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The Informational Value of Pressure-Based Single-Station Proxies for Storm Activity

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ABSTRACT

Air pressure readings and their variations are commonly used to make inferences about storm activity. More precisely, it is assumed that the variation of annual and seasonal statistics of several pressure-based proxies describes changes in the past storm climate qualitatively, an assumption that has yet to be proven.

A systematic evaluation of the informational content of five pressure-based proxies for storm activity based on single-station observations of air pressure is presented. The number of deep lows, lower percentiles of pressure, the frequency of absolute pressure tendencies above certain thresholds, as well as mean values and high percentiles of absolute pressure tendencies is examined. Such an evaluation needs long and homogeneous records of wind speed, something that is not available from observations. Consequently, the proxies are examined by using datasets of ground-level wind speeds and air pressure from the NCEP-driven and spectrally nudged regional model, REMO. The proxies are gauged against the 95th and 99th percentile time series of ground-level wind speeds to quantify the relation between pressure-based proxies and storminess. These analyses rely on bootstrap and binomial hypothesis testing. The analyses of single-station-based proxies indicate that the proxies are generally linearly linked to storm activity, and that absolute pressure tendencies have the highest informational content. Further, it is investigated as to whether the proxies have the potential for describing storminess over larger areas, also with regard to surface conditions. It is found that absolute pressure tendencies have improved informational value when describing storm activity over larger areas, while low pressure readings do not show improved informational value.

1. Introduction

When it comes to past observations of wind, researchers face problems that make the assessment of storm activity very difficult. Because changes in storminess affect ecosystems and living conditions, the evaluation of the past storm climate provides valuable knowledge for people, countries, or even more profit-orientated entities, such as insurance companies or the wind energy industry. However, time series of observed wind are mostly too short and inhomogeneous to evaluate past storm activity objectively. Changes in instruments used, sampling routines, the surrounding environments, or the location of weather stations almost always cause inhomogeneities (Trenberth et al. 2007). For instance, the recorded wind speed time series from the island of Helgoland located in the German Bight has been compromised by such inhomogeneities (Lindenberg 2011). Here, the yearly mean wind speed shows a sudden increase of about 1.25 m s^{-1} in 1989 when the German Weather Service, the Deutscher Wetterdienst (DWD), relocated the station from an onshore to a coastal place. Also, further improvements in the atmospheric surveillance of the atmosphere through satellites, and an increasing number of buoys and weather stations, lead to an increased detection rate of storm events, which therefore lead to likely false inferences about changes in the past storm climate (Shepherd and Knutson 2007).

In the past decades researchers started to use proxies that are usually based on homogeneous and long pressure observations to avoid these problems. One approach that is feasible for the midlatitudes stems from pressure readings from multiple stations that form triangles to derive geostrophic wind speed statistics over certain areas. This method goes back to Schmidt and von Storch (1993) and has been used in several studies during the years following (e.g., Alexandersson et al. 1998, 2000; Wang et al. 2009). Krueger and von Storch (2011) showed that the triangle proxy describes the variations in the past storm climate reasonably well.

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Another approach to counteract the problems named is to use pressure readings from single stations directly to derive time series of either annual or seasonal statistics that describe storminess qualitatively. Five kinds of proxies seem commonly used throughout the literature, with slight variations in their individual definitions. These proxies are the number of deep lows (i.e., the number of local pressure observations below a chosen threshold), lower percentiles of pressure, the frequency of absolute pressure tendencies exceeding certain thresholds, as well as high percentiles and mean values of absolute pressure tendencies.

These proxies have been applied to long time series of pressure readings in several regions in the Northern and Southern Hemispheres, often in combination with analyses of geostrophic wind speed statistics. The studies that analyze North Atlantic and European storminess have storminess indices in common that mostly show interdecadal variability, thus rendering any trend nonexistent when longer time scales are considered (e.g., Schmith et al. 1998; Jonsson and Hanna 2007; Allan et al. 2009; Bärring and von Storch 2004; Bärring and Fortuniak 2009; Alexander et al. 2005). Most of them also examined to what extent the storminess indices relate to large-scale variability of the atmosphere and analyzed the correlation between the North Atlantic Oscillation (NAO) and past storm activity. Depending on the region examined, they find quite different results. For instance, Scandinavian and central European storminess seems less influenced by the NAO (Bärring and von Storch 2004; Matulla et al. 2008), while storminess over Iceland, the Faroe Islands, and parts of the British Isles is significantly correlated to the NAO (Alexander et al. 2005; Hanna et al. 2008; Allan et al. 2009). In the Southern Hemisphere, studies that use pressure proxies are rare. Alexander and Power (2009), for instance, used twice-daily pressure readings from Australia's Victoria coast to analyze percentiles of pressure tendencies and found that the number of storms along the coast decreased by 40% since the 1850s. Further research appears to be needed to objectively evaluate storminess in the Southern Hemisphere.

The studies that use single-station proxies to evaluate past storminess commonly assume that the variation of the statistics of pressure proxies describes the variation of statistics of ground-level wind speeds. There are some studies that cast doubts on this assumption. Alexandersson et al. (1998) analyzed pressure observation from 21 stations in northwestern Europe and the North Atlantic. They found only low to moderate correlations between time series of geostrophic wind speed percentiles, which can describe storminess qualitatively, and the frequency of high pressure tendencies or the number of deep lows. The WASA Group (1998) comments on the findings of Alexandersson et al. (1998) that the large-scale low-frequency variability of air pressure shifts local pressure distributions to smaller or larger values without necessarily affecting the storm regime. The authors doubt that counting low pressure occurrences would be useful for assessing storminess. Furthermore, Kaas et al. (1996) suspect that high pressure tendencies, while indicative of strong synoptic disturbances, do not relate to storminess generally, because high pressure tendencies usually do not occur at the same location and time as high wind speeds.

Generally, the pressure proxies are based on synoptic experience and should reflect cyclone activity and storminess changes in the area around a weather station (Bärring and Fortuniak 2009). Until now, the assumption that the variation of the statistics of pressure proxies describes the variation of statistics of ground-level wind speeds has yet to be proven due to a lack of homogeneous wind observations. Thus far, only one study evaluated one of the proxies, albeit through arguable methods: Hanna et al. (2008) assessed the informational content of annual and seasonal mean pressure tendencies. In their study they used observed wind speeds, which were likely inhomogeneous because of weather stations being relocated or changes in the instruments. Furthermore, the authors examined the correlation with mean wind speed time series. They found correlations up to 0.63 and concluded that there would be a general link. However, storm activity relates to strong surface wind speeds. Consequently, we do not know whether mean values of pressure tendencies can describe storminess generally, or whether other proxies can.

For that reason, we aim at a systematic evaluation of the informational value of single-station pressure proxies that are used to describe storm activity. Such an investigation requires long and homogeneous data. Therefore, we use diagnostic 10-m wind and surface air pressure fields from the spectrally nudged and National Centers for Environmental Prediction (NCEP)-driven regional model, REMO (see Feser et al. 2001; Weisse et al. 2009) for the period 1959–2005. These fields belong to the coastDat dataset (available at http://www.coastdat.de from the Helmholtz-Zentrum Geesthacht). The hourly ground-level wind speed and surface air pressure fields cover Europe and the North Atlantic with $0.5° \times 0.5°$ resolution (around 50–60 km). Koch and Feser (2006) compared satellite-retrieved wind data with surface winds simulated in REMO and found that REMO describes wind speeds realistically. Weisse et al. (2005) show that surface wind fields and their statistics are homogeneous and reasonably well simulated over the sea in coastDat. The simulation of (extreme) wind speeds and their statistics over land highly depends on the physical parameterization scheme. Kunz et al. (2010) note—for a different model version of REMO—that REMO is capable of simulating extreme wind speeds over land. We therefore assume that the wind fields and their statistics are also reasonably well simulated over land.

The remainder of this paper is structured as follows: First, we will introduce the methods that are used, followed by the evaluation of the number of deep lows, lower percentiles of pressure, the frequency of absolute pressure tendencies exceeding certain thresholds, as well as high percentiles and mean values of absolute pressure tendencies for the annual and seasonal time scale, with regard to the thresholds used and other configurations in the proxy definitions. Afterward, we examine whether the proxies can represent large-scale storminess with respect to surface conditions.

2. Evaluation of single-station pressure proxies

a. *Tests employed*

The assumption that the variation of the statistics of pressure proxies describes the variation of the statistics of ground-level wind speeds implies that the statistics of pressure proxies and high atmospheric wind speeds are positively linearly related. To evaluate this assumption, we first derive annual and seasonal statistics of the proxies. Second, we gauge the derived statistics of proxies against annual (seasonal) 95th and 99th percentile time series of ground-level wind speeds to quantify the relation between pressure-based proxies and storminess. For that reason, we use the correlation as a measure of the informational content of the proxies.

After having derived respective correlations at all of the N grid points within the model domain, the evaluation will be done in two steps. First, we determine the proportions h_+ of positive correlations out of all N correlations. Then, we examine the number h of locally significant correlations.

The first test deals with the null hypothesis

$$H_0^1: h_+ = 50\% \times N, \tag{1}$$

with the number of positive correlations h_+. Given the null hypothesis H_0^1, the number h_+ is distributed as a binomial distribution $\mathcal{B}(h_+; N; 50\%)$. We reject H_0^1 if

$$\sum_{j \geq h_+} \mathcal{B}(j; N; 50\%) > 95\% \tag{2}$$

at, for instance, the 5% level. The rejection of the null hypothesis will take place when $h_+ > (50\% \times N)$. Then, the rejection would comply with the acceptance of the alternative hypothesis that, on average, the correlations are positive.

We also test the null hypothesis

$$H_0^2: h = 1\% \times N, \tag{3}$$

with the number h of correlations, which are found to reject the local null hypothesis of a zero correlation with a risk of 1%. A proportion of $h = 1\%$ is to be expected if there was no link between proxies and wind percentiles. Again, under the null hypothesis H_0^2, the probability of h is given by the binomial distribution $\mathcal{B}(h; N; 1\%)$, and H_0^2 may be rejected with a risk of, for example, 5% if

$$\sum_{j \geq h} \mathcal{B}(j; N; 1\%) > 95\%. \tag{4}$$

Rejection of H_0^2 (because of a too-large h) points to the alternative hypothesis that, on average, the correlations are not locally insignificant.

Both cases of null hypotheses allow an identification of a general positive linear relationship between pressure proxies and storm activity via their rejection. The conditions to reject H_0^1 are easier to meet than those to reject H_0^2. We found that a rejection of H_0^1 is always given when H_0^2 is rejected. On the other hand, a rejection of H_0^2 does not always seem achievable when H_0^1 is rejected. In our case, a rejection of H_0^1 points to a general linear relationship, while a rejection of H_0^2 also indicates a possibly strong general relationship.

The analysis of positive or significant correlations is hampered by the problem of the multiplicity of tests (for details see Livezey and Chen 1983; Storch 1982). We deal with this problem in an ad hoc manner by assuming that the number of independent correlations is $N' = 20$, the numbers h_+ and h are rescaled by N'/N, and N in the binomial distributions is replaced by N'. Then, the product $h' = hN'/N$ (respectively, h_+N'/N) is rounded as the binomial distribution requires integers.

When dealing with low percentiles of pressure readings, which are by design negatively correlated to storminess, we have to reverse the inequalities in (2) and (4) and replace the 95% by 5%.

For every proxy, if necessary, we also assess whether the chosen values in the proxy configurations play an important role for the informational content of the proxies. To do so, we look into significant differences between the median values of the distributions of correlations. The least significant difference, at 0.01 significance, is ± 0.049 for negative–positive differences. We have determined these values from a bootstrapped null distribution of median differences of correlations. Differences

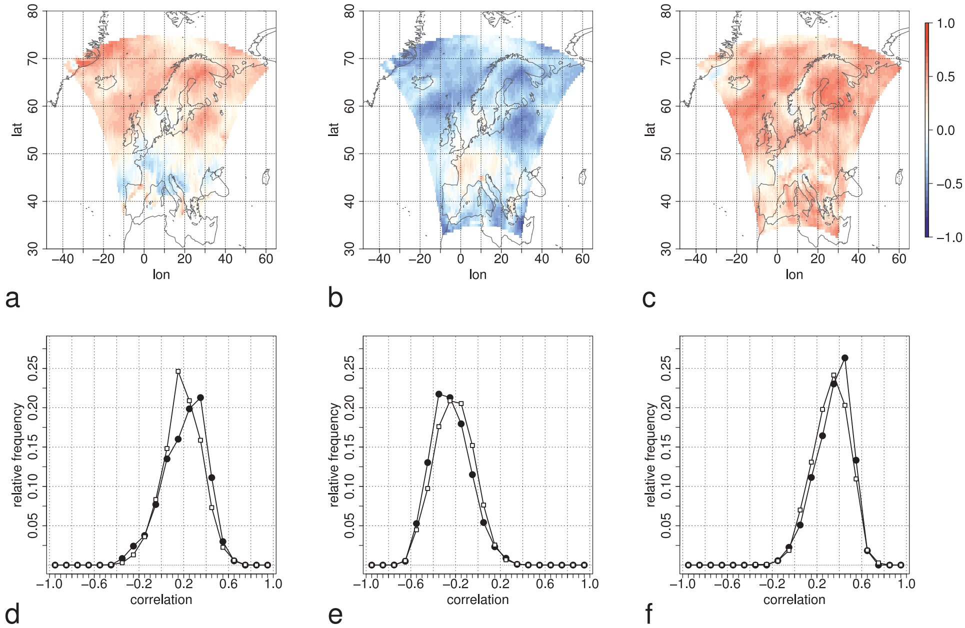

FIG. 1. (top) Spatial distributions of correlations between annual 95th percentiles of surface wind speeds and the annual (a) number of pressure readings below 980 hPa, (b) 1st percentile of pressure readings, and (c) 99th percentiles of absolute pressure tendencies in 24 h. (bottom) The histograms of correlations associated with these proxies in the same order. (d)–(f) The correlation with annual 95th percentiles of surface wind speeds (filled circles) and the correlation with annual 99th percentiles of surface wind speeds (white squares) are shown.

of median correlations are significant at 0.01 significance (which is a rejection of the null hypothesis of a 0 difference), if the differences exceed the given critical values, which are the 0.005 and 0.995 quantiles of the null distribution.

b. *Low pressure readings*

In this section we concentrate on the proxies based on low pressure readings. We first address the annual and seasonal frequency of pressure readings below a certain threshold. For our evaluation we use 980 hPa as a threshold, which is the value that has been used in most of the studies that deal with past storminess (e.g., Alexandersson et al. 1998; Bärring and von Storch 2004).

Figures 1a,d display the spatial distribution and histograms of correlations between the annual number of pressure readings below 980 hPa and annual 95th and 99th percentiles of surface wind speeds. Table 1 shows the 0.05 quantiles and the median correlation of annual and seasonal correlations. Also shown are the proportion of h_+ and h of positive correlations and rejected local null hypotheses at the 0.01 significance level.

The 0.05 quantiles of the ensembles of correlations are smaller than 0, except for the correlation between the number of pressure readings below 980 hPa and the 95th percentiles of surface wind speeds in spring seasons, which is slightly positive. Median correlations are positive, with values ranging from 0.08 to 0.26, and are

TABLE 1. The 0.05 quantile and median of the distribution of correlations between the number of pressure readings below 980 hPa and 95th and 99th percentiles of surface wind speeds for the annual time scale and the spring [March–May (MAM)], summer [June–August (JJA)], autumn [September–November (SON)], and winter [December–February (DJF)] seasons. Also shown are the proportion h_+ and h of positive correlations and rejected local null hypotheses at the 0.01 significance level. Bold numbers denote 0.01 significance, and italic numbers refer to 0.05 significance.

Ensembles of correlations	0.05 quantile	Median	h_+	h
Annual 95th/99th percentile wind speeds	−0.14/−0.11	0.24/0.19	**85.3%/86.4%**	*10.2%/8.4%*
MAM 95th/99th percentile wind speeds	0.01/−0.03	0.24/0.20	**95.3%/92.6%**	9.9%/3.8%
JJA 95th/99th percentile wind speeds	−0.16/−0.16	0.08/0.08	67.5%/66.5%	2.3%/1.3%
SON 95th/99th percentile wind speeds	−0.03/−0.05	0.17/0.16	**92.1%/89.0%**	0.9%/1.3%
DJF 95th/99th percentile wind speeds	−0.14/−0.11	0.26/0.23	**85.5%/86.0%**	**26.5%/17.7%**

a little higher for the 95th percentiles of surface wind speeds than for the 99th percentiles of surface wind speeds. The differences between median correlations are small; because the values range from 0.16 to 0.26, only the summer seasons have a smaller median correlation of 0.08. We can see in Fig. 1a that positive annual correlations can be found over the sea, Scandinavia, and the Baltic, while other parts of Europe are mostly covered by lower or even negative correlations.

Our analysis reveals, when we look at the proportions h_+ and h, that the sign of correlations is positive in general at the 0.01 significance level, except in the summer season. Only in winter, where the median correlation is highest, is the linear relationship between the number of pressure readings and storminess strong enough to be significant at the 0.01 level. In the winter season, the proportion h of rejected local null hypotheses of a 0 correlation is highest at $h = 26.5\%$. Still, median values of winter correlations remain low. We conclude that the number of pressure readings below 980 hPa is positively linearly linked to storm activity in general on the annual and seasonal time scale, although the informational value is weak.

The low informational value of this proxy partly results from the mean pressure field and its changes over time. The pressure field surrounding a weather station is not necessarily connected to surrounding storminess because high wind speeds can occur independently from low pressure values (WASA Group 1998). Another related reason for the weak informational value is the proxy's sensitivity to counting pressure occurrences below the right threshold. It is very likely that, depending on the threshold, either too few or too many occurrences of pressure readings are counted each year or season. There are, for instance, some regions in Europe that seldom experience pressure readings below 980 hPa, such as Italy. Consequently, the derived time series of low pressure readings might not be connected to storminess at all in such regions. Figure 2 shows the dependence of the median correlation on the chosen threshold. Interestingly, median values only differ slightly, show some variability, and increase with increasing threshold until they peak at 993 (980) hPa for 95th (99th) percentiles of surface wind speeds. The differences among different thresholds are not significant at all (at 0.01 significance). Overall, the distributions of correlations do not change visibly (not shown). However, we noticed that the regional distribution of correlations changes when the threshold increases. While smaller thresholds lead to high correlations over the North Atlantic and small or negative values over Europe, higher thresholds result in high correlations over the Baltic and Scandinavia and lower correlations over the North Atlantic (not shown). We believe that this behavior comes from the described sensitivity of counting the right number of pressure occurrences.

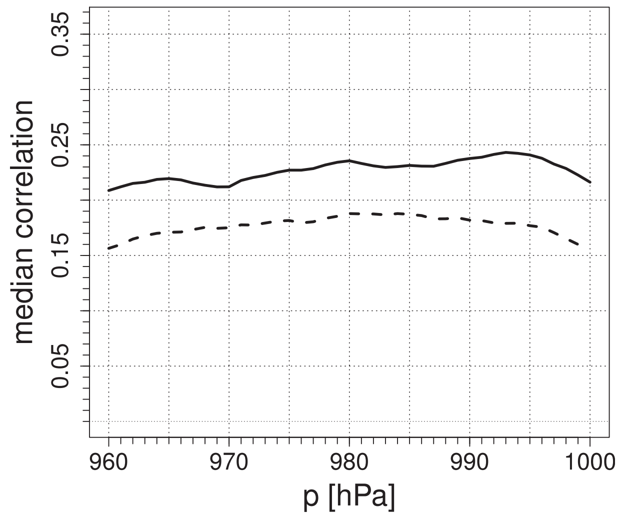

FIG. 2. Dependence of median correlations between the annual number of pressure readings below a certain threshold p and annual 95th (solid line) and 99th percentiles (dashed line) of surface wind speeds depending on the threshold p.

Similar to the number of low pressure readings, low percentiles of pressure readings are connected to deep lows (Matulla et al. 2012). In contrast to the number of low pressure readings, low percentiles of pressure readings do not suffer from sensitivity to a fixed threshold. In the following we evaluate annual and seasonal first percentiles of pressure. Usually, (very) low pressure readings relate to intense cyclones that bring high wind speeds. Consequently, low pressure percentiles are negatively linked to high wind speeds (Bärring and Fortuniak 2009), meaning that negative correlations between the proxy and high wind speed percentiles indicate informational value. The spatial distribution and histograms of correlations (Figs. 1b,e) indicate that negative correlations cover the North Atlantic, Scandinavia, the Baltic, and the Mediterranean area. Low absolute correlations can be found over central Europe. Median correlations in Table 2 range between -0.20 and -0.28. Winter storminess is best described with median correlations from -0.27 to -0.28. Differences between correlations for 95th and 99th percentiles of surface wind speeds are small, with differences of up to 0.05. From the proportion h_+ we learn that correlations are negative in general. The magnitude of the correlations is in the same order as that of the correlations of low pressure readings. Compared with the number of low pressure readings, median correlations have slightly higher absolute values. Additionally, the proportion h of rejected local

TABLE 2. The 0.95 quantile and median of the distribution of correlations between the annual 1st percentile of pressure readings and annual 95th and 99th percentiles of surface wind speeds for the annual time scale and the spring (MAM), summer (JJA), autumn (SON), and winter (DJF) seasons. Also shown are the proportion h_+ and h of negative correlations and rejected local null hypotheses at the 0.01 significance level. Bold numbers denote 0.01 significance, and italic numbers refer to 0.05 significance.

Ensembles of correlations	0.95 quantile	Median	h_+	h
Annual 95th/99th percentile wind speeds	0.06/0.07	−0.26/−0.21	**91.3%/89.0%**	*14.3%/10.9%*
MAM 95th/99th percentile wind speeds	0.00/0.06	−0.24/−0.20	**94.9%/89.5%**	*14.1%/12.3%*
JJA 95th/99th percentile wind speeds	0.09/0.10	−0.22/−0.20	**86.9%/85.8%**	*13.3%/11.3%*
SON 95th/99th percentile wind speeds	0.04/0.04	−0.22/−0.21	**91.1%/90.1%**	*13.1%/10.4%*
DJF 95th/99th percentile wind speeds	0.09/0.09	−0.28/−0.27	**88.3%/88.9%**	**29.0%/26.0%**

null hypotheses of a 0 correlation is higher because the proportions range from 10.4% to 29.0%. The proportion h is generally significant at the 0.05 level, and is even 0.001 significant for the winter season. The results show that low percentiles of pressure readings are linearly associated with storminess and have higher informational value than the number of low pressure readings, albeit the overall informational value appears weak. The weak informational value follows from the same reason as to why the number of low pressure readings has weak informational content, as given by Bärring and Fortuniak (2009) and Matulla et al. (2012): general changes in the large-scale pressure field can affect the pressure distribution with no obvious changes in storm activity.

c. High absolute pressure tendencies

High local absolute pressure tendencies reflect cyclonic activity and concentrate on high-frequency atmospheric disturbances (Kaas et al. 1996; Schmith et al. 1998). These tendencies denote the absolute pressure difference over a given period Δt. Alexandersson et al. (1998) analyzed the number of absolute pressure tendencies exceeding a threshold of 16 hPa in 24 h, and Bärring and Fortuniak (2009) used 25 hPa in 24 h. Other studies use different thresholds and time periods. A common or established value does not seem to exist throughout the literature. We therefore refrain from evaluating this proxy with a specific value as a threshold in mind. On the other hand, high percentiles of absolute pressure tendencies only depend on the frequency of available measurements. In the following we will evaluate 99th percentiles of absolute pressure tendencies. Because most of the observed time series were only measured once or twice per day in the long term, we concentrate on pressure tendencies with $\Delta t = 24$ h. We will come back to the choice of thresholds and time intervals later.

Median values of correlations range from 0.27 to 0.37 for all seasons (Table 3). They do not differ much between seasons and between correlations for the 95th and 99th percentiles of wind speed. The spatial pattern of correlations is very similar to the previous proxies. We find high correlations over the North Atlantic, Scandinavia, the Baltic, and the Mediterranean area, and low values over central Europe (Figs. 1c,f). Also, proportions h_+ of positive correlations are high, with values between 92.5% and 97.7%. The proportions h of rejected local null hypotheses vary between 20.4% for summer seasons and 42% for winter seasons. Both h_+ and h are significant at least at the 0.001 significance level, meaning that the proxy is generally linearly linked to storm activity.

Our analyses indicate that the informational value of high percentiles of absolute pressure tendencies is higher than that of the proxies based on low pressure readings. High absolute pressure tendencies partially detect atmospheric disturbances that cause storm activity. The proxy can potentially omit slowly developing disturbances or might detect a disturbance twice when the

TABLE 3. The 0.05 quantile and median of the distribution of correlations between the 99th percentiles of absolute pressure tendencies and 95th and 99th percentiles of surface wind speeds for the annual time scale and the spring (MAM), summer (JJA), autumn (SON), and winter (DJF) seasons. Also shown are the proportion h_+ and h of positive correlations and rejected local null hypotheses at the 0.01 significance level. Bold numbers denote 0.001 significance.

Ensembles of correlations	0.05 quantile	Median	h_+	h
Annual 95th/99th percentile wind speeds	0.05/0.05	0.37/0.34	**97.2%/97.4%**	**26.3%/21.5%**
MAM 95th/99th percentile wind speeds	0.01/−0.01	0.32/0.29	**95.3%/94.7%**	**33.1%/26.3%**
JJA 95th/99th percentile wind speeds	−0.02/0.01	0.273/0.28	**93.9%/95.7%**	**20.4%/21.8%**
SON 95th/99th percentile wind speeds	−0.05/−0.01	0.30/0.30	**92.5%/94.5%**	**27.9%/29.9%**
DJF 95th/99th percentile wind speeds	0.08/0.07	0.37/0.36	**97.7%/97.7%**	**42.0%/39.4%**

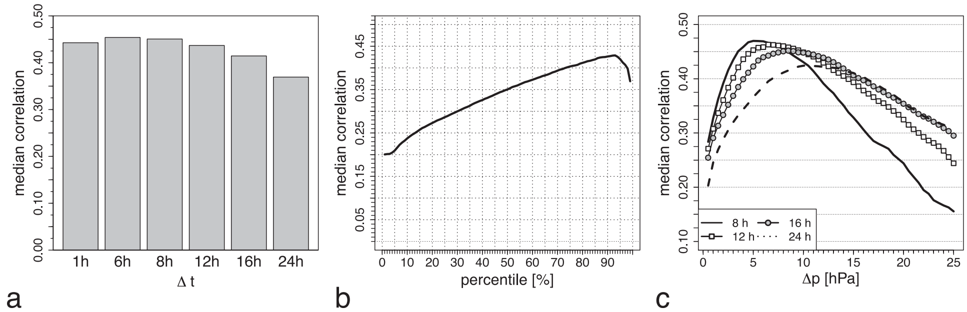

FIG. 3. (a) Dependence of median correlations between annual 95th percentiles of surface wind speeds and the annual 99th percentiles of absolute pressure tendencies on a given time period Δt. (b) The dependence on the percentile of absolute pressure tendencies used to calculate the median correlations with annual 95th percentiles of surface wind speeds. (c) The median correlation with the annual number of absolute pressure tendencies exceeding a certain threshold Δp is shown for different cases of Δt.

pressure is rising (Bärring and Fortuniak 2009). Further, and more importantly, the informational value of pressure tendencies suffers from the fact that high pressure tendencies usually do not occur at the same location and time as high wind speeds (Kaas et al. 1996). We will address this problem in section 3.

As noted earlier, absolute pressure tendencies depend on the choice of Δt. Figure 3a shows the dependence of annual median correlations to the used period Δt. Median correlations are lowest for Δt = 24 h, with values of 0.37, and highest for Δt = 6 h, with values of 0.46 for the annual 95th percentiles of surface wind speeds. Differences of median correlations are not significant among different Δt ranging from 1 to 16 h, but are between Δt = 24 h and the other periods. Also, the informational value gradually decreases with increasing Δt, which becomes understandable when we think of pressure tendencies as a kind of high-pass filters. With smaller values of Δt, absolute pressure differences detect more atmospheric disturbances peaking at Δt = 6 h. If Δt becomes too small, then atmospheric noise interferes and partially decreases the informational value. We also investigated whether the chosen percentile of absolute pressure tendencies plays a role (Fig. 3b), and found that the highest annual median correlations are obtained for the 93rd percentiles of absolute pressure tendencies. Higher percentiles than that lead to a small decrease, which means that the higher variability of too-extreme percentiles degrades the informational content.

Another approach used by Hanna et al. (2008) is to calculate annual or seasonal mean values of 24-hourly absolute pressure tendencies. We found that this type of tendency proxy leads to a strong description of storm activity. Annual median correlations are high with values of 0.43 (0.34) for annual 95th (99th) percentiles of surface wind speeds (Table 4). On the seasonal scale, values are similar ranging from 0.34 (0.29) to 0.50 (0.42) for 95th (99th) percentiles of surface wind speeds in the summer and winter season. The spatial distribution is almost equal to that of the other two tendency proxies (not shown), with equal patterns and higher correlations. Also, mean values of 24-hourly absolute pressure tendencies and storminess are generally positively linked, at least at the 0.01 significance level.

In the case of the number of absolute pressure tendencies exceeding a certain threshold, the assessment becomes more complicated. In principle, the number of pressure tendencies exceeding a threshold would have the same informational content as high percentiles of pressure tendencies if the right threshold was chosen.

TABLE 4. The 0.05 quantile and median of the distribution of correlations between the mean value of absolute pressure tendencies and 95th and 99th percentiles of surface wind speeds for the annual time scale and the spring (MAM), summer (JJA), autumn (SON), and winter (DJF) seasons. Also shown are the proportion h_+ and h of positive correlations and rejected local null hypotheses at the 0.01 significance level. Bold numbers denote 0.001 significance, and italic numbers denote 0.01 significance.

Ensembles of correlations	0.05 quantile	Median	h_+	h
Annual 95th/99th percentile wind speeds	0.12/0.05	0.43/0.34	**99.1%/97.8%**	**38.1%**/*19.5%*
MAM 95th/99th percentile wind speeds	0.02/−0.01	0.41/0.32	**96.1%/94.6%**	**51.3%/31.9%**
JJA 95th/99th percentile wind speeds	−0.02/−0.01	0.34/0.29	**94.3%/94.2%**	**31.0%**/*18.4%*
SON 95th/99th percentile wind speeds	0.07/0.03	0.41/0.37	**97.0%/96.2%**	**47.1%/32.1%**
DJF 95th/99th percentile wind speeds	0.16/0.14	0.50/0.42	**99.5%/99.5%**	**67.3%/49.0%**

We calculated median correlations of numbers of pressure tendencies for 8-, 12-, 16-, and 24-hourly values of Δt depending on the threshold Δp in 0.5-hPa increments. First, we see in Fig. 3c that smaller Δt have higher maximum median correlations than greater Δt. Second, we see that for every Δt different optimal thresholds Δp exist. While too-small values of Δp lead to a detection of too much atmospheric noise, and thus decreased informational value, higher values of Δp make the proxy insensitive to atmospheric disturbances. For instance, the median correlation of the number of pressure tendencies with $\Delta t = 8$ h peaks at $\Delta p = 5.5$ hPa, with a correlation of 0.47, and decreases thereafter steeply. Further, median correlations for $\Delta t = 24$ h are highest at a value of 0.42 when the threshold Δp is 10.0 hPa. The fact that thresholds, which are smaller than those used throughout the literature, lead to higher correlations emphasizes the point given by Kaas et al. (1996) that high pressure tendencies do not occur simultaneously with strong synoptic disturbances. In that case, smaller thresholds lead to an improvement in the detection of atmospheric disturbances that pass by in some distance. However, our sensitivity analysis reveals that it might be possible to optimize the description of past storminess for a given period Δt, which the frequency of measurements often determines, when the right threshold Δp is selected.

We have obtained all of the results through simulated winds in REMO. Because the statistics of atmospheric wind speeds are reasonably well simulated over sea (Feser et al. 2011), we expect that our obtained results are applicable in the real atmosphere, though we cannot estimate the real informational value of the proxies because of a lack of homogeneous wind speed observations.

3. Can single-station proxies represent large-scale storm activity?

Wind speed and storm activity primarily depend on an atmospheric pressure gradient. Such a pressure gradient is caused by atmospheric disturbances that pressure proxies seek to detect. However, as noted, it is very likely that strong atmospheric disturbances and winds occur remotely from the actual place where pressure measurements are taken. As a result, we would find a weakened link between storminess and pressure proxies at a certain place. On the contrary, we believe that the described characteristics can be used to make inferences about storminess in a larger area surrounding a station.

To examine such a dependence, we look into median correlations between two proxies and annual 95th and 99th percentiles of area-maximum surface wind speeds within a square of variable size surrounding the grid point from which the pressure has been taken to derive the proxies. The length of the sides of these squares depends on the geographical latitude. The squares are thus deformed to spherical rectangles. We have selected 1013 grid points from the model domain randomly to conduct our analyses. We concentrate on two proxies only, namely, the annual 1st percentile of pressure and the 99th percentile of absolute pressure tendencies to avoid further complications resulting from threshold dependencies. In our approach, which enhances the analyses of Kaas et al. (1996), the length of sides varies from 3 to 21 grid points, with a minimum length of about 120 km and a maximum length of about 1200 km. The average size of sides denotes the scale, on which the pressure proxies would represent storm activity, which we label as scale. The scale is divided into four classes: extra small, small, medium, and large. Large scales are scales of greater than 800 km, which mark the transition from the mesoscale to synoptic scales. The extra small class reaches up to 300 km, which includes the characteristic horizontal range of cold fronts that stretch from 80 to 300 km (Carlson 1991). Cold fronts that bring a transition from warmer to colder air masses are typical atmospheric disturbances in the extratropics. They are often accompanied by strong winds and falling or low pressure. We divided the scales in between the extra small and large class into two classes to achieve almost balanced group sizes. The small class denotes scales that are either smaller than or equal to 550 km, while the medium scale is smaller than or equal to 800 km, but greater than 550 km. In addition, we classified correlations as either land or sea to assess the informational content of proxies regarding surface conditions. The surface condition within a rectangle is classified as land for a land fraction of greater than 0.5 and as sea for a land fraction of equal to or smaller than 0.5. The results are presented in Fig. 4.

Consider first the median correlations between the annual 99th percentile of absolute pressure tendencies and the 95th percentiles of area-maximum surface wind speeds (Fig. 4a). The informational content over the combined land and sea surfaces remains almost constant over small and medium scales, with correlations slightly rising from 0.39 to about 0.42, and then decreasing a little to 0.39. Although the correlations do not vary much when increasing scales are regarded, it seems that absolute pressure tendencies are better at representing storminess within a greater area surrounding one station than at one particular point. Over sea, median correlations remain at about 0.42–0.45, with the highest correlation of 0.46 for medium scales. Over land, the correlations rise from 0.35 to about 0.38 at medium scales and decrease to 0.36 for large scales. Overall, the

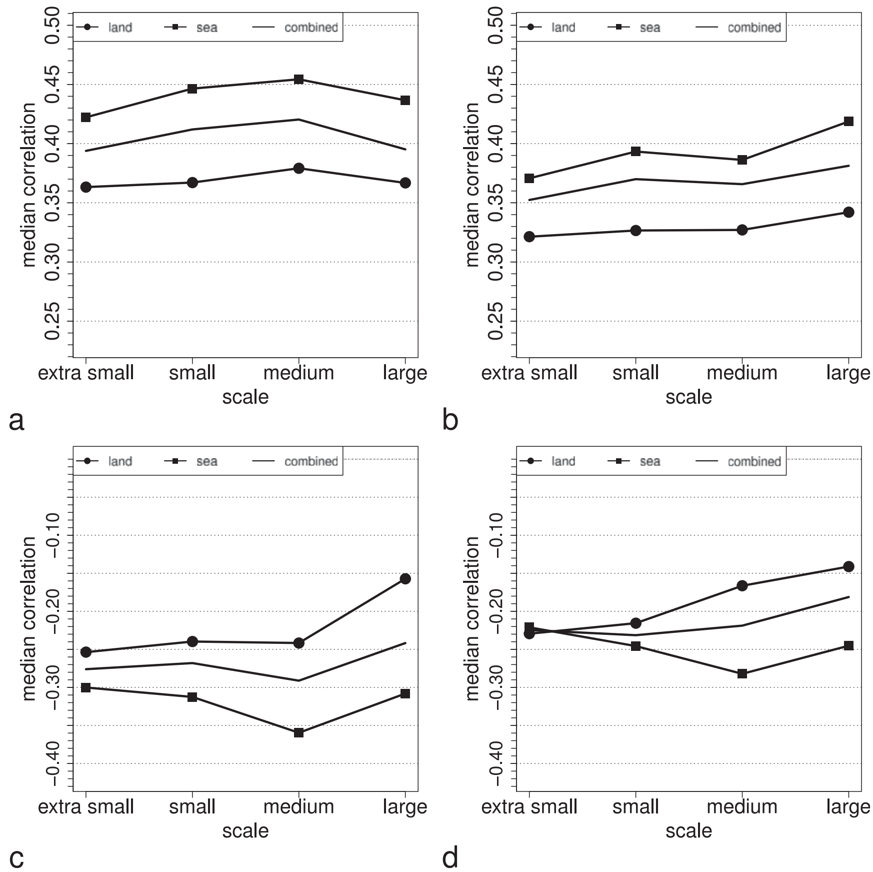

FIG. 4. Median annual group correlations of (a),(b) 99th percentiles of absolute pressure tendencies in 24 h and (c),(d) 1st percentiles of pressure with (left) 95th and (right) 99th percentiles of area-maximum surface wind speeds within a square of variable size surrounding grid points where the proxies have been calculated. We determined these squares by grid points. For that reason, the length of sides differs within a square because of different geographical latitudes. Shown are the median group correlations vs the average size of sides that represent the distance, on which pressure proxies might describe storm activity, for land, sea, and combined land–sea rectangles.

differences between land and sea surfaces are significant and between 0.05 and 0.1, suggesting that absolute pressure tendencies are not overly affected by surface properties. The higher informational value of the pressure tendencies probably compensates for the deterioration resulting from surface conditions.

Consider now the median correlations between the annual 1st percentile of pressure and 95th percentiles of area-maximum surface wind speeds. Note that negative correlations indicate informative value. Independent from surface conditions (solid line in Fig. 4c), the informational content increases between extra small and medium scales as the median correlation decreases from −0.27 to −0.29. For large scales, the correlation increases to −0.24. When compared with the annual median correlation at the same place (−0.26 from Table 2), we see that within the small and medium scales the informational content is somewhat superior, although differences are not significant (at the 0.01 level). A similar picture can be seen when we regard the influence of land and sea surface conditions. For sea surfaces, the informational content rises more drastically within the small to medium scales with correlations from −0.30 to −0.36 and decreases afterward to a correlation of −0.30. For land surfaces, the correlations increase slightly from −0.25 to −0.24 within small and medium scales, and steeply for large scales to −0.16. The differences in median correlations between land and sea surfaces grow from 0.05 to 0.20. Turbulent effects and ageostrophic dynamics over land that alter surface winds in the planetary boundary layer are responsible for the deterioration of the informational content over land. Over sea the frictional influence from the surface diminishes, resulting in a better description of storminess through low pressure. However, the informational value of low pressure readings remains low.

When we look at the correlations with more extreme percentiles (namely, the 99th) of area-maximum surface wind speeds (Figs. 4b,d), we notice some differences and similarities. First, the differences between land and sea surfaces range between 0.05 and 0.08 for the 99th percentile of absolute pressure tendencies. For the first percentile of pressure, on the contrary, the differences vanish for extra small scales and increase by 0.1 to large scales. The informational content over sea increases for both proxies within small and medium scales, and either decreases afterward (1st percentile of pressure) or remains almost constant (99th percentile of absolute pressure tendencies). The informational content decreases over land steadily with increasing scale for the first percentile of pressure. For the 99th percentile of absolute pressure tendencies it does not change significantly. Second, correlations are about 0.05 smaller than that of correlations with 95th percentiles of area-maximum surface wind speeds. Overall absolute correlations of the first percentile of pressure decrease from 0.23 to 0.13. At the same, the overall correlations of the 99th percentile of absolute pressure tendencies grow slightly, increasing from 0.35 to 0.38 within the scales. The higher variability of the 99th percentile of area-maximum surface wind speeds obviously makes the description of more extreme storm activity through pressure proxies difficult, especially at the extra small scales.

Generally speaking, we see that the 99th percentile of absolute pressure tendencies performs better in describing storm activity than the 1st percentile of pressure, in particular, over larger scales. Furthermore, we looked into the median correlations of high percentiles of absolute pressure tendencies with $\Delta t = 8$ h, because $\Delta t = 8$ h results in one of the highest informational contents (Fig. 3). Our analysis reveals that the behavior is very similar to the case of $\Delta t = 24$ h. The correlations with 95th percentiles of area-maximum surface wind speeds remain at about 0.5 for sea surfaces and 0.45 for land surfaces, and slightly decrease to 0.42 on large scales for land surfaces. The differences between land and sea surfaces grow from 0.05 to 0.09 throughout the scales. The correlation with 99th percentiles of area-maximum surface wind speeds for combined surface properties is about 0.42 for all scales. Over sea, the correlation increases from 0.42 to 0.45 from extra small to small scales and remains at that value. Over land, the correlation decreases from 0.42 to 0.35 from extra small to large scales. The differences between land and sea surfaces vanish for extra small scales and increase to about 0.1 throughout the scales. The differences are little over extra small scales because of the higher informational content that results from a smaller Δt.

The presented results also depend on the classification criteria for land and sea surfaces. We have used a land fraction of 0.5 as the threshold to distinguish between land and sea surfaces, which include mixed surface conditions. When making use of stricter thresholds we would expect higher absolute correlations over sea surfaces, because the influence of land surfaces would become weaker. Absolute correlations that follow from stricter thresholds to classify land and sea conditions (e.g., a land fraction smaller than 0.2 for sea surfaces and larger than 0.8 for land surfaces) are indeed different to the aforementioned results (not shown). Resulting correlations over land and sea surfaces behave almost the same qualitatively, but the differences between land and sea surfaces become more distinct. Further, the magnitude of the median correlations rises more drastically with increasing scales. Correlations of high pressure tendencies increase to 0.53 (0.47) when compared with 95th (99th) percentiles of area-maximum wind speed over sea at large scales. At the same, the correlation does not increase much over land surfaces. We also see an increased magnitude in the correlations of low pressure percentiles, in particular, over sea surfaces (up to -0.48).

Note that described effects strongly depend on the parameterization in the used limited area model. Atmospheric stability and frictional effects of vegetation cover and topography affect the near-surface winds, but because of the subgrid-scale processes involved, these effects are only parameterized on the subgrid scale in models. The influence of the details of these parameterizations on obtained median correlations is unknown and needs to be examined elsewhere. However, within the model the physics are consistent, making our results reliable. We can only speculate whether an advanced parameterization or a finer spatial resolution would either improve modeled winds or alter our results significantly.

4. Concluding remarks

This study systematically evaluates several single-station pressure-based proxies that have been and probably will be used to assess past and recent storm activity in the midlatitudes. We gauged the proxies against 95th and 99th percentiles of ground-level wind speeds and calculated correlations, which we use as a measure of informational value. Our results from examining the informational content of five different proxies indicate that the proxies are linked to storm activity in general. For the number of low pressure readings and low percentiles of pressure we found only weak informational value (absolute correlations of about 0.26), while proxies that are based on absolute pressure tendencies have higher informational value (up to a correlation of about 0.5 for mean tendencies). We also found that the correlations are systematically lower for the 99th percentiles of ground-level wind speeds because of the higher variability of extreme wind speeds. If, however, the informational value of the statistics of geostrophic wind speeds (Krueger and von Storch 2011) is taken as a standard, we see that even the statistics of absolute pressure tendencies have weaker informational value. Wind speeds in the midlatitudes directly relate to a pressure gradient that determines geostrophic wind speeds. Pressure tendencies, on the contrary, detect atmospheric disturbances and relate to storminess indirectly.

The tendency proxy that counts threshold exceedances is very sensitive to the threshold chosen, while the number of low pressure readings is insensitive toward changing the threshold value. When statistics of absolute pressure tendencies are considered, we find higher informational value when not too extreme percentiles or mean values are used.

Absolute pressure tendencies also have the potential of describing storminess for a larger area surrounding a weather station, which we have seen in a higher correlation on larger scales. Over sea, the proxies generally show higher informational value than over land. The informational value of low pressure readings, on the other hand, does improve considerably on increasing scales. Further, when comparing the first percentile of pressure with more extreme wind speeds within small scales, the differences even vanish between land and sea surfaces.

We found our results by using simulated air pressure and ground-level wind speed in REMO. We expect that our findings are as relevant in the real atmosphere as they are in the simulation.

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