Assessment of Value Added for Surface Marine Wind Speed Obtained from Two Regional Climate Models

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ABSTRACT

Hindcasts with reanalysis-driven regional climate models (RCMs) are a common tool to assess weather statistics (i.e., climate) and recent changes and trends. The capability of different state-of-the-art RCMs (with and without spectral nudging applied) to add value for surface marine wind speed in comparison to the reanalysis wind speed forcing is assessed by the comparison with observations in the eastern North Atlantic in 1998. Added value is elaborated on instantaneous wind speeds and their frequency distribution. The observations are discriminated into groups according to their proximity to land and assimilation status, meaning whether they are assimilated into the reanalysis or not. For instantaneous wind speeds RCMs do not show added value both in ‘‘open ocean’’ areas and the German Bight. However, in the English Channel, where local topography and associated local wind regimes become important, the regional models show an added value for instantaneous wind speeds. Concerning the wind speed distribution there is a clear indication for an added value of the RCMs in coastal regions, especially for higher wind speed percentiles, while in open-ocean areas no added value is found. In comparison to the unnudged simulation, the spectrally nudged simulations better represent both instantaneous wind speeds and their frequency distribution. These results hold independently of the measurements’ assimilation status. Strictly the findings of this study only hold for hindcast studies, the results may differ for other areas and years.

1. Introduction

Europe and the adjacent waters of the eastern North Atlantic and the North Sea lie within the midlatitude storm track and are therefore particularly prone to midlatitude cyclones. For the design and the maintenance of coastal protection measures, long and homogeneous time series of wind, waves, and surge are necessary to derive their statistics (in especially extreme value statistics) and to analyze long-term changes and trends. Additionally, these time series are needed for a variety of applications (e.g., the design and maintenance of offshore installations such as platforms and wind farms).

However, for marine areas (e.g., the northeast Atlantic and the North Sea), long and homogeneous datasets are rare. Regional atmospheric hindcasts obtained from regional climate models (RCMs) driven by global reanalyses form an alternative that can be used either to analyze long-term changes and trends (e.g., Fowler and Kilsby 2007; Weisse et al. 2005) or as forcing for other (e.g., hydrologic) wave or storm surge models (e.g., Gaslikova and Weisse 2006; Sotillo et al. 2005; Federico and Bellecci 2004; Kim and Lee 2003). This method of deriving smaller-scale information with a limited-area, high-resolution model using boundary conditions from a global model (e.g., a reanalysis) is called dynamical downscaling.

For regional hindcasts it is assumed that they will provide an improved representation of processes on scales below the reanalysis’ resolution such as fronts or mesoscale disturbances (e.g., Denis et al. 2002). Here,

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a crucial question is whether RCMs do indeed show an added value in comparison to the driving reanalysis. In the last few years this question was addressed by a number of studies (e.g., Castro et al. 2005; Sotillo et al. 2005; Feser 2006; Kanamitsu and Kanamaru 2007; Rockel et al. 2008). Summarizing current knowledge, whether a regional atmospheric hindcast can add value in representing a parameter, seems to be largely determined by the strength of influence of large-scale atmospheric motions on the parameter and the capabilities of the RCM in both retaining the large-scale value of the reanalysis forcing and improving the representation of smaller-scale peculiarities of the parameter.

Some examples for the assessment of added value in dynamically downscaled near-surface wind fields have been provided in Kanamitsu and Kanamaru (2007) and Sotillo et al. (2005). For the Atlantic basin northwest of Spain, especially far from coastal areas, Sotillo et al. (2005) found the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (NRA_R1) sufficient for realistically representing near-surface marine wind fields derived from in situ observations. On the other hand, Sotillo et al. (2005) found that toward coastal regions with complex orography in the Mediterranean, NRA_R1 near-surface wind fields are significantly enhanced by dynamical downscaling using RCMs, which is confirmed by Kanamitsu and Kanamaru (2007) for Californian coastal waters.

In contrast to Sotillo et al. (2005) this study elaborates on the added value of near-surface marine wind speed more systematically. The definition of added value used in this study is as follows: The RCM adds value to the reanalysis if the 10-m wind speed obtained from the RCM hindcast shows a better agreement with measured 10-m wind speed and its frequency distribution than the wind speed of the forcing reanalysis. This analysis and the work of Sotillo et al. (2005) complement each other to give a very broad picture of the capabilities of RCMs and the NRA_R1 to represent surface marine winds for European coastal waters and the adjacent North Atlantic.

The paper is structured as follows. In section 2 we describe the NRA_R1, the hindcasts, and in situ observations used in this study. The method of the added value assessment is explained in section 3. The results are presented in section 4 separated into instantaneous wind speed and their frequency distribution. Section 5 concludes the paper.

2. Datasets

a. The NCEP–NCAR reanalysis (NRA_R1)

The global reanalysis of atmospheric fields from NCEP–NCAR assimilates quality-controlled data with a scheme that is kept unchanged over the reanalysis period to eliminate perceived climatic changes due to changes in the data assimilation scheme (Kalnay et al. 1996; Kistler et al. 2001). Forecast 10-m horizontal wind speed components on a T62 Gaussian grid with a resolution of 1.875° × 1.875° were obtained from the National Oceanic and Atmospheric Administration/Office of Oceanic and Atmospheric Research/Earth Systems Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD) Boulder, Colorado, from their Web site (http://www.cdc.noaa.gov/) for the comparison with modeled and observed 10-m wind speeds.

b. Regional atmospheric hindcasts

Three regional atmospheric hindcasts are used in this study. The spectrally nudged regional climate model (REMO) simulation (SN-REMO) and the standard REMO simulation (STD-REMO) hindcasts with a horizontal resolution of 0.5° (≈50 km) were generated and described by Feser et al. (2001). The climate version (CLM) of the nonhydrostatic local model (LM) is provided by the German Weather Service/*Deutscher Wetterdienst* (DWD). The CLM hindcast with a resolution of 0.44° × 0.44° was provided by the Regional Atmospheric Modeling group at the GKSS Research Centre. All hindcasts are initialized and forced with the NRA_R1; the modeled domain covers almost the whole eastern North Atlantic and is depicted in Fig. 1. All three simulations use a type 2 dynamical downscaling as described by Castro et al. (2005) and Rockel et al. (2008).

REMO is a regional hydrostatic atmospheric model (Jacob and Podzun 1997). It has been developed from the Europa-Modell (EM) of the DWD and its dynamics are based on the primitive equations in a terrain-following hybrid coordinate system with 20 vertical layers. The prognostic variables of the model are surface pressure, temperature, specific humidity, liquid water, and horizontal wind components. REMO is set up in its climatic mode using the same parameterizations as in the global climate model ECHAM4 (Roeckner et al. 1996). Vertical diffusion and turbulent surface fluxes are parameterized following Louis (1979).

Feser et al. (2001) generated the current 58-yr (1958–2006) central European hindcast by forcing REMO with the NRA_R1 atmospheric global reanalysis applying the spectral nudging method after von Storch et al. (2000) with the nudging parameter set to $\alpha = 0.05$. Regional hindcasts or reconstructions are based on the idea that the skill of the driving global reanalysis is scale dependent; techniques are applied that keep the regional model solution close to that of the global reanalysis for larger scales that are well supported by data assimilation, but still allow the regional model to develop

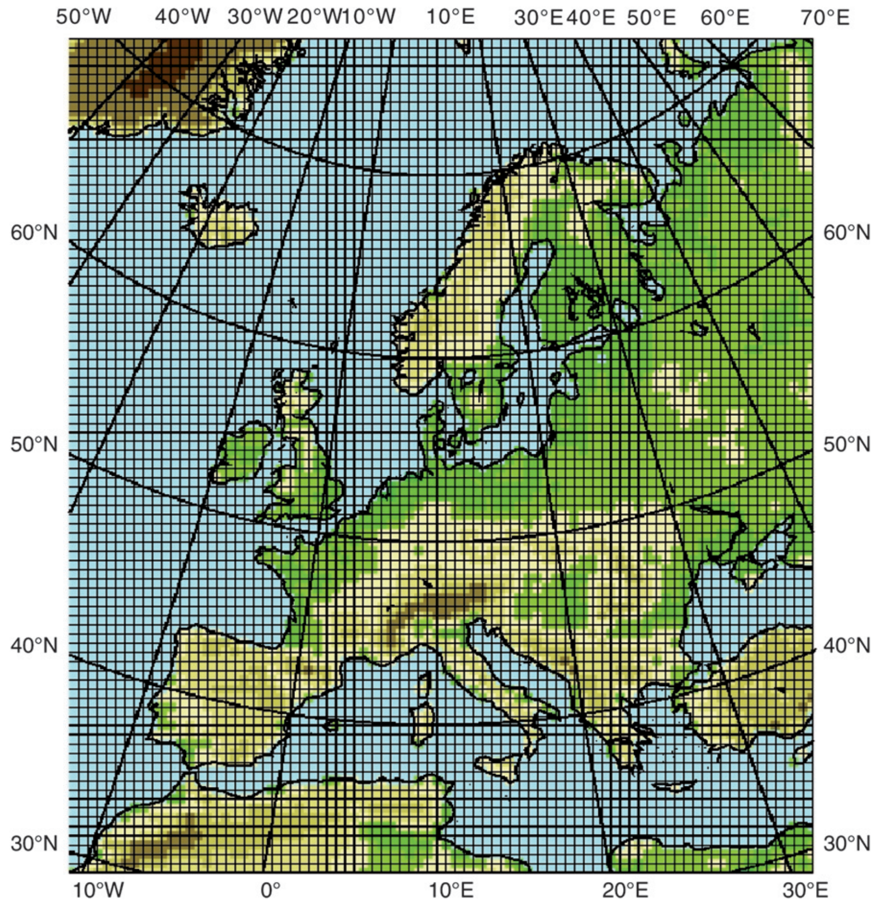

FIG. 1. Model domain of both SN-REMO and STD-REMO. (Courtesy of B. Geyer.)

independently from the global reanalysis on smaller scales, which are not reliably reproduced by the global reanalysis. Such techniques comprise scale-selective bias correction (e.g., Kanamaru and Kanamitsu 2007) or spectral nudging as proposed by Waldron et al. (1996) and von Storch et al. (2000). The spectral nudging approach is sometimes referred to as regional data assimilation without observations (von Storch et al. 2000).

In addition to the SN-REMO, a STD-REMO is examined in this study. The STD-REMO utilizes the conventional approach of initializing and periodically providing the model with updated boundary conditions at the surface and the lateral boundaries only. Apart from the spectral nudging both simulations have an identical model setup. This allows an assessment of the spectral nudging approach regarding the quality of simulated near-surface marine wind speed.

In addition, a simulation with CLM (Böhm et al. 2006) with spectral nudging after von Storch et al. (2000) applied ($\alpha = 0.5$) is assessed in this study. Physics and dynamics of the CLM are taken from the operational weather prediction model LM (Doms et al. 2005; Doms and Schättler 2005).

All three simulations deliver diagnostic 10-m wind speed, meaning that the 10-m wind speed is calculated from the prognostic wind speed at the lowest model level, being 32 m for both REMO simulations and 34 m for CLM.

c. *In situ data*

Wind speed observations in the North Atlantic and North Sea in 1998 are used in this analysis. The observations with a 1-h frequency are described in Table 1, their locations are depicted in Fig. 2 over the underlying NRA_R1 and REMO land–sea masks. Wind speeds were converted to 10-m height using the Coupled Ocean–Atmosphere Response Experiment (COARE) bulk flux algorithm in version 3.0b after Fairall et al. (2003) for anemometer height and stability correction. Records with implausible wind speed, air, and sea temperature data were discarded in this analysis. A typical value of relative humidity of 75% was assumed if humidity

TABLE 1. Marine wind speed observations, their location, platform type, and measurement height z_{obs}. Data were obtained from the Met Office (UKMO), Koninklijk Nederlands Meteorologisch Instituut (KNMI), Norwegian Meteorologisk Institutt (DNMI), and Deutscher Wetterdienst (DWD) and Bundesamt fuer Seeschifffahrt and Hydrographie (BSH).

Name	Lon (°E)	Lat (°N)	Type	z_{obs}	Institution
K1	−12.4	48.7	Buoy	3 m	UKMO
K5	−11.7	59.2	Buoy	3 m	UKMO
RARH	−9.9	57.0	Buoy	3 m	UKMO
Frigg	2.1	59.9	Rig	95 m	DNMI
F3	4.73	54.85	Rig	59 m	KNMI
NSBII	6.33	55.0	Buoy	10 m	BSH
K13	3.2	53.2	Rig	74 m	KNMI
Ems	6.35	54.17	Ship	10 m	BSH/DWD
DeBu	7.45	54.17	Ship	10 m	BSH/DWD
Chan	−2.9	49.9	Ship	14 m	UKMO
GRW	0.0	50.5	Ship	14 m	UKMO
Sand	1.8	51.1	Ship	14 m	UKMO

data was missing. This approach is justified by the minor influence of the relative humidity on the stability as compared to the air–sea temperature difference (e.g., Babin and Thompson 2000, their Fig. 2).

3. Method

The assessment is carried out for the year 1998 because of data availability reasons. NRA_R1 10-m wind speed forecast available every 6 h is time interpolated to the 1-h frequency prescribed by the RCMs and observations. For the comparison with observed wind speeds, NRA_R1, REMO, and CLM grid-box means are bilinearly interpolated to the station's location. It is expected that the wind field in the open ocean is largely determined by large-scale atmospheric motions, thus the possibilities of the RCM to add value to the NRA_R1 are expected to be limited there. In coastal areas, especially for complex and rough coastlines, where orographic-induced wind flow increases the spatial and temporal variability of the wind field, the RCMs are expected to add value to the NRA_R1.

Consequently, to discriminate whether the added value of regionally modeled wind speed is more pronounced near coastal areas with complex topographic features or strong gradients, the 12 observations are divided into coastal and open-ocean stations. A station is classified as a coastal station, if at least one of the four surrounding NRA_R1 grid boxes used to bilinearly interpolate NRA_R1 wind speed to the observation location is a land grid box and as an open-ocean station otherwise (see Fig. 2). The only exception from this classification scheme is the station K13, which is regarded as a coastal station because the main westerly wind conditions are heavily influenced by the British island and eastern and southern winds by the continental landmasses on both sides of the English Channel.

The comparison of reanalysis wind fields with in situ wind observations is heavily debated, since the reanalysis process itself involved the assimilation of measured surface marine data into the surface wind field products and is therefore not independent of the in situ wind field (e.g., Swail and Cox 2000; Sotillo et al. 2005). To elaborate on this issue the 12 in situ observations are additionally discriminated according to their proximity to land and their assimilation status, meaning whether they are assimilated into the reanalysis or not. With the help of the PREPBUFR files obtained from NCAR, the assimilation status of the observations into the NRA_R1 was determined. The 12 observations can thus be divided into the four groups (see Fig. 2):

- assimilated open-ocean stations:
  K1, K5, RARH
- not assimilated open-ocean stations:
  Frigg, F3, NSBII
- assimilated coastal stations:
  Chan, GRW, Sand
- not assimilated coastal stations:
  K13, Ems, DeBu.

The added value for both instantaneous wind speed and its frequency distribution are elaborated. The Brier skill score (BSS) is used to test to what extent the regionally modeled wind gives a better reproduction of in situ wind speed than the NRA_R1. It is defined (e.g., von Storch and Zwiers 1999) by

$$B = 1 - \sigma_F^2 \sigma_R^{-2}, \qquad (1)$$

where σ_F^2 and σ_R^{-2} represent the error variances of the "forecast" F (i.e., the time series of regionally modeled wind speeds) and the reference forecast R (i.e., the time series of NRA_R1 wind speeds). The error variances are computed relative to the same predictand, here the respective time series of observed wind speeds in 1998. By definition the BSS can vary between $-\infty$ and $+1$ (i.e., the forecast exactly matches the observations). While negative values indicate a better performance of the reference forecast (NRA_R1), positive values indicate an added value of the regionally modeled winds in comparison to the NRA_R1 time series.

As far as the wind speed frequency distributions are concerned the wind speed percentiles and the BSS will be used to assess the value added by the RCMs.

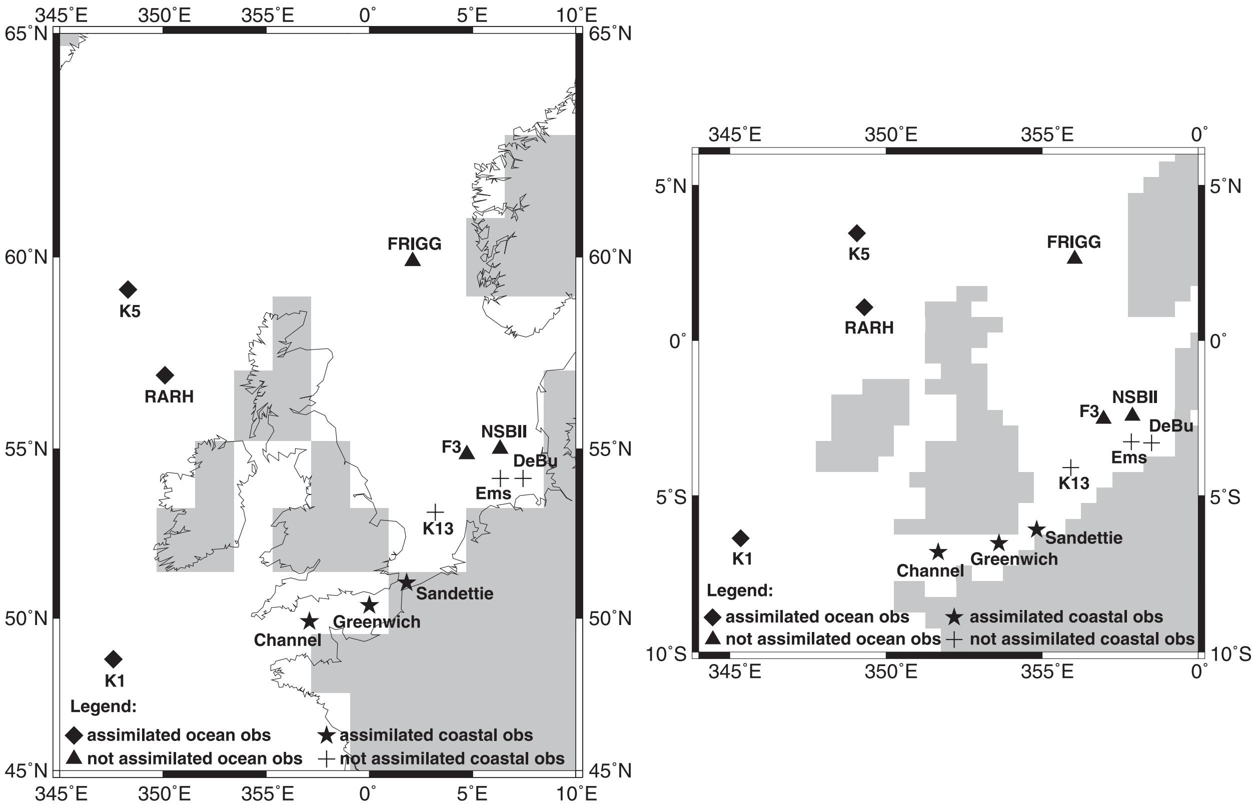

FIG. 2. Locations of wind speed observations (obs) over land–sea masks of (left) NRA_R1 and (right) REMO (rotated coordinate system).

4. Results

a. Instantaneous wind speeds

Measured wind speeds are compared with those modeled for the year 1998. For that purpose mean wind speed, standard deviations, correlation coefficients, and BSS have been determined and are depicted in Fig. 3.

Observed annual mean wind speeds vary approximately between 8 and 9 m s^{-1} (see Fig. 3a). The mean wind speeds at Ems and especially DeBu are higher than the mean wind speeds at the open-ocean stations, which seems unusual, although 1998 was an above-average wind speed year in the German Bight. Within the English Channel mean wind speeds are highest in the broad western mouth (Chan) decreasing toward the eastern outlet (Sand). The increasing influence of the surrounding landmasses may be responsible for this.

If the result of a comparison between hindcast, reanalyzed, and in situ wind speed is determined by the assimilation status of the in situ observation, it should be expected that for an assimilated observation the differences between NRA_R1 and in situ wind speed are lower than those between hindcast and in situ data. Similarly, the differences between the NRA_R1 and in situ observations assimilated into the NRA_R1 should be lower than those between NRA_R1 and unassimilated in situ data. However, a dependence of the comparison of observed and modeled annual mean wind speeds on the assimilation of the observation cannot be seen in contrast to the dependence on the distance from land.

The differences between the NRA_R1 and in situ wind are similar for the open-ocean observations, whether they are assimilated (K1, RARH, and K5) or not (Frigg, F3, and NSBII). In contrast, the absolute differences seem to be even higher for the assimilated coastal stations Chan, GRW, and Sand than for their unassimilated counterparts (K13, Ems, and DeBu), indicating that the complex topography in the English Channel, which the NRA_R1 cannot resolve, has a higher impact on the comparison than the assimilation status of the observation.

At open-ocean stations the regional models tend to overestimate the mean wind speed, while NRA_R1's annual mean wind speed is normally closer to the observed one. In contrast, the mean coastal wind is strongly underestimated by the NRA_R1, while the regional models show better agreement, although they also underestimate the mean coastal wind. Again these findings are independent of the assimilation status of the observation.

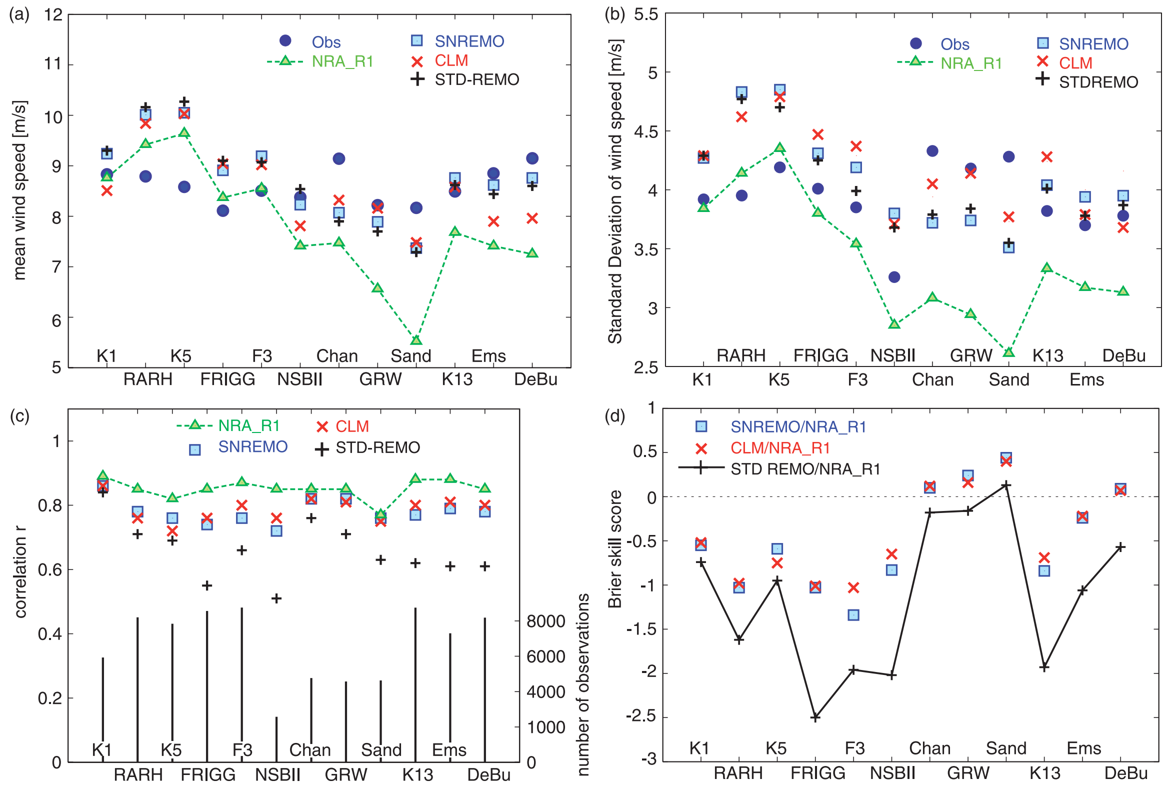

FIG. 3. Comparison of in situ, reanalyzed, and RCM-hindcast wind speed for 1998: (a) mean wind speed, (b) its std dev, (c) number of observations and correlation coefficient *r*, and (d) BSSs using NRA_R1 time series as reference forecast and SN-REMO, STD-REMO, and CLM time series as forecast.

The mean observed wind speed at K5 is around 1.5 m s^{-1} lower than that of the NRA_R1 and all three RCM simulations. However, comparisons with wind speed retrievals from the Hamburg Ocean–Atmosphere Parameters and Fluxes from Satellite (HOAPS) dataset [a multisatellite product based on Special Sensor Microwave Imager (SSM/I) measurements; Andersson et al. 2007], indicate that the bias is at least partly due to too low wind speed measurements at K5.

RCM wind speeds show a higher variability than NRA_R1 at all stations (see Fig. 3b). However, the regional simulations show more variability than observed at open-ocean stations, which is implausible as they give the wind speed averaged over a wide area and should therefore have lower wind speed variabilities than the point observations. The higher RCM variability may be connected to the models' overestimation of the mean wind. On the other hand it cannot be excluded that buoy measurements give a reduced wind speed variability as they may underestimate the wind speed in high sea states (e.g., Gilhousen 1987). In coastal areas there is no consistent behavior of modeled versus observed variability. For the light ships in the English Channel, REMO and CLM underestimate the variability, however, being much closer to the observed variability than the NRA_R1. Considering the coastal stations in the German Bight, RCM-hindcast wind speed variability is similar to the one observed.

As depicted in Fig. 3c NRA_R1 wind speeds show the highest correlation with observations approximately ranging from 0.8 to 0.9, apparently independent of observation assimilation status or proximity to coast. All regional simulations have lower correlation coefficients at all stations, however, the spectrally nudged simulations (SN-REMO and CLM) always show higher correlation coefficients than the standard REMO simulation.

To test to which extent the regionally modeled wind speed fits the observed data better or worse than the NRA_R1, the BSS is computed according to Eq. (1). While negative BSS values show a worse representation of the observations than by the reference NRA_R1 wind speeds, positive values show an improvement in comparison to the NRA_R1 time series.

As illustrated in Fig. 3d the spectrally nudged simulations always have a higher BSS than STD-REMO, thus CLM and SN-REMO always reflect the measurements better than the unnudged STD-REMO. While STD-REMO has negative BSS values at all stations apart

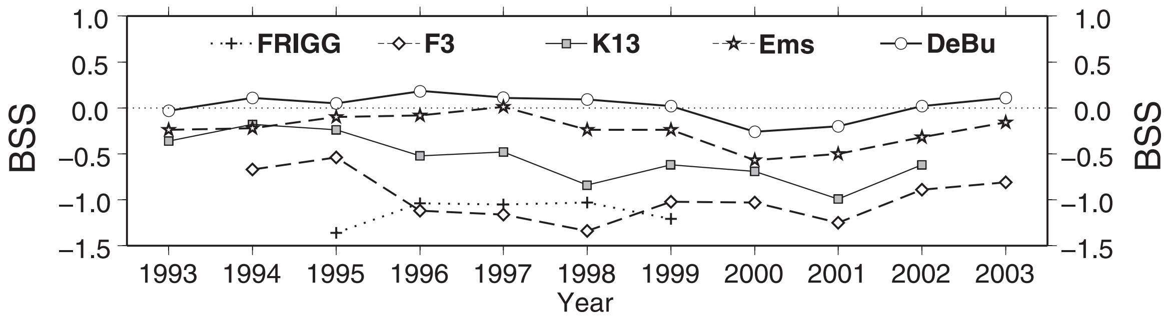

FIG. 4. Yearly BSSs at five stations.

from the coastal station Sandet-tie, SN-REMO and CLM have positive BSS values for the four coastal stations: English Channel, Greenwich, Sandettie, and DeBu. Thus, NRA_R1 wind speed time series fit the observations better at all open-ocean stations (independent of their assimilation status) and even at the two coastal stations K13 and Ems. Again the assimilation status of a coastal station is of minor importance, as SN-REMO has positive BSS values for all three assimilated light ships in the English Channel, but only for one unassimilated coastal station (DeBu).

To see whether these results are similar for different years, yearly BSSs with SN-REMO as forecast and NRA_R1 as "reference" were determined for several years for Frigg, F3, K13, Ems, and DeBu (multiyear data were not available from CLM and the other stations). One can infer from Fig. 4 that there is, if at all, only a small added value of SN-REMO for DeBu; for all other stations the regional model shows no added value in instantaneous wind speeds.

To judge whether the supposed added value for DeBu is significant, a t test for comparison of the expectation value of two independent normally distributed random variables X and Y was applied. The random variables X and S were chosen as

$$X = |F - O|$$
$$Y = |R - O|,$$

with F being the SN-REMO forecast, R is the NRA_R1 reference forecast, and O is the observation. In case of an added value of SN-REMO the expectation value of $X = \mu_X$ should be smaller than μ_Y. To allow for independence of X and Y, the available realizations of X and Y were subsampled, taking into account every 161st observation, which corresponds with a sampling interval of 6 days and 17 h. The sampling interval was arbitrarily chosen that large to be on the safe side concerning the independence of individual observations. The 17 h were chosen to avoid an overrepresentation of daily wind cycles. The H_0 was tested using a t statistic as described in von Storch and Zwiers (1999). The H_0 could not be rejected with an error probability $\alpha \leq 10\%$. Thus, SN-REMO has no significant added value at DeBu. The same test was applied for Frigg, F3, K13, and Ems. The H_0 could be rejected with $\alpha \leq 1\%$ for Frigg, F3, and K13 and $\alpha \leq 10\%$ for Ems showing that NRA_R1 winds are statistically significantly better than their regional model counterparts.

Up to this point, it can be concluded that in comparison to NRA_R1 there is no added value from regional models for instantaneous marine wind speed. However, there is an indication for an added value in the instantaneous wind speeds for rough coastal areas with a complex orography like the English Channel.

b. *Wind speed frequency distribution*

When wind speed distributions are concerned, the regional models always show a better representation of observed frequency distributions than the NRA_R1 for coastal areas (exemplarily shown in Fig. 5b for the light ship English Channel). The NRA_R1 is generally underestimating the observations variability in coastal areas, as can be expected from a mean value over 20 min and a wide area. The underestimation is biggest for the English Channel stations. This underestimation of variability together with NRA_R1's strong negative wind speed bias leads to overestimations of the lowest percentiles and underestimations of higher percentiles.

For open-ocean stations NRA_R1 wind speed variabilities better correspond with the observed variabilities. The regional models produce a lot of unobserved wind speed outliers for all stations (not shown). Together with the regional models' strong positive wind speed bias they lead to overestimations of higher percentiles in open-ocean areas, with overestimations increasing toward the highest percentiles. Observed wind speed frequency distributions in the open ocean are better reproduced by NRA_R1 (shown for RARH in Fig. 5a).

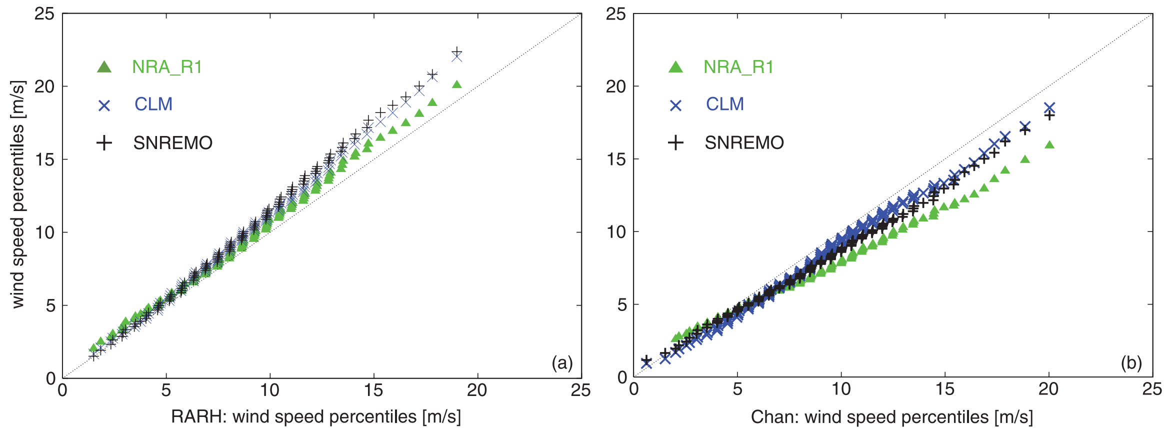

FIG. 5. Percentile–percentile distributions of wind speed in 1998, measured (*x* axis) vs NRA_R1, SN-REMO and CLM percentiles at (a) the buoy RARH as an open-ocean station and (b) the light ship English Channel as a coastal station. The 99 symbols (triangles, crosses, and Xs for NRA_R1, SN-REMO, and CLM, respectively) represent the wind speed percentiles in steps of 1%. Thus, the first (last) symbol represents the 1st (99th) percentile and the wind speed below which 1% (99%) of all in situ and modeled wind speeds can be found, respectively. In the ideal case of perfect agreement between in situ and modeled wind speed frequency distributions, all percentiles would lie on the bisector line.

For coastal areas there is a clear indication of a general added value of the spectrally nudged models for wind speed frequency distributions, not limited to 1998. This can be inferred from the yearly 50, 90, and 99 percentiles determined for Frigg, F3, K13, Ems, and DeBu. These percentiles are shown for F3 and DeBu in Fig. 6. Indeed SN-REMO represents the observed 50, 90, and 99 percentiles better than the NRA_R1 at DeBu and the two other coastal stations: K13 and Ems. Contrarily, NRA_R1 wind speed percentiles are closer to observed ones for the two open-ocean stations Frigg and F3. Similar results were found for CLM (not shown).

BSSs have been calculated using the observed yearly 50, 90, 95, and 99 percentiles and the respective SN-REMO and NRA_R1 percentiles as forecast and reference forecast. While it can be argued, that the calculated BSSs stem from just 5 (Frigg) to 11 (DeBu, Ems) available yearly percentile values and are therefore of limited value, the calculated positive and negative skills provide some indication of the general validity of the above findings. The results are displayed in Table 2 showing that there is an added value of SN-REMO for the distribution of higher wind speeds and their interannual variability in coastal areas, while NRA_R1 is better at reproducing distributions of higher wind speeds in open-ocean areas. The added value of NRA_R1 in the open ocean is mainly determined by the big wind speed bias of SN-REMO, but even after a bias correction the NRA_R1

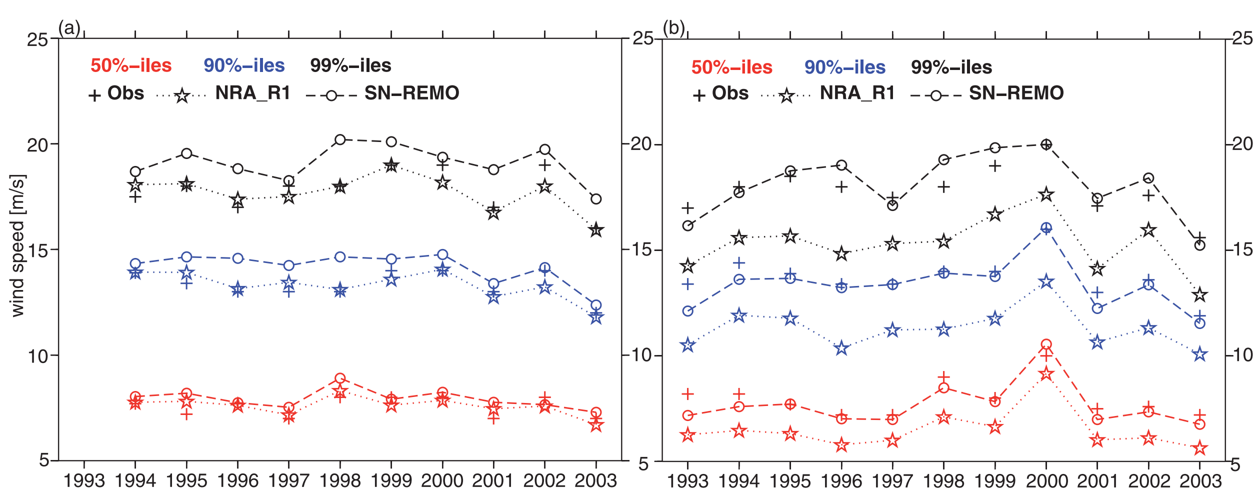

FIG. 6. Yearly percentiles of wind speed for (a) the platform F3 as an open-ocean station and (b) the light ship DeBu as a coastal station: observation (cross), NRA_R1 (dotted, star), and SN-REMO (dashed, circle). Red: 50%, blue: 90%, and black: 99%.

TABLE 2. BSSs of yearly percentiles from Frigg, F3, K13, Ems, and DeBu.

	Open ocean		Coastal stations		
%	Frigg	F3	K13	Ems	DeBu
99	−12.53	−6.86	0.37	0.78	0.93
95	−15.42	−2.67	0.58	0.93	0.95
90	−16.03	−6.18	0.80	0.95	0.95
50	−11.03	−1.69	0.86	0.90	0.90

has a strong positive skill for F3 and Frigg for all the mentioned percentiles.

5. Discussion and conclusions

In the eastern North Atlantic and the North Sea, marine wind speeds face a shift in the scale of driving processes in the transition from open ocean to coastal areas. In open-ocean areas surface wind speed is strongly determined by large synoptic-scale cyclones and pressure systems, while in coastal areas local medium- to small-scale wind regimes contribute more strongly to its characteristics.

In detail this study shows the following:

- For open-ocean areas there is no value added to the reanalysis forcing by the use of the RCMs REMO and CLM either for instantaneous wind speed or its frequency distribution.
- In coastal areas value is added by REMO and CLM only in frequency distributions.
- However, there is also an indication for added value in the instantaneous wind speeds for rough coastal areas with a complex orography like the English Channel.
- An influence of the observations assimilation status on these findings cannot be seen.

Frequent occurrence of mesoscale phenomena like mesocyclones (e.g., due to cyclogenesis in unstable cold air behind synoptic cyclones or a cold front or polar lows), fronts, land–sea breezes, or orographic-induced wind flow would increase the possibilities of RCMs to add value. Land–sea breezes and orographic-induced wind flow do not occur in the open ocean and are constrained to coastal areas. According to Harold et al. (1999) the centers of mesocyclone activity in the North Atlantic are north of 60°N and west of the British Isles (their Fig. 2). Thus, the mesocyclone activity at the analyzed stations is relatively low, which concludes that there is hardly any possibility for the RCMs to add value at the open-ocean stations, which is reflected by the negative BSSs.

Contrarily to our results, Sotillo et al. (2005) suggested an added value of SN-REMO even for single extreme wind events in the Mediterranean linked to regional winds (i.e., Bora, Tramontana, and Mistral). As the Mediterranean area studied by Sotillo et al. (2005) has a much more complex coastline and stronger topographic gradients, it is concluded that such topographic effects are more important in the Mediterranean than in the North Sea.

Combining the results of Sotillo et al. (2005) and this study it can be stated that the only added value of regionally modeled marine wind speed fields for hindcast purposes can be seen close to coastal areas with a complex orography like in the Mediterranean and the English Channel. Therefore, apart from a slightly better representation of the orography, there may be little advantage in using RCMs in this context.

Because of higher mesocyclone activity in wintertime (e.g., Harold et al. 1999) there might be seasonality in the results. However, according to Harold et al. (1999) the strongest seasonal changes in mesocyclone activity occur near the Norwegian Coast, near the ice edge, and south and southwest of Iceland. Thus, the analyzed stations are prone to a comparatively low seasonality in mesocyclone activity and therefore qualitative changes in the added value are unlikely. A dependence of the results on weather regimes cannot be excluded but cannot be investigated in detail with the limited amount of in situ data available.

There are several limitations to this study. In this study the analysis has been conducted for the North Sea and eastern North Atlantic; the regional models may behave differently in other areas. A part of the investigated area (North Atlantic west of the British Isles and the English Channel) was analyzed for 1998 only and the behavior may change in different years. Strictly the findings of this study only hold for hindcast studies:

- For the purpose of designing coastal and marine infrastructure when wind speed distributions are needed the NRA_R1 is recommended for open-ocean areas while hindcast wind speeds from regional models may improve the results in coastal regions.
- The meaning of the results for forecast studies cannot be judged. In the forecast mode boundary conditions are much less perfect, thus there is a remaining chance that the regional model improves for forecast purposes. For the assessment of added value in the context of numerical weather predictions please refer to Rife and Davis (2005) and references therein.
- The meaning of our results for climate change simulations is unclear.

The spectral nudging technique proposed by von Storch et al. (2000) can be interpreted as a poor man's regional data assimilation; in our case its use leads to a better reflection of instantaneous wind speeds by CLM and SN-REMO than by STD-REMO. However, the performance of CLM and SN-REMO is too poor to beat NRA_R1 wind speeds in open-ocean and ''less complex'' coastal areas.

One of the biggest limitations of this study might be the assumption that the partly extrapolated wind speed observations represent the truth–the actual wind speeds at 10-m height. Especially for high wind speeds and in high or ''choppy'' sea states the accuracy of buoy measurements is arguable (e.g., Gilhousen 1987). For anemometers atop NSBII, Ems, and DeBu a RMSE of 0.3 m s^{-1} or 20% is given, whichever number is larger (Bundesamt fuer Seeschifffahrt and Hydrographie, K. Herklotz 2007, personal communication). Wind speeds of the English bouys and light ships were converted to 10-m height after Fairall et al. (2003) for stability and anemometer height correction. Alternatively, they were converted to 10 m using the neutral logarithmic wind speed profile with a varying roughness length according to Charnock (1955). The results with these two different conversions mechanisms were negligibly different. The biggest deviations from actual wind speeds at 10 m may occur at the platforms Frigg, F3, and K13 mainly because of the big differences between measurement and extrapolation height of up to 85 m for Frigg and the heavy influence of the oil platform structure on the measurements.

Furthermore, there are uncertainties in the diagnostic 10-m wind speed from CLM and REMO. It can be argued that changes in the surface layer parameterization and especially the roughness parameter or Charnock constant might lead to improvements in the surface wind speed representation by REMO and CLM in the open ocean. However, Weisse and Schneggenburger (2002) show that differences between individual realizations of different ensembles (using different parameterizations of the momentum flux after Charnock 1955; Janssen 1989, 1991; Makin and Kudryavtsev 1999) cannot necessarily be considered as being entirely induced by the models sensitivity to the models parameterizations. Therefore, any tuning of the surface layer parameterization of REMO and CLM is not considered in this study.

Additional uncertainties can be introduced by the different temporal and spatial resolutions of the observed, reanalyzed, and modeled wind speeds. The NRA_R1 forecast used in this study is available every 6 h; modeled and observed means are available every hour. In the presented analysis the NRA_R1 was time interpolated to 1-h resolution. Subsampling the modeled and observed wind speeds to the 6-h frequency prescribed by NRA_R1 is an alternative approach. Both methods have been tested; the resulting differences were negligible.

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