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Automatic Generation of Exposure Correction Factors for the Calculation of Potential Wind

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Summary

The potential wind is the wind speed one would measure under ideal conditions, i.e. on a wind mast of 10 m height with only short grass and no obstacles or hills in the surroundings. It can be computed from the measured wind speed using direction-dependent exposure correction factors (ECFs), which are determined from the wind measurements themselves.

Climatology studies should be based on data that are representative of an area wider than the vicinity of the wind mast, so the data should exclude local effects (e.g. from nearby trees or buildings) and sensor changes or measurement site re-locations. If the “disturbance” of the measurement is not extreme, it can be compensated using ECFs (homogenisation).

Potential wind and ECFs help to answer a multitude of questions from different users, such as:

- Climatology: Is a change in wind speed over a 30-year period due to climate change or a change in local vegetation?
- Aviation: Should one expect significantly different wind speeds along an airport runway compared to what is measured?
- Inspection: Do station inspectors need to pay special attention to specific changes in the environment of a wind mast?
- Weather centre: Does a difference between forecasted and measured wind speed indicate a lower forecast quality?
- Construction sector: What extreme wind speeds should one assume when constructing buildings including primary water defence lines?

Essentially, there are two methods to compute ECFs: (1) the Gustiness method, based on the hourly maximum 3-second mean wind speed (gust) divided by the hourly mean wind speed and (2) the Sigma method based on 10-minute standard deviation divided by 10-minute mean wind speed. The latter method was proved to be superior in 2009 (Wever & Groen, 2009), but because 10-minute wind measurements were not stored before 2003, KNMI kept using the Gustiness method. Since this was a labour-intensive process, ECFs were only updated roughly every five years and therefore not always reflected most up-to-date changes. Now that KNMI has a substantial (and still growing) dataset, the Sigma method can be applied. Because this is already a major change in the method, we decided to make additional improvements that were not implemented before for continuity reasons, e.g. taking wind-direction dependence for reference surface roughness and height into account for coastal stations.

We developed, fine-tuned, tested and verified an algorithm that can automatically provide 10-minute ECF and potential wind speed updates based on the Sigma method. This allows us to give near-real-time insights to existing users, while also unlocking a broader range of users, including forecasters. At the same time, it reduces manual work load from months of intensive research every few years to occasional small support, advice

and maintenance tasks. For technical reasons, only a monthly update will be produced operationally for now.

The data are to be published on the KNMI Data Platform (KDP) where they are readily available both to internal and external users. The old Gustiness-method dataset should be discontinued after a certain grace period but remain available as a static dataset (migrated to KDP). This transition requires clear communication with existing and new users, and this report shall contribute to that.

Outline

Due to the broad scope of this report, most readers will want to focus on certain sections, depending on their specific interest. Here, we provide an overview that shall facilitate this. In **Section 1**, we give a high-level introduction into ECFs and potential wind including a historical summary and the theoretical foundation. **Section 2** dives deeper into the previously used Gustiness method. Some more technical details about the previous two ECF updates that made use of this method can be found in **Appendix B**. We then introduce a new method to compute ECFs, the Sigma method, in **Section 3**. This section gives a comprehensive overview of the theoretical basis and the specific choices that were made and gives detailed substantiation for these choices. In **Appendix A**, we describe the relation of the Sigma method with two other studies carried out at KNMI: GUSTO and TR-277. **Section 4** gives technical details about certain location-dependant configuration details. This is particularly relevant for coastal stations, which are extensively covered in **Appendix F**. In **Section 5**, we describe how the methodology described in this report can be automated, and **Appendix G** elaborates on this in more technical detail aimed at developers. We validate our new method in **Section 6**. Finally, **Section 7** summarises our conclusions and makes recommendations for future work.

1. Introduction

1.1. What are ECFs?

Exposure correction factors (ECFs) are a measure of the local surface roughness (up to 2 km from the wind mast) and are used to calculate the potential wind.

Potential wind

In simple words, the surface roughness (measured by the roughness length z_0) leads to a deceleration of the wind near the surface. Smooth surfaces (e.g. snow, $z_0 \approx 10^{-4}$ m) slow down the wind less than rough surfaces (e.g. a forest, $z_0 \approx 10^0$ m) (Wieringa, 1993). Thus, the surface roughness around the measurement site affects the wind measurements. Only with standardised site specifications, wind measurements can be intercompared.

The World Meteorological Organization (WMO, 2024) requires that the measurement of wind is done at a site with a surface roughness comparable to that of cut grass ($z_0 = 0.03$ m). Furthermore, the site must be flat, unobstructed by e.g. trees or buildings and the measurement should be done at 10 m height. Even when the WMO requirement with regard to obstacles is met (namely that the distance to the obstacle should be at least 10 times the obstacle's height), wind measurements are often disturbed, either by obstacles further away or because the surface roughness is not that of cut grass in some or all wind directions. Of course, these effects are real, but they need to be filtered out in order to make the measurements suitable for climate-change research (“is wind speed really decreasing or are there just more obstacles?”; Wever, 2012) and for the validation of weather models (where the surface roughness is averaged over grid boxes). In the 1970s, Jon Wieringa found a way to do this (and also correct for differences in measuring height) and introduced the potential wind based on measured exposure correction factors (ECFs).

The potential wind speed U_p is the measured wind speed U_m (e.g. the 10-min. average) multiplied by the ECF: $U_p = ECF U_m$. The ECF compensates for the effect that a different roughness (than the one of cut grass) and measuring height (than 10 m) have on the wind speed. The potential wind speed therefore meets the WMO requirement. No research has been done so far on a correction of the wind direction. (Higher surface roughness — more friction — not only reduces wind speeds, but also causes the wind vector to turn anti-clockwise — backing of the wind — which means a change in wind direction.) Therefore, no correction is applied to the wind direction.

1.2. Historical overview

First studies on exposure correction were carried out at KNMI in the 1970s (Wieringa, 1973, 1976; Wieringa & Rijkoort, 1983). Wieringa developed a method with which one could correct measured wind speeds for sheltering (due to obstructing obstacles or rougher surroundings) “without requiring a subjective evaluation of the surroundings and without needing reference stations”. This Gustiness theory forms the basis for all later work and

several decades of ECF algorithms even until today. It relates the maximum wind gust within one hour with the mean wind speed in that hour to compute the local roughness and, from it, the ECF.

In the 1980s, a different approach was developed by Beljaars: the Sigma theory, which states that the standard deviation of the wind speed contains information about the local roughness (Beljaars et al., 1983; Beljaars, 1983, 1987b). Thus, ECFs can also be computed from the standard deviation and the mean of wind speed within one hour or ten minutes. However, since the standard deviation was not measured routinely in that period, this method was not used for exposure correction (Beljaars, 1987a).

This only began to change slowly with the beginning of the new millennium. Verkaik (2000) revisited and compared the Wieringa and Beljaars methods. Among others, he concluded that both can compute ECFs with an uncertainty of 5 % (page 94 of Verkaik, 2000). In the following years, first studies at KNMI made use of the Sigma method, for example, Van der Meulen (2000) who computed potential wind to investigate the representativeness of wind measurements at certain sites. Wichers Schreur & Geertsema (2006) developed a framework for ECF computation based on the Sigma theory, which they called GUSTO and which is aimed more at Gustiness analysis than at exposure correction. The GUSTO method is very similar to the Sigma method as presented in this report, but not exactly the same (Appendix A.1). Wichers Schreur & Geertsema (2006) conclude that the GUSTO method is superior to the Gustiness method, which has most commonly been used until then. A report by the German Meteorological Service DWD, which focuses on the computation of local roughness, comes to the same conclusion, calling the Gustiness method a “poor man’s method” (Kofmann & Namyslo, 2023). (DWD does not publish data on local roughness, ECFs or potential wind.)

Though the Sigma method was applied in several incidental analyses at KNMI in the following years,¹ it was not operationalised. This was because the standard deviation of the wind speed was still not routinely archived until 2003. Arguably for that reason, Benschop (2005) still used a version of Wieringa’s Gustiness method to compute ECFs without any mention of Beljaars’s Sigma method.

The conclusion that the Sigma method is to be preferred for ECF computation was drawn again by Wever & Groen (2009) who also explicitly discussed the added value of the 10-minute observations available at KNMI since 2003. Building on the work by Verkaik (2000, 2006), they discussed that ECFs computed with the Sigma method tend to be slightly lower than those from the Gustiness method but also less sensitive to the so-called air-mass effect, which causes an overestimation of ECFs due to convective gusts. They also provided an empirical formula to eliminate this difference, i.e. for the conversion of Gustiness ECFs to Sigma ECFs. The ECF datasets determined by Stepek & Wijnant (2013) and similarly in 2020/2021 are based on this approach (see also Appendix B).

The present study has been carried out at a time when more than twenty years of 10-minute observations including the standard deviation of the wind are available throughout the Netherlands, making it feasible to leave the Gustiness method behind and switch to

¹including a confidential memo from March 2016 about limited representativeness of wind measurements at Rotterdam The Hague Airport

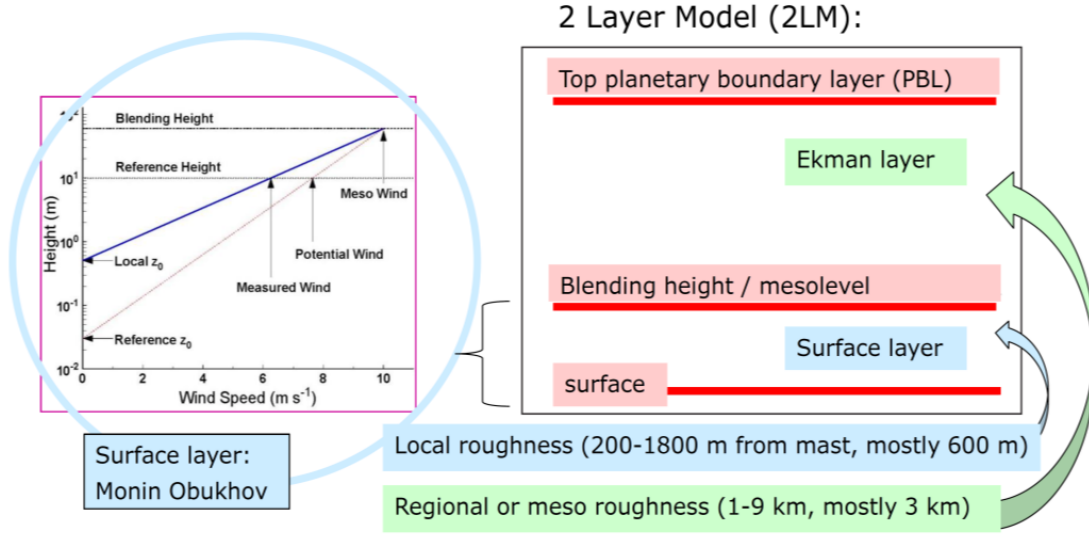


Figure 1: Illustration of the 2-layer model on which the ECF theory is based.

the Sigma method. This switch can be motivated by studies as far back as the one by Beljaars (1987a) as well as conclusions and recommendations from consecutive work (including Verkaik, 2000; Wichers Schreur & Geertsema, 2006; Wever & Groen, 2009; Koßmann & Namyslo, 2023). We mostly build on the work by Wever & Groen (2009) and develop a methodology that can even be used to compute ECFs and potential wind in near-real-time (i.e. every ten minutes).

1.3. Theoretical foundation

The most important exercise is to determine the local roughness length z_0 from which the ECFs can be computed. This is where the main differences between the Gustiness and the Sigma method lie, which we will elaborate on in the following sections.

Once the local roughness has been determined, ECFs are computed in the same way. This process is based on the Wieringa-Rijkoort Two-Layer Model (2LM method; see Wieringa & Rijkoort, 1983), which is illustrated in Fig. 1. Theoretical details are summarised in the report by Wever & Groen (2009), for instance. Here, we only mention the following highly relevant assumptions that are crucial to its implementation and proper application:

- The 2LM method only works for a neutral atmosphere. A widely used 'rule of thumb' is that by excluding wind speeds below 5 m/s one can assume a neutral atmosphere. Excluding wind speeds below 5 m/s² means that about 35 % of all wind measurements are excluded. In the new method, we also include available temperature measurements to assess whether the atmosphere is neutral.
- The 2LM method only works for measurement heights z_m above $20z_0$ where z_0 is the value of the local roughness length (local means up to 2 km from the wind

²For hourly data previously used in the Gustiness method, this means effectively wind speeds below 5.5 m/s because of how wind speeds are rounded off.

mast).³ If z_0 equals 0.5 m (corresponds to an ECF value of 1.22), then 2LM works for heights above 10 m. If the value of ECF is larger than 1.22, then wind measurements at 10 m height cannot be used for calculating the potential wind because the 2LM method is not valid at that height.⁴

- The 2LM method only works when the measurements are not too disturbed by obstacles. How large the disturbance of the obstacle is, depends on its porosity (e.g. the difference in trees in winter or summer) and a combination of the distance from the wind mast to the obstacle (D) and the height of the obstacle (H). It is important to realise that wind turbines are not ordinary obstacles: they are designed to take energy (wind) out of the flow, and in doing so, they introduce turbulence (gustiness). Thus, if we refer to obstacles in this report, we explicitly exclude wind turbines. For obstacles (excluding wind turbines!), measurements at the wind mast are not affected by the obstacle's wake if the distance from the wind mast to the obstacle (D) is larger than $30H$, so if $D/H > 30$ (Wieringa & Rijkoort, 1983). For $20 < D/H < 30$, the measurement is affected by the obstacle's wake, but the roughness correction with 2LM works well. For $10 < D/H < 20$, is increasingly harder and becomes impossible for $D/H < 10$ (Section 5.9.2 of WMO, 2024).⁵ Besides, roughness correction is also not possible if the wind blows from a narrow obstacle with a height of more than 8 m towards the wind mast and $D/W < 15$, where W is the width of the narrow obstacle (see Table 5.3 in WMO, 2024).

Formula for ECFs

As illustrated in Fig. 1, the main idea of the ECF theory is that only below a blending height z_b (here: 60 m), the wind is influenced by the local roughness length z_0 . Assuming a logarithmic wind profile, the measured wind speed U_m is first transformed from the measurement height z_m to z_b (using the local roughness) and then back to the reference height $z_{\text{ref}} = 10$ m (using the reference roughness length $z_{0,\text{ref}}$, which is 0.03 m for land stations).

With the aforementioned assumptions, ECFs can thus be computed from the local roughness length z_0 :

$$ECF = \frac{U_p}{U_m} = \frac{\ln \frac{z_b}{z_0} \ln \frac{z_{\text{ref}}}{z_{0,\text{ref}}}}{\ln \frac{z_m}{z_0} \ln \frac{z_b}{z_{0,\text{ref}}}}, \quad (1)$$

where U_p is the potential wind speed.

The ECF varies with wind direction and — for some sites — season. That is why ECFs

³Oemraw (1984): logarithmic wind profile valid between $20z_0$ (few meters above the ground) and about $0.2h$ (60 m for boundary layer height $h = 300$ m). See also: Geurts (1997).

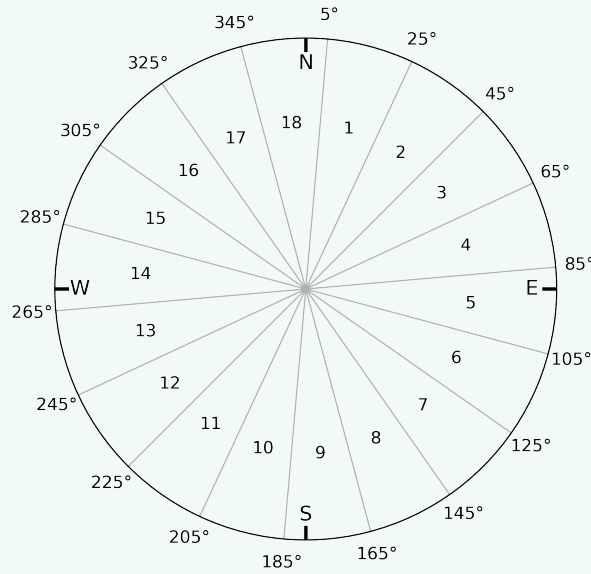
⁴For a wind measurement at 20 m height (e.g. De Bilt), z_0 must not be greater than 1 m which corresponds to an ECF value of 1.04 ($= 1.36/1.30$ where 1.36 is the factor due to the very high roughness length and 1.30 the factor due to the extra 10 m height compared to the standard height of 10 m). So for De Bilt, wind direction sectors with ECF larger than 1.04 cannot be used to derive the potential wind. Formula 1 was used to derive 1.04.

⁵This is in line with rules for station inspection at KNMI: measurement site does not pass quality control if $D/H < 10$ and advice is to only use measurements if $D/H > 20$.

have to be determined for wind direction sectors: Following Wever & Groen (2009), we use 20° wind-direction bins (e.g. $[25^\circ, 45^\circ)$, i.e. greater than or equal 25° and less than 45°). Note that we keep using an offset of 5° because hourly wind-direction data is rounded to 10-degree intervals. For some sites, we previously distinguished between winter (from November to March) and summer (from April to October).

Wind-direction sectors

Here, ECFs are calculated per 20° wind-direction sector (i.e. 18 sectors):



1.4. Coastal ECFs and curvature problem

Regarding coastal stations, we need to pay special attention to a number of points.

First, for land and sea stations, only the surface roughness depends on the wind-direction sector, but for coastal stations the height of the sensor and the reference roughness is also wind-direction dependent. However, for past ECF updates (e.g. Wieringa, 1976; Benschop, 2005; Wichers Schreur & Geertsema, 2006; Wever & Groen, 2009; Stepek & Wijnant, 2013), just one height z_m and reference roughness $z_{0,\text{ref}}$ were assumed for all wind directions at coastal sites, fully aware of the fact that this was a simplification. The main reason not to start using wind-direction dependent heights and reference roughnesses was for continuity in the potential-wind series. Now that we are changing the method anyway, we decided to take wind-direction dependency into account for height and surface roughness too. This is more complicated than simply: “height above (elevated) land and reference roughness of 0.03 m for wind from land and height above mean sea level and reference roughness of 0.002 m for wind from sea”. Hence, we take transition zones from sea to land or vice versa into account (e.g. internal boundary layer heights), and we estimate the uncertainty caused by assuming that the measured roughness (derived from the Sigma method) is representative for the whole profile up to 60 m height (see Section 4.4).

Secondly, about interpolating potential wind: the 2LM model was designed for interpolation, but Sterl (2019) shows that using coastal wind-speed data (including measurements from coastal stations) when interpolating potential wind measurements above land causes problems for a limited area when the wind blows from sea to land (see their Fig. 7). Based on Harmonie weather model data, they argue that the 2LM model is not valid at a coastal site because the wind at the top of the Ekman layer is still affected by the land-water transition for a limited distance downwind of the coastline. However, Stepek & Wijnant (2011) have been able to make an accurate interpolation map from potential wind speed normals (30-year averages). Sterl uses the Internal Boundary Layer (IBL) to show that 2LM does not work on the coast using the IBL formula by Wood (1982). Here, we used the formulas by Deaves (1981) to calculate the heights of the IBL and Transition Zone (TZ) to show that the error in the potential wind caused by the presence of the sea-land IBL is not significant at the measurement location (Appendix C).

Thirdly, about extrapolating potential wind: 2LM was explicitly not designed for extrapolation, but in the past, potential wind on land has been used to determine extreme winds over sea. For longer return periods this resulted in higher extreme wind estimates further inland than on the coast (curvature problem), which is unrealistic (Wever & Groen, 2009). The three main reasons for the curvature problem are (a) stability is different over land and sea which means that the error caused by assuming neutral stability when going up through the two layers of the 2LM model is not counterbalanced by the error introduced on the way down (Section 3.1 of Stepek & Wijnant, 2011), (b) sea roughness depends on wind speed and land roughness does not and (c) storm dynamics (Caires et al., 2012).

2. Old method to update ECFs: Sigma ECFs derived from hourly Gustiness ECFs

At KNMI, we used to calculate ECFs using the Gustiness analysis, where the maximum gust (3-second average) divided by the hourly average wind speed is a measure for the roughness of the terrain (Verkaik, 2000). Wever & Groen (2009) first extensively used a better procedure: the Sigma method, using 10-minute averages and the standard deviation of the wind speed (i.e. fluctuations) during those 10-minute periods (see also Section 1.2). The main advantage of the Sigma method is that it (at least partly) solves the so-called “air-mass effect” when “cold air-mass” showers cause convective gusts which are unrelated to the hourly average wind speed and the surface roughness. When this happens (in winter and mostly for north-westerly winds, so Sectors 15–17), the Sigma-method ECFs are lower and more realistic than the Gustiness-analysis ECFs. Unfortunately, the 10 minute measurements that the Sigma method is based on were not available for all KNMI stations operationally until 2003, so Wever & Groen also developed a formula to convert Gustiness-analysis ECFs into Sigma-method ECF.

Formula used in the Gustiness analysis

$$\left\langle \frac{U_{max}}{\bar{U}} \right\rangle = \left(1 + \frac{gAc\kappa}{\ln \frac{z_m}{z_0}} \right) \quad (2)$$

with:

- U_{max} [m/s]: maximum 3-second wind gust in previous hour (measured) (if the measurement interval had been 10 minutes, it would have been the maximum 3-second gust in the previous 10 minutes)
- $\bar{U}$ [m/s]: mean wind speed in the previous hour (measured)
- $g = \frac{\langle U_{max} \rangle - \bar{U}}{\sigma_u}$ [-]: standardized gust, which depends on measurement interval and wind speed; typical values for an average wind speed of 6 m/s are about 3.3 for a measurement interval of 1 hour like in the Gustiness analyses (Table D.1 from Appendix D) and 2.7 for a measurement interval of 10 minutes
- A [-]: attenuation factor of the measurement chain (depends e.g. on wind speed and sample period; see Table D.1 from Appendix D)
- c [-]: dimensionless standard deviation for neutral wind (referred to as scaling parameter). The value of c depends on the friction velocity and is a function of stability and boundary layer height: 2.2 is a typical value for the neutral limit
- κ [-]: the von Kármán constant (typically 0.4)
- z_m [m]: measurement height, which is typically 10 m
- z_0 [m] = local roughness length
- $\langle \cdot \rangle$: denotes the median of the distribution

Source: Wever & Groen (2009)

The ECFs are updated if they are significantly different (more than 0.05) from the previous ones (Verkaik, 2006). One would expect the number of significant changes in the

winter ECFs to be smaller than in the summer ECFs because of the effect of changing summer crops on the surface roughness, but for north-westerly winds (sectors 15-17), there are often more changes in winter ECFs than in summer ECFs. This is probably due to changes in the frequency of occurrence of the “air-mass effect” from one winter to the next and not due to changes in the surface roughness length. There is therefore less reason to accept significant changes found in the winter ECFs for north-westerly winds (especially those of sectors 15-17) compared to those of the summer ECFs. To truly judge if a given ECF is too high to be valid (i.e. > 1.22) the Sigma-method ECF should be considered and not the Gustiness-analysis ECF. Therefore, whenever a Gustiness analysis ECF exceeds 1.22, it is converted to the Sigma-method form and compared to 1.22 again. The Sigma ECFs are 5–9 % lower than the Gustiness ECFs (depending on the wind direction and the season) so often when a Gustiness ECF > 1.22 , the Sigma ECF is < 1.22 .

Both in the Gustiness and the Sigma method, the effect of measurement chain is taken into account by using the so-called attenuation factor A (Wever & Groen, 2009).⁶ It is basically a fudge factor to account for differences between what you measure (e.g. 3-second average wind speed based on 4-Hz samples like we do with the cup anemometer) and an ideal measuring chain with instantaneous samples. The value of A depends on the instrument (values of A in Appendix D are for the KNMI cup anemometer), wind speed and sample period (that is why A is different for hourly and 10-minute measurement intervals). In the old method, we derive the Gustiness ECFs first, so we use A from Table D.1 in Appendix D. Koßmann & Namyslo (2023) suggest that using non-mechanical (i.e. ultrasonic) anemometers would eliminate the necessity of including A (or $A = 1$).

Once the Gustiness ECFs are calculated, they are converted to Sigma ECFs using the method derived by Wever & Groen (2009).

Converting Gustiness ECFs into Sigma ECFs

$$ECF_{\sigma} = aECF_g^b, \quad (3)$$

where a and b are fit coefficients, which can be found in Table 4.5.2 of Wever & Groen (2009).

To prevent the domination of outliers and to have a more reliable estimate of median values, Gustiness method and Sigma method should only be applied when ten measurements or more are available (Wever & Groen, 2009). Therefore, we expect to be able to update Sigma ECFs (based on 10-minute measurements) more regularly than Gustiness ECFs (based on hourly measurements).

⁶Wever & Groen (2009) write about this (Section 2.2): *Factor A compensates for the fact that the wind gust measured by the KNMI network is not an instantaneous wind speed, but a moving 3 second average with a sampling frequency of 4 Hz. This means that every 10 minutes, the standard deviation (σ) is calculated from 2400 wind speed samples. The filtering of the wind speed signal by the measuring chain will modify the shape of the spectrum, attenuating more strongly the higher frequencies and the apparent value of $\sigma u/U$. That anemometers show inaccuracies at very low wind speeds due to the discrete measuring system is not accounted for. Also, overspeeding effects due to the low response time of the anemometers are not accounted for.*

Let us summarise the old method to derive and update ECFs:

- ECFs are given per 20° wind direction bin and sometimes different for summer and winter.
- ECFs can only be determined when we can assume a logarithmic wind profile (neutral atmospheric stability) because only then is the 2LM method valid: In the old method we assume that the atmosphere is neutral for wind speeds above 5.5 m/s.
- ECFs can only be determined if disturbances by obstacles are small enough: $D/H > 10$ (with D the distance from obstacle to wind mast and H the height of obstacle). The method does not work if the obstacles are wind turbines!
 - ECF below 1.22 and $D/H > 10$ for 10 m wind masts
 - ECF below 1.04 and $D/(H - 10) > 10$ for 20 m wind masts (such as the one at De Bilt)
- ECFs can only be determined if we have 10 measurements or more in a 20° wind sector bin

The potential wind is only calculated if these requirements are met for at least 75 % of the wind directions (especially if this 75 % includes the prevailing wind direction) and are supposed to be updated at least every 3 years.

3. New method to update ECFs: Sigma ECFs from 10-min. wind measurements

3.1. Overview

In the new method we no longer convert the Gustiness ECFs to Sigma ECFs, but we directly calculate the Sigma-ECFs (using Eq. 4).

Formula used in the Sigma method

$$\left\langle \frac{\sigma_u}{\bar{U}} \right\rangle = \frac{Ac\kappa}{\ln \frac{z_m}{z_0}} \Rightarrow z_0 = \exp \left(\ln z_m - \frac{Ac\kappa}{\left\langle \frac{\sigma_u}{\bar{U}} \right\rangle} \right) \quad (4)$$

with:

- σ_u [m/s]: standard deviation of the wind speed in the previous 10 minutes (measured)
- $\bar{U}$ [m/s]: mean wind speed in the previous 10 minutes (measured)
- A [-]: attenuation factor of the measurement chain (depends e.g. on wind speed and sample period; see Table D.1 from Appendix D)
- c [-]: dimensionless standard deviation for neutral wind (referred to as scaling parameter). The value of c depends on the friction velocity and is a function of stability and boundary layer height: 2.2 is a typical value for the neutral limit
- κ [-]: the von Kármán constant (typically 0.4)
- z_m [m]: measurement height, which is typically 10 m
- z_0 [m] = local roughness length
- $\langle \cdot \rangle$: denotes the median of the distribution

Source: Wever & Groen (2009)

The 10-minute measurements required to directly calculate the Sigma ECFs are available since 2003. As mentioned in Section 2, the Sigma method (partly) removes the “air-mass effect” polluting the ECFs and allows for a higher ECF update frequency. By going from 3-yearly manual updates to near real-time automated updates based on running-average ECFs (per wind direction sector of 20°), the new ECFs are much more up-to-date. Besides, the old method (based on the converted Gustiness ECFs) used hourly wind-direction measurements valid only for the last 10 minutes of the hour. In the new method, the wind direction and wind speed are for the same 10-minute interval and therefore much better aligned.

We remark that apart from the specific variations of the Gustiness method and the Sigma method described here (which are from Wever & Groen, 2009), KNMI also used the so-called GUSTO method (Wichers Schreur & Geertsema, 2006) and a method by Benschop (2005) for some purposes, in particular aviation and construction. The former is comparable to the Sigma method and the latter with the Gustiness method described in this report. Some minor differences can be found in the choice of certain parameters and constants. Details are described in Appendices A.1 and A.2.

It should be noted that the procedure of past ECF updates using the Gustiness method (e.g. Stepek & Wijnant, 2013, see also Appendix B) was fundamentally different to what is proposed in the present report. During each of the past studies, the ECFs were updated manually for the years from the previous update. For example, the 2020 update focused in particular on the period 2013–2020. ECFs were updated for a given period of several months or years within the period of interest when a significant change was detected manually. As such, ECFs can become outdated unnoticed after the publication of the update even though they are still used to compute potential wind. For example, at the time of writing, the most recent Gustiness ECFs published in 2020 are still being used to compute and publish potential-wind series. More technical details about the 2013 and 2020 updates are given in Appendix B.

In previous ECF updates, the ECF changes were extensively compared to metadata (e.g. to inspection reports and Google Earth photos). This will become obsolete because the new method is capable of automatic ECF updates up to every ten minutes and also when the change in ECF is insignificant. Instead, the new method should be more incorporated into station-inspection procedures: If ECFs change significantly, inspection should check if the change is caused by a real change within 2 km from the wind mast. An objective way to check the quality of the potential-wind updates, is to compare time series of potential wind based on measurements and models for all AWS stations: The difference between measurement and model potential winds should be small (Van den Brink & Bosveld, 2017). Besides, we substantiate the quality of the Sigma-method ECFs by comparing them to Gustiness-method ECFs (Section 6).

There are several reasons why better and more regular updates of the ECFs and potential wind are important:

1. It is a WMO requirement to keep the potential wind regularly updated (WMO, 2024).
2. Better (updated) potential winds provide a better and more efficient tool for calculating trends, climate normals (i.e. 30-year averages; see Stepek & Wijnant, 2011), climate scenarios and extremes (e.g. for water defenses and building norms).
3. Better (updated) potential winds enable a fairer comparison with model output, which helps model validation (Van den Brink & Bosveld, 2017) and nowcasting (local effects are excluded in potential wind which enables a more realistic comparison to model output). Besides, near-real time potential winds based on measurements, near-real time potential winds from the HARMONIE model should be made available for all AWS stations for comparison.
4. At airports the accuracy of the wind speed measurements has to be better than 10 % and representative of the wind at all positions along the length of the runway. The 10 m tall wind mast must be located at least 90 m from the centre line of the runway and there is usually one mast near each of the two touchdown zones. If the wind speed at any point along the length of the runway differs from the measured wind speed by more than 10 %, additional wind measurement locations have to be installed. If the ECFs differ by more than 0.1, then this implies that the surface roughness and/or obstacles near the runway cause the wind-speed measurements

to be less representative than required. More regular updates of the ECFs could be used to monitor the representativeness of the wind-speed measurements, providing a signal that action is needed. Besides, if any ECF is greater than 1.22, the wind above the part of the runway near the wind mast will be so disturbed that it is unlikely to be representative of the wind at another part of the runway.

5. Real-time potential wind could be used as input in other real-time products, for example for high-resolution maps of the current wind speed as shown in the KNMI app (De Baar et al., 2023).

Automating ECF computation requires a reliable methodology that avoids outliers or other unphysical/unrealistic changes in ECF time series as much as possible. To achieve this, we basically considered two aspects:

1. **Filter out certain measurements.** This is done to enforce the assumptions of the 2LM model, but also to avoid outliers. A number of physical criteria were considered to find an optimal filter:
 - a) Wind-direction filter: A minimum wind speed of 1.0 m/s ensures that the wind direction is measured reliably.
 - b) Maximum-roughness filter: The 2LM method requires that the ratio of measurement height and local roughness length (representative up to 2 km from the wind mast) $z_m/z_0 > 20$. The higher the roughness length z_0 , the higher one needs to measure. Most KNMI measurements are at $z_m = 10$ m height, so that means that 2LM only works for $z_0 < 0.5$ m (for a 6 m high mast z_0 should be below 0.3 m and for a 20 m high mast below 1 m). Filtering out data points that lead to roughness lengths (e.g. due to close obstacles) larger than 0.5 m is therefore crucial.
 - c) Neutrality filter: The 2LM method requires the atmosphere to be neutral (implying a logarithmic wind profile). In the old method, we assumed that we excluded non-neutral situations by excluding wind speeds below 5 m/s (effectively wind speeds below 5.5 m/s because of how wind speeds are rounded off) and this meant that about 35 % of all wind measurements were excluded. Here, we added an explicit filter for neutral stability using the near-surface temperature gradient. Other quantities as well as seasonal and diurnal dependencies were investigated too, in the hope of minimising the number of discarded data points.
 - d) Precipitation filter: There is no clear relationship between precipitation and ECF outliers. The hypothesis that convective precipitation could lead to higher values of the standard deviation of the wind speed and therefore the values of ECF was not confirmed by our experiments. A precipitation filter was therefore not included in the method (see Section 3.4.4).
2. **Sample frequency.** As mentioned in Section 2, the Gustiness analysis required at least 10 hourly wind measurements (i.e. a total of 600 minutes of wind observations) to prevent the domination of outliers and to have a more reliable estimate of median values (Wever & Groen, 2009). With the new method based on 10-minute

measurements, we show that we can increase the update frequency and reduce the sample size to 30, i.e. well below 600 minutes (see Section 3.3).

One aim of this project was to find an optimum combination of sample frequency and filter for neutral atmosphere in order to keep as many measurements as possible while minimising the number of outliers. The choice of optimal sample frequency and filter configuration was based on a full year (2019) of measurements at Schiphol.

3.2. Bare minimum filters

The requirement of the 2LM method that $z_m/z_0 > 20$ can be translated to:

$$Ack \frac{U}{\sigma_u} > \ln(20), \quad (5)$$

and $\ln(20) \approx 2.996$. We disregard data points where this is not fulfilled. Depending on the wind speed (because A depends on U), this is the case for turbulence intensities σ_u/U larger than $0.23 \dots 0.26$. Besides being a hard theoretical requirement, this maximum-roughness filter effectively filters out extreme ECF spikes that would occasionally occur at some locations where obstacles are nearby in some directions.

Furthermore, it is necessary to enforce a minimum wind speed to have a reliable wind-direction measurement. We assume this to be the case from 1.0 m/s. This is a lower wind speed than suggested in KNMI (2000) (Section 3.1) where it is mentioned that the KNMI wind vane only starts to move at 2 m/s wind speed, but recent wind tunnel experiments show that that already happens at 0.8 m/s. Ultimately, this minimum-wind speed requirement is irrelevant because the neutrality filter (see below) requires much higher wind speeds (we conclude at least 5.0 m/s in Section 3.4.1).

Note that these two “bare minimum” filters are not sufficient to enforce all strict requirements of the 2LM method; in particular, they do not enforce neutral stability. Thus, other filters are required, which we will discuss in Section 3.4.

3.3. Median sample size

Computing the ECFs requires taking the median over a number of standard deviation over wind speed ratios $\langle \sigma_u/\bar{U} \rangle$ (Eq. 4). Because we want to automate the computation of ECFs, it is of particular importance that outliers are prevented by design, as human intervention (which could manually filter out extreme outliers based on expert judgement) is not intended.

In our experiments, we vary the number of samples taken N . We always take the N most recent data points (after filtering) from the same directional sector. Taking all samples from a fixed period (say, the previous X months) instead is not feasible here because the number of data points would vary greatly depending on the wind direction. For example, there are a lot more samples in X months in the prevailing wind sectors than, say, in north-easterly sectors.

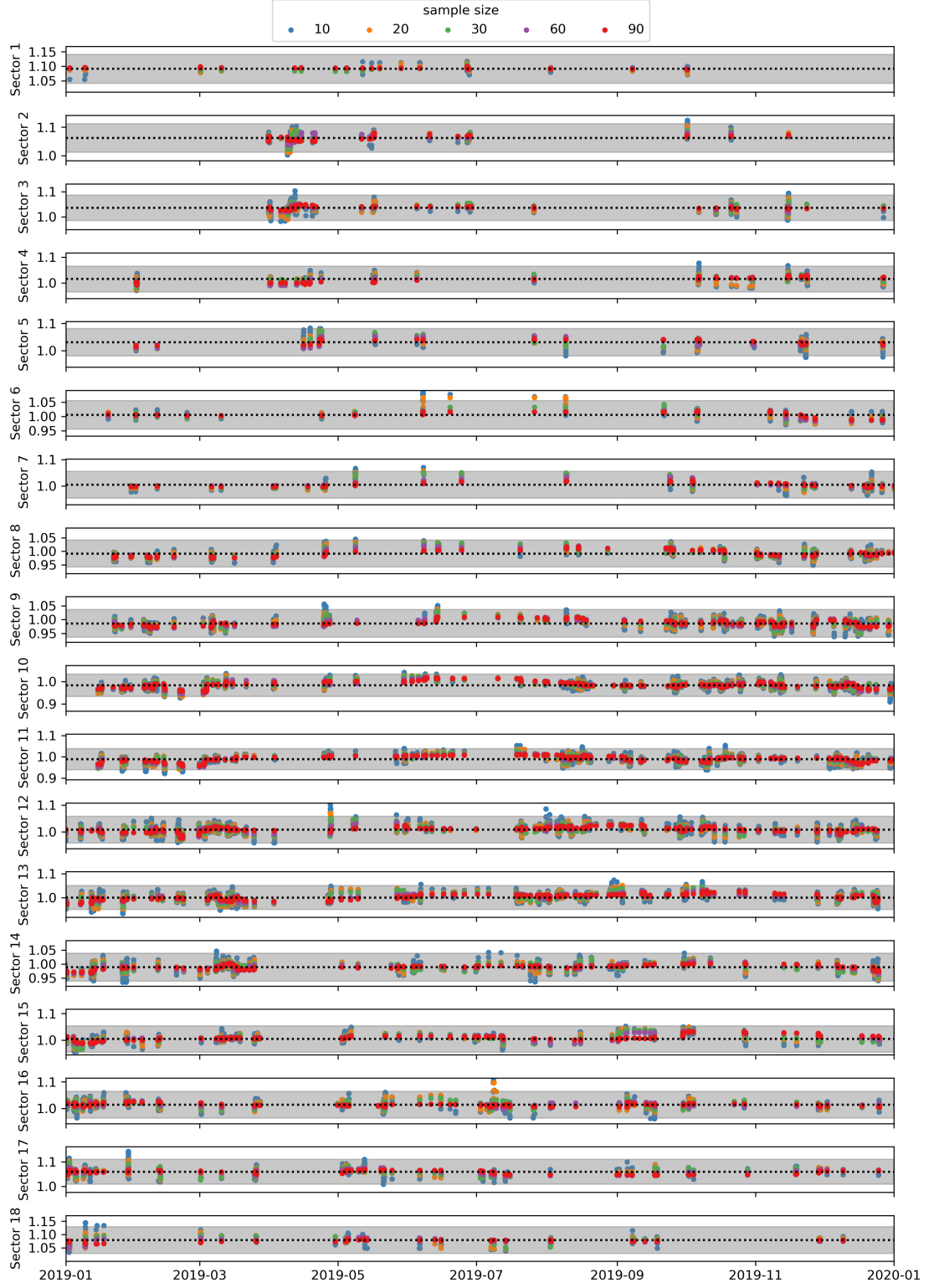


Figure 2: Time series of ECFs per directional sector for 2019 at Schiphol. The differently coloured dots indicate ECF values that are computed using different sample sizes for $\langle \sigma_u / \bar{U} \rangle$ (as indicated in the legend on the top right). The black dotted line is the ECF when taking the median over the entire year, and the grey area indicates the significance band of ± 0.05 around that yearly average.

Recall that in the Gustiness method, 10 hourly samples were used representing 600 minutes of measurement. Now that we use 10-minute measurements, we can either keep the sample size the same (10) which represents 100 minutes of measurements or keep the represented period the same (600 minutes) which implies a sample size of 60. In addition to these 10 and 60, we also investigated samples sizes of 20, 30 and 90. An example of this is shown in Fig. 2, where we present example time series for one year (2019) of ECFs at Schiphol (sub-location 27) using a particular filter configuration (maximum-roughness filter, $U > 5.0$ m/s, $T_{2m} - T_{10cm} \in [-0.3, 1.1]$ K) and various sample sizes. (Throughout this report, T_{2m} and T_{10cm} denote the “standard” and “grass” air temperatures, respectively, which are measured at heights of 1.5 m and 0.1 m and which we label with “2m” and “10cm”, respectively, for brevity.) According to the most recent update of ECFs using the Gustiness method, the ECFs remained constant in this period. We can therefore also compute an average ECF for each directional sector by taking the median over all data points in that year. In Fig. 2, this is shown as the black dotted line, and the grey area indicates a band of ± 0.05 around that average ECF, which was previously used to classify a change in ECF as significant. It is based on the uncertainty of 5 % for ECFs computed with the Gustiness and the Sigma method (Verkaik, 2000).

The ECF time series illustrates how taking a larger sample size leads to fewer outliers and variations while keeping the filter the same. We assume that all ECF values (coloured dots) should lie within the grey band because the ECF remained constant in this period. In this example, this is not the case for 10 samples, but it is increasingly the case for 30 or more samples. Note that this is only an example of one station and one year, but it suggests that 30 samples could be sufficient to compute reliable ECFs with the Sigma method. Representing 300 minutes of observations, this would allow for more regular ECF updates than with the Gustiness method. More extensive experiments on the sample size, among others, are discussed in the following section where we will omit sample sizes 20 and 90 for the sake of readability, but our analyses showed that even including them would lead to the same conclusions.

3.4. Optimising filter configuration and sample size

Our goal was to maximise the number of samples that are used to compute ECFs and maximise the fraction of ECF values within the ± 0.05 significance band (i.e. minimising outliers). To quantify this optimisation exercise, we consider the fraction of data points in a directional sector after all filters were applied over the total number of observations in that sector (before filtering). To quantify the number of non-outliers (inside the ± 0.05 significance band), we consider the fraction of ECF values within ± 0.05 of the average ECF in a period of constant ECFs. The former is a measure of quantity, i.e. how regularly the ECFs can be updated, and the latter is a measure of quality, i.e. how reliable the resulting ECFs are. Both should be as high as possible.

To find the optimal filter configuration and sample size, we focused on Schiphol (KNMI AWS station 240 at main wind mast near 27 touchdown where wind is measured at 10 m height), which is a station with little vegetation (i.e. seasonal changes in ECFs), few obstacles that cause problems for deriving ECFs and with little temporal evolution of

Table 1: Experiments that were conducted for filter optimisation. All experiments include the maximum-roughness filter explained in Section 3.2. Filters are combined with a logical “and”. For better overview, experiments without an experiment code are omitted in the following, in particular in Fig. 3.

Exp. code	Min. wind speed	Neutrality filter ($T_{2m} - T_{10cm}$)	Max. precip.
U1	1.0 m/s		
U1-T47	1.0 m/s	$[-0.3, 1.1]$ K	
	3.0 m/s		
	3.0 m/s	$[-0.2, 1.2]$ K	
U3-T47	3.0 m/s	$[-0.3, 1.1]$ K	
	4.0 m/s	$[-0.2, 1.2]$ K	
U4-T47	4.0 m/s	$[-0.3, 1.1]$ K	
U5	5.0 m/s		
U5-T57	5.0 m/s	$[-0.2, 1.2]$ K	
	5.0 m/s	$[0.0, 1.0]$ K	
U5-T47	5.0 m/s	$[-0.3, 1.1]$ K	
U5-T45	5.0 m/s	$[0.1, 0.9]$ K	
U5-T37	5.0 m/s	$[-0.4, 1.1]$ K	
	5.0 m/s	$[-0.2, 0.8]$ K	
	5.0 m/s	$[-1.1, 1.5]$ K	
	5.0 m/s	$[-0.5, 0.9]$ K	
	5.0 m/s	$[-0.3, 0.8]$ K	
	5.0 m/s	$[-0.3, 0.5]$ K	
U5-T07	5.0 m/s	$[-0.7, 0.7]$ K	
	5.0 m/s	$[-0.5, 0.5]$ K	
U5-P	5.0 m/s		0.1 mm/h
	5.0 m/s	$[-0.2, 1.2]$ K	0.1 mm/h
U5-T47-P	5.0 m/s	$[-0.3, 1.1]$ K	0.1 mm/h
U5-Td	5.0 m/s	07:00-18:59: $[0.25, 1.5]$ K 19:00-06:59: $[-0.25, 1.0]$ K	
	Apr-Nov: 4.0 m/s Dec-Mar: 6.0 m/s	$[-0.2, 1.2]$ K	
Um-T57	Apr-Sep: 5.5 m/s Dec-Mar: 4.0 m/s	$[-0.2, 1.2]$ K	
Umd-Tmd	Mar-Sep, day: 3.0 m/s Nov-Mar, night: 3.0 m/s else: 5.0 m/s	Mar-Sep, day: $[-0.2, 1.2]$ K Nov-Mar, night: $[0.5, 1.0]$ K else: $[-0.2, 1.2]$ K	
U5-Tsd	5.0 m/s	JJA, day: $[-0.5, 0.7]$ K MAM+SON, day: $[-0.5, 1.1]$ K DJF, day: $[-0.3, 1.1]$ K MAM+JJA+SON, night: $[0.0, 0.3]$ K DJF, night: $[0.0, 0.4]$ K	
U55	5.5 m/s		
	5.5 m/s	$[-0.2, 1.2]$ K	
	5.5 m/s		0.1 mm/h
	5.5 m/s	$[-0.2, 1.2]$ K	0.1 mm/h

data points, a minimum wind speed of 5.0 m/s, a vertical temperature gradient between -0.3 K and 1.1 K (i.e. $[-0.3, 1.1]$ K) and no filtering for precipitation (Experiment U5-T47) yields the best results in terms of both quantity and scores on the one hand and practical maintainability on the other hand. In the following sections, we will discuss this choice in more detail.

3.4.1. Neutral stability and minimum wind-speed filter

While a minimum wind speed of 1.0 m/s is already included in the bare minimum filter, we investigated stronger minimum wind speeds. In the old method (Section 2), we enforced the 2LM method’s requirement for a neutral boundary layer by only including wind speeds > 5.5 m/s. Without discussing it in detail, WMO (2024) recommends to use > 4.0 m/s, which is presumably (although not explicitly mentioned) done to exclude non-neutral winds. We presume that such a low threshold is more suitable for regions that generally have lower wind speeds than the Netherlands. Anyway, we investigated a range of minimum wind speeds from 1.0 to 5.5 m/s, ultimately finding the optimal wind-speed threshold at 5.0 m/s.

The neutrality requirement of the 2LM method is enforced more explicitly than before. We use the vertical temperature gradient near the surface ($T_{2m} - T_{10cm}$) to filter out non-neutral conditions. This also improves the quality of the ECFs. The reason we use the near-surface temperature gradient is that it is available at nearly all KNMI land stations. We determined the optimal filter configuration through the experiments at Schiphol outlined in Table 1, yielding optimal quantity and quality scores for a near-surface temperature gradient $T_{2m} - T_{10cm} \in [-0.3, 1.1]$ K.

The optimal neutrality filter can also be validated by analysing temperature measurements at Cabauw, both near the surface and on the tower. The latter is more representative of the boundary layer as a whole. Figure 4 shows that $\Delta\theta = 0$ (i.e. neutrality) coincides with a broader range of near-surface ΔT values. Our chosen filter (indicated in red) captures that range. Furthermore, this analysis reveals that only filtering out slow wind speeds (< 5.0 m/s) does not reliably remove all non-neutral conditions (bottom row of Fig. 4) and that additional explicit filtering for neutral conditions is of added value.

That our optimal filter configuration yields the best results in terms of the quantity score is no coincidence as the neutral stability filter is centred around the peak of the distribution of $T_{2m} - T_{10cm}$ (Fig. 5). Although this does not provide a physical reasoning for this particular choice, it does show that it includes a maximum number of measurements in the ECF computation.

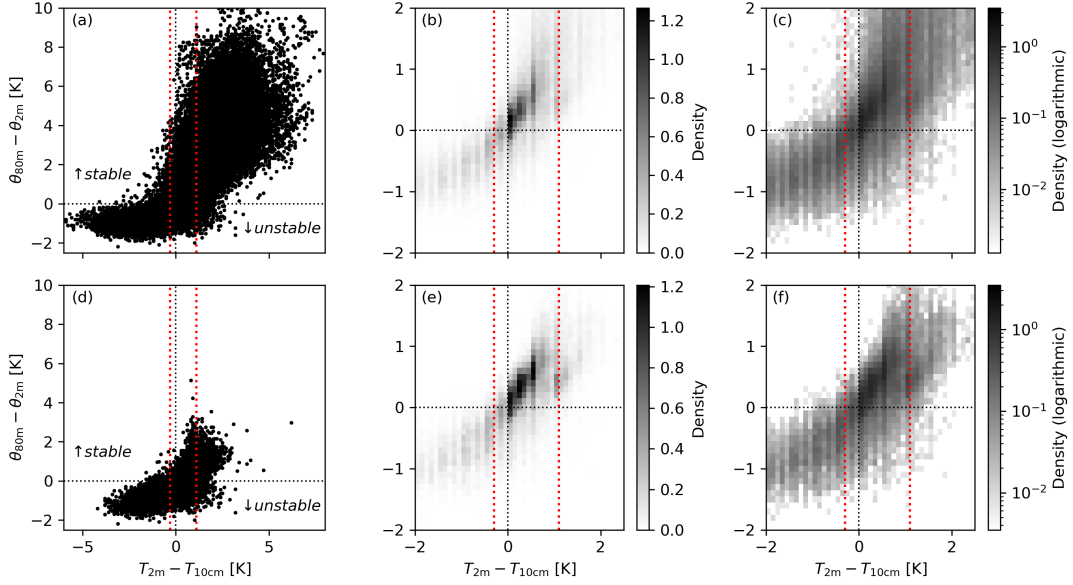


Figure 4: Scatter plot of the difference in potential temperature between 80 m and 2 m versus the difference in (regular) temperature between 2 m and 10 cm at Cabauw for 2016–2018: (a, d) regular scatter plot, (b, e) density plot (2D histogram), (c, f) logarithmic density plot. The top row (a–c) contains all the data, the bottom row (d–f) only moments where the surface observations pass the maximum-roughness filter ($z_m/z_0 > 20$) and the optimal wind-speed filter ($U \geq 5.0$ m/s). The red dotted lines indicate the thresholds used in Experiment U5-T47, which is the filter configuration chosen for the operational algorithm.

Neutrality

If we consider two heights $H_2 > H_1$, then we can roughly assume that a parcel wants to rise if the temperature T_1 at H_1 is larger than the temperature T_2 at H_2 . The atmosphere is unstable. The opposite is true if the temperature below is lower than above, in other words $T_1 < T_2$ (stable). The atmosphere is neutral if $T_1 = T_2$ (or strictly speaking: potential temperature $\theta_1 = \theta_2$). Thus, one way to decide whether the atmosphere is neutral, is to consider the temperature difference between different heights. What we have available at KNMI’s AWSs are the temperature at 10 cm height ($T_{10\text{cm}}$) and the temperature at 2 m height ($T_{2\text{m}}$). Therefore, an obvious filter for neutral stability is $T_{2\text{m}} - T_{10\text{cm}} \approx 0$. (It is not necessary to use the potential temperature here because the change in pressure and its effect on potential temperature is not significant for such small height differences.)

It has to be pointed out that this is a highly simplified approach as the temperature gradient so close to the surface may not be representative of the boundary layer as a whole. However, the fact that we aimed to develop a methodology that is usable at as many KNMI stations as possible (where only standard surface measurements are available) and in near-real time meant that we could not use more sophisticated measurements to determine neutrality (e.g. radiosonde soundings).

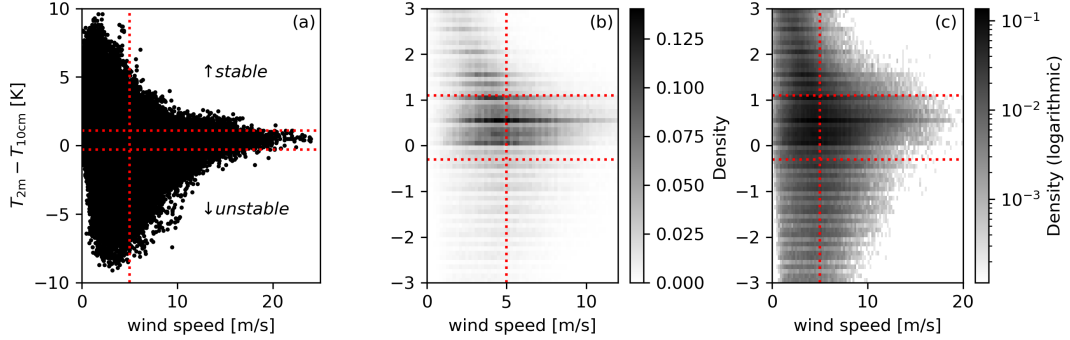


Figure 5: Scatter plot of the near-surface vertical temperature gradient over the 10-min. wind speed at Schiphol for 2016–2024: (a) regular scatter plot, (b) density plot (2D histogram), (c) logarithmic density plot. The red dotted lines indicate the optimal filter thresholds (Experiment U5-T47).

We also investigated different stability classification methods. However, most of them are unsuitable for our purposes because they require measurements from greater heights (e.g. Richardson number) or are not available at (all) KNMI stations (e.g. Monin-Obukhov length). One method that does not suffer from these limitations and that we investigated a bit further is the σ_A method. It goes back to Islitzer & Slade (1968) and is well documented in Bailey (2000). The method uses the standard deviation of the wind direction along with the wind speed to make a Pasquill-Gifford stability classification. Bailey (2000) points out that the method needs tuning for each site, which is not feasible in our case. Furthermore, a preliminary test at Cabauw did not yield satisfactory results, which is why we did not follow up on this any further.

3.4.2. Seasonal and diurnal cycle

Typical wind speeds and atmospheric stability differ per season and time of the day. Thus, we also considered seasonal and diurnal filter options.

In particular, we investigated under what conditions outliers occur in different seasons or times of the day. To this end, we computed instantaneous ECFs (i.e. sample size 1) after applying only the bare-minimum filter. We then analysed the measurements linked to ECF values that are considered outliers. It has to be noted that not all these measurements would in fact cause ECF outliers because a sample size > 1 would eliminate the most extreme measurements.

Depending on the season and time of the day, ECF outliers can be attributed to different wind speeds or stability conditions (Fig. 6). For example, we see more outliers above wind speeds of 5 m/s (neutrality filter) during summer months than during winter months. This is probably due to daytime unstable conditions. This is confirmed in Fig. 7, which shows a detailed climatology of the parameters we use in our filters. For example, it shows that by filtering with a minimum wind speed of 3 m/s or more, we can effectively filter out stable conditions during summer nights but unstable conditions during summer daytime to a much lesser extent.

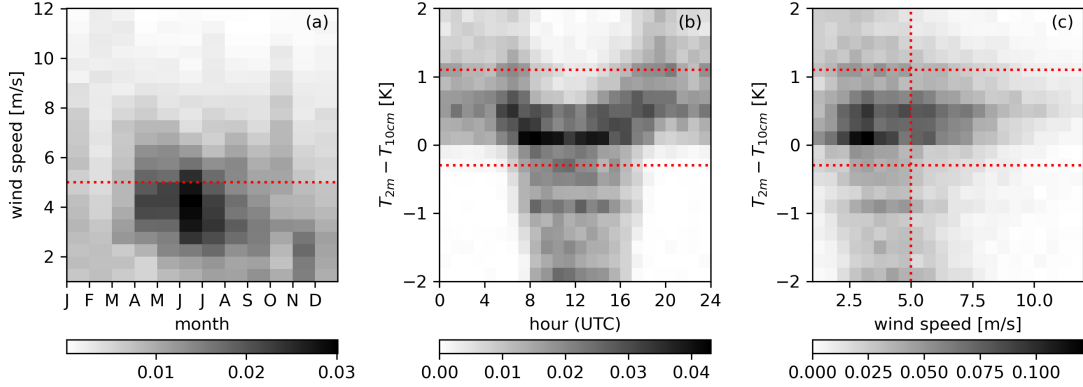


Figure 6: 2D histograms of observations at Schiphol (2016–2024) that cause outliers from the long-term average when computing instantaneous ECFs: (a) wind speed per month, (b) vertical temperature gradient per time of day, (c) vertical temperature gradient over wind speed. The darker the shading the more data points with corresponding values produce ECF outliers. The red dotted lines indicate the optimal filter (that is not used here).

These insights suggest that a filter configuration that depends on the season and/or the time of the day could help to optimise the quality and quantity scores. For example, Fig. 6 inspires us to design a season-dependent wind filter that is less strict in winter than in summer (Um-T57), hypothesising that this will increase the number of measurements from which we can compute ECFs, while keeping the quality high. We can even go one step further and make both the wind and the neutrality filter dependent on both the season and the time of the day (Umd-Tmd).

To shed more light on the seasonality of the atmospheric stability in particular, we also carried out the analysis of the potential-temperature difference at Cabauw for summer, winter and the combination of spring and autumn (Fig. 8). This shows a number of general points: (1) In winter, there is less daytime variability in both the near-surface temperature and the 80-m potential-temperature gradient than in other seasons due to less solar radiation. (2) In summer nights, there is less variability in both temperature gradients compared to nights in other seasons, possibly because nights are shorter. Strong vertical temperature gradients at night occur when there is no/little cloud and the surface temperature drops because of radiative cooling. If the night lasts less long, this effect remains smaller. (3) The seasonal differences are larger during the day than at night.

Overall, we can conclude that atmospheric neutrality depends on the season both if defined by the near-surface gradient of air temperature and the 80-m gradient of potential temperature. We designed a filter that takes this into account by being stricter (using a narrower temperature filter) at nighttime and using slightly different thresholds per season during the day (U5-Tsd; blue lines in Fig. 8).

None of these attempts of seasonal and/or diurnal filters lead to a better combination of quantity and quality scores compared to the optimal filter (see Fig. 3). The seasonal wind filter (Um-T57) does have a relatively high quantity score as it is a lot less strict

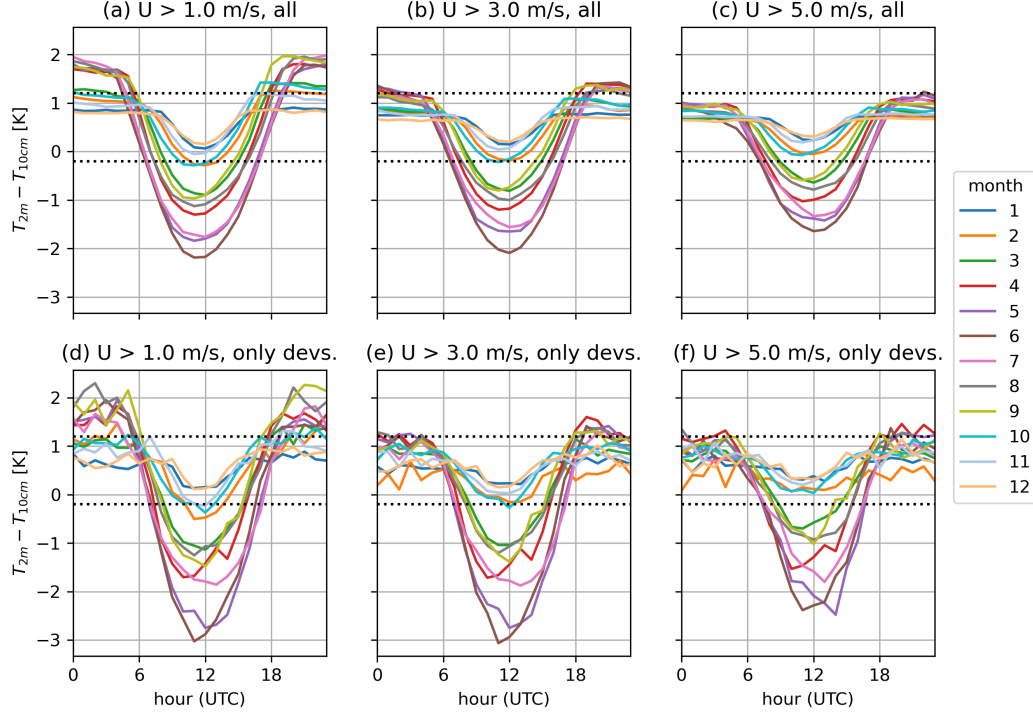


Figure 7: Climatology of the vertical temperature gradient at Schiphol (2016–2024) by month and time of the day for wind speeds (a, d) > 1.0 m/s, (b, e) > 3.0 m/s and (c, f) > 5.0 m/s where the top row (a–c) contains all observations that exceed the wind-speed threshold and the bottom row (d–f) only those that cause outliers (as in Fig. 6). The black dotted lines indicate the optimal neutrality filter (which is not used here).

during winter months, but the quality score is relatively low. Similarly, the seasonal and daytime-dependent filter Umd-Tmd leaves us with more samples (though not as many as Um-T57) but still produces more ECF outliers than the optimal filter. The seasonal and diurnal neutral-stability filter inspired by the potential-temperature analysis, U5-Tsd, is among the configurations that produces the least outliers among the tests we conducted, but it also has the lowest quantity score, which is problematic for stations where certain directional sectors do not occur very often. Such a strict filter would lead to less frequent ECF updates. Given that the relative increase in quality compared to U5-T47 is low, but the decrease in quantity score is large, we argue that the seasonal neutrality filter of U5-Tsd is not effective.

Despite a clear dependence of our filter parameters on the time of the year and the day, this exercise gives us confidence that a simple filter approach with the same filter configuration for all seasons and times of the day is preferred over a complicated approach with different settings per month and time of the day (conform Occam’s razor, the principle of solving problems using as few variables as possible). Our optimal filter, U5-T47, is among the highest-scoring filters in terms of the number of outliers and has a reasonable quantity score.

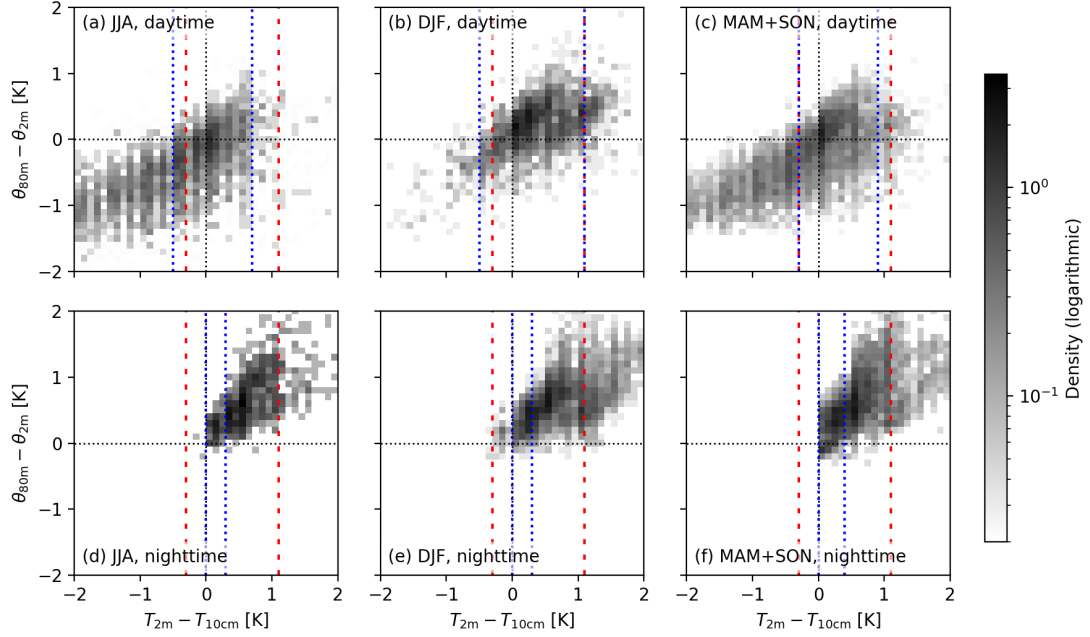


Figure 8: Logarithmic density plot of the difference in potential temperature between 80 m and 2 m versus the difference in (regular) temperature between 2 m and 10 cm at Cabauw for 2016–2018 differentiating between seasons (columns) and day/night (rows). The figure only includes moments where the surface observations pass the maximum-roughness filter ($z_m/z_0 > 20$) and the optimal wind-speed filter ($U \geq 5.0$ m/s). The red dashed lines indicate the optimal filter thresholds (Experiment U5-T47) and the blue dotted lines the filter thresholds that take night–day and seasonal differences into account (U5-Tsd).

3.4.3. Influence of snow

It is easy to imagine that a snow-covered landscape has a different roughness and would thus lead to an effect on the ECFs. Furthermore, we initially foresaw issues with the grass-temperature measurements ($T_{10\text{cm}}$), which we rely on for our neutral-stability filter, when snow is present. Thus, we analysed a number of cases with snow cover at Schiphol, one of which we present in Fig. 9.

On 16 December 2010 (Fig. 9g), snowfall started at Schiphol, and a significant amount of snow remained present until the end of December.⁷ Indeed, we see negative ECF deviations in several directional sectors during this period (Fig. 9a), indicating a lower local roughness. (Note that here we present the deviation of the ECFs from the long-term mean and we colour-code the directional sector to be able to show all ECFs in a single time series). Since significant snowfall is rare in the Netherlands, it is hard to determine whether this is just a one-off result or if we can draw a more general conclusion from this.

One could attempt to filter out snow cases by excluding measurements when a present

⁷<https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten> (KNMI: Geografische overzichten van het weer in Nederland; accessed 25-08-2025)



Figure 9: Deviations of ECF values from long-term average and a number of meteorological parameters for a case with snow at Schiphol: (a) ECF deviations with optimal filtering, (b) wind speed, (c) wind-speed standard deviation, (d) wind direction, (e) temperatures at 10 cm (blue) and 2 m (red), (f) temperature difference between 2 m and 10 cm, (g) present-weather code indicating precipitation type, (h) precipitation intensity and (i) pressure. The colours in a–d indicate the wind-direction sector.

weather sensor (PWS) reports snow and continue to exclude these measurements until the 2-m temperature has been positive for a certain amount of time (Fig. 9g). However, not all stations have a PWS or other near-real time measurements of snow. Anyway, if snow indeed has a real physical effect on the ECFs, we do not wish to filter this effect out.

The example also suggests that snow can cause erroneous 10-cm temperature measurements, which we use for our proposed neutrality filter. After snow started falling (see Fig. 9g), the 10-cm temperature seems to remain constant at around 0°C for several hours starting from the night of 17 December 2010 (Fig. 9e). Then, it “jumps” to about -5°C. The 2-m temperature shows a more realistic behaviour in that period. For the rest of the period the 2-m and 10-cm temperature curves are not disconnected and closely follow each other. We suspect that the ground sensor was covered in snow, keeping the temperature around 0. Then, the sensor was cleared of snow and started to report correct air-temperature values again.

We do not see a large need to take extra measures to filter out such erroneous temperature measurements due to snow. We assume that the behaviour shown in Fig. 9e only happens in rare cases where there is more than 10 cm of snow. These periods will then be filtered out inadvertently because the temperature difference will (falsely) indicate an unstable atmosphere (Fig. 9f): the snow layer will be warmer than the air above. Thus, if anything, we are losing a few “valid” (allegedly unstable, but maybe neutral) data points, but no data points get filtered out that should have been kept.

Finally, days with snow are rare in the Netherlands, have become rarer over recent years due to global warming and will continue to do so (De Vries et al., 2013, 2014). This is another reason why we do not regard snow as a big issue for our methodology.

As a side note, we remark that another factor that could influence the 10-cm temperature measurements is more conceivable: too long grass due to poor maintenance. We did not perform any research on this, but we expect the measured extremes of $T_{2m} - T_{10cm}$ on sunny days and clear nights with relatively low winds (near the filter limit of 5 m/s) to be less extreme than they should be. As a consequence, more stable and unstable cases will pass the filter than if the grass is maintained properly. This could lead to false diurnal changes in the ECFs when the wind speed is near 5 m/s, with too high ECFs on sunny summer days and too low ECFs on clear winter nights. Figure 6c (Schiphol) shows that the too low ECFs occur slightly more often (2.5 % of the time) than the too high ECFs (2 % of the time). Thus, if it is a problem, it will not be a problem a lot of the time.

3.4.4. Lacking correlation with convective precipitation and other meteorological parameters

The ECF method assumes that fluctuations in the wind (3-second gusts compared to hourly average wind speeds in the Gustiness method and standard deviation compared to 10-minute mean wind speed in Sigma method) are caused by surface roughness (the effect of obstacles is similar, but limited because of the D/H requirement described in Section 1.3 and 4.2). There are however other reasons for wind to fluctuate that have nothing to do with surface roughness: convection, gravity waves, obstacles and sensor

limitations. In this section, we determine if there are significant ECF outliers because of wind fluctuations that are not caused by surface roughness. If so, that would call for additional filters.

We start by pointing out that simply filtering out any precipitation does not lead to better quality scores as shown in Fig. 3 (Experiments U5-P and U5-T47-P). We filtered by the precipitation rate only (i.e. “all kinds” of precipitation) because filtering for only convective precipitations is not possible based on the weather code from the PWS, which only includes “intermittent” precipitation (see also De Haij, 2007). Other ways of filtering for convective precipitation specifically would require more sophisticated measurements that are not available in near-real-time.

To further underline the conclusion that the simple precipitation filter does not improve results and to get a clearer picture of the physical reasons behind outliers in an ECF time series, we analysed some examples (Figs. 10 and 11). Similar to Fig. 9, we again show deviation of the ECFs from the long-term mean, and additionally, we present the ECFs that would be computed if only the “bare-minimum” filter was applied to get an impression of the impact of our optimal filter.

Convection can occur with and without precipitation (e.g. summer thermals), isolated or organised (e.g. near an area of low pressure or in a line on a cold front or trough). A good example of wind fluctuations due to convection are downdrafts associated with heavy showers. To find such an example, we selected a weather situation with a cold front/trough, heavy precipitation and enough wind to pass the neutrality filter (> 5 m/s): 25-03-2026 (see Fig. 12). ECFs at Twente hardly change the entire day (Fig. 10a), despite a lot of convective precipitation (Fig. 10h). Note that it is an educated guess that we are dealing with convective precipitation, but apart from the weather maps, the temperatures at 10 cm and 2 m (Fig. 10e, f) support that hypothesis.

On the other hand, significant ECF outliers do occur when there is no precipitation (or suggestions of dry convection), as illustrated by an example from a winter evening at Leeuwarden (Fig. 10j, q). Even when we consider precipitation in the environment of a station through e.g. radar images (not shown), we do not find a significant correlation between ECF outliers and precipitation. These findings corroborate our decision not to filter for precipitation.

We do not see a clear correlation of ECF outliers with other meteorological parameters either (Figs. 10 and 11). In the example from Leeuwarden (right column of Fig. 10), there is no indication that filtering by any of the presented meteorological parameters would prevent the outlier in this particular case. Because we aim to use our method in near-real-time and we prefer a simple filtering approach (again Occam’s razor), we limit ourselves to parameters that are measured at automatic weather stations. Apart from wind and temperature, this includes precipitation (intensity, duration and some basic precipitation types) and pressure.

For example, one might expect passing weather fronts to cause disturbances in the ECFs. In the example from Schiphol in the left column of Fig. 11, a number of fronts pass: first a warm front around 03:00, then a cold front around 18:00 and finally an occlusion around 06:00 of the next day. The passage of the cold front and the occlusion are visible in the

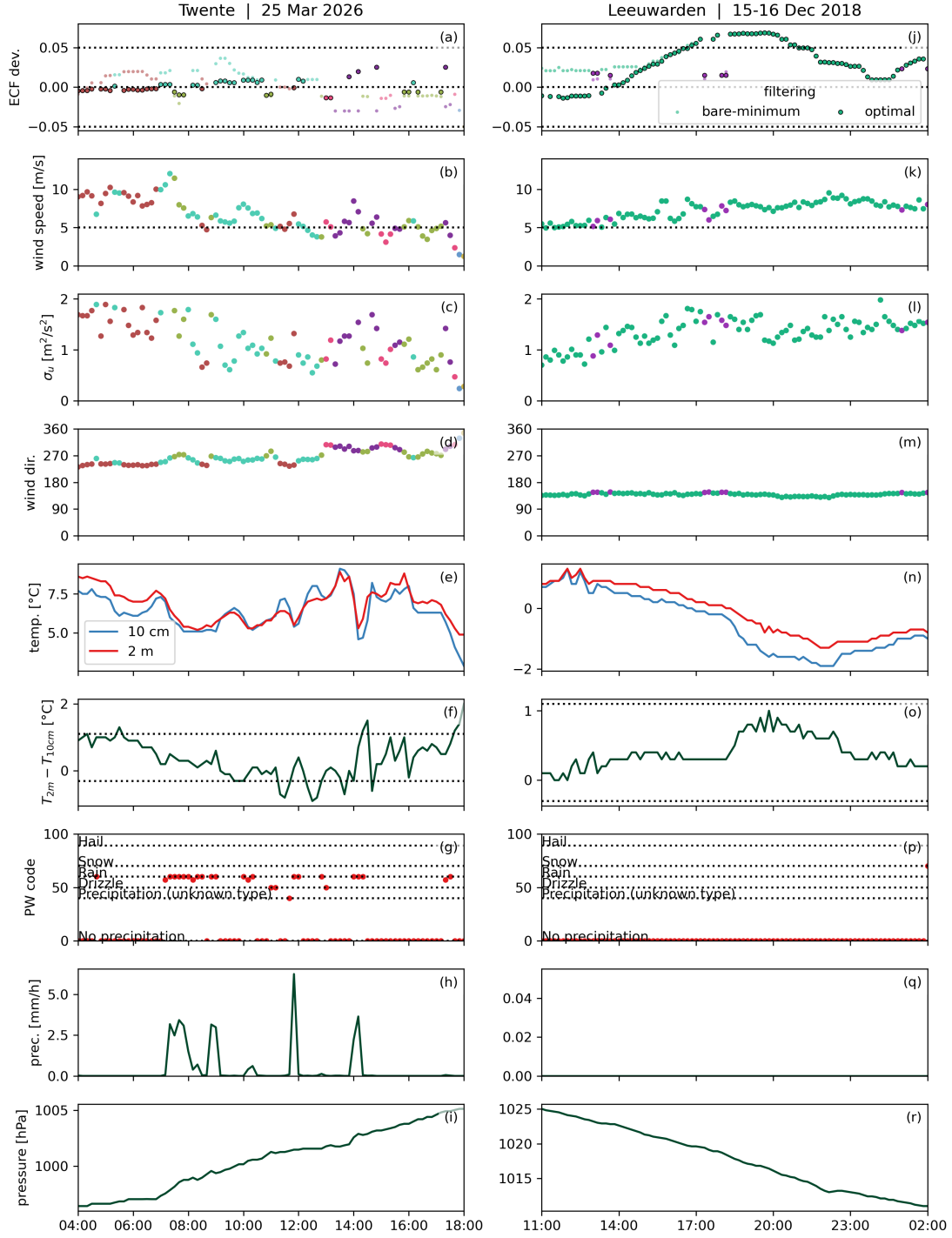


Figure 10: Deviations of ECF values from long-term average and a number of meteorological parameters for cases at (a-i) Leeuwarden and (j-r) Twente: (a, j) ECF deviations with optimal filtering (strong circles) and bare-minimum filtering only (faint dots), (b, k) wind speed, (c, l) wind-speed standard deviation, (d, m) wind direction, (e, f) temperatures at 10 cm (blue) and 2 m (red), (f, o) temperature difference between 2 m and 10 cm, (g, p) present-weather code indicating precipitation type, (h, q) precipitation intensity and (i, r) pressure.

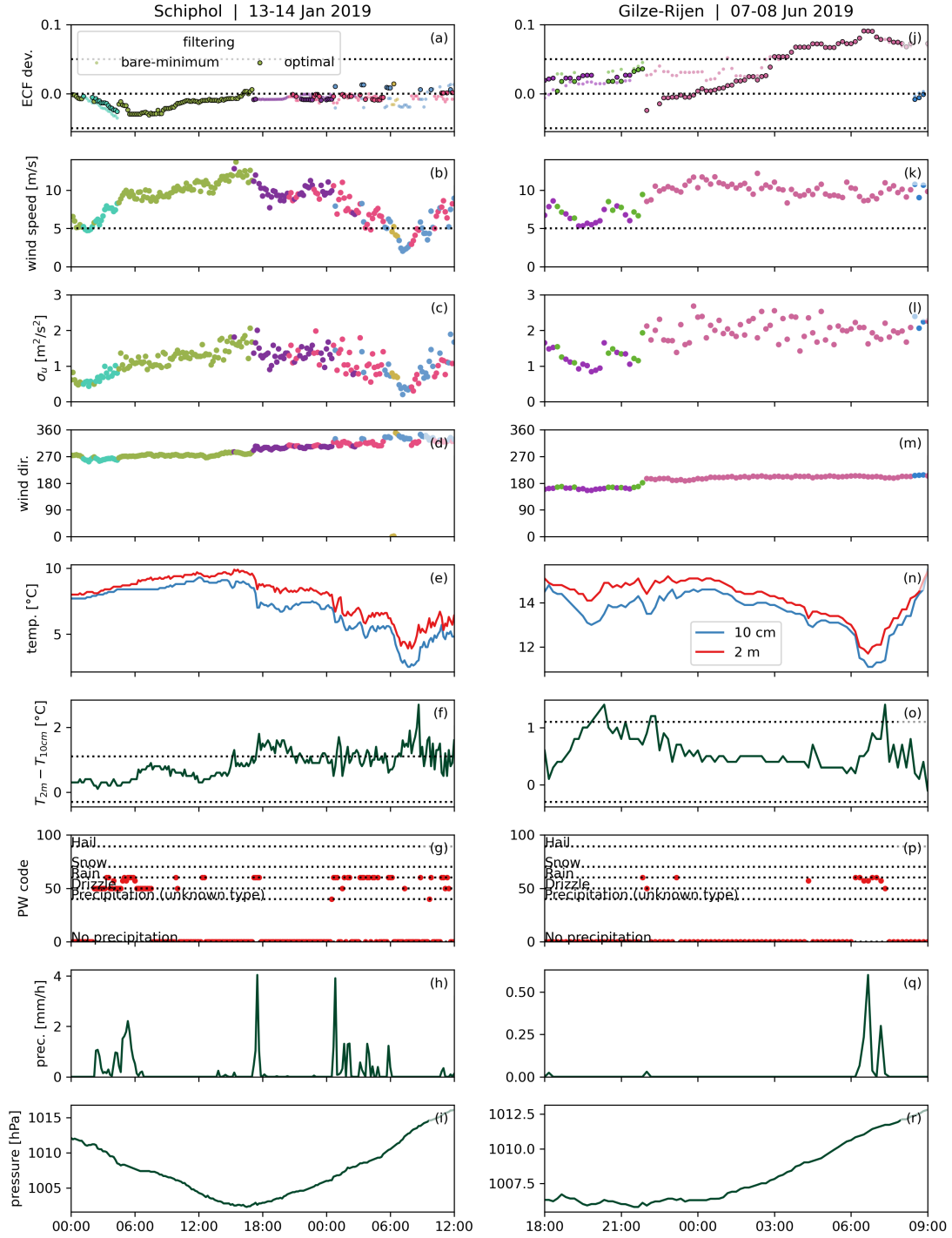


Figure 11: Same as Fig. 10 but then for cases at (a-i) Schiphol and (j-r) Gilze-Rijen.

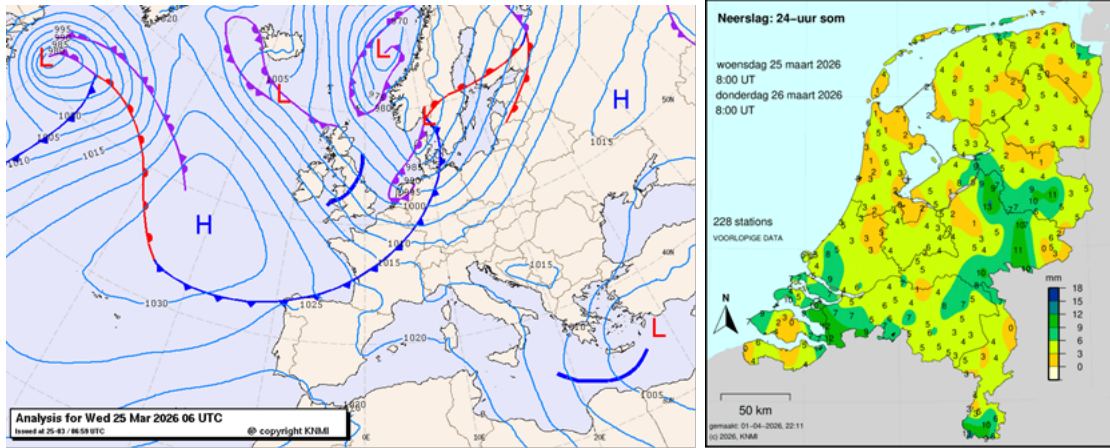


Figure 12: Meteorological situation on 25 March 2026: (left) analysis for 06:00 UTC and (right) accumulated precipitation from 08:00 UTC until 08:00 UTC on the following day. The maps are from <https://www.knmi.nl/nederland-nu/klimatologie/daggegevens/weerkaarten> (KNMI: Weerkaarten archief Europa; accessed 13-04-2026) and <https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten> (KNMI: Geografische overzichten van het weer in Nederland; accessed 13-04-2026), respectively.

time series of wind speed, wind direction and temperatures (Figs. 11b, d, e). However, during the entire period and, in particular, the passage of the fronts, no significant change of the ECFs occurs (Fig. 11a). This suggests that filtering out fronts, e.g. via (dropping) pressure (Fig. 11i) is not suitable to prevent ECF outliers.

Finally, we exhibit an example from Gilze-Rijen where the ECFs do change significantly within a short period (right column of Fig. 11). Here, a sudden increase of ECFs (Fig. 11a) happens when the standard deviation is increased too (Fig. 11c). By definition, turbulence due to a rougher surface affects ECFs, it is unlikely that the roughness changes drastically within such a short period. (In fact, the ECFs for this sector drop again at the next occurrence of this wind direction.) Though there is precipitation when the ECF has deviated from the mean (from 06:00), there are no signs in the measurements of convective activity during the onset of the increase of ECFs (between 00:00 and 03:00), which also rules out this source for an elevated standard deviation. However, along with the standard deviation, the wind speed itself is also stronger (Fig. 11b). But the complex relationship between wind speed and standard deviation in the ECF formula makes it hard to identify the root cause.

In principle, gravity waves can also contribute to variability of the wind even at 10 m. However, this happens at most a few times per year, only for a short period (1–2 hours) and, on land, only during stable nights when wind speeds are expected to be lower than our minimum wind speed (see Knoop et al., 2026, in particular their Fig. 4). Therefore, we disregard gravity waves here.

There are indications that the wind sensors (cup and vane) themselves are affected by precipitation. Wauben (2007) compared the field performance of three different sonic anemometers with the KNMI cup and vane over a period of one year. He found that the

Table 2: KNMI stations considered during filter optimisation and periods where ECFs remain relatively constant.

KNMI Station		Constant period	Whole yrs.	Analysis period
Schiphol	240	01-01-2016–31-07-2025	9	01-01-2019–31-12-2021
Vlissingen	310	01-01-2004–31-12-2019	15	01-01-2010–31-12-2012
Lauwersoog	277	01-01-2004–31-07-2025	21	01-01-2013–31-12-2015
Leeuwarden	270	01-01-2007–31-07-2012	5	01-01-2008–31-12-2010
Rotterdam AP	344	01-01-2017–31-07-2021	4	01-01-2017–31-12-2019
Gilze-Rijen	350	01-01-2021–31-07-2025	4	01-01-2021–31-12-2023
Volkel	375	01-01-2014–31-05-2019	5	01-01-2015–31-12-2017
Hoogeveen	279	01-01-2017–31-07-2025	8	01-01-2019–31-12-2021
Twente	290	01-01-2019–31-07-2025	6	01-01-2020–31-12-2022
Maastricht AP	380	01-04-2018–30-06-2021	3	01-04-2018–31-03-2021

cup overestimates the wind speed by up to 0.15 m/s during precipitation. The effect on the standard deviation was not directly investigated, but the fact there is little effect on the maximum gust suggests that there is little effect on the standard deviation too. An overestimation of the wind speed by 0.15 m/s with no change in the standard deviation of the wind speed will lower the ECF by about 1 %, so this effect is negligible.

We summarise that filtering data points by other meteorological parameters than in our optimal filter has little added value. This is mostly due to the ambiguity that such filters would introduce. While in some cases extra filtering could prevent outliers in the ECF time series, it would also further reduce the number of data points that remain available for ECF computation. Especially in directional sectors that only occur rarely, this would further reduce the update frequency. Thus, we argue that this is not a compromise that is worth the gain.

3.5. Testing the optimal algorithm

Having identified an optimal filter configuration and sample size for Schiphol (Fig. 3), we need to verify that it works well at other stations too. Unlike at Schiphol, rough land, orography, seasonal variations, sharp roughness contrasts (e.g. at the coast) and obstacles are a lot more common at other locations, making it more challenging to calculate ECFs. To test and attempt further optimisations of our algorithm, we expand our analysis to a larger subset of KNMI stations.

3.5.1. Country-wide performance

We tested our algorithm in terms of quantity and quality scores at a range of different stations, representing airports, coastal and inland stations. We considered ten KNMI stations (Table 2 and Fig. 13) where we computed the quantity and quality scores in the same way as described in Section 3.4.

Our quality measure requires the identification of periods in which the ECFs remain relatively constant (at least within ± 0.05). For simplicity, we identified these periods

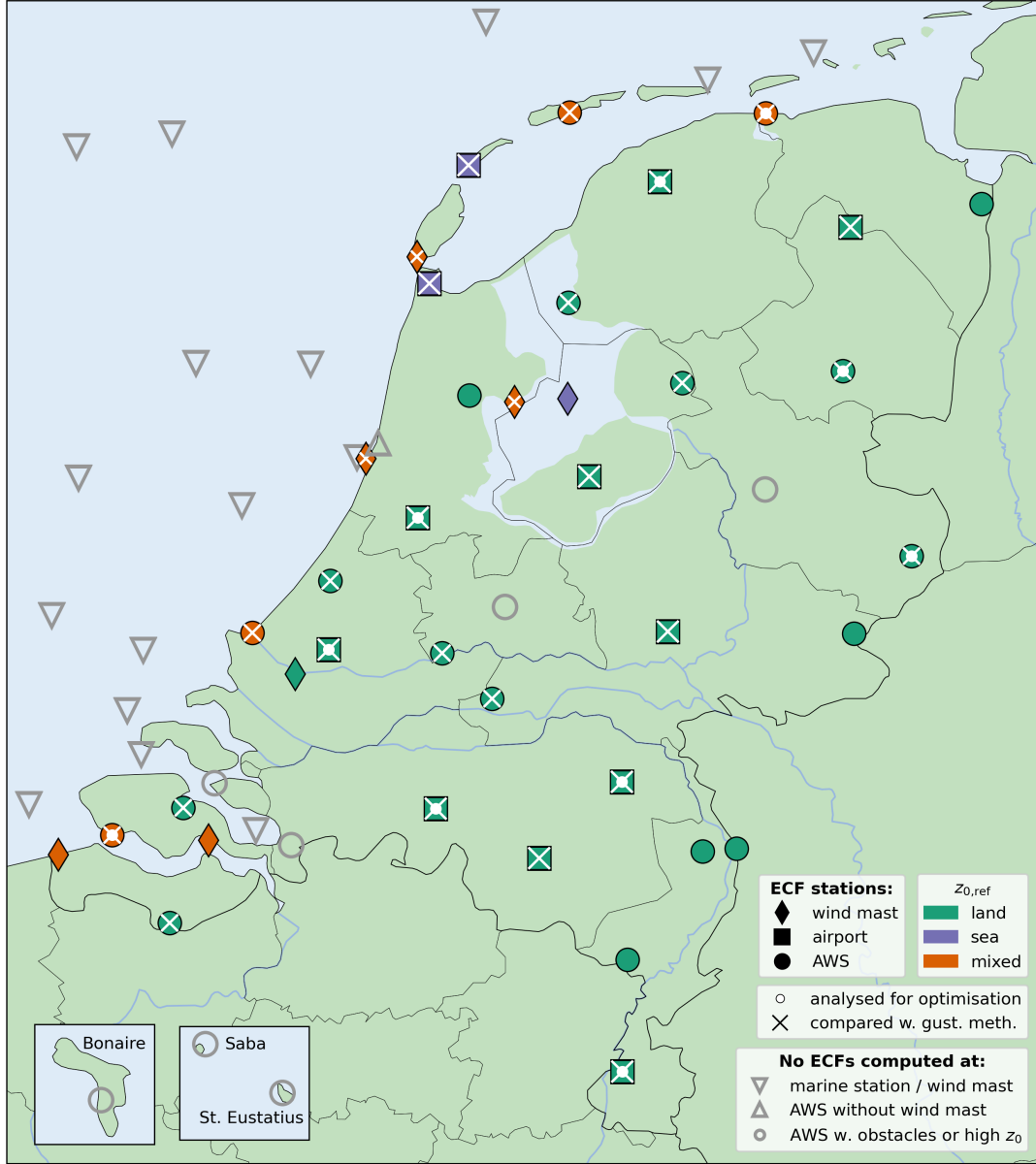


Figure 13: Map of KNMI surface stations in the European Netherlands and Caribbean Netherlands (bottom left insets). Filled symbols indicate stations where ECFs can be computed and empty symbols stations where that is not possible. The colour of the symbols indicates which reference surface roughness is used: land ($z_{0,\text{ref}} = 0.03$ m), sea ($z_{0,\text{ref}} = 0.002$ m) or a mix depending on the direction. Stations with a white dot are included in the process of optimising the algorithm (see also Table 2). At stations with a white cross, a comparison with Gustiness ECFs was conducted (see Section 6).

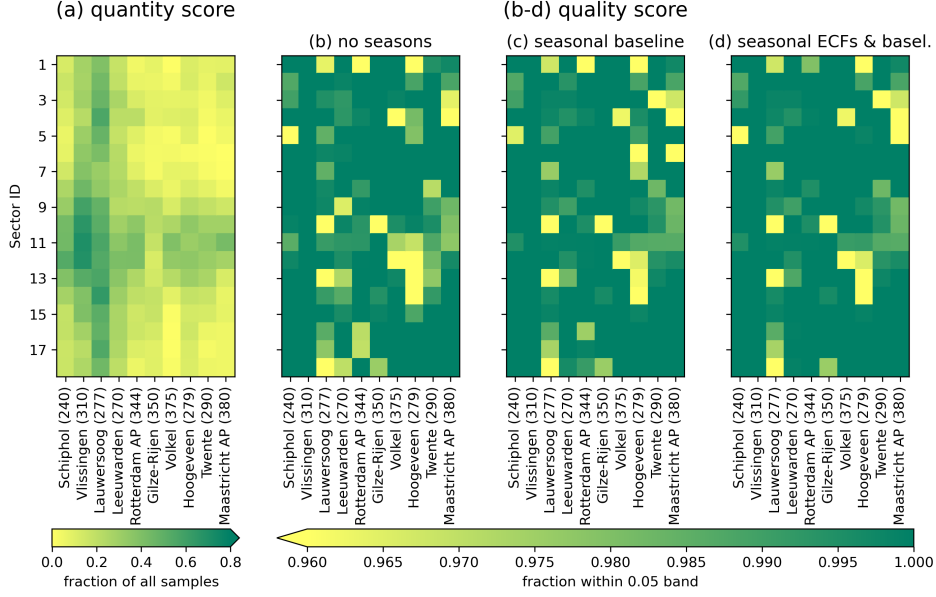


Figure 14: Quantity and quality scores (same as Fig. 3) for a number of stations across the Netherlands using the optimal algorithm (U5-T47; see Section 3.4). The quality score is given with respect to long-term averages (see Table 2) that (b) do not and (c, d) that do take seasons into account. ECFs are computed (b, c) without and (d) with explicit seasonal distinction.

by eye from ECF time series plots (similar to Fig. 2) and considered periods where the ECFs remain constant in all directional sectors. Although that limits the maximum length somewhat, we still find a period of at least 3 years at each of the stations (Table 2). For all stations, we analyse 3 years (roughly in the middle of the constant period), but for the long-term average ECFs, we use the entire constant period (whole years that is, to avoid any seasonal biases).

Overall, though still reasonably high, the quantity and quality scores at most stations are lower than at Schiphol (Fig. 14a, b). To some extent, that is not surprising as Schiphol is a rather “simple” area in terms of wind measurements. Inspection of time series (not shown) can help to understand the larger number of outliers to some extent. However, it is not always clear which observation sample(s) exactly cause(s) a deviation in the ECF time series as we take a moving-window median. The median is taken over 30 samples (see Section 3.3) from the same directional sector, so the samples could be from different days or even months, smearing out daily or seasonal effect. Therefore, this analysis has its limits.

Nonetheless, it shows that some outliers do appear to have physical reasons (e.g. are due to local turbulence from convection or obstacles or associated with precipitation), others are due to shortcomings in the way we compute the quality score. Generally, temporary changes in local roughness can lead to realistic changes of ECFs larger than the threshold of 0.05 that we use to classify outliers. We attempted a correction for one possible cause for this: a strong seasonal cycle.

3.5.2. Seasonality

In a first attempt to correct for any seasonality, we change how we determine outliers. We use the same underlying ECFs as before (“no seasons”, Fig. 14b) but to determine the quality score, we compute two different long-term ECF averages: one for summer and one for winter. Following Stepek & Wijnant (2013), we considered 1 November until 31 March as winter and 1 April until 31 October as summer. This is what we call the “seasonal baseline” method (Fig. 14c).

For some stations and sectors, distinguishing between summer and winter ECFs improves quality scores (Fig. 14c). In particular, this is the case in sectors with a seasonal cycle and a lot of measurement samples (e.g. at Hoogeveen). However, even at Hoogeveen some sectors remain where the seasonal cycle is so strong that this correction is not sufficient. On the other hand, in sectors with very few samples (low quantity score), the seasonal quality score can even lead to a lower quality score because we further split up the dataset, making each average even less reliable (e.g. Sector 6 at Maastricht Airport, see Fig. 15d). There are even cases where no pronounced seasonal cycle is present,⁸ but still the seasonal quality score coincidentally suggests a higher quality (e.g. Sectors 4–5 at Hoogeveen, not shown).

It is important to point out that this exercise only constitutes variations on how we compute our quality score. In some cases, one way of computing quality works better and in other cases another score might be better suited. The underlying ECF data remain the same.

This changes if we also make the ECFs themselves season-dependent. In the old Gustiness method, a distinction was made between summer and winter ECFs for some stations that exhibit a strong seasonality. However, earlier ECF updates using that method were not real-time (Appendix B) and only had one set of ECFs per season, not reflecting the gradual change in vegetation from one season to the next. A near-real-time product such as the one we propose here will exhibit the gradual changes of the seasons inherently. Nonetheless, we investigated if it could be of added value to still incorporate a distinction between the seasons into our algorithm.

The idea is that as soon as a new season starts (e.g. summer), measurements from the previous one (winter) will not be taken into account any longer for the 30 samples over which the median is taken. Instead, at the beginning of a new season, we assume that measurements from the end of the previous same season are much more representative. For example, on 1 April, measurements from 1 April and 31 October of the previous year are used to compute ECFs instead of measurements from the previous day (31 March). This method is referred to as “seasonal ECFs + baseline” in Fig. 14 and illustrated in Fig. 15a where the ECF value changes much faster to the average of the season than when seasons are not explicitly taken into account (green vs. purple dots).

A low quality score (without seasons) can be improved by taking seasons into account in the ECF computation (Fig. 14d). However, just as with the seasonal baseline (discussed above; Fig. 14c), this approach also introduces new problems, some of which are

⁸In the ECF updates in 2013 and 2020, a distinction was made between summer and winter ECFs at Hoogeveen (see Appendix B), but for these sectors the seasonal cycle has always been seen as weak.

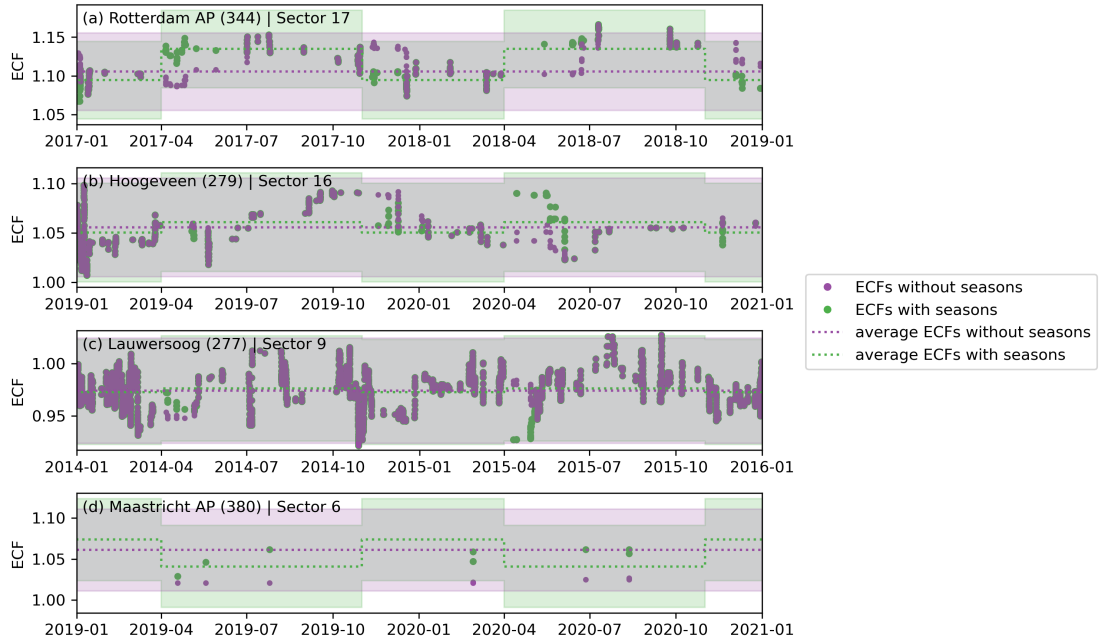


Figure 15: Exemplary ECF time series with seasons (green) and without (purple). The dots indicate the individual ECF values, the dotted line the long-term averages and the shaded areas the ± 0.05 bands around them.

exemplified in Fig. 15b-d.

The seasonal approach can cause a real change in local roughness that occurs in one season to be reversed when the next season starts. An example of this is shown in Fig. 15b where the ECFs sharply drop in winter 2019/2020 but go back to the value from autumn 2019 before that drop when summer begins. The fact that the ECFs again decrease after that suggests that the drop in winter was real and that the seasonal approach leads to dubious ECF values (overestimation).

The opposite can occur too: an outlier ECF at the end of a season can influence ECFs that are computed months later. An example of this is shown in Fig. 15c. At the end of October 2014 (i.e. end of the summer half year), the ECFs are shortly a lot lower than on average before relaxing back towards the long-term average. At the beginning of April 2015 (i.e. the next summer half year), these outlier values are taken into account again: The outlier is duplicated in a sense. Such behaviour is particularly common if there is no seasonal cycle.

At some stations, there are sectors where ECFs can only be computed a few times per year or less. In such cases, distinguishing between seasons makes little sense and can even lead to wrong results. For example, in Fig. 15d, there is so little data that it is impossible to say whether the values with or without seasons are more reliable. In any case, the seasonal averages are likely wrong as it is very unlikely that local roughness is higher in winter than in summer.

In summary, there is insufficient added value of an explicit distinction between summer

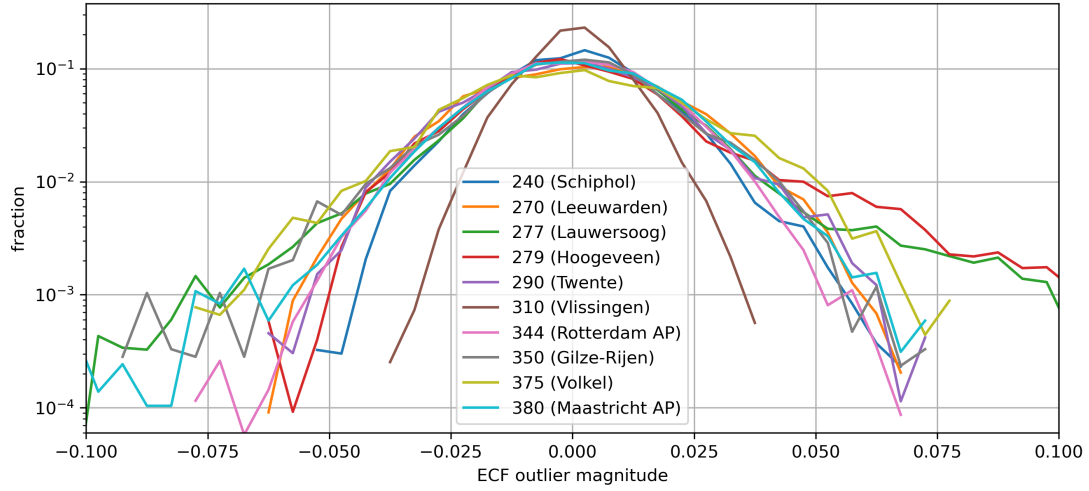


Figure 16: Distribution of the deviation of ECFs from the long-term mean per station.

and winter ECFs, while at the same time this would introduce a number of new problems, as the examples above illustrate.

Overall, we conclude that many of the apparent quality issues can be explained by a seasonal cycle, “real” excursions of the ECFs or other shortcomings of our quality measurement (one could see them as “false-negatives”). For example, in some cases we see proof that ECFs change significantly because of seasonal effects (crops or trees with leaves in summer and not in winter). On a smaller time scale (hours, night/day), we also see significant temporary changes in ECFs that have nothing to do with local roughness changes, but are caused by convection due to daily cycle or (presumably convective) precipitation. However, there remain some outliers that are correctly indicated by the quality score (“true-negatives”). Most of these occur in sectors with very scarce data (e.g. Sectors 6 at Maastricht AP, many sectors at Hoogeveen, Sector 3 at Twente). We argue that it is probably impossible to completely rule out some degree of error when automating ECF computation. Figure 16 shows that the magnitude of such deviations from the long-term average is within ± 0.05 for more than 99 % of ECF values and thus at an acceptable level.

3.5.3. Wind from sea at coastal stations

There have been several studies in the past about problems with coastal (i.e. North Sea and Lake IJssel) measurements and ECFs. This includes the extrapolation and interpolation of potential wind and the curvature problem, discussed in Section 1.4. Specifically for wind from the sea, which is what this section is about, it is important to realise that sea is different from land in two ways:

1. The sea surface is generally smoother than land, so offshore a higher wind speed is needed to mix layers and to go from stable to neutral conditions. That is why Benschop (1996) suggested a higher minimum wind speed for a neutral filter at sea (10 m/s) than over land (6 m/s).

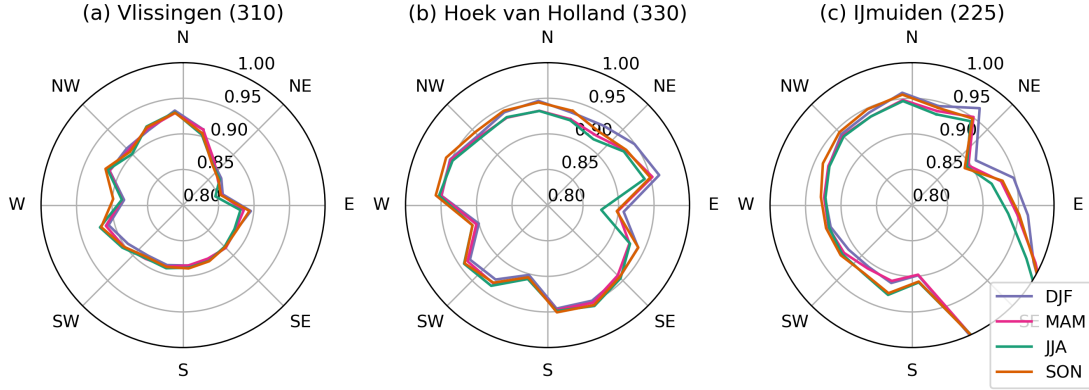


Figure 17: Seasonally averaged ECFs at three coastal stations based on observations from six years of data (2019–2024). Note that the radial axis (representing the ECF) ranges from 0.8 to 1.0 to better highlight the differences among seasons (even though ECFs in SE sectors exceed 1.0 at IJmuiden).

2. The sea warms up and cools down more slowly than land, which means that there is no daily cycle in surface temperature and atmospheric stability over sea like there is over land (over land generally more stable at night due to radiative cooling of the surface and more unstable during the day because the sun heats the land). Furthermore, seasonal differences are less pronounced offshore than onshore.

Having said all this, we show in this section, that there are no problems with calculating ECFs and potential wind with 2LM using coastal measurements.

If our neutral-stability filter was insufficiently equipped for coastal stations, we would see differences in ECFs among seasons. The roughness in directional sectors facing the sea should on average be constant over time. However, stability over the North Sea has a clear seasonality, e.g. with more unstable conditions in autumn due to relatively cold air over relatively warm sea water. If our neutral-stability filter let through such unstable conditions to a significant extent, we would find significant differences between autumn ECFs and the other seasons

At three coastal stations, we do not find significant differences between autumn ECFs and the other seasons (Fig. 17), suggesting that there are no or only very little shortcomings in our neutral-stability filter for wind coming from sea. In particular, we draw the reader’s attention to the sectors that face the sea: southerly sectors for Vlissingen, north-westerly for Hoek van Holland and westerly for IJmuiden. The differences between autumn (SON, orange line in Fig. 17) and the other lines are minuscule (in the order of at most 1 %).

In another analysis, we want to show that ECF theory works for coastal stations, at least for wind from the sea. We exploit the fact that at Hoek van Holland, two wind masts are located in close vicinity to each other: a 16-m mast on the Noorderhoofdpier and a 41-m mast about 600 m SSW of it on the Splitsingsdam (as described in Section 4.1). We consider the period from 13/11/2012 until 30/04/2018 when measurements of wind speed and its standard deviation are available for the Splitsingsdam and only wind-speed measurements for the Noorderhoofdpier. Here, we use ECF theory to “convert”

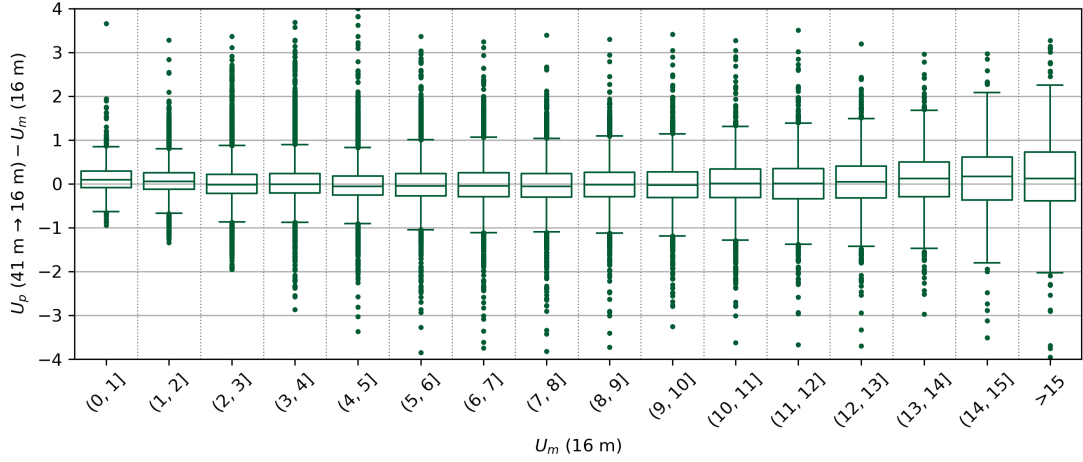


Figure 18: Boxplots of the absolute differences (in m/s) in sea-facing sectors (16–18 and 1–2) between (1) wind speeds measured at the 41-m Splitsingsdam mast converted to the height of the 16-m Noorderhoofd pier mast and (2) wind speeds measured at 16 m height at Noorderhoofd pier itself. The boxplots are presented as a function of measured 16-m wind speeds at Noorderhoofd pier. Each box extends from the lowest quartile of the data (Q1, lowest 25 % of the data below this) to the third quartile (Q3, highest 75 % above this), with a line at the median. The whiskers extend from the box to the farthest data point lying within $1.5 \times$ the inter-quartile range (IQR) from the box ($\text{IQR} = Q3 - Q1 = \text{height of the box}$: whiskers are therefore larger if the box is bigger). Flier points are those past the end of the whiskers (some of which lie beyond the plot limits).

the Splitsingsdam wind speeds to the height of the Noorderhoofd pier. To this end, we substitute the reference roughness length with the computed local roughness length, $z_{0,\text{ref}} = z_0$, and we use the heights of the Splitsingsdam and Noorderhoofd pier masts as measurement and reference heights, respectively ($z_m = 41$ m and $z_{\text{ref}} = 16$ m). Finally, we compare the converted wind speeds to the wind speeds that were actually measured at the Noorderhoofd pier (details on the computation of potential wind are discussed below in Section 3.6).

Considering sea-facing sectors (that are unaffected by obstacles and wind turbines), we do not find significant deviations between converted and measured wind speeds (Fig. 18), suggesting that doubts about our algorithms applicability at coastal stations are unfounded. In particular, more than half of the converted Splitsingsdam measurements are less than 0.8 m/s different from the Noorderhoofd pier measurements, since each of the boxes of the boxplots in Fig. 18 contains 50 % of the data (and 25 % is higher and 25 % lower). Importantly, the largest deviation occur at stronger wind speeds and not at slow winds where we would expect them if the 2LM theory was seriously violated due to non-neutral conditions. Even when we only use wind speeds > 11 m/s (roughly in line with Benschop, 1996) to compute the factors to convert the wind speed, the median and the distribution of deviations do not change significantly from what is shown in Fig. 18 (not shown). The same is true when splitting up the boxplots into individual sectors instead of averaging over all sea-facing sectors (not shown). Some signals are more pronounced

then (in particular the slightly larger differences at wind speeds above 13 m/s), but the overall conclusions remain the same.

These analyses give us confidence that there are no fundamental issues with our methodology at coastal stations. Past studies, too, have computed exposure correction factors at coastal stations without mentioning irregularities (e.g. Wieringa, 1976; Benschop, 2005; Wichers Schreur & Geertsema, 2006; Wever & Groen, 2009; Stepek & Wijnant, 2013). However, more than at inland locations, the potential wind is only representative of a location itself and has no validity at some distance downwind. This is due to the strong change in local roughness at the land-water boundary.

3.6. Potential wind

Recall that the potential wind speed is the product of measured wind speed and ECF (Eq. 1). Despite the apparent simplicity, we still need to discuss some aspects of this process.

3.6.1. Computing potential wind when no ECF was computed

The fact that we are filtering out a substantial number of observations means that we do not have a new ECF available at every point in time (see e.g. Fig. 9a). How often new ECFs can be computed differs greatly per location and wind direction. For example, at a location with a large number of updates like Lauwersoog (see quantity score in Fig. 14a), it hardly ever takes more than three months before a new ECF can be computed, even for the wind directions that occur the least. Most of the time (median), it takes about a week. For a station with fewer updates like Volkel, this is only achieved for the south-westerly sectors. For other sectors the median update frequency can be as much as three weeks to one month. In extreme cases, it can also take more than one year before a new ECF value can be computed. Note that we count at most one ECF-update per 24 hours to determine these median values because most of the time when the wind blows from a certain direction, several 10-minute samples after each other can be used to compute new ECFs, which would result in the median being 10 minutes in (nearly) all cases.

Regardless of the ECF update frequency, potential wind should be generated for every wind measurement (i.e. usually every 10 minutes). Assuming that local roughness does not change quickly over time, we continue to use the most recent directional sector's ECF value until a new one is available that meets the filter requirements. Note that an ECF value is always calculated with the most recent 30 measurements in a directional sector that meets the filter requirements, so changes in calculated ECFs will be gradual. An example of this is given in Fig. 19, where we show that at some points in time ECFs can be computed, while at others they are "repeated".

3.6.2. Validating repeated ECFs

We further analyse the validity of repeated ECFs by considering data from Cabauw where wind measurements from different heights are available. In particular, we consider measurements from 10 and 20 m height. We compute ECFs and potential wind for both

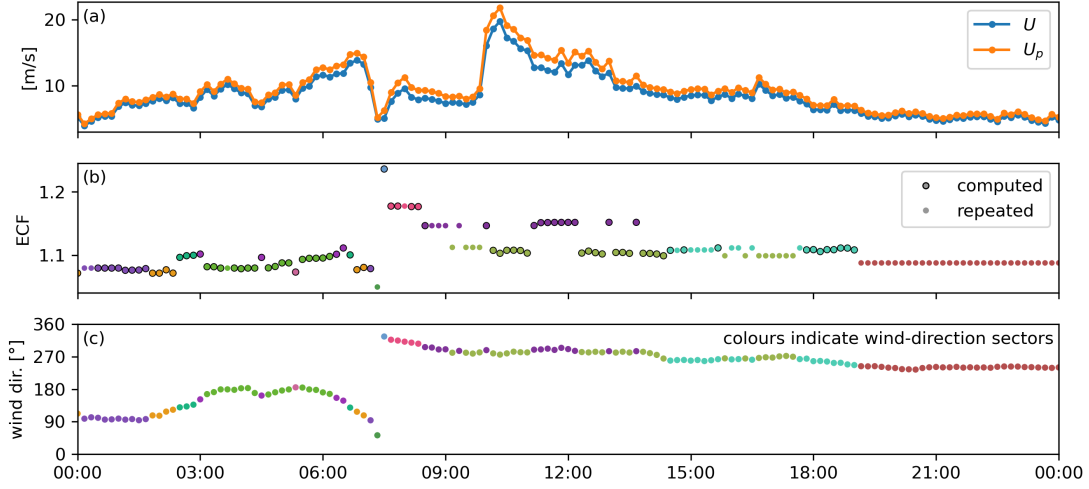


Figure 19: Time series of (a) measured and potential wind speed, (b) computed and repeated ECFs and (c) wind direction on 5 July 2023 at De Kooy.

sets of measurements (using our optimal filter U5-T47 described in Section 3.4). The resulting potential wind is valid for 10 m height in both cases and should thus be the same. Figure 20 shows the result of this analysis: We compare results when we (1) only consider measurements that have passed the U5-T47 filter, so ECFs are calculated (blue) and (2) only consider measurements that have not, so ECFs are repeated (red). Note that there are no calculated ECFs (blue) below 5 m/s because all those measurements are filtered out.

The potential wind speeds based on calculated ECFs (blue) and on repeated ECFs (red) are very similar for wind speeds above 5 m/s, both in absolute sense (Fig. 20a) and in relative sense (Fig. 20b). This increases our confidence that for the measurements that pass the U5-T47 filter, repeating ECFs works well. This comes not entirely as a surprise, because ECFs are based on 30 samples, so even if we can calculate a new ECF with a measurement that passes the filter, the ECF is still also based on 29 “old” measurements (so effectively we compare repeated ECFs based on 30 “old” measurements to calculated ECFs based on 1 “new” and 29 “old” measurements).

When we calculate the potential wind with the 2LM method, we assume that the wind profile is logarithmic (neutral atmosphere). When we calculate the potential wind we start with the measurements at 10 m, go up to 60 m height assuming a logarithmic wind profile and local roughness (determined with the ECFs), and then go down to 10 m again assuming a logarithmic wind profile and a reference roughness (0.03 m over land, 0.002 m over sea). Any remaining errors if the profile is not (entirely) neutral are cancelled out because the error on the way up is counterbalanced by the error on the way down (see Fig. 21 as well as Section 4.1 of Stepek et al., 2011). However, in this case, we use measurements at 10 m and 20 m to start with, but in both cases calculate the potential wind at 10 m height. Figure 20 suggests that for wind speeds above 3 m/s, the effect that the error going up (from 20 m to 60 m) is not completely counterbalanced with the

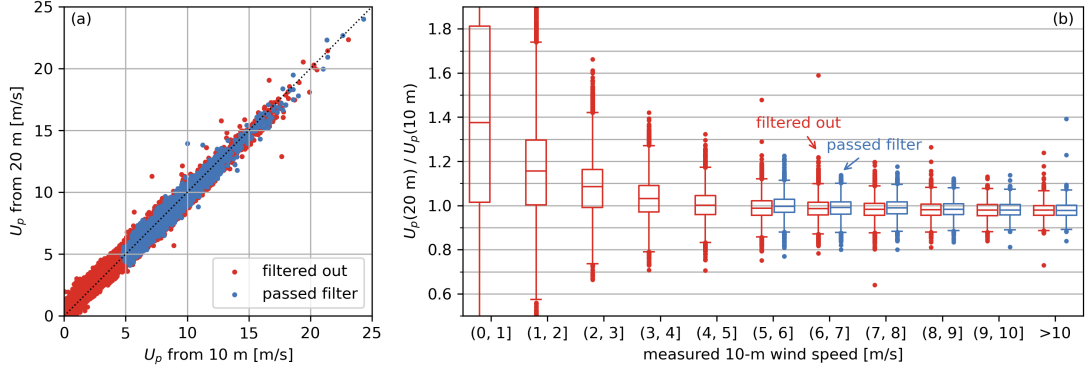


Figure 20: Potential wind computed from wind observations at 20 m and at 10 m height at Cabauw for the years 2016–2018: (a) Scatter plot distinguishing between samples that were filtered out (red) and that passed the filter (blue). (b) Boxplots of the ratio of the potential wind from 10 m and 20 m, binned by measured wind speed (at 10 m). For each wind-speed bin, the left/red boxplots contains samples that were filtered out and the right/blue boxplot samples that passed the filter. Just like in Fig. 18, each box extends from the lower quartile (Q1) to the upper quartile (Q3) of the data, with a line at the median. The whiskers extend from the box to the farthest data point lying within $1.5 \times$ the inter-quartile range (IQR) from the box. Flier points are those past the end of the whiskers.

error going down (from 60 m to 10 m) is not significant.

3.6.3. Stability effects

Nevertheless, computing potential wind under non-neutral conditions constitutes an inaccurate use of the underlying 2LM theory. If the atmosphere is unstable instead of neutral, there is more vertical mixing and roughness effects are less long-lived. This means that the potential wind (by definition based on the assumption of neutral stability) “overcompensates” for roughness effects. The opposite is true for a stable atmosphere.

A useful starting point for further analysis of stability-related errors is a study by Verkaik (2001b). He tried to quantify wind speed extrapolation and interpolation errors made when using the 2LM method. This is not exactly what we are looking for, but his findings are still quite helpful. For example, Verkaik concludes that differences in stability between land and sea cause extrapolation errors, which contribute to the curvature problem mentioned in Section 1.4. He also concludes that 2LM interpolation errors are not caused by stability, but by errors in the mesoscale roughness (footprint). Some aspects of Verkaik’s report are summarised in Appendix E.

Conform Verkaik (2001b), we argue that there are no stability related errors when interpolating wind speeds with 2LM as long as stability effects on the way up from the surface layer to the macro level are cancelled out on the way down. This is only true if you start from and go back to the same height (this is the reason why the 2LM method can be used for interpolating wind speed normals at 10-m height (Steppek & Wijnant, 2011)). Figure 20 shows that if you start from 20 m and go back to 10 m, you overes-

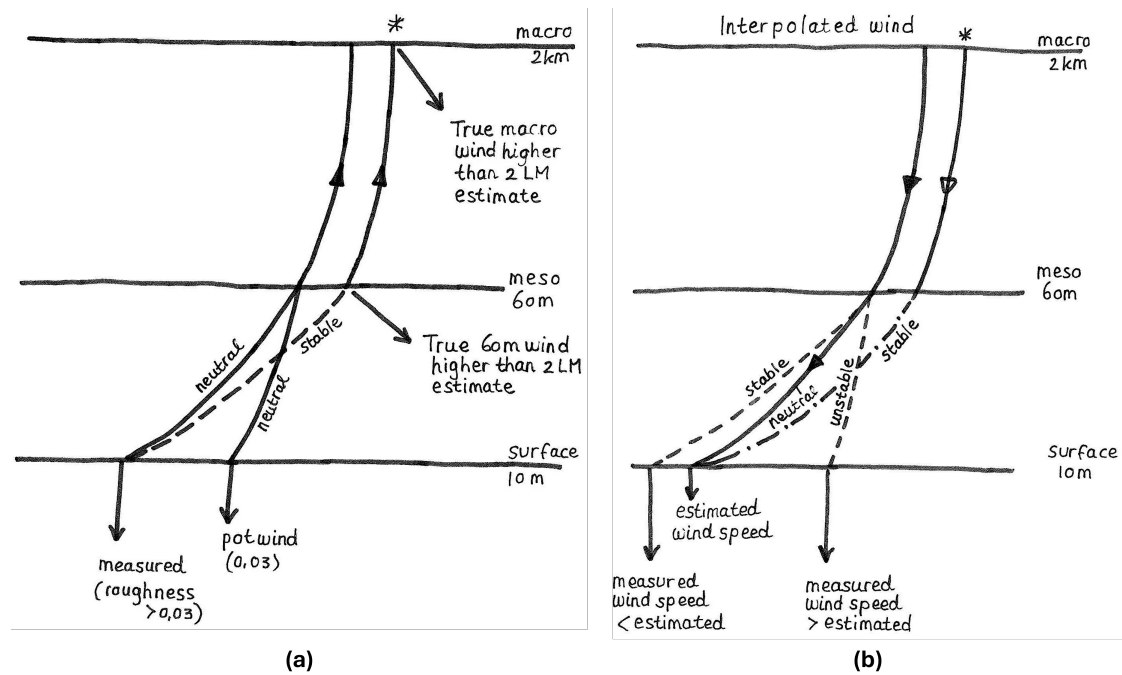


Figure 21: Illustration of the effect of applying 2LM under non-neutral conditions: (a) when “going up” and (b) when “going down”.

estimate “non-neutral” wind speeds below 3 m/s. If you start from 20 m, you make an extra error on the way up (ratio of the 20-m wind to the 10-m wind is higher in stable than in neutral conditions), resulting in a higher meso-wind and an overestimation of the potential wind.

Figure 21 illustrates why stability-errors are cancelled out with the 2LM method if you start and end at the same height. On the way up from 10 m, an estimate of the 60 m wind speed is made by extrapolating the potential wind with $z_0 = 0.03$ m and a neutral wind profile. If the atmosphere is not neutral but stable, the estimate is too low (see Fig. 21a) because the measured 10-m wind speed has in reality a stronger increase of wind speed with height (stable wind profile) above it than the 2LM assumes (neutral wind profile). Besides, this overestimation of the 60-m wind speed, would lead to a an overestimation at the macro level at the top of the planetary boundary layer (again the neutral profile is assumed but with a regional z_0 from a land-use map). The true macro wind is indicated with an asterisk (*) in both panels of Fig. 21. The exact same step as on the way up, is taken on the way back down to 60 m, so the overestimate at 60 m remains exactly as it was (assuming the macro-level interpolation is perfect). Going down from 60 m to 10 m, 2LM assumes a neutral wind profile and the z_0 from the Gustiness or Sigma method, but here a second mistake is made because the atmosphere is stable, not neutral. This time, the 2LM estimate is too high: In reality, the stable profile (indicated with a dotted-dashed line) is followed instead of a neutral wind profile (see Fig. 21b). The error on the way up is cancelled out exactly, since identical z_0 and real stable wind profiles are used/assumed for both the upward as the downward transformations.

That there are no stability-related errors when using potential wind to interpolate wind

measurements, does not mean that no stability-related errors are made when applying ECFs at wind speeds < 5 m/s. Looking at Fig. 21a, one can imagine that coming back down from the true 60 m wind speed via a stable wind profile with less change of speed with height than the dashed line (because 0.03 m is a lower z_0) gives a resulting “potential wind” (that accounts for stability) that is probably higher than the normal potential wind speed based on neutral stability. This is what we expect because roughness effects and obstacle wakes last longer in a stable atmosphere where vertical mixing is less than in a neutral atmosphere. This means that we need to increase the measured wind speed more in a stable atmosphere (in other words: the normal potential wind is underestimated in a stable atmosphere). The difference between the two sorts of potential wind is the stability-related error.

We summarise the stability-related error as follows:

- If $z_0 > z_{0,\text{ref}}$ (i.e. the surface roughness is larger than the reference surface roughness, which is 0.03 m for land or 0.002 m for sea), $\text{ECF} > 1$ and the potential wind “increases” the measured wind:
 - Then the potential wind is too high if the atmosphere is unstable instead of neutral (measured wind should not be corrected).
 - Then the potential wind is too low if the atmosphere is stable instead of neutral (but still correction in the right direction).
- If $z_0 < z_{0,\text{ref}}$, $\text{ECF} < 1$ and the potential wind “decreases” the measured wind:
 - Then the potential wind is too low if the atmosphere is unstable instead of neutral (measured wind should not be corrected).
 - Then the potential wind is too high if the atmosphere is stable instead of neutral (but still correction in the right direction).

Instead of calculating potential wind only when neutral conditions are met (i.e. when we also calculate ECFs), we decided to continue to calculate potential wind for all measurements like it has been done in the past. This is mainly to maintain consistency in the climatological record. However, we do publish flags along with the time series that indicate if conditions are non-neutral. That way, the user may choose to not use the potential wind from such periods depending on their use case, and it would simplify a later re-computation of the time series when further research has been conducted on this issue.

3.6.4. Uncertainty

Let us investigate the uncertainty of the computed potential wind speed. For the measured wind speed, several sources of uncertainty should be considered:

1. The uncertainty of the wind cup itself: A brief analysis of a small number of recent wind-tunnel experiments suggests that the absolute bias is around 2 % at very low wind speeds (3 m/s) and less than 1 % at higher wind speeds (10–30 m/s).

2. Inertia may keep the cup in motion while the wind speed is decreasing, which is called overspeeding. This effect is reinforced by (horizontal) turbulence. Knoop et al. (2021) estimate the effect on the measured wind speed to be 1.5 % at 10 m height (at Cabauw). Note that other studies give different and even somewhat contradictory estimates (e.g. Kristensen, 1998; Bosveld, 1999; Wauben, 2007; Groen, 2011).
3. Convection leads to an inclination of the wind vector and goes along with (vertical) turbulence. Both can affect the measured (horizontal) wind speed.
4. Water on the wind cup (from precipitation or condensation) leads to different mechanical properties of the wind cup, which affects the wind-speed measurement. As discussed in Section 3.4.4, Wauben (2007) estimated this effect to be up to 0.15 m/s.

Instead of a detailed analysis of each of these sources of uncertainty, we use a year-long comparison of the KNMI wind cup with a number of sonic anemometers at the test field at De Bilt (Wauben, 2007). It shows (see their Appendix D) that the absolute bias of the measured wind speed increases with the wind speed from about 0.08 m/s at 1 m/s (8.0 %) over 0.20 m/s at 4 m/s (5.0 %) to about 0.40 m/s at 6.5 m/s (6.2 %). For higher wind speeds, insufficient data were collected. We assume that these figures give a realistic estimate for the overall uncertainty of the measured wind speed, including all the effects mentioned above (with the only caveat being that this was determined at De Bilt where conditions are poor for wind measurements).

We can compute the uncertainty of the potential wind with a standard error-propagation formula. For the measured wind speed, we assume 5.5 % to be a good estimate for the uncertainty at common wind speeds. According to Verkaik (2000), the uncertainty of the ECFs computed with both the Gustiness and the Sigma method is 5 %. The potential wind being the product of measured wind speed and ECF, its total uncertainty E_{tot} is the square root of the sum of the squared errors E_i :

$$E_{tot} = \sqrt{\sum_i E_i^2} = \sqrt{0.055^2 + 0.05^2} \approx 0.074. \quad (6)$$

For a broad range of wind speeds, this uncertainty of the potential wind of about 7 % appears very reasonable compared to what we found in Fig. 20b where we addressed two sources of uncertainty: using 30 “old” measurements (repeated ECFs) as opposed to 29 “old” and 1 “new” measurements (calculated ECFs; recall that we calculate the ECFs based on the median value of the most recent 30 standard deviation over wind speed ratios; see also Section 3.3) and stability effects between 10 m and 20 m height. In particular, for wind speeds above 3 m/s, the median of the ratio of the two deviates from 1 by less than 4 %. Furthermore, above 4 m/s, more than half of the data (from lower to upper quartile, i.e. the box of the boxplots in Fig. 20b) deviates by less than 5 % from 1.

For very low wind speeds, similar absolute differences (Fig. 20a) result in larger relative differences (Fig. 20b) because the difference is expressed as a fraction of a lower wind

speed value. That the absolute deviations are indeed not larger for lower wind speeds is confirmed by analysing the distribution of absolute deviations (not shown). For lower wind speeds, the median ratio of potential wind from 20-m and 10-m measurements is greater than 1, which is indicative of more stable and unstable conditions that correlate with weaker wind speeds (see Fig. 5) and thus in line of expectations. Under non-neutral conditions the assumption of a logarithmic wind profile is not valid, and it is therefore not surprising that the two potential winds coincide less. Also note that at such low wind speeds, wind speed measurements themselves have a larger uncertainty (of 0.1 m/s instead of 1 %). Thus, the potential wind should be used with caution or not at all for such low wind speeds.

While deviations larger than the 7.4 % we computed above even at stronger wind speeds may be indicative of a higher uncertainty of the potential wind, they can partly be explained by known limitations of our algorithm. As shown above (e.g. Fig. 8), our neutrality filter still accepts some non-neutral conditions. But only under neutral conditions, the 2LM method’s assumption of a logarithmic wind profile is valid. This explains some of the differences between the potential wind from 10-m and 20-m measurements.

By design, this analysis can merely provide an indication of the uncertainty and is not conclusive to that end. None of the two potential wind values is considered more reliable than the other. Thus, while this analysis is not suitable to prove the theoretical uncertainty for the potential wind of 7.4 % with a confidence of two or more standard deviations, it does not altogether refute that uncertainty estimate either.

Finally, another source of uncertainty is the wind direction. This source of uncertainty is a combination of the $\pm 3^\circ$ uncertainty of the wind direction measurement itself (e.g. Wauben, 2007) and the uncertainty caused using wind-direction sectors (see page 11). Wind direction measurements are not constant in time and when they fluctuate close to the border of a sector, the wind may “feel” the local roughness from both sectors, whereas the resulting ECF will be assigned to only one of the two sectors (the one where the 10-minute mean wind direction ends up). The standard deviation of the 12-second averages of wind direction, calculated over periods of 10 minutes was found to be typically 10–20° at De Bilt, the measurement site with the highest ECFs (and therefore most variable wind direction) of the Netherlands (Stepek, 2025), so the 20° wide sectors of ECFs should not be any narrower. The fluctuations of the wind direction are chaotic and are also present upwind of the wind mast. This means that the air that passes the wind vane often originates outside the 20° sector. Furthermore, local roughness may even differ over the width of a sector. These effects are highly dependent on the local situation. However, we do not expect the effect on the uncertainty to be significant because we average over 30 10-minute periods when computing ECFs. Moreover, the 10-minute average wind speed measurements to which the ECF is applied, is affected by a similar spread in wind directions during the 10-minute period. Furthermore, the uncertainty caused by wind direction is smaller in the Sigma method than it was in the old Gustiness method because the new method is based on 10-minute measurements, whereas the old method was based on hourly average wind speed measurements and the 10-minute average wind direction measurement of the last 10 minutes of the hour.

4. Station-dependent implementation details

While our algorithm can be universally applied at all KNMI stations, certain details are still station-dependent. These details are described in this section.

4.1. Availability of 10-minute measurements

For the period before April 2003, no 10-minute measurements were archived in KNMI's climatological information system RobuKIS, and for some stations (including the Caribbean Netherlands), they were archived from an even later date. For a number of stations, the standard deviation of the 10-minute wind measurements is missing or has only recently been added (December 2025), probably due to the fact that data gathering of these measurements was done through radio transmission. Because we now have the standard deviation of the 10-minute measurements for Cadzand (KNMI no. 308) and Hansweert (315), we can start building up an ECF dataset for these stations.

For Hoek van Holland (330), there is a period where the standard deviation and average of the 10-minute wind measurements are disturbed by wind turbines: from 13-11-2012 until 30-04-2018. This is because the operational wind mast was at a different location for that period: Lage Lichtopstand Splitsingsdam (measurements also used for the Maeslandkering). In 2018, the wind mast at the old location (Noorderhoofdpier) was made operational again because the measurements at Splitsingsdam were too disturbed by wind turbines. We managed to retrieve the 10-minute averages at Noorderhoofdpier for 13-11-2012 until 30-04-2018 (when Noorderhoofdpier was not KNMI's operational wind mast) from HavenBedrijf Rotterdam, but these measurements are and will not be stored in RobuKIS.⁹ Unfortunately, the standard deviation (and the gusts) at the Noorderhoofdpier could not be retrieved from HavenBedrijf Rotterdam for this period.

Thus, we cannot calculate Sigma ECFs for Hoek van Holland for 13-11-2012 until 30-04-2018 because we do not have all the 10-minute measurements we need for that at Noorderhoofdpier. The question is if we can assume that the ECFs at Noorderhoofdpier have not changed much in the 5.5 year period of missing data. That is why we checked if the ECFs just before and just after the period in question are similar, and they are (they differ by 3 % or less), suggesting no significant changes in local roughness during that period. We therefore assume that the ECFs from before 13-11-2012 remain valid for the entire period and use them to compute the potential wind from the 10-minute measurements at Noorderhoofdpier until 30-04-2018.

4.2. Disregarded stations

There are two reasons why potential wind is not (or should not be) derived for a station:¹⁰

1. If the station is a sea station where the measured roughness in all wind direction sectors is a sea roughness. In that case a Benschop (height) correction (Benschop,

⁹They will be stored on KNMI Data Platform KDP, but only because they are used to calculate the climate normals.

¹⁰For the 2020 potential wind update, stations that were not part of the LH15 set or where the observation series was too short to derive climate normals were excluded too.

1996) is sufficient, and this is usually applied operationally (if potential wind was derived before, this should be stopped).

2. Measurements are too disturbed: ECFs are calculated with the 2LM method and this method is only valid if we can assume a logarithmic wind profile (neutral atmospheric stability) and small enough disturbances by obstacles. We assume this to be the case if the following requirements are met for less than 75 % of the wind direction sectors (13 or 14 of the 18 sectors, depending on expert judgement), especially if the disturbed sectors include the prevailing wind direction, and for at least 3 years (as agreed in KNMI-WAG):

- a) $ECF < 1.22$ and $D/H > 10$ for 10-m wind masts (where D and H are the distance from the wind mast and height of obstacles, respectively)¹¹
- b) $ECF < 1.04$ and $D/(H - 10) > 10$ for 20-m wind masts¹²

Furthermore, wind-turbine wakes can significantly disturb wind measurements. As a rule-of-thumb, the wake of a wind turbine on land can be felt at a distance 20 times the rotor diameter (NEN, 2017). Thus, sectors with wind turbines where this is the case, should be excluded too, and we add another point to our list of requirements for measurements that are too disturbed:

- c) Wind turbine closer than 20 times the rotor diameter (NEN, 2017)

With this, we exclude the following stations (for the coastal stations, see also Appendix F, which contains a comprehensive discussion of all coastal stations):

- De Bilt (KNMI no. 260) — too few undisturbed sectors
- Heino (278) — too few undisturbed sectors
- Oosterschelde (312) — sea station
- Vlakte van de Raan (313) — sea station
- Schaar (316) — sea station
- Stavenisse (324) — large obstacle closeby
- Tholen (331) — sea station
- Woensdrecht (340) — too few undisturbed sectors
- Saba (871) — too few undisturbed sectors
- Sint Eustatius (873) — too few undisturbed sectors
- Bonaire (990) — too few undisturbed sectors

Thus, 38 land stations remain for which ECFs can be produced (see Fig. 13) some of which have several wind masts (see Section 4.3). Note that many of the excluded stations were

¹¹2LM theory is not valid at heights below $20z_0$. So if $z_m = 10$ m, then the value of z_0 should be lower than 0.5 m, which means that ECF should be lower than 1.22.

¹²If $z_m = 20$ m, the value of z_0 should be lower than 1 m which means that ECF should be lower than 1.04 (1.36/1.30 where 1.36 is the factor due to the very high roughness length and 1.30 the factor due to the extra 10 m height compared to the standard height of 10 m).

also excluded in previous potential-wind updates (see Appendix B), most notably De Bilt, one of KNMI's longest running stations. Thus, the exclusion of this centennial station does not constitute a change in practice, though it is still displeasing for climatologists. No improvement is expected here due to the growing urbanisation of the environment at De Bilt. For Woensdrecht and Stavenisse, the situation could potentially be improved more easily. For the BES stations (Bonaire, Sint Eustatius and Saba), the exclusion is mostly due to the topography. Deelen (275) was previously excluded due to nearby trees ($D/H < 10$), but these trees have been cut recently, and Sigma ECFs < 1.22 . Therefore, we compute ECFs for Deelen again.

Using publicly available data from the National Institute for Public Health and the Environment (RIVM),¹³ we checked all stations for nearby wind turbines. At IJmuiden, Berkhout, Lauwersoog, Heino, Vlissingen, Schaar, Hoek van Holland, Woensdrecht and Rotterdam Geulhaven, wind turbines are close. Schaar (316), Woensdrecht (340) and Heino (278) have been excluded for other reasons, so a detailed check is not required. At Berkhout (249), Lauwersoog (277), Vlissingen (310) and Hansweert (315), the distance of the closest wind turbine is about 23, 31, 34 and 38 times the rotor diameter, respectively, so their distance to the wind sensor is more than 20 times the rotor diameter and therefore not considered problematic (NEN, 2017). At IJmuiden (225), Hoek van Holland (330) and Rotterdam Geulhaven (343), the distance is about 11, 17 and 16 times the rotor diameter, respectively, but because this only affects a single sector in each of the cases, the stations do not need to be excluded (see also Appendix F).

4.3. Stations with more than one wind mast

ECFs can be used to get an estimate of the representativeness of wind measurements or a wind mast's suitability to serve as backup for another mast, which is particularly relevant for aviation. The International Civil Aviation Organization (ICAO) has strict requirements regarding this.

At both civil and military airports, often several wind sensors are present. This is because wind needs to be measured close to the touch-down zone of a runway, and a runway may be used in both directions. While for climatological purposes, it is often sufficient to consider the potential wind from one site at an airport (the "main mast"), aviation is interested in the ECFs for all of the wind masts at an airport. Table 3 gives an overview of the KNMI stations with more than one wind mast (all of which are airports, marked with squares on the map in Fig. 13).¹⁴ This table shall facilitate the development of ECF applications for aviation in the future. Note that at military airports, some wind masts have a lower height of 6 m instead of the usual 10 m (indicated in Table 3).

¹³<https://www.atlasleefomgeving.nl/kaarten?config=3ef897de-127f-471a-959b-93b7597de188&gm-b=1544180834512,true,1;1605001908247,true,1> (Atlas Leefomgeving: Windturbines-ashoogte; accessed 11-03-2026)

¹⁴In this report, when we present results from airport stations, we always use data from the respective main mast.

Table 3: Wind masts at airports with more than one mast. Additional masts marked with an asterisk * are 6 m tall instead of the usual 10 m. Masts are designated with “a” (masts near a meteorological field) or the runway designator (mast near touchdown of the indicated runway). (‡) At Woensdrecht, no ECFs are computed because the measurements are too disturbed.

Airport	KNMI no.	Main	Additional (*some 6 m)						
De Kooy	235	a	03*	21*					
Schiphol	240	27	06	18C	18R	22	36L	36C	36R
Lelystad	269	23	05						
Leeuwarden	270	a	06*	24*					
Deelen	275	a	20*						
Eelde	280	05	23						
Woensdrecht‡	340	a	07*	25*					
Rotterdam	344	06	24						
Gilze-Rijen	350	a	10*	28*					
Eindhoven	370	a	04*	22*					
Volkel	375	a	06*	24*					
Maastricht	380	22	04						

4.4. Sector-dependent measurement height and reference roughness

Previously, the reference roughness $z_{0,\text{ref}}$ and the measurement height z_m in Eq. 1 were assumed to be one value for a particular station, not dependent on wind direction. However, this is not always correct for coastal stations where the wind either blows from the sea or from land, and sea has a much smaller roughness than land. Moreover, the land may have a different height than the mean sea level, which essentially means that z_m is different in those directions. In past ECF updates, measurement heights were mostly kept unchanged for continuity (see also Appendix B), but now that we make a completely new dataset with the Sigma method, the heights have been updated too.

We consider several sources of information to determine the measurement height:

1. We use the “KNMI stationsgids information” (SAIS) as the source of information on the height of the wind sensor relative to the ground or the water level where the mast stands.
2. For a sensor on land:
 - a) Height is the height above the surrounding land if the distance to the coast is more than 1800 m.
 - b) If there is a roughness change from water to land (or vice versa) at less than 1800 m from the wind mast, we calculate the height of the internal boundary layer (IBL) and the height of the transition zone (TZ) with Deaves formula’s (see Appendix C). If the sensor measures in the IBL, the roughness is adapted to the roughness at the location of the mast (land) and the height is the height above the land near the mast.
 - c) If there is a roughness change at less than 1800 m from the wind mast and

the sensor measures in the TZ (above IBL, but below the TZ top), the height is between the height above the surrounding land and water.

- d) If there is a roughness change at less than 1800 m from the wind mast and the sensor measures above the TZ top, the height is the height above water.

3. For a sensor above water (usually sea):

- a) Height is the height above the surrounding sea if the distance to the coast is more than 1800 m.
- b) If there is a roughness change from land to water (or vice versa) at less than 1800 m from the wind mast, and the sensor measures in the IBL, the roughness is adapted to the roughness at the location of the mast (sea) and the height is the height above the sea.
- c) If there is a roughness change at less than 1800 m from the wind mast and the sensor measures in the TZ (above IBL, but below the TZ top), the height is between the height above the surrounding sea and land.
- d) If there is a roughness change at less than 1800 m from the wind mast and the sensor measures above the TZ top, the height is the height above land.

The IBL analysis we carried out in cases of a roughness change also included an estimation of the maximum error that may be introduced by our choice of parameters (see Appendix C). For all of the stations, this error was less than the method-inherent uncertainty of 5 % (see Appendix F).

Similarly, to determine the reference roughness length, we considered the surroundings up to 600 m from the wind mast because at 10 m height the local surface roughness is determined by the roughness 200–1800 m from the wind mast, with the largest effect at 600 m, as illustrated in Fig. 1 (Verkaik, 2006, see Section 5.4.1). The selection of land or sea/water wind directional sectors was done visually (with Google Earth) and if in doubt by considering z_0 computed by Eq. 4.

Tables 4 and 5 show z_m and $z_{0,\text{ref}}$ for all stations and sectors we considered here. For the coastal stations, detailed discussions on how land/sea sectors were determined can be found in Appendix F.

5. Automated algorithm

Here, we summarise the optimal methodology that we developed. On a high level, it works as follows:

1. Retrieve wind observations for one wind mast as well as corresponding 10-cm and 2-m temperatures nearby. (Note that temperatures may be from a different station if a station consists only of a wind mast.) The following 10-minute quantities are needed:
 - a) wind direction at sensor height D
 - b) wind speed at sensor height U
 - c) standard deviation of the wind speed at sensor height σ_u
 - d) air temperature measured at 1.5 m height, labelled T_{2m} in this report (1-minute average)
 - e) air temperature measured at 0.1 m height T_{10cm} (1-minute average)
2. Determine the wind-direction sector (see page 11).
3. Filter out observation samples that do not meet the requirements of our optimal filter (U5-T47, see Table 1). Samples are discarded if any of the following conditions is not met:
 - a) maximum-roughness filter: $A\kappa U/\sigma_u > \ln(20)$ (see Section 3.2) with A from Table D.1, $c = 2.2$ and $\kappa = 0.4$
 - b) minimum-wind-speed filter: $U \geq 5.0$ m/s
 - c) neutral-stability filter: $-0.3 \text{ K} < T_{2m} - T_{10cm} < 1.1 \text{ K}$
4. Take the median $\langle \sigma_u/U \rangle$ over $N = 30$ samples (that were not filtered out) from the same directional sector (see Section 3.3). Compute the ECF with Eq. 4 using z_m and $z_{0,ref}$ from Tables 4 and 5, respectively. (If the current sample was filtered out, the previous ECF from the same sector remains valid and this entire step is not necessary.)
5. Compute the potential wind speed by multiplying U with the ECF (Eq. 1).
6. Publish both the ECF and the potential wind speed.

Even though all of the above steps will be automated without any human intervention, the details of the technical implementation will differ depending on the update frequency. In particular, near-real-time (i.e. 10-minute) updates require different data access and slightly different technical choices in the implementation than e.g. monthly updates. The former is currently not feasible at KNMI for technical reasons. Thus, for now, we are developing an implementation for automatic updates of ECFs and potential wind once a month. Nonetheless, we provide a proposed flow in Appendix G for both monthly and 10-minute updates.

While many use cases can only be unlocked with near-real-time updates, monthly updates do provide sufficient value for others. In the past, ECFs were updated every few years,

but potential-wind series were published monthly based on these ECFs. All users of this dataset will be able to make use of our new dataset. This includes climate researchers and the construction sector. Added value is created by updating the ECFs more regularly. This allows site inspectors and aviation to get more up-to-date information about local roughness. Site inspection could use this information to focus their attention on changes in the environment that are revealed by ECF changes. The same is true for aviation where ECFs are also used to determine a backup scheme for the various wind masts on an airport and the representativeness of the wind measurements. Even faster updates of the potential wind could be valuable for use in other data products, including high-resolution observation maps (KNMI app), and could give forecasters important insights.

Practically, these applications may be developed based on the dataset that we intend to publish and update monthly. At the time of writing, these automatic monthly update are expected to become available later in 2026. Apart from new applications, automating ECF and potential-wind updates makes the process more reliable and less labour-intensive.

Apart from these opportunities we also point out some risks that are associated with the proposed automation. While taking the human out of the process leads to more up-to-date information and less subjectivity, it also takes away the possibility of interventions based on experience and intuition. As discussed in Section 3, our observations filter is — though of high quality — not perfect and will inevitably produce some outlier ECFs.

6. Comparison of new Sigma-method ECFs and 2020-update ECFs

Apart from developing the new method of computing ECFs, we are also creating a new dataset of Sigma ECFs and potential wind, which we are going to make available on the KNMI Data Platform (KDP). This dataset starts in April 2003 when 10-minute measurements from KNMI weather stations started to be archived and published. Note that for some KNMI stations, 10 minute measurements were archived from a later date (De Kooy, Vlieland, Leeuwarden, Twente, Cadzand, Hansweert, Gilze-Rijen, Eindhoven, Volkel, Saba, Sint Eustatius, Bonaire).

We compared Sigma-method ECFs with Gustiness-method ECFs, particularly to give an idea about what differences to expect switching from one dataset to the other.¹⁵ However, this can also be seen as a validation of the methodology proposed here. Van den Brink & Bosveld (2017) showed that potential wind computed from Gustiness-method ECFs and potential wind from the HARMONIE weather model agree remarkably well, largely removing model biases in the wind speed. This can be seen as a validation of the Gustiness method. Thus, by comparing Gustiness and Sigma ECFs, we indirectly validate the latter.

For the comparison, we used the most recent Sigma-converted Gustiness-method ECFs, which were published in 2020 (see also Appendix B). In total, 28 stations are available (see Fig. 13) because new Gustiness ECFs were not computed for all KNMI wind masts during this update. In the past (including in 2020), ECFs were updated once every few years for the years before that. In general, the ECF value for a particular station and sector remained valid for at least several months, but often years until a significant change was detected manually. For example, in Sector 5 at Leeuwarden, the ECF was 1.054 until 28-02-2015, then it changed to 1.027 only to be changed again to 1.098 on 01-07-2015. That value remained valid until the end of the researched period in 2020. This is fundamentally different to the Sigma ECFs, which can be re-computed whenever a measurement is taken in a sector (and it is not filtered out). Anyway, since the Sigma dataset begins in 2003, we have about 18 years of overlap with both Sigma and Gustiness ECFs available, which are used in this comparison.¹⁶

One needs to keep in mind that the two methods are different in a number of aspects:

1. The theoretical basis: The Sigma method uses the wind speed and its standard deviation to determine the local roughness, while the Gustiness method uses the wind speed and the speed of the strongest gust.
2. The data used: The Sigma method uses 10-minute measurements and the Gustiness method hourly.
3. The filter method: We changed the previously used minimum wind speed from 5.5 m/s to 5.0 m/s, and we added a maximum-roughness filter (Section 3.2) and a

¹⁵As discussed in Appendix A.2, this comparison is also useful when switching from the method described in KNMI TR-277 (Benschop, 2005).

¹⁶Based on the most recent Sigma-converted Gustiness-method ECFs from 2020, potential wind is still being computed and published on a monthly basis. The quality of this dataset is expected to diminish over time as the local roughness remains “frozen” as it was in 2020 when the ECFs were determined.

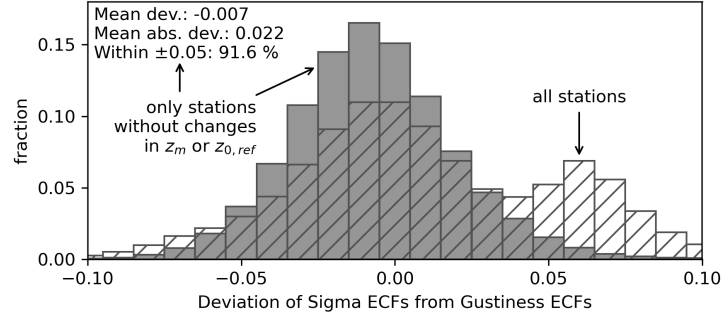


Figure 22: Distribution of the deviation of ECFs computed with the Sigma method with respect to the Gustiness-method ECFs as published in 2020. In the top left, the mean and mean absolute differences of the two datasets are printed along with the fraction of values where the absolute difference is less than 0.05.

neutral-stability filter (Section 3.4.1).

4. Sector dependence: We introduced sector-dependent reference roughness lengths $z_{0,\text{ref}}$ and measurement heights z_m (Section 4.4).
5. We updated $z_{0,\text{ref}}$ and z_m where needed.

We want to give an idea of the differences between the two methodologies: directly applied Sigma-method ECFs (this report) and Sigma-converted Gustiness-method ECFs (2020 update). To this end, we only include 21 stations where no changes were made to $z_{0,\text{ref}}$ and z_m compared to the 2020 ECF update. At the following two stations, some periods are taken out of the comparison:

1. Hoek van Holland 2012–2018: During this period a different wind mast was used (Lage Lichtopstand Splitsingsdam as opposed to Noorderhoofdpier) and measurements there turned out to be of too low quality because they were strongly affected by nearby wind turbines (as described in Section 4.1).
2. Maastricht Airport before 2014: A different wind mast was considered the main mast before 2014, so we only use the period after 2014.

The method-inherent differences between the new Sigma-method (including the new filtering approach) and the old Sigma-converted Gustiness-method ECFs from the 2020 update are small. This is shown by the dark bars and statistics in Fig. 22. If anything, the new ECFs tend to be slightly lower than the old ones. However, the vast majority of ECF values (91.6 %) lies within the uncertainty margin of ± 0.05 , indicating good agreement. This strengthens the confidence we have in our algorithm.

Note that the scores above should not be interpreted as a “bias” or weakness of our algorithm with respect to the old method. That would imply that the old method is superior to the new one, whereas the opposite is true (e.g. Beljaars, 1987a; Verkaik, 2000; Wichers Schreur & Geertsema, 2006; Wever & Groen, 2009; Kofmann & Namyslo, 2023). The analysis merely illustrates that users switching from the old ECFs from the 2020 update to the new Sigma ECFs should be aware that there are changes, but that

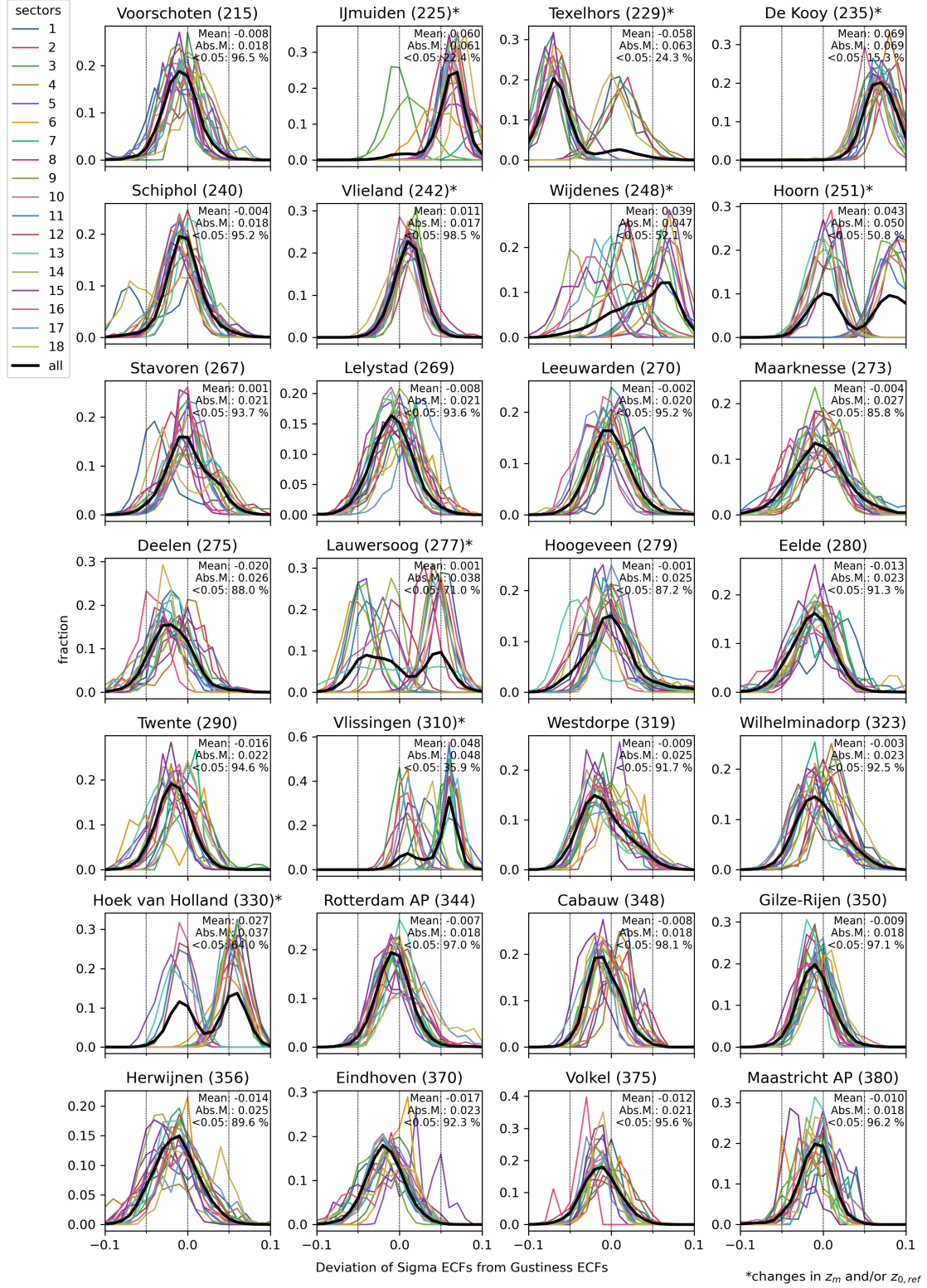


Figure 23: Same as Fig. 22 but split up by station and directional sector. At stations marked with an asterisk * changes were made to $z_{0,ref}$ or z_m compared to 2020.

changes due to method and filters are small.

Significant differences appear if we also include seven stations with updates in $z_{0,\text{ref}}$ and z_m (hatched bars in Fig. 22). Visualising the differences of the ECFs from the two methods per station and directional sector (Fig. 23) shows that this is due to larger deviations at those stations. In particular, the change in reference roughness length has a strong impact on the ECFs (see Fig. 23, e.g. Texelhors where $z_{0,\text{ref}}$ was changed in several sectors but not z_m as opposed to Vlieland where z_m was changed but not $z_{0,\text{ref}}$). In the past, most stations by far used the land value of $z_{0,\text{ref}} = 0.03$ m. Switching to the much lower sea value of $z_{0,\text{ref}} = 0.002$ m for all sectors (e.g. De Kooy) or only some (e.g. IJmuiden) increases the ECFs for those sectors. While these differences are significant, we believe that they reflect the truth more accurately, which should give users confidence to trust these new data.

Users of the potential wind need to take care when dealing with long periods that may require a “mixing” of the Gustiness and Sigma datasets. For instance, the Sigma dataset will not reach a length of 30 years before 2033, which is required to compute a climatological normal for the wind speed. The comparison in Fig. 23 will aid in determining whether the two datasets can be combined without introducing a discontinuity when combining the two datasets. Again note the overlap of the two datasets with Sigma potential wind starting to become available from 2003 when Gustiness potential wind was still being produced. However, we recommend not to use Gustiness-method potential wind from much after 2020 any longer because Gustiness ECFs start to become outdated after the most recent update in that year.

7. Conclusions and outlook

Since the 1970s, exposure correction for wind measurements has been computed from the (hourly) mean wind speed and maximum wind gust (Gustiness method), and this has been done for data going back to about 1950. In 2009, a superior method using average and standard deviation of 10-minute wind measurements (Sigma method) was extensively tested, but because 10-minute measurements have only been archived since 2003, the Sigma method was not implemented (Wever & Groen, 2009). Instead, a work-around was developed where Sigma-method ECFs were derived from Gustiness ECFs. Now that we have more than twenty years of 10-minute measurements, it is possible to start calculating ECFs without this work-around. Because this is already different, we also implemented other improvements that were recommended but postponed before: We optimised the neutral filter and stopped assuming one reference roughness and reference height for different wind sectors (relevant for coastal sites).

The goal of the neutral filter is to take out as many stable and unstable measurements as possible because ECF methods only work for neutral atmosphere (quality score). We want to do this without losing too many measurements so that we can make regular updates (quantity score). The optimal filter proved to be a filter with wind speed > 5 m/s and a vertical temperature difference $T_{2m} - T_{10cm}$ between -0.3 K and 1.1 K (as opposed to just > 5.5 m/s in earlier ECF updates). We also considered other parameters for filtering, such as (convective) precipitation, snow cover, daytime- and season-dependent filtering, but none of them lead to a better combination of quality and quantity scores. Previous ECF updates distinguished between summer and winter at some stations, which we showed to be of no significant added value since our approach inherently takes gradual changes into account anyway.

We made an estimate of the uncertainty of the potential wind calculated with our method, considering four sources of uncertainty: (1) the sensor itself, overspeeding effect of the sensor caused by (2) variations in the horizontal component of the wind (inertia) or (3) variations in the vertical component of the wind (convection) and (4) additional uncertainty when there is precipitation. Instead of analysing each source extensively, we used an estimate for the overall uncertainty of the measured wind speed and the exposure correction factor, arriving at an overall uncertainty estimate for the potential wind speed of about 7 %. Furthermore, non-quantifiable sources of uncertainty need to be considered, namely the uncertainty from the wind direction and our use of wind-direction bins of 20° width and the question whether potential wind should even be computed under non-neutral conditions. Further research on the latter question should be carried out, but for the sake of consistency with previous datasets, we continue to compute and publish potential wind for every measured wind-speed sample.

In our new method, we took into account that for coastal stations we are dealing with reference roughnesses and sensor heights that depend on wind direction (sector). We cannot just assume a wind profile determined by one surface roughness, but often part of the profile is determined by water and another part by land roughness (internal boundary layers).

We made an effort to compare our new method to old methods, including the most recent ECF/potential wind update in 2020 (converted Gustiness to Sigma) and methods used

for aviation purposes: GUSTO (Sigma Wichers Schreur & Geertsema, 2006) and TR-277 (Gustiness Benschop, 2005). The difference going from the most recent ECF/potential wind update is small, except when coastal stations are taken into account where we started to take the wind-direction dependence of reference roughness and measurement height into account. The small differences with the Gustiness method constitute an indirect validation of the methodology proposed in this report because the Gustiness method has been validated against HARMONIE (Van den Brink & Bosveld, 2017).

A more extensive validation of the Sigma method could be carried out with large-eddy simulation (LES) or computational fluid dynamics (CFD). Both are well suited for studying idealised roughness transitions and the stability dependence. For obstacle effects, CFS may be more suitable than LES. Alternatively, the study by Van den Brink & Bosveld (2017), which compared potential wind from the Gustiness method and from HARMONIE could be repeated with the Sigma method.

We developed a robust and reliable version of the Sigma method that is capable of near-real-time computation of ECFs and potential wind. However, at the time of writing of this report, there are still some technical issues to overcome outside this project before we can actually produce ECFs and potential wind in near-real time. For now, we produce monthly updates for climatological purposes (e.g. for aviation reports, climate scenarios or interpolation maps such as by Stepek & Wijnant (2011)), which will be made available on the KNMI Data Platform (KDP). We will continue looking for ways to produce near-real time updates (e.g. for weather forecasters). We recommend that the quality of the new dataset is evaluated every few years as deemed necessary to identify any potential for further improvement, and we invite feedback from users.

A. Comparison with previous exposure-correction methods at KNMI

A.1. GUSTO method

Here, we show that the GUSTO method as presented by Wichers Schreur & Geertsema (2006) is equivalent to the Sigma method discussed in this report.

Wichers Schreur & Geertsema (2006) define the ECF as (their Eq. 4.2):

$$ECF = \frac{\ln\left(\frac{z_m}{z_{0,\text{ref}}}\right)}{\ln\left(\frac{z_b}{z_{0,\text{ref}}}\right)} \left(1 + \frac{\ln\left(\frac{z_b}{z}\right)}{\ln\left(\frac{z_m}{z_0}\right)}\right). \quad (\text{A.1})$$

Note that there is no distinction between measurement height z_m and reference height z_{ref} . For 10-m wind masts, this makes no difference, but for wind masts of other heights, the GUSTO method is not suited.

We now transfer the equation above into the form shown in Eq. 1 of this report. First, we apply the multiplication on the bracket:

$$ECF = \frac{\ln\left(\frac{z_m}{z_{0,\text{ref}}}\right)}{\ln\left(\frac{z_b}{z_{0,\text{ref}}}\right)} + \frac{\ln\left(\frac{z_m}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_b}{z_m}\right)}{\ln\left(\frac{z_b}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_m}{z_0}\right)}. \quad (\text{A.2})$$

We expand the first fraction and sum the two fractions:

$$ECF = \frac{\ln\left(\frac{z_m}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_m}{z_0}\right) + \ln\left(\frac{z_m}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_b}{z_m}\right)}{\ln\left(\frac{z_b}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_m}{z_0}\right)}. \quad (\text{A.3})$$

Recalling logarithm laws ($\ln ab = \ln a + \ln b$ and $\ln a/b = \ln a - \ln b$), this can be expanded:

$$ECF = \frac{(\ln z_m - \ln z_{0,\text{ref}})(\ln z_m - \ln z_0) + (\ln z_m - \ln z_{0,\text{ref}})(\ln z_b - \ln z_m)}{\ln\left(\frac{z_b}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_m}{z_0}\right)}. \quad (\text{A.4})$$

Expanding further, some terms eliminate each other:

$$ECF = \frac{-\ln z_m \ln z_0 + \ln z_{0,\text{ref}} \ln z_0 + \ln z_m \ln z_b - \ln z_{0,\text{ref}} \ln z_b}{\ln\left(\frac{z_b}{z_{0,\text{ref}}}\right) \ln\left(\frac{z_m}{z_0}\right)}. \quad (\text{A.5})$$

Then, we regroup:

$$ECF = \frac{\ln z_m (\ln z_b - \ln z_0) - \ln z_{0,\text{ref}} (\ln z_b - \ln z_0)}{\ln \left(\frac{z_b}{z_{0,\text{ref}}} \right) \ln \left(\frac{z_m}{z_0} \right)} \quad (\text{A.6})$$

$$= \frac{(\ln z_m - \ln z_{0,\text{ref}}) (\ln z_b - \ln z_0)}{\ln \left(\frac{z_b}{z_{0,\text{ref}}} \right) \ln \left(\frac{z_m}{z_0} \right)}. \quad (\text{A.7})$$

Finally, we again apply logarithm laws to arrive at the expression from Eq. 1:

$$ECF = \frac{\ln \left(\frac{z_b}{z_0} \right) \ln \left(\frac{z_m}{z_{0,\text{ref}}} \right)}{\ln \left(\frac{z_b}{z_{0,\text{ref}}} \right) \ln \left(\frac{z_m}{z_0} \right)} \quad (\text{A.8})$$

Having shown that the formula for the ECFs is the same (apart from the missing distinction between z_m and z_{ref}), we turn to the calculation of the local roughness z_0 . Wichers Schreur & Geertsema (2006) use the following expression (their Eq. 4.7):

$$z_0 = z_m \exp \left(-\frac{c\kappa}{\frac{\sigma_u}{AU}} \right). \quad (\text{A.9})$$

We can transform this into the same form as the one we use (Eq. 4):

$$z_0 = \exp (\ln z_m) \exp \left(-\frac{A c \kappa}{\frac{\sigma_u}{U}} \right) \quad (\text{A.10})$$

$$= \exp \left(\ln z_m - \frac{A c \kappa}{\frac{\sigma_u}{U}} \right). \quad (\text{A.11})$$

For the scaling parameter, Wichers Schreur & Geertsema (2006) use $c = 2.185$, while we use $c = 2.2$ (following Wever & Groen, 2009). Furthermore, their attenuation factors (see their Eq. 4.5 and Section 3) are different to ours (see Table D.1). For wind speeds above 5 m/s, the GUSTO attenuation factors are a bit lower. The difference is about 2 % at 5 m/s and 12 % at 20 m/s. This does not mean that the roughness lengths and ECFs will also be lower by that percentage because the attenuation factor is in the exponent. Wever & Groen (2009) assessed that choosing $c = 2.5$ instead of $c = 2.2$ (a difference of nearly 14 %) leads to an ECF that is about 2 % lower. Thus, we argue that these differences in the parameter choice are negligible.

The GUSTO method (Wichers Schreur & Geertsema, 2006) and the Sigma method used here (Wever & Groen, 2009) are thus equivalent except for the following points:

1. The GUSTO method assumes $z_{\text{ref}} = z_m = 10$ m. Unlike the Sigma method, it is thus not suitable for wind masts whose height is not 10 m.
2. The choice of the scaling parameter c and the attenuation factors A is different, which could cause the resulting ECFs to differ by at most a few per cent.

A.2. Gustiness method from TR-277

Here, we discuss how the methods from this report relate to the method from KNMI technical report TR-277 (Benschop, 2005), which has been used for aviation purposes.

The method used by Benschop relates the averaged wind speed with the maximum wind gust. Though the author mentions that it can be used with 10-minute or hourly observations, we will focus on the 1-hour version as that is most comparable with our Gustiness method. A direct comparison of Benschop’s theory with the Sigma method presented here is not meaningful because the latter uses the standard deviation of the wind speed instead of the maximum gust. Benschop mentions that he uses the maximum gust instead of the standard deviation because the standard deviation was not available to him, a problem that has been solved by now.

Both our Gustiness method and the one by Benschop (2005) are based on the paper by Verkaik (2000). This suggests that the two methods are essentially the same. The ECF formulas in both methods are exactly the same. For the median ratio of maximum wind gust U_{max} and the averaged wind speed $\bar{U}$, Benschop (2005) uses an operational formula:

$$\left\langle \frac{U_{max}}{\bar{U}} \right\rangle = 1 + \frac{0.88\tilde{u}_p}{\ln \frac{z_m}{z_0}}, \quad (\text{A.12})$$

where $\tilde{u}_p = 2.99$ for hourly data. This is the same formula as the one in our Gustiness method (Eq. 2) if:

$$Agc\kappa = 0.88\tilde{u}_p \quad (\text{A.13})$$

$$\Leftrightarrow Ag = \frac{0.88\tilde{u}_p}{c\kappa} = 2.99. \quad (\text{A.14})$$

This constant value for Ag is in line with the wind-speed dependent values we use here (Table D.1), in particular for wind speeds between 4 and 7 m/s. For stronger wind speeds, Ag is somewhat lower here than in the Benschop method, e.g. by about 3 % at 20 m/s. This difference is even less than the one between GUSTO method and Sigma method discussed above (Section A.1). Similarly, we thus argue that the differences in parameter choice are negligible.

In terms of filtering and data selection too, Benschop’s method is highly comparable to our Gustiness method. Benschop (2005) uses a minimum wind speed of 5 m/s and at least one year of observations and at least 20 samples per directional sector. The Gustiness method uses the same minimum wind speed and at least 10 samples in a directional sector over several years. This makes the approach by Benschop somewhat stricter and less useful at stations where some wind directions only occur seldomly, in particular since it uses directional sectors of 10° (versus 20° here).

For a comparison of the results of the Sigma method and the Gustiness method (which we established here is highly comparable to the method in TR-277), see Section 6.

B. Review of the 2013 and 2020 potential wind updates

Table B.1: Measurement height z_m (in m) and reference roughness length $z_{0,\text{ref}}$ (in m) of each coastal station used in the 2013 and 2020 potential wind updates. Information for 2013 are from Stepek & Wijnant (2013). Information for 2020 are based on personal communication with A. Stepek. Changes in 2020 are set in bold. The table also includes information whether the environment up to 600 m from each station is land, sea or both. The 2020 included a limited number of stations because (*) they were not part of the LH15 set, (†) their time series were not long enough to compute climate normals or (‡) measurements were too disturbed.

Station	Env. 600 m	2013		2020	
		z_m	$z_{0,\text{ref}}$	z_m	$z_{0,\text{ref}}$
Valkenburg/Voorschoten (210/215)	land	10.0	0.03	10.0	0.03
Texelhors (229)	land	11.5	0.03	11.5	0.002
De Kooy (235)	land	10.0	0.03	10.0	0.03
Vlieland-Vliehors (242)	land	10.0	0.03	13.0	0.002
Terschelling-Hoorn (251)	land	10.0	0.03	10.0	0.03
Stavoren (267)	land	10.0	0.03	10.0	0.03
Nieuw Beerta (286)	land	10.0	0.03	n/a*	
Wilhelminadorp (323)	land	10.0	0.03	10.0	0.03
Woensdrecht (340)	land	10.0	0.03	n/a†	
Houtribdijk (258)	sea	17.25	0.002	n/a*†	
Hoofdplaat (311) ¹⁷	sea	16.5	0.03	16.5	0.03
Oosterschelde/BG2 (312)	sea	16.5	0.002	16.5	0.002
Vlakte van de Raan (313)	sea	16.5	0.002	n/a*†	
Schaar/Oosterschelde 4 (316)	sea	16.5	0.002	16.5	0.002
Hoek van Holland (330)	sea	15.0	0.03	15.0	0.03
Tholen/Marollegat (331)	sea	16.5	0.002	16.5	0.002
IJmuiden (225)	mixed	18.5	0.03	18.8 ¹⁸	0.03
Wijdenes (248)	mixed	10.0	0.03	10.0	0.03
Lauwersoog (277) ¹⁹	mixed	var.	0.03	var.	0.03
Cadzand (308)	mixed	17.1	0.03	17.0	0.002
Vlissingen (310)	mixed	20.0	0.03	27.0	0.03
Hansweert (315)	mixed	16.0	0.03	n/a*†	
Stavenisse (324)	mixed	16.5	0.03	n/a*†	

Here, we document a number of relevant aspects of the previous two potential-wind studies at KNMI in 2013 and 2020. The one in 2013 was documented in a technical report (Stepek & Wijnant, 2013), but for the 2020 update, documentation has not been published, which we attempt to correct here. Note that part of the information is based on personal notes by A. Stepek and may be incomplete. More basic background on the methodology used in both reports can be found in Section 2.

¹⁷closed 01-03-2016

¹⁸before 23-09-2015: 18.6

¹⁹At Lauwersoog, sector-dependent z_m was used in 2013 and 2020 already: 14 m for sea-facing sectors (northern half) and 10 m for land-facing sectors.

In particular, we note that both updates only used one value for the reference roughness length and the measurement height, independent of the wind direction (contrary to the sector-dependent approach developed in this report; see Section 4.4). The only exception was Lauwersoog where two heights were used: 14 m for wind from the sea and 10 m for wind to the sea (but reference roughness for all wind directions was 0.03 m). An overview of the coastal stations is given in Table B.1.

B.1. The 2013 potential wind update

In the 2013 potential wind update, for most coastal stations, except for Vlieland (KNMI no. 242), Terschelling Hoorn (251), Vlissingen (310) and Wilhelminadorp (323), the height was used relative to the sea. Strangely enough, this did not mean that the sea reference roughness was chosen. Instead, for most coastal stations the reference roughness for land was chosen (for some stations an explanation why was given in Stepek & Wijnant, 2013).

The reference roughness was only sea roughness (0.002 m) for stations K13 (252), Auk Alpha (253)²⁰, Meetpost Noordwijk (254), Houtribdijk (258), Huibertgat (285), Oosterschelde/BG2(312), Vlake van de Raan (313), Schaar/Oosterschelde4 (316), Lichteiland Goeree (320), Europlat (321) and Tholen/Marollegat (331):

- Houtribdijk (258) is treated like a sea station with $z_{0,\text{ref}} = 0.002$ m because 16 of the 18 wind sectors have a sea roughness (height is 17.25 m above NAP instead of 10 m above the dyke)
- IJmuiden and Hoek van Holland are treated as land stations despite the fact that more than half of the wind directions are from the sea. This was done because in the past the masts were further inland and choosing a sea reference roughness would have made the measurements inhomogeneous. Hoek of Holland: 14.65 m mast on a pier of 2 m height (sensor height should be 16.65 m), but assumed 15 m (for consistency).
- There is a recommendation for Texelhors (229), Vlieland-Vliehors (242) and Cadzand (308) that $z_{0,\text{ref}}$ should really be 0.002 m. Cadzand mast on a tower (sensor at 17.10 m).
- Vlissingen: 20 m mast, station elevation 8 m, but sensor height assumed 27 m (for consistency).

B.2. The 2020 potential wind update

This update was not comprehensive in terms of the number of stations for which ECFs were calculated but was performed conform the method described in Stepek & Wijnant (2013). First, the ECFs of the LH15 stations were calculated so there would be potential wind with up-to-date ECFs for the climate normals (coastal stations in red):

- De Kooy (235)

²⁰Oil production stopped in October 2018. Decommissioning Program approved in 2021 (personal communication KNMI inspection).

- **Valkenburg (210)/Voorschoten (215):** Valkenburg until 02-05-2016 and Voorschoten from 03-05-2016
- Schiphol (240): There are many wind masts at Schiphol Airport and to see for sure which mast the wind measurements for station Schiphol in RobuKIS table BGH come from, a comparison was made with the measurements in table TOW from the various wind masts. On 13-10-2020 the measurements came from TOW.240_W_18Cm27. On 21-5-2014 the TOW.240_W_18Cm27 wind measurements start at 09:40 UTC and are the same as in the hourly table BGH. These measurements are from a wind mast referred to as WM27, which is the main wind mast and is situated 105 m south of the east-west oriented runway “Buitenveldert” near touch down 27 (at the east end of the runway; coordinates are 52° 19' 01.8650" N, 4° 47' 23.2539" E). Before 21-5-2014, the main wind mast was at the location of the AWS (195 m south of the present location in direction 172°).
- De Bilt (260) replaced by Cabauw (348) because measurements were too disturbed for ECF update.
- Marknesse (273)
- Leeuwarden (270)
- Deelen (275) replaced by Hoogeveen (279) because measurements were too disturbed for ECF update.
- Eelde (280)
- Twente (290)
- **Vlissingen (310):** We used the second most recent ECF file²¹ from the previous update as the departure point for the 2020 update. Only one ECF set was calculated (04-12-2007 until 28-11-2020) for the period since the reference period to meet the deadline for the calculation of the climate normal. There were no significant differences compared to the reference period set. Despite the lack of any significant difference, the new set was used to calculate potential wind because the date 03-12-2007 was the last date that the hourly average wind speed (FH in RobuKIS table BGH) is (incorrectly) transformed from 20 m height (above land) to 10 m height using the Benschop correction (valid above the sea and not above land). None of the sectors on the land side (to the north of the wind mast) had roughness lengths greater than 1 m (the greatest was 0.5 m), so the 2LM requirement was met (roughness length should be less than the measurement height divided by 20). After the climate normal deadline there was more time for a detailed analysis and a set of ECFs for each year since 05-12-2007 was calculated (on 06-07-2021). None of the ECFs were significantly different from the ones in the reference period, so the 04-12-2007-28-11-2020 set did not have to be altered.
- Rotterdam (344): 2014–2020 the ECFs were below 1.22 for all wind direction sectors and $D/H > 10$. The main wind mast was the one near TD06 during this period.

²¹upfac310_19971002_20071203.txt

Before 07-01-1998, the main mast was the one near TD24 (Verkaik, 2001a), and prior to 2014, $D/H < 10$ for this mast.²²

- Gilze-Rijen (350)
- Eindhoven (370)
- Volkel (375)
- Maastricht (380)

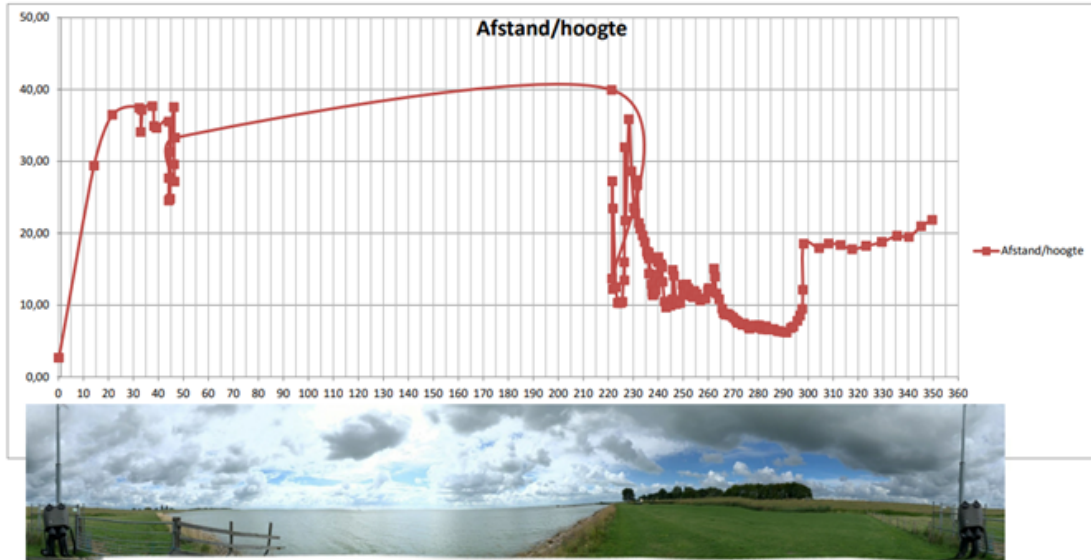
For the wind normals interpolation map in KNMI's *Bosatlas van weer en klimaat*,²³ the ECFs and potential wind of other stations also had to be updated. This was however done in a simplified manner because of limited time: The same ECFs were assumed for the whole period since the start of the one-but-last period of the latest update at the time. ECFs for the one-but-last period were calculated again to check parameters. This was done for the following stations (again coastal stations in red; sea stations in blue):

- **IJmuiden (225)**: 2 sets of ECFs because of change in height 23-09-2015
- **Vlieland (242)**: changed $z_{0,\text{ref}}$ from 0.03 m to 0.002 m and $z_m = 13$ m (10-m mast + 1.5-m block + 1.5 m elevation) from 01-01-1995 (start of the measurement series); moved to sea stations; there are 2 sets of KNMI cup anemometer and wind vane mounted on top of the Vlieland wind mast (referred to as double mounting) since 26-09-2013 (source: SAIS) and this has been corrected for (Section B.2).
- **Wijdenes (248)**: $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m. Because the land to the west and the IJsselmeer are below sea level, a height of 11.5 m would have been more accurate, but the difference is probably insignificant and there is a benefit in continuing with the same height as in the 2013 update (10 m). One single set of ECFs was calculated for the period (2010–2021) since the second last set of the previous update due to lack of time. The new ECFs are not significantly different from the last set from the previous update but now Sector 14 increases significantly (from 1.254 to 1.329; which was 1.292 in the last set) instead of Sector 13 (was an increase from 1.183 to 1.234, but the new ECF is 1.219). The new Sector 12 is again higher than in the last set and now 0.035 higher than the ECF of the second last set which may mean that an ECF of the period 2013 (when the last set was calculated) to present may be significantly higher. In the last set 3 sectors were higher than the acceptable 1.220 (13–15) and now only two (14 and 15). The trees in Sector 14 were pruned in March 2022 making D/H acceptable again (see Fig. F.10). Timing of the pruning is based on the decrease of Sigma-method z_0 (not shown).
- **Terschelling-Hoorn (251)**: $z_{0,\text{ref}}$ remains 0.03 m; ECFs not significantly changed compared to last ECFs (2004–2012) from the most recent update
- **K13 (252)**: On 21-09-2011 it was established that the height sensor was not at 73.8, but at 75.3 m. ECFs calculated with these 2 heights do not differ significantly. For the 2020 potential wind update the 2012–2021 ECFs (using 75.3m height) were compared to the ECFs for the only other period 1996-2012 (using 73.8m height).

²²See confidential memo by J. van der Meulen from 1 March 2016.

²³See: <https://www.knmi.nl/over-het-knmi/nieuws/bosatlas-van-weer-en-klimaat/>

[a]



[b]

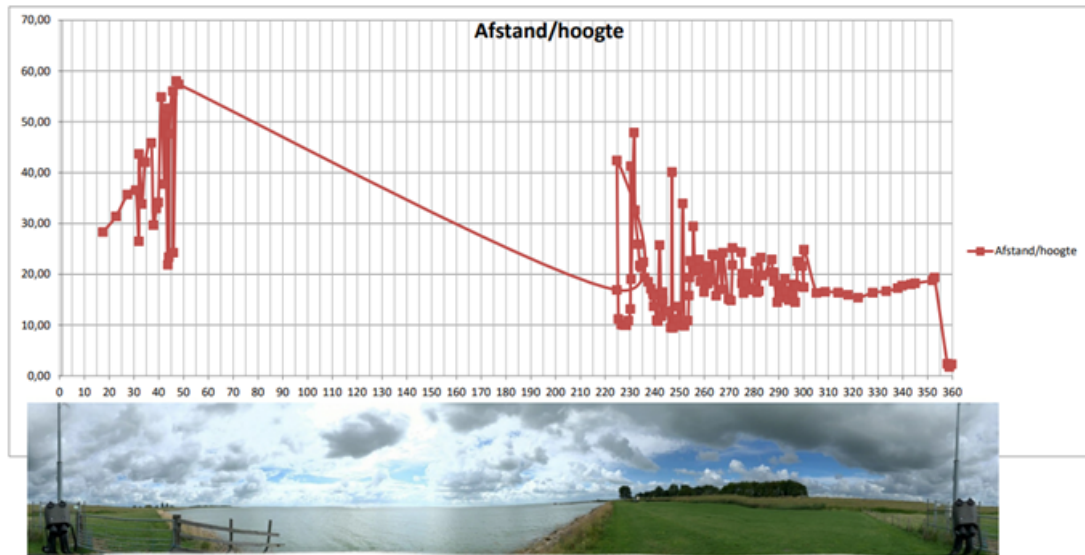


Figure B.1: D/H for Wijdenes from inspections on (a) 28-07-2022 and (b) 18-07-2024: improvement between 265° and 297° (Sector 14 and half of 15). (Source: SAIS)

Because the difference was insignificant, the decision was made to keep the 1996–2012 set of ECFs and just change the final date to 2021. So, there is just one set of ECFs from 1996–2021 using sensor height 73.8m. There was no wind direction (DD) information at K13 between 25-12-2020 20 UTC and 27-5-2021 13 UTC because the wind vane and the SIAM were not connected. Calculating the potential wind for locations at sea is generally superfluous because KNMI also publishes wind speeds valid at 10 m height that are calculated by applying the Benschop height correction factor. However, potential wind from K13 (and Europlatform and F3) should be used for the interpolation map of the normals of the potential wind 2000–2030.

- Stavoren (267): $z_{0,\text{ref}} = 0.03$ m; before 01-12-1999 the wind mast stood in the harbour with Lake IJssel on one side and land on the other. No differences were observed in the surroundings of the “new” measurement location (further from the coast) based on photos from 2004 and 2020 in SAIS) and no significant difference between the ECFs of the previous update (2004–2012) and the 2012–2021 ECFs. Therefore, the existing ECF set remains valid.
- Lauwersoog (277): $z_{0,\text{ref}} = 0.03$ m. The sensors are 14 m above sea level and the sea lies to the north of the sensors. The sensors are 11–14 m above the land and the Waddenzee, which lie to the south, but the height has always been assumed to be 10 m probably because the many obstacles in the harbour were assumed to make the ground level of the wind profile effectively higher (displacement height). There were no significant changes in ECFs since 2012, so the existing ECF set remains valid, so with height above land of 10 m. Looking into it after the 2020 update, we concluded that we should not have used a displacement height (and a 10 m height above land) because the buildings in the harbour are too far apart.
- Heino (278): update ECFs and potential wind impossible because the measurements are too disturbed (since 1993 more than 4 sectors with $ECF > 1.22$).
- Huibertgat (285): $z_{0,\text{ref}} = 0.002$ m; $z_m = 18$ m; no significant difference between the 2012–2021 ECFs and the last set of the previous update. Therefore, the existing ECF set remains valid.
- Cadzand (308): $z_{0,\text{ref}} = 0.002$ m; $z_m = 17$ m; no significant difference between the 2012–2021 ECFs and the last set of the previous update (both with $z_{0,\text{ref}} = 0.03$ m) although the change in Sector 5 was almost significant: +0.038; because we want to use a sea reference roughness (0.002 m) instead of a land reference roughness (0.03 m), ECFs were multiplied by factor 1.081 for the whole period (starting 01-01-1972) conform (Wever & Groen, 2009, Section 2.4).
- Oosterschelde/BG2 (312): $z_{0,\text{ref}} = 0.002$ m; $z_m = 16.5$ m; no significant difference between the 2012–2021 ECFs and the last set (one set since beginning: 01-01-1982) of the previous update. Therefore, the existing ECF set remains valid.
- Schaar/Oosterschelde4 (316): $z_{0,\text{ref}} = 0.002$ m; $z_m = 16.5$ m; no significant difference between the 2012–2021 ECFs and the last set of the previous update (1996–2012). Therefore, the existing ECF set remains valid.
- Westdorpe (319): $z_{0,\text{ref}} = 0.03$ m; $z_m = 10$ m; significant difference between 2012–

2021 ECFs and the last set of the previous update: ECFs for one-but-last set of the previous period (2001–2009) were kept unchanged; 2 new sets were added: 2010–2013 (ECF for sector 6 was significantly lower compared to the ECF from the one-but-last set whereas the ECF from Sector 7 was significantly higher due to tall trees and Sector 8 almost significantly higher; no metadata was found in SAIS to explain these changes) and 2014–2021 (no significant change compared to the one-but-last set) .

- **Lichteiland Goeree (320):** $z_{0,\text{ref}} = 0.002$ m; height sensor was changed from 38.3 m to 37.2 m on 18-10-2011 when the wind vane and the 2D sonic and cup anemometer were replaced with two sets of cup and vane installed on a double mounting, which has not been corrected for in the 2020-update (Section B.2). So, the last set of ECFs from the previous update ends on 17-10-2011 and the new set starts on 18-10-2011. Since 30-11-2017, CIBIL takes the wind measurements from the sensor set giving the higher wind speed at that moment ('calculatie maximum'). This became possible when collecting the measurements by XML was introduced at Lichteiland Goeree, but that did not change the ECFs significantly.
- **Europlatform (321):** $z_{0,\text{ref}} = 0.002$ m; $z_m = 29.10$ m. Since 30-11-2017 CIBIL takes the wind measurements from the sensor set giving the higher wind speed at that moment ('calculatie maximum'). This became possible when collecting the measurements by XML was introduced at Europlatform, but that did not change the ECFs significantly. The existing set of ECFs of last update (since 01-07-1996) remains valid. Europlatform is a sea station and the Benschop correction is applied operationally to provide wind speed measurements valid at 10 m height. It would be worth including it for the interpolation map of the normals of the potential wind 2000–2030, since Europlatform, K13 and F3 together are representative of the spatial distribution of the wind speed normals for the sea surrounding the Netherlands. Double mounting not corrected for in the 2020-update (Section B.2).
- **Wilhelminadorp (323):** $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m. No data for 06-01-2014 11 UTC until 05-12-2017, so the newly calculated ECF set is not for 2012–2021 (like for most other stations), but for 2017–2021; no significant difference between the 2017–2021 ECFs and the last set of the previous update (2010–2014). Therefore, the existing ECF set remains valid.
- **Tholen/Marollegat (331):** $z_{0,\text{ref}} = 0.002$ m and $z_m = 16.5$ m. Only 2 sets of ECFs and the last of the previous update remains valid because the ECFs have not changed since then; there are problems with the availability of the measurements: Martijn van Dijk RWS emailed that the wind mast was broken between 25-09-2020 14 UTC and 06-09-2022 10 UTC, so potential wind calculations were stopped on 25-09-2020. Check-up on 15-12-2025 showed that there is still no Sigma-method potential wind for Tholen/Marollegat, but Gustiness-analysis potential wind is still being produced. No action will be taken to improve this because automated Sigma potential wind based on 10-minute measurements is close to being implemented and then the hourly potential wind will be obsolete,
- **Herwijnen (356):** $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m. For Sector 4 the 2012–2021 winter ECFs are significantly higher than the last set of ECFs of the previous update, so

a new set was added; also the filenames of 7 old ECF sets were corrected (period summer and winter was wrong).

A few extra stations were updated (not one of the LH15 stations and not required for the wind normals interpolation map):

- [IJmond \(209\)](#): $z_{0,\text{ref}} = 0.002$ m and $z_m = 16$ m; there was no potential wind for IJmond in the 2013 update even though there are wind measurements since 30-01-2001 (section 6.1 of Stepek & Wijnant, 2013). The potential wind at IJmond have never been published on the KNMI website (unclear why), but IJmond is a sea station and the Benschop correction is applied operationally to provide wind speed measurements valid at 10 m height, so the calculating the potential wind speed would have no added value.
- Cabauw (248): $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m (replacement De Bilt as mentioned above)
- Lelystad (269): $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m
- Hoogeveen (279): $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m (replacement Deelen as mentioned above)
- [F3 \(239\)](#): $z_{0,\text{ref}} = 0.002$ m and $z_m = 60$ m. The potential wind at F3 have never been published on the KNMI website (unclear why), but despite the fact that F3 is a sea station, it would be worth including it for the interpolation map of the normals of the potential wind 2000–2030 (the series starts in 1994) because there are no other measurements in that area. No correction is applied for the disturbance due to the double mounting (Section B.2) because correction in this case is not worthwhile.
- Hoofdplaat (311); $z_{0,\text{ref}} = 0.03$ m and $z_m = 16.5$ m; closed since 01-02-2016
- Hoek van Holland (330): $z_{0,\text{ref}} = 0.03$ m and $z_m = 15$ m

Following the requirements outlined in Section 4.2, measurements were too disturbed to derive ECFs and potential wind in 2020 at (and Table B.2 gives some additional information for some stations):

- De Bilt (260)
- Deelen (275) after 24-07-2012 (the nearby 5–8 m tall trees at 15–110 m distance do not meet the $D/H > 10$ requirement)
- Heino (278) has for the whole series at least 4 Gustiness ECFs > 1.22 and more later on in the series
- Woensdrecht (340) has at least 13 sectors where the Gustiness ECF > 1.22 and at least 2 sectors where $D/H < 10$ for the whole series series
- Rotterdam Geulhaven (609/343)

Table B.2: Individual obstacles per station and sector as noted when compiling the 2020 potential wind update.

Station	Sector	Period	Obstacle
De Kooy (235)	17, 18	01-04-2017–31-03-2020	Shrub at 100 m golf course
F3 (239)	18, 1	Since 01-01-1994	Larger “rough” platform at 60 m
Cabauw (248)	14, 15	Since 06-01-2012	Forest, closest at 117 m (Sector 15)
	13	Since 05-06-2013	Forest at 220 m
De Bilt (260)	12–17	1993 (20-m mast) until 31-03-2020	Lines of trees and KNMI building
Lelystad (269)	15 (winter)	01-11-2017–31-03-2018, 01-11-2019–31-03-2020	Line of trees at 400 m from wind mast
	16 (winter)	01-11-2013–31-03-2014, 01-11-2014–31-03-2015	Line of trees at 400 m from wind mast
	17 (winter)	05-09-2018–31-03-2019	Line of trees at 600 m from wind mast
Leeuwarden (270)	9	07-05-2019–31-07-2019	
Marknesse (273)	12 (summer)	01-01-2003–31-03-2008 (and almost all ECFs since then)	Line of trees near farm at 240 m from wind mast
Deelen (275)	4–8, 10-14 (summer)	24-07-2012 until trees pruned some time between 11-03-2021 and 03-05-2022	Small trees (those 5 m or taller are seen as obstacles very close (5–60 m) from wind mast
Heino (278)	1, 2, 8–10, 15–18	01-01-2012–23-03-2021 and back to start of series in 1993	Lines of trees 80–260 m from wind mast
Eelde (280)	7	01-04-2006–31-03-2009 (summer), 01-04-2018–31-03-2019 (winter)	
	15–17 (winter)	01-11-2012–31-03-2013 (17), 01-11-2013–31-03-2014 (16), 01-11-2015–31-03-2016 (15), 01-11-2019–31-03-2020 (15)	
Twente (290)	7–9 (winter)	Before 2015 except: 01-01-2001–04-03-2005 (7, 9), 05-03-2005–28-02-2014 (9), 01-05-2009–31-12-2014 (7)	
	17	05-03-2005–31-03-2006	
Woensdrecht (340)	7–10	Whole measurement period	Wooded area 90–170 m from mast
Gilze-Rijen (350)	12, 13	01-07-1998–29-11-2020	
	16, 17	01-01-1960–31-12-1974	
Eindhoven (340)	15 (winter)	01-04-2008–31-03-2010	
Volkel (375)	Usually 15–18 but sometimes only 16 and sometimes also 14 and 1	01-01-1978–29-11-2020	

Double mounting

At some stations there are 2 sets of KNMI cup anemometers and wind vanes mounted on the mast. This is referred to as double mounting. Because the anemometers are in each other's wakes for certain wind directions, measurements must be corrected for these effects. In the 2020 update this has been done for Vlieland, but not for the other locations with a double mounting (Lichteiland Goeree, Europlatform and F3). In more recent years, the hourly wind variables used to calculate the Gustiness ECFs are selected from the anemometer (and wind vane) with the higher wind speed, so the correction should not have been applied for Vlieland after the selection was introduced (not clear when this was) and no correction is required for Lichteiland Goeree and Europlatform (after 17-03-2022). F3 is an exception because since 17-11-2021, the selection is no longer applied and currently (11-02-2026) it looks like the selection will stop for the other three locations too. For future ECF updates this has to be looked into: (1) if the double mounting has been installed at new locations, (2) what is the orientation of the double mounting and are there any changes in this orientation and (3) how do we correct for these changes (in the case of 10-minute measurements, we should not correct, but select the cup and vane with the higher wind speed because it is not disturbed and a correction is also not needed for hourly measurements where a selection has been applied).

Double mounting stations that were analysed for the 2020-update:

- **F3 (239)**: Double mounting requires a correction of +12 % over a wind direction sector of 20° when one anemometer is in the wake of the other (Wauben, 2014), based on measurements from 2012. Strangely, when the wind blows in the opposite direction the correction is only +3 % when the other anemometer measures in the wake. Stepek's 2020 update analyses of 2010, 2012 and 2019 showed that the wind speed used to calculate the ECFs (DS_CODE = FD on the arm towards 160°) of Sector 17 needs to be increased by +6 % (DS_CODE = FD2 is on the 340° arm and is not used to calculate ECFs). An analysis of binned data evenly spread over the sector 17 wind directions (325–344°) revealed a correction of +5.3 %. However, both anemometers measure in the wake of the larger of the 2 platforms (the wind mast is on the smaller one 60 m to the south) and the roughness length of Sectors 18 and 1 is equivalent to that of an urban area (≈ 0.5 m). This probably explains the unexpected difference described in the first 2 sentences of this paragraph, since it is likely that Sector-17 measurements are affected by the wake, at least for some of the time. So, there is no point in correcting for the relatively small effect of the double mounting wake, since the measurements are so disturbed by the larger platform that the ECFs are invalid. So, no attempt is made to correct the disturbed measurements: the ECFs have been made identical for all directions (0.826) and perform only the transformation to 10 m with reference roughness 0.002 m. Since 17-11-2021, the hourly wind variables used to calculate the Gustiness ECFs are no longer selected from the anemometer (and wind vane) with the higher wind speed.
- **Vlieland (242)**: Analysis of the measurements shows that (1) correction of +6 % for both anemometers (when in the wake of the other) and (2) southerly anemometer (242_W_wind in de TOW table RobuKIS) provides the hourly measurements that are used to calculate the Gustiness ECFs. The largest change in ECF ever at

Vieland (increase of 0.03 in Sector 18) is the one due to the installation of the double mounting (on 10-12-2013 [from ECF analysis] or 26-09-2013 [KNMI Inspection report]). Sector-18 winds are northerly, so the southerly anemometer (used for the ECF calculation) is in the wake of the other anemometer and an increase in Gustiness ECF is to be expected (ECF is based on the maximum gust divided by the hourly average wind speed and in the wake the average is lowered more than the gust). When the wind blows from the opposite direction (Sector 9), the southerly anemometer should not be disturbed and indeed the increase in ECF is much smaller (0.008). We also see this small increase in ECFs (noise) in other sectors where we expect no wakes from anemometers. The Sector-18 ECF calculated for the period before the installation of the double mounting (0.982) has been multiplied by 1.12 to correct for the wake effect (corrected ECF 1.100). The ECF correction is a little larger than needed for the +6 % correction to the wind speed mentioned earlier, because analysis of three other masts with a double mounting (Lichteiland Goeree, Europlatform and F3) revealed that larger corrections were necessary.

- [Lichteiland Goeree \(320\)](#): Double mounting with the anemometers on a North-South line. Both anemometers need a correction of about +8 % (averaged over the worst affected 20° sector) when in the wake of the other anemometer (Wauben, 2014). At Lichteiland Goeree (and Europlatform), the wind set with the higher wind speed is used in the main location (*_W_0) since 30-11-2017 when retrieval via XML files started, so the wind speed of *_W_0 requires no correction but this was only implemented in RobuKIS after 17-03-2022 due to confusion due to the use of two different location codes for the same platform.
- [Europlatform \(321\)](#): there are no analyses for Europlatform in Wauben (2014), so it is unclear in which direction the mounting pointed and for what directions the worst wake effects are present. Station inspection photos show that the anemometer arms are oriented along the NE-SW line. In 2006, 2007 and 2016, “DS_CODE 321_W_0” (sensor location used to calculate the Gustiness ECFs) has the same wind measurements as “321_W_1”, and the “W_1 anemometer” is on the SW facing arm. However, in 2017 “W_0” is the same as “W_2” and then W2 is on the SW facing arm (W1 on the NE facing arm). The previous 2 sentences are based on analyses of limited periods (see, for example, the bullet points below). The measurements that are used to calculate ECFs therefore always seem to come from the SW facing arm and require a correction when the wind is NE. However, in 2017, the 10-degree wide sector that required the largest correction shifted 12 degrees from 43° to 55°.
 - From 13-12-2006 10:20 to 14-12-2006 09:10 UTC with wind direction $(225 \pm 4)^\circ$, the NE facing anemometer (W_2) requires a wind speed correction of $+(18 \pm 3) \%$.
 - From 30-03-2007 22:40 to 31-3-2007 10:00 UTC with $(43 \pm 4)^\circ$, the SW facing anemometer (W_1) also required a correction of $+(18 \pm 3) \%$.
 - From 23-3-2017 04:20 to 23:50 UTC the SW facing anemometer (W_2) required a correction of $+(15 \pm 5) \%$ for wind direction $(55 \pm 5)^\circ$ and for $(33 \pm 7)^\circ$ only $+(2 \pm 2) \%$.

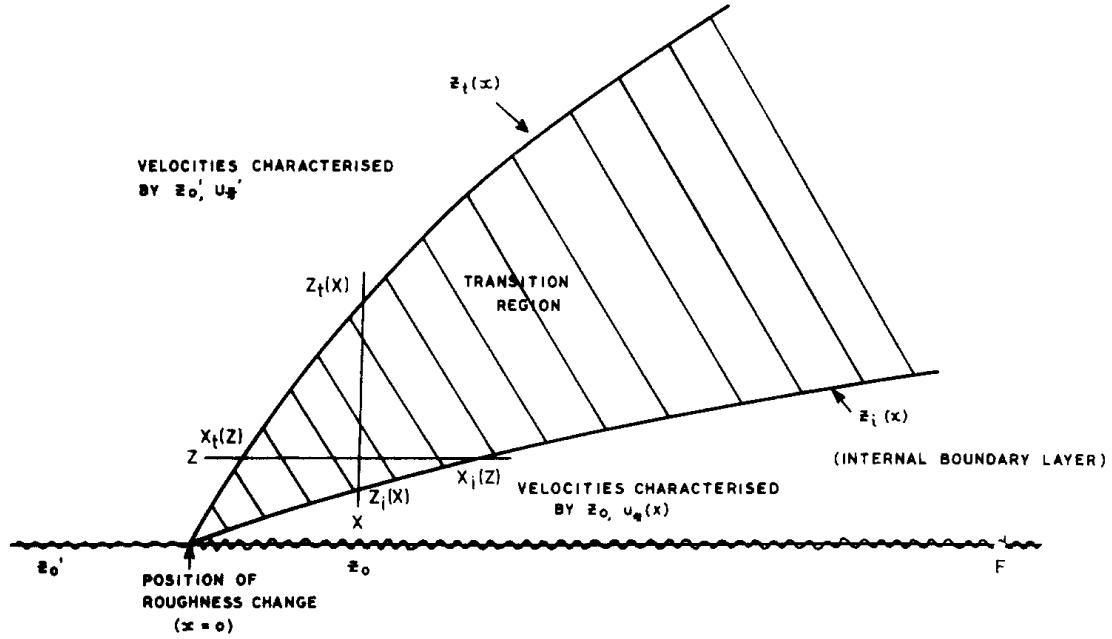


Figure C.1: Regions of influence of a roughness change, showing internal boundary layer and transition region (from Deaves, 1981).

C. Internal boundary layer (IBL) and transition zone (TZ)

For stations near a significant change in surface roughness (e.g. on the coast), it is important to find out whether the measurement is representative for the surface roughness in the layer up to 60 m because the method for deriving the potential wind assumes this.

When there is a change in surface roughness, the flow does not adapt to this new roughness instantaneously: it takes some time before the flow is in equilibrium with the new surface roughness (z_0 in Fig. C.1). The layer where the flow has adapted to the new surface roughness is called the internal boundary layer (IBL). This layer grows gradually with distance from the place of the roughness change. Above the IBL is a transition zone where the flow is not in equilibrium with the new surface roughness, but also not with the old one. Above the transition zone, the flow is in equilibrium with the surface roughness from before the change (z_0' in Fig. C.1).

The measurement is representative for the roughness length determining the wind speed profile from measurement height up to the top of the surface layer (60 m) if:

1. Measurement height $z_m > z_t$ (height of the transition zone). If this is the case, the whole layer between the measurement height and 60 m feels the new surface roughness z_0' .
2. Measurement height is in the transition zone ($z_m < z_t$ and $z_m > z_i$ [height of the IBL]) and $z_m > 1/4$ th of the profile up to 60 m, ($z_m > [z_i + (60 - z_i)/4]$ and $z_t > 60$ (which is usually the case). This is because the largest effect of the surface roughness on the wind profile is in the lowest part and we assume that the changes

in the top 3/4th of the profile up to 60 m are small enough to ignore.

Note: $z_m < z_i$ (measurement is in the IBL and profile is determined by the roughness after the change) or if $z_m < [z_i + (60 - z_i)/4]$, then a large part of the profile up to 60 m will be determined by the transition zone roughness or the roughness before the change. In that case it is important that we assess the maximum mistake we make by assuming the roughness length obtained from the wind measurements determines the profile up to 60 m. If that mistake remains lower than 5 % (accuracy of the method assessed by Verkaik, 2000), then the mistake is acceptable.

Deaves (1981) experimentally derived formulas for the height of the IBL z_i and the transition zone z_t (though the roughness values tested were not below 0.001 m). As a function of the distance x to the roughness change, z_i can be calculated as follows:²⁴

- For transition from rough to smoother surface (R-S): $z_i/z_0 = 0.07x/\sqrt{z_0z'_0}$.
- For transition from smooth to rougher surface (S-R): $z_i/z_0 = 0.36(x/z_0)^{0.75}$.

The value of the height of the transition zone z_t does not depend on whether the transition is from smooth to rough or from rough to smooth: $z_t/z_0^+ = 10(x/z_0^+)^{0.6}$ (where z_0^+ is the larger of the two values z_0 and z'_0).

Because the wind speed increase with height is greatest near the ground, we assume that the roughness determining the wind speed increase in the layer from z_m to a fourth of the way up from z_m to 60 m (referred to as 4th-height) can be used as a representative estimate for z_0 for the whole layer up to 60 m. We can calculate the height of the IBL at the wind mast and we know the roughness determining the IBL is valid at this height. With this value (z_0 at z_i) and the Gustiness-method roughness (referred to as Gustiness z_0 in the rest of this document) at z_m , it is possible to calculate the rate of change in z_0 from z_i to z_m when $z_m > z_i$. Assuming this rate change also applies from z_m to 4th-height (which is only correct when both heights are in the TZ), we can estimate a value for z_0 at 4th-height. Finally, we assume the average of z_0 at z_m and z_0 at 4th height to be the most representative value of z_0 for the layer up to 60 m.

As an example, consider Sector 9 at Cadzand. The shortest distance from (the 11-m high) dunes to the wind mast (in the sea) is 245 m. We estimate the land roughness for this sector, which is affected by forest and houses (on lower land behind the dunes), to be 0.4 m (larger than the Gustiness $z_0 = 0.226$ m because this value represents a combined effect of land and sea roughness). Deaves R-S (from 0.4 m to 0.002 m, $x = 245$ m) gives an IBL height of 1.2 m, so the sensor (at 17 m above mean sea level) measures low in the TZ (top TZ at 188 m). The effective measurement height (z_m) should be between the height above sea and the height with respect to land but since the sensor measures low in the TZ, we take the effective height as the height above sea. At 1.2 m, the roughness is adapted to the sea (0.002 m) and the rate of increase of the roughness between 1.2 m and 17 m equals 0.014 m per meter height (= 0.224 m in 15.8 m). Based on this rate, the roughness at 27.75 m (quarter of the way up to 60 m from sensor height), is 0.377 m (= 0.226 + 10.75 · 0.014) and the average and our best estimate for the roughness of the

²⁴Another method to calculate the height of the IBL (which is used by Van den Brink et al., 2017) is by Wood (1982): $z_i = 0.28z_{0,r}(x/z_{0,r})^{0.8}$ with $z_{0,r}$ the roughness of the most rough surface. So, in Wood (1982), the height of the IBL does not depend on the lowest roughness $z_{0,s}$.

profile up to 60 m is 0.302 m ($= (0.226 + 0.377)/2$). So, the mistake in ECF that is made by assuming that the whole profile up to 60 m can be described by the Gustiness z_0 at sensor height is 1.6 %, which is below the 5 % uncertainty of the method. We insert our parameters ($z_b = 60$ m, $z_m = 17$ m, $z_{\text{ref}} = 10$ m) into Eq. 1 and get:

- $ECF_1 = 1.0034$ (method up with estimated z_0 for sensor height to 60 m of 0.302 m and down with land reference roughness of 0.03 m) or
- $ECF_2 = 0.9787$ (method up with Gustiness z_0 of 0.226 m and down with land reference roughness of 0.03 m).

Thus, the maximum difference ($ECF_1 - ECF_2$) is 1.6 % (underestimation).

D. Attenuation factors

Table D.1: Wind speed dependence of the coefficients A (attenuation) and g (normalized gust) for the cup anemometer used by KNMI and for measurement periods of 1 hour and 10 minutes. These values were computed by Wever & Groen (2009) following Verkaik (2000).

U	1 hour			10 minutes		
	A	g	Ag	A	g	Ag
1	0.917	3.014	2.76	0.824	2.397	1.97
2	0.923	3.163	2.92	0.866	2.563	2.22
3	0.919	3.231	2.97	0.878	2.639	2.32
4	0.914	3.270	2.99	0.882	2.684	2.37
5	0.908	3.297	2.99	0.881	2.714	2.39
6	0.902	3.317	2.99	0.879	2.737	2.41
7	0.896	3.332	2.99	0.876	2.754	2.41
8	0.890	3.344	2.98	0.873	2.768	2.42
9	0.885	3.356	2.97	0.869	2.782	2.42
10	0.880	3.366	2.96	0.866	2.792	2.42
11	0.875	3.376	2.96	0.862	2.804	2.42
12	0.871	3.383	2.95	0.859	2.812	2.41
13	0.866	3.389	2.94	0.855	2.819	2.41
14	0.862	3.399	2.93	0.852	2.831	2.41
15	0.858	3.402	2.92	0.848	2.835	2.40
16	0.854	3.407	2.91	0.845	2.839	2.40
17	0.851	3.413	2.90	0.842	2.847	2.40
18	0.847	3.420	2.90	0.839	2.854	2.39
19	0.844	3.423	2.89	0.836	2.858	2.39
20	0.840	3.435	2.89	0.833	2.873	2.39
21	0.837	3.444	2.88	0.830	2.883	2.39
22	0.834	3.435	2.86	0.827	2.872	2.37
23	0.831	3.440	2.86	0.824	2.878	2.37
24	0.828	3.443	2.85	0.821	2.881	2.37
25	0.825	3.446	2.84	0.819	2.885	2.36
26	0.822	3.447	2.83	0.816	2.886	2.35
27	0.819	3.452	2.83	0.813	2.892	2.35
28	0.817	3.455	2.82	0.811	2.896	2.35
29	0.814	3.471	2.83	0.809	2.915	2.36
30	0.812	3.480	2.82	0.806	2.926	2.36
31	0.809	3.464	2.80	0.804	2.907	2.34
32	0.807	3.468	2.80	0.801	2.910	2.33
33	0.804	3.469	2.79	0.799	2.913	2.33
34	0.802	3.471	2.78	0.797	2.915	2.32
35	0.799	3.480	2.78	0.795	2.925	2.32

E. Extrapolation and interpolation of wind speed after Verkaik (2001b)

Here, we summarise some aspects of the HYDRA report (phase 11/12) by Verkaik (2001b) that are relevant to Section 3.6.3.

Extrapolation

Based on $1/L$ statistics, Verkaik concludes that the atmosphere is mostly stable over land and unstable on the North Sea. This contributes to the error of extrapolating wind speed measurements with 2LM from land to offshore (Section 1.4).²⁵

Interpolation

- Verkaik estimated the wind speed at a certain location starting from an interpolated wind field at macro level (2 km). The interpolated wind field at macro level was created with the potential wind at all of the 16 KNMI measurement stations he had available, except for the one for which he wanted to validate the estimated wind speed (leave-one-out method). He used the 2LM method to transfer these potential winds via mesolevel (60 m) to macrolevel where the wind speeds were interpolated. He did this in four different ways: one where he assumed the wind at macro level uniform and three ways where the value of R indicates the max distance of impact from a measurement, $R = 70$ km giving the best result. Figure E.1 (with $R = 70$ km) shows that there are significant errors in the interpolation maps with the average bias ranging from +1 to ~ 1 m/s: the largest error is for station Meetpost Noordwijk (254): +1.2 m/s. The error is dependent on wind direction (see Fig. E.2 for Cabauw) because of under/overestimation of mesoscale roughness. Verkaik suggests this can be improved by increasing the 3 km length scale for the mesoscale roughness footprint that was used.
- In Fig. E.3 for Cabauw, there is only a significant difference between measured and estimated wind speeds for very low wind speeds (below 2 m/s). The estimated wind speed is then higher than the measured one. This is not due to stability effects, because these are cancelled out, but probably due to an imperfect interpolation of the macro wind speeds. The fact that when the measured wind speed is 0 m/s, the estimate is 1 m/s, supports this idea, since nearby stations will sometimes have positive non-zero speeds but never negative non-zero speeds.
- Verkaik compared wind speed measurements and estimates (using 2LM and local gustiness roughness) at Schiphol. He gives the relative error of the estimated wind speed as a function of stability ($1/L$) for four different wind directions in Fig. E.4. The figure shows that for stable atmosphere ($1/L > 0$), the estimated wind speed is mostly overestimated (except for south-westerly winds, 240°). For unstable atmosphere ($1/L < 0$), the speed is mostly underestimated (except for northerly winds,

²⁵ L is the Monin-Obukhov length indicating a stable boundary layer when $L > 0$, unstable when $L < 0$ and neutral when $L \approx 0$ and buoyancy is caused more by shear than convection, generally assumed to be the case for wind speeds above 5 m/s.

360°). So, Verkaik looks at the stability related error of the estimated of the measured wind speed (using 2LM and local gustiness roughness), but we are interested in something else, namely the stability-related error of the potential wind (using 2LM and local roughness 0.03 m). His conclusion that the estimate of the measured wind speed is too high for stable conditions does not contradict our conclusion that the potential wind is too low for stable conditions. When Verkaik estimates the measured wind speed at 10 m, he goes down from 60 m using a neutral wind profile with the real z_0 which gives a higher 10-m wind speed than a stable wind profile. When we go up from 10 m (measured wind speed) and back down again from 60 m to obtain the potential wind (at 10 m), we use a neutral profile both ways but going up we underestimate the 60-m wind speed when the atmosphere is stable instead of neutral. This means the potential wind speed is lower than what would have been measured if the surroundings of the wind mast were ideal (flat grass with no obstacles).

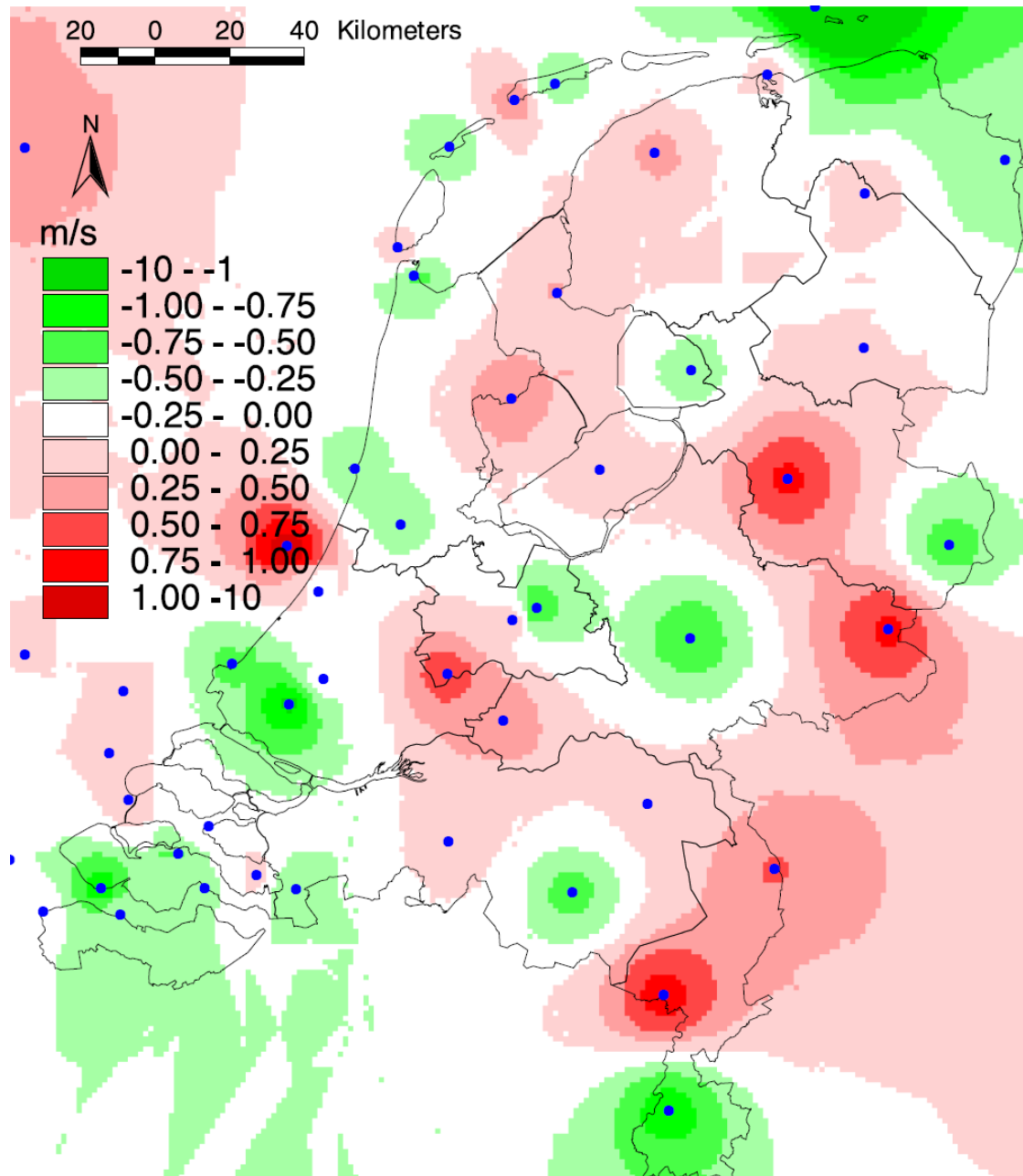


Figure E.1: Figure B.11 from Verkaik (2001b): Bias in average surface wind speed (Estimated–Measured). $R = 70$ km.

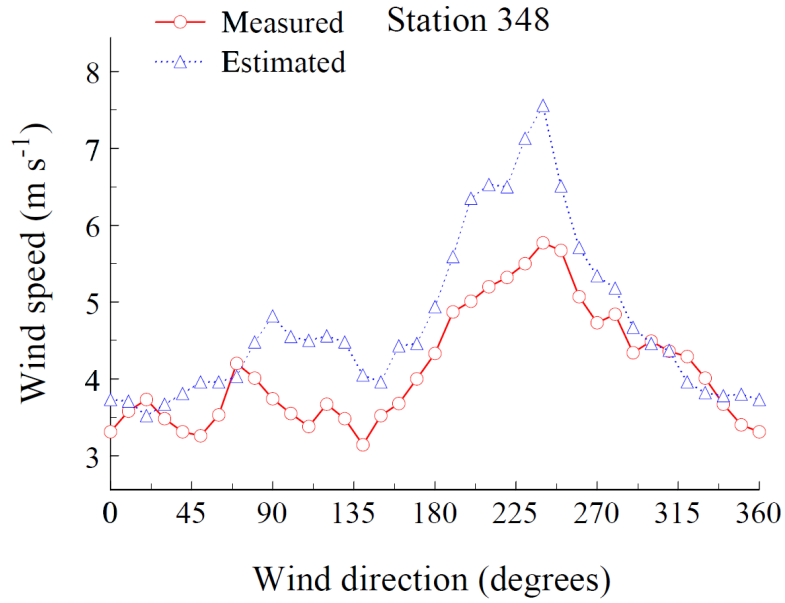


Figure E.2: Figure B.22 from Verkaik (2001b): Average wind speed (measured and simulated) as a function of wind direction for $R = 70$ km at station 348 Cabauw. Data selection $U_{\text{meas}} \geq 2 \text{ m s}^{-1}$.

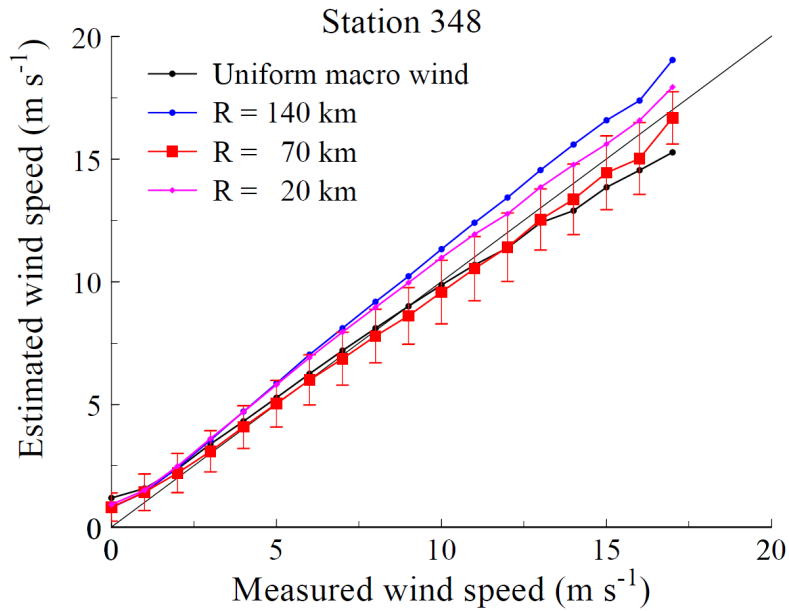


Figure E.3: Figure B.21 from Verkaik (2001b): Wind speed dependence of the simulated wind speed for the four runs at station 348 Cabauw.

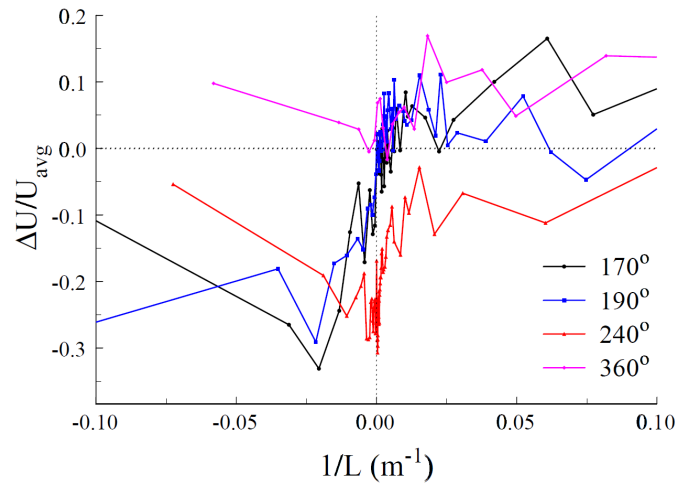


Figure E.4: Figure B.35 from Verkaik (2001b): Stability dependence of relative error in wind speed. One point comprises the average of 30 measurements. Station 240 Schiphol, period 1996–2000, four wind directions sectors.

F. Coastal station details

In this appendix detailed metadata is given only for coastal stations. This is because the new method to calculate ECFs described in this report includes two changes that are only relevant for coastal not for land and sea stations: wind-direction dependent reference roughness and measurement height.

F.1. Valkenburg/Voorschoten (210/215)

Valkenburg (210) closed since 03-05-2016 04 UTC and replaced by Voorschoten (215). Both stations are more than 4 km from the coast (and therefore $z_{0,\text{ref}} = 0.03$ m for all wind direction sectors). We should make potential wind for both and inform users that they are effectively one location with respect to potential wind. Sensor height for both locations is 10 m (also used for Gustiness ECFs).

F.2. IJmuiden (225)

According to station information in SAIS, the wind sensors are at 14.38 m above Lichtopstand Zuidpier, and Lichtopstand Zuidpier is at 4.40 m+NAP.²⁶ For wind directions from land, the sensor height is therefore 14.38 m, for wind directions from sea, sensor height is 18.78 m above sea level. For Sector 5, sensor height should be relative to mean sea level because up to 650 m from the mast, the surface is sea and the Gustiness z_0 (0.025 m) is closer to sea roughness (0.002 m) than the roughness of the land in Sector 5 (industrial area with a roughness estimated to be about 0.3 m). For Sectors 7 and 8, sensor height should be relative to the dune tops: 10 m and 12 m, respectively (explained below).

Definitely, sea up to 600 m from wind mast between 244° and 351° (which is Sectors 13–17) and between 10° and 86° (Sectors 2–4 and most of Sector 1). Mostly sea between 86° and 118° (land at 560–587 m), which are Sectors 5 and 6. Quite a tall obstacle at 75 m between 110° and 115°, which may affect Sector 6. Pier of rocks at 280–293 m from wind mast between 107° and 118° is not very tall and probably does not affect Sector 6. Definitely land up to 600 m from the wind mast between 150° and 199° (Sector 9 and most of 8 and 10). Between 199° and 244° a mix of land and sea: between 199° and 232° (Sector 11) more land than sea and between 232° and 244° (Sector 12) more sea than land. Between 351° and 10° (Sector 18) pier at > 489 m, so mostly sea. Finally: Sector 7 is the harbour, so mostly sea unless maybe if there are a lot of ships moored.

However, the calculated ECFs do not always agree with what was assessed ‘visually’ with Google Earth. There are several possible reasons why:

- The value of z_0 is determined by the surface between 200 and 1800 m from a 10-m wind mast, so what happens at distances > 600 m from the wind mast also plays a role.

²⁶See also: https://confluence.knmi.nl/pages/viewpage.action?pageId=85531178&spaceKey=WWO&title=Metadata%2Balle%2BAWS%2Ben%2Bincl.%2BBES%2Beilanden%2Ben%2BNoordzee&preview=%2F85531178%2F245671023%2FPositie%20en%20hoogte%20NL%20synoptische%20stations_alle_%2017_10_2025%20Nieuw%20formaat.xls

Table F.1: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for IJmuiden (225) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	mostly sea	sea (z_0 relatively large for sea)	0.002	18.78
2	sea	unclear (Gustiness $z_0 > 0.03$ m)	0.002	18.78
3	sea	unclear (Gustiness $z_0 > 0.03$ m)	0.03	18.78
4	sea	sea (z_0 closer to 0.002 m than 0.03 m)	0.002	18.78
5	mostly sea	land	0.03	18.78
6	mostly sea (quite a tall obstacle at 75 m)	land (z_0 relatively large for land)	0.03	14.38
7	mostly sea (harbour)	land	0.03	10.0
8	mostly land	land	0.03	12.0
9	land (sand and dunes 540 m from mast)	unclear (Gustiness z_0 also unclear but slightly closer to land than sea roughness)	0.03	14.38
10	mostly land (sand)	sea	0.002	18.78
11	mix sea/sand, more sand	sea	0.002	18.78
12	mix sea/sand, more sea	sea	0.002	18.78
13	sea	sea	0.002	18.78
14	sea	sea	0.002	18.78
15	sea	sea (Gustiness z_0 closer to sea than land roughness)	0.002	18.78
16	sea	unclear (Gustiness z_0 relatively large for sea)	0.002	18.78
17	sea	unclear (Gustiness z_0 relatively large for sea)	0.002	18.78
18	mostly sea	unclear (Gustiness z_0 closer to sea than land)	0.002	18.78

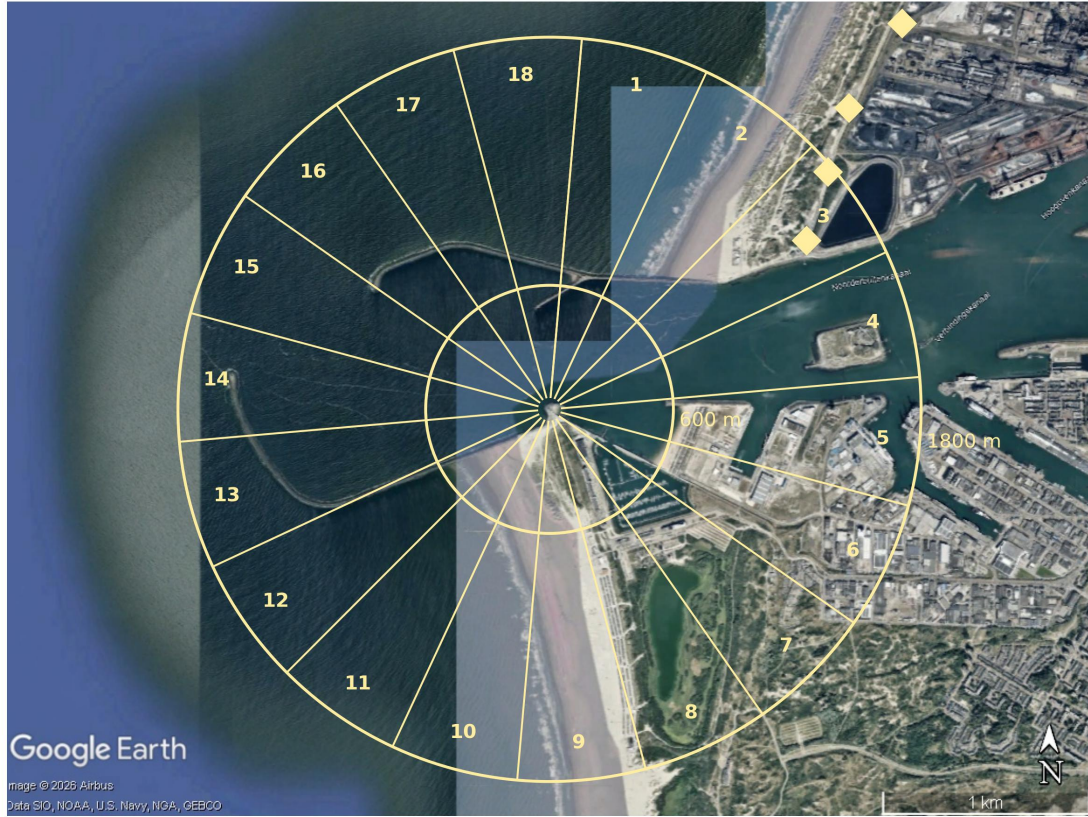


Figure F.1: Directional sectors around the wind mast at IJmuiden (225). Squares mark the positions of wind turbines.

- Sand is land, but has a roughness length (0.0003 m) much lower than that of sea (0.002 m). This explains why we chose sea roughness (closer to sand roughness than land roughness) as a reference roughness for Sectors 10–12.
- Wind turbines 1.5–3 km from the wind mast (Sectors 2–3). These wind turbines have been built after 2011 (Cibis & Cleijne, 2011) and before 23-3-2012 (Google Earth historic photos). There is an increase in Σz_0 in Sectors 2 and 3 after 2012.
- Airmass effect (convective gusts not proportional to the average wind speed) in winter may cause an overestimation of the Gustiness z_0 for NW'ly winds. We calculate higher values for Gustiness z_0 than for Sigma z_0 for Sectors 16 and 17.
- Also sensor height is not always trivial: when there are dunes close by, the sensor height should be relative to the dune tops (Sectors 7 and 8).

Sea sectors: 1, 4–5, 15 and 10–18

Sectors 10–18 and 1 are obviously sea when looking at Google Earth, but Gustiness-method values for z_0 are too high for sea in sectors 16, 17 and 1 (0.015–0.024 m). For the

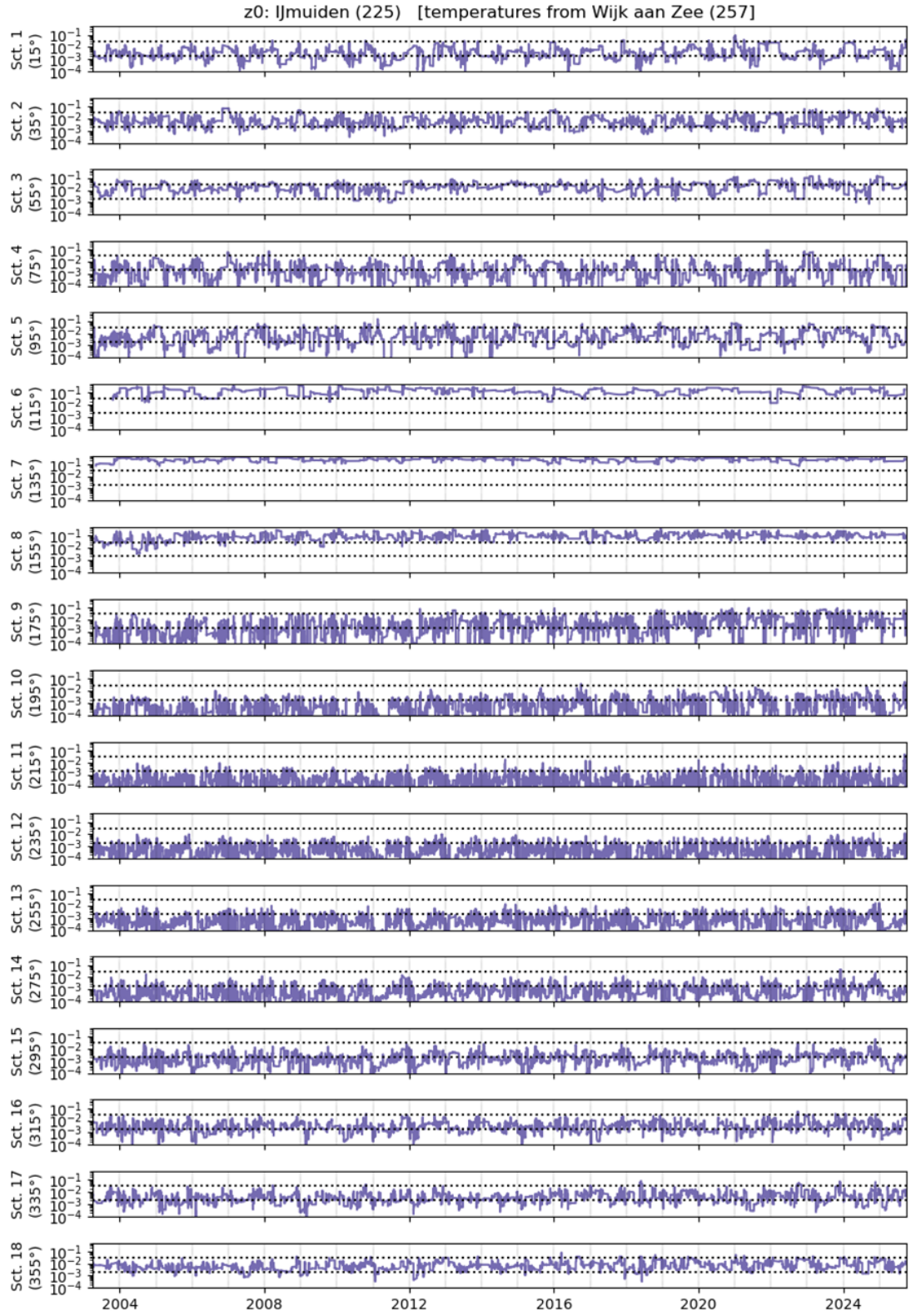


Figure F.2: Roughness length z_0 (computed with Sigma method) for IJmuiden. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).



Figure F.3: Obstacles in Sector 6 at IJmuiden: (top) pier of rocks at 280–293 m between 107–118° and (bottom) obstacle at 75 m between 110–115° (photos from Google Street View).

other sea sectors, Gustiness-method values for z_0 are below 0.005 m, except for Sectors 4, 15 and 18 (0.010-0.011 m).

Sector 5 (Gustiness $z_0 = 0.025$ m): very similar to the sea half of Sector 6 (see below). The change from rough to smooth happens at the beach huts (650 m from the mast) where we go from a kind of industrial area (estimated $z_0 = 0.3$ m) to a small stretch (20 m) of sand, then sea (estimated $z_0 = 0.002$ m). Deaves R-S (from 0.3 m to 0.002 m, 650 m) gives an IBL of 3.7 m above mean sea level at the mast and the top of the transition zone is 301 m. The sensor (at 18.78 m) is therefore low in the transition zone and should measure a z_0 closer to 0.002 m than 0.3 m. Judging from the Gustiness z_0 (0.025 m), this is the case, and a reference roughness of land (0.03 m) is more appropriate than that of sea (0.002 m). In the TZ, the value of z_0 determining the wind profile from sensor height up to the top (301 m) will increase from 0.025 m to 0.3 m. Assuming a linear increase with height, the z_0 at 60 m will be 0.040 m (we assume a z_0 of 0.03 m describes the wind profile from sensor height to 60 m well enough and we give more weight to z_0 in the lower part of the profile because that is where the wind changes most). In that case, ECF is underestimated by 0.4 %, which is below the uncertainty of the method (5 %).

Land sectors: 3 and 6–8

Sector 8 is the only one filled with land from close to the mast out to 1800 m, but Gustiness z_0 is rougher than the grass reference z_0 (> 0.03 m) for Sectors 2–3 and 6–8. For Sector 7, the Gustiness z_0 is the highest (0.341 m) due to dunes that start only 70 m from the mast. For Sector 7 and 8 we use a measurement height relative to the dune tops, 10 and 12 m respectively (see below):

Sector 3: Gustiness z_0 probably > 0.03 m because of the dunes and wind turbines closer than 1800 m from the wind mast. Sigma z_0 for Sector 3 definitely closer to land reference z_0 (0.03 m) than to sea reference z_0 (0.002 m), but more unclear for Sector 2. Because the first 600 m from the wind mast is sea, we take the height relative to the sea (18.78 m). Note that two of the wind turbines are closer than 20 times the rotor diameter (which is 90 m), so an influence of their wake on the wind measurements cannot be ruled out (see Fig. F.1).

Sector 6 (Gustiness $z_0 = 0.177$ m) is complicated: half is like Sector 5 and the other half like Sectors 7 and 8 combined:

- Half of Sector 6 is like Sector 5 (with Gustiness $z_0 = 0.025$ m): sea out to 630 m from the mast and then land (rows of beach huts at 650 m, then the Felison cruise terminal with big car park, then a lot of harbour buildings) out to 1800 m from the wind mast and even further. The sensor measures low in the transition zone and should measure a z_0 closer to 0.002 m than 0.3 m (see explanation Sector 5).
- Half of Sector 6 is like Sector 8 (with Gustiness $z_0 = 0.192$ m), but with fewer and lower dunes (starting 110 m from the mast and extending to 210 m from the mast; height dunes only 1 m higher than the height of the pier the mast stands on, so we do not need to lower the measurement height, but can keep it 14.4 m above land), but also like Sector 7 (with Gustiness $z_0 = 0.341$ m) with the effect of Marina Seaport starting 260 m from the mast. To get an average z_0 for Sector 6 of 0.177 m (Gustiness z_0) when we expect half of Sector 6 to have a z_0 of 0.025 m, this half of the sector should have a z_0 of 0.329 m ($0.177 \text{ m} = (0.025 + 0.329)/2$). This value seems a bit large compared to Sector 8 ($z_0 = 0.192$ m) with far more dunes with similar heights. However, below we argue for Sector 7 that the Gustiness z_0 should be used despite it being larger than expected compared to Sector 8. The same argument applies to Sector 6 because it also contains dunes and harbour like Sector 7. Therefore, we accept $z_0 = 0.329$ m for this half of Sector 6 (gives an average z_0 equal to the Gustiness z_0 for the whole Sector 6).

Sector 7: has the highest dune tops (7.4–9.5 m +NAP from AHN) and close to mast (from 70 m), so sensor height relative to these dune tops is 9.3–11.4 m (18.78 m+NAP minus 9.5 m+NAP and 18.78 m+NAP minus 7.4 m+NAP, respectively), so we use the average (10 m) as sensor height for Sector 7. IBL calculation is tricky: dunes to sand is easy because distance from the dunes to the mast is so short (70 m) that the IBL height at the location of the mast (Deaves R-S 0.341 m to 0.0002 m, 70 m) is far below sensor height (12 cm). The transition zone height is 83 m. However, behind the dunes, the large Marina Seaport extends from 270 m to 840 m from the mast with z_0 varying from 0.002 m when empty to 0.1 m (we estimate) when full of ships. Deaves S-R (0.002 m or

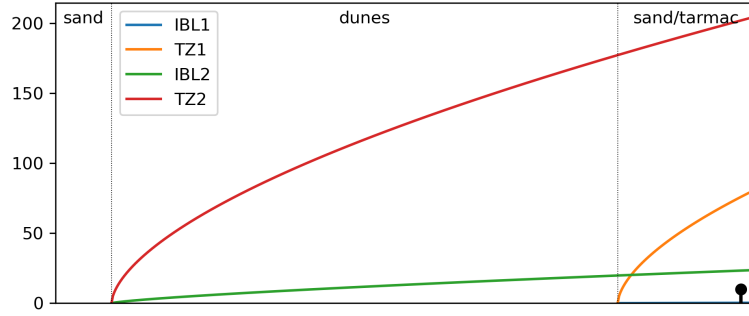


Figure F.4: Illustration of the IBL and TZ heights in Sector 9 at IJmuiden. Note that IBL1 is barely visible because it is only 25 cm high at the wind mast (right). Distances and heights are true to scale.

0.1 m to 0.341 m, 270 m) gives IBL of 18.3 m above the dune tops, so about 8 m above the sensor. So, the first analysis says the profile up to 60 m starts with $z_0 = 0.341$ m and gets even rougher (combined roughness dunes and harbour 0.341 m, so roughness dunes probably higher than 0.341 m) and the second says from 8 m above the sensor the profile is determined by a z_0 that decreases with height. In conclusion: we use z_0 as calculated with the Sigma method, which is 0.143 m (averaged over 2020–2025 — though no big changes over time in this sector — and assuming sensor height 10 m) since the IBL analysis gives contradictory results.

Sector 8 ($z_0 = 0.192$ m): dunes are 2 m lower than those of Sector 7 (so about 6 m). Therefore, we use $z_m = 12$ m. The dunes extend far in this direction, so no IBL analysis required.

Land or sea (?) sectors: 2 and 9

Sector 2: Gustiness $z_0 > 0.03$ m, but Sigma z_0 bounces between 0.002 m (sea) and 0.03 m (land). However, this sector is more than half sea up to 1800 m from the wind mast (Google Earth), so we take a sea $z_{0,\text{ref}}$ and height above sea.

Sector 9: Gustiness $z_0 = 0.019$ m which indicates neither sea nor land, but is a little closer to 0.03 m (land) than 0.002 m (sea). Furthermore, there are dunes which start about 100 m from the mast and extend out to 500 m from the wind mast, so the first 600 m is mostly land with a fairly high roughness length. Sector 9 dunes are 2 m lower than for Sector 8 (so about 4 m high) and are just as high as the pier on which the wind mast stands. We therefore use the standard sensor height above land (14.38 m). There are 2 roughness changes affecting Sector 9 (see Fig. F.4): one from dunes to sand/concrete at about 100 m from the wind mast (referred to as IBL1 and TZ1) and one from sand to dunes at about 500 m from the wind mast (IBL2 and TZ2):

- **IBL1/TZ1:** The dunes start at 88 m (165°) to 115 m (184°) from the wind mast. We assume that the roughness of the dunes equals 0.192 m (which is the Gustiness z_0 that we get for Sector 8 which is only affected by dunes). Deaves R-S (from dunes with $z_0 = 0.192$ m to concrete/sand with $z_0 = 0.0003$ m, $x = 88$ m) gives an

IBL1 height of 25 cm (far below sensor height) and the top TZ1 at 76 m. Based on this, we expect that in the layer between sensor height and 60 m, the value of z_0 that determines the change of speed with height increases from 0.019 m (z_0 calculated with Gustiness method) to nearly 0.192 m (z_0 dunes).

- **IBL2/TZ2:** However, there is another roughness change to consider at 450-560 m from the mast, where the dunes give way to the beach. Deaves S-R (from sand [0.0003 m] to dunes [0.192 m], $x = 450$ m) gives an IBL2 height of 23.3 m above the dune tops and 8.9 m above the sensor (23.3–14.38 m). The top of TZ2 is at 202 m.
- Combining the two IBLs, we get a wind speed profile that at sensor height (14.38 m) is determined by the Gustiness method z_0 (0.019 m). Below IBL2 (23.3 m) z_0 should be 0.192 m (roughness of dunes), but it is in fact smaller because 14.38 m lies within TZ1, where the roughness length increases with height from 0.0003 m at 25 cm up to 0.192 m at 76 m. So, TZ1 appears to be dominant at 14.38 m and the z_0 determining the profile should continue to increase with height up to the height of IBL2 (23.3 m). In the lowest 14 m of TZ1 the determining z_0 has increased by about 0.019 m (0.019–0.0003 m). How much will it increase in the next 9 m up to 23.3 m height? By $0.019 \times (9/14) = 0.012$ m if the change is linear, giving a determining z_0 of 0.031 m at height 23.3 m. The layer above this, between 23.3 and 76 m, lies both in TZ1 (roughness increasing with height) and TZ2 (roughness decreasing with height), so we assume the net effect is that the roughness determining the profile in this layer does not change much with height. So, between 14.32 m and 60 m height a z_0 of 0.031 m determines the wind speed profile at most heights.
- In that case, the ECF is underestimated by 1.3 %, which is below the uncertainty of the method (5 %).

F.3. Texelhors (229)

At Texelhors (229), Sectors 1–4 and 18 are clearly land directions for which $z_{0,\text{ref}} = 0.03$ m and $z_m = 11.5$ m (height relative to land). For the remaining sectors (5–17), there is mainly sand ($z_0 \approx 0.0003$ m) up to 600 m from the wind mast where it is better to use the sea $z_{0,\text{ref}}$ than the land $z_{0,\text{ref}}$ (0.002 m instead of 0.03 m). Also because beyond those 600 m there really is sea and roughness lengths calculated from the wind measurements are affected by surfaces up to 1800 m from the wind mast (effect largest at 600 m).

The distance to the coast is less than 600 m for sectors 10–15 and more than 600 m for sectors 5–9 and 16–17. However, for all these sectors (5–17), the sensor is measuring in the IBL (Section C) and we should therefore take z_m as the height relative to the land (11.5 m).

For the comparison of the Gustiness and Sigma method, it is relevant that (see also Table B.1):

- $z_{0,\text{ref}}$ has been assumed 0.03 m for all directions for the 2013 update of the potential wind (different from sectors 5-17 now) and that the recommendation was to change

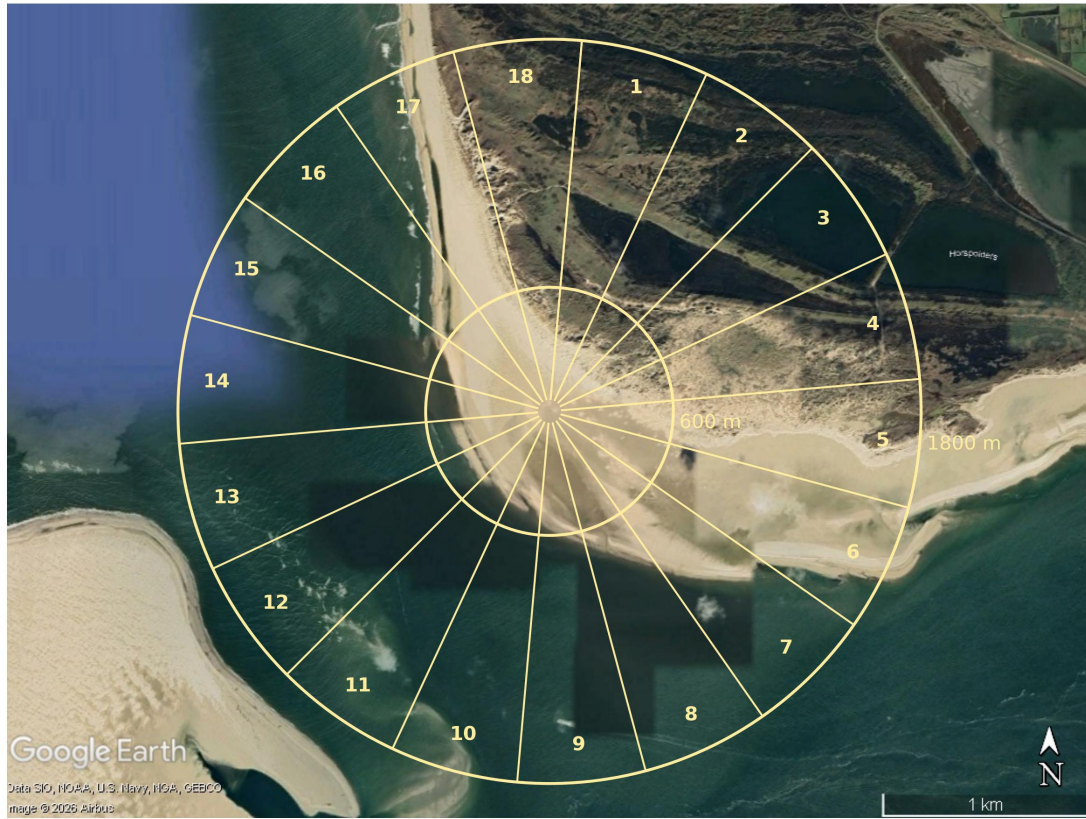


Figure F.5: Directional sectors around the wind mast at Texelhors (229).

that (Stepek & Wijnant, 2013).

- $z_{0,\text{ref}}$ has been assumed 0.002 m for all directions for the 2020 update of the potential wind (different from sectors 1-4 and 18 now). The WIKLI period (01-03-1969–31-12-1974; the earliest set of ECFs) was converted manually from $z_{0,\text{ref}}$ of 0.03 m to 0.002 m by multiplying the existing ECFs by 1.081.
- Both for the 2013 and the 2020 potential wind update, the height was assumed 11.5 m.

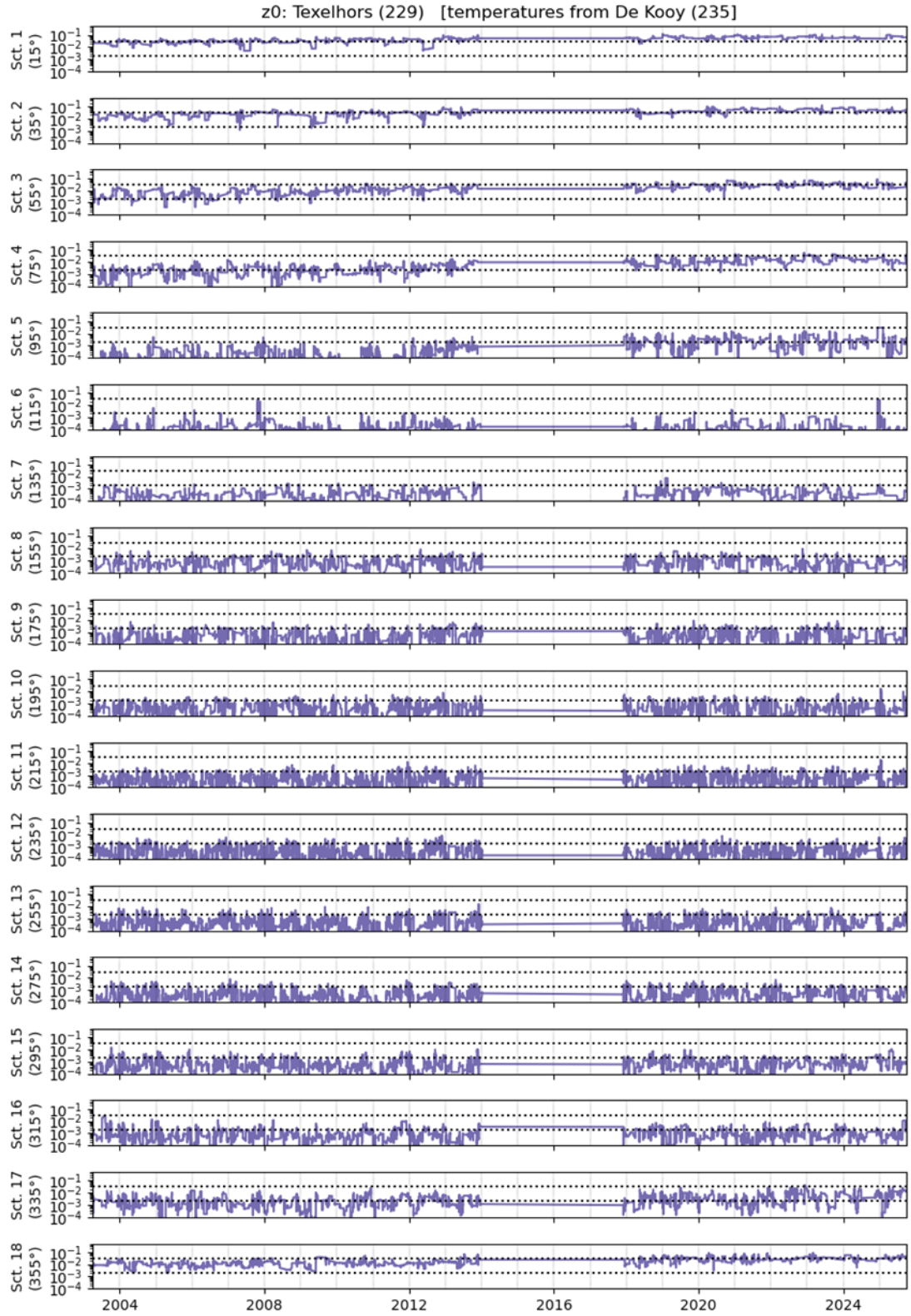


Figure F.6: Roughness length z_0 (computed with Sigma method) for Texelhors. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness). Data retrieval from Texelhors was stopped on 06-01-2014 because of planned financial cuts but resumed from 05-12-2017 (horizontal line should not be interpreted as a constant value of z_0).

Table F.2: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Texelhors (229) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	land (sand and dunes)	land	0.03	11.5
2	land (sand and dunes)	land	0.03	11.5
3	land (sand and dunes)	land	0.03	11.5
4	land (sand and dunes)	land	0.03	11.5
5	land (sand and dunes)	sea	0.002	11.5
6	land (sand)	sea	0.002	11.5
7	land (sand)	sea	0.002	11.5
8	land (sand)	sea	0.002	11.5
9	land (sand and dunes)	sea	0.002	11.5
10	mostly land (sand)	sea	0.002	11.5
11	mostly land (sand)	sea	0.002	11.5
12	mostly land (sand)	sea	0.002	11.5
13	mostly land (sand)	sea	0.002	11.5
14	mostly land (sand)	sea	0.002	11.5
15	mostly land (sand)	sea	0.002	11.5
16	land (sand)	sea	0.002	11.5
17	land (sand)	unclear	0.002	11.5
18	land (sand and dunes)	land	0.03	11.5



Figure F.7: Directional sectors around the wind mast at De Kooy (235). Squares mark the positions of wind turbines.

F.4. De Kooy (235)

At De Kooy (235), the wind mast was moved by 120 m on 11-01-2001 according to KNMI metadata (from the old KNMI department KS-KA1). The earliest inspection report in the KNMI metadata is from 01-04-2004, but it contains no relevant information except that there were complaints of northerly wind speeds being too low. There are wind turbines about 1.8 km north of the wind mast (Fig. F.7), but they are too low to have an effect on the measurements.

Up to 600 m from wind mast all land. Elevation land at location wind mast: 1 m +NAP. The height of the wind mast is 10 m above the surrounding terrain, so the wind sensors are mounted at 10 m above land for wind directions from land (no wind direction from sea).

F.5. Vlieland Vliehors (242)

Vlieland Vliehors (242) is surrounded by land (in all directions more than 600 m from the sea). However, in this case “land” is sand with a low surface roughness for a land site (0.0003 m).



Figure F.8: Directional sectors around the wind mast at Vlieland Vliehors (242).

Elevation of the land at location wind mast according to SAIS:²⁷ 1,43 m above NAP/MSL. Wind mast mounted on a concrete block of 1.5 m. Sensor height therefore $1.43 + 1.5 + 10 = 12.93$ m above MSL/NAP. There is a complication with the measurement height because the ground elevation S-SE of the wind mast is higher (on average 2 m higher at more than 20 m from the wind mast). This means that from that direction the height of the sensor relative to the ground is 2 m lower (9.5 m). Comparing ECFs for 9.5 m and 11.5 m height (sand roughness going up to 60 m and sea roughness going down), the difference is 2 % (overestimation), so not significant.

As the distance to the coast is more than 600 m for all wind directions, Verkaik's rule of thumb (Section C) suggests that the height of the sensor should be the height relative to the land. This also follows from calculating the height of the IBL from sea to sand (z_i RS; see Section C): We always measure in the IBL as long as the sensor is measuring below 16 m ($z_m < 16$ m) because for $x > 600$ m, $z_i > 16$ m. Because the wind mast is more than 600m from the sea in any direction, the sensor always measures in the IBL and the measurement height should be taken relative to the ground for all wind directions.

In that case, the ECF is underestimated by at most 2,8 %, which is well within the uncertainty of the method (5 %).

²⁷ *ruimtelijk inspectierapport Vlieland 20250702*

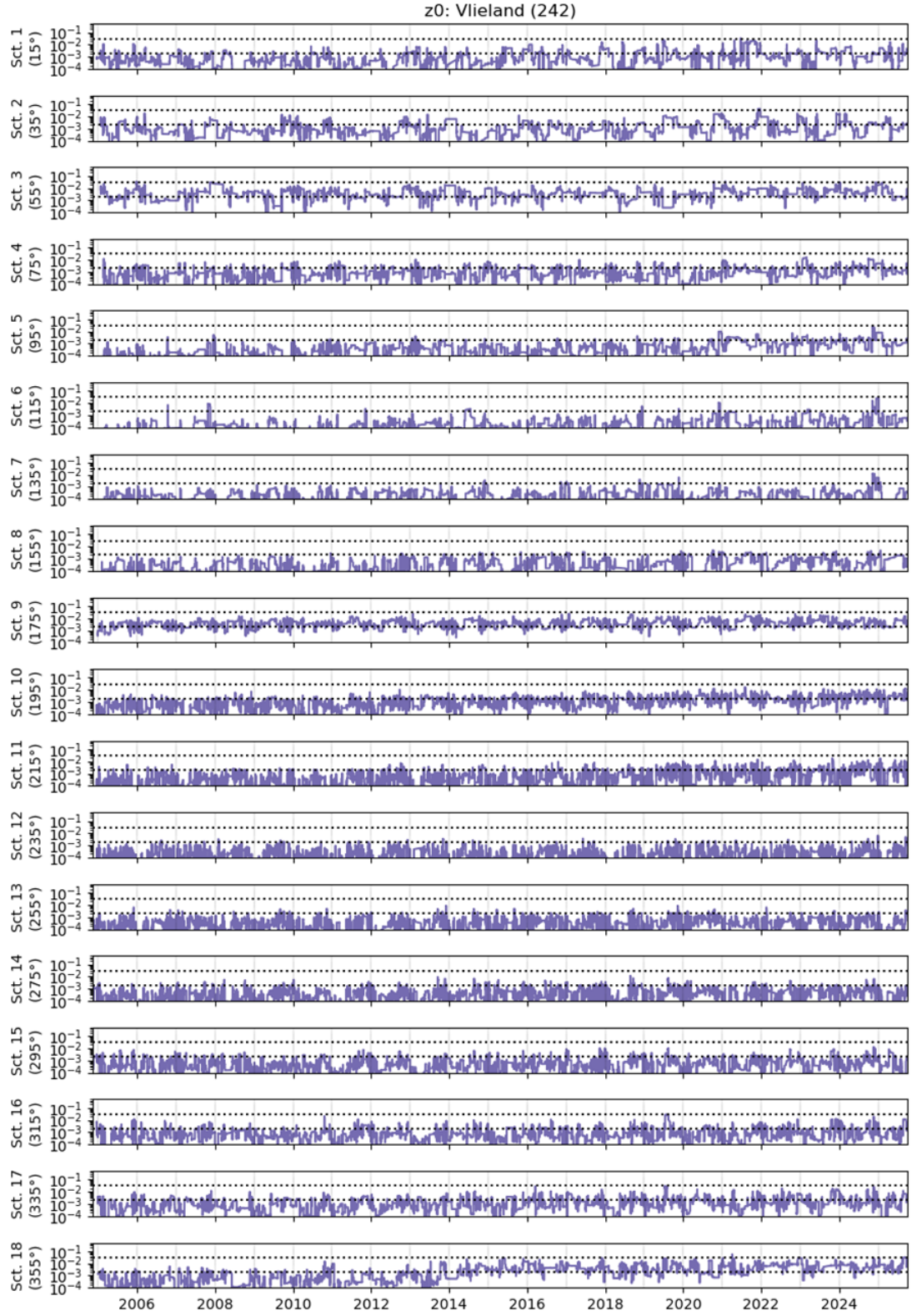


Figure F.9: Roughness length z_0 (computed with Sigma method) for Vlieland Vliehors. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).

Table F.3: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Vlieland Vliehors (242) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	land (sand)	sea	0.002	11.5
2	land (sand)	sea	0.002	11.5
3	land (sand)	unclear	0.002	11.5
4	land (sand)	sea	0.002	11.5
5	land (sand)	sea	0.002	11.5
6	land (sand)	sea	0.002	11.5
7	land (sand)	sea	0.002	11.5
8	land (sand)	sea	0.002	11.5
9	land (sand)	unclear	0.002	11.5
10	land (sand)	unclear	0.002	11.5
11	land (sand)	unclear	0.002	11.5
12	land (sand)	sea	0.002	11.5
13	land (sand)	sea	0.002	11.5
14	land (sand)	sea	0.002	11.5
15	land (sand)	sea	0.002	11.5
16	land (sand)	sea	0.002	11.5
17	land (sand)	unclear	0.002	11.5
18	land (sand)	unclear	0.002	11.5

Because we are dealing with sand ($z_0 \approx 0.0003$ m), it is better to use the sea reference roughness than the land reference roughness ($z_{0,\text{ref}} = 0.002$ m instead of 0.03 m). Most of the ECFs based on the Sigma method confirm this, as do the Gustiness ECFs (not shown, but the value of z_0 is 0.001-0.004 for 12 of the 18 wind direction sectors and between 0.006 and 0.021 m for the other 6 wind direction sectors).

For the comparison of the Gustiness and Sigma method, it is relevant that (see also Table B.1):

- $z_{0,\text{ref}}$ has been assumed 0.03 m for all directions for the 2013 update of the potential wind (different from all sectors now).
- $z_{0,\text{ref}}$ has been assumed 0.002 m for all directions for the 2020 update of the potential wind (same as all sectors now).
- For the 2013 potential wind update height was assumed 10 m, for 2020 potential wind update 13 m (now 11.5 m).

The z_0 calculated for the 2020 update were closer to 0.002m than 0.03m, except for the z_0 of Sector 18 after the double mounting was installed on 26-09-2013. The ECF of Sector 18 increased by an insignificant 0.04 to become 1.022 after the installation because the anemometer providing the official measurements was in the wake of the second anemometer on the double mounting. However, 1.022 was rejected due to the

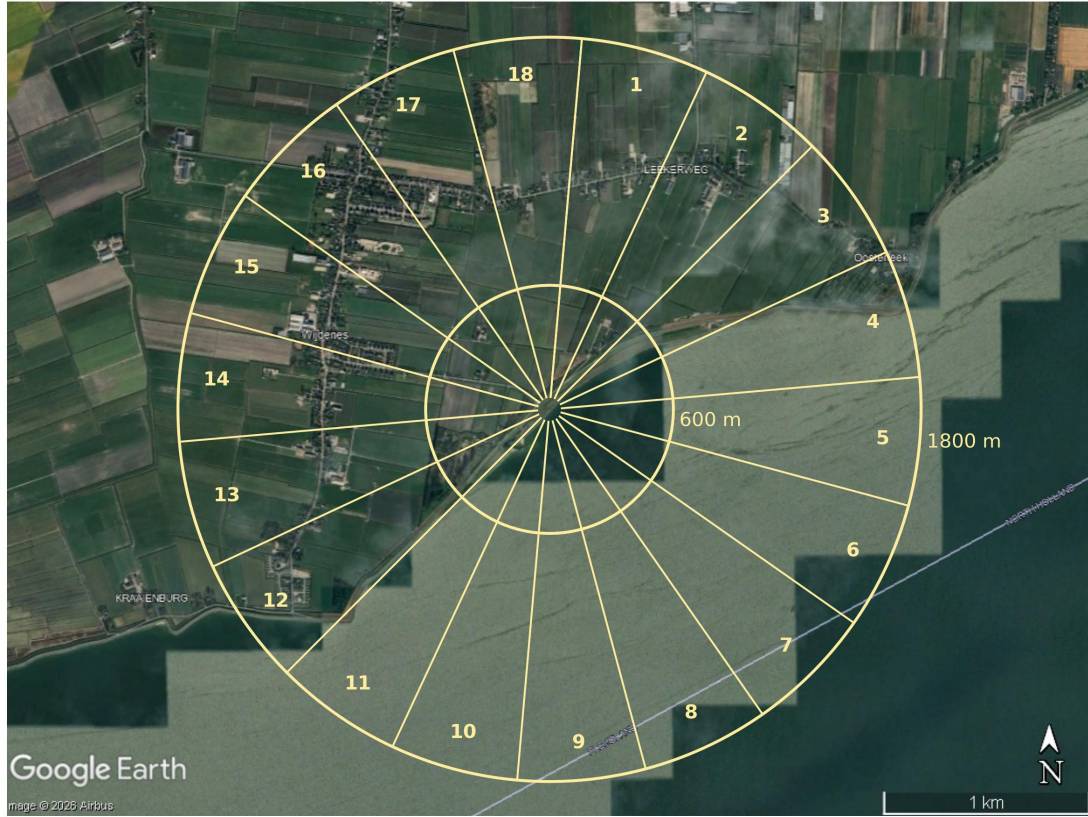


Figure F.10: Directional sectors around the wind mast at Wijdenes (248).

wake effect and instead the ECF of the period before the double mounting (0.982) was multiplied by 1.12 (giving $ECF = 1.100$) to correct for the lower speed caused by the wake (see Section B.2).

F.6. Wijdenes (248)

The land elevation at the site of the wind mast is 0.8 m above mean sea level at the site of the wind mast (SAIS: source AHN). However, there is a dam of 3 m high nearby (at less than 100 m for wind directions between 250° and 27° (sector 1 and 14–18), but this dam does not affect the measurement height of $z_m = 10$ m.

Definitely sea up to 600 m from the wind mast between 59° and 199° (Sectors 4–10) and mostly sea between 199° and 224° (Sector 11). Sector 3 (45° – 64°) is half sea (55° – 64°) and half land (45° – 55°) up to 600 m (with for the “sea half” there is land beyond 600 m). Other sectors land.

- **Sector 3:** the Sigma z_0 values bounce from sea to land roughness (Fig. F.11), which is what one would expect with a sector half affected by sea and half by land (up to 600 m) and is on average 0.0148 m. At 600–1800 m from the mast, there is also some land for wind directions 55° – 64° . Gustiness ECF 0.983, which is unclear, but closer to what you would expect for land than for water, so we chose a land

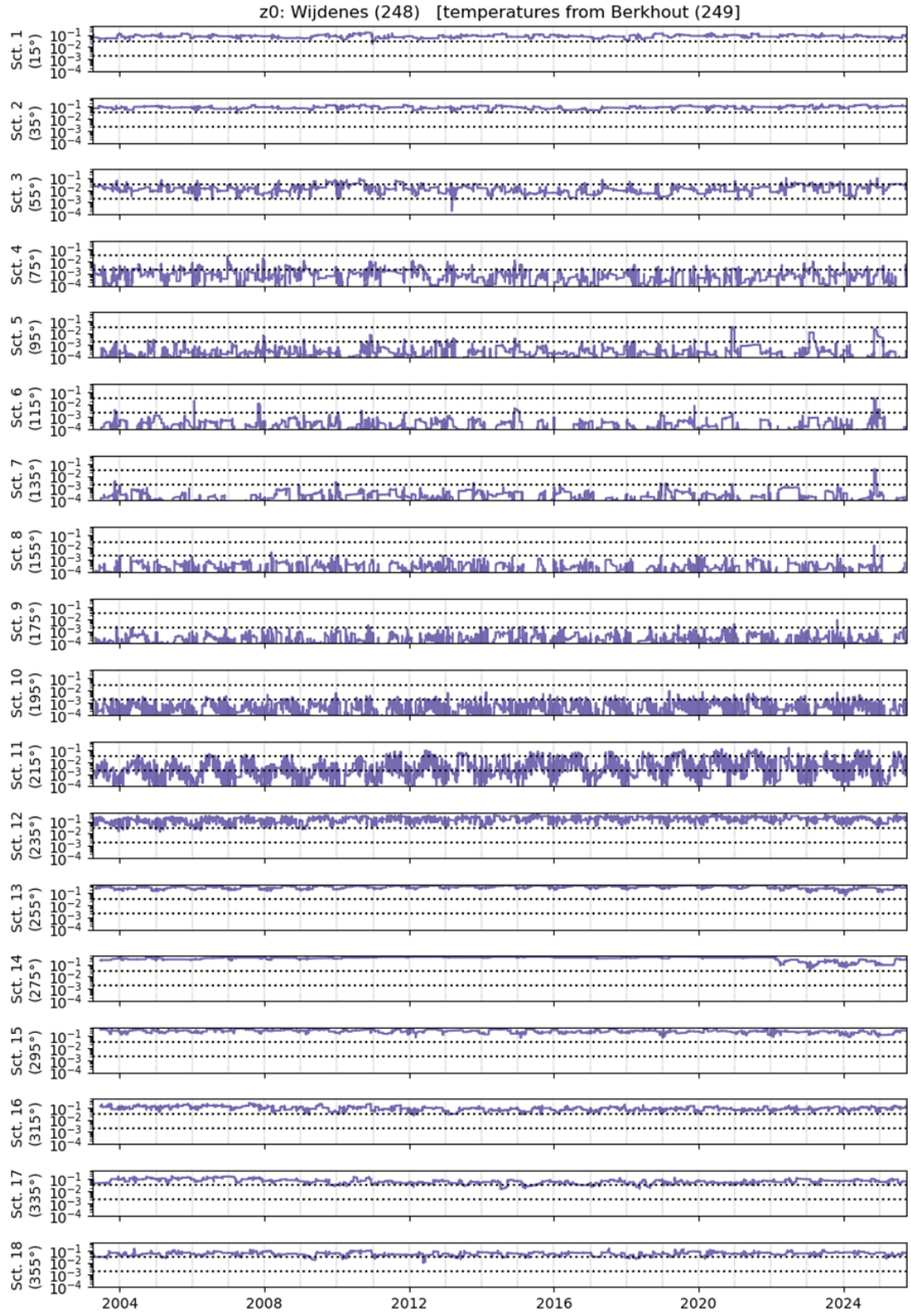


Figure F.11: Roughness length z_0 (computed with Sigma method) for Wijdenes. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).

Table F.4: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Wijdenes (248) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	land	land	0.03	10.0
2	land	land	0.03	10.0
3	land/sea	varies (mean slightly closer to land)	0.03	10.0
4	sea	sea	0.002	10.8
5	sea	sea	0.002	10.8
6	sea	sea	0.002	10.8
7	sea	sea	0.002	10.8
8	sea	sea	0.002	10.8
9	sea	sea	0.002	10.8
10	sea	sea	0.002	10.8
11	mostly sea	unclear (mean closer to sea value)	0.002	10.8
12	land	land	0.03	10.0
13	land	land	0.03	10.0
14	land	land	0.03	10.0
15	land	land	0.03	10.0
16	land	land	0.03	10.0
17	land	land	0.03	10.0
18	land	land	0.03	10.0

reference roughness.

- **Sector 4–10:** Gustiness ECFs < 0.93 (z_0 not available) what you expect for water, so this confirms that these are sea sectors.
- **Sector 11:** Gustiness ECF 0.963 (z_0 not available), which is unclear, but closer to what you would expect for land than for water. Sector 11 is almost entirely water, also for 600–1800 m from the mast but at a bit more than 200 m there is a small harbour with 2 dams crossing the sector (Fig. F.12). Maybe that generates enough turbulence to raise the measured z_0 above that of water. Also, the last few degrees of Sector 11 are land up to 600 m from the mast, so when the wind blows from this direction a higher z_0 would be measured. Sigma z_0 values show this in the way that they are often below 0.002 m and only rarely above 0.03 m (mean value 0.0071 m, so closer to sea value). Based on this, we chose to make Sector 11 a sea rather than a land sector.
- **Sector 12–18 and 1–2:** Gustiness ECFs ≥ 1 (what you expect for land) so this confirms that these are land sectors. The 3 m high dam does not affect the Gustiness ECFs significantly. One would expect the effect to be strongest for the sector where the dam is closest to the mast (Sector 16), but that is not the case: Sectors 12–15 have higher Gustiness ECFs. That can be explained by the woods



Figure F.12: Small pier and some trees (at about 268 m) in Sector 11 at Wijdenes (photo from Google Street View).

affecting those sectors. To the other side (Sectors, 17, 18, 1 and 2) the ECFs are lower, but only for Sectors 18 and 2 significantly lower.

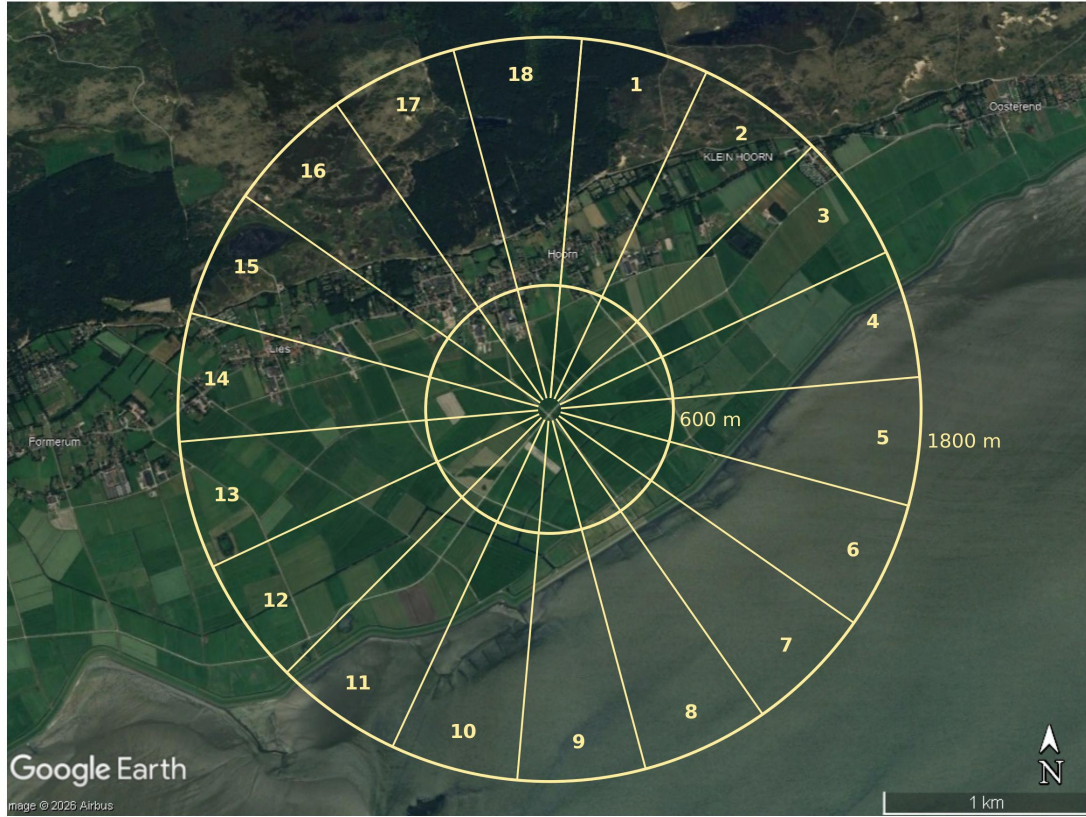


Figure F.13: Directional sectors around the wind mast at Terschelling-Hoorn (251).

F.7. Terschelling (251)

Terschelling-Hoorn (251) is surrounded by land (more than 715 m from the Wadden Sea and even further from the North Sea). However, for wind direction sectors 4–10, the Waddenzee seems to have a clear effect on the values of z_0 : Both z_0 values based on the Sigma method (Fig. F.14) and on the Gustiness method suggest that taking $z_{0,\text{ref}} = 0.002$ m (sea) is better than taking 0.03 m (land) for these sectors. Sectors 11 and 12 show a roughness based on Sigma ECFs that is not clearly that of sea or land. However, the roughness based on the Gustiness ECFs of sector 11 (0.012 m) is closer to that of sea and the roughness based on the Gustiness ECFs of sector 12 (0.018 m) closer to that of land. Thus, we take $z_{0,\text{ref}} = 0.002$ m for Sector 11 and $z_{0,\text{ref}} = 0.03$ m for Sector 12.

Klapmast with wind sensors at 10 m height. Elevation 0.73 m above NAP, so for wind directions from the Waddenzee (Sectors 4–10) $z_m = 10.73$ m. However, the closest distance to the Waddenzee is 715 m. At that distance the height of the IBL from sea to land (Deaves S-R formula) is 20.7 m, so the sensor measures below the IBL and we should select the height relative to the ground (10 m). In that case, the ECF is overestimated by 3.7 %, which is below the uncertainty of the method (5 %).

For the comparison of the Gustiness and Sigma method, it is relevant that (see also

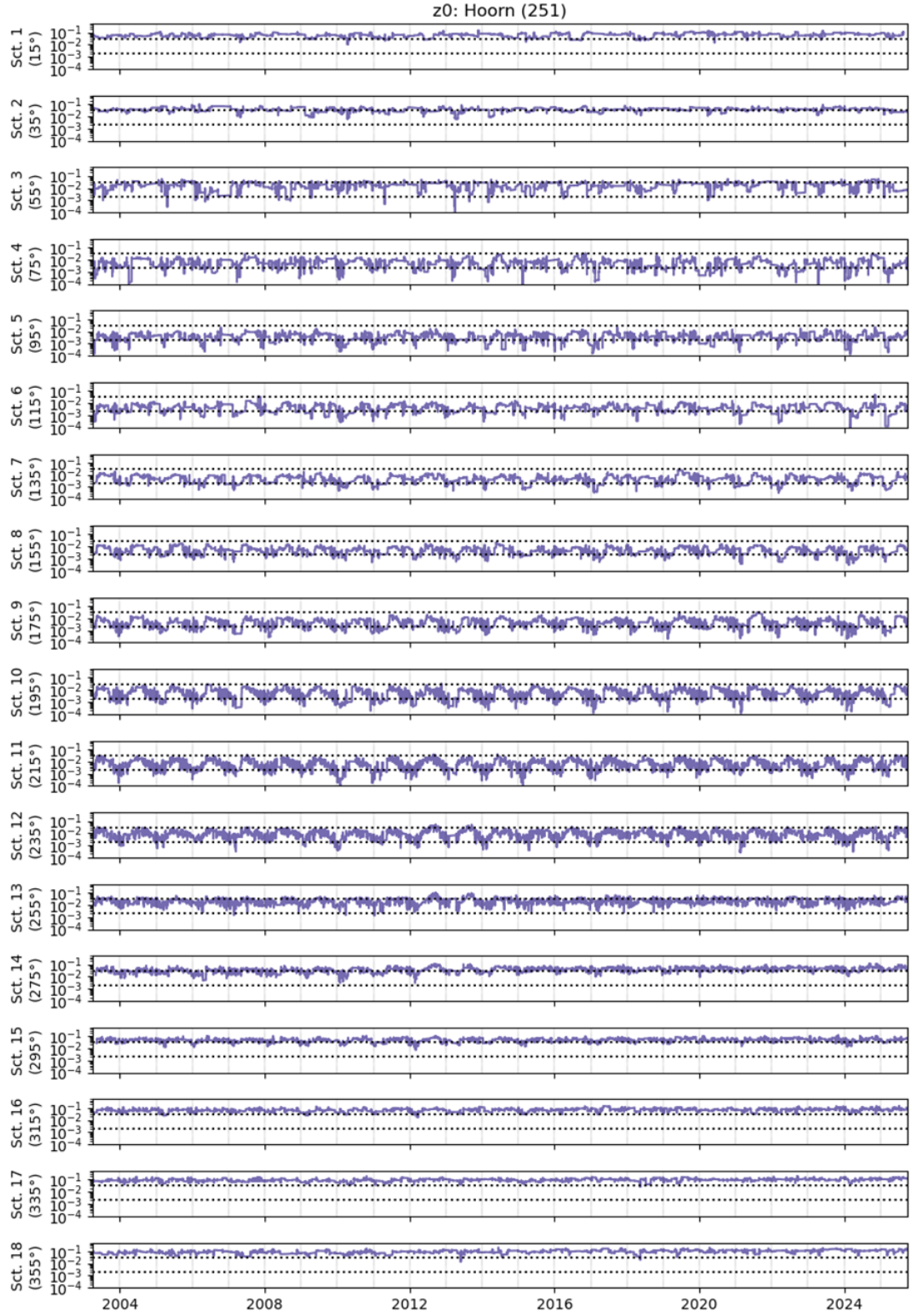


Figure F.14: Roughness length z_0 (computed with Sigma method) for Terschelling-Hoorn. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).

Table F.5: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Terschelling-Hoorn (251) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	land	land	0.03	10.0
2	land	land	0.03	10.0
3	land	land	0.03	10.0
4	land (Wadden Sea)	unclear	0.002	10.0
5	land (Wadden Sea)	unclear	0.002	10.0
6	land (Wadden Sea)	unclear	0.002	10.0
7	land (Wadden Sea)	unclear	0.002	10.0
8	land (Wadden Sea)	unclear	0.002	10.0
9	land (Wadden Sea)	unclear	0.002	10.0
10	land (Wadden Sea)	unclear	0.002	10.0
11	land	unclear	0.002	10.0
12	land	unclear	0.03	10.0
13	land	land	0.03	10.0
14	land	land	0.03	10.0
15	land	land	0.03	10.0
16	land	land	0.03	10.0
17	land	land	0.03	10.0
18	land	land	0.03	10.0

Table B.1):

- $z_{0,\text{ref}}$ has been assumed 0.03 m for all directions for the 2013 and the 2020 update of the potential wind (different from 4-11 sectors now).
- Both for the 2013 and 2020 updates, height was assumed 10 m (same now).

F.8. Houtribdijk (258)

Houtribdijk is a dam between Markermeer and IJsselmeer. Sensor height is 17.25 m (10-m wind mast on a 7.25 m high dam). The dam represents less than one wind direction sector (rest surrounded by water) and the ECFs in sectors where the dam is present are not significantly different from the other sectors. That is why we consider Houtribdijk a sea station. Nonetheless, Houtribdijk should be included in the Sigma potential wind update because no Benschop correction is applied operationally.

F.9. Stavoren (267)

At Stavoren (267), there is a *klapmast* (before 24-11-2010: *klimmast*) with wind sensors at 10 m height. The Stavoren wind mast is surrounded by land, but between 313° and 356° (mainly Sector 17), the IJsselmeer is just less than 600 m away. There are no z_0 values computed with the Sigma method, but the z_0 values computed with the Gustiness



Figure F.15: Directional sectors around the wind mast at Stavoren (267).

method are all between 0.03 m and 0.10 m (land roughness) except for Sectors 8, 9 and 17 (0.02 m).

For Sector 17, the Deaves SR formula (Section C) gives an IBL height of 18.2 m (smooth: 0.002 m, rough: 0.03 m, distance: 600 m). So, the measurement (below 18.2 m) is adapted to land roughness, but a large part of the profile from 18.2 m to 60 m is in the transition zone (top transition zone according to Deaves: 114.2 m) and is determined by a z_0 between 0.02 m (measured at 10 m) and 0.002 m.

The error in ECF we make by assuming $z_0 = 0.02$ m on the way up to 60 m (whereas this value should be lower — we assume 0.015m — for most of the layer between 18.2 and 60 m) is an overestimation of about 1 % which is below the 5 % uncertainty of the method and therefore insignificant.

F.10. Lauwersoog (277)

The wind mast is on a *strekdam* (Fig. F.16) of 4.87–4.97 m (Google Earth/AHN) above sea level (which is about 1 m higher than suggested by Verkaik (2001a)). The ground at the AWS is 2.80–2.85 m +NAP.

- For Sectors 5–9: the same as Sectors 10 and 11 except that the extent of the land



Figure F.16: Situational photo of the wind mast (left) at Lauwersoog (277).

near the mast is shorter, so the effective measurement height is 14.0 m instead of the 13.5 m of Sectors 10 and 11.

- For Sector 10 and 11: the first 60 m, respectively 70 m, from the mast is land with a height varying from +0.5 to +5.0 m +NAP (AHN). If we assume the most representative (median) height to be 3 m +NAP, then we get a measurement height of +12 m. However, 60–70 m (above land) is a relatively short distance compared to the hundreds of metres that the air has travelled above sea (and the sensor measures in the TZ from sea to land), so in this case we take the average of the height above land and the height above sea: 13.5 m.
- For Sector 12: the first 500–545 m from the mast is land with a height varying from +0.5 to +7.2 m +NAP (AHN). If we assume the most representative (median) height to be 4 m +NAP, then we get a measurement height of +11 m.
- For Sector 13: the first 185–500 m from the mast is land with a height varying from +3.0 to +8.5 m +NAP (AHN). If we assume the most representative (median) height to be 5m +NAP, then we get a measurement height of +10 m.
- For Sector 14: the first 90–200 m from the mast is land with height varying from +0.5 to +5.8 m +NAP (AHN). If we assume the most representative (median) height to be 4 m +NAP, then we get a measurement height of 11 m. However, as in Sector 11 the distance over land is relatively short compared to that over sea, but longer than in Sector 11, so we take the measurement height to be a little higher: 12 m.

Definitely sea between 272° and 97° (Waddenzee, so part of time sand!) which is Sectors 1–4 and 15–18 and half of Sector 14. Sector 5 (85–104°) is mostly sea up to 600 m (but land and two silos and a building beyond). Mostly land between 214° and 249° (Sector 12 and half of Sector 11). Harbour between 214° and 98° (half of Sector 6 and 11 and

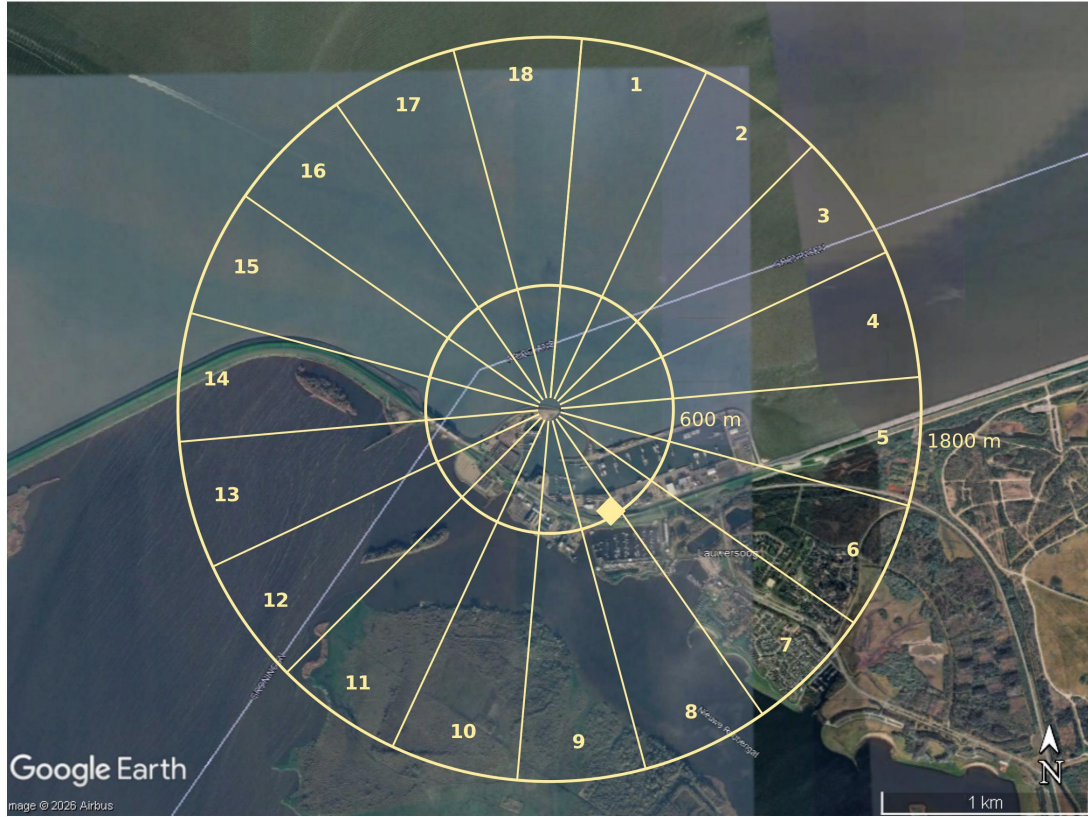


Figure F.17: Directional sectors around the wind mast at Lauwersoog (277). The square marks the position of a wind turbine.

Sectors 7-10). Looking closer at Sector 6, it is actually mostly harbour and therefore considered mostly sea (unless maybe if there are a lot of ships moored). Mostly water between 249° and 272° (Sector 13 and Sector 14).

Sector 5: mostly sea, but land beyond 1-2 km (bushes and small trees, so z_0 estimated as 0.2 m) and for part of the sector (between 92° and 100°) there is a small area of silos and a building at 860-885 m. That is probably why Sigma z_0 varies between land and sea roughness. The Gustiness z_0 is 0.019 m (very slightly closer to land than sea roughness). Deaves R-S (from 0.2 to 0.002 m, $x = 1400$ m) gives an IBL height of 9.8 m. So, the sensor (at 14 m) measures in the TZ. At 9.8 m, $z_0 = 0.002$ m and at 14 m the Gustiness $z_0 = 0.019$ m, so in the TZ z_0 increases with 0.017 m ($= 0.019 - 0.002$) in 4.2 m ($= 14 - 9.8$), which is 0.004 m per meter height. The estimate for the lower quarter of the profile between 14 and 60 m, is the average of z_0 at 14 m and z_0 at 25.5 m ($= 14 + (60 - 14)/4$), which is the average of 0.019 m and 0.066 m ($0.019 + 11.5 \times 0.004$): 0.042 m. When using z_0 of 0.019 m for the whole profile up to 60 m instead of our best estimate of 0.042 m, we underestimate the ECF with 2.3 %, which is below the 5 % uncertainty of the method.

Sector 6-8 and 10: The Sigma method clearly gives a roughness closer to land than to sea for Sectors 6-8 and 10 (harbour). Only an empty harbour without ships will give a

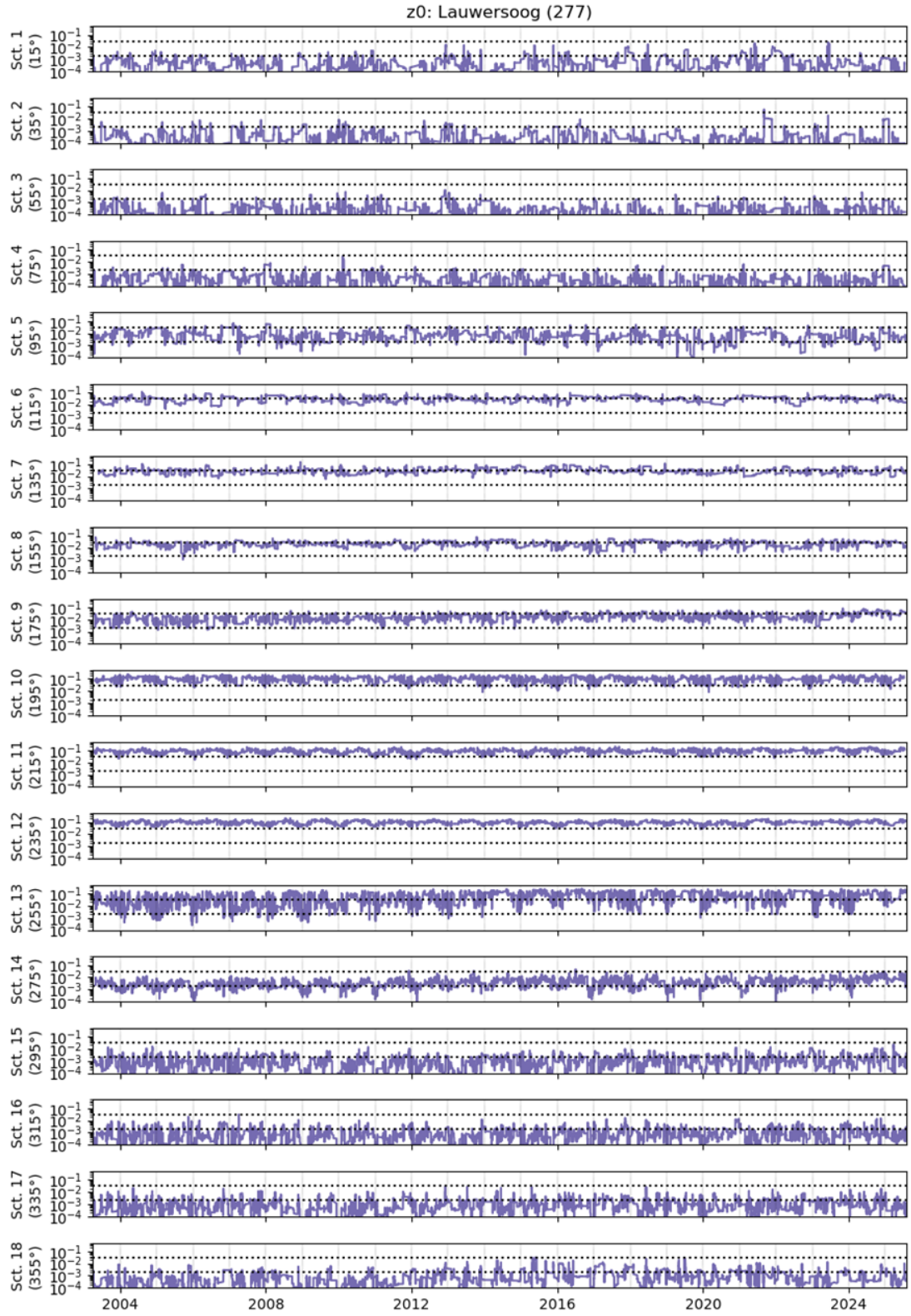


Figure F.18: Roughness length z_0 (computed with Sigma method) for Lauwersoog. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).

Table F.6: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Lauwersoog (277) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	Wadden Sea	sea	0.002	15.0
2	Wadden Sea	sea	0.002	15.0
3	Wadden Sea	sea	0.002	15.0
4	Wadden Sea	sea	0.002	15.0
5	mostlyly Wadden Sea	unclear (slightly closer to sea, but Gustiness z_0 closer to land, average of the two just closer to land)	0.03	14.0
6	mostly sea (harbour)	land	0.03	14.0
7	mostly sea (harbour)	land	0.03	14.0
8	mostly sea (harbour)	land	0.03	14.0
9	mostly sea (harbour)	unclear, but increasing to land value (Gustiness z_0 closer to land)	0.03	13.5
10	mostly sea (harbour)	land	0.03	13.5
11	half land, half harbour	land	0.03	13.5
12	land	land	0.03	11.0
13	mostly land	mostly land (Gustiness z_0 closer to land)	0.03	10.0
14	mostly Wadden Sea	closer to sea (Gustiness z_0 slightly closer to land)	0.002	12.0
15	Wadden Sea	sea	0.002	15.0
16	Wadden Sea	sea	0.002	15.0
17	Wadden Sea	sea	0.002	15.0
18	Wadden Sea	sea	0.002	15.0

z_0 of water (0.002 m). For a harbour full of ships we expect a roughness close to 0.1 m. Therefore, the values we find with the Sigma method (about 0.03 m or higher) seem not unrealistic (Fig. F.19). Of Sectors 6–8, Sector 6 has the highest roughness length (0.09 m from the Gustiness method with effective sensor height 14 m) with land 600–900 m from the mast. Deaves R-S with $x = 750$ m and the rough $z_0 = 0.3$ m (half of the sector is a town and the other half bushes and short trees) gives an IBL of 4.3 m at the wind mast. Estimating the z_0 representative of the lower quarter of the wind profile between 14 and 60 m by extrapolating the change in z_0 (from 0.002 to 0.091 m) between 4.3 and 14 m gives 0.146 m. The maximum error made by assuming the Gustiness z_0 is representative for the profile up to 60 m is an underestimate of the potential wind speed by 2.3 %. The maximum error is lower than the 5 % uncertainty of the method.

Sector 9: the Sigma z_0 is more often below 0.03 m before 2012 than after 2012 (in both cases sometimes above 0.03 m), maybe because of a new building in 2012. There are no significant differences in ECFs for the two periods with Gustiness ECFs of the



Figure F.19: View of Sector 6 at Lauwersoog (photo from Google Street View).

2020-update (0.913 for 01-01-2004 until 31-12-2009 and 0.910 for 01-01-2010 until 16-3-2021). The Gustiness z_0 is 0.061 m for 01-01-2012 to 22-03-2021 using height 14 m and 0.047 m using height 10 m, which are both land roughness. Effective sensor height is 14 m because there is 50 m of land near the mast but for hundreds of meters further away there is sea and sensor height above sea level is 15 m.

For part of **Sector 10** (190–200°) $D/H < 10$ which is probably caused by the new *Stichting Zeehondencentrum* building 318 m SSW from the wind mast (built between 2023 and 2025).

Sector 11: how high is the internal boundary layer in Sector 11 when the wind from Lauwersmeer reaches the wind mast?

- Deaves S-R (from sea [$z_0 = 0.002$ m] to land [z_0 estimated 0.3 m for area with buildings and car park in harbour area], $x = 500$ m which is the average distance from the wind mast to the Lauwersmeer) in Sector 11 gives an IBL1 height at the mast as 28.2 m, which is higher than the sensor height of 13.5 m, so z_0 should be close to that of the sea (0.002 m). However, with the Gustiness method we measure 0.129 m (Davenport describes this as occasional/scattered obstacles separated by 8–20 times the height).
- This is because there is a second transition from sea to land nearer the wind mast. In Sector 11 the first 60–75 m is land and then several hundred metres sea. Deaves S-R (from sea [$z_0 = 0.002$ m] to mostly smooth car park [$z_0 = 0.03$ m], $x = 70$ m) gives an IBL2 of 3.6 m and a TZ2 top of 31 m, so we measure halfway up this TZ2 and z_0 should be between 0.002 and 0.03 m. It is not.
- This may be due to a third transition (R to S) between the two S-R ones already mentioned. Deaves R-S (from $z_0 = 0.3$ m to $z_0 = 0.002$ m, $x = 256$ m which is the average distance from the wind mast to the roughness change: 171 m (224°) – 342 m (205°)) gives an IBL3 height of 1.5 m and a TZ3 top of 172 m. So, we measure low in the TZ3, and the Gustiness method should give a z_0 between rough (0.3 m) and smooth (0.002 m): that is indeed what the Gustiness method gives.

Which z_0 is representative of the wind profile between sensor height 13.5 m ($= 15 - 1.5$) and 61.5 m ($= 60 + 1.5$)? The Gustiness method tells us that $z_0 = 0.129$ m at 13.5 m height. The wind speed increases most in the lower part of the profile, so we need to estimate the z_0 representative for heights between 13.5 and about 25 m (the lower quarter: $13.5 + (61.5 - 13.5)/4 = 25.5$ m). Between 3.6 m (IBL2) and 13.5 m (in TZ2 and TZ3), z_0 increases from 0.03 to 0.129 m, so by 0.1 m per 10 m. Assuming this increase rate continues up to 28.2 m (IBL1), z_0 at 25 m should be 0.244 m ($= 0.129 + [(25 - 13.5) \times 0.1]/10$). We argue that the best representative value of z_0 for the profile up to 60 m is the average of z_0 between 13.5 and 25 m: 0.187 m ($= (0.129 + 0.244)/2$). This value is larger than what the Gustiness analysis gives, so an error is made when calculating the ECF. ECF is underestimated by 1.9 %, which is below the 5 % uncertainty of the method.

Sectors 8–10 are similar to Sector 11, but with a lower error. A single small-scale wind turbine (rotor diameter of 16 m) in Sector 8 is too far away (about 550 m) to have any influence on the wind mast (see Fig. F.17).

Sector 13: mostly land, because the first 180 m (264°) to 500 m (245°) land. *R.J. Cleveringssluizen* 252° – 267° (462–602m). $D/H < 10$ only for 190 – 200° (Sector 10), so no objection to make potential wind for this sector.

Sector 14: mostly water, but near the mast a dam and road out to 90–200 m and beyond the water a dam road and island beyond 600–900 m. The Gustiness z_0 is 0.019 m and is therefore very slightly closer to the reference roughness length of land (0.03 m) than to that of water (0.002 m). However, the Sigma method gives a lower z_0 (0.005 m) and therefore we use the sea $z_{0,\text{ref}}$.

F.11. Nieuw Beerta (286)

Nieuw Beerta (286) is surrounded by land (almost 6 km from water) and sensor height is 10 m.

F.12. Cadzand (308)

Measurement height $z_m = 17$ m. Definitely sea up to 600 m from the wind mast from 234 – 48° (Sector 13–18, 1–2 and half of 12). 226° – 234° (rest of Sector 12) mostly sea.

- Sea, then pier and beyond sea again (out to at least 1800 m from the mast) 49 – 77° (Sector 3, part of Sector 4)
- Sea, then harbour/pier, beyond beach (with low roughness) and then land from 77 – 145° (5–7 and part of Sector 4)
- Sea, then beach and beyond land (out to 1800 m from the mast) from 145 – 213° (Sector 8–10 and part of Sector 11).
- Sea, then beach (out to 1800 m from the mast) from 214 – 228° (part of Sector 11).
- The low Gustiness roughness length of Sector 3 (0.001 m) shows that roughness is not increased by a 7 m tall pier between 50° and 148° (Sector 3–7), 85–160 m from

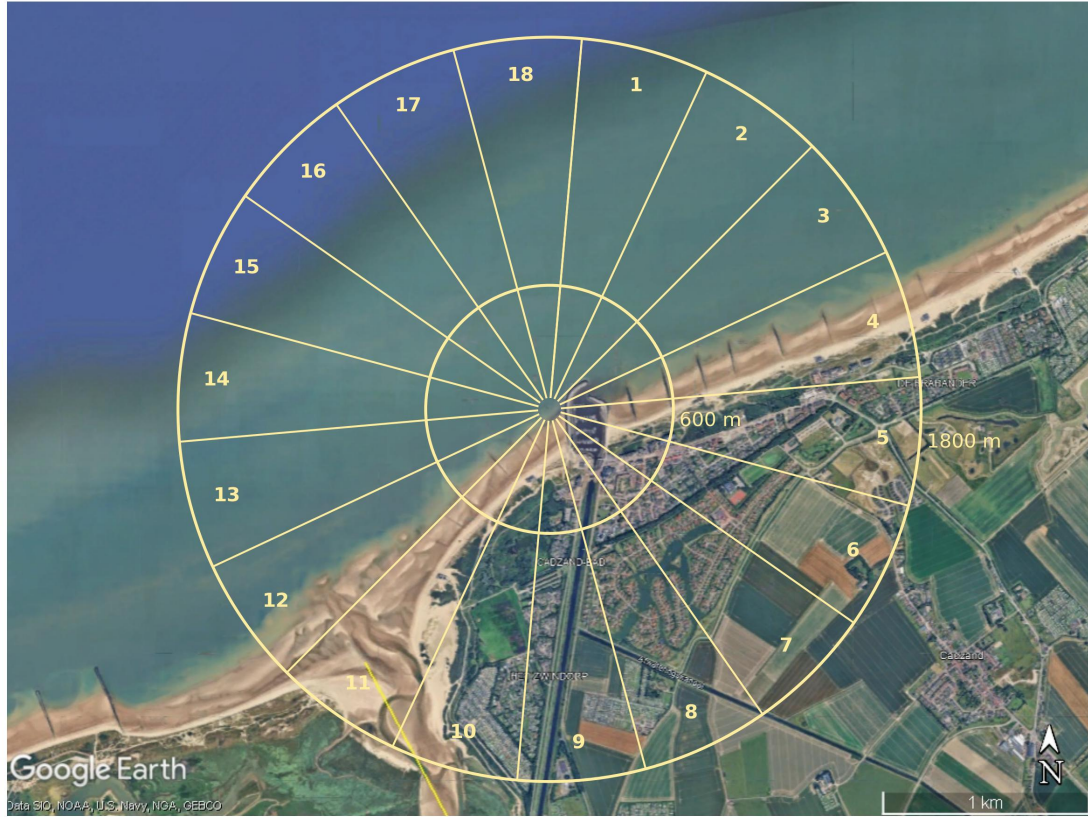


Figure F.20: Directional sectors around the wind mast at Cadzand (308).

the wind mast.

Sector 7 and 8: two tall buildings (Fig. F.22) at 395 m and 363 m from the mast in Sectors 7 and 8, respectively, contribute to the high roughness lengths (0.312 and 0.209 m respectively from the Gustiness method) but the mast does not measure in the direct wake of the buildings (where the method is invalid). The building that affects Sector 7 is five to ten stories high (estimated height: 13–30 m, on average 21.5 m) and the building affecting Sector 8 is six stories high (estimated height: 15–18 m, on average 16.6 m). The ground the buildings stand on is 10 m above mean sea level (Sector 7) and 7 m (Sector 8), respectively, (from AHN) and this means that $D/H = 395/(21.5 + 10) = 12.5$ in Sector 7 and $D/H = 363/(16.5 + 6) = 16.1$ in Sector 8. This means that the method for measuring the roughness length would be valid if measuring at 10 m height and in fact the measurement height is higher than that, so the method is certainly valid.

Sector 9: the shortest distance from (the 11 m high) dunes to mast is 245 m. We estimate the land roughness for this sector, which is affected by forest and houses, to be 0.4 m (larger than the Gustiness z_0 of 0.226 m because this value represents a combined effect of land and sea roughness). Deaves R-S (from 0.4 m to 0.002 m, $x = 245$ m) gives an IBL height of 1.2 m, so the sensor (at 17 m) measures low in the TZ (top TZ at 188 m). At 1.2 m, the roughness is adapted to the sea (0.002 m) and the rate of increase of the roughness between 1.2 m and 17 m equals 0.014 m per meter height ($= 0.224$ m



Figure F.21: View towards the harbour (Sectors 3–7) at Cadzand (photo from Google Street View).



Figure F.22: Tall buildings at Cadzand in (left) Sector 7 and (right) Sector 8 (photos from Google Street View). The building in Sector 7 is six storeys high (15–20 m) and the one in Sector 8 five to nine storeys (15–30 m).

in 15.8 m). Based on this rate, the roughness at 27.75 m (quarter of the way up to 60 m from sensor height), is 0.377 m ($= 0.226 + 10.75 \times 0.014$) and the average and our best estimate for the roughness of the profile up to 60 m is 0.302 m ($= (0.226 + 0.377)/2$). So, the mistake in ECF that is made by assuming that the whole profile up to 60 m can be described by the Gustiness z_0 at sensor height is 1.6 %, which is below the 5 % uncertainty of the method.

Sector 10: the distance from (16 m high) dunes to mast is 619 m. Sector 10 is the land sector with the lowest Gustiness z_0 (excluding Sector 4, 11 and 12 where the larger part of the sector is affected by sea). We estimate the land roughness for this sector, which is affected by dunes, shrubs and trees and beyond that by housing, to be 0.4 m (larger than the Gustiness z_0 of 0.110 m because this value represents a combined effect of land and sea roughness). Also, we expect the roughness to be very similar to the one in Sector 9. There are two opposite effects compared to Sector 9: (1) higher z_0 because in Sector 10 dunes are higher and more parallel to the sector (in Sector 9 more perpendicular), resulting in a stronger effect on the wind and (2) lower z_0 because there are fewer buildings beyond the dunes in Sector 10. Deaves R-S (from 0.4 m to 0.002 m,

Table F.7: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Cadzand (308) based on Google Earth and values of Gustiness z_0 . (Standard deviation of wind speed has only recently become available, so past Sigma z_0 could not be computed.)

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Gustiness z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	sea	sea (0.001 m)	0.002	17.0
2	sea	sea (0.001 m)	0.002	17.0
3	mostly sea (sea, then pier and beyond sea)	sea (0.001 m)	0.002	17.0
4	land and sea (sea, then harbour and beyond beach/land)	land (0.023 m)	0.03	17.0
5	mostly land (sea, then harbour/pier and beyond beach/land)	land (0.132 m)	0.03	17.0
6	mostly land (sea, then harbour/pier and beyond beach/land)	land (0.171 m)	0.03	17.0
7	mostly land (sea, then harbour/pier and beyond beach/land)	land (0.312 m)	0.03	17.0
8	sea, then beach/land	land (0.209 m)	0.03	17.0
9	sea, then beach/land	land (0.226 m)	0.03	17.0
10	sea, then beach/land	land (0.110 m)	0.03	17.0
11	sea, then beach/land	land (0.052 m)	0.03	17.0
12	mostly sea	land (0.027 m)	0.03	17.0
13	sea	sea (0.003 m)	0.002	17.0
14	sea	sea (0.002 m)	0.002	17.0
15	sea	sea (0.004 m)	0.002	17.0
16	sea	sea (0.006 m)	0.002	17.0
17	sea	sea (0.008 m)	0.002	17.0
18	sea	sea (0.003 m)	0.002	17.0

$x = 619$ m) gives an IBL height of 3.1 m, so the sensor (at 17 m) measures low in the TZ (top TZ at 328 m). At 3.1 m the roughness is adapted to the sea (0.002 m) and the rate of increase of the roughness between 3.1 m and 17 m equals 0.0078 m per meter height ($= 0.110 - 0.002 = 0.108$ m in 13.9 m). Based on this rate, the roughness at 27.75 m (quarter of the way up to 60 m from sensor height), is 0.194 m ($= 0.110 + 10.75 \times 0.0078$) and the average and our best estimate for the roughness of the profile up to 60 m is 0.152 m ($= (0.110 + 0.194)/2$). So, the mistake in ECF that is made by assuming that the whole profile up to 60 m can be described by the Gustiness value of z_0 at sensor height is 1.3 %, which is below the 5 % uncertainty of the method.

This implies that the further the roughness change is from the mast, the smaller the error. If we compare Sector 10 (error 1.3 %) and Sector 9 (error 1.6 %), both with a roughness change from 0.4 to 0.002 m, but Sector 10 further from the mast than Sector 9 (619 instead of 245 m), Sector 9 with the shortest distance gives the highest error. The size of the roughness change is however also relevant. If we assume a lower z_0 for

the land (e.g. 0.2 m), Deaves R-S (from 0.2 m to 0.002 m, $x = 619$ m) gives an IBL height of 4.3 m. The rate of change of z_0 is then 0.0085 m (0.108 m in 12.7 m) per meter height. With this rate, the roughness at 27.75 m is 0.201 m ($= 0.110 + 10.75 \times 0.0085$) and the average 0.156 m. So, the mistake in ECF that is made by assuming that the whole profile up to 60 m can be described by the Gustiness z_0 at sensor height is 1.4 %, which is below the 5 % uncertainty of the method.

IBL error in other sectors is less than in Sectors 9 and 10. So, a roughness change from 0.2 to 0.002 m gives a larger error than a roughness change from 0.4 to 0.002 m (1.4 instead of 1.3 %). In other words: the lower the roughness of the rough area (smooth area always sea), the larger the error. For Cadzand, the land-sea sectors with the lowest land area roughness are Sectors 9 and 10 because Sectors 6–8 and 12 have a much larger urban area in the land part of the sectors. Sector 5 is like Sectors 9–10 and will therefore have approximately the same z_0 . So, we looked at the sectors with the highest errors (Sector 9 shortest distance and lowest land roughness and Sector 10 also with lowest land roughness): for all other sectors the errors will be smaller.

Even though the roughness of the land in Sector 4 looks lower than that of Sectors 9 and 10 (Google Earth), the error due to the presence of an IBL should not be larger than that of Sectors 9 and 10 but smaller because: (1) There is no IBL for more than half of the sector there is sea out to 1800 m from the mast. (2) In the part of the sector with an IBL, the distance to land is longer than in Sectors 9 and 10.

The larger part of Sector 11 (213–224°) has one IBL with sea out to 1900 m (longer than in Sector 9) then a swampy tidal area with a roughness estimated to be 0.03 m or less (lower than in Sector 10) and the smaller part has two IBLs due to dunes (estimated $z_0 = 0.2$ m, so lower than in Sectors 9 and 10) between 400 m (longer distance than Sector 9; IBL1 with R-S transition) and 1300 m (IBL2 with S-R transition) and sea before and after the dunes. So, for both parts of Sector 11, it is not yet clear if the error due to the IBL will be larger or smaller than for Sectors 9 and 10. Deaves R-S for the larger part with one IBL gives the height of the IBL at the mast as 32 m, so the Gustiness z_0 that would be obtained at the sensor height of 17m would determine the wind profile up to 32 m. This covers the lower quarter (17 to 27.75 m) of the profile between 17 and 60 m, so any error due to the IBL will be small. The smaller part of the sector has two IBLs. IBL1 rises to a height of 2.8 m (below which the z_0 determining the profile is 0.002 m) at the mast (top of TZ is 191 m) and the rate of increase of the z_0 which determines the wind profile is $(0.052 - 0.002)/(17 - 2.8) = 0.00352$ m per metre height, where the Gustiness z_0 is 0.052 m. The lowest quarter of the profile is determined by the z_0 at 22.375 m height (halfway between 17 and 27.75 m), which should be 0.071 m (obtained by extrapolating the rate of increase of z_0 between 2.8 and 17 m). The error due to using the Gustiness z_0 (0.052 m) instead of the z_0 determining the profile between 17 and 60 m is an underestimate of 0.9 %. So, in both parts of Sector 11 the IBLs cause an error which is lower than the uncertainty of the method itself (5 %).

F.13. Vlissingen (310)

Elevation land at location wind mast: 8 m +NAP. The height of the 20 m tall wind mast is mostly 24 m above the surrounding terrain, since the terrain is mostly 4 m +NAP for

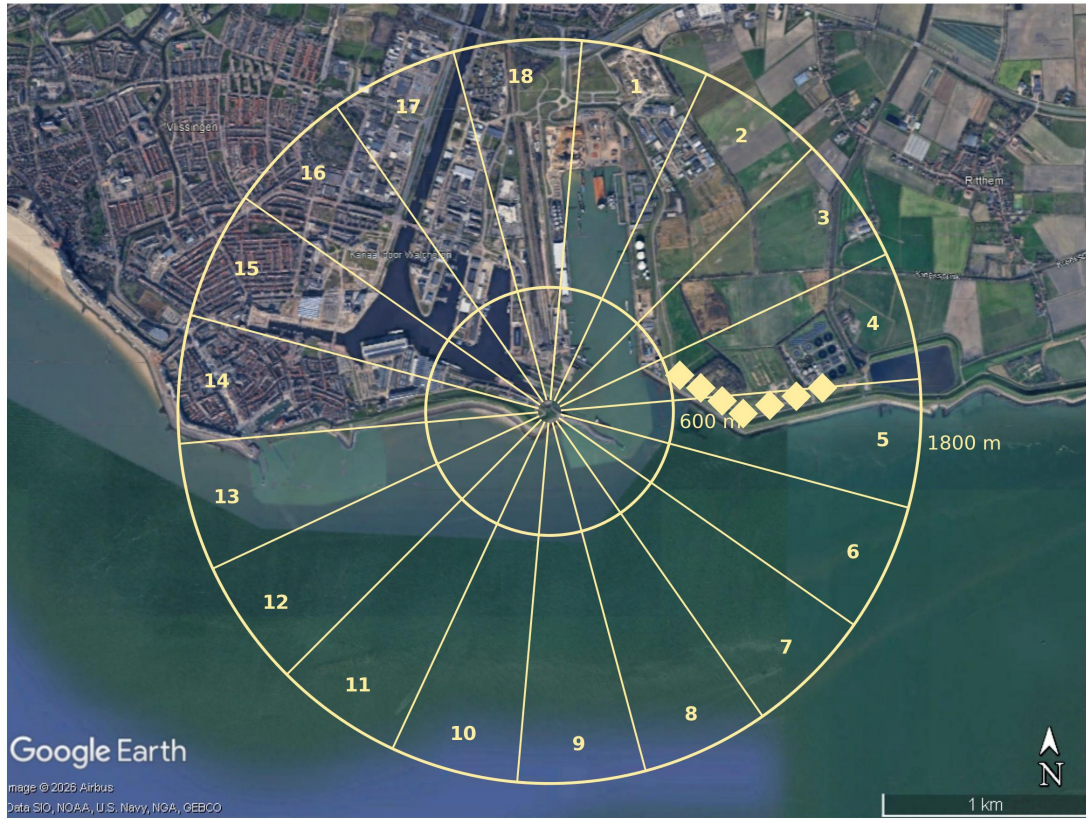


Figure F.23: Directional sectors around the wind mast at Vlissingen (310). Squares mark the positions of wind turbines.

wind directions from land and 28 m above mean sea level for wind directions from sea.

- Sectors 3 and 4 have an effective sensor height of 28 m despite having a Gustiness z_0 of land because up to at least 480 m from the mast there is sea and only the closest 45–68 m is land.
- Sector 12 has an effective sensor height of 25 m because the Gustiness z_0 lies between that of land and sea, The sensor measures halfway up the transition zone from the sea to the land (coastline 165 m from the mast). The average height of the land is 6 m in this sector, so the sensor height above land is 22 m and above sea 28 m (average 25 m).
- Sector 13 is like Sector 12, so the effective height is also 25 m.
- Sectors 14 and 18 are typical land sectors and therefore have an effective height of 24 m.
- Sectors 16 and 2 have an effective height of 26 m because water dominates these sectors.
- Sectors 1, 15 and 17 have effective heights of 25 m because they are partly like one and partly like the other neighbouring sector: Sector 1 partly like Sector 2 (effective

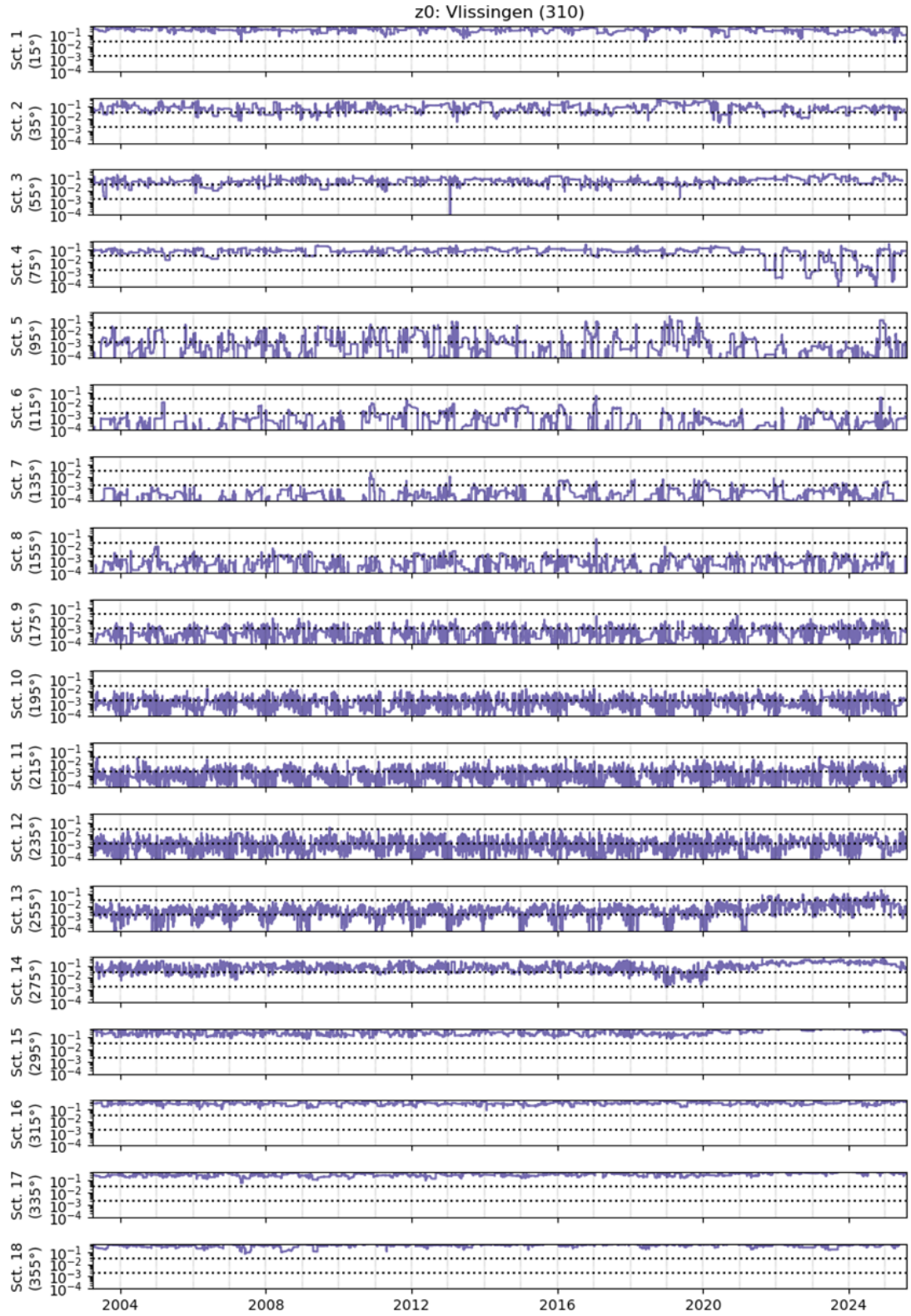


Figure F.24: Roughness length z_0 (computed with Sigma method) for Vlissingen. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).

Table F.8: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Vlissingen (310) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	both	land	0.03	25.0
2	mostly sea	land	0.03	26.0
3	both	land	0.03	28.0
4	both	land (both since 2021; Gustiness z_0 land, so we chose land $z_{0,\text{ref}}$)	0.03	18.0
5	sea (possibly disturbed by moored ship)	mostly sea	0.002	28.0
6	mostly sea (possibly affected by pier/dyke)	sea	0.002	28.0
7	mostly sea	sea	0.002	28.0
8	mostly sea	sea	0.002	28.0
9	mostly sea	sea	0.002	28.0
10	mostly sea	sea	0.002	28.0
11	mostly sea	sea	0.002	28.0
12	mostly sea	sea	0.002	25.0
13	mostly sea	sea (both since 2021; Gustiness z_0 closer to sea, so we chose sea $z_{0,\text{ref}}$)	0.002	25.0
14	1/4 sea, 3/4 land	land (increase since 2021)	0.03	24.0
15	half sea, half land	land	0.03	25.0
16	mostly sea	land	0.03	26.0
17	both	land	0.03	25.0
18	mostly land	land	0.03	24.0

height 26 m) and 18 (effective height 24 m), Sector 15 partly like 14 (effective height 24 m) and 16 (effective height 26 m) and Sector 17 partly like Sector 16 (effective height 26 m) and 18 (effective height 24 m).

Definitely land up to 600 m from wind mast between 273 and 294° which is half of Sector 14 and half of Sector 15. The other half of Sector 14 is half land and half sea, which brings the overall ranking of Sector 14 to a quarter sea and 3 quarters of land. Water and 483–600 m land between 43 and 81° (Sector 3 and 4). For Sector 5, there is water up to 600–900 m and beyond land between 81 and 97° and only sea between 97–101°. There is also a ship ‘parked’ quite often at about 110 m from the wind mast 84–96°. Between 120 and 268° (Sectors 7–13), there is mostly sea, but land up to 145 m from wind mast. The pier/dam affects Sector 6. Between 268 and 43° (Sectors 1, 2, 16–18) is the harbour, which is partly sea and partly land. For Sector 2 it is mostly sea (low land and water up to 293–360 m, beyond water up to 588–881 m), for Sector 16 also mostly sea (up to 200 m some land near the mast and more land beyond 490 m, rest sea) and for Sector 18 mostly land (only 22–26 m wide water in the locks at 130–157 m from the mast).



Figure F.25: Directional sectors around the wind mast at Hoofdplaat (311).

Sector 4: in 2021, there is a change in Sigma z_0 from a clear land value to one that varies from sea to land (Fig. F.24). Gustiness z_0 values are only available up to 31-12-2020 and are indeed clear land values of around 0.130 m. There is a wind turbine at 632 m (73°), but that turbine has been there since 2004 and the growth of the trees at 700–850 m from the wind mast should have caused an increase of roughness, not a decrease which is what we see. So, it is unclear why we see the change in z_0 in 2021. Besides, the distance of the closest wind turbine (see Fig. F.23) to the wind mast more than 20 times their rotor diameter (29 m), so their wakes are not expected to cause any issues.

Sector 13: Google Earth shows no changes in this sector. The dam at 100–136 m from the wind mast stays about 9 m high. Again, it is unclear why the Sigma z_0 increases after 2021.

Sector 14: idem Sector 13. The increase in Sigma z_0 cannot be explained by changes on Google Earth.

F.14. Hoofdplaat (311)

Surrounded by sea (Westerschelde). Sensor height 16.5 m+NAP. Roughness based on Gustiness ECFs: > 0.03 m (Sectors 8–13 and 17) and < 0.016 m (all other sectors). In previous potential wind updates, $z_{0,\text{ref}} = 0.03$ m and $z_m = 10$ m for all wind directions.

Not very relevant any longer because Hoofdplaat closed 01-03-2016 and no standard deviations were archived, so no Sigma ECF computation possible.

F.15. Oosterschelde (312)

Surrounded by sea. Sensor height 16.5 m+NAP. z_0 based on Gustiness ECFs mostly 0.001 m and max. 0.005 m. Because the measured roughness is a sea roughness in all wind direction sectors, a Benschop (height) correction is sufficient and applied operationally: calculating the potential wind is therefore not useful (Section 4.2).

F.16. Vlake van de Raan (313)

Surrounded by sea. Sensor height 16.5 m+NAP. In 2013 potential wind update, $z_{0,ref} = 0.002$ m and $z_m = 10$ m, but there has been no 2020 potential wind update because it was not one of the LH15 stations and it was also too short for deriving climate normals. Also, it is a station where the roughness in all directions is a sea roughness (all z_0 based on Gustiness ECFs are < 0.006 m). Because the measured roughness is a sea roughness in all wind direction sectors, a Benschop (height) correction is sufficient and applied operationally: calculating the potential wind is therefore not useful (Section 4.2).

F.17. Hansweert (315)

The 16-m wind mast is in the Westerschelde, so “ground level” is 0 m above sea level. Sensor height is therefore also 16 m above sea level for wind directions from land.

For directions between 137° and 313° (Sector 8–15 and part of Sector 7 and 16) there is only water up to 600m from the wind mast. Beyond this 600 m, there is water up to 2.7-3.7 km from the mast for Sector 15 and most of Sector 16 (only for 5° of Sector 16 land at about 1 km). For about half of Sector 7 there is a 2m high pier (AHN) at about 50 m with beyond that a reservoir with water or mud and then land at 812–897 m. For the other half of Sector 7, there is only water. The sectors that have land closer than 600 m are Sectors 1–6 and 17–18. Between 2 and 88° (Sectors 1–4), the distance to the coast is less than 300 m, so we consider those mostly land sectors. For 5, 17 and 18 it is mostly water only considering distance up to 600 m. For Sector 6, there is land at 450 m from the mast, affecting half of the sector (105 – 114°). The other half (114 – 124°) is a mix of sea and land. The land is low ($+0.2$ m AHN) and starts at 690–800 m from the mast. Nearer to the mast is water, then a 2 m high pier at about 500 m and beyond that a reservoir with water or mud. So, even though the Gustiness ECF suggests that Sector 6 should be sea, we consider it a land sector.

In Sector 4, the land begins 190 m from the mast and it is the sector with the shortest distance to land. The land is urban out to about 1100 m from the mast with a z_0 estimated to be 0.5m. The Deaves R-S (0.002 to 0.5 m, $x = 190$ m) gives an IBL height of only 0.8 m at the mast and a TZ top of 177 m height. The wind measurements are done at 16 m, which is a quarter of the way up between 0.8 and 60 m, so the error made by assuming that the Gustiness z_0 determines the wind profile between 16 and 60 m should be small.

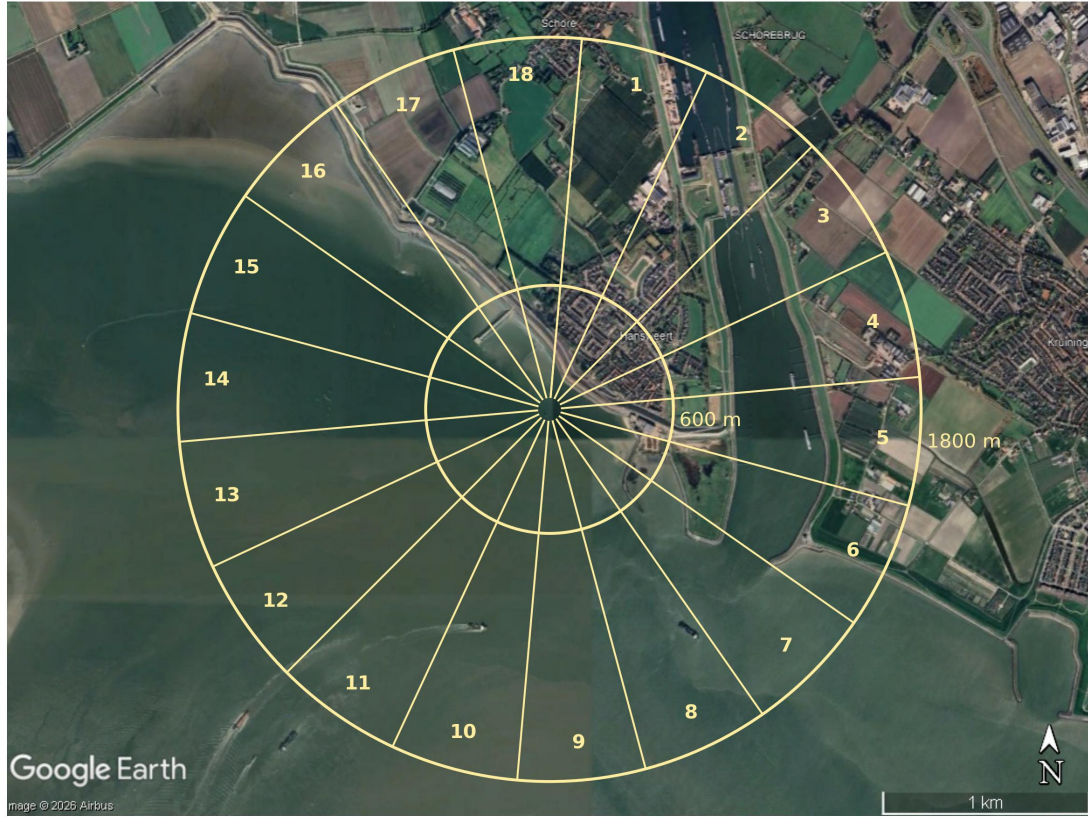


Figure F.26: Directional sectors around the wind mast at Hansweert (315).

The other sectors with land up to 1 km from the mast (1–3, 5–6 and 16–18) all have the land further away than in Sector 4, so the error should be smaller. However, a lower roughness length than 0.5 m for the land in those sectors would imply a larger error.

Sectors 1-3 have the same roughness length (0.5 m), but the land is further away from the mast, so the error is smaller.

Sector 18 has a lower land roughness (0.1 m, starting 370 m from the mast). The IBL height is 3.7 m and the top of the TZ at 138 m height. A quarter of the way up between 3.7 and 60 m is 18 m, so we measure the wind slightly below this height and the Gustiness z_0 will be slightly (but probably not significantly) lower than the roughness that determines the wind profile between 16 and 60 m. The error made by using the roughness length obtained from the measurements is probably not larger than the uncertainty of the method (5 %).

Sectors 16 and 17 have land with the same roughness length as Sectors 5 and 18 and the distance from the mast is longer, so the error will be smaller. Also, there is land in only a quarter of the directions in Sector 16, so errors introduced by the IBL are duly smaller.

Sectors 5 and 6 are similar to each other but different from the other sectors because there are 3 IBLs to consider. The transition in Sector 5 that is closest to the mast is 400 m away where the wind moves from land with z_0 of 0.2 m (small amount of urban and

Table F.9: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Hansweert (315) based on Google Earth and values of Gustiness z_0 . (Standard deviation of wind speed has only recently become available, so past Sigma z_0 could not be computed.)

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Gustiness ECFs	$z_{0,\text{ref}}$ [m]	z_m [m]
1	mostly land	land (1.10)	0.03	16.0
2	mostly land	land (1.10)	0.03	16.0
3	mostly land	land (1.08)	0.03	16.0
4	mostly land	land (1.05)	0.03	16.0
5	mostly sea	land (1.01)	0.03	16.0
6	mostly land	sea (0.97)	0.03	16.0
7	mostly sea	sea (0.92)	0.03	16.0
8	sea	sea (0.95)	0.03	16.0
9	sea	sea (0.95)	0.03	16.0
10	sea	sea (0.96)	0.03	16.0
11	sea	sea (0.95)	0.03	16.0
12	sea	sea (0.96)	0.03	16.0
13	sea	both (0.98)	0.002	16.0
14	sea	both (0.98)	0.002	16.0
15	sea	land (1.00)	0.002	16.0
16	mostly sea	land (1.03)	0.03	16.0
17	mostly sea	land (1.04)	0.03	16.0
18	mostly sea	land (1.05)	0.03	16.0

mostly fields) to the sea, followed by a sea to land transition at 930 m and lastly land (z_0 of 0.1 m) to sea at 1330 m from the mast. The first and last transitions (both land to sea) have IBL heights (respectively 2.8 and 13.2 m conform Deaves) at the mast below the anemometer, so at 13.2 m z_0 is 0.002 m. The middle transition (sea to land) generates an IBL above the mast at 40.5 m, where z_0 is 0.2 m. Assuming a linear increase of governing z_0 with height (0.00725 m per metre height), at 21.5 m (halfway up the lowest quarter of the profile between 16 and 60 m) z_0 should be 0.06 m and at 16 m it should be 0.02 m. The error made by assuming the z_0 at 16 m governs the wind speed profile up to 60 m (instead of 0.06 m) leads to a 3 % underestimate of the potential wind and that is smaller than the uncertainty of the method (5 %). Sector 6 is similar but half of the directions are mostly sea, so the error introduced by the IBLs will be smaller.

Sector 7 only has a very small piece of land at 850–1030 m from the mast, in only a quarter of the directions of the sector, so it is almost entirely sea. The fact that the ECF is the lowest of all the sectors, also shows that Sector 7 is a sea sector.

Gustiness ECF suggests Sector 15 is a land sector, while there is clearly sea up to 2.7 km from the mast (Google Earth). We have decided to choose a sea reference roughness.

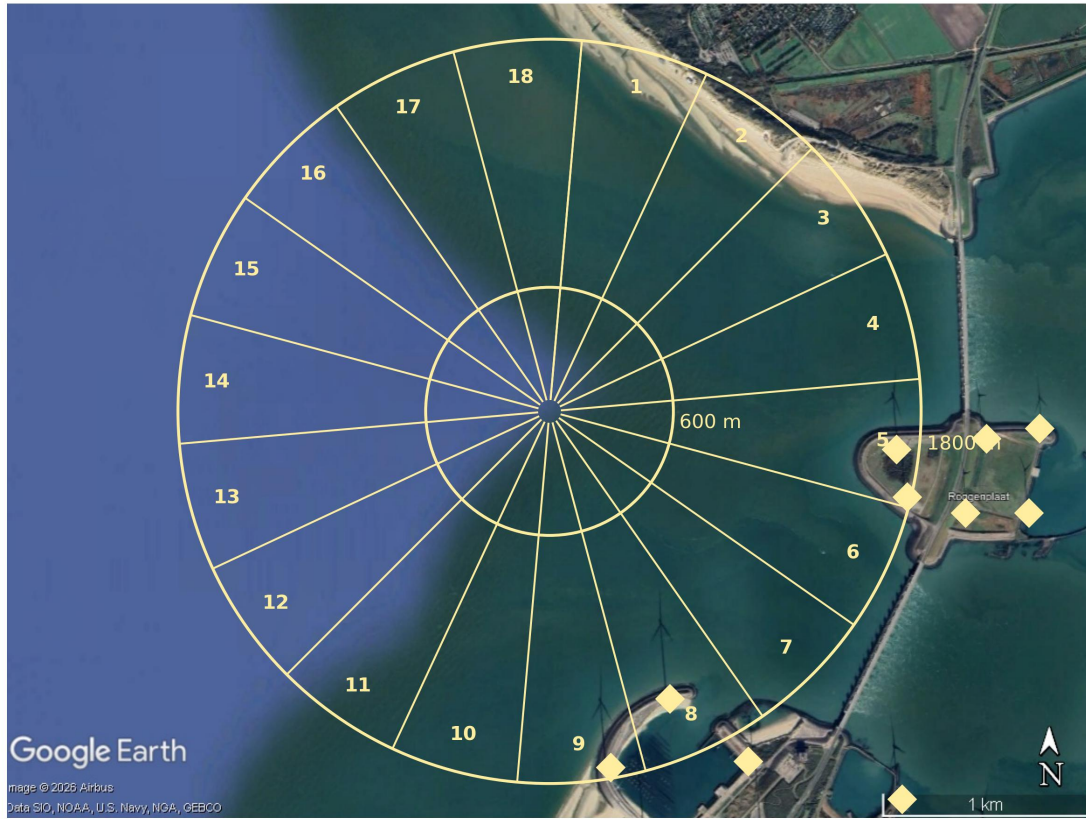


Figure F.27: Directional sectors around the wind mast at Schaar (316). Squares mark the positions of wind turbines.

F.18. Schaar (316)

Surrounded by sea. Sensor height 16.5 m+NAP and $z_{0,ref} = 0.002$ m. z_0 based on Gustiness ECFs (Sigma ECFs not available because standard deviation is not available) all < 0.018 m (closer to sea roughness 0.002 m than to land roughness 0.03 m) except Sectors 1, 2 and 18 (< 0.024 m, so closer to land roughness 0.03 m). The latter, slightly higher roughness lengths are caused by dunes and the village of Westerschelde at a distance of 1700 m or more from the wind mast. The Benschop correction is applied to the operational wind speed measurements to estimate the wind speed at 10 m, so calculating the potential wind speed for this location is not necessary. Besides, there are four sectors (5 and 7–9; see Fig. F.27) with wind turbines whose wakes could affect the wind measurements because their rotor diameter is only between 10.9 and 19.8 times the distance from the wind mast.

F.19. Westdorpe (319)

Westdorpe (319) is surrounded by land. Sigma-method ECFs confirm this. *Klapmast* (before 07-09-2011: *klimmast*) with wind sensors at 10 m height.



Figure F.28: Stavenisse/Tholen (324): wind measurements are too disturbed by 5 m tall building next to the wind mast.

F.20. Wilhelminadorp (323)

Wilhelminadorp (323) is surrounded by land (almost 2 km from water). Sigma-method ECFs confirm this. *Klapmast* with wind sensors at 10 m height.

F.21. Stavenisse (324)

Definitely sea up to 600 m from the wind mast between 264° and 60° (Sectors 14–18 and 1–3). Land for other sectors.

The 10-m wind mast²⁸ from RWS stands on the ground right beside a 5-m tall flat-roofed building (Fig. F.28). Ground level at the site is 2.60 m above mean sea level (source: AHN5²⁹), so sensor height is 12.6 m above sea. The land near the mast is generally 0.5–1.0 m, so the sensor height is 12 m above land.

The building is higher and closer than the WMO guidelines advise, so the measurements are disturbed. Furthermore, the mast stands just outside of the sea dyke (dyke top is 7 m above MSL and at its closest 34 m from the mast in direction 155°). The land on the other side of the dyke is 0.5–1.0 m above MSL, so the dyke is an obstruction to the air flow of 6.0–6.5 m height. Such a disturbance of the flow extends upwards to at least twice the height of the obstruction and ten times the height downstream, so the wind the sensor measures is also disturbed by the dyke. For these reasons, it has been decided not to calculate ECFs for Stavenisse/Tholen anymore.

²⁸No information in SAIS at the time of writing, but height confirmed by Jan-Willem Schoonderwoerd.

²⁹Average ground level at the site is 0 m according to metadata (https://confluence.knmi.nl/pages/viewpage.action?pageId=85531178&spaceKey=WW0&title=Metadata%2Balle%2BAWS%2Ben%2Bincl.%2BBES%2Beilanden%2Ben%2BNoordzee&preview=%2F85531178%2F245671023%2FPositie%20en%20hoogte%20NL%20synoptische%20stations_alle_%2017_10_2025%20Nieuw%20formaat.xls) at the time of writing this report, but that is wrong (confirmed by Damian Napoles Soto by email on 31-10-2025).

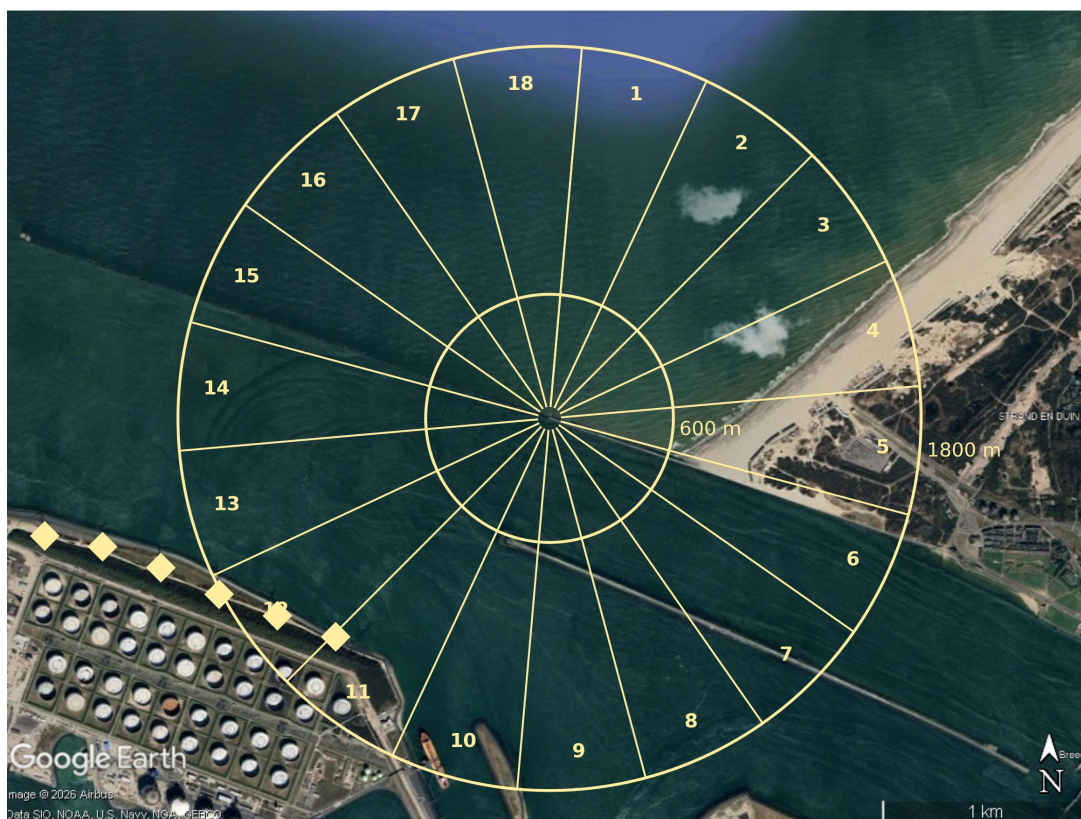


Figure F.29: Directional sectors around the wind mast at Hoek van Holland (330). Squares mark the positions of wind turbines.

F.22. Hoek van Holland (330)

Location information in SAIS:

- *Bovenop lage lichtopstand splitsingsdam, wordt nog gebruikt t.b.v. Maaslandkering. Was tussen 20121113 en 20180430 operationeel: uitleg: lage lichtopstand sensorhoogte 38,60 m nap + pierhoogte ca 2,0m nap = +40,60m nap (sensorhoogte tov msl).*
- *Bovenop lichtopstand noorderhoofdpier (operationeel) op mast; ca. 860 m zeewaarts vanaf vloedlijn strand. Opnieuw operationeel per 20180501. uitleg: lichtopstand sensorhoogte +14,65 m nap + pierhoogte ca +2,00 m nap = +16,65 m nap (sensorhoogte t.o.v. msl) (vanaf 20070831, nieuw bordes, windopstelling).³⁰*

According to station information in SAIS, the sensor at *Noorderhoofdpier* is 14.65 m above the pier and pier height is 2 m, so sensor height is 16.65 m +NAP for wind directions from the sea.

Location *Lage Lichtopstand Splitsingsdam* was operational between 13-11-2012 and 30-

³⁰This has no consequences for ECFs because the changes are insignificant. A new set of ECFs gets calculated since 04-12-2007, but that is because of a change in the Benschop correction and has nothing to do with the change in measurement setup (Steppek & Wijnant, 2013).

Table F.10: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Hoek van Holland (330; Noorderhoofdpier, 01-05-2018–08-12-2020) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Gustiness z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	sea	sea	0.002	16.65
2	sea	sea	0.002	16.65
3	sea	sea	0.002	16.65
4	sea	sea	0.002	16.65
5	sea (land at > 600 m)	sea	0.03	16.65
6	mostly sea (2° pier)	sea	0.002	16.65
7	sea	unclear	0.002	16.65
8	sea	unclear	0.002	16.65
9	sea	unclear	0.002	16.65
10	sea (<i>2e Maasvlakte</i> at 1.5–3.0 km)	sea	0.03	16.65
11	sea (<i>2e Maasvlakte</i> at 1.5–3.0 km)	land	0.03	16.65
12	sea (<i>2e Maasvlakte</i> at 1.5–3.0 km)	sea	0.03	16.65
13	sea (<i>2e Maasvlakte</i> at 1.5–3.0 km)	sea	0.03	16.65
14	sea	sea	0.002	16.65
15	mostly sea (2° pier)	sea	0.002	16.65
16	sea	sea	0.002	16.65
17	sea	sea	0.002	16.65
18	sea	sea	0.002	16.65

4-2018, but the measurements were disturbed by wind turbines to the southwest of the wind mast and 2LM does not work for these directions (see Fig. F.29). That is why the old wind mast at Noorderhoofdpier became operational again. It is impossible to derive Sigma ECFs for Noorderhoofdpier during the period that Splitsingsdam was operational, because only 10-minute average wind speed and direction a sensor height were available for that period (so no standard deviation).

The ‘gap’ in the Gustiness ECFs (based on the Gustiness analysis of hourly measurements) during the Splitsingsdam period, is filled with data calculated with measurements at Noorderhoofdpier from before and after the period from 31-10-2012 to 30-04-2018 (when measurements Splitsingsdam are available in RobuKIS). Only for Sectors 6 and 10–13, the roughness lengths were significantly different at Splitsingsdam, compared to those of Noorderhoofdpier. For the other sectors, ECFs calculated with the Splitsingsdam measurements can be used to calculate potential wind for Hook of Holland in the ‘gap’ period. For Sectors 6 and 10–13, the average of two sets of Noorderhoofdpier ECFs (before and after the mentioned period) was taken and multiplied by transformation factors (Noorderhoofdpier/Splitsingsdam) based on the analyses of 2 years of parallel measurements. These transformed ECFs for Sectors 6 and 10–13 can be applied to the Splitsingsdam measurements of wind speed to calculate potential wind for Hook of Holland in the ‘gap’ period. We use the same method as for the Gustiness ECFs (as described above) to fill the ‘gap’ in the Sigma potential wind (so for Sectors 6 and 10–13 there is one ECF per

sector for the whole ‘gap’ period).

Lichtopstand Noorderpier is about 600 m from the coast, which means that it is surrounded by sea except in the direction of the pier (2° at about 108° and 289° : Sectors 6 and 15). As the distance to the coast is more than 600 m for all wind directions, Verkaik’s rule of thumb (Section C) suggests that the height of the sensor should be the height relative to the sea. However, we measure high values for the roughness for Sector 5 ($85\text{--}104^\circ$, beach closer than 1 km) and 10–13 ($185\text{--}264^\circ$, Tweede Maasvlakte with land and wind turbines between 1.5–3.0 km).

We investigated if we could find a significant change of ECFs from the wind turbines:

- Only the three closest wind turbines south-east of the mast (see Fig. F.29) have a rotor diameter of less than 20 times their distance (between 16.7 and 19.8), so their wake could affect the wind mast (NEN, 2017). They are all in the same sector (12), so the station does not need to be excluded because of this (Section 4.2).
- Zuidwal wind park (6 turbines, the most easterly at 1.5 km from Noorderpier mast in direction 223°) was installed in October 2004, but speed fraction $H_vH/Goeree$ dropped by only 1–2 % in the sector that would be most affected by the wind farm (Sector 12: $225\text{--}244^\circ$). The ECFs also did not change significantly in the period 01-01-2001–31-12-2007.
- Between the second quarter and the end of of 2014, the 6 turbines were replaced by 9 larger ones. Based on the available roughness lengths at Noorderhoofdpier (before 2001 and after 2014 only for 2018–2020), we can see that the only (nearly) significant difference in Gustiness ECF is for Sector 11 (ECF increases by 0.046 and z_0 by 0.074 m). The ECF of Sectors 10, 12 and 13 increased too, but by less than 0.046 (by more than 0.020).
- Also, the Sigma ECFs from before and after October 2004 and from before and after 2014 (avoiding the Splitsingsdam period 31-10-2012–30-04-2018) were compared, especially for Sectors 10–13, to assess the impact of the wind turbines on the measurements at Noorderhoofdpier: no significant differences were found.

Sector 5 ($85\text{--}104^\circ$) Noorderhoofdpier: IBL height calculation

- Closest distance to flood line 687 m (in direction 104°). There, the distance to the dunes is about 1 km. For calculating the height of the IBL we should take the distance to the dunes because ‘beach’ does not count as land (has an even lower surface roughness than sea). The Deaves R-S formula (R: 0.2 m, S: 0.002 m) then gives an IBL height of 7 m, so the sensor at 16.56 m measures low in the transition zone (top transition zone: 331.5 m).
- We assumed the roughness of the dunes to be 0.2 m even though we measured a lower z_0 of 0.032 m in Sector 5. This is because Deaves R-S using the measured roughness (R: 0.032 m, S: 0.002 m) gives an IBL height of 17.5 m, which is above the anemometer height (16.56 m). This would imply that we measure in the IBL, which cannot be true because z_0 should then be 0.002 m, whereas the measured $z_0 = 0.032$ m is much higher. So, we must measure in the transition zone (TZ),

close to the bottom of this zone because the TZ is usually hundreds of metres high (331.5 m in this case). Since the z_0 that determines the increase of wind speed with height in the TZ increases from 0.002 m at the bottom of the TZ (i.e. top of the IBL) to the roughness of the dunes at the top of the TZ and we measure near the bottom of the TZ, the dunes of Hoek van Holland must have a much higher roughness length than 0.032 m: 0.2 m for the sake of argument. The Deaves R-S formula with R equal to 0.2 m gives an IBL height of 7.0 m, so then we do indeed measure in the TZ and the measured z_0 of 0.032 m makes more sense.

Sector 5 (85-104°) Noorderhoofdpier: Maximum error calculation

- For the layer between 7.0 m (IBL height Deaves R-S using the estimated roughness of the dunes, R: 0.2 m and S: 0.002 m) and 60 m, the most representative roughness is closer to the measured roughness at 16.56 m (low in the TL) of 0.032 m than to the roughness at the top of the TL (the 0.2 m of the dunes) because the top of the TZ is at 331.5 m. That is why we use $z_0 = 0.1$ m (closer to 0.032 than to 0.2 m) as input for the maximum error calculation. ECF_1 should in this case be calculated by going up with $z_0 = 0.1$ m (our best guess of a roughness representative of the profile between sensor height 16.65 m and 60 m) and down with $z_{0,\text{ref}} = 0.03$ m. For ECF_2 use $z_0 = 0.032$ m as measured.
- ECF is underestimated by 3.5 %, which is below the uncertainty of the method (5 %).

Sector 10-13 (185-264°) Noorderhoofdpier: IBL height calculation

- Tweede Maasvlakte at 1.5–3.0 km. The Deaves R-S formula (R: 0.4 m, S: 0.002 m) then gives an IBL height of 7.4 m, so the sensor at 16.56 m measures low in the transition zone (top transition zone 558 m). The roughness of the Maasvlakte (0.4 m) was calculated from the Splitsingsdam measurements of Sector 12 (sector at Splitsingsdam with the highest roughness) and conform Wieringa (1993) for more urban areas (0.4–1.5 m). So, the whole profile up to 60 m is determined by a mix of sea and land roughness (closer to sea roughness of 0.002 m because we are low in the transition zone). That is why for Sectors 11 and 12 of Noorderhoofdpier, the measured roughness is closer to 0.002 m than to 0.4 m (Sector 12: 0.108 m).

Sector 10-13 (185-264°) Noorderhoofdpier: maximum error calculation

- For the layer between 7.4 m (IBL height Deaves R-S using estimated roughness of the Maasvlakte R: 0.4 m and S: 0.002 m) and 60 m, the most representative roughness is closer to the measured roughness at 16.56 m (low in the TL) of 0.108 m than to the roughness at the top of the TF (the 0.4 m of the Maasvlakte) because the top of the TZ is at 558 m. That is why we use $z_0 = 0.2$ m (closer to 0.108 than to 0.4 m) as input for the maximum error calculation. ECF_1 should in this case be calculated by going up with $z_0 = 0.2$ m (our best guess of a roughness representative of the profile between sensor height 16.65 m and 60 m) and down with $z_{0,\text{ref}} = 0.03$ m. For ECF_2 use $z_0 = 0.108$ m as measured.

- ECF is underestimated by 2.7 %, which is below the uncertainty of the method (5 %).

To conclude: For Sectors 5 and 10–13 we assume $z_{0,\text{ref}} = 0.03$ m and for the other sectors $z_{0,\text{ref}} = 0.002$ m. For all sectors, we assume height above sea ($z_m = 16.65$ m), also for Sectors 5 and 10–13, because we measure low in the transition zone (so almost in IBL). Note: for both the 2013 and 2020 potential wind update, $z_{0,\text{ref}} = 0.03$ m and $z_m = 15$ m for all sectors.

F.23. Tholen (331)

Surrounded by sea. For all sectors z_0 based on Gustiness ECFs < 0.015 m. Sensor height 16.5 m+NAP.

For Tholen, where the measured roughness is a sea roughness in all wind direction sectors, a Benschop (height) correction is sufficient and applied operationally (not available in RobuKIS). So, it is not useful to calculate the potential wind (Section 4.2).

F.24. Woensdrecht (340)

Woensdrecht (340) is surrounded by land (more than 4 km away from water). Sigma-method ECFs confirm this. Wind sensors at 10 m height. However, because $ECF > 1.22$ (from Gustiness method) and $D/H < 10$ in 4 of the 18 sectors, we do not calculate ECFs or potential wind for this station (also did not do that for the 2020 update).



Figure F.30: Directional sectors around the wind mast at Rotterdam Geulhaven (343). Squares mark the positions of wind turbines.

F.25. Rotterdam Geulhaven (343)

Rotterdam Geulhaven (343) is located in an industrial area (harbour) on a dam in the river Scheur. Wind sensors on a 10-m mast, which is located at 3.5 m+NAP (SAIS), so $z_m = 13.5$ m (assuming that the river about 18 km from the mouth is at mean sea level). According to visual inspection, water in the first 600 m around the mast in most sectors (except Sectors 6–10). But sigma z_0 suggest land in all sectors (Fig. F.31). Thus, we use $z_{0,ref} = 0.03$ m for all sectors.

All sectors have a land-water transition, so we only estimate IBL, TZ and ECF error (Section C) for two sectors that we assume to represent the upper and lower bounds:

- Sector 9 has the closest land-water boundary at $x = 380$ m. The land is characterised by large industrial buildings, so we assume $z'_0 = 1.0$ m (and $z_0 = 0.002$ m). The Deaves SR formula gives an IBL height of 1.2 m and a TZ top at 353 m. Using the sigma z_0 of 0.116 m for this sector, we can determine an ECF underestimation of about 2.1 %, which is less than the 5 % uncertainty of the method and therefore insignificant.
- With Sector 16, we then consider a sector with a land-water boundary that is further away (between 860 and 1550 m, so we use $x = 1205$ m) and where the land

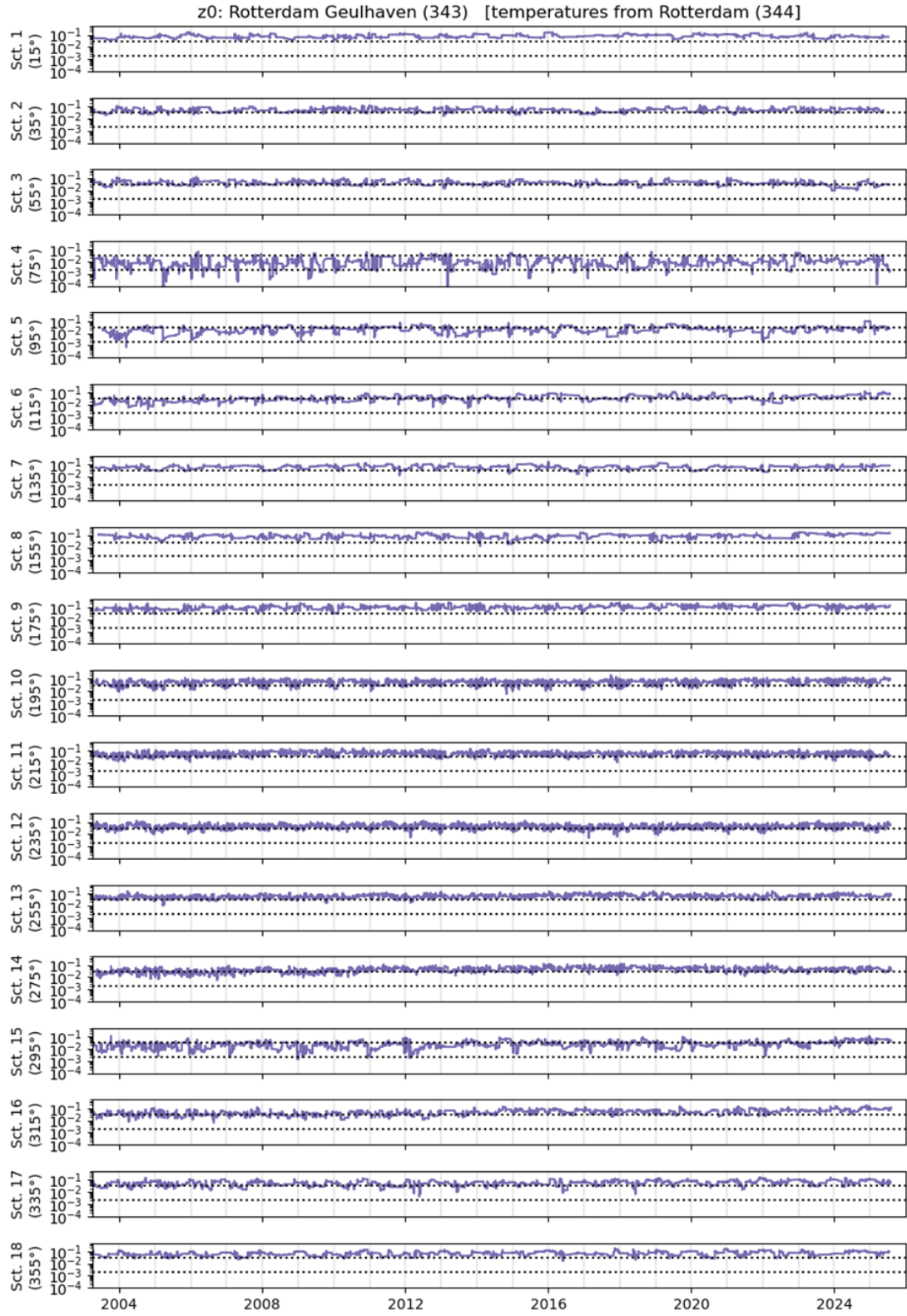


Figure F.31: Roughness length z_0 (computed with Sigma method) for Rotterdam Geulhaven. Dashed horizontal lines indicate 0.03 m (roughness grass used as reference land roughness) and 0.002 m (roughness rough sea used as reference sea roughness).

Table F.11: Reference roughness $z_{0,\text{ref}}$ and measurement height z_m per wind-direction sector for Rotterdam Geulhaven (343) based on Google Earth and values of Sigma and Gustiness z_0 .

Sctr.	Sea or land up to 600 m from mast based on Google Earth	Sea or land based on Sigma z_0	$z_{0,\text{ref}}$ [m]	z_m [m]
1	water (river)	land	0.03	13.5
2	water (river)	land	0.03	13.5
3	water (river)	land	0.03	13.5
4	water (river)	land	0.03	13.5
5	both (dam)	land	0.03	13.5
6	both (harbour)	land	0.03	13.5
7	both (harbour)	land	0.03	13.5
8	both (harbour)	land	0.03	13.5
9	both (harbour)	land	0.03	13.5
10	both (harbour)	land	0.03	13.5
11	water (river)	land	0.03	13.5
12	water (river)	land	0.03	13.5
13	water (river)	land	0.03	13.5
14	water (river)	land	0.03	13.5
15	water (river)	land	0.03	13.5
16	water (river)	land	0.03	13.5
17	water (river)	land	0.03	13.5
18	water (river)	land	0.03	13.5

z_0 is somewhat lower ($z'_0 = 0.5 \text{ m}$). The Deaves SR formula gives an IBL height of 1.7 m and a TZ top at 268 m. Using the sigma z_0 of 0.069 m for this sector, we can determine an ECF underestimation of about 1.7 %, which is less than the 5 % uncertainty of the method and therefore insignificant.

Sector 16 contains four wind turbines at distances of about 1030 m, 1320 m, 1660 m and 2140 m from the wind mast (Fig. F.30). The diameters of the rotor is 90 m for the two closer ones and 117 m for the other two. The three closest ones may affect the wind mast because they are closer than 20 times the rotor diameter (NEN, 2017). The sigma z_0 of this sector does not show any peculiarities though (Fig. F.31). Thus, we consider Sector 16 as less reliable, but we still compute ECFs and potential wind for it.

There is a dyke on the northern river bank. It has a height of about +6 m +NAP, while the land behind it has a height of about -2 m +NAP. Thus, we consider the dyke to be an obstacle of 8 m height, and its wake would be felt at a distance up to ten times that height, so 80 m. This is much less than the closest distance of the shore to the mast, which is more than 600 m.

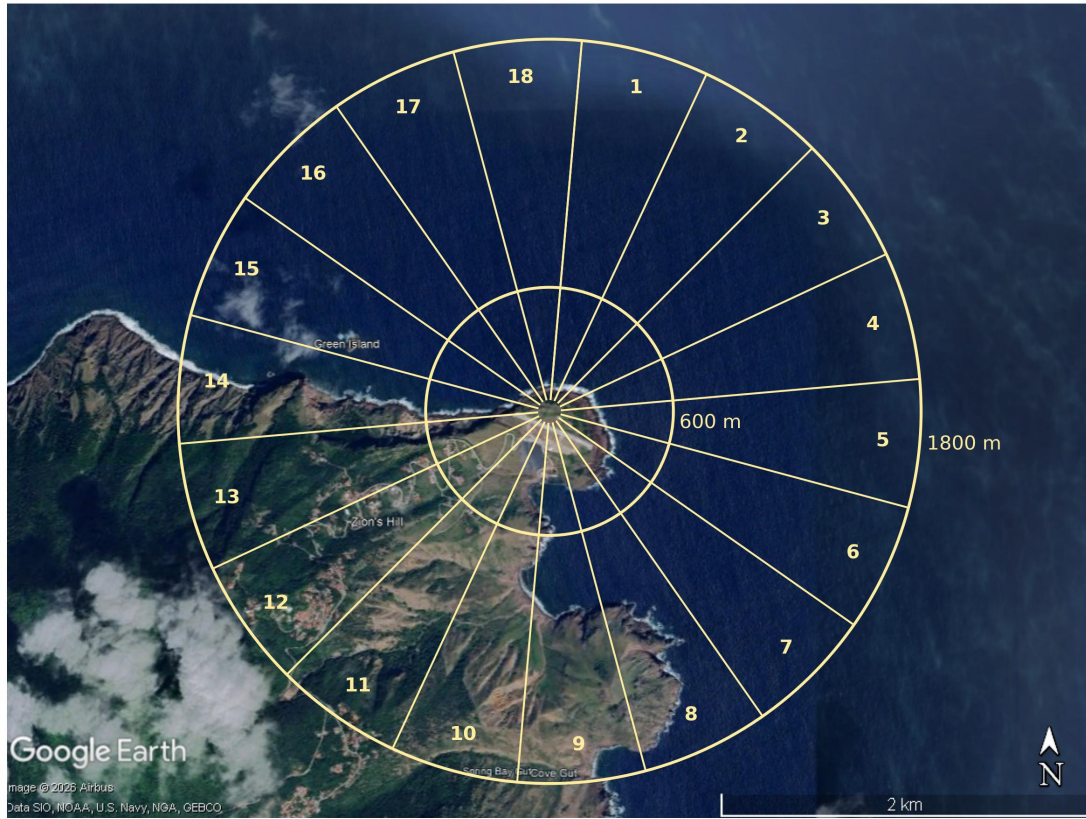


Figure F.32: Directional sectors around the wind mast at Saba (871).

F.26. Saba (871)

Measurements available since 01-01-2016. The shortest distance between the wind mast and the sea is 100 m. The wind sensors are on a 10 m high wind mast. The elevation of the land is +31 m above MSL at the AWS, but 4 m lower at the site of the wind mast.³¹ So, for directions from the sea, the height of the sensor is $31 - 4 + 10 = 37$ m +NAP.

Because at Saba the wind is mostly northeasterly (trade winds), there are a lot of sectors for which we do not have enough wind measurements to derive ECFs. There are enough measurements for Sectors 1–9 (5°–184°), but in several directions the wind is disturbed (also rocks and debris near the wind mast):

- For Sectors 1–7 and 14–18 (in directions from west to north to southeast: 280°–160°), steep cliffs (31 m) and height differences cause increased turbulence (wind is forced to go upward) and underestimation of surface roughness with the Sigma method.
- For Sectors 6–9, there are height differences, but for Sectors 11–13 it is even worse with steep mountains and a volcano.

We therefore conclude that the measurements at Saba are too disturbed and that it is

³¹Saba inspection report 15-09-2021 by Damian Napoles Soto (KNMI)



Figure F.33: View towards the runway and wind mast with cliffs beyond at Saba.

impossible to calculate accurate ECFs or potential wind those measurements.

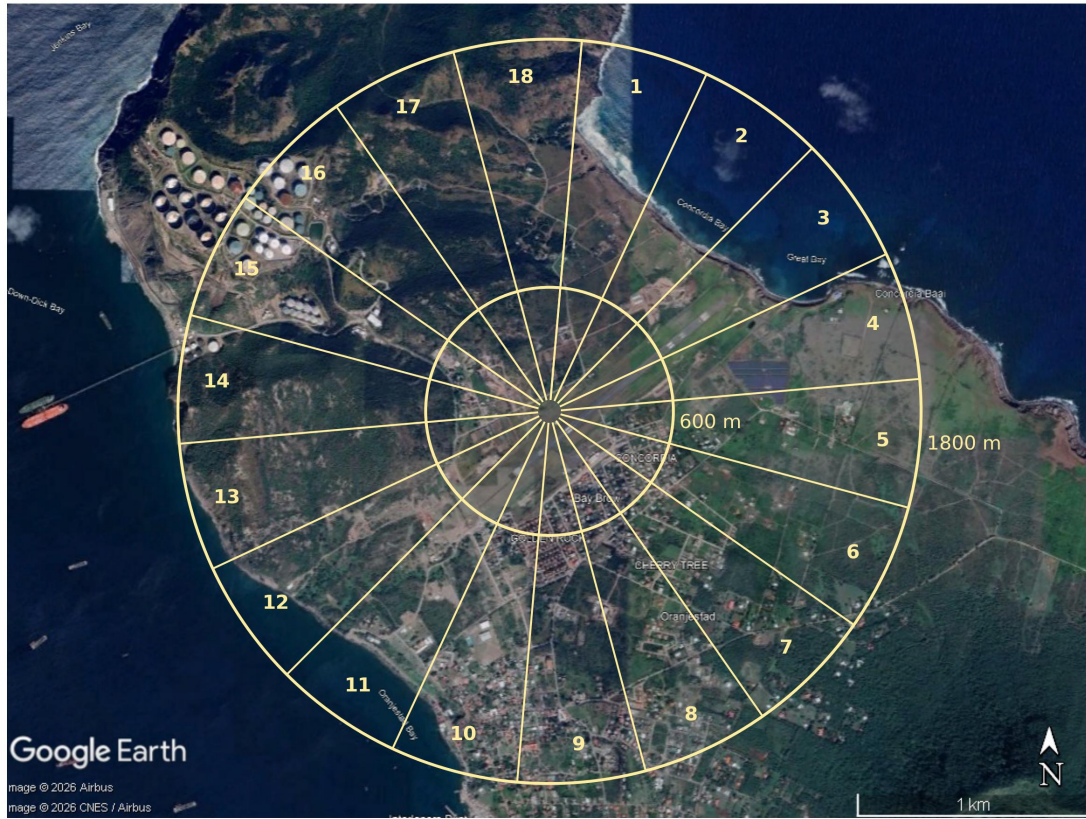


Figure F.34: Directional sectors around the wind mast at Sint Eustatius (873).

F.27. Sint Eustatius (873)

Sint Eustatius (873) is surrounded by land (closest distance to the sea: 1 km). There are two mountains at less than 600 m from the wind mast in the direction from SW to NW (239° – 337° , so Sectors 13–16 and half of Sector 17). The effect of volcano “The Quill” to the S-SE (121° – 151° , so Sector 7, see Fig. F.35) is similar ($D/H < 10$) even though the volcano is quite far away (> 2 km). However, the prevailing wind is from the NE (trade winds), so most of the time the wind measurements are not disturbed by the volcano and the two mountains.³²

Conform the requirements listed in Section 4.2 (more than four wind direction sectors with $ECF > 1.22$ where the potential wind theory does not apply), we do not calculate potential wind for Sint Eustatius. However, we could provide ECFs for the non-disturbed trade-wind direction sectors for aviation monitoring.

Sensors are on a 10-m wind mast. Measurements done and available in RobuKIS since 01-01-2016.

³²KNMI inspection report Sint Eustatius 2024



Figure F.35: View from the wind mast towards S-SE at Sint Eustatius.

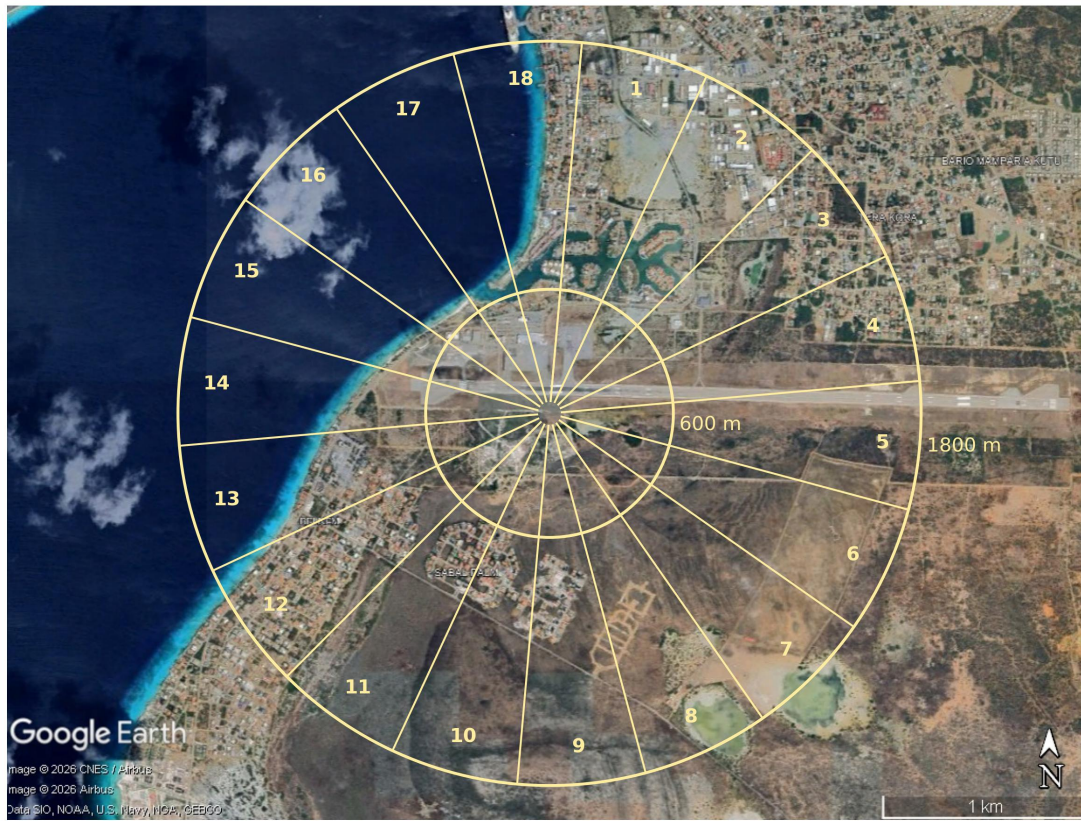


Figure F.36: Directional sectors around the wind mast at Bonaire (990).

F.28. Bonaire (990)

Bonaire (990) is surrounded by land (closest distance to water: 667 m). Largest disturbance of wind measurements from trees and tall shrubs between 141° – 155° and 200° – 261° (still $D/H > 10$), but prevailing wind direction is E-NE, so most wind measurements are not disturbed. To the SE “other roughness features (?) can cause problems for the quality of the wind measurements, especially in combination with strong gusts”.³³ Sensors are on a 10-m wind mast. Measurements done since 1-1-2013 and available in RobuKIS since 1-1-2016.

For Bonaire, we can calculate Sigma ECFs for Sectors 3, 4, 5 and 6 (45° – 124°), but there are nearly no measurements in other sectors because of the prevailing wind direction of the trades. Therefore, we will not calculate the potential wind for Bonaire as agreed in KNMI-WAG: We need 13-14 good sectors (Section 4.2) and only have 4, maybe only 3 if the disturbances to the SE are significant. Just as at Sint Eustatius, we could provide ECFs for the non-disturbed trade-wind direction sectors for aviation monitoring.

³³KNMI Inspection report Airport Flamingo Bonaire (18-10-2024)

G. Proposed algorithm implementations

In Section 5, we summarise the developed algorithm. Here, we propose how to implement this algorithm. The overviews below are thus aimed at software developers.

We differentiate between a near-real-time program (which runs every ten minutes) and a monthly program. Though both have many commonalities, there are some differences to ensure efficiency. In any case, the same code library should lie at the basis of computing ECFs and potential wind, regardless whether it is for a single 10-minute sample, for one month or even for a number of years (e.g. for research purposes). By using the same code library, it is guaranteed that the resulting time series of ECFs and potential wind are always the same.

For near-real-time updates, the following implementation is proposed:

	Algorithm	Remarks
1	Determine for which 10-minute timestamp ECFs were last computed and decide from that which would be the next one(s). ³⁴	Though taken at fixed 10-minute intervals, observations become available at unpredictable times. In particular, it can happen that more than one observation becomes available at (almost) the same time. Regardless of whether the implementation processes one sample at a time or several at once, the order of the observations matters because ECFs are computed over the 30 <i>most recent</i> samples.
2	Retrieve wind observations (D , U , σ_u) for one particular wind mast.	ECFs are computed per wind mast. It does not make sense to do this for a station with several sublocations (e.g. airports with several wind masts) as a whole because local roughness can differ per sublocation.
3	Determine the closest station with temperature measurements (T_{2m} , T_{10cm}) and retrieve those too.	For most stations, temperature measurements are available at the same location. For the few ones where that is not the case, it is probably best to use a lookup table of the closest station with temperature measurements. The lookup table may change due to station re-location or when temperature sensors are removed from the current closest station.

³⁴Also consider the fact that (depending on the used input source), for certain periods at certain stations ECF computation may be impossible. Currently the only known example is Hoek van Holland for the period 13-11-2012–30-04-2018 (see Section 4.1). For such periods, no new ECFs can be computed, but potential wind should be computed using the most recent ECFs (i.e. as if observation samples are filtered out).

4	Determine the wind-direction sector and the corresponding reference roughness length $z_{0,\text{ref}}$ and measurement height z_m .	See page 11 for the definition of the sectors. For $z_{0,\text{ref}}$ and z_m , a lookup table is recommended (see Table 2). The table changes if wind masts are re-located.
5	Determine if the observation sample meets all the filter requirements: ³⁵ • $A\kappa U/\sigma_u > \ln(20)$ • $U \geq 5.0$ m/s • $-0.3 \text{ K} < T_{2\text{m}} - T_{10\text{cm}} < 1.1 \text{ K}$ If so, U and σ_u go into the set of 30 samples with the same directional sector over which the median is taken. If more than 30 samples are in that set hereafter, the oldest sample is discarded.	The 30-sample set can be implemented as a local file or database, which stores 30 samples that pass the filters per directional sector. Without this, the algorithm would need to retrieve a larger number of samples each time and the amount of samples is not predictable beforehand depending on how often a wind direction occurs and filter conditions are met. (It can be a few hours to several months of data). Special care should be taken that this 30-sample store needs to remain intact after the program ends and even in case of maintenance or disruptions.
6	Retrieve the 30 samples corresponding to the current directional sector.	This does not necessarily contain the current sample (if it has not passed the filter). If less than 30 samples are present, no ECF can be computed. However, generating some kind of masked output (including a flag with the reason, e.g. non-neutral, wind too fast) is still required.
7	Compute the median $\langle \sigma_u/U \rangle$ over these 30 samples. Also determine the attenuation factor A using the median wind speed.	For A , the lookup table in Appendix D can be used. These values only change if different wind sensors are used (e.g. sonic anemometers instead of the current wind cups).
8	With $\langle \sigma_u/U \rangle$, A and z_m , compute the local roughness z_0 . Together with $z_{0,\text{ref}}$, compute the ECF. Finally, compute the potential wind speed.	Use Eqs 4 and 1. Keep track of the timestamp for this ECF, which is the time of the youngest observation in the 30-sample set. Note that we re-compute the ECF every 10 minutes even if the latest observation does not pass all filters. Since the computation is not very expensive, this may be easier for a generic program flow.

³⁵Ideally, we also want to exclude 10-minute windows in which a marked discontinuity (MD) occurred, because with an MD, average wind speed and standard deviation are computed over a shorter period. Since we currently do not have such a dataset at our disposal, we do the next best thing: using a dataset with MD. A dataset without MD would lead to unreliable wind directions, which is highly undesirable. If we had datasets with and without MD, we could filter out observations with MD by comparing the two. Note that MDs occur roughly 1 % of the time.

9	Publish the ECF and the potential wind speed as well as some meta-information about the ECF. Save the 30-sample store locally.	The published data should include at least: the timestamp of the potential wind speed (identical to the observation timestamp but not necessarily identical to the ECF timestamp), the ECF, the potential wind and flag(s) about why an ECF was computed or not. In addition, we could also include (in order of importance): the timestamp of the ECF, D , the sector ID, U . Publication should be on the KNMI Data Platform in netCDF files following CF conventions per 10 minutes and/or per wind mast.
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At the time of writing, 10-minute updates of ECFs and potential wind are technically not feasible at KNMI. Thus, we are developing software for monthly updates for now, which works as follows:

	Algorithm	Remarks
1	Determine for which month ECFs were last computed and decide from that which would be the next one(s).	Similar as in real-time flow. Monthly updates are always computed for whole months and no sooner than seven days after the end of a month (because until then, delayed measurements may still arrive).
2	Retrieve wind observations (D , U , σ_u) for one wind mast and the period of interest.	Similar as in real-time flow.
3	Determine the closest station with temperature measurements (T_{2m} , T_{10cm}) and retrieve those too.	Similar as in real-time flow.
4	Retrieve this wind mast's 30-sample store (i.e. 30 samples per sector that were previously saved). Put them into the same data structure (e.g. dataframe) as the retrieved observations.	See Step 5 of the real-time flow for an explanation of the 30-sample store.
5	Determine the wind-direction sector for all the samples as well as the reference roughness length $z_{0,ref}$ and measurement height z_m that corresponds to each sample's directional sector.	Similar as Step 4 of the real-time flow, but note that $z_{0,ref}$ and z_m differ per sample.
6	Remove observation samples that do not fulfil all the filter requirements (but do keep track of the reason, e.g. non-neutral, wind speed too low).	Requirements listed in Step 5 of the real-time flow.

7	Using a rolling window over 30 samples in the same directional sector, compute the median $\langle \sigma_u/U \rangle$ as well as the median wind speed $\langle U \rangle$. Using the latter, determine the attenuation factor A for each window.	Similar as in real-time flow, but here a rolling window is used to achieve a fast performance when dealing with a month or more of data.
8	Again using rolling windows over 30 samples in the same directional sector, first compute the local roughness z_0 and then the ECF.	Similar as in real-time flow (Eqs 4 and 1), but rolling windows are used again for performance.
9	Fill gaps in the ECF time series (compared to the timesteps of the measured wind speed) by repeating ECFs and filling in flags with the reason.	See Section 3.6.1 for an explanation of repeated ECFs. In technical terms, this corresponds to forward-filling the ECF series.
10	Compute the potential wind speed.	Corresponds to last part of Step 8 in the real-time flow (Eq. 1).
11	Publish the ECF and the potential wind speed as well as some meta-information about the ECF. Save the renewed 30-sample store locally.	Similar to Step 9 in real-time flow.

Note that both implementations require the 30-sample store. For each wind mast, it contains up to 30 observation samples per directional sector (so a total of up to 540 sets of D , U , σ_u and timestamps per wind mast). These need to remain intact between consecutive runs and program deployments. Given the amount of data, a simple file is probably easiest and cheapest.

Even once the real-time implementation becomes available, the monthly version should still remain operational. First, many users will find monthly files of ECFs and potential wind more handy than 10-minute files. Secondly, measurement data may be delayed (up to 7 days), so the monthly files may be more complete than the 10-minute dataset.

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