Interpolating wind speed from the sparse Dutch network to a high resolution grid using local roughness from land use maps.

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1 ABSTRACT

There are different ways of creating gridded maps from observations. The aim of this study was to find an adequate method of producing interpolated maps of the yearly and monthly normals of the surface wind speed at all grid points in The Netherlands.

For 31 stations in the Netherlands, we had potential wind speed time series with 30 years of data (with at least 20 yearly or monthly averages) available as input for our method. Using Wieringa's 2 layer model (2LM) of the planetary boundary layer (later refined by Verkaik) the wind speed at the top of the boundary layer was calculated for each location. At this height above the relatively flat Dutch landscape, the ("macro") wind flows freely, undisturbed by variations in the underlying surface roughness. This makes it an ideal height for interpolating the wind speed. After interpolation, surface wind speeds were calculated for all the grid values of the macro wind using the 2LM and a map of the surface roughness of The Netherlands. The 2LM and WAsP (the wind energy industry standard for wind resource assessment) use identical physics but WAsP assumes a constant macro wind where we interpolate normals of the macro wind. Because we had to work with normals, all information on wind direction was lost. This information is required in WAsP for correction of the wind speed due to nearby obstacles or speed-up of the wind caused by hill slopes, whereas the 2LM takes neither into account.

Many aspects of the method were varied to improve the output map. For example, which stations to use and which not, the interpolation method, the size of the spatial footprint used to determine the values of the terrain roughness and whether or not to include roughness due to local differences in orographic height. In order to choose the most adequate version of the method, we looked at two aspects: how well the output compared to model and measured winds and how well the pattern of wind speeds met the expectations of wind experts. Our most adequate method makes use of input data from all but one station: the quality of the measurements at Rotterdam Geulhaven are too poor due to it's unique location in a built-up international port area. We used the inverse distance weighting interpolation method with an IDP of 2. The local surface roughness was represented by 2.5 km pixels and the meso- or regional roughness by 10 km pixels. Additional regional roughness due to orography was not used.

2 INTRODUCTION

Knowledge of the spatial distribution of the long-term average wind speed is essential for many activities e.g. the siting of wind turbines. However, wind energy resource and other models require gridded maps which include estimates of the wind speed at locations where no measurements are available. Generating gridded maps from point data, e.g. from the meteorological observation stations, is referred to as interpolation. Many interpolation methods are available and were previously used for meteorological data, e.g. multiple linear regression (Gurtz et al., 1999), inverse distance weighted (IDW) interpolation (Ni et al., 2006; Menzel, 1999), splines (McVicar et al., 2007; Jeffrey et al., 2001) or kriging (Jeffrey et al., 2001). The purpose of this study was to find an adequate method of producing interpolated maps of the yearly and monthly climate normals of the surface wind speed in The Netherlands.

3 DATA

Of the 26 stations with “as measured” (not corrected for surface roughness) wind speed normals (1981-2010), only De Bilt was not used for validation because the speed has, until recently, wrongly been corrected for non-standard anemometer height. The same correction method (Benschop, 1996) is rightly applied for the sea stations and for some coastal stations where the correction is proper only for wind coming from the sea. Wind direction is important at coastal locations but the roughnesses used in this study are independent of direction so the calculated and also the verification speeds are less than perfect. Stations Hupsel, Nieuw Beerta and Arcen are close to the border with foreign countries where only older surface roughness information (Wieringa, 1983) was available for our calculations. Therefore the potential wind speed from these stations is not used as input for the calculations The size of this border error is assessed using the border station "as measured" speeds. The only station excluded from both calculation and verification is Rotterdam Geulhaven. This station is used primarily for operational purposes in the very large harbour of Rotterdam and is not normally used in climatological research. So only 4 of the 31 input stations were excluded from the calculation and the locations of the remaining 27 are shown in Figure 3 as crosses. Calculations were also made with less stations.

4 METHOD

4.1 *The 2-layer model (2LM) of the Planetary Boundary Layer (PBL)*

The description of the 2LM in this section is based on Wieringa's work in the 1970’s and 1980’s, further developed by Verkaik around the turn of the century and more recently by Wever and Groen (2009). A detailed description of the calculations is given by Verkaik and Smits (2001); a limited and more general description is given here.

Spatial wind speed variations on spatial scales less than the order of 100 km are caused mainly by differences in surface roughness and atmospheric stability. Stability is assumed to be neutral but this simplification does not limit the applicability of the model very much, as will be shown in the last paragraph of this section. Wind speed variations, compared to the spatial average of the speed, decrease with height, because the higher one goes the fewer obstacles there are to disturb and slow the flow. At a “blending height” the variations have become relatively small, the wind speed is spatially more homogenous and is therefore more suitable for interpolation. In this model two blending heights are used. We assume that in the surface layer most of the local, small-scale disturbances close to the site of interest cause variations that grow quickly, but by the time they reach a blending height of about 60 m have blended into the general flow. The wind at this height is referred to as the mesowind. In the upper layer more time (and space because the air is moving) and height is needed before the regional, large-scale disturbances no longer disrupt the flow of what is referred to as the macro wind. This occurs at the top of the PBL (< 2 km deep).

The input for our method is the potential wind speed, which is computed from the measured wind speed by firstly using the local roughness length to calculate the 60 m wind. This mesowind speed is translated back downwards to the potential wind speed at a standard height and with a standard low roughness length, e.g. that of grass which is 0.03 m. The first step in our method is to undo the downward transformation to obtain the mesowind. The height transformations are done using the logarithmic wind speed profile (Garrat, 1992).

The local roughness lengths necessary to be able to compute potential wind speeds are calculated for each meteorological observation station by regularly analysing the wind gust ratio (gust divided by hourly average wind speed) for 18 sectors (20 degrees wide) of wind direction. The wind gust ratio is a measure of local surface roughness and increases with increasing roughness because the average wind speed decreases (obviously) while the gust is less affected.

For the next step up to the top of the PBL, the regional or meso roughness is required. To estimate the meso, but also the local, roughness lengths, we used a land-use map of The Netherlands, LGN3+. This map is based on satellite images from 1995 and 1997 (the middle of the current climate period, 1981-2010). Verkaik and Smits (2001) describe how the 100 m resolution roughness classes are averaged. We used the program “roughn_map” (available from the site of the HYDRA project in which Verkaik implemented the 2LM) to average the 100 m pixels to get our local 2.5 km and regional 10 km pixels. The “roughn_map” input parameter “evaluation height” should be made equal to the blending height. For the local roughness the choice of 60 m was obvious, but for the regional roughness less so. Keeping the ratio height to pixel size constant, 250 m was chosen. The regional roughness is insensitive to this height (Verkaik et al, 2005) was limited to 1000 m. The roughness length is averaged over all wind directions. Pixels with values >0.0012 and < 0.029 were set to 0.03 m (grass) because such pixels were mostly combinations of land and water and we were interested in the wind speed above land. The “roughn_map” coordinates specified the lower left corner of the pixel, so half a pixel width was added for correct interpretation by our program. Maps with additional orographic roughness were also made.

At the top of the PBL, both the macrowind, S_{macro}, and the two vector components U_{macro} and V_{macro} are IDW interpolated onto the 10 km resolution grid of the regional surface roughness map. The directly interpolated S_{macro} is compared to the value calculated with the separately interpolated values of U_{macro} and V_{macro} and the differences are negligibly small. Moving down again through the upper layer, the interpolated V_{macro} is used to calculate the mesowind and these 10 km grid values are IDW interpolated onto the 2.5 km grid to facilitate the step back through the lower layer. The local 2.5 km resolution roughness length is used for the final transformation from mesowind to the surface wind speed at 10 m above the ground.

In this model stability is assumed to be neutral. This may seem to be a severe limitation of the applicability of the model. However, the error caused by assuming neutral stability when going up through the two layers is counterbalanced by the error introduced on the way down (De Rooy and Kok, 2002). For this reason the 2LM can be used for the interpolation of wind speed measurements when, as is often the case, data on the local stability is unavailable.

4.2 *Inverse Distance Weighted Interpolation*

In R we used the IDW function of the GSTAT package. A variable of this function is IDP (inverse distance weighting power) which controls how quickly the input values lose their influence on the surrounding area as distance from the point increases. Using a very low power, such as

0.5, means that the influence decreases so slowly that the interpolated output values are almost the average of the input values. A very high IDP, e.g. 8, barely alters the input values because the influence of the one input location does not reach the other. We tried 5 different IDP values (0.5, 1, 2, 4 and 8) for the interpolation of the macrowind speed. Interpolation methods "Splines" and "universal kriging" have not been tried because these methods require that input values remain unchanged by interpolation.

5 RESULTS

Macrowind level (top of the PBL, 10 km grid)

Statistic\Method	**Best method (methods 2-6 are variations)** method 1	**Interpolation highly averaged, IDP = 0.5** method 2	**Interpolation not averaged, IDP = 8.0** method 3	**Orographic roughness added** method 4	**Only input stations with homogenous surroundings** method 5	**Sensitivity analysis for station relocations** method 6
Leave one out cross-validation MAE of V_{macro} (m/s)	0.629	0.627	0.666	***0.851***[a]	0.436	0.685
Mean abs. difference, in brackets mean bias, of (S_{macro} – model[b]) (m/s)	0.99 (-0.72)	0.72 (-0.58)	***1.03 (-0.74)***	0.92 (-0.03)	-	0.99 (-0.71)
Expert judgement (NW-SE gradient)	Fairly good	Very good	Fairly bad	***Very bad***	Fairly good	Fairly good

a) the worst results are in ***bold italics***
b) In the second row the model is the ECMWF model 20 year average wind speed at a height of 2 km

Surface level (10 m above the ground, 2.5 km grid)

Statistic\Method	**method 1**	**method 2**	**method 3**	**method 4**	**method 5**	**method 6**
7 Good stations Mean abs bias (%)	3.77	***9.84***	2.91	3.9	3	4.88
10 Bad stations Mean abs bias (%)	7.99	11.36	7.43	7.77	***18.5***	6.83
5 Coastal stations Mean abs bias (%)	15.17	17.28	15.93	14.92	32.12	14.98
3 Border stations Mean abs bias (%)	18.71	18.8	16.67	26.38	16.83	19
Coastal – Good stations (m/s) [c]	1.67	1.01	1.76	1.60	***0.32***	1.66

c) difference in “as measured” wind speed normals between coastal and good stations is 2.45 m/s

Table 1: Overview of the validation results at the top of the PBL and at 10 m above the ground for 6 methods showing the effect of varying the amount of averaging (IDP) of the IDW interpolation (1-3), of introducing additional roughness due to orography (4), of excluding input stations with inhomogeneous local roughness (5) and of station relocations (6).

In table 1 methods 2-6 are variations of the best method (method 1) where only one parameter, mentioned in the column title, was changed to illustrate it’s effect on the verification results at 2 levels. A 500 m resolution roughness map was used to decide which stations were good or bad: good have homogenous surroundings within a radius of 3 km and bad do not. With a 5 km radius only 2 good stations were found. The last row shows the surface wind speed difference between the coast and inland area's. The good stations (excluding the two sea stations for which no "as measured" normal was available; see figure 6) represent the inland area well.

Methods 2-5 all have the worst result of a row in table 1, which leaves only Method 1 and 6 to chose from. Method 1 was chosen because the older set of station coordinates (Method 1) represent the station locations in the period 1981-2010 better than the ones of Method 6 (updated in 2010) that include recent changes.

The method 1 maps of the yearly (and 12 monthly) normals of the surface wind are on www.klimaatatlas.nl and the average accuracy of good and bad stations is 6.3%.

Figures 3 and 4 show the S_{macro} wind speeds generated by methods 1 and 4 with the input station locations shown as crosses. The scale of figure 4 (method 4) has higher values than the other maps because of the additional orographic roughness. Especially the highest hills near Maastricht, in the extreme southeast, make this map compare so badly to Figure 5. ECMWF numerical weather prediction model analysis winds for 1989-2008 (Berrisford, 2009), with resolution 60 km, are used for the verification, because few measurements are available at the top of the PBL.

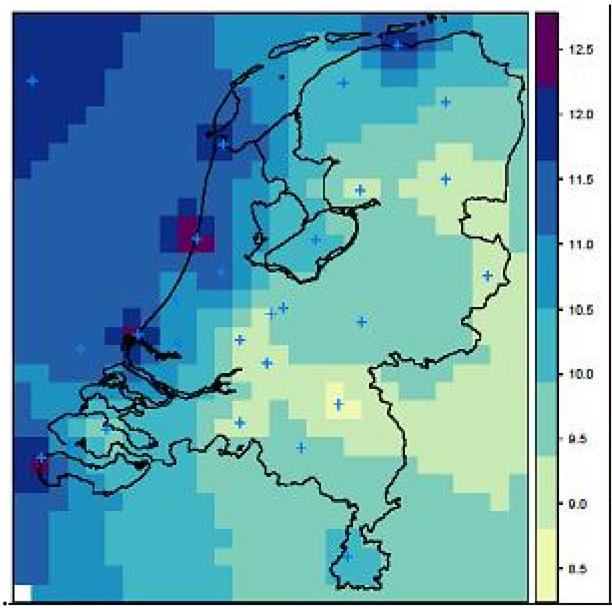

Figure 3: S_{macro} of Method 1

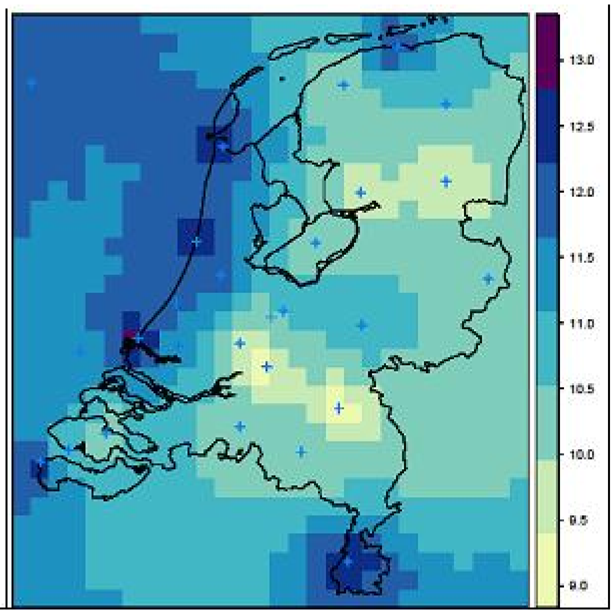

Figure 4: S_{macro} of Method 4

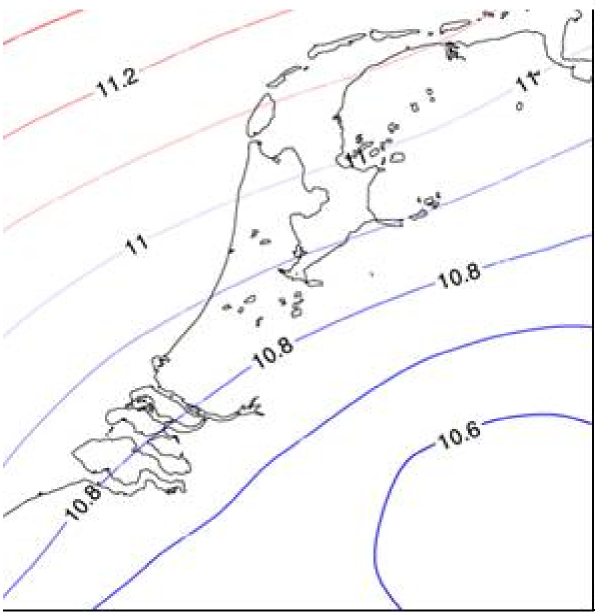

Figure 5: ECMWF model speed at 2 km above ground

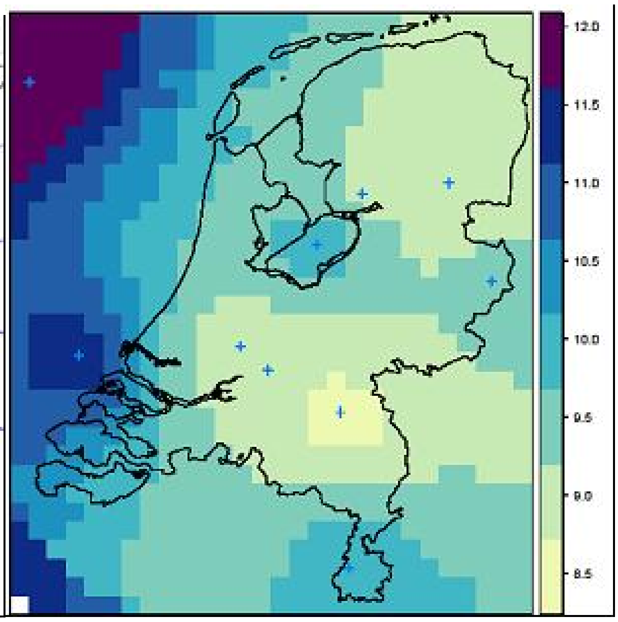

Figure 6: S_{macro} of method 5

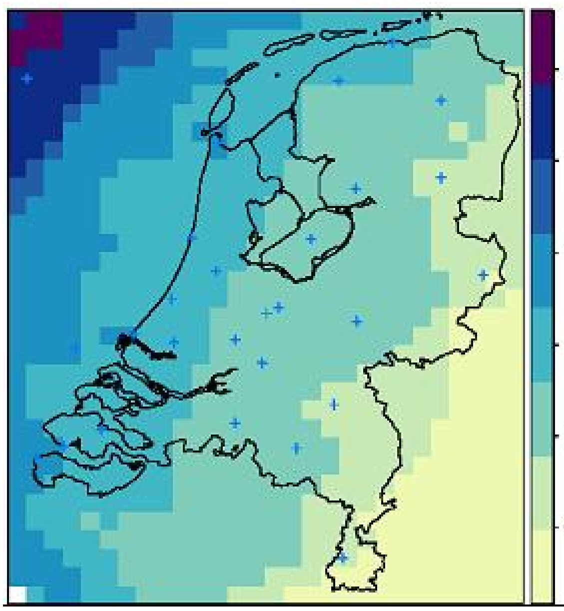

Figure 7: S_{macro} of method 2

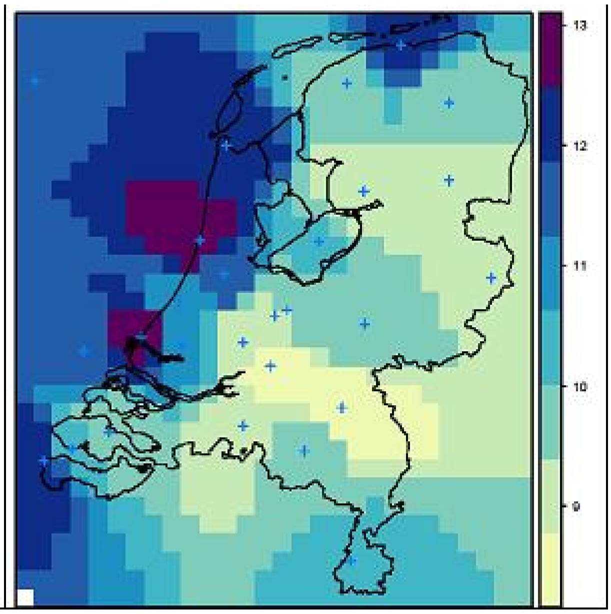

Figure 8: S_{macro} of method 3

Method 2 (figure 7) with a low IDP provides a smooth wind field which makes it look the most like figure 5. Conversely, this results in a poor surface verification: high macrowind station values are lowered by the averaging, in turn producing surface speeds lower than the verification value. Method 3 (figure 8) contrasts nicely with a very blotchy appearance where the high IDP limits the areal influence of the station and provides a good surface verification score.

Method 5 (figure 6) is different from the others because there are fewer input stations and the low wind speeds of the inland area are interpolated out to the coastal area. The heterogeneous roughness of the “bad” stations is not ideal but the higher potential wind speeds near the coast have to be included to give a good picture of the spatial variation of the wind speed.

Method 6 provides a sensitivity analysis for station location. Of the 27 input stations, 19 were moved more than 100 m, 5 more than 1 km and 2 between 2 and 3 km: these were Schiphol (just southwest of the large Ijssel Lake in the middle of the country) and Eindhoven (the first station north of Maastricht in the southeast of the country). The surface wind differences were almost zero for all but four stations, which included Schiphol and Eindhoven. The change for Schiphol was by far the greatest at 10% of the “as measured” wind speed, the average of the four was 4%.

6 DISCUSSION

A leave one out cross validation (LOOCV) of the interpolated V_{macro} against the station values has been done, but this should also be done for the calculated surface wind against the "as measured" speeds. Because we validate at input station locations, interpolation methods that alter these values, e.g. method 2, get a bad score. Such methods might however perform better in area's between station locations. Using the proposed LOOCV would allow us to see how good the pixel values are between input stations. The first time the 2LM was used to create a map of the annual surface wind speed in The Netherlands (Wieringa, 1986), the average accuracy was about 0.25 m/s which is 5%. This result was achieved with 31 validation stations of which 16 had been used to provide the input wind speed data for the interpolation. The average error of “good” and “bad” stations found for Method 1 (see table 1) is 6.3%. Wieringa validated his results with stations not used as input, which is more similar to LOOCV than our validation is. This implies that if the “leave one out” validation is worse than 6.3%, it is unlikely to be a lot worse.

One main difference between the Wind Atlas Analyses and Application Program (WAsP) and the 2LM is that in the 2LM the macrowind speed is interpolated, whereas in WAsP it is assumed constant. Assuming the 2 km ECMWF winds are correct, the maximum error introduced by assuming the macrowind is constant is about 1% of the speed. Another difference is that WAsP requires information on wind direction (30^{o} sectors) to assess roughnesses whereas the 2LM in this study was applied to normals where no direction information is available. Therefore, the 2LM roughnesses had to be direction independent averages. On the other hand, the 2LM input potential wind speeds were calculated using direction dependent roughness (20^{o} sectors). A significant advantage of WAsP is that it corrects the wind for nearby obstacles and for speed-up of the wind caused by hill slopes. Orography in 2LM can only decrease the speed. Another advantage of WAsP is that it provides more than just the average wind speed, e.g. the frequency distribution. WAsP generates predicted annual wind speeds with an accuracy of about 5% (Frank et al, 2001) which is comparable with the accuracy found in this study although of course no direct comparison with the same input stations has been made.

A map of the wind speed normal at 100 metres above the ground, which is more directly relevant to the wind energy industry will be made available on www.klimaatatlas.nl.

Fitting a plane surface through the S_{macro} values would force the interpolation into a pattern similar to that of the ECMWF model and possibly produce more accurate surface wind speeds.

The comparison of the macrowind speed with the ECMWF model analysis could be improved by averaging all the 10 km macrowind pixels in each 60 km model pixel before comparing the two. In this study averages of 1-3 10 km pixels above station locations were used in order to compare the station values to the model, but then one compares 10 km resolution values with 60 km values. Another difference between the two datasets is that S_{macro} is calculated assuming neutral stability while the model takes varying stability into account. However, these stability errors tend to cancel each other out when dealing with long-term averages. Another difference between the two wind speeds is their height: in the 2LM the height of the PBL varies with the friction velocity which means our values of S_{macro} are not all at the same height and the maximum height is about 1.4 km, far short of 2 km. This should not make the comparison meaningless however because in theory the wind speed increases gradually and slowly with height above the PBL.

The fact that the macrolevel is lower than the model height does make the S_{macro} values, above the western coastal area and the sea area northwest of The Netherlands, suspect because they are equal to or higher than the model values (compare figures 3 and 5). Especially the local maxima near the west coast disturb the smooth pattern one would expect to see. These are in part caused by using the same roughness irrespective of the wind direction. At western coastal sites with prevailing winds from sea, the regional roughness is overestimated if the 10 km pixel average includes land. Consequently, the macrowind speed will be too high there.

Better results will probably be obtained by interpolating the hourly wind speeds and then calculating the normals for each pixel instead of interpolating the station normals. This method allows the possibility of using roughness lengths from a series of land use maps valid for successive periods (LGN3+ and LGN4, 5 and 6) which also vary with the wind direction and therefore better reflect the roughness experienced by the wind at the time of measurement. It would then also be possible to use the station locations appropriate for any given sub-period (between successive station relocations) instead of one set of locations for the whole period as in this study.

Another potential improvement might be to replace IDW interpolation with kriging with external drift. We suspect that using the regional roughness as external drift would help to keep the high values of V_{macro} above the rougher terrain where they belong. Unless we use IDW with very low values of IDP (very strong averaging of the station values), this method produces problems near stations with surface roughnesses that vary significantly around the station, e.g unrealistically high surface wind speeds over smoother, lower lying terrain near the hilly station of Maastricht when using Method 4 with the additional orographic roughness.

7 CONCLUSIONS

The interpolated map of annual surface wind speed produced using long series of potential wind speed, the 2LM of the PBL and a high resolution surface roughness map provides wind speeds with the following accuracies. For validation stations in open terrain with few obstructions ("good" stations) the accuracy was better than 5%. Locations with large roughness variations within 3 km have an accuracy better than 10%. Very near the coast and the Dutch border the accuracy is worse, but still better than 20%. The monthly normal map accuracies are similar.

The sensitivity analysis for station location (method 6) shows that, for most stations, relocations had no effect. However, the most extreme change was 10% of the “as measured” surface wind speed which is about the same as the Method 1 average error for “bad” stations.

The IDW interpolation method with IDP of 2 gave the best results. A lower IDP gave too much smoothing, causing large adjustments of the station values of V_{macro} which in turn produced errors in the surface wind speeds validated at the station locations. A higher IDP gave better surface validation results but worsened the macro level validation.

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