? Give a p-value.

> Old version: “The colder seasons winter (DJF) and spring (MAM) show slight positive correlations for both intervals,...”
>
> New version: “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),...”

Page 8, line 4: “indicates an increasing bar thickness during wetter periods”. And how does that match with soil wetness and compactness mentioned before? I think this only tells you that more storms co-vary with more rain, but there is no causation more rain = more sand transport. This should be at least discussed if the low sample size does not allow a comparison like drier storm seasons vs. wetter storms seasons in comparison to the barcode. Maybe you could make a quick test for your period if/how wind above your chosen threshold is correlated with precipitation and temperature.

> We do not totally agree with the reviewer on this point, since conditional on the small sample size we have indeed attempted to separate the effect of

temperature and precipitation from the influence of wind on dune mobilization. The correlation between the layers thickness and the number of days with specific wind directions has been estimated including or excluding frost days or rainy days. As explained in the text, there are some differences in the expected direction, i.g. excluding frost days includes the correlation to the wind. This aspect is already discussed in our 'Discussion and Conclusion' section on page 11 line 24 -29. The reviewer is correct that using only statistical analysis it is not possible to totally disentangle the effect of wind and of rain if both co-vary, and when the differences in correlations are not very big, but In our discussion we do rely on field measurements and physical insights.

We added another sentence (underlined) and hope to better address this comment:
“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 interval. 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 intervals.”

Page 8, line 5: “non-negligible” – Please give a value and p-value here. Why only the black?

Old version: “Autumn is the only season showing some non-negligible correlation for black intervals (0.33).”

New version: “Autumn is the only season showing a non-negligible, albeit not significant correlation for black layers ($r=0.33$; $p=0.09$). ”

Page 9, line 17: “this season and direction” – It makes sense to use the best combination but you should reconsider whether the best combination might not be the full wind season (e.g. SONDJFM) as mentioned before.

We calculated the results for the whole wind year (SONDJFM). However, the whole wind year results show lower correlation values and less differentiated results for the black and white layer. Because one goal was to analyze seasonal differences the seasonal analysis was retained and the results for the whole wind year are mentioned in the text.

As you mentioned the dunes in Lithuania, it would make sense to also provide your regression model for re-use or reproduction of results.

We added slope and intersect values in Table 1.

Page 10, line 2: To which extent could you use the deviation of the black-white ratio from being relatively equal (~1) to say sth. about years of more easterly or more westerly years? I did not really get that point from the manuscript.

> This part of the manuscript is about the question whether there exist an optimal ratio between westerly and easterly winds which might promote the thickness of the black layer. We wrote on page 7, line 5-7: "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 smaller or larger ratios would produce thinner or thicker black layers."
> So this section is not about the black-white ratio, but on the possibility to record the ratio westerlies-to-easterlies on the thickness of the black layer.

Page 10, line 10-13: This fit makes little sense. Please replace LOESS with a linear fit and give the equation, r^2 and p-value (should be very close to what I wrote above). There is indeed no optimum (why should there?) but a linear fit is highly significant. What could that mean?

> Please, see answer to this comment above.

Page 10, line 17-20: The link between wind climate and sea-level is a bit more complicated depending on the region and timescale of wind/sea-level co-variations. The description here is too vague and some references should be given in addition. Note that most readers do not know anything about sea-level variations of the Baltic Sea.

> This section was indeed too short in the old version and we expanded it to make it clearer also for readers not familiar to sea-level variability. Originally, it was intended to indirectly support the link between the dune layers and wind, in view of the dearth of wind observations in this area.

Page 10, line 29: And how does the link of the wind forcing look like= How can it be explained?

> We hope that the previous addition about the link between wind and Baltic Sea level already clarifies this question .

Page 11, line 15-16: Rather than being suspicious about coastdat2 here, I would highlight that the positive link to sea-level is very useful as sea-level data goes further back in time than reanalysis and might be also more reliable than spurious trends in 20CR (Krueger et al. 2013), which do not affect yet the short period in this study.

> We agree with the reviewer and added information about the longer time span of sea-level data. Nevertheless in our case it was not the intention to use these data, because the dunes only span 26 years. We wanted to make our results more robust by also shiwung the link of the dune layers to other observational data in addition to the reanalysis. Regarding the 20CR reanalysis, we think another note regarding 20CR might be confusing.

Page 11, line 25-26: Very speculative. With "some rain" it might be true but not with more rain. If the “some rain” effect would be important, you should expect to get a negative correlation in your evaluation, but it is positive. I would add that more rain might just co-vary with more windy conditions. The mentioned erosion is also a very good point here.

> We were here quoting a previous study by Borówka, so that this reasoning is not entirely based on our speculation. We have rephrased the paragraph:
> Old version: “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 the dune processes, depends on the seasonal wind conditions.”
>
> New version: “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. ”

Page 12, line 5: The p-values and adding an analysis of the full wind season ONDJFM might lead to an even more robust conclusion.

> For the sake of clarity we would rather prefer to mark significant (by the 0.05 significance level) results with a *. This was also a suggestion of the first reviewer.

Figures:
Fig. 3+4+5: Use consistent tick marks on the y-axis. What means “- mv” in the figure titles? For all bar charts, you could consider using white, black and grey for white, black and mixed intervals. This would make it more intuitive.

> We will change this accordingly.

Figure 8: I would rather use a linear fit. What are the units on both axis?

> Please see answers above.

Figure 9: If possible, use bigger symbols for the gauge locations.

> We enlarged the symbols.

Table 1: Why not give the regression model (slope, intersect) in addition, also p-values?

> We added the slope and intersect of our regression model. Regarding p-values, please, see above.

Additional references:

Christensen, O. B.; Kjellström, E. & Zorita, E.: Projected Change—Atmosphere. In: The BACC II Author Team (Eds.): Second Assessment of Climate Change for the Baltic Sea Basin, Springer International Publishing, 2015, 217-233, doi:10.1007/978-

3-319-16006-1_11

Lehmann, A.; Getzlaff, K. & Harlaß, J. (2011): Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. Clim. Res., 46, 185-196, doi:10.3354/cr00876

Lindenberg J, Mengelkamp H-T, Rosenhagen G (2012): Representativity of near surface wind measurements from coastal stations at the German Bight. Met Z 21:99-106.

Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M., Bärring, L., Briede, A., Claremar, B., Hanssen-Bauer, I., Holopainen, J., Moberg, A., Nordli, O., Rimkus, E., and Wibig, J.: Recent Change – Atmosphere. In: The BACC II Author Team (Eds.): Second Assessment of Climate Change for the Baltic Sea Basin. Springer International Publishing, 2015, 69-97, doi:10.1007/978-3-319-16006-1_4
Interactive comment on Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-71, 2016.

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. ~~**Dunes as wind proxies are not a totally new idea to the scientific community, but existing studies have so far**~~

The present analysis is based on the dune record derived from geo-radar measurements by ~~Ludwig et al. (2016)~~(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. ~~Here, we present a detailed statistical analysis of~~ 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 ~~. Therefore we based our analysis on~~ we used a gridded regional meteorological reanalysis data set (coastDat2) ~~over~~ 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 ~~number~~ frequency of days with ~~west and south-west wind directions above a pre-defined wind speed threshold and the~~ specific wind conditions in a given season and dune migration velocities derived for that season. To some extent, the dune ~~intervals~~ records can be seen analogous to ~~a tree ring widths~~tree ring width record, and hence we used a proxy-validation method usually applied in dendrochronology~~when the available meteorological record is short~~, namely the cross-validation with the leave-one-out-method~~. This~~ , when the observational record is short. The revealed correlations between the wind record from the reanalysis and the ~~reconstructed~~ wind record derived from the dune structure is in the range ~~of~~ between 0.28 and 0.63 ~~. Thus, our study verifies that dendrochronological methods can be applied to validate migrating dunes as a wind proxy, deriving acceptable validation values.The identified link between the dune annual layers and wind conditions from the meteorological reanalysis was additionally supported by the co-variability between dune layers and sea-level variations in the Southern Baltic Sea. Baltic Sea level variability in winter time is known to be strongly driven by westerly winds over this~~

~~region. These results, therefore, provide an independent support, solely based on observations, of the link between annual dune layers and prevailing wind conditions~~yielding similar statistical validation skill, as dendroclimatological records.

1 Introduction

~~Future climate~~ 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 ~~. To analyse~~ (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 et al. (2016)~~ 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~~reflecting~~ . This bar code reflects the width of different dune ~~intervals~~ layers that are annually formed. ~~This present study statistically analyzes the link between this new proxy record, and wind~~

~~conditions in order to evaluate and calibrate the potential to reconstruct past wind conditions. Aeolian processes are the result of interactions between climatic factors like temperature, precipitation or wind and land surface. Therefore it can be assumed that coastal dunes include information about changes of these atmospheric parameters . The analysed dunes migrate and are composed of~~ These dunes migrate by the action of wind and in the processes of migration alternating layers with varying sediment and grain-size properties ~~, which~~ are formed. These layers, therefore, contain information about how the dune structure responded to past wind conditions~~during migration~~. 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). ~~This kind of dunes do not only exist at the Polish coast, but also~~ 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 ~~novelty of the Ludwig et al. (2016) study lies in the focus~~ reconstruction by Ludwig (2017) is the first attempt to use dunes as wind proxies on seasonal to annual resolution.

~~Proxy-based reconstructions of wind conditions may offer the advantage of a better temporal homogeneity over long-periods compared to observational records, for which changes in the location of the measure device may result in very large step-changes in the mean wind and wind variability. In addition, dune-based records may help fill spatial gaps in observational data sets, which might be of special interest for analyses of a changing wind climate. For example, many wind analyses using pressure measurements as wind proxy, to take advantage of the more homogeneous properties of pressure readings over time . Other studies try to infer information of past wind events from documented damages on dikes or forests .Many studies have addressed past changes in wind climate based on different approaches. Some analyse wind speed changes and some wind direction changes , both on different time scales and with different data sets. These studies include analyses of observations derived from instrumental records , which are likely not totally consistent due to instrumental changes or relocations. Other studies have used meteorological reanalysis , which should in principle overcome the inhomogeneity problem, instead of direct station observations~~ 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 ~~with a combination of~~ by combining weather information (e.g. surface weather stations, satellites, etc.) of past weather ~~records, and simulations with~~ observations, and a meteorological forecast model. These simulations obtained with data-assimilation assimilate the available observational records to produce a gridded, ~~homogeneous~~ 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, ~~these kind of data may span a limitedperiod in which the records can be considered homogeneous. However~~the time span covered by reanalysis is also limited. On the other hand, the connection to observations ~~is an advantage, as, in theory, meteorological reanalysis being close to the available - possibly sparse and incomplete - observation records, provide a multivariable data set that is complete~~

in space and timemay 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 links relationship at interannual time scales between mean seasonal wind conditions in different seasons and the annual dune intervalslayers, and assess the relationships between the reconstructed wind and wind characteristics and actual wind characteristics, derived from the reanalysis, with a focus on wind direction and wind 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. Although the analysed dune archive covers only a shortperiod Unfortunately, the period covered by this dune system is rather short, from 1987 to 2012 we 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 adopted 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

In the following the reanalysis product coastDat2, used in this study, is introduced and briefly discussed. FurthermoreHere, 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. (2016).

2.1 Meteorological data

For the main investigation, wind data from the regional meteorological reanalysis data set coastDat2 is used. The meteorological reanalysis is the result of a model simulation in which observations have been assimilated. In contrast to the operational reanalysis used for real weather forecasts, in which the model has been continuously improved through time, the meteorological model is the same for the whole period of reanalysis. The number of observations assimilated in the reanalysis may change over time as well, but since one of the aims of meteorological reanalysis is to produce a homogeneous data set, the changes in the number and coverage of observations is usually kept to a minimum, at least over several decades. For reanalysis that span longer periods, like the 20CR product covering the last 150 years, this condition cannot be fulfilled. In our case, the coastDat2 data set covers the period from 1948 onwards. Thus, it can be considered to be largely homogeneous. In this study, the analysed data set is Ludwig et al. (2017). In the following the reanalysis product coastDat2, a result of a regional climate simulation with the non-hydrostatic operational weather prediction model COSMO-CLM in CLimate Mode (COSMO-CLM,) driven by meteorological initial and boundary conditions from the global low-resolution NCEP/NCAR Reanalysis 1 data (1948-present;

T62 (1.875°,≈ 210km), 28 level,). 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 on hourly temporal resolution. However, the information derived from the dunes cannot provide such high temporal resolutions, hence, we decided that daily averaged data is sufficient. compared the measured wind conditions at three German coastal stations (Kiel, Warnemünde, Kap Arkona) with the COSMO-CLM (used to generate coastDat2) model output. He reported a slight systematic overestimation of wind speed, but good agreement regarding daily mean wind speeds, generally acceptable results regarding the daily wind speed variability - notwithstanding an underestimation of high wind speeds - and comparable wind directions. 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. Although meteorological reanalysis are close to 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. 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 , especially in autumn and winter, and hence can be seen as a good proxy regarding wind in this region. The reason for not using direct observational data for the calibration and verification of our analysis are the mentioned inhomogeneities of such data sets especially with regard to wind information. And although there exist 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. 2016).The relationship between wind and sand migration may additionally be dependent on other atmospheric parameters, like precipitation and temperature. Regarding temperature, we used the daily mean 2-meter temperature from coastDat2. Regarding precipitation we used the daily sum of total precipitation from coastDat2, which includes convective and large-scale precipitation as well as snow. The results obtained with coastDat2 data were also confirmed with precipitation data provided by the Climate Research Unit . This latter gridded data set is the result of a spatial interpolation of station data. The obtained results were found to be comparable (not shown)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. (2016) 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 ~~mostly occur~~ 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)~~due to sediment deposition on its lee side~~. Hence, the stronger or more frequent westerly winds are, the more sand is transported to the lee side of the dunes, which also ~~leads to~~ 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. ~~Nevertheless, winds are the most important drivers of aeolian processes in general.~~ Borówka (1980) reported the mean annual total precipitation ~~amount~~ 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 ~~intervals~~ layers dominated by light quartz grains and ~~intervals with interspersed intervals~~ layers with interspersed deposits of heavy minerals. Both ~~intervals~~ layers are caused by seasonally changing wind conditions (Borówka, 1980). The quartz ~~interval~~ 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).~~GPR has already been used to analyse dunes by .~~

~~Ludwig et al. (2016)~~ Ludwig et al. (2017) showed that a quartz-dominated ~~interval and an interval~~ layer and a layer enriched in heavy minerals represent a whole year. This alternating pattern is termed sedimentary bar code (Fig. ~~1), and its thickness~~ 1). The thickness of the individual bars varies from year to year. The link between layer thickness and wind is ~~not-linear~~not linear, as the grain mobilization requires ~~winds~~ 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 ~~rather~~ 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. (2016) analysed a dune complex composed of six~~ Ludwig et al. (2017) analysed a cluster of five dunes, providing individual bar codes that were later ~~complied~~ 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 higher 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 validation 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 dataand , 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 ($1.875^\circ \approx 210km$), 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 ~~focuses mainly~~ 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 ~~intervals~~ 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 ~~method to validate the statistical model~~validation method, all observations except one are used to ~~calibrate the~~ 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 ($\tilde{y}$), which can be compared to the actual values (act(y)) derived from coastDat2. We ~~compare both~~ 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 we calculate , and the correlation coefficient between predictand and actual values.

In addition, we try to find 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 that better describe which promotes the thickness of the black intervalblack 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 depend 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.

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

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

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 intervals 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

As already mentioned, the The dunes in the study area consist of alternating intervals layers with different sedimentary characteristics which are termed "bar-code". Quartz-dominated intervals layers are imaged by white bars and have a mean thickness of 6.37 m. The black bars (intervalslayers) 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 intervals layers corresponds to the annual cycle in the meteorological characteristics and this allows for the dating of each pair of intervalslayers. In the study area, the time period covered by the ~~intervals~~ layers formed in the dunes span the ~~years~~ period 1987-2012.

The thickness of both type of ~~intervals varies~~ layers varies from year to year, but not independently of each other~~, as the~~. The thickness of the black and white ~~intervals correlates with~~ 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 ~~intervals~~ 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 ~~intervals~~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 ~~interval~~ layer thickness. Autumn is the only season showing ~~some~~ a non-negligible, albeit not significant correlation for black ~~intervals (~~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 ~~intervals~~ 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. ~~1. The~~ One measure is the mean wind speed per wind direction calculated only in the days with mean wind from that particular wind direction. ~~2. The~~ 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 ~~to be~~ as the least effective season for sand transport regardless of the ~~wind condition definition~~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 ~~interval~~ 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 ~~interval~~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 ~~intervals~~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 ~~be also~~ also be seen for autumn, especially for the black ~~interval~~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 ~~not only erode~~ 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 ~~interval~~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 ~~interval~~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 ~~interval~~ 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 ~~interval~~ layer thickness as predictor and wind speed as predictand. For SW winds correlations are highest for wind speeds from 3 to 5 m/s (~~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 ~~interval~~ layer is tested with the leave-one-out-method (~~See~~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 ~~comparable results~~ results that are similar to accepted validation values ~~of~~ in dendrochronological analyses.

We see a strong positive (negative) connection between the migration velocity of the black ~~interval~~ 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 ~~intervals~~ 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 ~~interval~~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. ~~As already mentioned, westerlies transport white and black particles together to the east, where they deposit and build a new interval. Easterly winds on the other hand~~ Easterly winds winnow only the lighter white grains and transport them backwards to the west, hence a black ~~interval~~ layer forms. This effect suggests that there might be an optimal ~~difference~~ ratio of days with west and east winds per year that results into a thicker black ~~interval~~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 ~~interval~~ layer thickness per year (~~s.~~ 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 ~~should~~ 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 ~~interval~~ 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 ~~, as described before, derived due to~~ 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

~~However, to show~~ 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 ~~is~~ 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 ~~correlation~~ 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 ~~a link between both through~~ 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 ~~validated~~ provides a more quantitative support of the migrating coastal dunes, identified by a geological analysis of ~~Ludwig et al. (2016) as a new~~ 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 ~~comparable to meteorological~~ 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. (2016)~~ 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. (2016)~~ 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. ~~This result~~ 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 ~~with the help of the~~ 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. ~~Ludwig et al. (2016)~~ 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 ~~interval. This~~ 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 ~~intervals~~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 ~~interval~~ 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 ~~interval~~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 ~~comparable~~ 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 ~~intervals~~ 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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References

Alexandersson, H., Tuomenvirta, H., Schmith, T., and Iden, K. (2000). Trends of storms in nw ~~europe~~ Europe derived from an updated pressure data set. *Climate Research*, 14:71 – 73.

Andersson, H. C. (2002). Influence of long-term regional and large-scale atmospheric circulation on the ~~Baltic~~ Baltic sea level. *Tellus A*, 54:76–88

Bierstedt, S. E., Hünicke, B. and Zorita, E. (2015). Variability of wind direction statistics of mean and extreme wind events over the Baltic Sea region. *Tellus A*, 67, 29073

Birks, H. J. B. (1995). Quantitative palaeoenvironmental reconstructions. *Maddy, D. and Brew, J. S., editors; Statistical modeling of Quaternary Science Data, Technical Guide, Quaternary Research Association, Cambridge*, 5:161–254.

Borówka, R. K. (1979). Accumulation and redeposition of eolian sands on the lee slope of dunes and their influence on formation of sedimentary structures. *Quaest. Geogr.*, 5:5–22.

Borówka, R. K. (1980). Present day dune processes and dune morphology on the Łeba barrier, polish coast of the baltic. *Geografiska Annaler. Series A, Physical Geography*, 62(1/2):75–82.

Borówka, R. K. (1995). Dunes on the Łeba barrier - their history and dynamics of present-day aeolian processes. *J. Coastal Res.*, 22:247–251.

Borówka, R. K. and Rotnicki, K. (1995). Balance of the aeolian sand transport on the beach and the problem of sand nourishment of the active dune field on the Łeba barrier. *J. Coastal Res.*, 22:257–265.

Bristow, C., P. J. and Goodal, T. (1996). Internal structure of aeolian dunes in ~~abu dhabi~~ Abu Dhabi determined using ground-penetrating radar. *Sedimentology*, 43:995–1003.

Bräuning, A. and Mantwill, B. (2004). Summer temperature and summer monsoon history on the ~~tibetan plateau~~ Tibetan Plateau during the last 400 years recorded by tree rings. *Geophys. Res. Lett.*, 31:L24205.

Buynevich, I. V., Bitinas, A., and Pupienis, D. (2007). Lithological anomalies in a relict coastal dune: Geophysical and ~~paleoenvironmental~~ Paleoenvironmental markers. *Geophys. Res. Lett.*, 34:1–5.

Chaverot, S., Hequette, A., and Cohen, O. (2008). Changes in storminess and shoreline evolution along the northern coast of ~~france~~ France during the second half of the 20(th) century. *Zeitschrift ~~Fur~~ Für Geomorphologie*, 52:1–20.

Clemmensen, L. B., Andreasen, F. andNielsen, S. T., and Sten, E. (1996). The late holocene coastal dunefield at ~~vejers, denmark~~Vejers, Denmark: characteristics, sand budget and depositional dynamics. *Geomorphology*, 17:79–98.

Clemmensen, L. B., Hansen, K. W. T., and Kroon, A. (2014). Storminess variation at ~~skagen, northern denmark~~ Skagen, northern Denmark since ad 1860: Relations to climate change and implications for coastal dunes. *Aeolian Research*, 15:~~101–112.~~ 101–112.

Compo, G.P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, O., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D., and Worley, S. J. (2011) The Twentieth Century Reanalysis Project. *Quarterly J. Roy. Meteorol. Soc.*, 137:1–28.

Costas, I. (2013). *Climate Archive Dune*. PhD thesis, Hamburg University.

Christensen, O. B.; Kjellström, E. and Zorita, E. (2015). Projected Change—Atmosphere. In: The BACC II Author Team (Eds.): Second Assessment of Climate Change for the Baltic Sea Basin. *Springer International Publishing*, 217–233.

De Kraker, A. M. J. (1999). A method to assess the impact of high tides, storms and storm surges as vital elements in climatic history. the case of stormy weather and dikes in the northern part of ~~flanders~~Flanders, 1488 to 1609. *Climatic Change*, 43:287–302.

Dee, D., Fasullo, J., Shea, D., Walsh, J., and the National Center for Atmospheric Research Staff (Eds). The climate data guide: Atmospheric reanalysis: Overview & comparison tables. Retrieved from https://climatedataguide.ucar.edu/climate-data/atmospheric-reanalysis-overview-comparison-tables.

Ekman, M. (2007). A secular change in storm activity over the Baltic Sea detected through analysis of sea level data. *Small Publ. Hist. Geophys.* 16

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R., and Xia, L. (2015). Storminess over the ~~north atlantic and northwestern europe1000~~North Atlantic and northwestern Europe1000a review. *Q.J.R. Meteorol. Soc.*, 141:350–382.

Franzén, L. G. (1991). The changing frequency of gales on the swedish west coast and its possible relation to the increased damage to coniferous forests of southern ~~sweden~~Sweden. *Int. J. Climatol.*, 11:769–793.

Geyer, B. (2014). High resolution atmospheric reconstruction for ~~europe~~ Europe 1948–2012: coastdat2. *Earth Syst. Sci. Data.*, 6:147–164.

Girardi, J. D. (2005). A ~~gpr~~ GPR and mapping study of the evolution of an active parabolic dune system. Master's thesis, Napeague New York. Stony Brook University, Dept. of Geosciences.

Gulev, S. K., Zolina, O., and Grigoriev, S. (2001). Extratropical cyclone variability in the northern hemisphere winter from the ~~ncep~~NCEP/~~ncar~~ NCAR reanalysis data. *Climate Dyn.*, 17:795 – 809.

Hünicke, B. and Zorita, E. (2008). Trends in the amplitude of Baltic Sea level annual cycle. *Tellus A*, 60:154–164

Hünicke, B., Zorita, E., Soomere, T., Madsen, K. S., Johansson, M., and Suursaar, Ü. (2015). *Second Assessment of Climate Change for the Baltic Sea Basin*, chapter Recent Change—Sea Level and Wind Waves, pages 155–185. Springer International Publishing.

Jaagus, J. and Kull, A. (2011). Changes in surface wind directions in ~~estonia~~ Estonia during 1966 - 2008 and their relationships with large-scale atmospheric circulation. *Estonian Journal of Earth Sciences*, 60:220 – 231.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D. (1996). The ~~ncep~~NCEP/~~ncar~~ NCAR 40-year reanalysis project. *Bull Am Meteorol Soc*, 77:437–471.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woolen, J., Chelliah, M., Ebiszusaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., , and Fiorino, M. (2001). The ~~ncep~~NCEP/~~ncar~~ NCAR 50-year reanalysis: Monthly means cd–rom and documentation. *Bull. Am. Meteorol. Soc.*, 82:247–267.

Krueger, O., Schenk, F., Feser, F., and Weisse, R. (2013). Inconsistencies between long-term trends in storminess derived from the ~~20cr~~ 20CR reanalysis and observations. *J. Clim.*, 26:868–874.

Krueger, O. (2014) The Informational Value of Pressure-Based Proxies for Past Storm Activity. *Technical report*, HZG Report.

Lancaster, N. (1994). Controls on aeolian activity: some new perspectives from the ~~kelso dunes, mojave desert, california~~Kelso dunes, Mojave desert, California. *Journal of Arid Environments*, 27:113–125.

Lehmann, A., Getzlaff, K., and Harla, J. (2011). Detailed assessment of climate variability of the ~~baltic~~ Baltic sea area for the period 1958-2009. *Clim. Res.*, 46:185 – 196.

Ludwig, J. (2017) Climate Signals in Coastal Deposits. Dissertation, Universität Hamburg, Fachbereich Geowissenschaften, http://ediss.sub.uni-hamburg.de/volltexte/2017/8258/pdf/Dissertation.pdf

Ludwig, J., Lindhorst, S., Betzler, C., Bierstedt, S. E., and Borówka, R. K. Annual wind climate reconstructed from coastal dunes (~~leba, poland~~Łeba, Poland). Aeolian Research (~~2016~~2017) under revision.

Matulla, C., Schöner, W., Alexandersson, H., von Storch, H., and Wang, X. L. (2007). European storminess: late nineteenth century to present. *Clim. Dyn.*, 31:125–130.

Michaelsen, J. (1987). Cross-validation in statistical climate forecast models. *J. Clim. Appl. Met.*, 26:1589–1600.

Mitchell, T. D. and Jones, P. D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.*, 25:693–712.

Nilsson, C., Stjernquist, I., Bärring, L., Schlyter, P., Jänsson, A. M., and H., S. (2004). Recorded storm damage in swedish forests 1901-2000. *Forest Ecol. Manag.*, 199:165 – 173.

Reimann, T., Tsukamoto, S., Harff, J., Osadczuk, K., and Frechen, M. (2011). Reconstruction of holocene coastal foredune progradation using luminescence dating - an example from the ~~swina barrier (southern baltic~~ Swina Barrier (southern Baltic sea, nw ~~poland~~Poland). *Geomorphology*, 132:1–16.

Rockel, B. W. and Hense, A. (2008). The regional climate model ~~cosmo-clm (cclm~~COSMO-CLM (CCLM). *Meteorol. Z.*, 12:347–348.

Rutgersson, A., Jaagus, J., Schenk, F., Stendel, M., Bärring, L., Briede, A., Claremar, B., Hanssen-Bauer, I., Holopainen, J., Moberg, A., Nordli, O., Rimkus, E., and Wibig, J. (2015). Recent Change – Atmosphere. In: The BACC II Author Team (Eds.): Second Assessment of Climate Change for the Baltic Sea Basin. *Springer International Publishing*, 69–97

von Storch, H., Langenberg, H., and Feser, F. (2000). A spectral nudging technique for dynamical downscaling purposes. *Mon. Weather Rev.*, 128:~~3664 – 3673.~~ 3664–3673.

Wang, X. L., Swail, V. R., and Zwiers, F. W. (2006). Climatology and changes of extratropical cyclone activity: Comparison of era-40 with ~~ncep–ncar~~ NCEP-NCAR reanalysis for 1958–2001. *J. Clim.*, 19:3145 – 3166.

Weidemann, H. (2014). *Klimatologie der Ostseewasserstände: Eine Rekonstruktion von 1948 bis 2011*. PhD thesis, University of Hamburg.

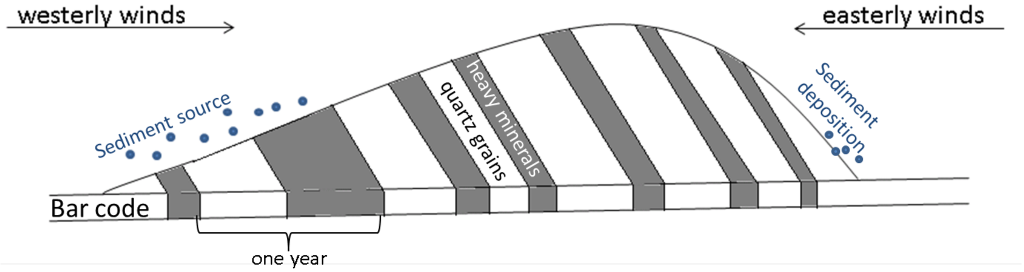


Figure 1. Schematic representation of of the Łeba dune structure (adapted from ~~Ludwig et al. (2016)~~Ludwig et al. (2017)).

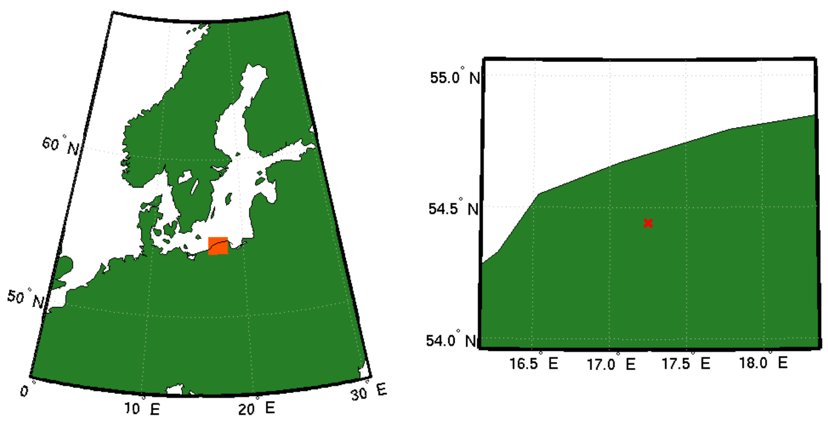
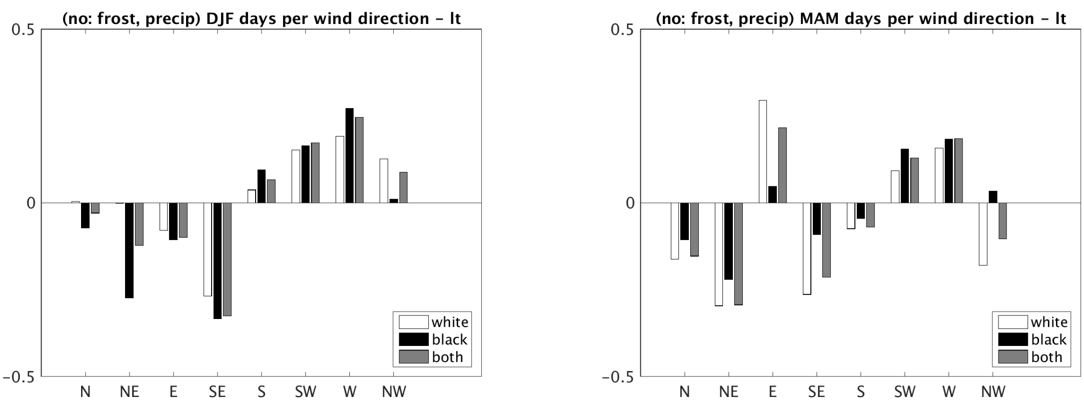


Figure 2. Location of investigation area. Left: Red box marks analysed gridded wind information from coastDat2 (1987-2012). Right: Analysed area with dune location (red dot) close to Łeba, Poland.



a) b)

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 ~~interval~~ layer (yellow), black ~~interval~~ layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF), spring (MAM) and for eight wind directions.

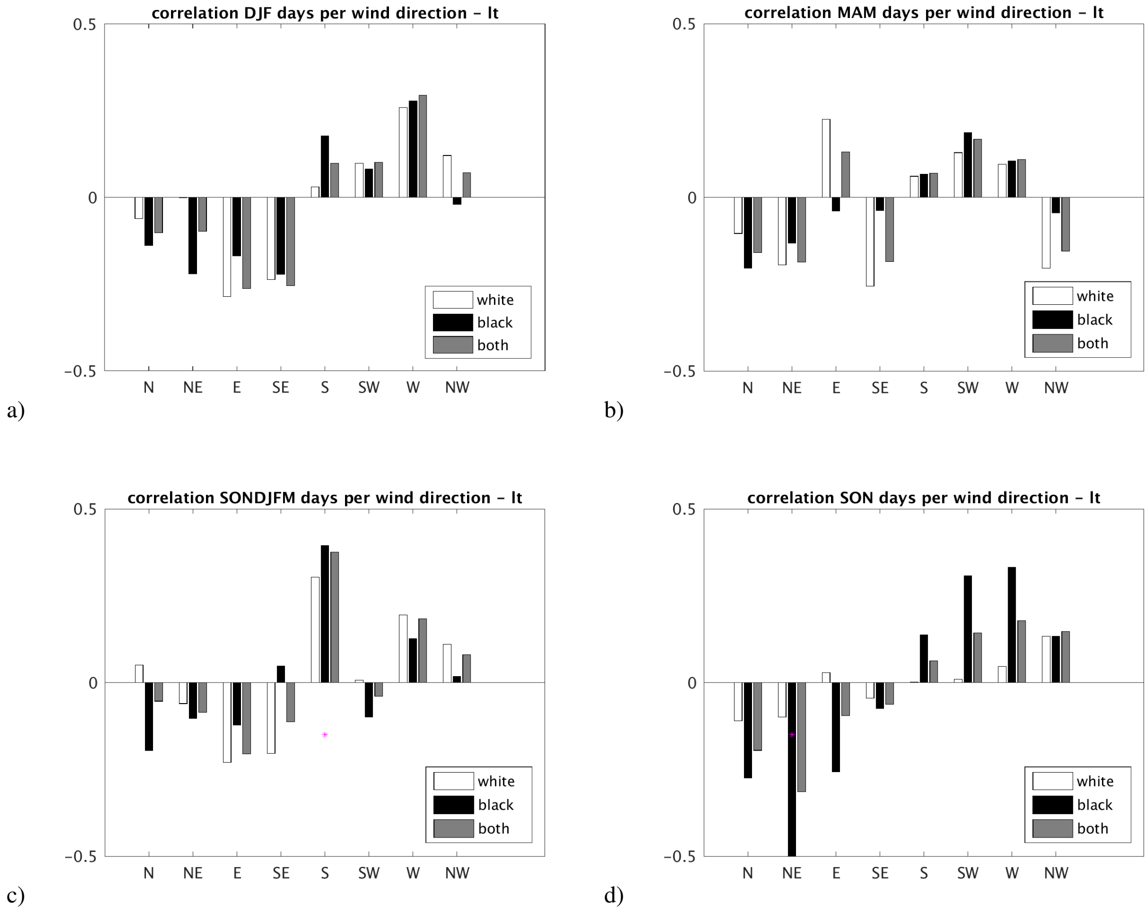


Figure 4. Correlation between the number of days per wind direction and dune thickness (lt-layer thickness) of the white ~~interval~~ layer (yellow), black ~~interval~~ layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF), spring (MAM), ~~summer~~ wind season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

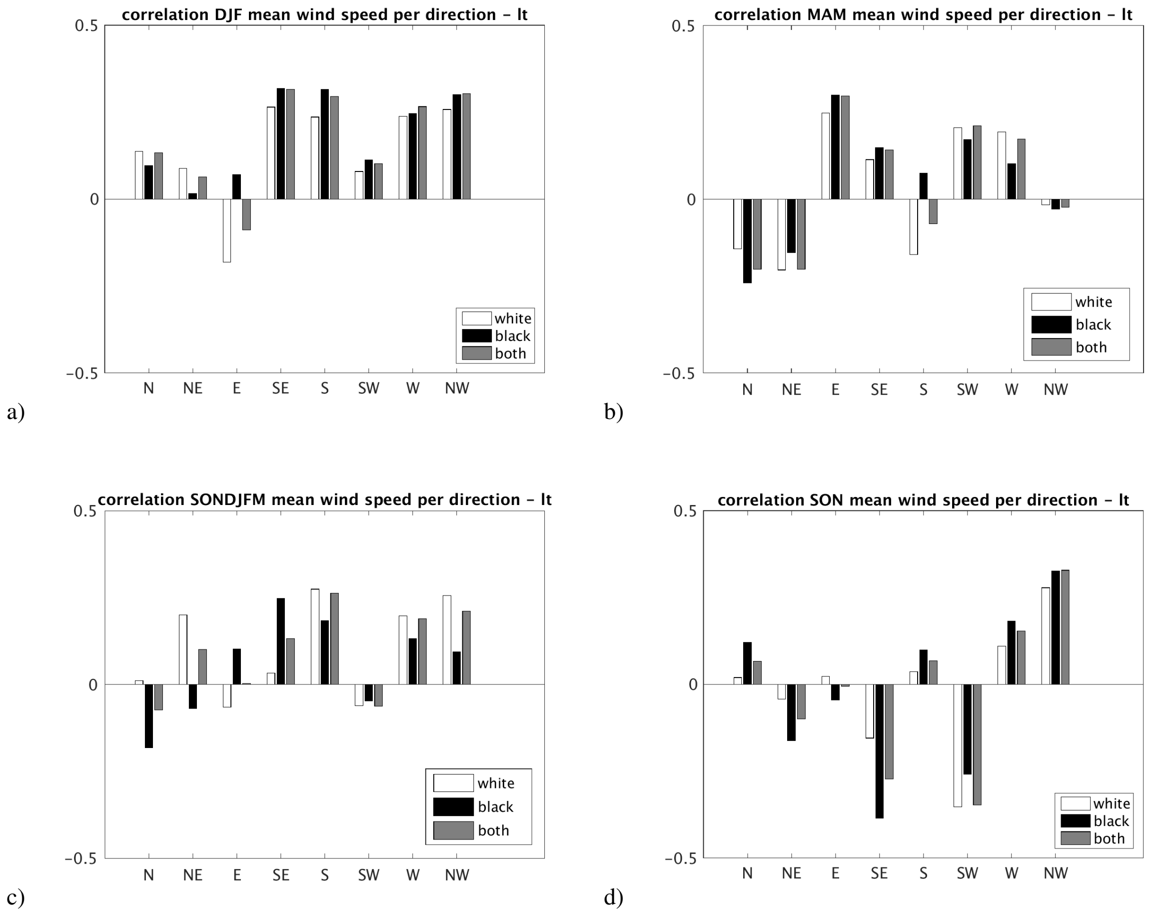


Figure 5. Correlation between mean wind speed and dune thickness (lt-layer thickness) of the white ~~interval~~ layer (yellow), black ~~interval~~ layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF), spring (MAM), ~~summer~~ wind season (~~JJA~~SONDJFM) and autumn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

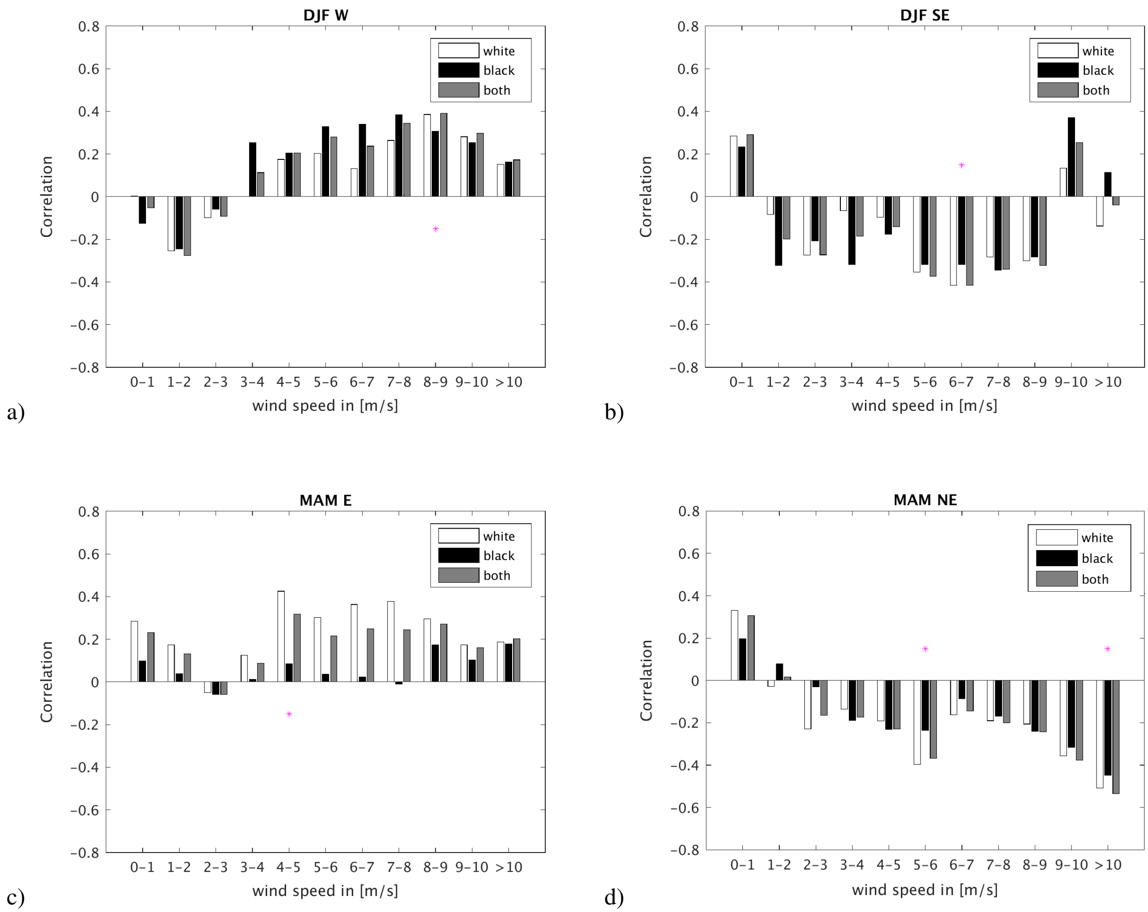


Figure 6. Correlation between the number of days per wind direction in a specified range of wind speeds and dune thickness of the white ~~interval~~ layer (yellow), black ~~interval~~ layer (blue) and both together (red). The correlations are shown for the seasons winter (DJF; a+b) and spring (MAM; c+d)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

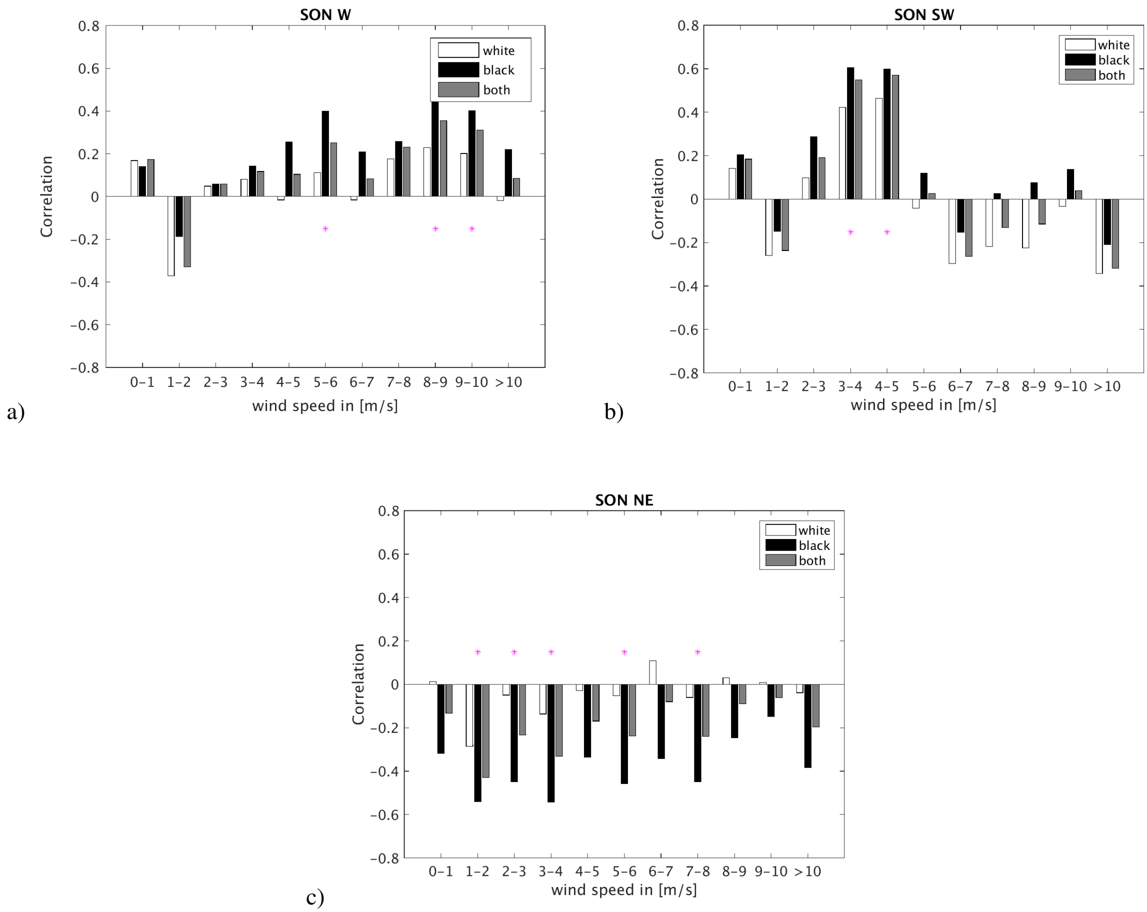


Figure 7. Correlation between the number of days per wind direction in a specified range of wind speeds and dune thickness of the white ~~interval~~ layer (yellow), black ~~interval~~ layer (blue) and both together (red). The correlations are shown for the seasons autumn (SON) for W (a), SW (b) and NE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

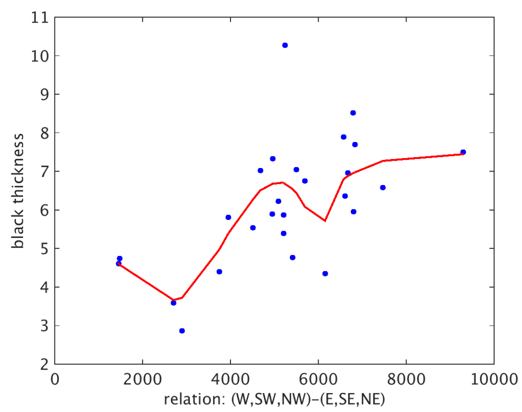


Figure 8. Scatter plot of the difference between the number of westerly (W, SW, NW) and easterly (E, SE, NE) winds and the black ~~interval~~ layer thickness. The red line shows the smoothing with a loess filtering (~~s. See~~see Sect. 3).

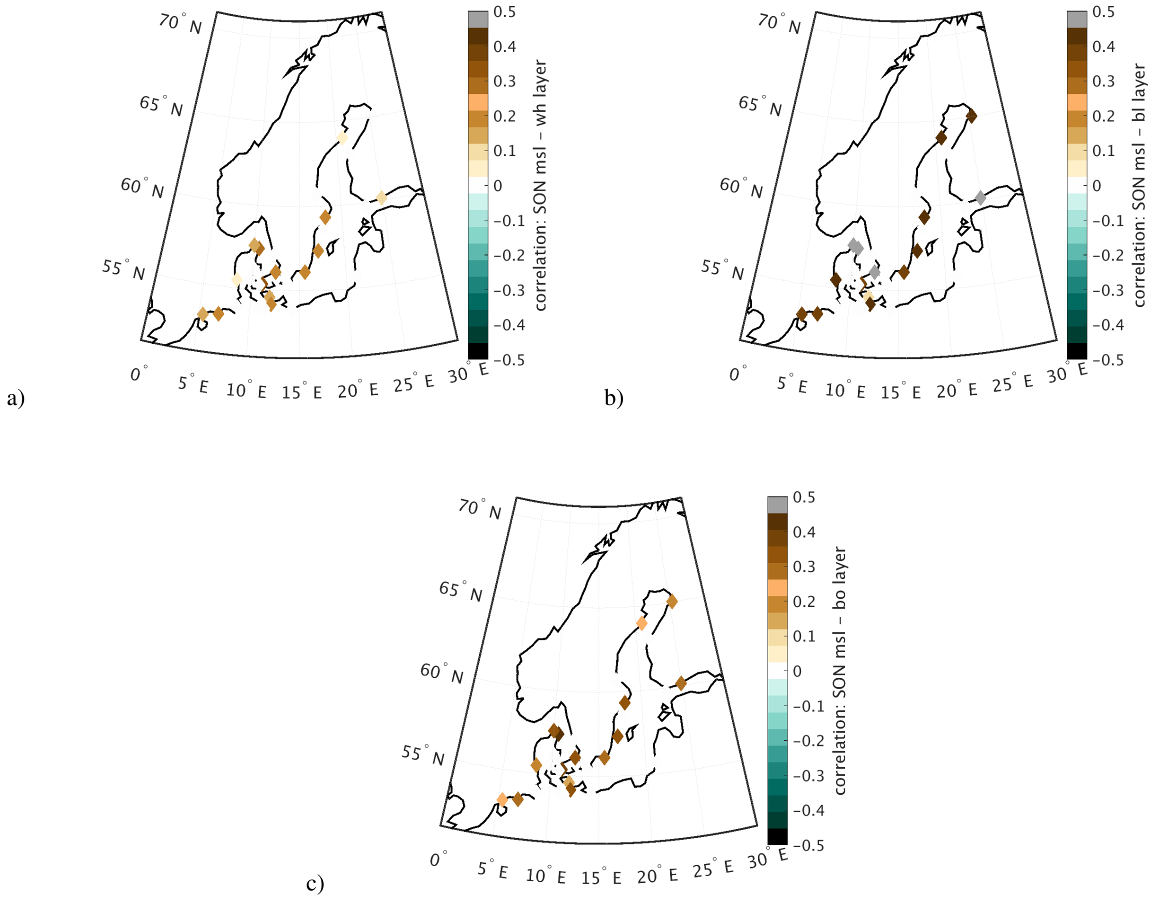


Figure 9. Correlation between mean sea level data from Baltic coastal stations and the dune layer thickness values during autumn (SON) for a) the white layer, b) the black layer and c) both layers combined.

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%