Spatial Extension of Coastal Impact on the Mean Surface Wind over the Baltic Sea

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Abstract

The coastal wind field over sea is affected by various influences, resulting from the changing terrain. Mean wind wind speed in coastal areas is generally lower than at the open sea. The spatial extension of the coastal impact on the mean wind speed is worked out for the Baltic Sea by a comparison of analysed geostrophic wind with ship observed surface wind. It is shown that the zone of coastal influence on the surface windfield extents up to 50 km distance to the coast with the greatest variations within the first 20 km.
Keywords: Wind speed, Baltic Sea, Resources, Boundary Layer

Introduction

The coastal zone can be regarded as a transient zone, where the roughness increases from low values at the open sea over higher values in the coastal zone due to influences of limited fetch or water depth on roughness to at least the high roughness of land surfaces. Also the occurance of land or sea breezes affects the surface wind field driven by the large scale pressure field as well as such effects like channeling by the topography of the land. Thus a good knowledge about the coastal impact on the mean surface wind field may be used to give a guideline for the location of offshore wind power plants. Information about the coastal influence on the surface wind field is obtained by calculating ageostrophic ratios of observed surface wind to analysed geostrophic wind speed for the 2-year period 1992/1993 as a function of the distance to the coast. Geostrophic winds are estimated from pressure observations of voluntary observing ships and coastal weather stations. Validation of estimated ageostrophic coefficients was achieved by using independent data from 1994.

Data

The dataset to estimate geostrophic wind fields and derive ageostrophic coefficients contains daily observations of ships and synoptic stations at land from January 1992 until December 1993 at 00, 06, 12 and 18 UTC. During this period nearly 10300 ship wind observations at the Baltic Sea were gathered. Most of the ship observations were located in the south-east parts.
There are two kinds of wind observations on voluntary observing ships: Direct measurements and Beaufort estimates of wind according to WMO 1100 scale (WMO, 1970). The wind speed of direct wind measurements is reduced from an assumed average height of 20 m (CARDONE, 1990) to 10 m using the logarithmic wind profile. Wind estimations on ships should correspond to wind speeds at a height of 10m (WMO, 1970). Accuracy of ship positions is 0.1° latitude and longitude.
Validation of surface wind fields was done using the same kind of data from 1994. For 1994 there are about 8300 observations at our disposal. All data were provided by the Deutscher Wetterdienst.

The Analysis

The analysis scheme was developed at the Institut für Meereskunde (IfM) in Kiel (ENNENGA, 1985, BUMKE und HASSE, 1989). It is based on the polynomial method (PANOFSKY, 1949; GILCHRIST and CRESSMANN, 1954). The polynomial method is applied to each grid point of a 1° latitude/ longitude field. A second order pressure field is determined simultaneously by observations of wind and air pressure:

$$p^* = a_{00} + a_{10}x + a_{20}x^2 + a_{11}xy + a_{01}y + a_{02}y^2 \qquad (1)$$

x and y are the distances in north and east directions between the positions of observations and grid point. The asterix marks an estimated parameter. The relation of the pressure to the wind field is assumed to be geostrophic. This necessitates a boundary layer parameterisation to get geostrophic winds from surface wind observations. For this purpose a stability dependent approach of LUTHARDT and HASSE (1981) was used, derived for situations with onshore winds in the German Bight.
The geostrophic wind components u_g^* and v_g^* are given by

$$u_g^* = -\frac{a_{01} + 2 a_{02} y + a_{11} x}{f \rho} \qquad (2)$$

$$v_g^* = \frac{a_{10} + 2 a_{20} x + a_{11} y}{f \rho} \qquad (3)$$

Here f is the Coriolisparameter and ρ the air density.
The solution of the polynom (1) is given by minimizing the sum S.

$$S = (1-W)\sum C^2(p-p^*)^2 + W \sum C^2((u_g - u_g^*)^2 + (v_g - v_g^*)^2) \qquad (4)$$

C is a Cressman-function, which provides for decrasing influence of an observation with increasing distance to a gridpoint (CRESSMANN, 1954). W weights the relative influence of pressure and wind observations , for analysis W=0.3 was choosen.
Due to the sparsity of ship observations additional information from coastal stations was required. Coastal stations in this context are all synoptic stations with a height of 50 m and less. Due to possible orographic influence wind observations of coastal stations are excluded. Since we intend to derive the spatial extension of coastal influence at sea, only ship wind observations were taken into account, which were not influenced by orographic effects. To fulfill this condition a distance to the coast of more than 100 km was assumed to be sufficient. As a consequence all wind observations closer than 100km to the coast can be regarded as independent from

the analysis. Interpolation of air temperature and water temperature has been done by averaging the observations linearly over areas of 2° latitude/longitude. Again the information of coastal stations was used for interpolation. Due to the insufficient number of water temperature observations water temperatures have been estimated as a five day average.

Comparison to Observations

In this chapter analysed fields, interpolated linearly on the positions of the ship observations, are compared with direct ship observations. The pressure field is well described by the analysi). This is shown by a correlation coefficient of 0.99 and an RMS-deviation between calculated and observed air pressure of 1.0 hPa.

It should be noted here that the analysis scheme for air pressure observations as well as for wind observations used for analysis includes an error detection scheme. Because of the sparsity of temperature observations erroneous observations of air or water temperatures cannot be detected. Thus in contrast to the comparison of analysed to observed air pressure possibly erraneous temperature data are included in the following. For analysed water temperatures it was found that they are not biased compared to ship measurements. The correlation coefficient is rather high, it is 0.95 .

For the observed and analysed wind data the following ageostrophic angle were found: The mean difference between analysed and observed wind direction is 26.8°. If the stability is given by the temperature difference between analysed air and sea surface temperature ΔT_{ana}, the ageostrophic angle α can be described by a linear relation in the range of -3K $\geq$ ΔT $\leq$ 3K.

$$\alpha = 24.9 + 1.8 \cdot \Delta T \qquad (5)$$

The comparison of analysed geostrophic wind speeds to observations results in a complex correlation coefficient (MARSDEN, 1987) of 0.82, which considers wind direction and wind speed of analysed geostrophic and observed wind vectors.

Mean Fields of Geostrophic Wind Speed

Fields of geostrophic wind speed and direction have been calculated from synoptic data of the period from 1992 to 1994, every 6 hour. As an examle the result for 1994 is given in Figure 1.

The characteristics are that mean wind speed decreases from the south west to the north east. Compared to the conditions at other maritime European regions, e.g. the North Sea and Irish Sea (TROEN and PETERSEN,1989), the wind speeds are lower especially in the northern parts of the Baltic Sea. Thus it is very important to make the best use of the potential available wind energy by an optimal siting of the wind turbines.

Coastal Influence on the Mean Surface Wind

To consider the coastal influence on the mean wind speed a coefficient q is defined to give the ageostrophic ratio of analysed geostrophic and observed mean windspeeds. This coefficient is calculated for distance classes, because the ship positions are given only in terms of 0.1°latitude and longitude.

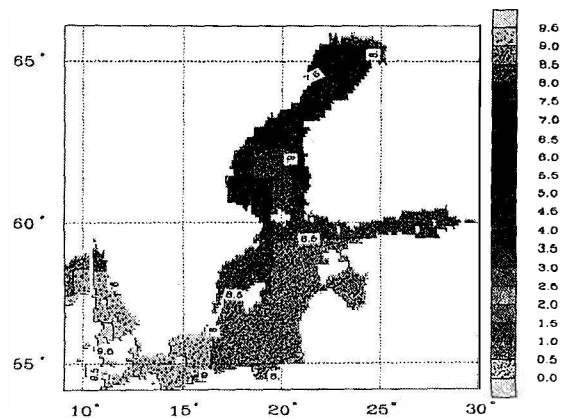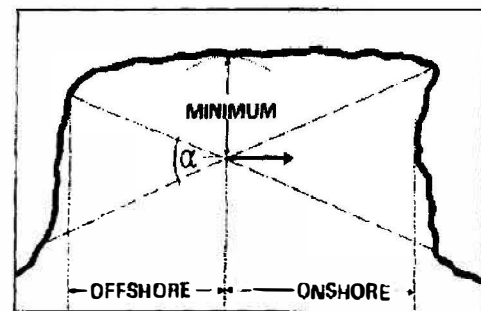Figure 1: Average geostrophic wind speed [m/s] in 1994.

Figure 2: Definition of offshore, onshore and minimum distance to coast. The ships position is starting point of the wind vector. Variability of wind direction is given by α.

The wind field in coastal areas is influenced by the change of roughness with higher roughness over land than at sea. If the wind is directed from land to sea, we can imagine a zone of wind speed adjustment to the new roughness conditions. Earlier studies (e.g. Theunert, 1986) showed that this zone of adjustment exists on both sides of the shore. So it is to expect that onshore wind speeds will change in a similar manner. Coefficients are calculated for different distance classes to coast. A wind direction dependent distance to coast has been defined in the manner illustrated in Figure 2. Every ship positions onshore and offshore coast distances have been assigned considering the wind direction.

The variability of wind direction is taken into account by averaging the coast distance for an interval of analysed wind direction ±20°, taking the ageostrophic angle according to equation (5) into account. The variability of wind direction is assumed to be independent of wind speed.

Since onshore as well as offshore winds have a zone of adjustment to new roughness conditions, it can be expected that the distribution of land and sea will have some impact on the surface wind field. Thus the ageostrophic ratio should be a function of a combination of onshore and offshore distances(Tab. 1) to the coast, giving smallest coefficients q in semi-enclosed areas with a small onshore and a small offshore distance to the coast.

Table 1: The ratio q of observed surface to analysed geostrophic windspeed for classes of onshore (rows) and offshore (columns) distances to the coastline.

q	offshore distance [km]					
	-5	-10	-20	-30	-50	>50
onshore distance -5	.48	.45	.65	.56	.63	.78
-10	.55	.59	.70	.77	.77	.68
-20	.62	.63	.72	.73	.80	.74
-30	.65	.74	.73	.72	.79	.76
-50	.76	.75	.81	.79	.75	.83
>50	.74	.79	.78	.85	.83	.86

Coastal impact on wind speed reaches up to 50 km from the coastline, while for distances greater than 50 km the coefficient q show no significant variations. In the distance classes up to 20 km the ratio between analysed and observed surface wind speed shows the greatest variations, from 20 to 50 km offshore and onshore distance to the coast the value of q increases only from 0.72 to 0.86 . This means that a significant impact on the mean windfield will vanish after 20 km offshore distance to the coast.

For winds blowing along the coast there are no onshore and offshore distances to the coast defined, in this case the coefficients q are calculated as a function of the minimum distance to the coast (Fig. 2). The results are given in Table 2.

Table 2: The ratio q of observed surface to analysed geostrophic wind speed for classes of minimum distances to the shore.

dist. [km]	-5	-10	-15	-20	>20
q	.63	.76	.80	.83	.86

Mean Fields of Surface Winds

Tables 1 and 2 can be used to estimate factors of wind speed reduction for each coastal area as a function of mean relative wind direction. If a large extension of open sea (in this case the distance to the opposite coast is greater than 50 km) is adjascent at a coastal site, slow changes of the coefficients q are evident. In the onshore case the range of q is between 0.74 and 0.86 and for offshore case q varies from 0.68 to 0.86. In semi-enclosed areas, that means onshore and offshore distances are smaller 20 km, the coefficient q has values between 0.48 and 0.72 . Generally coastal influence on the mean surface wind field will have an impact during the first 50 km distance to the coast line. The changes of wind speed at the land-sea transition appears to be composed of two parts: the more pronounced change within 15 to 20 km next to shore due to the different roughnesses of land and sea, and a change due to a variation in roughness due to the sea state in coastal waters, e.g. induced by change of depth or fetch limitations. Applying the coefficients of

Table 1 and 2 on the geostrophic wind fields, we get as expected a remarkably high reduction of the mean wind speed in coastal areas. This is shown in an example for the year 1994 in Figure 3.

Figure 3: Surface wind speed [m/s] in 1994, calculated from geostrophic winds by applying the ageostrophic coefficients of Tables 1 and 2.
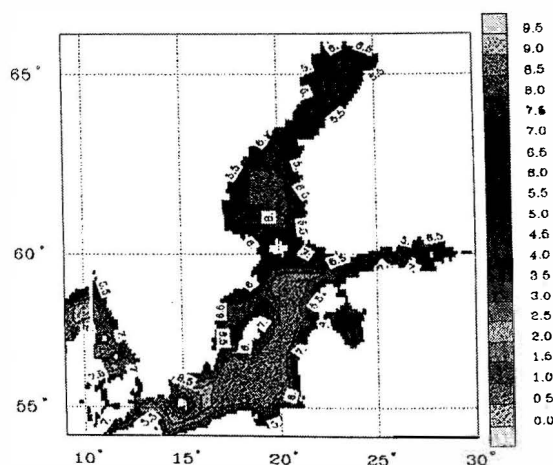
Generally wind speeds are highest during winter months and lowest during summer months. So we get the following picture: In areas with coast lines orientated parallel to the mean wind direction the coastal impact on the mean wind speed is small and limited to distances to the coast of less than about 10 km. In semi-enclosed areas and at coasts orientated perpendicular to the mean wind direction the coastal impact on the mean wind speed is high and should not be neglected up to down- or upwind distances of about 20 km to the coast. Because ageostrophics ratios of surface wind speed to geostrophic wind speed are calculated as a function of onshore and offshore distances to the coast only, all other processes, which may influence the surface wind field, are included in a statistical sense only. The coefficient q can depend on prameters like the windspeed and the stability over the coastal near sea surface, which is not considered in this approach.

Validation

Validation of estimated ageostrophic coefficients has been achieved by using analysed geostrophic wind fields and ship wind observations from 1994. These are independent from the calculated ageostrophic coefficients because these have been estimated from data of 1992 and 1993 only.

For the year 1994 the following relationships between analysed and observed wind are found. The complex correlation coefficient is 0.83 for observed and analysed wind. The annual analysed mean wind speed has no bias compared to ship observations of wind speed; the mean value for all ship observations and for analysed surface winds is 7.1 m/s. The variability of the wind speed field is described well by the interpolated wind field; the standard deviation of analysis is 4.2 m/s compared to 4.0 m/s resulting from ship observations of wind speed. The variation of wind speed is depicted by the Weibull distributions of wind speed p(U). The function is determined by

the two form parameters A und k.

$$p(U) = \frac{k}{A} \left(\frac{U}{A}\right)^{k-1} \exp\left(-\left(\frac{U}{A}\right)^k\right) \qquad (6)$$

Figure 4 show the Weibull functions fitted to the observations and the analysis. The agreement for the IfM surface wind analysis using the ageostrophic coefficients to the observations is good, while the Weibull function estimated for surface wind speeds of the European Area Model of the German Weather Service does not fit the Weibull distributions of the direct observations well.

Figure 4: Weibull distribution of surface wind speeds for the total Baltic Sea: full line: ship observations;dotted line: European Area Model; dashed dotted: this study
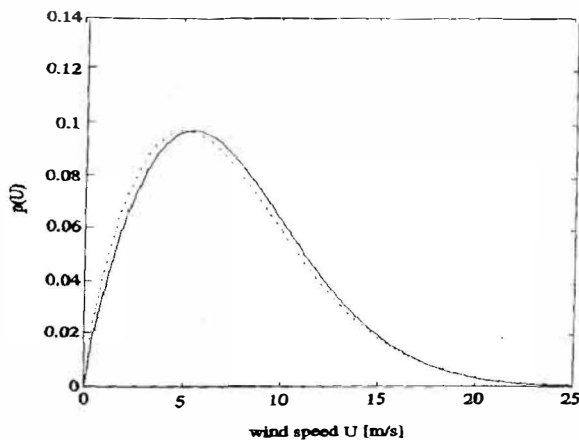
High wind speeds over sea are underestimated and moderate wind speeds are overestimated by the European Area Model. This is due to an underestimation of the mean value and the variance of wind speed.

In this approach ageostrophic coefficients depend on coastal distances only. Thus e.g. stability effects are neglected in the boundary layer. It is to expect that therefore seasonal means are not represented as well as the annual mean due to an annual cycle of stability.

We conclude that this analysis method is suitable to calculate annual mean wind speeds and the annual variance of the wind speed over the Baltic sea. For seasonal investigations a greater data base is neccessary to take the dependence on coastal distances and stability into account. A first approach by dividing the whole data set into three categories; stabil, neutral, and instabil due to air-sea temperature differences, results in a better estimate of the monthly mean, but the uncertainties in the estimated ageostrophic coefficients of each distance interval are high due to the not sufficient number of observations. Another result of this study is that the coastal influence on the mean wind speed is only marginal at distances of more than about 15 to 20 km to the coast. This should be reflected in measurements of drag coefficient, too.

Measurements of drag coefficients on our R.V. ALKOR using dissipation method showed (NEUGUM, 1995) that within a 10 km distance to the coast of Lolland drag coefficient is given by

$$C_{DN} = \left(0.87 + 0.0673 \cdot U_{10}\right) \cdot 10^{-3}$$

corresponding for 7 m/s wind speed to

$$C_{DN} = 1.34 \cdot 10^{-3}.$$

At the open sea east of Gotland drag coefficient is estimated to

$$C_{DN} = \left(1.11 \pm 0.17\right) \cdot 10^{-3}$$

for wind speeds ranging from about 5 to 12 m/s. Thus measurements of drag coefficient correspond well to the coefficients estimated by this statistical approach of ageostrophic coefficients as a function of the distance to the coast for the Baltic Sea.

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