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Effect of uncertainties in the storm climate on the design and assessment of the Dutch primary water defences

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Sofia Caires
Jacco Groeneweg

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Summary

Key message:

Uncertainties and trends in storm climate have not been included in safety assessment and design of our primary flood defenses. This cannot be justified, since this study shows that a combination of a 5% increase in wind speed and 12% in wind climate uncertainty leads to a 1.5 – 4 m increase in required crest height in the coastal regions and 1 – 2 m increase along the dikes in the eastern part of IJsselmeer and Markermeer. Neglecting storm climate uncertainties is only justified when the storm climate becomes significantly milder and the decreasing trend is at least about half of the uncertainty in the storm climate.

This knowledge cannot be implemented in the “Beoordelings- en Ontwerpinstrumentarium” (BOI, i.e. the tools used for design and safety assessment for the Dutch primary sea defenses) yet, because it cannot be quantified accurately enough. The information of trends and uncertainty in storm climate used in this study is based on expert judgement (survey and workshop) and is no more than a rough estimate. Further research into storm climate trends and uncertainties, and impact on hydraulic loads has a high priority, since it is relevant for primary flood defenses in coastal regions and (large) lakes.

Although uncertainties in hydraulic loads are explicitly taken into account in BOI, the probabilistic tools do not yet take uncertainties in the storm climate (e.g. due to climate change) into account. Changes in storm climate may lead to significant impacts on hydraulic loads. The goal of the present exploratory study is to estimate the magnitude and impact of wind-climate uncertainties and to determine how we should deal with wind climate uncertainties for water defense design and assessment.

In order to get ‘realistic’ variations of the present wind statistics parameters in a sensitivity analysis, the relevant knowledge of wind statistics and climate-change experts was combined in a joint-expert recommendation of scenarios, in terms of parameter variations:

- In relation to the currently applied wind statistics parameters, the applied exponential distributions may have led to conservative point estimates and an underestimation of the standard deviation of the point estimates. An “adaptive statistics” scenario is defined where the point estimates are decreased by 5% and the standard deviation is increased to 10%.
- It cannot be excluded that in future climate remnants of tropical cyclones (post-tropical cyclones) reach the North Sea and the Netherlands more often. Therefore, a future (2100) scenario is defined where the current point estimates are increased by 5% and the standard deviation is increased to 12%.

- There is no evidence yet that the extratropical (mid-latitude) storm climate is changing significantly.
- It is difficult to separate natural variability of the wind climate from statistical uncertainty, since natural variability is accounted for in the statistical uncertainty.

In addition to the two scenarios mentioned above, also other combinations of decreasing and increasing point estimates and increasing standard deviations were considered in a sensitivity analysis. In total six scenarios were defined. The scenarios have been agreed upon by the experts and were given with the disclaimer that the values for the point estimates and standard deviation are rough estimates and should only be used for the uncertainty analysis of this study. A scenario with a change in wind direction of 10° in clockwise direction (wind speed unchanged) was added afterwards.

For the defined scenarios, Hydra-NL computations were carried out to determine the effect on the water level and required crest height (HBN) at locations in the lakes and coastal region. The following conclusions can be drawn from the consequence analysis:

- Including the trends and uncertainties in the storm climate mostly results in higher hydraulic loads. Hydraulic loads only decrease if the uncertainty in the storm climate is less than twice the decrease in the point estimate (trend).
- The water level and HBN values change very little for the “adaptive statistics” scenario (point estimates -5% and statistical uncertainty 10%) for locations at the lakes as well as coastal regions.
- For the “future scenario” with increased point estimates (5%) and increased standard deviation (12%) the water levels increase significantly, up to 40-60 cm at the lakes for wind-dominant locations. HBN increases by 1 – 2 m at those lake locations and 1.5 - 4 m at the coastal regions.
- A change in wind direction of 10 degrees has a secondary effect on the water levels and HBN levels in IJsselmeer and Markermeer (in most but not all cases an increase, of no more than 20 cm), and on the surge level in the coastal regions (up to about 0.25 m increase), compared to order 1 m increase in storm surge level in the “future scenario”.

From the expert meeting the conclusion was drawn that the wind statistics need to be updated. However, in this study it was concluded that the hydraulic loads were only very little affected in case of the “adaptive statistics” scenario. As the considered variations in the wind statistics parameters are rough estimates, this conclusion could be different in case the point estimates or standard deviation changes. E.g. changing only one of the parameters and keeping the other unchanged results in a 10% change in water level or HBN. Although relevant, we recommend not to adjust the reference wind statistics yet, but take the lessons learned into account when deriving new wind statistics based on seasonal forecasts, as presently been carried out by KNMI within the “Maatwerk” program.

The effect of the future scenario (increase of 5% of the current point estimates, standard deviation of 12%) on hydraulic loads is significant and therefore relevant for BOI. Since the

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estimates of the changes in wind statistics are rough, we recommend to first investigate the storm climate trends and uncertainties. Only when the uncertainty estimates are more certain, it becomes relevant to implement the changes in BOI.

The present probabilistic models to determine Hydraulic Loads along the Dutch coast and tidal waters, as incorporated in the BOI Design and Assessment Tools, do not allow for incorporating future trends in sea levels and storm climate in a physically correct and consistent way. It is therefore recommended to develop an alternative probabilistic model that is more flexible with respect to incorporating climate change effects.

References

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Nederlandstalige samenvatting

Kernboodschap:

Onzekerheden en trends in het stormklimaat worden niet beschouwd bij het ontwerp en de veiligheidsbeoordeling van onze primaire waterkeringen. Dat is onterecht, want deze studie toont aan dat de combinatie van 5% windtoename en 12% windklimaatonzekerheid leidt tot 1,5 tot 4 meter toename in de vereiste dijkhoogte langs de Kust, en 1-2 meter toename langs de oostelijke IJsselmeer- en Markermeerdijken. Het verwaarlozen van stormklimaatonzekerheden is alleen terecht wanneer het stormklimaat significant milder wordt, en de dalende trend tenminste half zo sterk is als de onzekerheid in die trend.

Toch is het nog te vroeg om deze inzichten direct te implementeren in het Beoordelings- en Ontwerpinstrumentarium (BOI) voor de primaire keringen. Er is namelijk dermate weinig kwantitatieve kennis over het toekomstig stormklimaat, dat de trends en onzekerheden in stormklimaat voor de huidige verkenning afgeschat moesten worden op basis van expert judgement. Nader onderzoek naar trends en onzekerheden in stormklimaat (en impact daarvan) heeft dan ook hoge prioriteit, zeker omdat dit relevant is voor een groot deel van de primaire keringen: in getijwateren, langs de grote meren, en in overgangsgebieden.

Voor het ontwerpen en beoordelen van primaire keringen wordt in Nederland gebruik gemaakt van officiële probabilistische methoden, welke onderdeel uitmaken van BOI. Ondanks dat onzekerheden in hydraulische belastingen expliciet in rekening worden gebracht, worden onzekerheden in het stormklimaat nog niet beschouwd. Deze onzekerheden kunnen het gevolg zijn van klimaatveranderingen. Veranderingen in het stormklimaat kunnen leiden tot niet-verwaarloosbare effecten op de hydraulische belastingen. Het doel van de huidige verkennende studie is om de grootte van de stormklimaat onzekerheden en hun effecten op de hydraulische belastingen af te schatten en te bepalen hoe we om zouden moeten gaan met stormklimaatonzekerheden bij het ontwerp en de beoordeling van de waterkeringen.

Om enigszins realistische schattingen van variaties van parameters van de huidige windstatistiek te verkrijgen, zijn experts op het gebied van statistiek en klimaatverandering gevraagd naar hun mening, met het doel om tot een aantal scenario's te komen. Hieruit zijn de volgende punten naar voren gekomen:

- In de huidige windstatistiek zijn exponentiele verdelingen gebruikt. Naar verwachting wordt het gemiddelde met 5% overschat en wordt de standaard afwijking onderschat (deze zijn thans locatie afhankelijk en in de orde grootte van 5%). Dit heeft geleid tot de definitie van een ("aangepast statistiek") scenario waarbij het gemiddelde met 5% is verlaagd en de standaard deviatie tot 10% is verhoogd.
- Het kan niet worden uitgesloten dat uitlopers van tropische cyclonen in de toekomst de Noordzee en Nederland vaker zullen bereiken. Om deze reden is een toekomstscenario (zeg 2100) gedefinieerd waarbij de gemiddelden met 5% zijn verhoogd en de standaarddeviatie is verhoogd naar 12%.

- Klimaatverandering heeft naar verwachting geen grote invloed op de bijdrage van reguliere (extra-tropische) stormdepressies aan het stormklimaat, al is die verwachting relatief onzeker.
- Het is moeilijk om natuurlijke variabiliteit in het windklimaat te scheiden van statistische onzekerheid .

Niet alleen de twee bovengenoemde scenario's zijn beschouwd, maar ook andere combinaties van verhoogde en verlaagde gemiddelden en verhoogde standaarddeviaties. In totaal zijn op deze manier 6 scenario's gedefinieerd. De experts zijn het eens over de gedefinieerde scenario's, maar deze zijn wel afgegeven met de disclaimer dat het om zeer ruwe parameterschattingen gaat en dat deze alleen voor de consequentie analyse in deze studie gebruikt mogen worden. Na afloop is een zevende scenario toegevoegd waarbij de windrichting 10˘ (met de klok mee) is gedraaid. De windsnelheid blijft ongewijzigd.

Met behulp van Hydra-NL berekeningen is het effect van de verschillende scenario's op de waterstand en de benodigde kruinhoogte (HBN) bepaald op locaties in de meren en kustregio's. De volgende conclusies zijn uit de consequentie analyse getrokken:

- Verdisconteren van trends in het stormklimaat leidt meestal tot hogere hydraulische belastingen. Deze lijken alleen maar af te nemen wanneer de onzekerheid in het stormklimaat niet meer dan twee maal het gemiddelde (van een dalende trend) is.
- Het "aangepaste statistiek" scenario (gemiddelde -5% en standaard afwijking 10%) leidt nauwelijks tot veranderingen in waterstand en HBN.
- Het toekomst scenario (gemiddelde +5% en standaard afwijking 12%) leidt tot significante toenames van de waterstand (40 - 60 cm op de meren voor wind-dominante locaties). Het HBN neemt 1 – 2 m voor wind-dominante locaties en 1.5 - 4 m voor kustlocaties.
- Een 10˘ verandering in windrichting heeft in vergelijking met de potentiele toename in stormopzet (van orde grootte 1m) door toekomstige windklimaatonzekerheden een secundair effect op de waterstand en HBN in het IJsselmeer en Markermeer (meestal een toename, van maximaal circa 0.2 m) en op de stormopzet in de kustregio's (ongeveer een toename van 0.25 m).

Uit de expert meeting werd de conclusie getrokken dat de huidige windstatistiek geactualiseerd zou moeten worden. Het effect van het "aangepaste statistiek" scenario op de hydraulische belastingen is marginaal. De beschouwde variatie van de statistiek parameters zijn echter ruwe schattingen. Door slechts een van de twee parameters te veranderen en de ander onveranderd te laten, verkrijgen we veranderingen van ongeveer 10% in waterstand en HBN. Ondanks dat dit een niet te verwaarlozen verandering is, bevelen we aan om de huidige windstatistiek vooralsnog niet aan te passen, maar de ervaringen uit deze studie mee te nemen bij de afleiding van nieuwe wind statistiek gebaseerd op seizoensverwachtingen. Deze afleiding vindt thans plaats door KNMI in het "Maatwerk" programma.

Het effect van het toekomstscenario (toename van 5% van het gemiddelde en toename tot 12% van de standaarddeviatie) op de hydraulische belastingen is zeer significant. Omdat de parameterschattingen van het toekomstscenario zeer grof zijn, bevelen we aan om eerst beter de trends en onzekerheden in het stormklimaat in beeld te krijgen. Pas wanneer de onzekerheidsschattingen duidelijk zijn wordt het relevant na te denken hoe de onzekerheden in het stormklimaat in het BOI programma kunnen worden geïmplementeerd.

De huidige probabilistische modellen voor de bepaling van Hydraulische Belastingen voor de Nederlandse kustwateren, zoals opgenomen in het BOI en WBI, zijn niet geschikt om zeespiegelstijging en stormklimaatveranderingen op een fysisch correcte en consistente wijze mee te nemen. Daarom wordt aanbevolen toe te werken naar een BOI-instrumentarium (en daarin besloten probabilistisch belastingmodel) dat meer flexibel is als het gaat om het meenemen van klimaateffecten.

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1 Introduction

1.1 Motivation

The design and assessment of the Dutch primary water defences is carried out with official probabilistic tools, which have been implemented in the legal assessment and design instrumentation, referred to as BOI (in Dutch: Basis en Ontwerp Instrumentarium). According to the new legislation, uncertainties in hydraulic loads must explicitly be accounted for in BOI, since they can have a major effect on the design and assessment of the water defences. However, although ample attention has been devoted to (climate change induced) sea level rise and how it can affect the hydraulic loads, the probabilistic tools do not yet consider (climate change) uncertainties in the storm climate. No studies have yet been done to assess it within the framework of BOI. Assessing the uncertainties in the storm climate can be of importance since the bandwidth of the extreme wind estimates due to climate variations of the past century and differences between climate models is in the order of 10%. In addition, it is important to consider that a 1% extreme wind speed increase can lead to a 3% increase in storm set-up. Although the storm climate seems to have become slightly milder between 1990 and 2010, there are also reasons for alertness: the rather extreme Dollard storm floods of 1/11/2006 and 6/12/2013, the heavy summer storm of 25/7/2015 (an equally severe summer storm occurred a century ago), and the Hurricane Ophelia (2017), which had just lost its hurricane power before reaching Ireland. According to a recent KNMI-Deltares study, with a slightly different path, Ophelia could have caused a near-normative event in the IJsselmeer region (De Vries et al., 2018).

As noted above, storm-climate trends may lead to non-negligible impacts on hydraulic loads. Furthermore, uncertainty in the storm climate without a visible systematic trend may also lead to non-negligible impacts: it is expected that an uncertainty of 2-7% on the storm-climate estimates (depending on the water system) is sufficient to be dominant in relation to the regular WBI water level uncertainties, which are often some decimetres. Therefore, it is legitimate to perform an exploratory study into the magnitude and impact of wind-climate uncertainties and to determine how we should deal with wind climate uncertainties for water-defence design, assessment and policy studies.

1.2 Activities

We distinguish three phases in order to explore the effect of trends and uncertainties in the wind climate on hydraulic loads:

1. Identify storm-climate trends and uncertainties based on expert advice.
2. Translate them to water levels, wave conditions and resulting water-defence heights for a number of locations along the lakes and coast.
3. Advice for possible actions regarding follow-up research and implementation.

Phase 1:

The extreme wind statistics used in the design and assessment of the safety of the Dutch primary water defences have been determined based on KNMI homogenized (potential) wind velocity observations in the period between 1979 and 2008 (Wever and Groen, 2009). The considered extreme wind statistics were determined for 12 directional sectors and comprise the 10,000-yr return values and the 95% confidence intervals for statistical uncertainty, see Caires

(2009). Experts are requested to provide advise on how these statistics should be adjusted to account for uncertainties in storm climate. This leads to various scenarios.

Phase 2:
The wind direction dependent extreme wind speed statistics, including statistical uncertainty, will be adjusted according to the scenarios defined in Phase 1. In the translation of the effects on the hydraulic loads on the primary defences a distinction needs to be made between lake water defences and coastal water defences.

For lakes, only dikes will be considered and the probabilistic assessment tool Hydra-NL (https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/omgevings/omgevings/hydra-nl-0/) to determine the hydraulic loads: water level, required crest height (abbreviated to HBN), and possibly the wave conditions at reference water levels for revetment assessment. These hydraulic loads have been analysed.

For the coastal region, i.e. Wadden Sea, Western Scheldt and the Holland Coast, the water level is currently determined from the sea level statistics and is not implemented as an output parameter in the probabilistic load model. Despite the strong correlation in the load model, changing the wind statistics will not affect the water level. Therefore, the translation of the scenarios will be done with simple calculation rules. A rough estimate of the impact on the hydraulic loads at a number of coastal locations has been made. For the time being, the impact assessment has not yet been carried out based on a more physical (simplified) model train, as applied for the lakes, with wind as an independent stochastic load variable and water level as an output parameter. We think that makes sense in a follow-up study, but not for an initial exploration.

Dunes are not considered, because the current load model for dunes requires considerable adjustment to include the effect of adjusted wind. Furthermore, in the dune model the water level is the only independent stochastic load variable and the wind is connected to it via a deterministic relationship.

Phase 3:
Advice is given for possible actions regarding follow-up research and implementation (in the program BOI). We will also indicate a prioritization.

2 Expert assessment

2.1 Approach

In order to apply in some sense ‘realistic’ parameter variations in the uncertainty analysis, wind statistics and climate-change experts were asked for their opinion and recommendations. The approach followed consisted of preparing a web-based survey, asking the relevant experts to fill in the survey and subsequently inviting them for a workshop, aiming at a joint-expert recommendation for the parameter variations.

2.2 Survey

A number of experts on Dutch wind statistics and climate change effects were asked to fill the survey in https://docs.google.com/forms/d/e/1FAIpQLSeKnXubBB8wTpcvukLXF0vnMEBQvyVp7YtCpUcqL9UnGe-jCg/viewform?vc=0&c=0&w=1. The survey questions and their replies are given in Appendix A.

The survey was filled in by Marcel Bottema (WVL), Henk van den Brink (KNMI), Geert Jan van Oldenborgh (KNMI), Andreas Sterl (KNMI), Cees de Valk (KNMI), Ine Wijnant (KNMI) and Renske de Winter (Deltares). Rein Haarsma (KNMI), Reinder Ronda (KNMI), Steven Knoop (KNMI) and Bart van den Hurk (Deltares) were also invited to fill in the survey but were unable to do it.

The survey consisted of 10 questions.

The first question asked the expert about his/her opinion on factors leading to uncertainties in the extreme wind statistics used in the design and assessment of the safety of the Dutch primary water defences. Statistical uncertainty, natural variability, effects of climate change on extra-tropical cyclones and effects of climate change on tropical cyclones were given as options but the experts could suggest other factors.

In the second question they were asked to order the given factors in terms of importance. Statistical uncertainty and natural variability where identified as the most relevant, followed by effects of climate change on tropical cyclones. With relation to the effects of climate change on extra-tropical cyclones the (educated) expert opinion was that natural variations are larger than the projected effects, Therefore the effect is substantially uncertain and a low confidence is given in projecting changes due to effects of climate change on extra-tropical cyclones. Additional effects that have been mentioned were the effects of large offshore wind developments and the increasing surface roughness due to constructions on land.

Questions 3 to 6 were about the currently applied standard deviations of the 10,000-yr return values estimates of Schiphol. The values for Schiphol were chosen as reference given that the Schiphol estimates are used as basis for the design and assessment of the primary water defences in Lake IJssel (and the tidal river area and Vecht-IJssel delta).Experts were asked whether they would recommend adjusting the omni and directional standard deviation values for the present, 2035 and 2100 and why. Furthermore, they were asked whether the proposed adjustments could be assumed to be valid for all return periods (not only 10,000-yr) and the whole of the Netherlands (not only Schiphol). The general opinion was that the current values of the standard deviations were probably too low and that the uncertainties would increase in the future. There were no firm statements in terms of spatial variability and contradicting replies to whether the relative standard deviations would depend on the return period. Overall, the expert opinion was that the uncertainties due to statistical uncertainty and natural variability (affecting the present and future standard deviations equally) are larger than due to climate change effects. The effect of climate change on tropical cyclones wherementioned as motivation for higher standard deviations in the future.

Questions 7 to 10 had to do with the currently applied 10,000-yr return values point estimates of Schiphol. Similar to what was done for the standard deviations, the experts were asked whether they would recommend adjusting the omni and directional values for the present, 2035 and 2100 and why, and whether the proposed adjustments could be assumed to be valid for all return periods and the whole of the Netherlands. The general opinion was that the present values may be overestimates due to statistical distribution considered in Caires (2009) and the observed trends in decreasing wind speeds above the Netherlands due to increases in surface roughness. With respect to the future, changes in tropical cyclones are mentioned by some as a possible reason for considering higher point estimates and large-scale offshore wind farm developments as a possible reason for considering lower point estimates. There were no firm statements in terms of spatial variability and whether the relative standard deviations should depend on the return period.

2.3 Workshop

The workshop took place at KNMI at April 12. The workshop was attended by Sofia Caires (mediator), Jacco Groeneweg (mediator and minutes taker), Marcel Bottema (organizer/participant), Henk van den Brink (participant), Andreas Sterl (participant), Cees de Valk (participant), Ine Wijnant (participant) and Steven Knoop (participant). Renske de Winter and Gert-Jan van Oldenborgh were unable to attend the workshop but provided input by filling the survey. Steven Knoop (KNMI) attended the workshop but did not fill in the survey.

The slides given in Appendix A with the results of the survey were presented in the workshop. The main points that have been discussed were:

- Effect of climate change on extra-tropical cyclones: The general consensus is that there will be no effect. More precisely, global warming will not change the wind climate over the Netherlands and the North Sea beyond the large range of natural climate variability that has been experienced in the past; with a large degree of uncertainty no changes are expected.
- Effect of climate change on tropical cyclones: It cannot be excluded that the frequency with which remnants of tropical cyclones reach the North Sea and the Netherlands will increase. The opinion of the experts is that this effect should be considered since, although there is low confidence in the projection, the impact can be large.
- Historical (century long) decreasing trend in winds above the Netherlands: This trend should be considered in the currently applied estimates (present) and should be investigated further. Wind above the North Sea does not decrease.
- Effects of planned large-scale wind farm developments in the North Sea: This should be kept in mind but at the moment the effect is still unclear.
- Seasonal effects: As pointed out as extra feedback by Renske de Winter, the changes in the seasonality of storms should be further investigated. In principle remnants of tropical cyclones occur early or before the start of the storm season. However, given the large uncertainties there are no concrete adjustments that can be recommended.
- Directional effect: As for the effect on extra-tropical cyclones, given that global warming is not expected to change the wind climate over the Netherlands and the North Sea beyond the large range of natural climate variability; with a large degree of uncertainty no changes are expected.
- Assumptions of Caires (2009): In relation to the currently applied estimates (present), the applied exponential distributions may have led to conservative point estimates and an underestimation of the standard deviation of the point estimates.

- Statistical uncertainty: Due to the above-mentioned exponential assumption, the statistical uncertainty is considered to be underestimated in the current statistics.
- Natural variability: It is difficult to separate natural variability from statistical uncertainty since natural variability is accounted for in the statistical uncertainty. If another period of data had been used to determine the current estimates, they would most likely differ, and this could be accounted for by increasing the standard deviation of the current estimates.

The recommendations that have followed from the discussion are given next.

2.4 Expert recommendation

The following recommendations followed from the expert workshop discussion. The standard deviation and point estimate adjustments have been agreed upon by the experts and are given with the disclaimer that they are very rough and should only be used for the purposes of the uncertainty analysis of this study, which is reported in the next chapter. The experts do not support the use of these values in other applications.

Time horizons: Given the large uncertainties whether climate change will be affecting the distributions of extreme winds, and when, it has been decided to consider only two reference times, namely the present and 2100.

Point statistics: The current values (Caires, 2009) are considered to be overestimates because the applied statistical distribution is considered to give conservative estimates and historical observations show a slightly decreasing trend in the wind speeds above the Netherlands due to an increase in surface roughness. Therefore, it is concluded that the current values might be decreased by 5%. Given the approximate character of the expert advice this decrease is proposed to be equally applied for all locations, return periods and wind direction sectors. For 2100 an increase of 5% of the current values is recommended mainly because a higher probability of tropical cyclone remnants reaching the Netherlands cannot be ruled out.

Uncertainties: The current values of the standard deviations (Caires, 2009) are approximately 5% and differ per location. They are considered to be low because the full uncertainty in the tail of the distribution was not accounted for when computing the standard deviation of the estimates. It is recommended to increase the standard deviations (by approximately a factor 2) to 10%. Given the approximate character of the expert advice this increase is proposed to be applied for all locations, return periods and wind direction sectors. For 2100 a higher value of 12% is recommended for the standard deviations, due to all uncertainties in terms of remnants of tropical cyclones, climate projections, wind farm developments, etc.

The table below shows the values from the expect elicitation that were agreed upon. It has further been recommended that the effects of the adjusted values should also be considered separately in the uncertainty analysis. More precisely, to consider the scenarios derived on the basis of Table 2.1 and given in Table 2.2.

Expert-judgement estimations	Present	2100
Points statistics	Current Values – 5%	Current values + 5%
Standard deviations	10%	12%

Table 2.1 Expert recommendations for the extreme wind speed point estimates and standard deviation of the extreme wind speed point estimates to be used the uncertainty analysis. 'Current Values' refers to the values given in Caires (2009) and which have been used as basis for the water defences assessment of 2017 Caveat: The given values are rough expert estimates, derived solely for the purposes of this study.

Scenarios	Point estimate	Standard deviation
1a	Current Values	10%
1b	Current Values – 5%	Current Values
1c	Current Values – 5%	10%
2a	Current Values	12%
2b	Current Values + 5%	Current Values
2c	Current Values + 5%	12%

Table 2.2 Expert recommendations for the uncertainty analysis scenarios. Note that the current values for the point estimate and standard deviation differ per location. The current standard deviations are approximately 5%.

After the workshop, a scenario 3 was added to the scenarios in Table 2.2, in which a change in wind direction has been considered. The wind speed is considered to be unchanged. A typical change in wind direction of 10 degrees is considered to be realistic, although the uncertainty of this estimate is large.

3 Effect of storm climate uncertainties on Hydraulic Loads

In the previous chapter various scenarios have been defined that reflect possible uncertainties in the storm climate. In the present chapter we investigate the impact of these scenarios on the Hydraulic Loads for the most relevant areas in The Netherlands. These are two lakes (Markermeer and IJsselmeer) and three coastal areas (Wadden Sea, Western Scheldt and the Holland Coast). In other regions the wind is less dominant and variations in wind statistics will have less impact on the hydraulic loads than for the coast and lakes.

The first Section, Section 3.1, describes how the wind statistics, that are used as input for the probabilistic assessment tool Hydra-NL, have been adjusted for the defined scenarios. For the lakes a different approach has been applied than for the coastal region. Therefore, the effect of the scenarios on the hydraulic loads has been analysed in two different Sections: Section 3.2 describes the impact for the lakes, Section 3.3 for the coastal area.

3.1 Adjustment of wind statistics

The probabilistic tool Hydra-NL requires statistical distributions for various stochastic variables, such as lake level, sea water level, wind speed and wind direction. In the case of the lakes it is assumed that the impact of the changing storm climate on extreme lake levels is small. Sea level rise has not been considered to assure an unambiguous analysis of the effect of storm climate uncertainty. Therefore, the scenarios in Table 2.2 only require adjustment of the wind speed statistics. Both the point estimates and the statistical uncertainty have been changed. The additional scenario 3 leads to a change in wind direction statistics.

The statistical uncertainty is not a separate stochastic variable in Hydra-NL. The statistical uncertainty is integrated in the point estimates, or average wind statistics, following the method described in Geerse (2016). The statistical distributions for wind without uncertainty and without correction for the wind drag maximization form the basis. These are taken from WBI 2017 (Chbab, 2017). The maximization of the wind drag is not taken into account in order to keep the analysis as clear as possible. Otherwise, changes due to a different scenario might be partly undone due to wind drag capping. This means that the reference statistics are the wind statistics including statistical uncertainty, but excluding wind drag maximization. These distributions are available within Hydra-NL.

For the lakes, Hydra-NL makes use of the (potential) wind statistics at Schiphol. For Markermeer the directional distribution considers 12 directions, for IJsselmeer 16. Along the coast, the wind statistics at five stations are relevant, i.e. Terschelling-West, De Kooij, IJmuiden, Hoek van Holland and Vlissingen. For each of the six scenarios seven input files have been generated, five for the coastal locations and two for Schiphol. Per direction and per location the exceedance curves for all scenarios have been plotted in order to check whether they make sense. This seems to be the case. The plots are included in Appendix B, as part of the (Dutch) memo provided by HKV. One important conclusion that can already be drawn is that the statistical distributions of scenario 0 (reference) and scenario 1c (adaptive statistics) are almost similar. Consequently, the difference in impact on hydraulic loads will be small if the point estimates are decreased by 5% and the standard deviation is increased to 10%. The same holds for the scenarios 1a (increase of standard deviation to 10%) and 2b (increase of point estimate with 5%).

The impact of scenario 3 can be considered by rotating the directional wind speed statistics over 10 degrees in clockwise direction. As a consequence also the directional wind speed for a given probability of exceedance rotates over 10 degrees, as illustrated in Figure 3.1 for the Schiphol wind statistics and an annual probability of exceedance of 1/10.000.

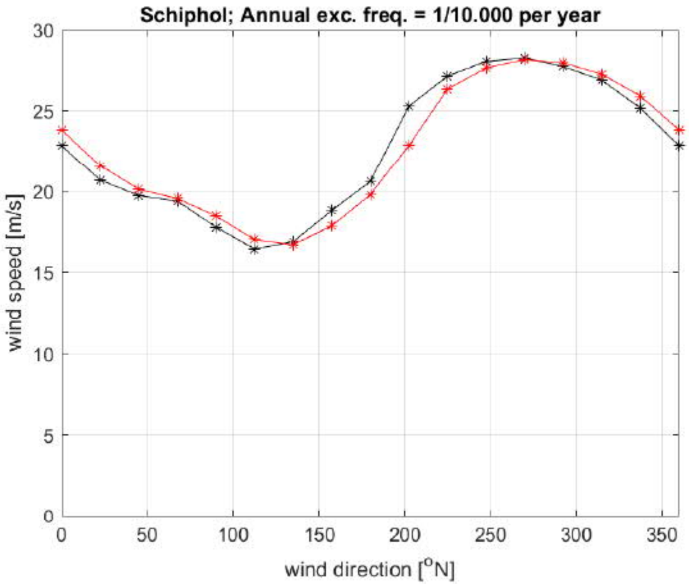

Figure 3.1 Directional wind speed at Schiphol for an annual probability of exceedance of 1/10.000 years: original (black) and shifted over 10 degrees (red)

3.2 Impact analysis for IJsselmeer and Markermeer

By changing the wind statistics, the Hydraulic Loads, in terms of water level, required crest height (abbreviated as HBN, i.e. 'Hydraulisch Belasting Niveau') and wave conditions at a reference water level (for assessment of revetments), will change. The changes in water level and HBN have been determined with Hydra-NL for all scenarios and been compared to the reference scenario. In addition, the conditional wave conditions at reference levels have been determined for scenarios 1c and 2c for two representative locations. Since the conclusions for the latter computations are in line with the conclusions for water level and HBN, these results of the conditional wave conditions (relevant for assessment of revetments), have not been described in more detail.

The computations were performed including model uncertainties. Seven locations distributed over IJsselmeer and six locations at Markermeer (see Figure 3.2) have been considered. These locations have been taken from the DEMO databases in Hydra-NL. The water levels have been determined for the trajectory norm, given in Appendix C for each location.

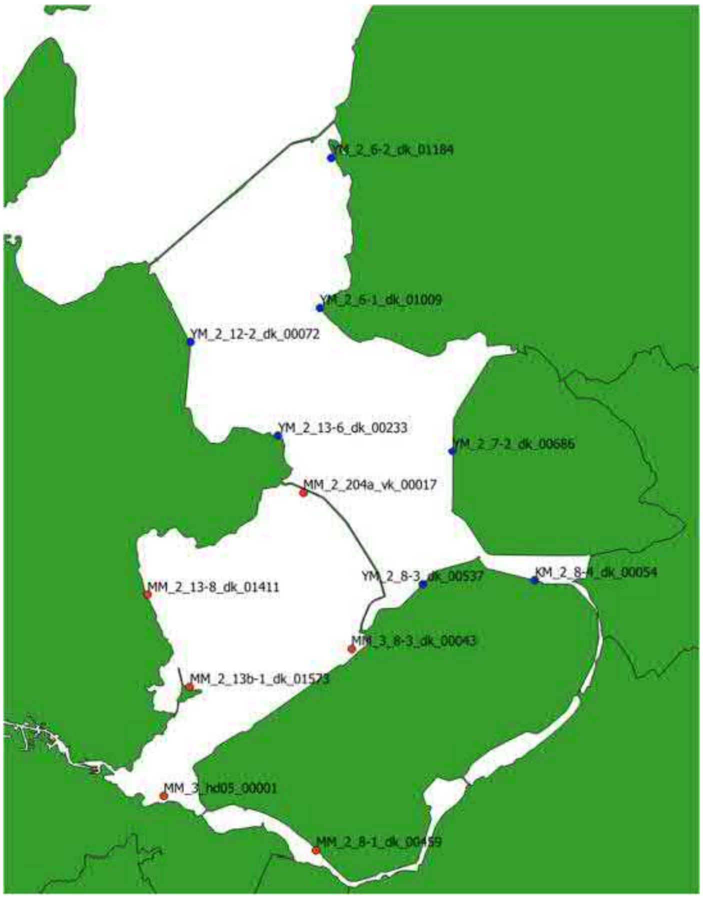

Figure 3.2 Locations in IJsselmeer (blue) and Markermeer (red) for which Hydraulic Loads have been determined.

The water levels obtained for the 6 scenarios have been compared to the water levels obtained with the reference wind statistics at the 7 locations in IJsselmeer and 6 locations in Markermeer. The comparison is presented in Figure 3.3 and Figure 3.4 for IJsselmeer and Markermeer respectively.

The IJsselmeer locations YM_2_12-2_dk_00072, YM_2_13-6_dk_00233 and YM_2_6-1_dk_01009 are close to the centre of the lake and are therefore lake level dominated. This means that impact of the wind on the water level is very modest. The water levels at these three locations are almost the same and show hardly any variation over the various scenarios. Also location YM_2_7-2_dk_00686 is lake level dominated, but the influence of the wind cannot be neglected. For the most severe scenario 2c the water level at this location increases by 10%, compared to the reference situation. The three other locations are strongly wind dominated.

When only the point estimates change by 5% (standard deviation unchanged, i.e. scenarios 1b and 2b) the water level changes by 10%. This change can be expected and is further explained in Section 3.3. Scenario 1c, which entails a decrease of the point estimates of 5% and an increase of the standard deviation to 10%, leads to almost the same values for the water levels as obtained with the reference wind statistics. This is due to the fact that the resulting statistical distributions are almost similar, as mentioned in Section 3.1. The most severe scenario 2c leads to increases of the water level of 40 - 60 cm. The surge level increases by approximately 20%.

Changing the wind direction over 10 degrees in clockwise direction hardly affects the water level. Only at the north eastern location YM_2_6-2_dk_01184, which is wind dominated, a decrease in wind speed from South West (see Figure 3.1) causes a water level decrease of approximately 15 cm.

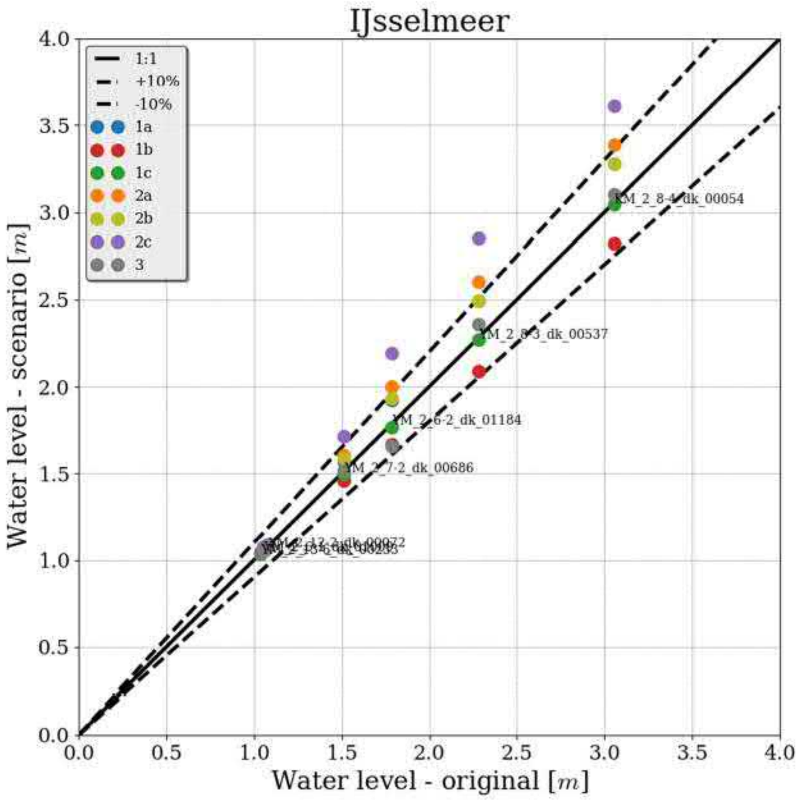

Figure 3.3 Comparison of water levels for reference case (horizontal axis) versus defined scenarios (vertical axis) at all locations at IJsselmeer. Scenario 1a (blue) almost gives identical results as scenario 2b. The solid black line is the 1:1 line, the dashed lines 10% lower and higher values.

The locations at the westbound of Markermeer are dominated by the lake level. Therefore, there is hardly any variation over the different scenarios. At the southbound of Markermeer (location MM_3_hd05_00001), the lake level is dominant, but the effect of the wind cannot be neglected, resulting in some variation in the water level. The remaining Markermeer locations are strongly wind dominated. The effect of the scenarios is similar to the effect seen for IJsselmeer. For the most severe scenario 2c, an increase of water levels of 40 - 50 cm have been observed, due to an increase of circa 20% (or more see location MM_2_8-1_dk_00459) in surge levels.

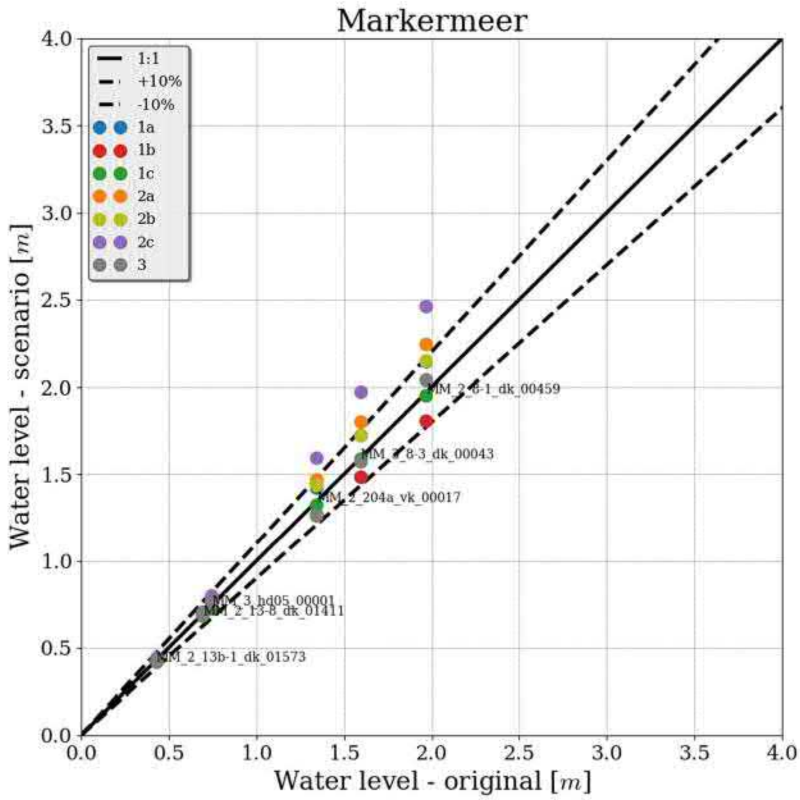

Figure 3.4 Comparison of water levels for reference case versus defined scenarios at all locations at Markermeer

The required crest height has been determined for a critical overtopping discharge of 5 l/s/m. The in-situ cross sections available in Hydra-NL have been used. Furthermore, the computations have been carried out for both the trajectory norm and the profile norm (in Dutch: “doorsnede-eis”). In the latter the effect of inhomogeneity along the trajectory and the contribution of wave overtopping to the failure distribution (i.e. 24%) have been taken into account. The profile norm is typically a factor 8 to 12 smaller than the trajectory norm. Only the HBN results for the profile norm have been presented here in Figure 3.5 and Figure 3.6 for IJsselmeer and Markermeer respectively. In Appendix C the profile norms are given for all locations.

For scenarios 1b and 2b, in which the point estimates change by 5%, the lake level dominated locations (YM_2_6-1_dk_01009, YM_2_13-6_dk_00233 and YM_2_12-2_dk_00072) show a variation of approximately 5%. The water level is not affected by the wind changes, but the wave height, and successively the wave runup and wave overtopping, is. For the wind dominated locations KM_2_8-4_dk_00054, YM_2_8-3_dk_00537 and YM_2_6-2_dk_01184 a 5% change in wind speed (and unchanged standard deviation, see scenarios 1b and 2b) results in a 10% change in HBN, since both the wave height and the water level contribute to a change in HBN. A similar change is obtained when only the standard deviation is increased to 10%, without changing the point estimates (scenario 1a). For the most extreme scenario 2c the increase in HBN varies between 1 and 2 m. Also, for the location YM_2_7-2_dk_00686, where the water level is dominated by the lake level, the increase in wind speed causes an increase in HBN of 1.5 m for scenario 2c.

The latter conclusions also hold for the wind-dominated locations MM_3_8-3_dk_00043 and MM_2_8-1_dk_00459. The HBN values increase by 1.2 - 1.8 m for scenario 2c. For location MM_3_8-3_dk_00043, the increase can be attributed to the larger (potential) wind speed, increasing from 35.5 m/s to 40.2 m/s from a north westerly direction. The lake level remains approximately the same. As a consequence, the wave heights increase from 3.8 m to 4.4 m, and the water level increases from 2.6 m + NAP to 3.3 m + NAP. This means that 35% of the HBN increase can be attributed to an increase in local water level and the rest to an increase in wave runup and overtopping. At the southern location MM_3_hd05_00001 the wind causes high waves and the HBN increases from 2 m + NAP to 2.6 m + NAP.

Finally, the effect of changing wind direction over 10 degrees is at most 2 dm for HBN. This is a secondary effect compared to the effect caused by the future climate (scenario 2c).

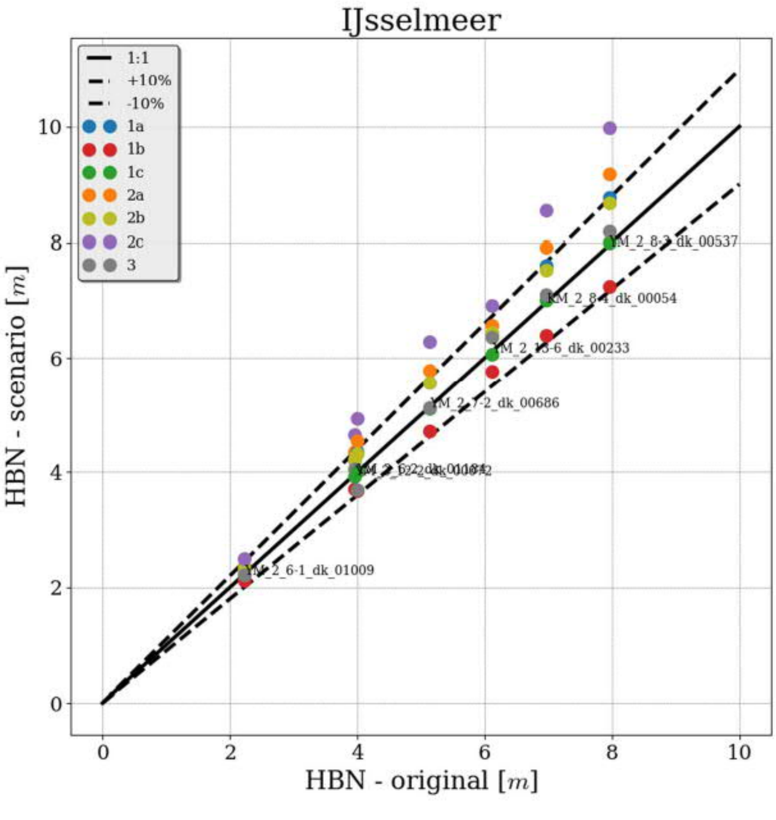

Figure 3.5 Comparison of required crest height for reference case versus defined scenarios at all locations at IJsselmeer

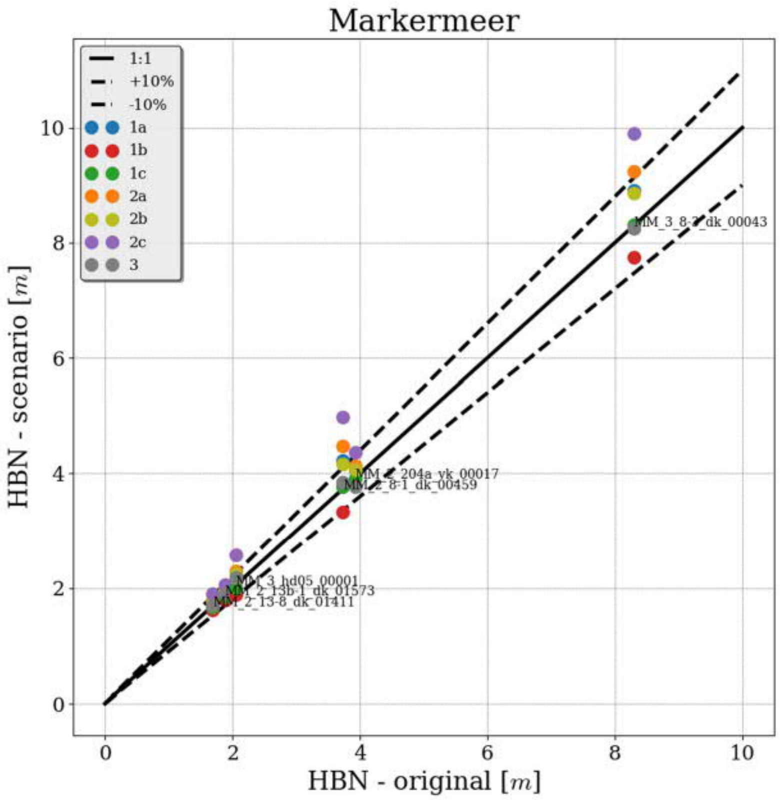

Figure 3.6 Comparison of required crest height for reference case versus defined scenarios at all locations at Markermeer

From the water level and HBN computations at the lakes we can conclude that the water level hardly changes for the "adaptive statistics" scenario 1c. The same holds for HBN. For the scenario 2c the water level changes by 40-60 cm and HBN by 1 – 2 m at wind-dominated locations. This is only due to changes in wind speed. A change in wind direction of 10 degrees (Scenario 3) hardly seems to affect the water levels and HBN levels.

3.3 Impact analysis for coastal area

At the lakes the water level is an output parameter, being determined by wind and lake level. However, along the coast the sea water level is modelled as a stochastic variable, strongly correlated to the wind. As a result, simply changing the wind statistics will hardly affect the local water level. All possible wind climate effects will be virtually undone by the water level statistics. Therefore, the translation of the change in wind climate to water levels will be done with simple calculation rules, resulting in a rough estimate of the effect of the wind climate scenarios on the hydraulic loads.

3.3.1 Pragmatic approach

The storm surge depends on various factors, such as wind speed, fetch length of the wind, wind direction, water depth, geometry of the coast and the location. The storm surge is roughly proportional to the square root of the wind speed and inversely proportional to the water depth.

For the North Sea the relation between wind speed and storm surge, as shown in Figure 3.7 for various wind directions, has been used.

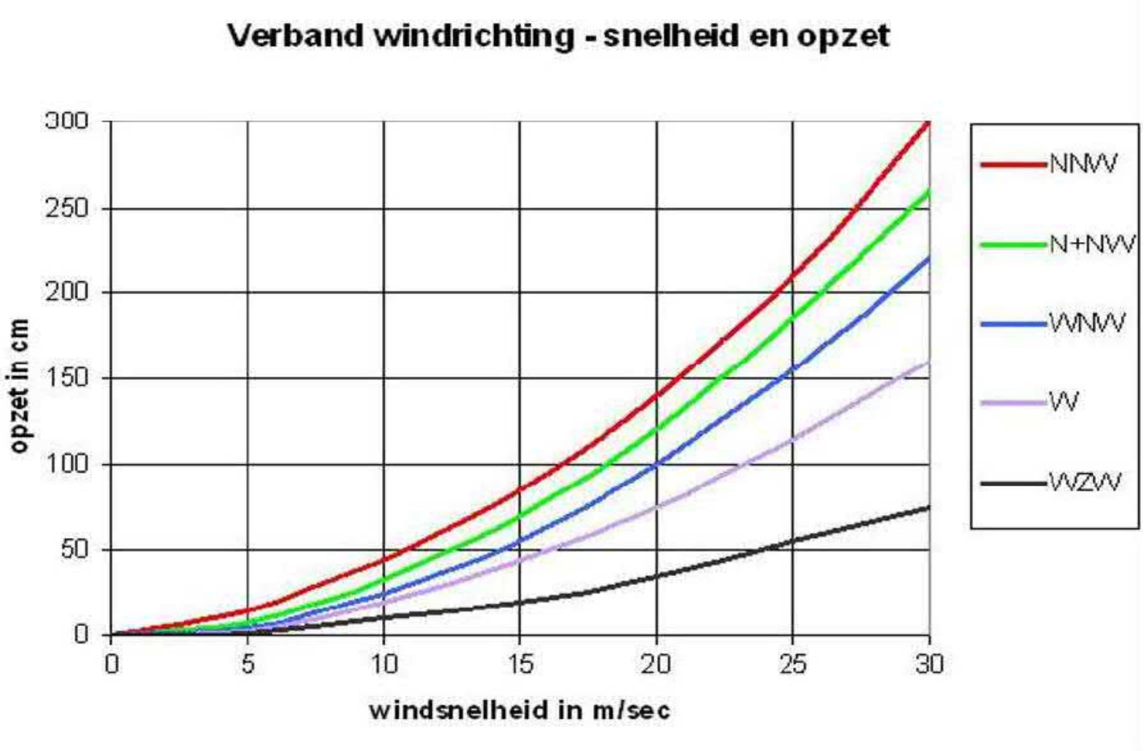

Figure 3.7 Theoretical relations between wind speed and storm surge at North Sea for various wind directions (Source: presentation "Meteo effecten op waterstand" of Jan Kroos)

The quadratic relationship can be written as

$$h = aU^2$$

with *h* the storm surge, *U* the wind speed and *a* a coefficient depending on different factors, e.g. depth, fetch. The relative change in storm surge as a function of the relative change in wind speed is

$$\frac{\Delta h}{h} = 2\frac{\Delta U}{U}$$

In other words, a relative change of 10% in wind speed results in a relative change of 20% in storm surge.

For each location we follow the following steps:

1. For the basic scenario 0 (reference wind statistics) we determine with Hydra-NL HBN and the corresponding values for water level, wind speed U and wind direction belonging to the illustration point;
2. We estimate the contribution of the tide to the water level and determine the storm surge *h*;
3. Per scenario we make an estimate for the relative change in wind speed, i.e. the combined effect of change in point estimate and uncertainty;

4. Per scenario we determine the correction $\Delta h = 2\frac{\Delta U}{U} h$;
5. Per scenario we perform Hydra-NL computations with a water level correction Δh and wind statistics corresponding to the specific scenarios.

Steps 2 and 3 are described in more detail in the sections below.

3.3.2 Determination of storm surge contribution

In step 2 the contribution of the storm surge to the water level in the illustration point needs to be determined. In Chbab (2015) the normative temporal evolution of the water level has been determined for several locations: Vlissingen, Hoek van Holland, Den Helder, Harlingen and Lauwersoog. The temporal evolutions are location dependent and have been determined by adding the average astronomical tide to a storm surge evolution, including a phase lag between both. The storm surge evolutions have a trapezoidal shape with a basic period of 30-44 hours and top period of 2-4 hours. The phase lag between the surge peak and the peak of the astronomical tide varies between 2.5 and 5.5 hours. Here we follow the WBI approach and determine the difference between the maximum water level (from the temporal evolution) and the maximum astronomical tide. Note that the water level statistics in WBI are based on the maximum water levels.

In Figure 3.8 the astronomical tide is added to the trapezoidally shaped storm surge level with a peak level of 4.5 m + NAP, assuming that the peak of the tide is 4.5 hours earlier than the storm surge peak. The difference between the maximum water level and the maximum storm surge level is 0.5 m. Due to the phase lag this difference is not 1.1 m, i.e. the maximum of the astronomical tide (relative to NAP).

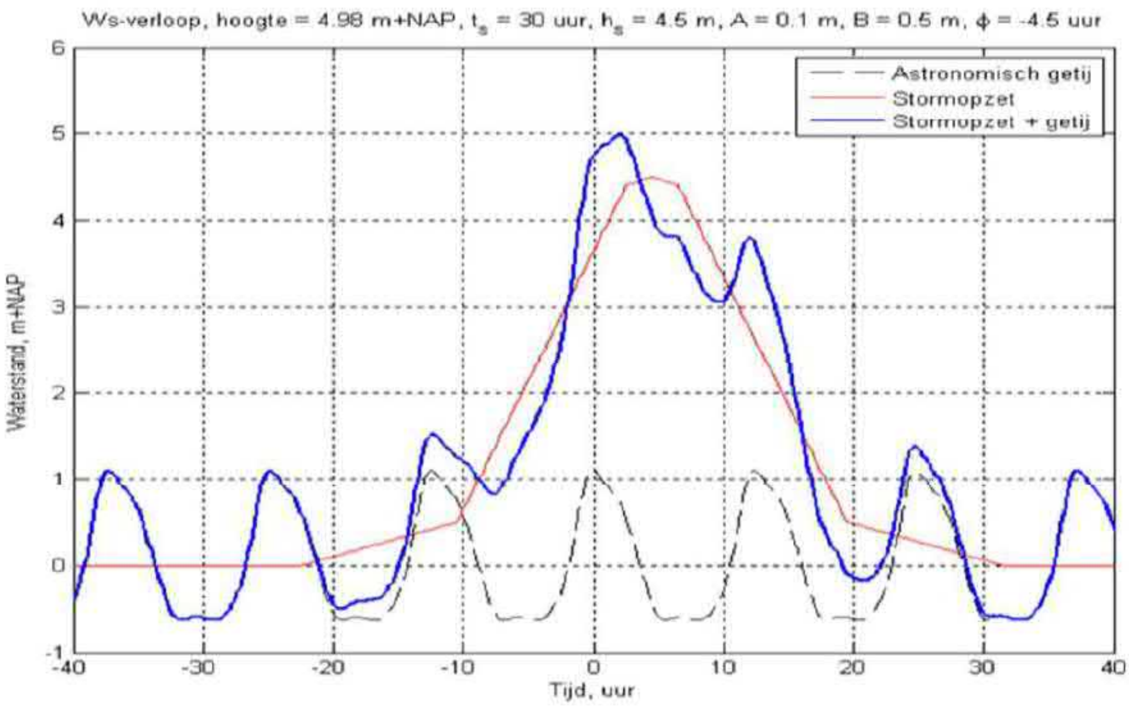

Figure 3.8 Temporal evolution of the water level at Hoek van Holland, corresponding to a water level of 5m+NAP (source: Figure 6.4 in Chbab, 2015)

We determined the difference between maximum water level and maximum storm surge level for all stations mentioned in Chbab (2015). These are given in Table 3.1. Although for locations deep in the Western Scheldt and in the eastern part of the Waddenzee, in particular the Eems Dollard, these differences will have another value, we made the pragmatic choice to uniformly allocate the values to the entire region. This means that the contribution of the surge level to the water level in the illustration point is determined by subtraction 1.0 m from the water level at all locations in the Western Scheldt and 0.5 m for locations along the Holland coast. For locations in the Wadden Sea 0.4 m is added.

Location	Phase leg tide and surge (hours)	Peak surge (m)	Peak average astronomical tide (m+NAP)	Maximum water level (m + NAP)	Maximum water level - maximum surge (m)
Vlissingen	2.5	5	2	6	1.0
Hoek van Holland	-4.5	4.5	1.1	5	0.5
Den Helder	2.5	5	0.6	5.5	0.5
Harlingen	5.5	5	1.1	4.6	-0.4
Lauwersoog	5.5	5	1	4.6	-0.4

Table 3.1 Difference between maximum water level and maximum surge level at five main stations, determined from figures in Chbab (2015)

3.3.3 Estimate of relative change in wind speed

In Step 3 the relative change in wind speed is determined. If only the point statistics change and the standard deviation remains the same, the relative change is obvious. If also the standard deviation changes than the relative change is not a general factor anymore. Here we describe how the relative change in wind speed has been determined for all scenarios.

For five base stations the statistical distributions corresponding to the six scenarios have been determined, see Section 3.1. Differences exist between the wind statistics in Hoek van Holland, IJmuiden and De Kooij, but for the purpose of the present analysis these differences have been neglected. Therefore, for the locations along the Dutch coast we only use the IJmuiden statistics to estimate the relative change in wind speed from the reference wind statistics for any of the six scenarios. Vlissingen and Terschelling-West are considered to be representative for the Western Scheldt and the Wadden Sea respectively.

In Step 1 the illustration point was determined for the basic scenario, including the normative wind speed and wind direction. Suppose that U = 25 m/s and the most probable wind direction is 270 ^{o}N. The probability of exceedance curve for the westerly wind at IJmuiden is shown in Figure 3.9 for all scenarios. The change in wind speed is determined by considering the wind speed of the alternative scenario with the same probability of exceedance as U = 25 m/s for the basic scenario. E.g. for U = 25 m/s the probability of exceedance is 1/1000 per year for the basic scenario. For scenario 2c the wind speed U = 28 m/s has a probability of exceedance of 1/1000 per year. The change in wind speed is therefore 3 m/s, as illustrated in Figure 3.9.

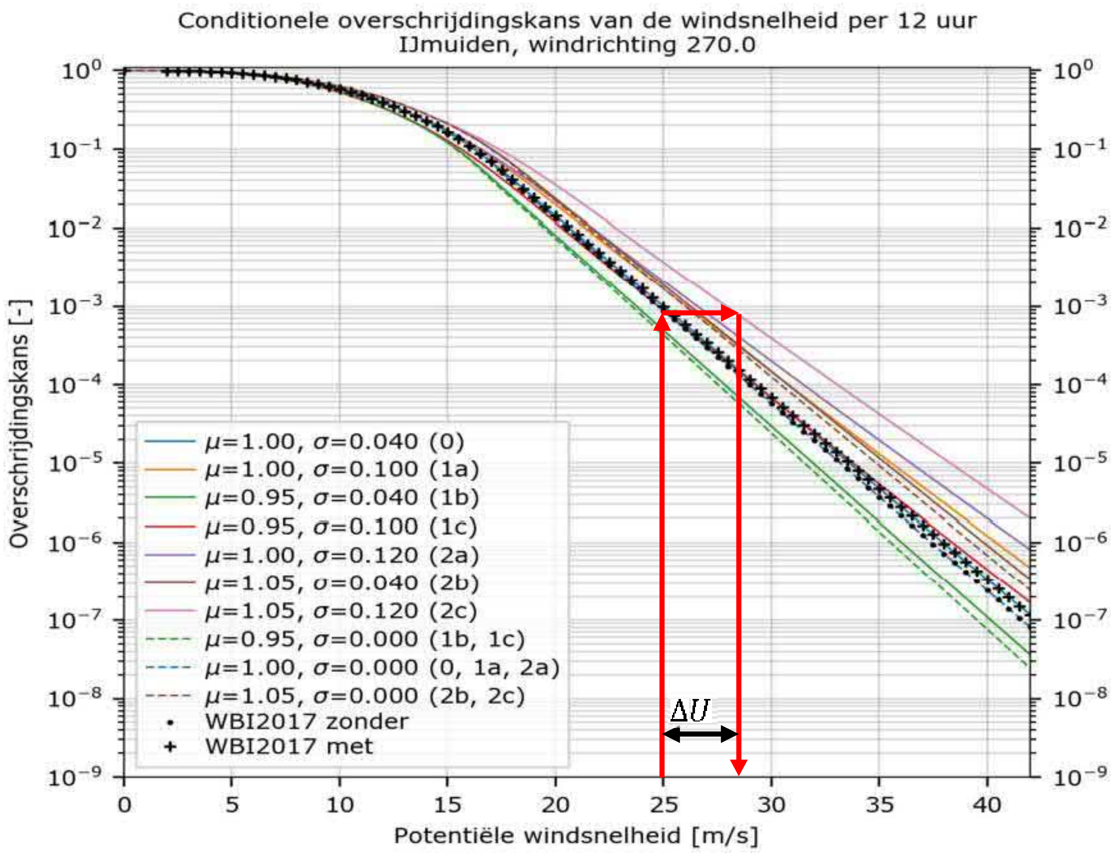

Figure 3.9 Probability of exceedance curves for the reference wind climate and the six scenarios with (solid lines) and without (dashed lines, σ=0) uncertainties for western wind at IJmuiden. Note that the current value for the standard deviation IJmuiden is σ=0.040.

3.3.4 Results of Hydra-NL computations

It is not useful to determine the effect of the wind changes on the water level for the coastal region. Therefore, we only make HBN computations. The method that was used is similar to the method that was used for the lakes. The locations in the DEMO databases of Hydra-NL have been considered. For Wadden Sea, Western Scheldt and Holland Coast these have been given in Figure 3.10.

The Hydra-NL computations have been performed with a critical wave overtopping discharge of 5 l/s/m. The in-situ cross sections stored in the DEMO databases have been used. The HBN levels have been determined for the profile norms.

Figure 3.10 Locations in Wadden Sea (red), Western Scheldt (blue) and along the Holland Coast (magenta) for which HBN levels have been determined.

The HBN levels have been determined for the six scenarios and compared to the HBN's obtained with the reference wind statistics. For the Holland Coast, Wadden Sea and Western Scheldt the comparison is presented in figures Figure 3.11, Figure 3.12 and Figure 3.13 respectively. The trends are even more unambiguous than in the lakes. Here at all locations the wind is the main threat for high HBN values. An increase in wind leads to an increase in both water level (actually storm surge) and wave heights, and therefore to an increase in HBN. Due to the pragmatic approach the relative effect of wind changes on storm surge is more or less uniform over all locations. Dike cross sections vary in slope and height and width of the berm, or do not have a berm at all. Consequently, the wave run up and wave overtopping varies per location and explains the variation in HBN increase.

From the HBN results we can conclude that the HBN level hardly changes for the "adaptive statistics" scenario 1c. For scenario 1a, where the point estimates remain unchanged, and scenario 1b, with unchanged standard deviation, a 10% change in HBN is obtained (up to 1.5 m). For the most severe scenario 2c however HBN changes by 1.5 m to even 4 m have been observed.

The 4 m change in HBN was observed for location HK_3_hd02-00005 along the Holland Coast.

The basic scenario resulted in a wind speed of 35.2 m/s from 300 ºN and surge estimate of 4.9 m. Going from the basic scenario 0 to scenario 2c provides a relative change in wind speed of 15% and consequently an absolute change in surge of circa 1.5 m (= 2 * 15% * 4.9 m), explaining almost 40% of the HBN increase. The increase in wind speed results in an increase in wave height from 4.0 to 5.0 m. The spectral wave period $T_{m-1,0}$ increases slightly by 0.3 s tot 10s. The increase in wave height and period explain the remaining 60% in HBN.

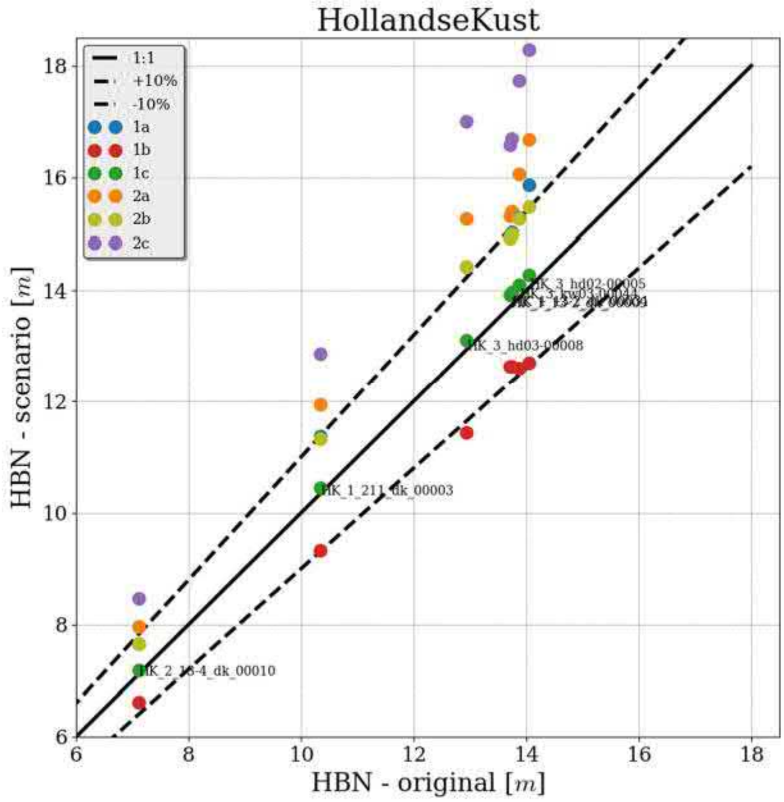

Figure 3.11 Comparison of required crest height for reference case versus defined scenarios at all locations along the Holland Coast

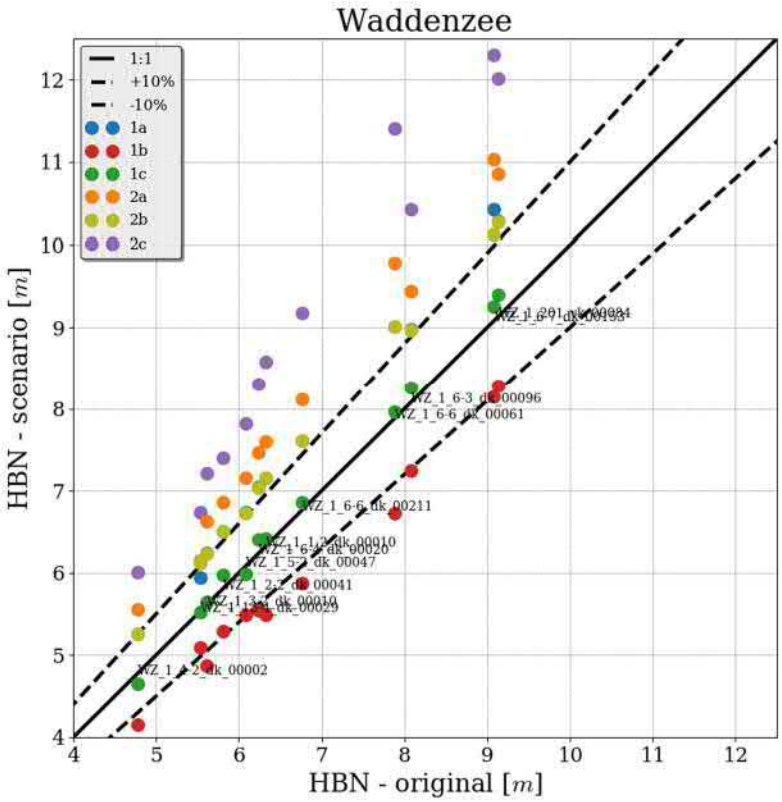

Figure 3.12 Comparison of required crest height for reference case versus defined scenarios at all locations at the Wadden Sea

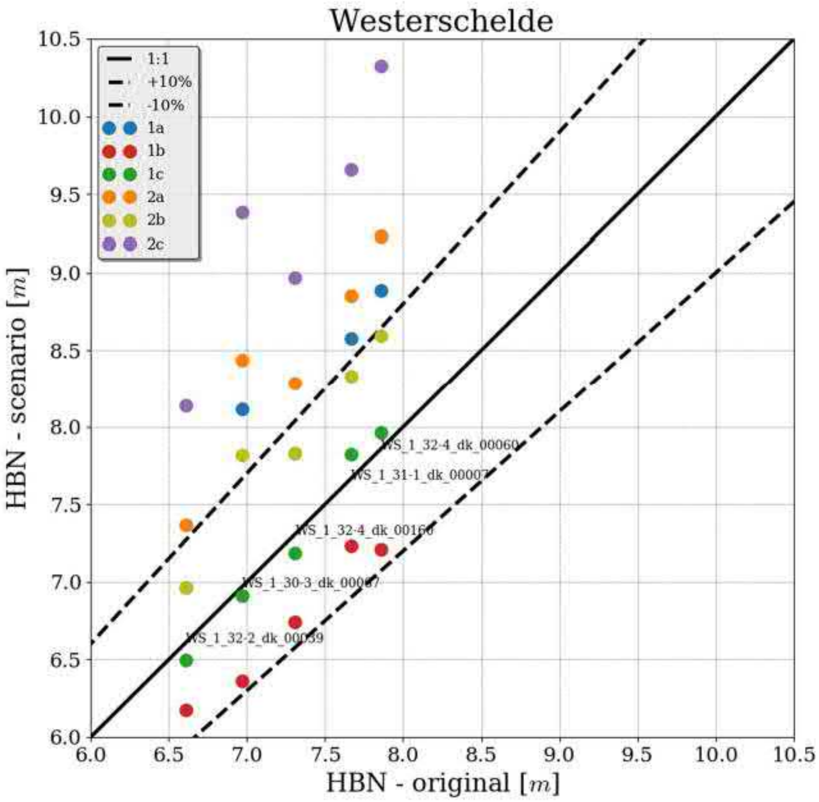

Figure 3.13 Comparison of required crest height for reference case versus defined scenarios at all locations at the Western Scheldt

3.3.5 Estimate of impact of wind direction change

The effect of a change in wind direction of 10 degrees (scenario 3) is small for the lakes, compared to the potential future climate impacts on wind speed. The same conclusion is not necessarily true for the coastal areas. It is not useful to change the wind statistics, due to the definition of the load model of the coastal regions and therefore the effect can only be estimated qualitatively.

Given the orientation of the North Sea the normative direction is NNW, also illustrated in Figure 3.7. With a rotation of the wind over 10 degrees the maximum wind speed turns more towards NNW and leads to higher surge levels. As can be seen in Figure 3.14 the wind speed increases approximately 1 m/s in the north-western sector, so let's say 3%. A 3% increase in wind speed leads to a 6% increase in storm surge level. For a 30 m/s wind speed from NNW this is almost a 20 cm (6% of 3 m) change in surge level. For the normative wind speeds given in Appendix C this will be approximately 25 cm. Compared to the change in storm surge level due to future scenario 2c (approximately 20% x 5m = 1m) this is a secondary effect, as for the lakes.

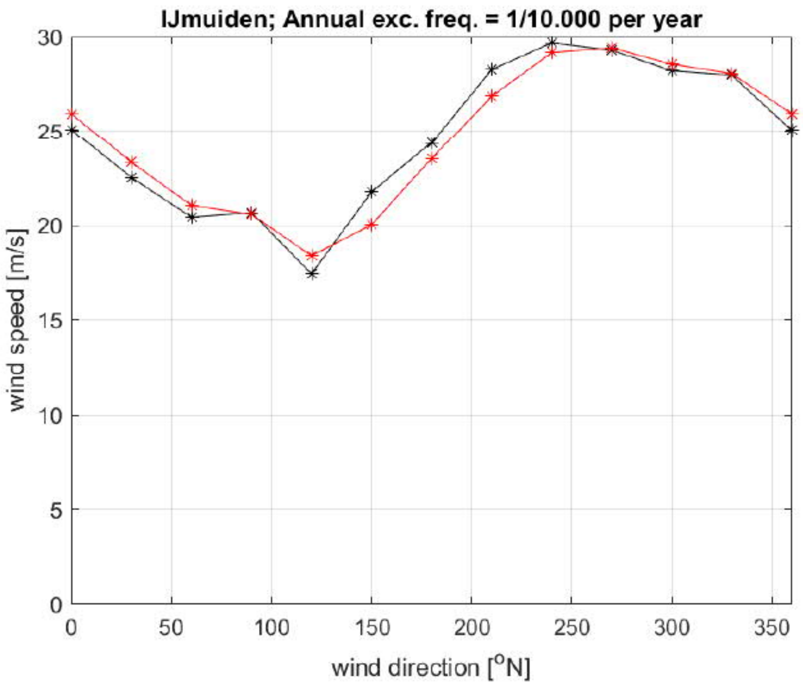

Figure 3.14 *Potential wind speed 10,000-yr return value estimates in m/s at IJmuiden: original (black) and shifted (red).*

4 Conclusions and recommendations

Based upon the conclusions and recommendations stated below, we formulate the key message of the present study as follows.

Key message:

Uncertainties and trends in storm climate have not been included in safety assessment and design of our primary flood defenses. This cannot be justified, since this study shows that a combination of a 5% increase in wind speed and 12% in wind climate uncertainty leads to a 1.5 – 4 m increase in required crest height in the coastal regions and 1 – 2 m increase along the dikes in the eastern part of IJsselmeer and Markermeer. Neglecting storm climate uncertainties is only justified when the storm climate becomes significantly milder and the decreasing trend is at least about half of the uncertainty in the storm climate.

This knowledge cannot be implemented in BOI yet, because it cannot be quantified accurately enough. The information of trends and uncertainty in storm climate used in this study is based on expert judgement (survey and workshop) and is no more than a rough estimate. Further research into storm climate trends and uncertainties, and impact on hydraulic loads has a high priority, since it is relevant for primary flood defenses in coastal regions and (large) lakes.

4.1 Conclusions

Although ample attention has been devoted to the effects of (climate change induced) sea level rise on hydraulic loads, uncertainties in the storm climate (for example due to climate change) and their effect on hydraulic loads have not yet been considered in the design and assessment of our primary sea and lake defences. In the present exploratory study, the results of an expert meeting on storm climate uncertainties in terms of changes in wind statistics, as well as their effect on the hydraulic loads are presented.

The main conclusions from the expert workshop are:

- Although uncertain, it is expected that climate change will hardly affect the contribution of extra tropical cyclones to the storm climate in the North Sea. Global warming will not affect the wind climate over the Netherlands and the North Sea beyond the large range of natural climate variability that has been experienced in the past.
- It cannot be excluded that the frequency with which remnants of tropical cyclones reach the North Sea and the Netherlands will increase. Although there is low confidence in the climate projections, the opinion of the experts is that this effect should be considered since the impact can be large.
- In relation to the currently applied estimates, the applied exponential distributions may have led to conservative point estimates and an underestimation of the standard deviation of the point estimates.
- It is difficult to separate natural variability from statistical uncertainty since natural variability is accounted for in the statistical uncertainty.

With respect to the wind statistics the following was concluded:

- It is concluded that the current values might be decreased by 5%. since the current values of the point estimates are considered to be overestimates and historical observations show a slightly decreasing trend in the wind speeds above the Netherlands due to an increase in surface roughness. Because the current values of the statistical uncertainties are considered to be low, it is recommended to increase the standard deviations (by approximately a factor 2) to 10%.
- For the future (say 2100-scenario) an increase of 5% of the current values is recommended mainly because it cannot be ruled out that the probability of tropical cyclone remnants reaching the Netherlands will increase. A higher value of 12% is recommended for the standard deviation to take into account uncertainties like remnants of tropical cyclones, climate projections, wind farm developments, etc.
- Given the approximate character of the expert advice, the recommended changes in point estimates and standard deviations are proposed to be applied for all locations, return periods and wind direction sectors.
- A scenario in which a change in wind direction of 10° in clockwise direction (wind speed unchanged) has been added.

The given standard deviation and point estimate adjustments have been agreed upon by the experts and are given with the disclaimer that they are very rough and should only be used for the purposes of the uncertainty analysis of this study.

Hydraulic loads, in terms of water level and required crest height (HBN), were calculated in the lakes and coastal regions with the defined wind statistic scenarios. The following conclusions can be drawn from the impact analysis:

- Including the trends and uncertainties in storm climate mostly results in higher hydraulic loads. Hydraulic loads only decrease if the uncertainty in the storm climate is less than twice the decrease in the point estimate (trend), see scenario 1c.
- The water levels and HBN's hardly change when replacing the currently applied wind statistics by the "adaptive statistics" scenario 1c (point estimates -5% and statistical uncertainty 10%). However, in case either the standard deviation is increased to 10% (scenario 1a) or the point estimate is decreased by 5% (scenario 1b), a 10% change in water level and HBN is observed.
- For the future scenario with increased point estimates (5%) and increased standard deviation (12%), the water levels increase significantly (40 - 60 cm at the lakes for wind-dominant locations), compared to the values obtained with the currently applied wind statistics. The HBN increases by 1 – 2 m at wind-dominated lake locations and 1.5 - 4 m at the coastal regions.
- A change in wind direction of 10 degrees in IJsselmeer and Markermeer hardly seems to affect the water levels and HBN levels, at most 20 cm. A similar change in the coastal regions is qualitatively estimated to result in 25 cm increase of the storm surge level. Compared to the change in storm surge level due to future scenario 2c (approximately 20% x 5m = 1m), this is a secondary effect, as for the lakes.

The effects of the defined changes on the wave conditions for revetment assessment have also been determined for a few scenarios and a few locations in IJsselmeer and are in line with the conclusions for water levels and HBN.

4.2 Recommendations

From the expert meeting it was concluded that the wind statistics need to be revised. The main point was that the exponential distributions in the reference statistics may lead to conservative point estimates and an underestimation of the standard deviation of the point estimates.

However, this study has shown that the effect of a decrease of the point estimates by 5% and increase of the standard deviation to 10% show a minor effect on the hydraulic loads. The considered variations in the wind statistics parameters are rough estimates. Changing only one of the parameters and keeping the other unchanged results in a 10% change in water level or HBN. Though relevant, we recommend that a revision of the statistics is given lower priority and to take the results of this study into account when considering the new wind statistics based on seasonal forecasts, that are presently being derived by KNMI within the “Maatwerk” program.

For the future scenario, a 5% increase of the current point estimates and a higher value for the standard deviation (12%) were used, mainly to take into account the higher probability of tropical cyclone remnants reaching the Netherlands. and regarding uncertainties in climate projections, wind farm developments, etc. As already mentioned, these estimates are very rough and can only be used for the present sensitivity analysis to get a first impression of the effect on the hydraulic loads. We therefore recommend to investigate the probability of tropical cyclone remnants reaching the Netherlands in more detail and determine more accurate changes in wind climate. If an increase of 5% of the point estimates is not realistic and only 10% standard deviation should be considered (i.e. scenario 1a), the increases in water level and HBN would be 50% to 70% less than those of a 5% increase of the point estimates. Only when the uncertainty estimates are clearer, it becomes relevant to think about the implementation of the changes in the program BOI.

The present probabilistic models to determine Hydraulic Loads along the Dutch coast and tidal waters, as incorporated in the BOI Design and Assessment Tools, do not allow for incorporating future trends in sea levels and storm climate in a physically correct and consistent way. It is therefore recommended to develop an alternative probabilistic model that is more flexible with respect to incorporating climate change effects.

Further recommendation following from the expert meeting are:

- Historical observations show a slightly decreasing trend in the wind speeds above the Netherlands due to an increase in surface roughness. This trend (and perhaps also other trends) should be considered upon the derivation of wind statistics. Note that a decreasing trend has not been observed above the North Sea.
- Effects of planned large-scale wind farm developments in the North Sea should be taken into account when estimating the wind climate uncertainties.
- Changes in the seasonality of storms should be further investigated. In principle remnants of tropical cyclones occur early or before the start of the storm season. However, given the large uncertainties there are no concrete adjustments to storm climate that can be recommended yet.

References

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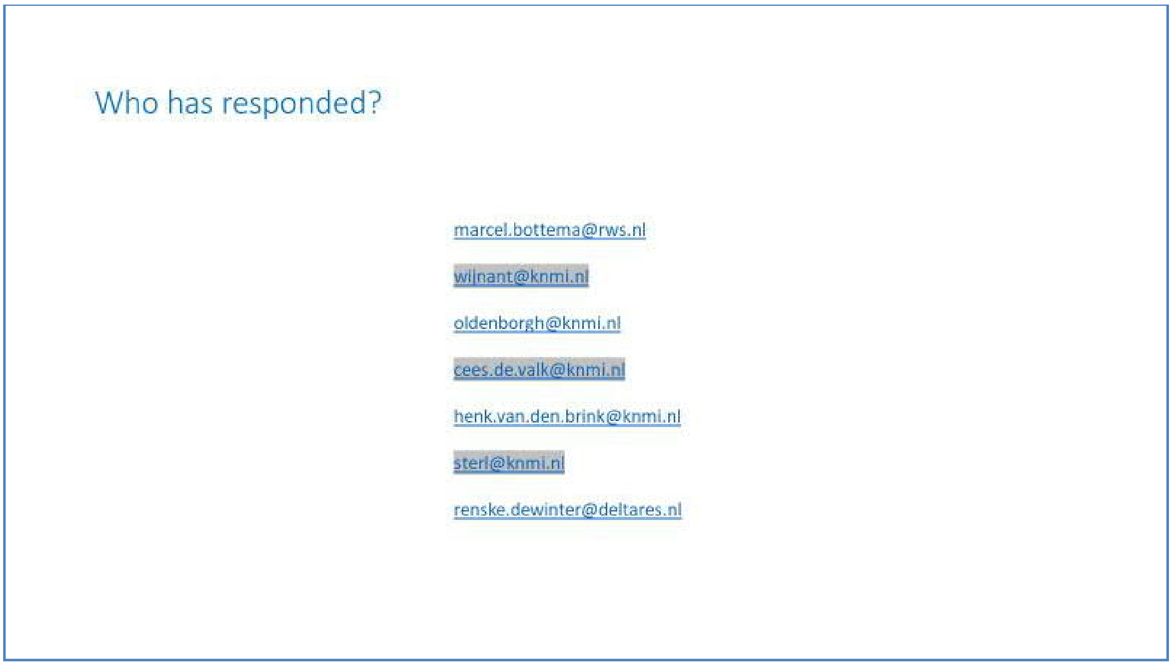
Wever, N and G. Groen, 2009: *Improving potential wind for extreme wind statistics*. KNMI Scientific Report WR2009-02, March 2009.

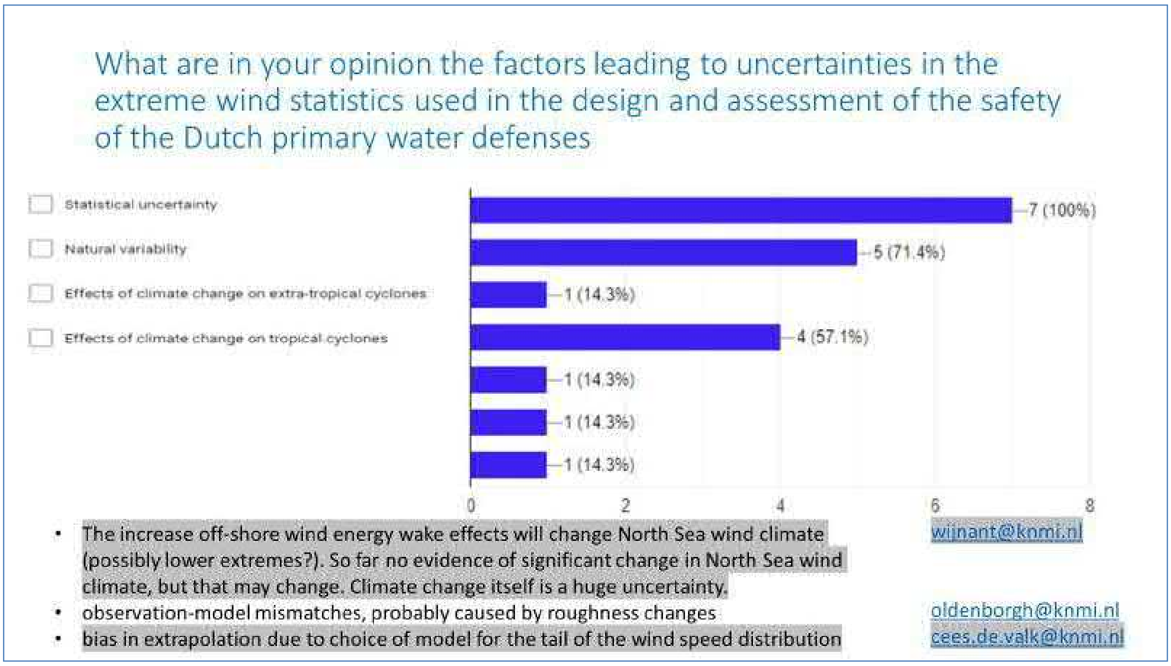
A Expert survey

The experts were asked to fill the survey in https://docs.google.com/forms/d/e/1FAIpQLSeKnXubBB8wTpcvukLXF0vnMEBQvyVp7YtCpUcqL9UnGe-jCg/viewform?vc=0&c=0&w=1. The questions and their replies are given in the following sections per question using the slides that where presented at the expert workshop. The last section of this Appendix contains extra feedback given by Renske de Winter (who could not attend the workshop). Some of the replies and comments are given in Dutch.

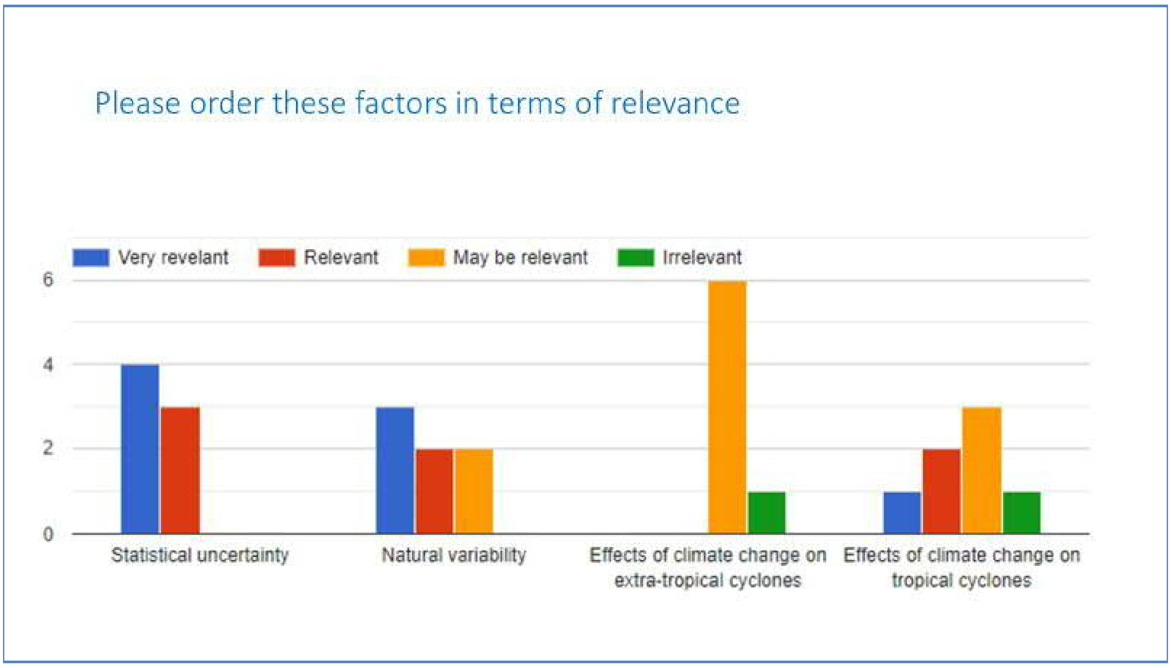
A.1 Survey participants



A.2 Question 1



A.3 Question 2



A.4 Question 3 (Standard deviations)

Can you please indicate by how much you think that the standard deviations of the estimates should be adjusted in the present (if at all), in 2035 and 2100?

Schiphol	10,000 yr	present
Directional sector	Point estimate (m/s)	Standard deviation of uncertainty (% of point estimate)
Omni	35.7	5%
North	27.1	4%
30°N	22.3	6%
60°N	24	4%
East	23.8	5%
120°N	18.9	4%
150°N	20.7	5%
South	25.6	5%
210°N	33.1	5%
240°N	34.6	6%
West	35.4	5%
300°N	34.2	6%
330°N	30.6	5%

marcel.bottema@rws.nl	5-10%
wijnant@knmi.nl	I can't give you numbers. Uncertainty for the present probably already higher (numbers are based on hindcast from 40 to more than 10 years ago and we have already seen evidence since of tropical cyclones reaching our latitudes). Uncertainty will be even higher for 2035 and 2100 (you will have to include the uncertainty about climate change).
oldenborgh@knmi.nl	Larger than given due to uncertainties in the trends.
cees.de.valk@knmi.nl	For OMNI and potential wind speed, yes: percentages seem to reflect the sampling uncertainty well, and the impact of natural variability seems to be limited. The impact of inhomogeneity is more difficult to assess. (as for total uncertainty: the quantile estimate itself may be positively biased by more than 5%) I do not know the uncertainties of the directional estimates.
henk.van.den.brink@knmi.nl	I think that the uncertainties are too low, as they incorporate only the statistical uncertainty from a model with only 1 parameter. These numbers should be doubled at least.
sterl@knmi.nl	order of magnitude ok
renske.dewinter@deltares.nl	Towards the future standard deviations may become a bit wider

A.5 Question 4 (Standard deviations)

Do you think that these effects (the uncertainty percentages filled) can be assumed to be valid in the whole of the Netherlands?

marcel.bottema@rws.nl	Dat lijkt bij gebrek aan info (uit lange reeksen van hoge resolutiemodellen) vooralsnog een goede hypothese
wijnant@knmi.nl	Yes. I cannot imagine that you can distinguish uncertainties for locations so close together for once in 10.000 year events. The factors leading to uncertainty for Schiphol are the same elsewhere in the Netherlands.
oldenborgh@knmi.nl	No
cees.de.valk@knmi.nl	Possibly not valid for coastal stations, but I have not looked into this yet.
henk.van.den.brink@knmi.nl	If you mean that the relative uncertainties are more or less constant over The Netherlands: yes.
sterl@knmi.nl	ja
renske.dewinter@deltares.nl	Storm charcteristics over sea might be quit different than above land, esspesically when wind direction is relevant

A.6 Question 5 (Standard deviations)

Do you think that these effects (the uncertainty percentages filled) can be assumed to be valid for other return periods (e.g. 1,000-yr and 100,000-yr)?

marcel.bottema@rws.nl	OK als starthypothese, maar zal nadere verificatie vragen als er nadere info is. Eerste aanbevolen stap is te kijken of evt. klimaattrends in gegeven windpercentielen (bijv eens per 1, 10, ..., 10000, 100000) jaar wind met elkaar in lijn liggen en met trends in de jaargemiddelde wind.
wijnant@knmi.nl	No (I expect the statistical uncertainty to be different?)
oldenborgh@knmi.nl	No idea
cees.de.valk@knmi.nl	These percentages would be approximately the same. However bias of the present estimates may increase somewhat with return period.
henk.van.den.brink@knmi.nl	No, you have to exclude the possibility that another phenomenon takes over (e.g. tropical cyclones)
sterl@knmi.nl	no, smaller for shorter return periods, higher for longer return periods
renske.dewinter@deltares.nl	I would not know that

A.7 Question 6 (Standard deviations)

Can you please explain what was your motivation for adjusting the given standard deviations of the estimates?

marcel.bottema@rws.nl	% stdev zou bij ander verdelingstype (logGW Cees de Valk?) wat hoger kunnen uitvallen, ook in huidig klimaat. Sowieso kan je vraagtekens stellen als directionele extremen een lager % hebben dan de omnidirectionele. Obv plus of min 10% variabiliteit huidig windklimaat en soortgelijke range in klimaatmodellen, zou je rekenen op een extra orde 5% (rel stdev) tgv klimaatonzekerheid, te combineren met de getallen in bovenstaande tabel. Waarmee je uiteindelijk op tabelwaarden van 5-10% komt. Voor NW-NO en ZO-ZW-wind wellicht zelfs 10% omdat veranderingen van voorkeursrichtingen van stormen hier relatief sterk kunnen doorwerken (gegeven de verschillen in percentielwaarden van naburige windrichtingen).
wijnant@knmi.nl	See above
oldenborgh@knmi.nl	I would not do a stationary analysis but take the observed trends into account, this increases the uncertainties.
cees.de.valk@knmi.nl	I did not adjust them. I compared values to my own analyses of the data of Schiphol and of large datasets of seasonal ensemble forecasts from different models.
henk.van.den.brink@knmi.nl	Only statistical, based on only one (1-parameter) model, no other effects are taken into accout (e.g. model uncertainty, other phenomena, trends).
sterl@knmi.nl	corresponds to own calculations
renske.dewinter@deltares.nl	Toward the future I would expect that the uncertainty becomes wider, this is not perse statistical uncertainty, but might be related to changes in the climate

A.8 Question 7 (Point estimates)

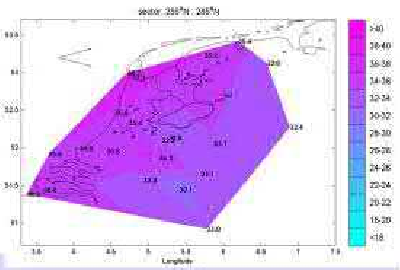
Can you please indicate by how much you think that the point estimates should be adjusted in the present (if at all), in 2035 and 2100?

Schiphol Directional sector	10,000-yr Point estimate (m/s)	present Standard deviation of uncertainty (% of point estimate)
Omni	35.7	5%
North	27.1	4%
30°N	22.2	6%
60°N	23	4%
East	21.8	5%
120°N	18.5	4%
150°N	20.7	5%
South	25.6	5%
210°N	33.1	5%
240°N	34.6	6%
West	35.4	5%
300°N	32.2	6%
330°N	30.6	3%

marcel.bottema@rws.nl	onbekend en samenstel van diverse factoren
wijnant@knmi.nl	Again, I can't give you numbers. Extremes may be higher (due to tropical cyclones), or lower (if climate change causes the prevailing wind direction to change to land-winds)?
oldenborgh@knmi.nl	Present: a few percent down for Schiphol, the observations show a 20%-30% decrease over 1950-2018. Future: I assume this trend will continue, so they should be lower, but until we attributed the trend we cannot make numerical projections.
cees.de.valk@knmi.nl	For OMNI, I would reduce the point estimate by order 7% (2.5 m/s)
henk.van.den.brink@knmi.nl	That requires quite some work to give an estimate for these numbers. We also have the issue that we have to derive the directional estimates from the omni-directional or vice-versa.
sterl@knmi.nl	no adjustment
renske.dewinter@deltares.nl	-

A.9 Question 8 (Point estimates)

Spatial validity of the adjustments in the point estimates



marcel.bottema@rws.nl	zie eerdere antwoord op stdev
wijnant@knmi.nl	I do not understand the question.. do you mean that the change of the once in 10.000 year westerly wind extremes for the whole of the Netherlands will be similar to the change in Schiphol? I think yes. Again I cannot imagine that you can distinguish uncertainties for locations so close together for once in 10.000 year events. The factors leading to uncertainty for Schiphol are the same elsewhere in the Netherlands.
oldenborgh@knmi.nl	No, the downward trend is absent in the coastal stations and only present inland.
cees.de.valk@knmi.nl	I do not know this, but similar adjustments might be expected.
henk.van.den.brink@knmi.nl	yes.
sterl@knmi.nl	I do not understand the question
renske.dewinter@deltares.nl	The figure show a good coverage over land, I'm not sure if they can be applied for coastal defences. Land wind characteristic are influenced by e.g. more trees ect. while extreme wind conditions above sea tend to originate from sea (So Southwest to Northwest) and not from land

A.10 Question 9 (Point estimates)

Do you think that these effects (the adjustments filled) can be assumed to be valid for other return periods (e.g. 1,000-yr and 100,000-yr)?

marcel.bottema@rws.nl	zie eerdere antwoord op stdev
wijnant@knmi.nl	No.
oldenborgh@knmi.nl	I think so.
cees.de.valk@knmi.nl	They would increase somewhat with return period but not much.
henk.van.den.brink@knmi.nl	yes
sterl@knmi.nl	I do not understand the question
renske.dewinter@deltares.nl	-

A.11 Question 10 (Point estimates)

Can you please explain what was your motivation for adjusting the given point estimates?

marcel.bottema@rws.nl	Trend moeilijk aan te geven door samenspel diverse factoren: - Klimaattrend sowieso onzeker. Mogelijk 2-5% afname (al dan niet bovenop een mogelijke afname sinds 1990), maar dit is allerminst zeker. Essentie is juist dat de stormklimaatonzekerheid groter is dan de trend, en dat het die onzekerheid is die evt. in ontwerpbelastingen kan doorwerken. - Extrapolatiemethoden van Cees de Valk geven wellicht tot orde 5% lagere 1/10000 wind maar grootte en richting van de verandering tov WBI-waarden is nog allerminst zeker. - 1/10000-openwaterwind kan ook orde 5% hoger uitvallen dan uit huidige stat extrapolaties door effecten dragaftopping. - En dan is er nog de vraag hoe goed/representatief/bruikbaar de nu gebruikte KNMI-landwind überhaupt is (krommingsprobleem HYDRA- en SBW-wind project)
wijnant@knmi.nl	See above
oldenborgh@knmi.nl	There are strong downward trends in the observations for all inland stations that are currently not reproduced by climate models.
cees.de.valk@knmi.nl	I compared values to my own analyses of the data of Schiphol, using different models of the tail.
henk.van.den.brink@knmi.nl	You have to know how representative the 1979-2008 period is (even in a stationary climate) to know whether the values are too low, good, or too high. And -as already said - other phenomena like tropical cyclones can take over for high return periods. Besides this, the concept of potential wind is a weak concept, so it is unclear how strongly this concept influences the answers.

A.12 Extra feedback

+ Renske de Winter

Mbt wind karakteristieken voor kustverdediging zou ik graag nog het volgende mee willen geven:

- 1. Ik weet niet in hoeverre er al gekeken is naar frequentie van stormen, voor kustafslag kan het relevant zijn of een 1:100y storm vaker voorkomt, ook al blijft de sterkte van de 1:10.000y storm hetzelfde.
- Voor zo ver ik weet is er nog niet gekeken of er een verschuiving optreed wanneer in het jaar stormen optreden. Momenteel wordt er tussen april en oktober onderhoud gepleegd aan bv de oosterschelde dam. Tijdens dit onderhoud kan de kering niet altijd sluiten, omdat bv sluitkleppen eruit worden gehaald. In het huidige klimaat is dat geen probleem, echter door bv afzwaaiers van tropische cyclonen zou het moment van het stormklimaat kunnen veranderen. Wat grote gevolgen zou kunnen hebben aan het plegen van onderhoud aan de keringen.

B Adapted wind speed statistics for defined scenarios

MEMO

Aan: Jacco Groeneweg (Deltares)
Van: Guus Rongen (HKV lijn in water)
Datum: 22 mei 2019
Projectnummer: PR4051.10
Onderwerp: Methodebeschrijving en resultaten windstatistiekscenario's met statistische onzekerheid

1 Introductie

In opdracht van Deltares heeft HKV voor zes scenario's de windstatistiek inclusief statistische onzekerheid afgeleid. Dit is statistiek waarbij de statistische onzekerheid is uitgeïntegreerd. Dit memo geeft een overzicht van de door HKV uitgevoerde werkzaamheden voor de zes scenario's. De statistische onzekerheid is uitgeïntegreerd voor de stations: de Kooy, Hoek van Holland, IJmuiden, Schiphol, Vlissingen en West Terschelling. Voor Schiphol verwerken we de statistische onzekerheid in de windstatistiek voor 12 en 16 windrichtingssectoren.

De zes scenario's waarvoor de statistische onzekerheid is verwerkt, zijn weergeven in Tabel 1.

Scenario's	Gemiddelde (Point estimate)	Standaardafwijking
1a	Huidige waarden (100%)	10%
1b	Huidige waarden – 5% (95%)	Huidige waarden (locatieafhankelijk)
1c	Huidige waarden – 5% (95%)	10%
2a	Huidige waarden (100%)	12%
2b	Huidige waarden + 5% (105%)	Huidige waarden (locatieafhankelijk)
2c	Huidige waarden + 5% (105%)	12%

Tabel 1 Scenario's waarvoor de statistische onzekerheid in de windstatistiek wordt uitgeïntegreerd

In hoofdstuk 2 wordt de gebruikte methode omschreven. Hoofdstuk 3 bevat figuren van de resulterende overschrijdingsfrequentielijnen, waarmee de resultaten visueel kunnen worden gecontroleerd.

2 Methode

Het uitintegreren van de statistische onzekerheid vindt plaats volgens de methode beschreven in (Geerse, 2016). Het multiplicatieve onzekerheidsmodel geldt voor de windstatistiek. Dit wil zeggen dat de grootte van de onzekerheid afhankelijk is van de grootte van de windsnelheid. Voor alle windstations volgt de statistische onzekerheid een normale verdeling. Vergelijking (1) geeft de methode om de onzekerheid uit te integreren in formulevorm.

$$
\begin{aligned}
P(V > v) &= P(XY > v) \\
&= \int dx\, f(x) P(XY > v | X = x) \\
&= \int dx\, f(x) P(Y > v/x | X = x) \\
&= \int dx\, f(x) \left[1 - F_{Y|X=x}(v/x)\right]
\end{aligned}
\quad (1)
$$

Waarin X de windsnelheid is zonder statistische onzekerheid, Y de normale verdeling van de statistische onzekerheid en V de windsnelheid met daarin de statistische onzekerheid verwerkt.

De overschrijdingskansen van de windsnelheid zonder statistische onzekerheid zijn beschikbaar vanuit WBI2017-gegevens van de basisstochasten (Chbab, 2017). Ook de onzekerheidsparameters (gemiddelde en standaardafwijking) zijn uit deze bron beschikbaar. De overschrijdingskansen van de windsnelheid zonder statistische onzekerheid zijn als basis gebruikt voor het uitintegreren. Dit komt overeen met de overschrijdingskansen uit het Hydra-NL invoerbestand van de windstatistiek *zonder* onzekerheid. Winddragafkapping voor windsnelheden groter dan 28 tot 30 m/s is niet verwerkt in de statistiek.

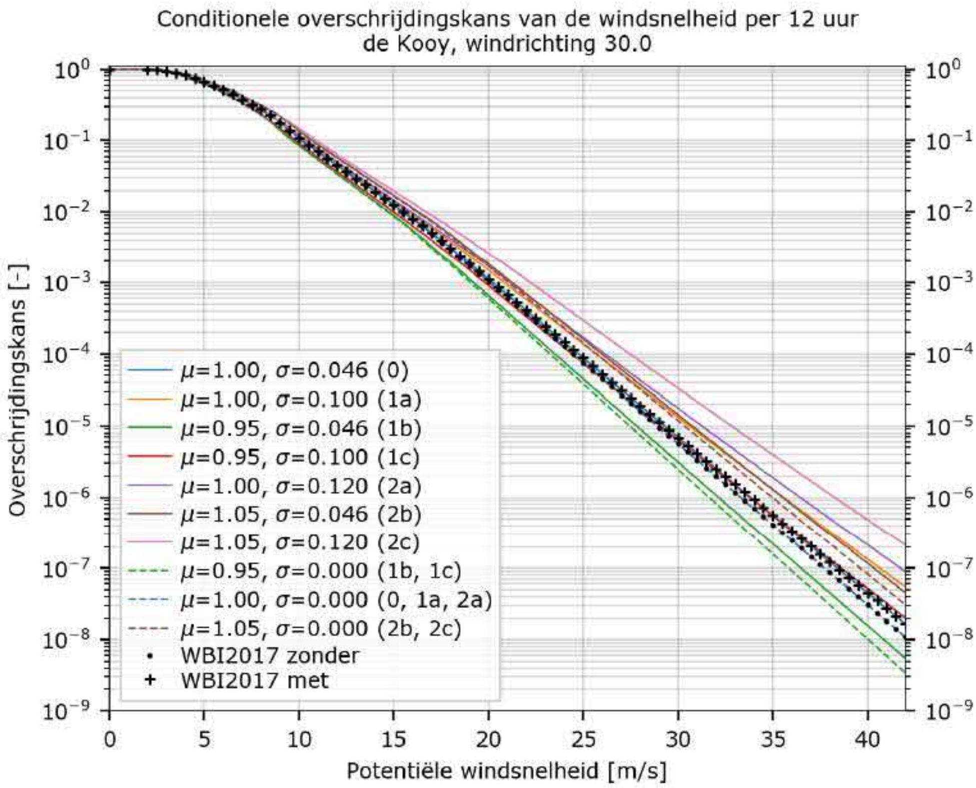
3 Resultaat

Dit hoofdstuk geeft de resultaten van het uitintegreren, door de overschrijdingsfrequentielijnen voor de zes scenario's met en zonder statistische onzekerheid te weergeven. De nul-variant is als zevende variant toegevoegd. Deze bevat de standaardparameters voor de modelonzekerheid, en is daarmee een variant waarmee de methode kan worden geverifieerd. De frequentielijnen zijn per station en richting weergeven in één figuur. Elke figuur bevat 12 lijnen:

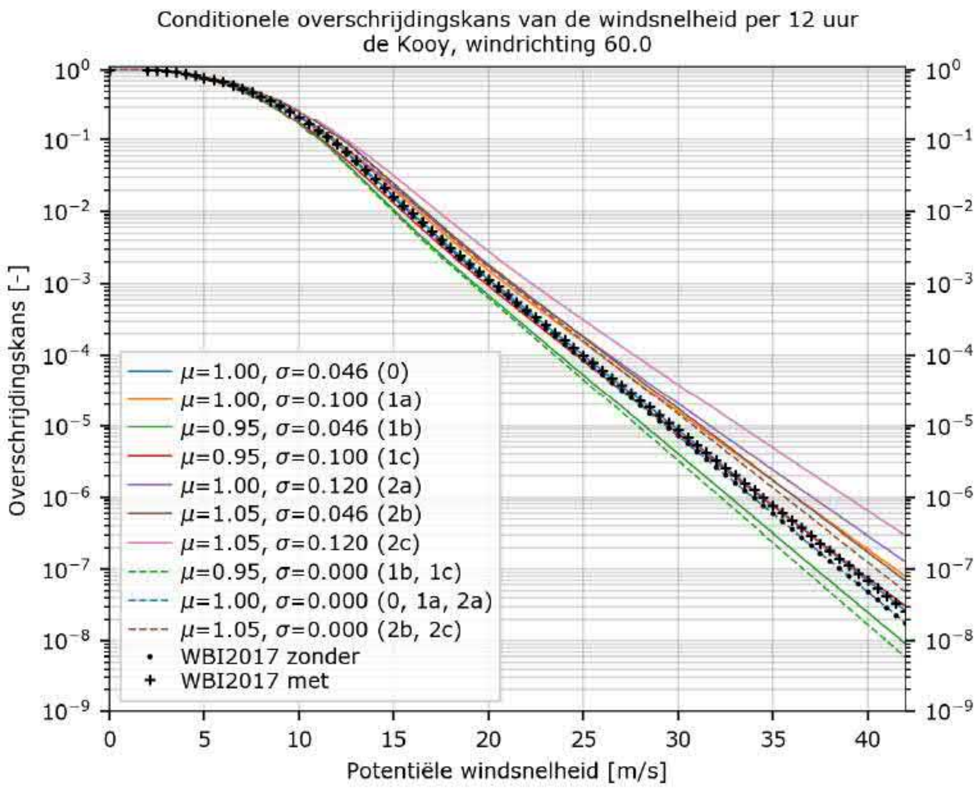
- De zes lijnen voor de zes scenario's met onzekerheid zoals gepresenteerd zie Tabel 1;
- Drie lijnen voor de zes scenario's zonder onzekerheid. Alleen dus met een variatie van het gemiddelde, want de standaardafwijking is 0;
- Eén lijn met de nul-variant inclusief onzekerheid. De nul-variant zonder onzekerheid komt terug in de drie lijnen zonder onzekerheid en is dus niet expliciet weergeven;
- Twee lijnen met WBI2017 statistiek. Deze moeten op de lijnen van de nul-variant liggen.

Elk van de volgende paragraven bevat de figuren per windrichting voor een station, waarin voor Schiphol nog de uitsplitsing is gemaakt tussen 12 en 16 richtingsectoren.

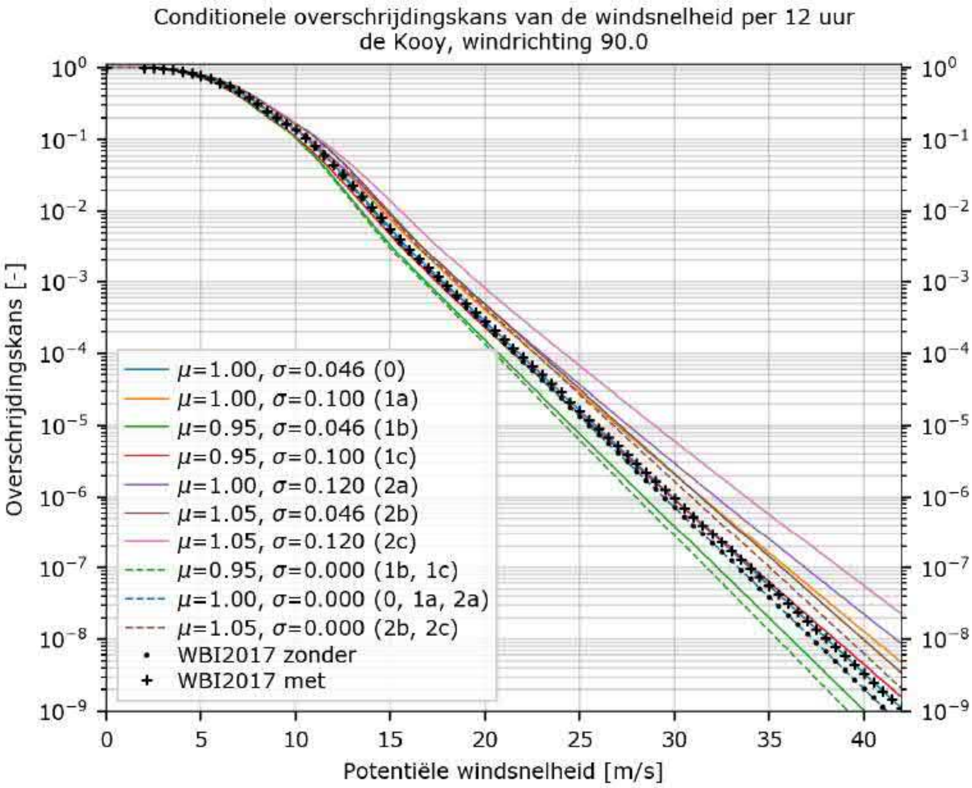
3.1 de Kooy



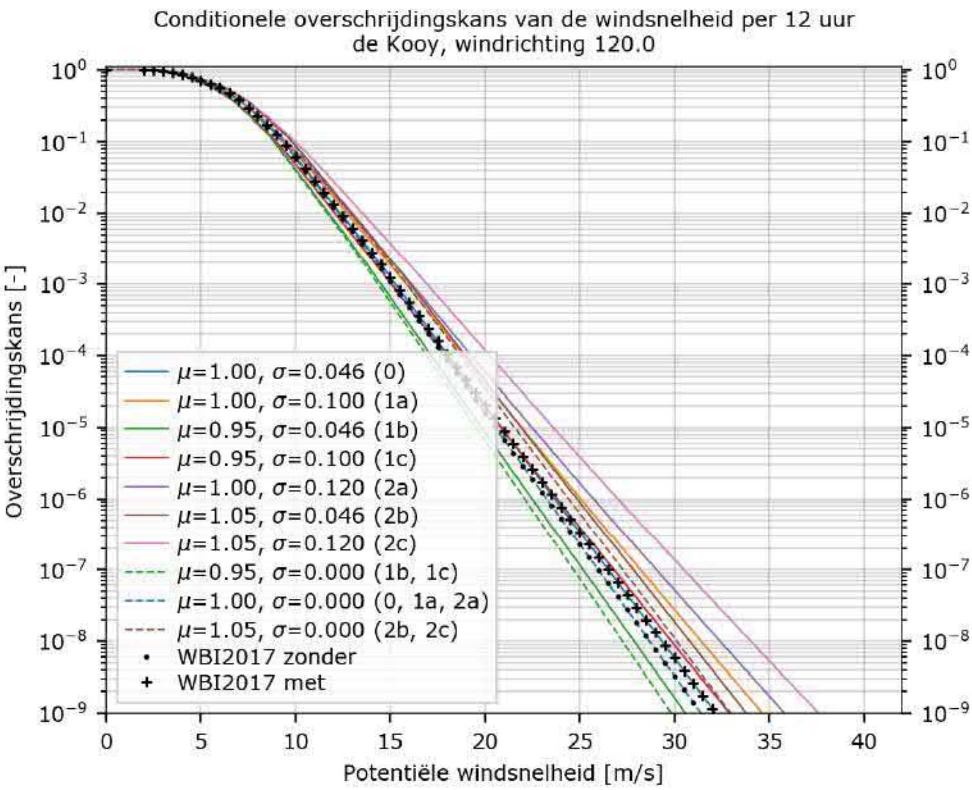
Figuur 1 Overschrijdingsfrequentielijnen voor windrichting 30.0 voor de Kooy.



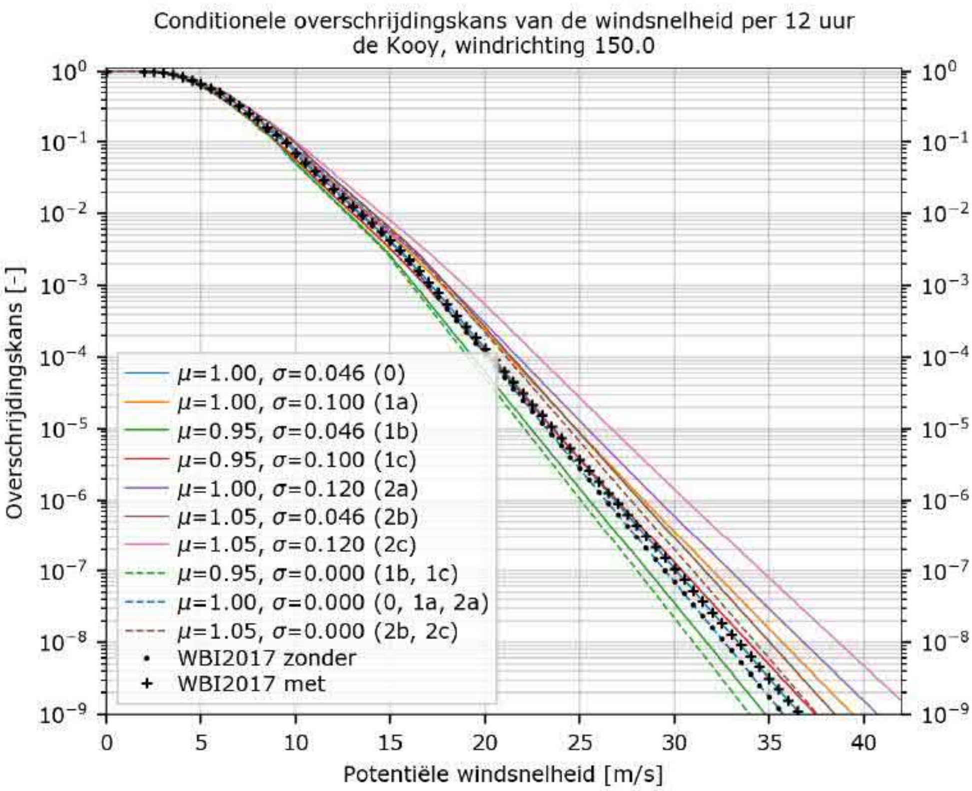
Figuur 2 Overschrijdingsfrequentielijnen voor windrichting 60.0 voor de Kooy.



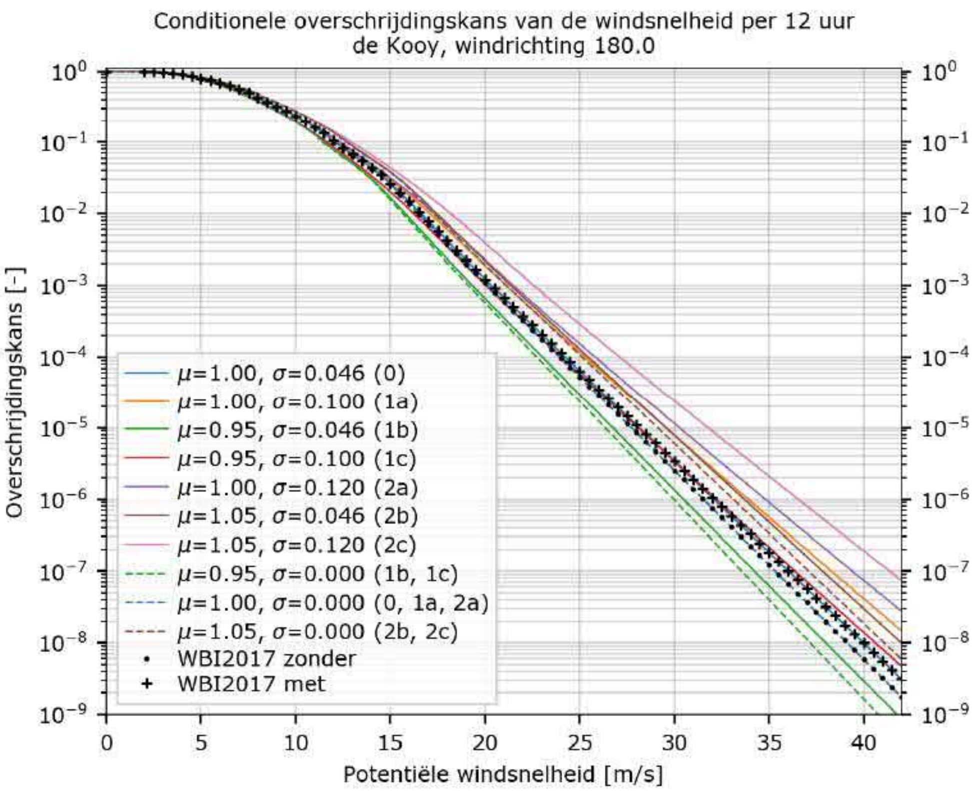
Figuur 3 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor de Kooy.



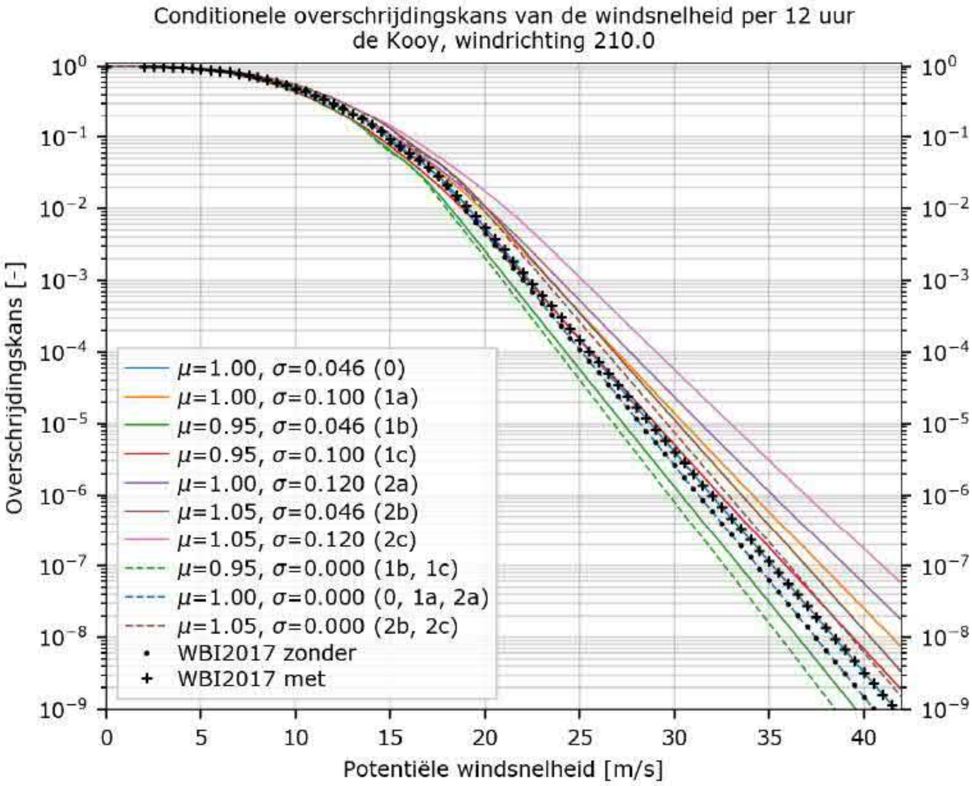
Figuur 4 Overschrijdingsfrequentielijnen voor windrichting 120.0 voor de Kooy.



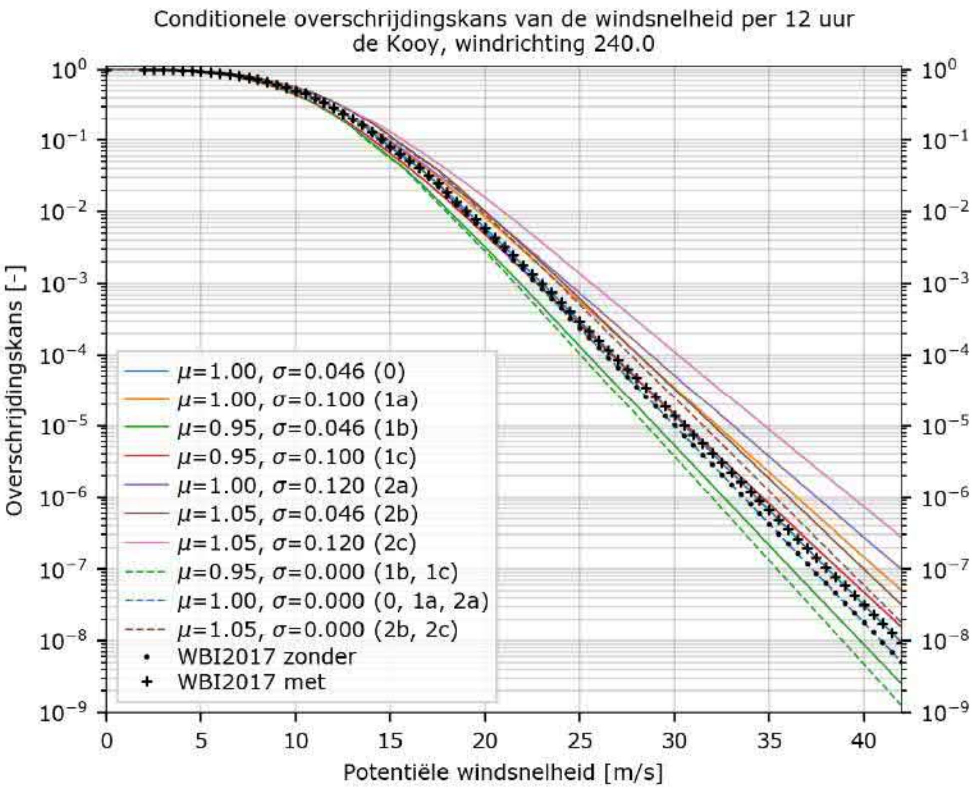
Figuur 5 Overschrijdingsfrequentielijnen voor windrichting 150.0 voor de Kooy.



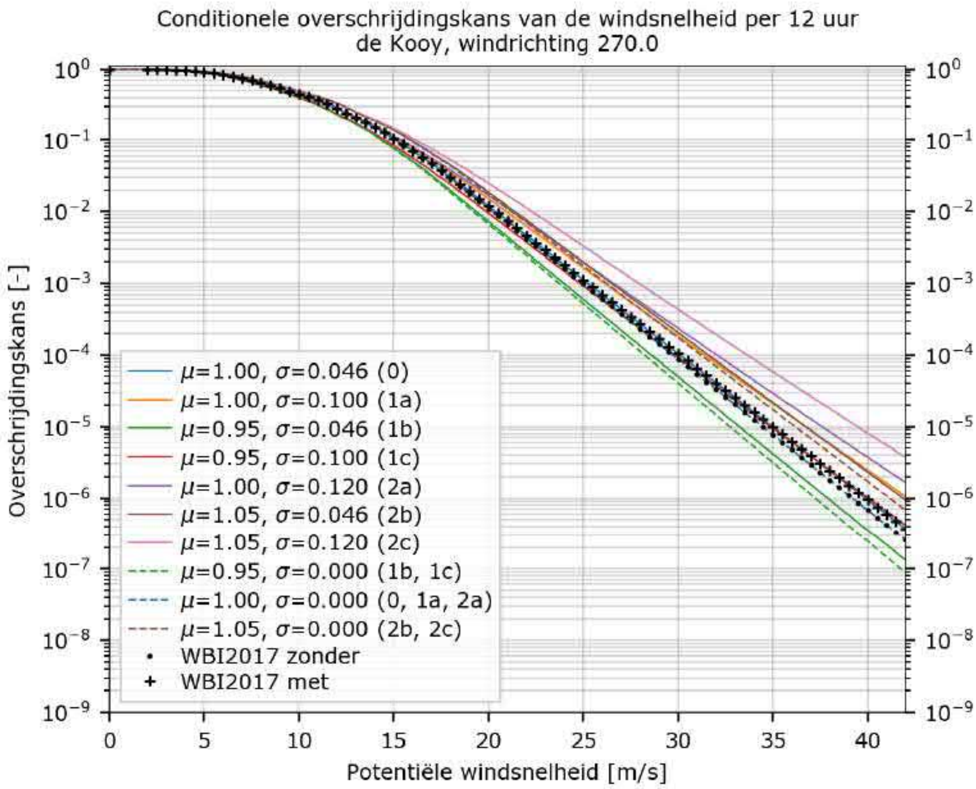
Figuur 6 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor de Kooy.



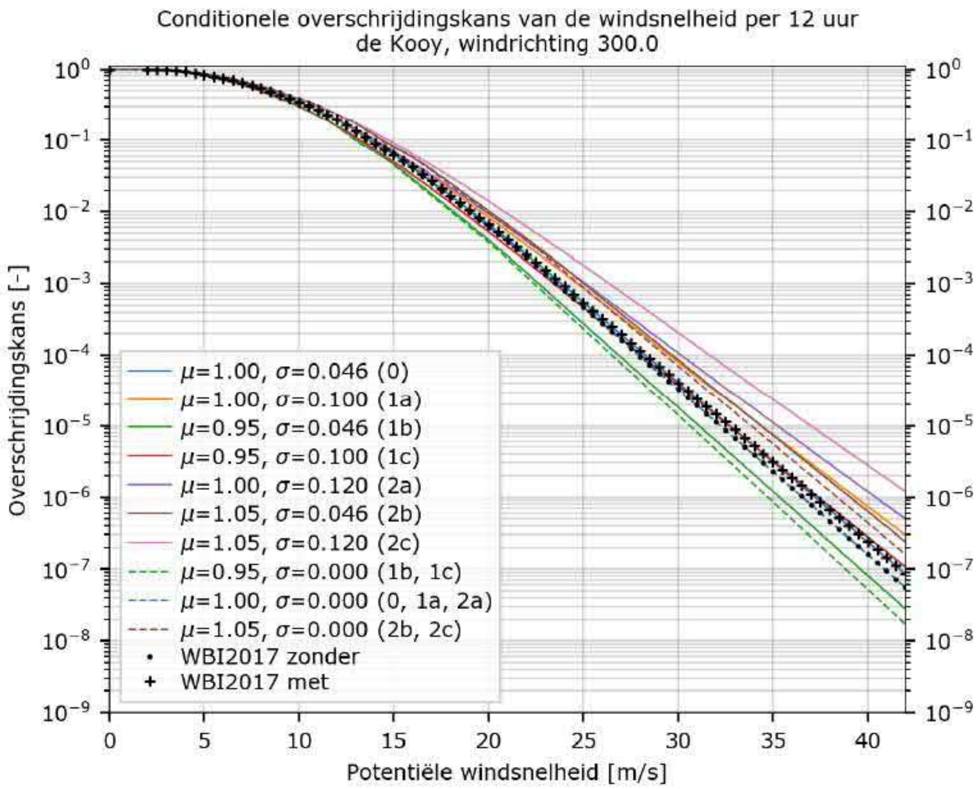
Figuur 7 Overschrijdingsfrequentielijnen voor windrichting 210.0 voor de Kooy.



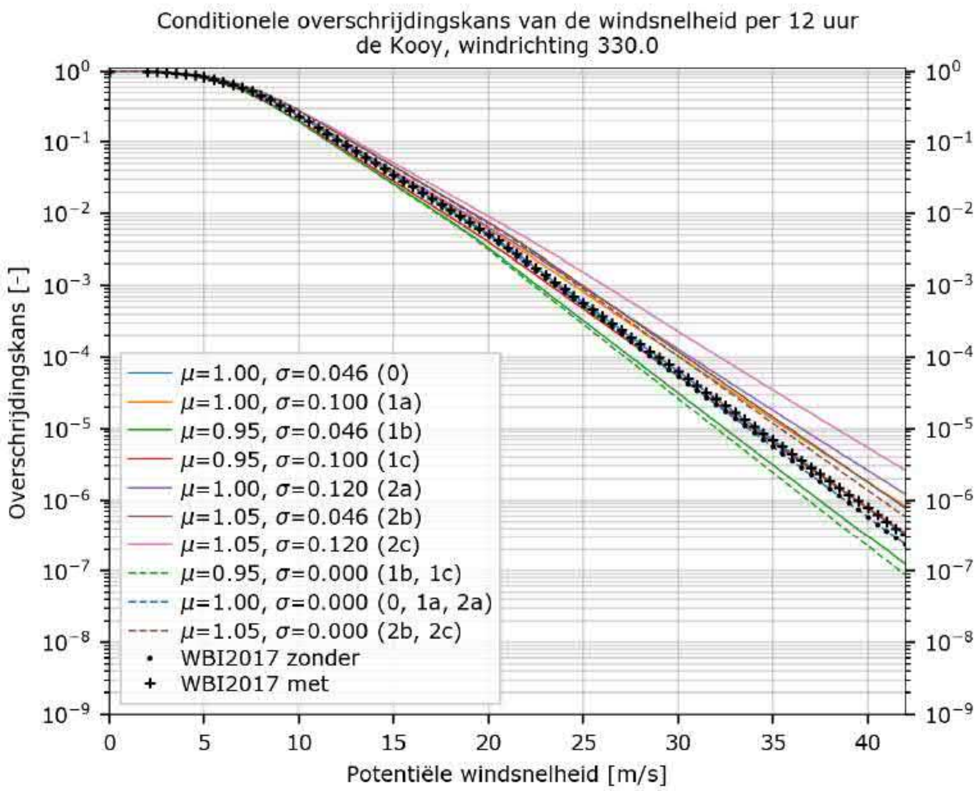
Figuur 8 Overschrijdingsfrequentielijnen voor windrichting 240.0 voor de Kooy.



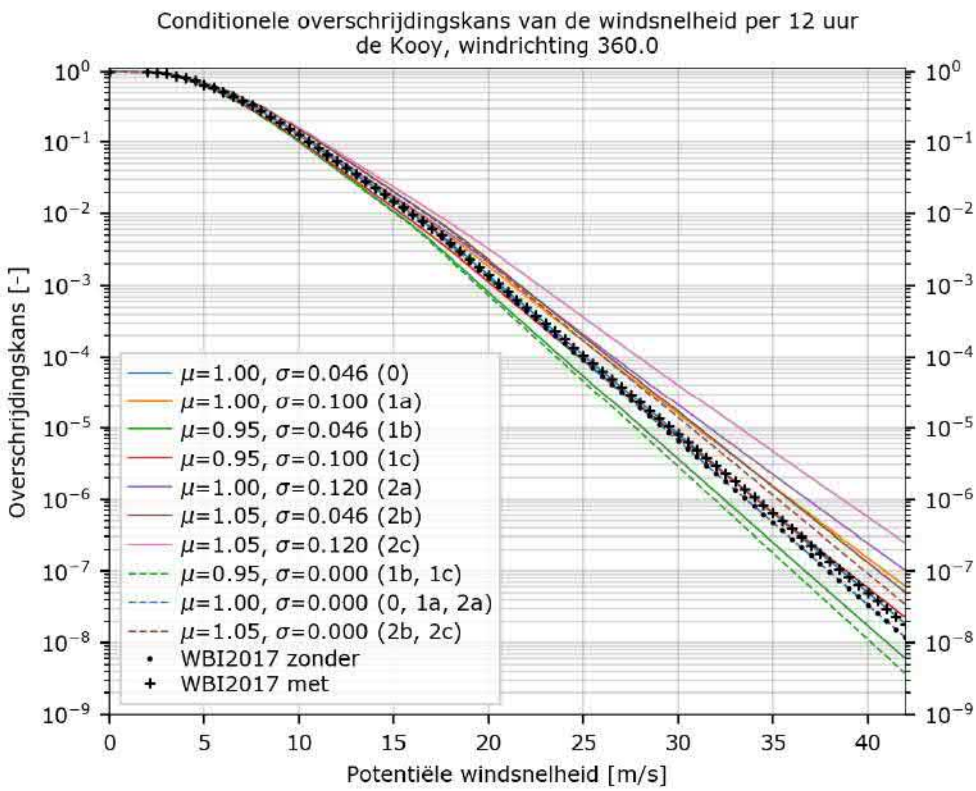
Figuur 9 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor de Kooy.



Figuur 10 Overschrijdingsfrequentielijnen voor windrichting 300.0 voor de Kooy.

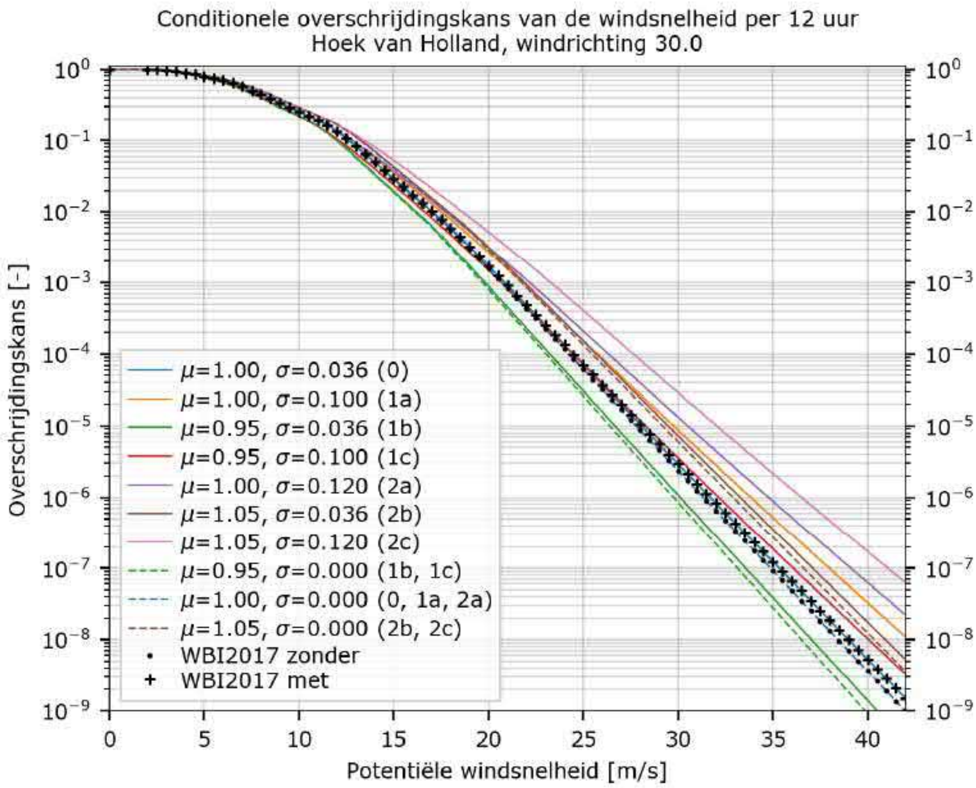


Figuur 11 Overschrijdingsfrequentielijnen voor windrichting 330.0 voor de Kooy.

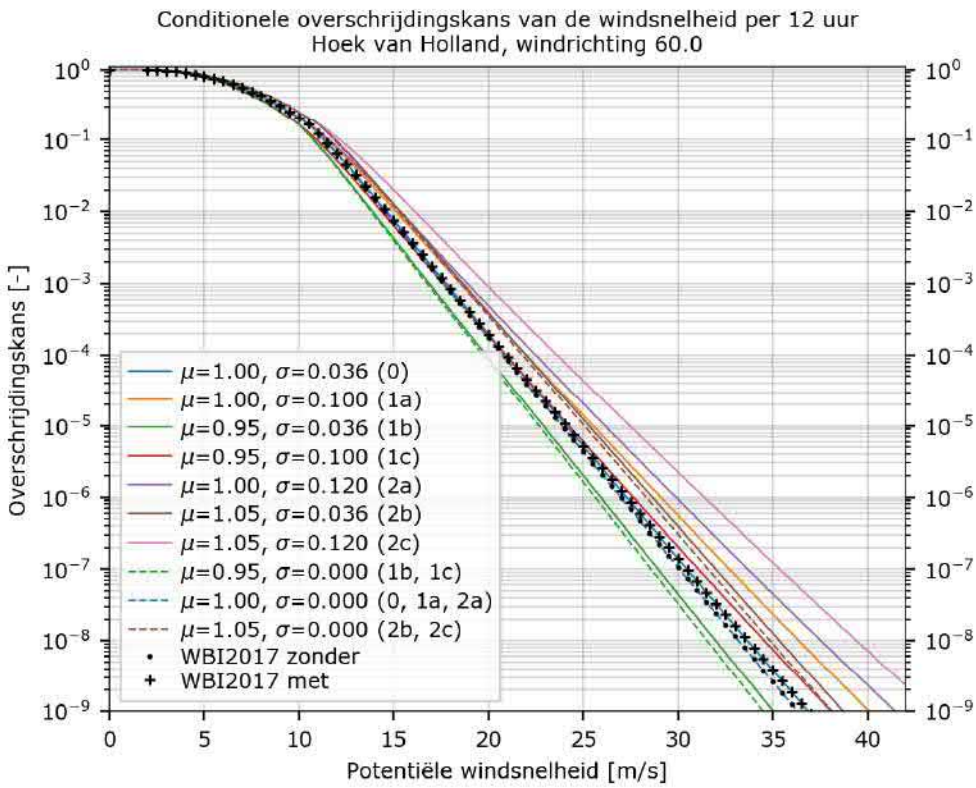


Figuur 12 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor de Kooy.

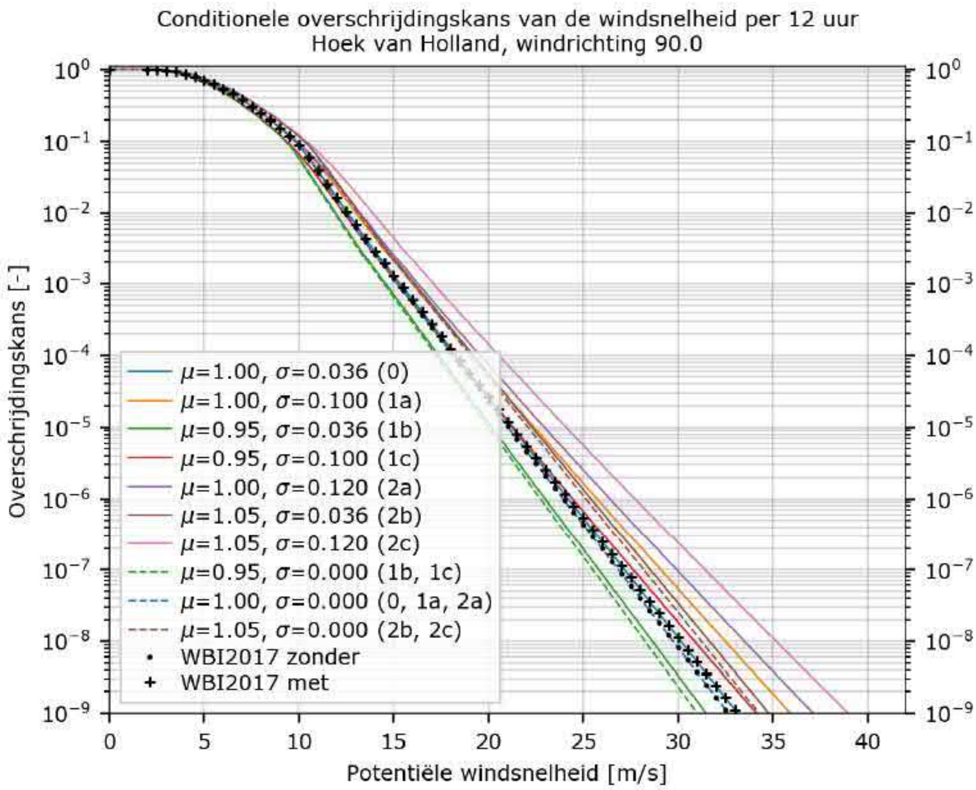
3.2 Hoek van Holland



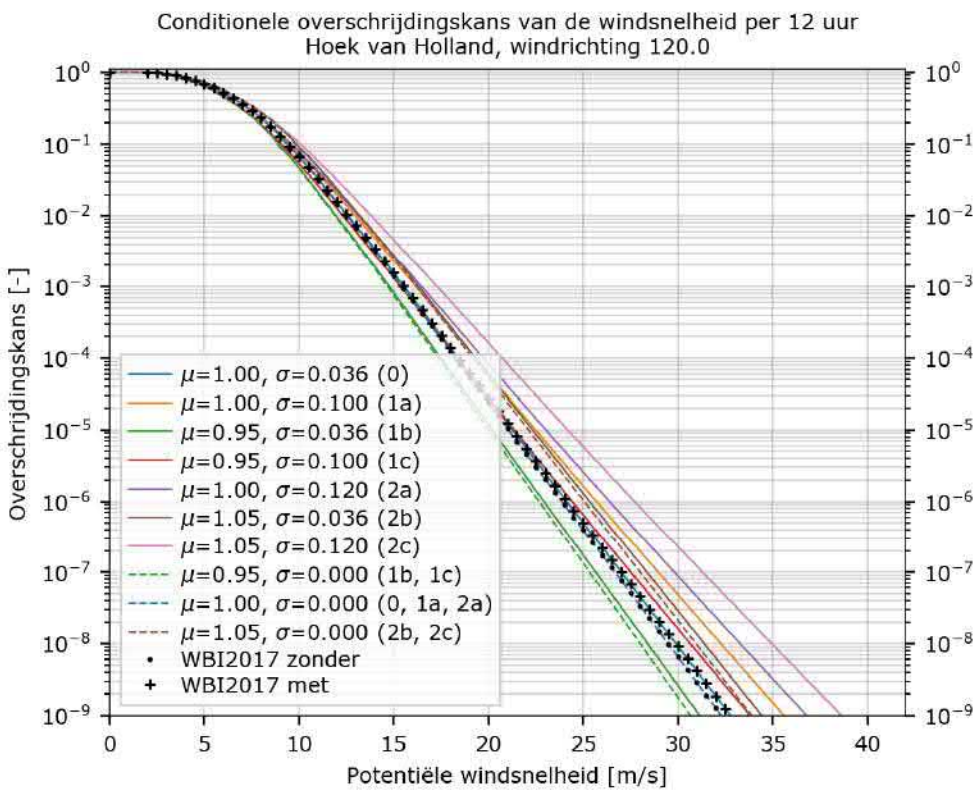
Figuur 13 Overschrijdingsfrequentielijnen voor windrichting 30.0 voor Hoek van Holland.



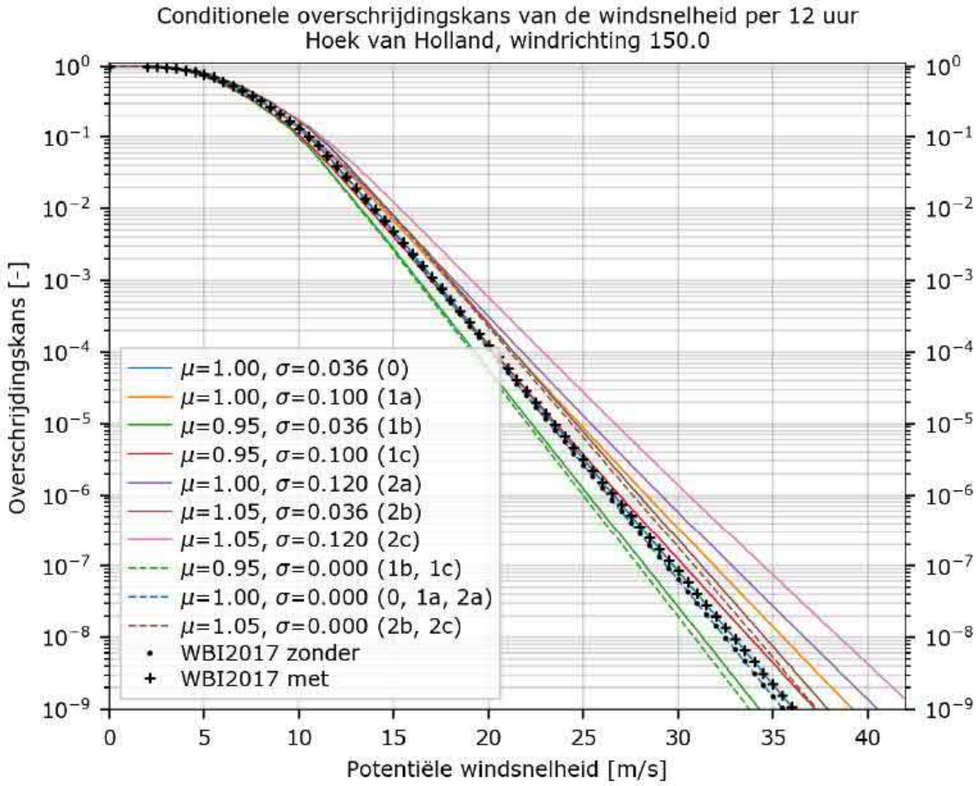
Figuur 14 Overschrijdingsfrequentielijnen voor windrichting 60.0 voor Hoek van Holland.



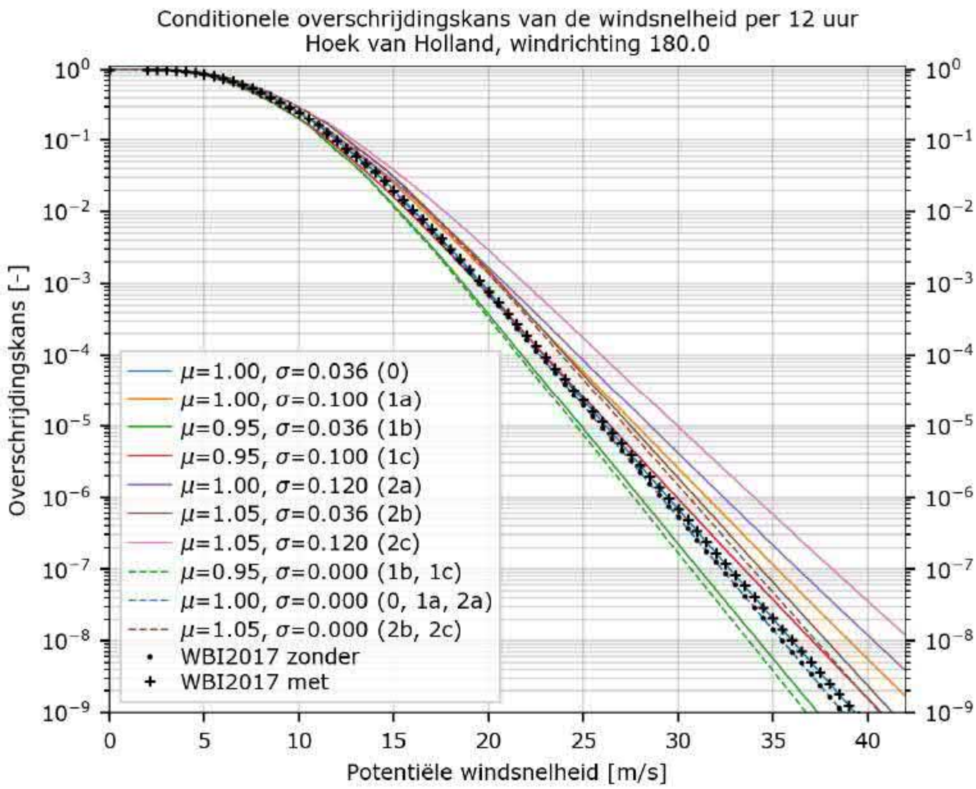
Figuur 15 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor Hoek van Holland.



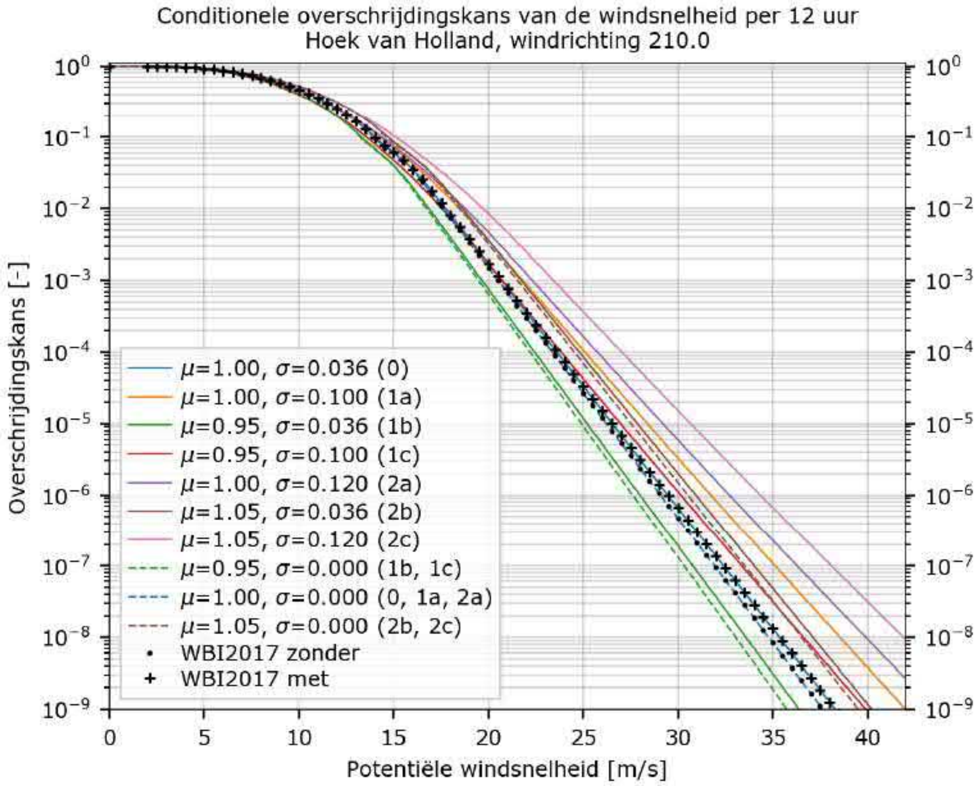
Figuur 16 Overschrijdingsfrequentielijnen voor windrichting 120.0 voor Hoek van Holland.



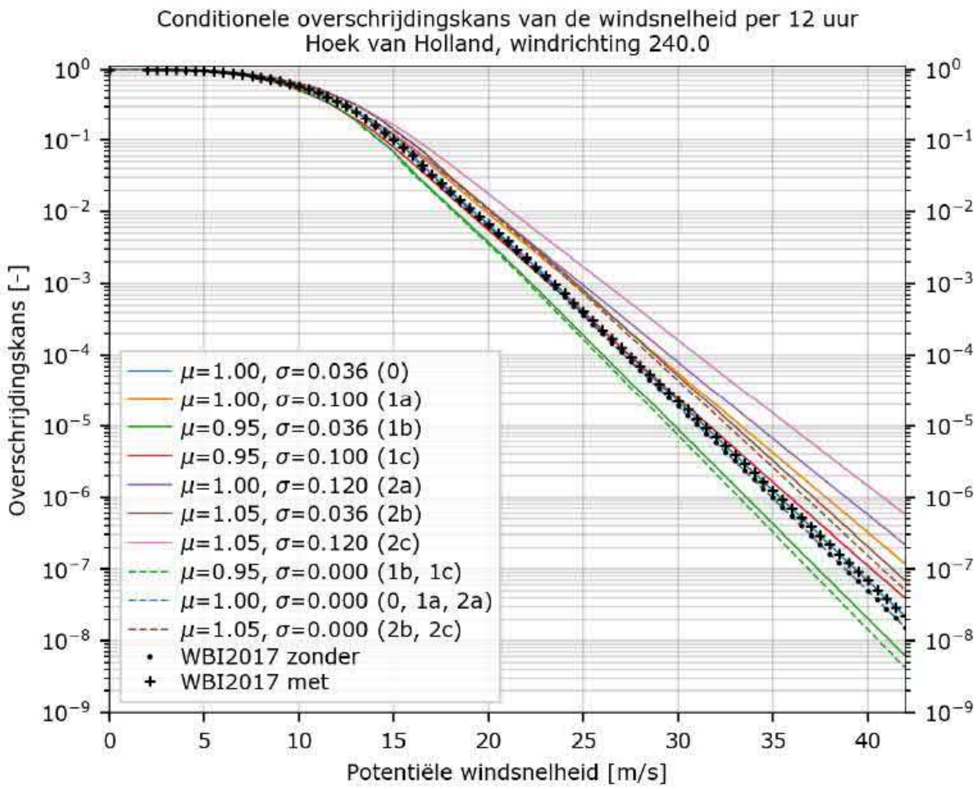
Figuur 17 Overschrijdingsfrequentielijnen voor windrichting 150.0 voor Hoek van Holland.



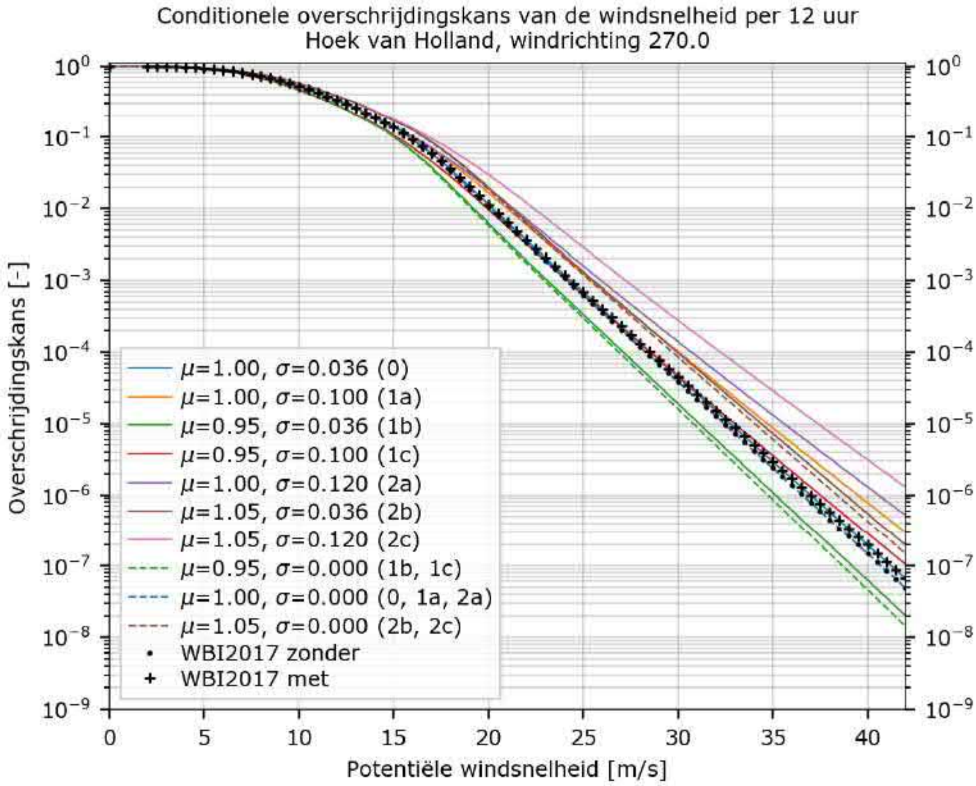
Figuur 18 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor Hoek van Holland.



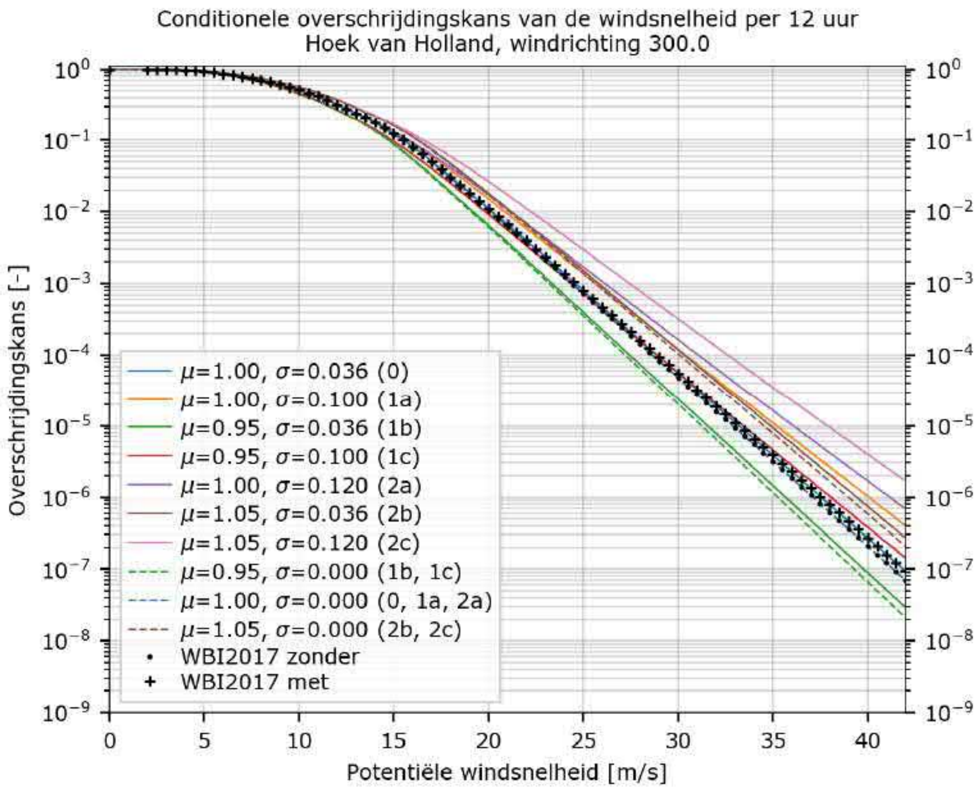
Figuur 19 Overschrijdingsfrequentielijnen voor windrichting 210.0 voor Hoek van Holland.



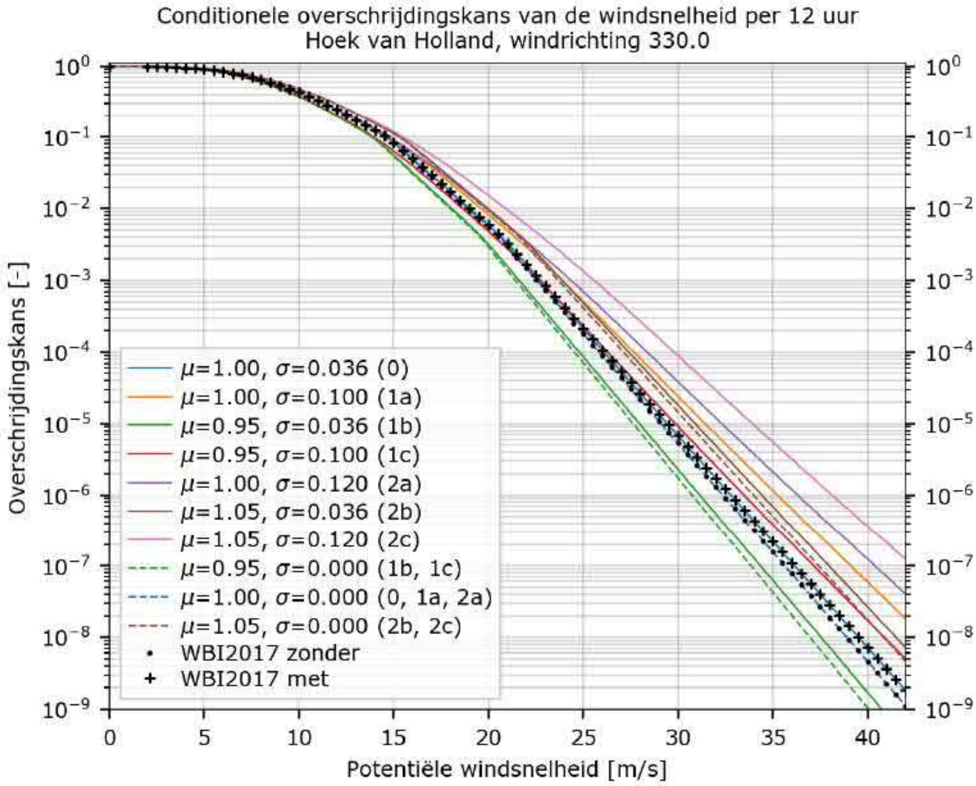
Figuur 20 Overschrijdingsfrequentielijnen voor windrichting 240.0 voor Hoek van Holland.



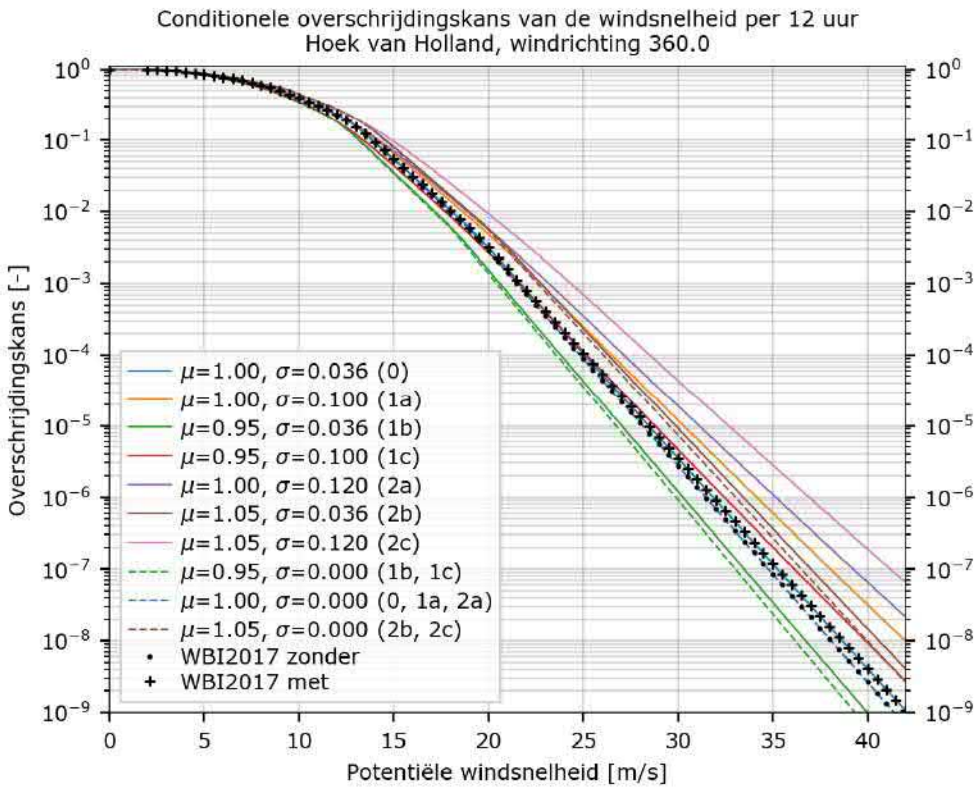
Figuur 21 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor Hoek van Holland.



Figuur 22 Overschrijdingsfrequentielijnen voor windrichting 300.0 voor Hoek van Holland.

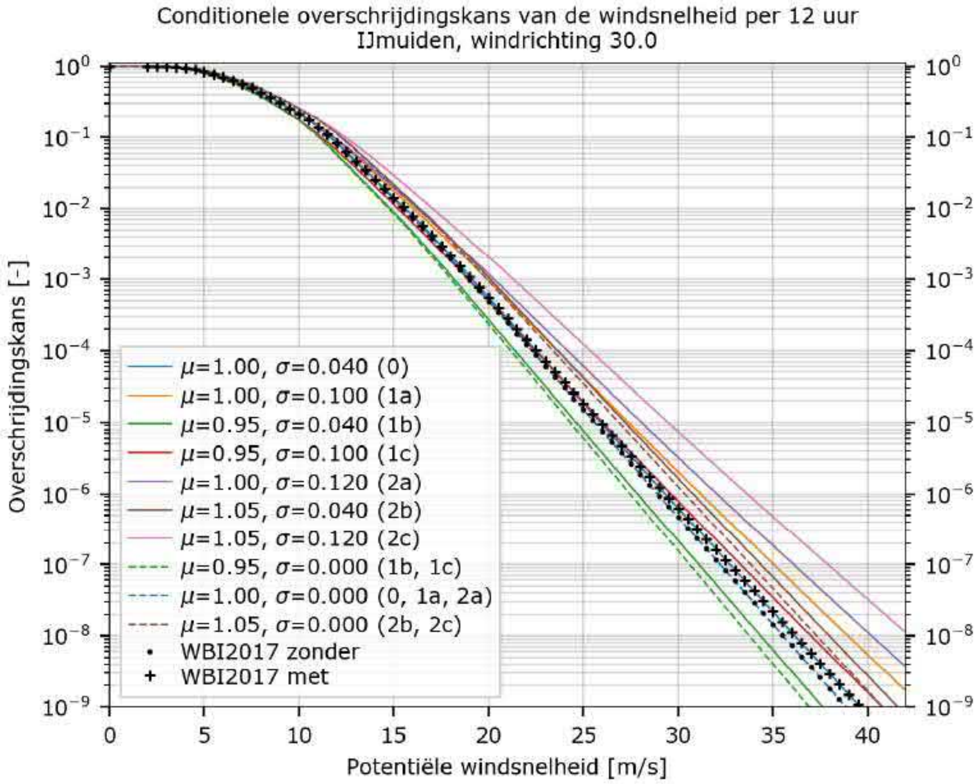


Figuur 23 Overschrijdingsfrequentielijnen voor windrichting 330.0 voor Hoek van Holland.

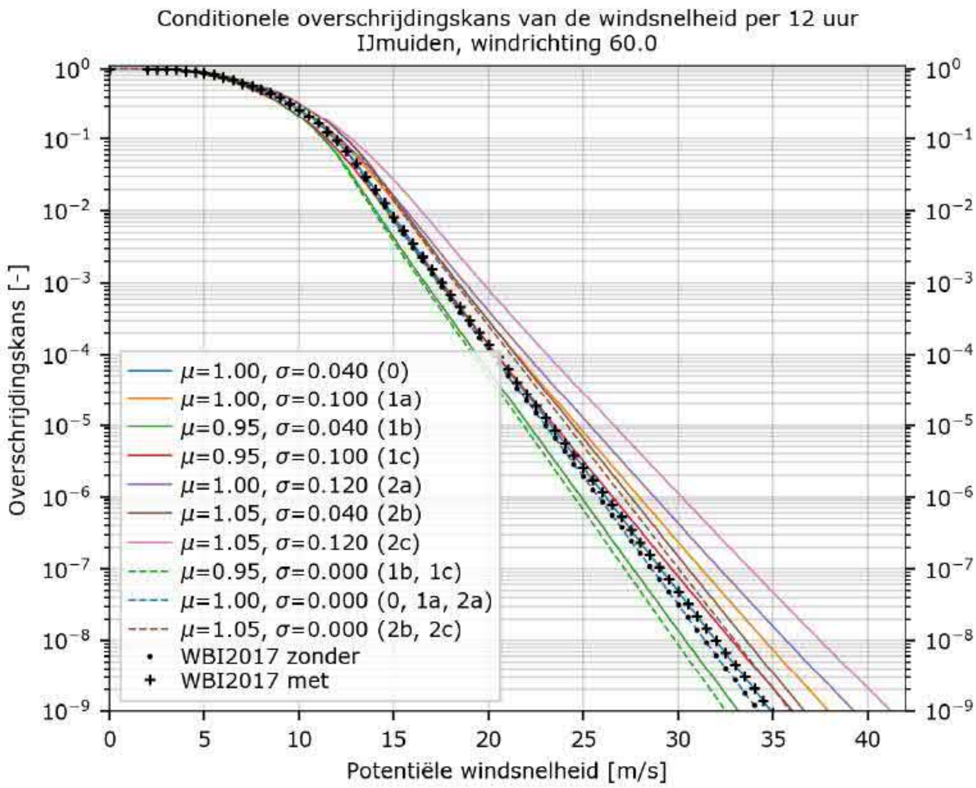


Figuur 24 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor Hoek van Holland.

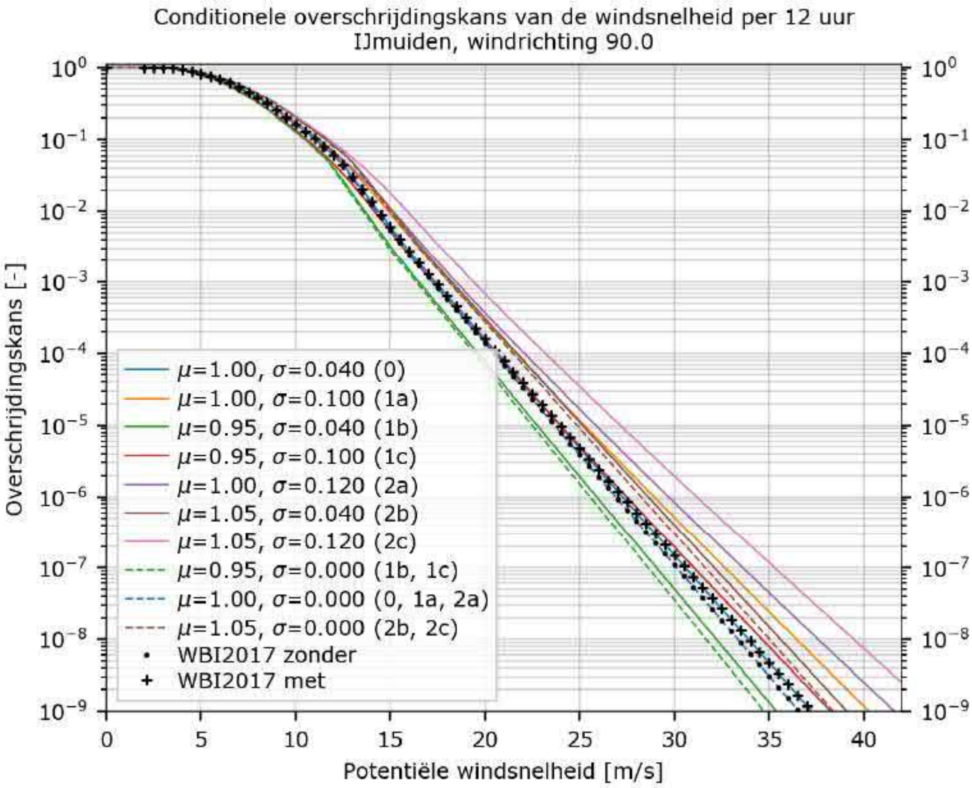
3.3 IJmuiden



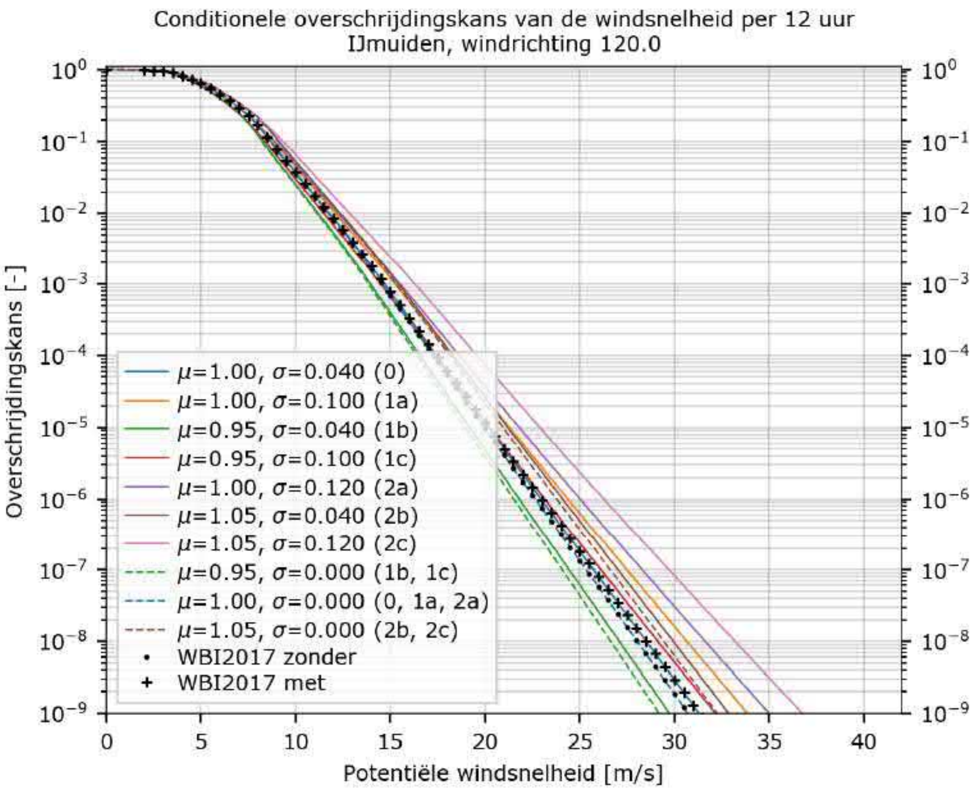
Figuur 25 Overschrijdingsfrequentielijnen voor windrichting 30.0 voor IJmuiden.



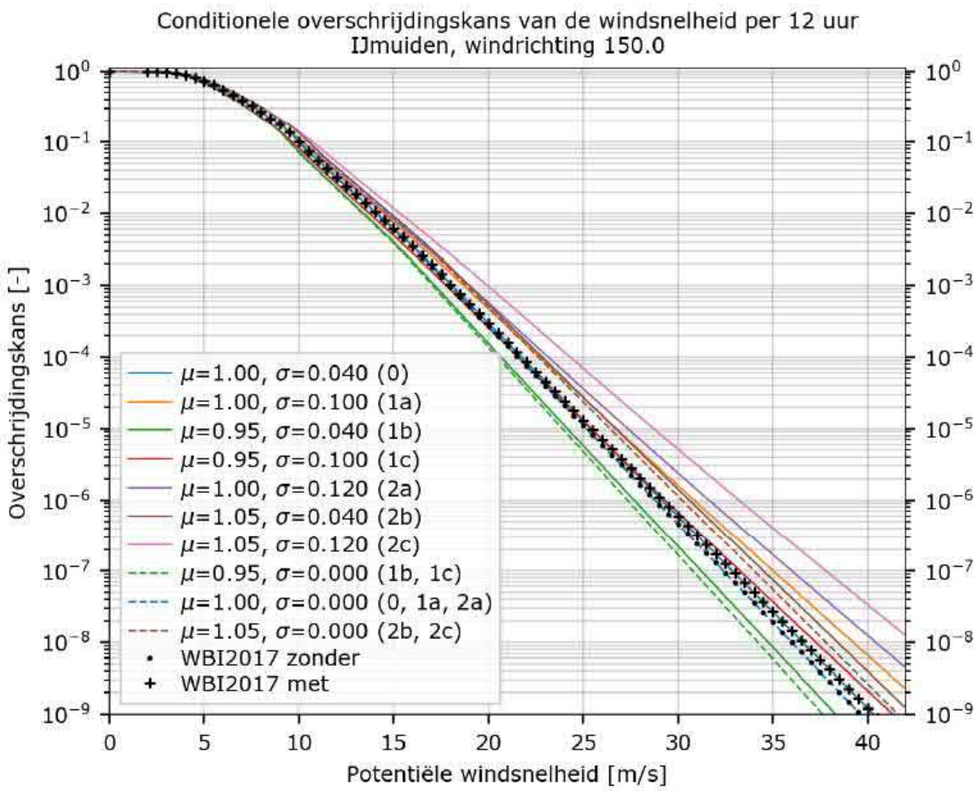
Figuur 26 Overschrijdingsfrequentielijnen voor windrichting 60.0 voor IJmuiden.



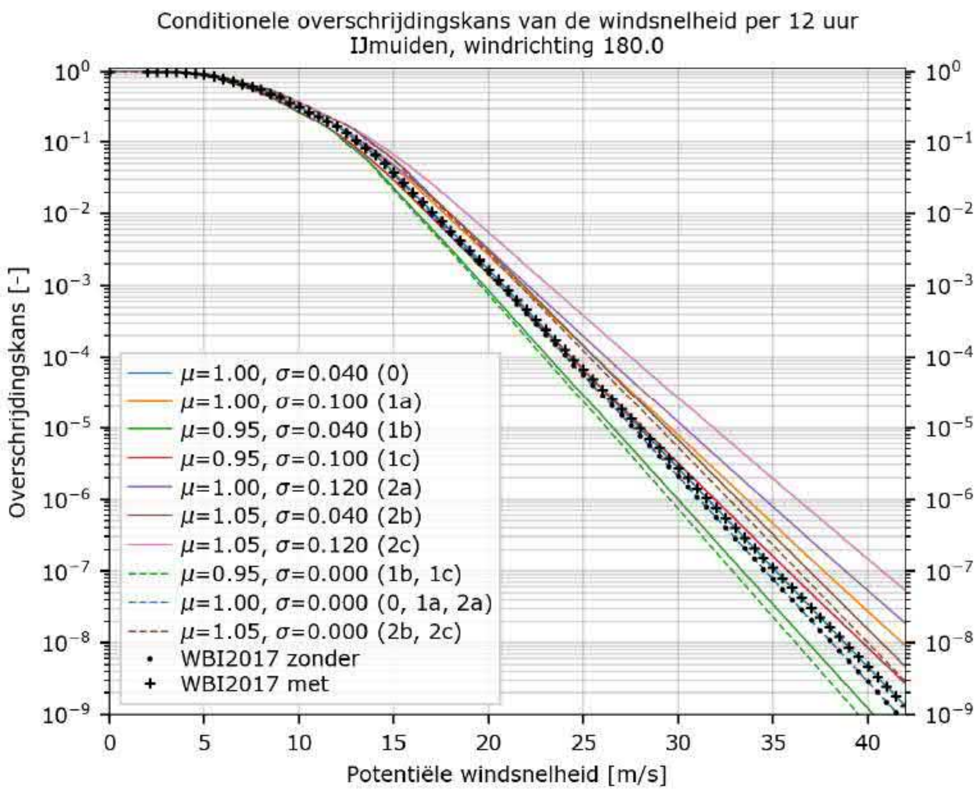
Figuur 27 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor IJmuiden.



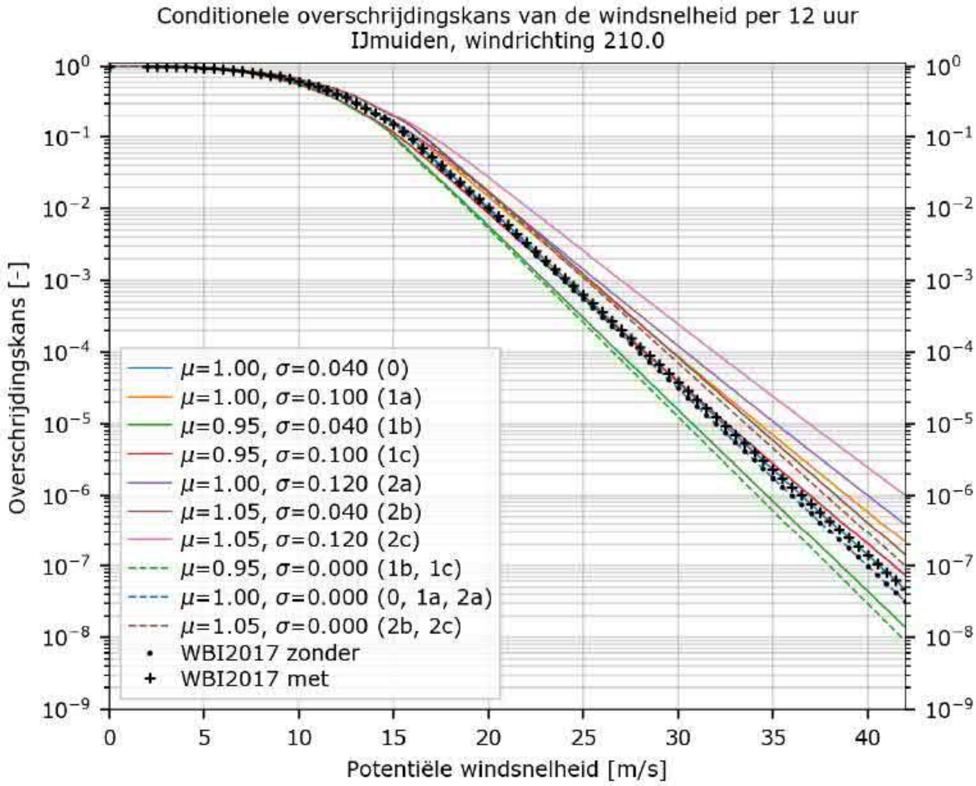
Figuur 28 Overschrijdingsfrequentielijnen voor windrichting 120.0 voor IJmuiden.



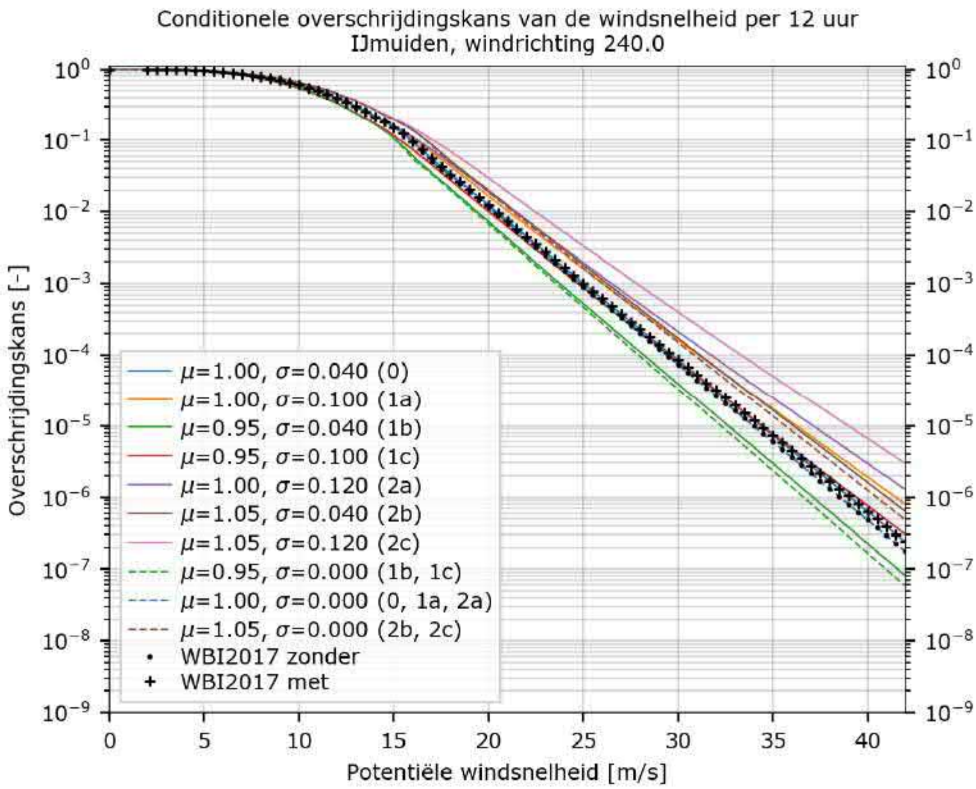
Figuur 29 Overschrijdingsfrequentielijnen voor windrichting 150.0 voor IJmuiden.



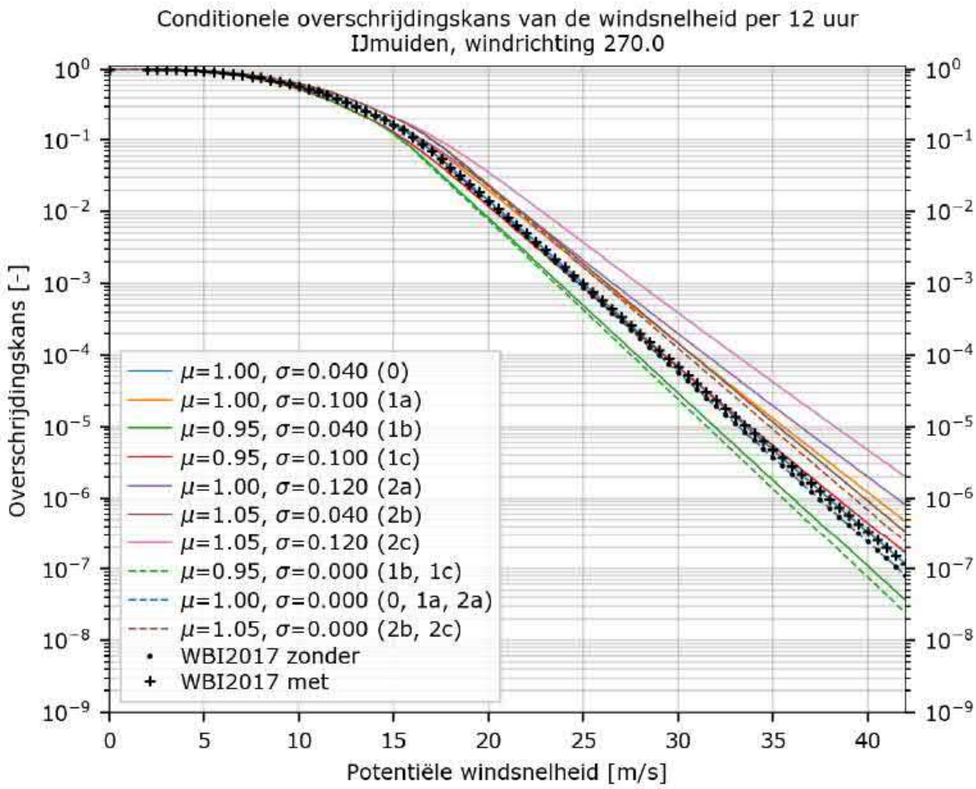
Figuur 30 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor IJmuiden.



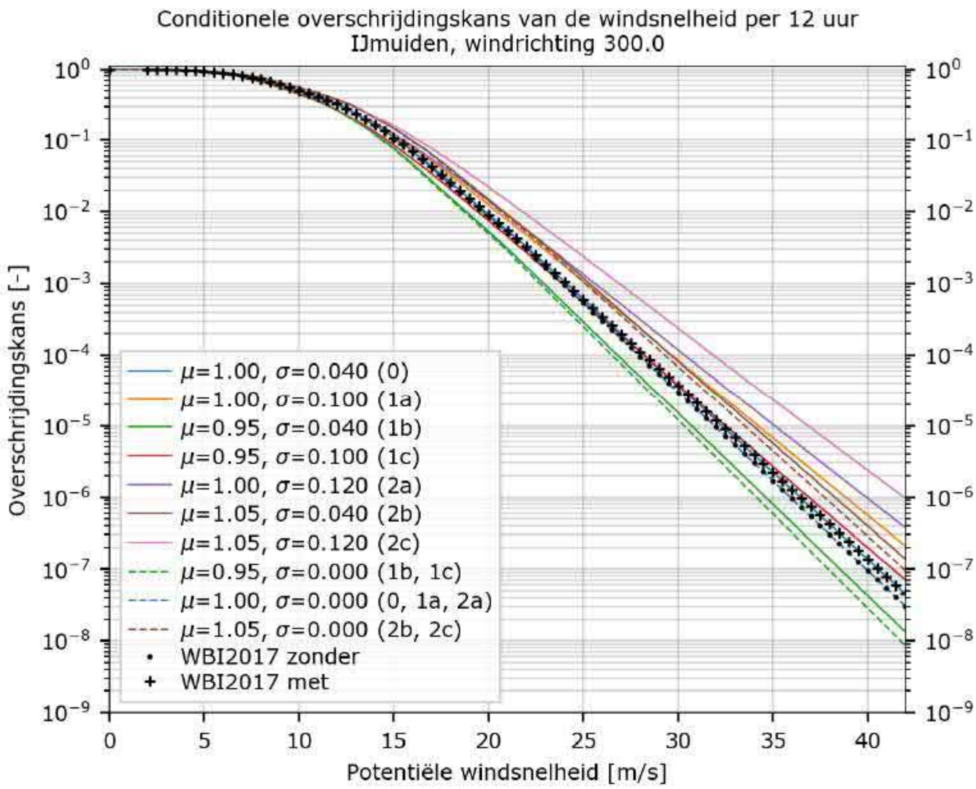
Figuur 31 Overschrijdingsfrequentielijnen voor windrichting 210.0 voor IJmuiden.



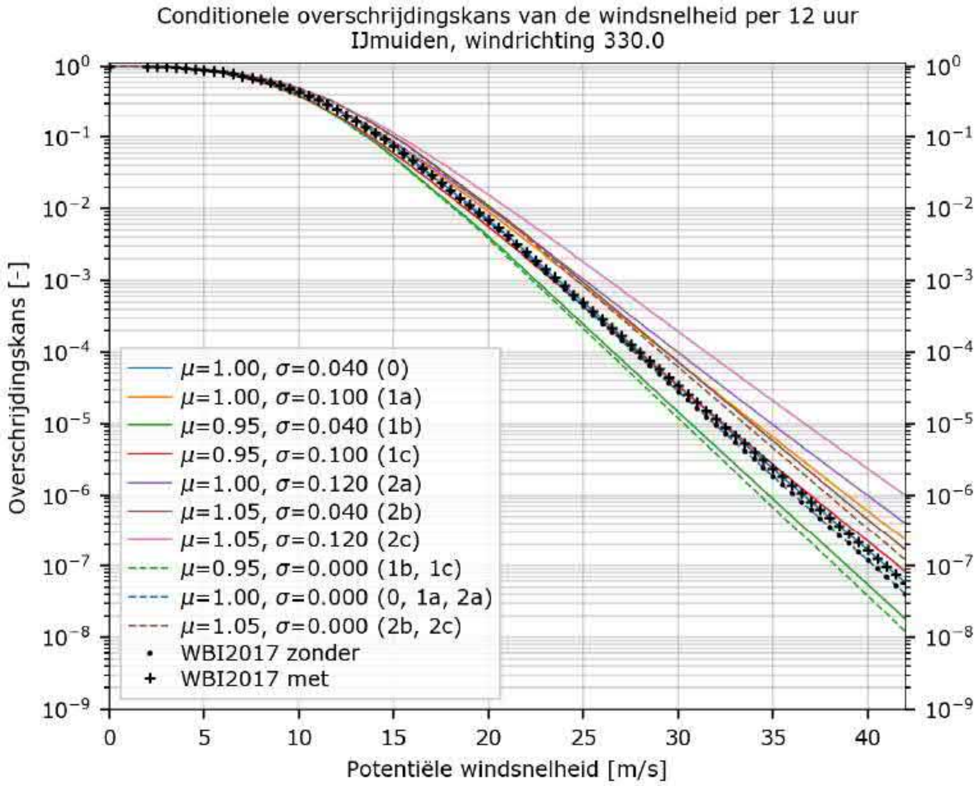
Figuur 32 Overschrijdingsfrequentielijnen voor windrichting 240.0 voor IJmuiden.



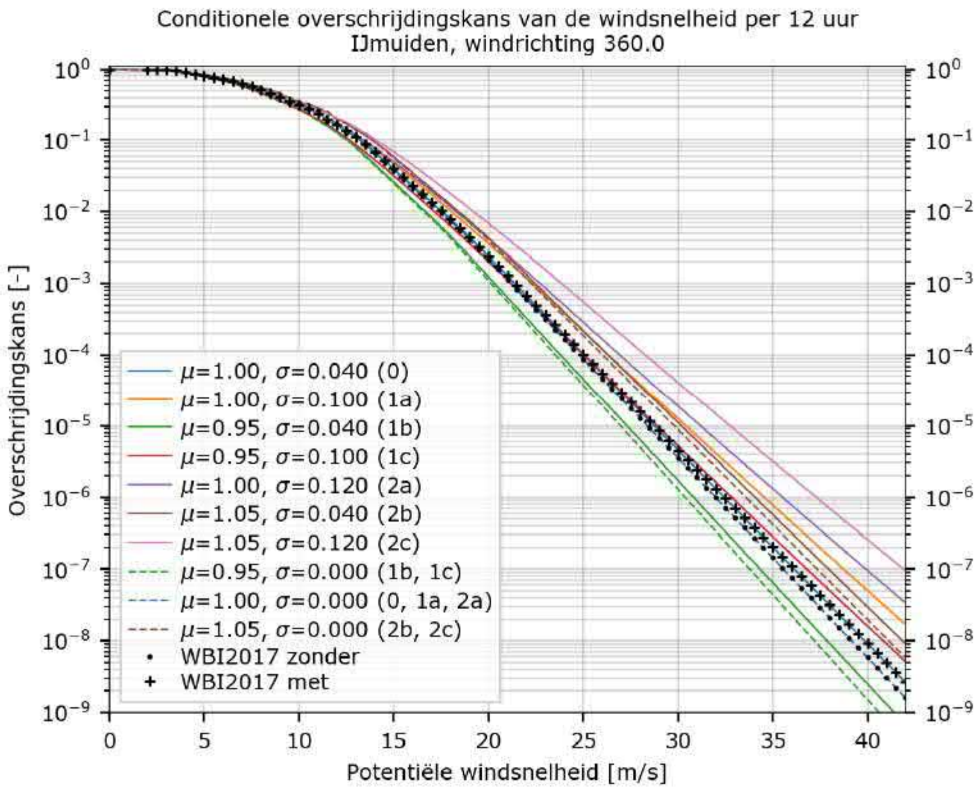
Figuur 33 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor IJmuiden.



Figuur 34 Overschrijdingsfrequentielijnen voor windrichting 300.0 voor IJmuiden.

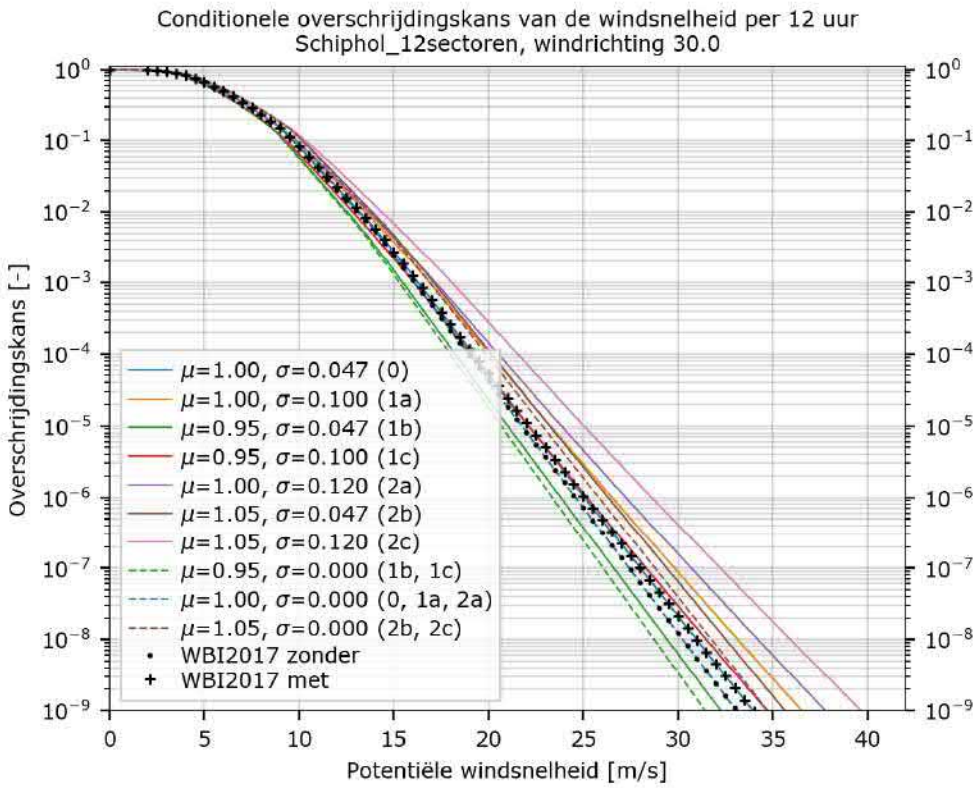


Figuur 35 Overschrijdingsfrequentielijnen voor windrichting 330.0 voor IJmuiden.

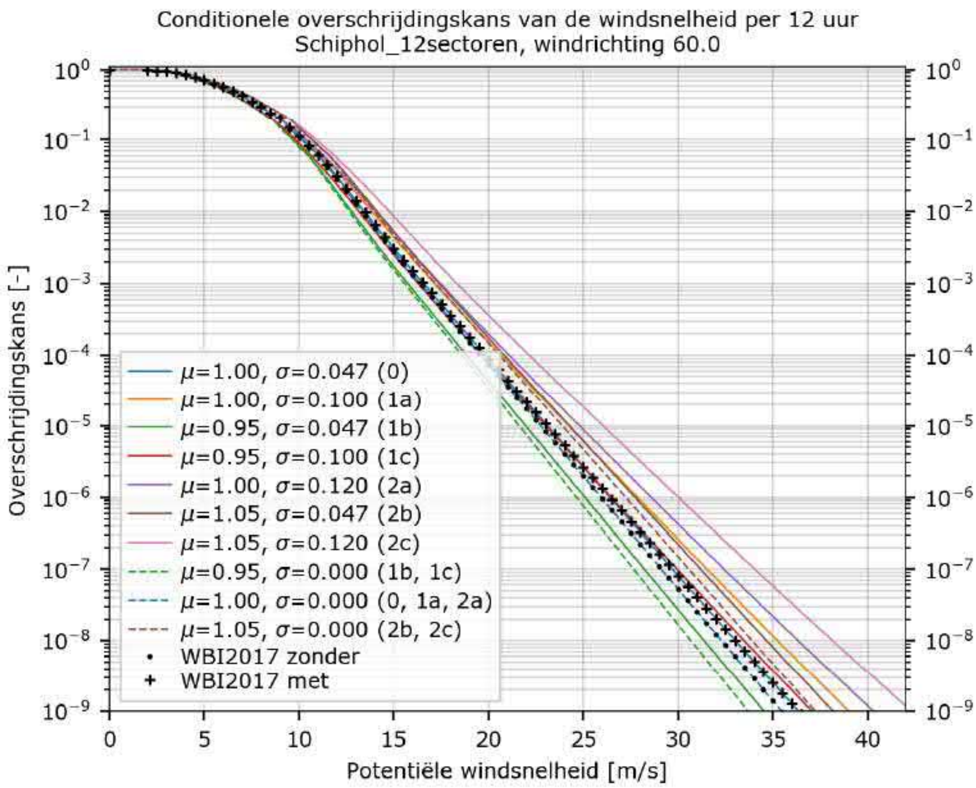


Figuur 36 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor IJmuiden.

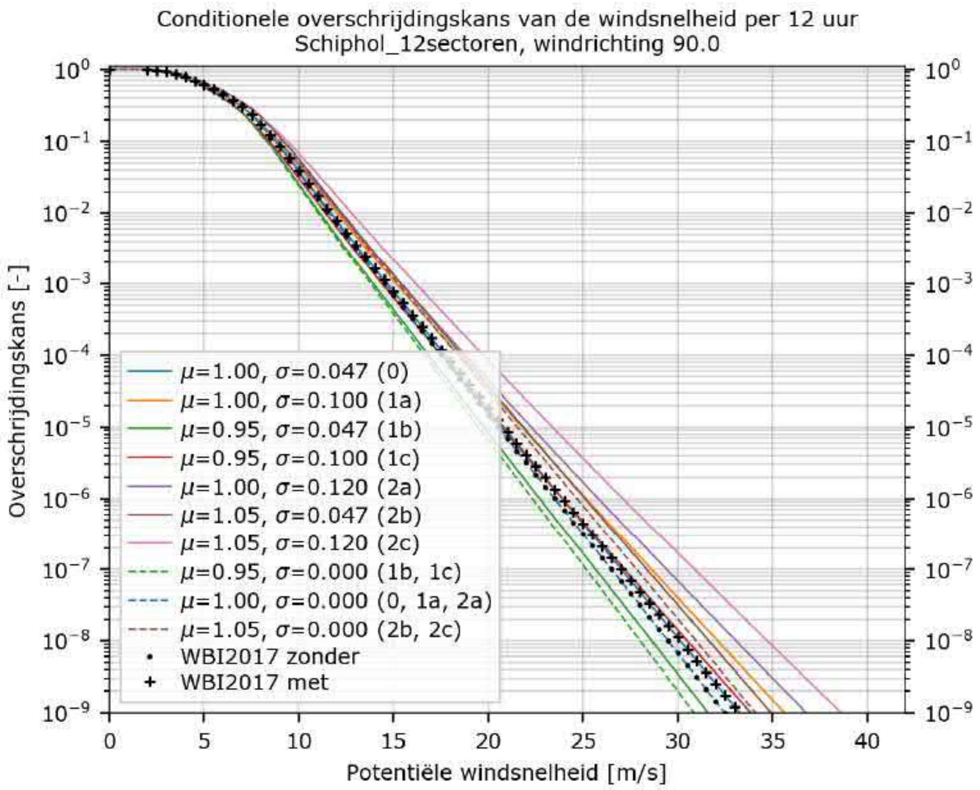
3.4 Schiphol (12 sectoren)



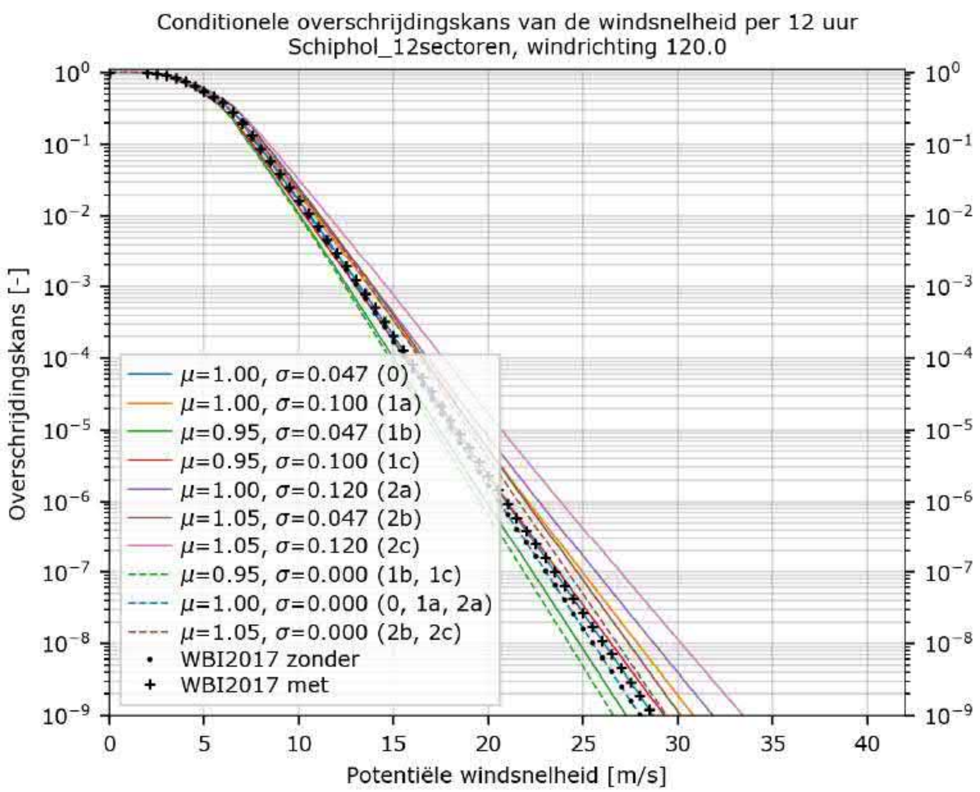
Figuur 37 Overschrijdingsfrequentielijnen voor windrichting 30.0 voor Schiphol (12 sectoren).



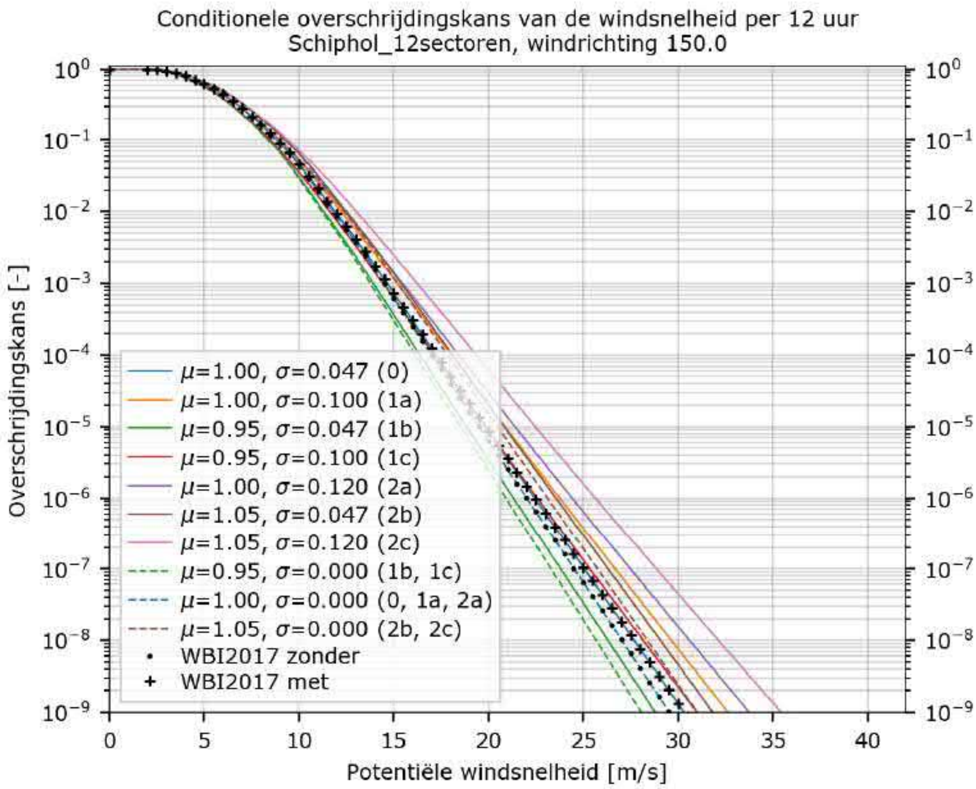
Figuur 38 Overschrijdingsfrequentielijnen voor windrichting 60.0 voor Schiphol (12 sectoren).



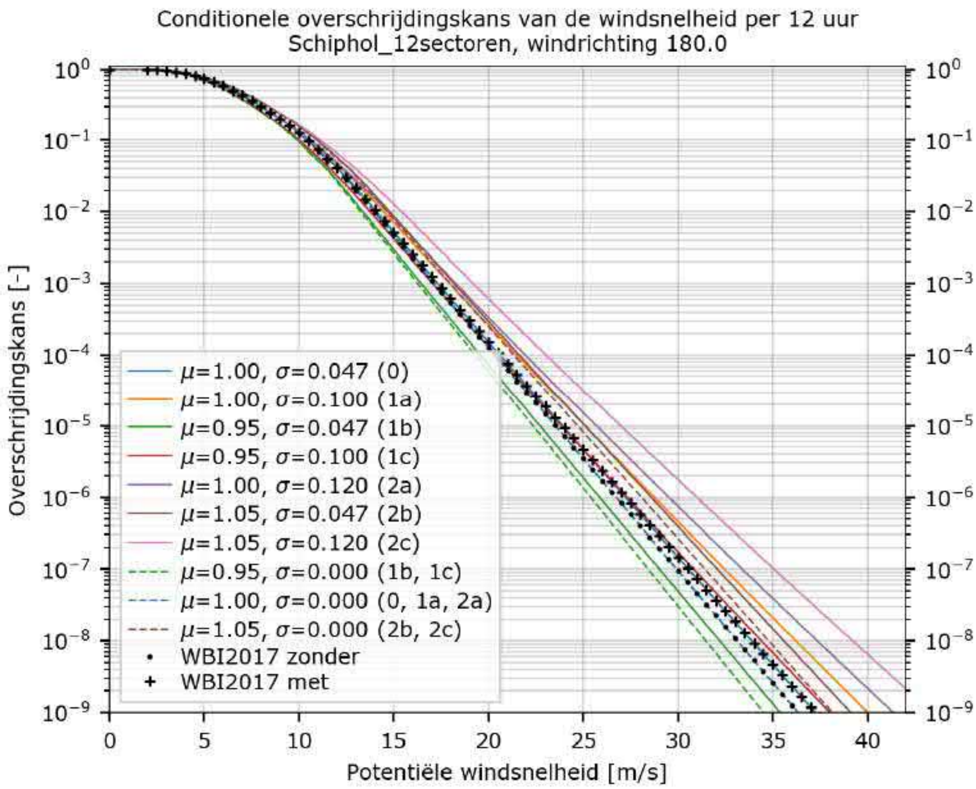
Figuur 39 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor Schiphol (12 sectoren).



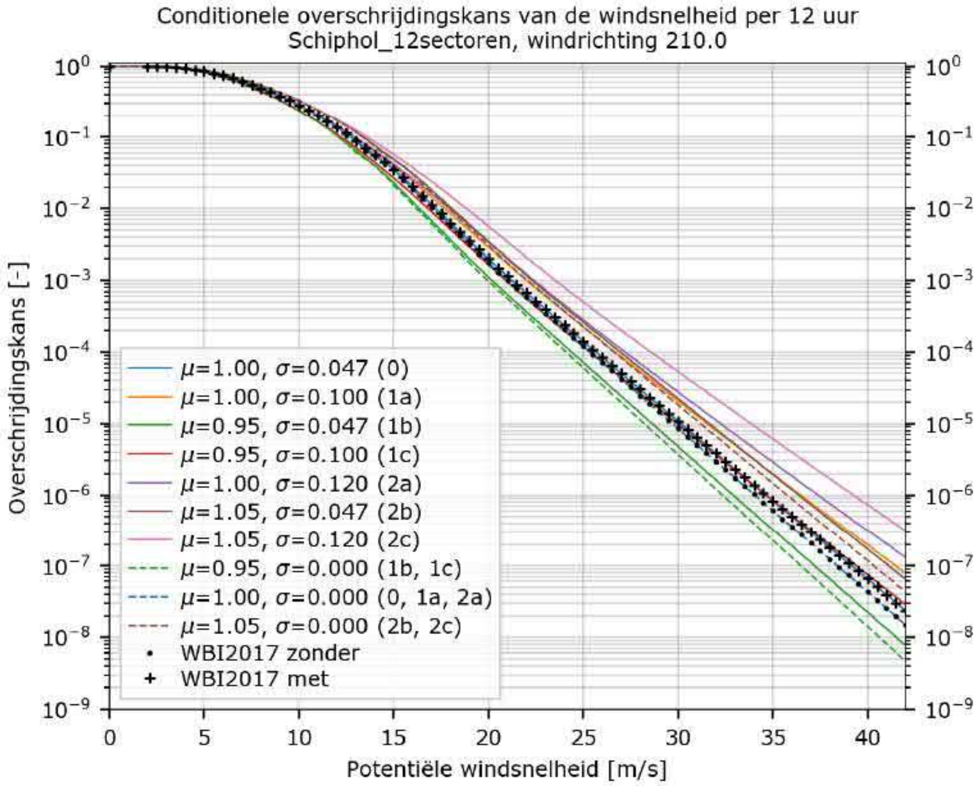
Figuur 40 Overschrijdingsfrequentielijnen voor windrichting 120.0 voor Schiphol (12 sectoren).



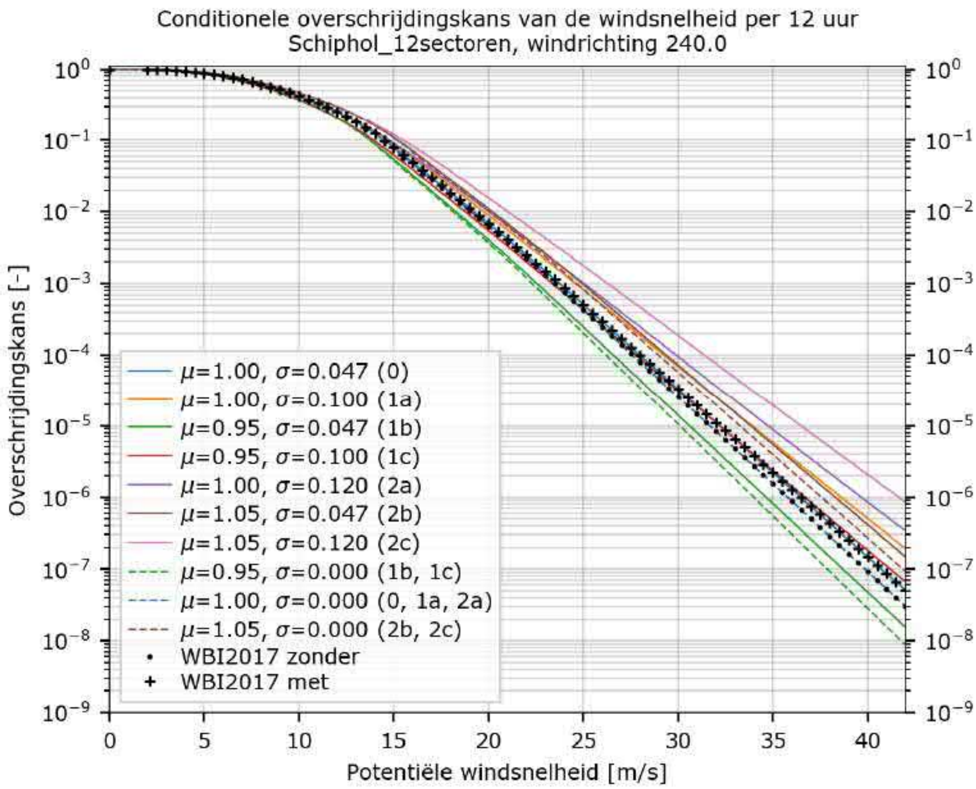
Figuur 41 Overschrijdingsfrequentielijnen voor windrichting 150.0 voor Schiphol (12 sectoren).



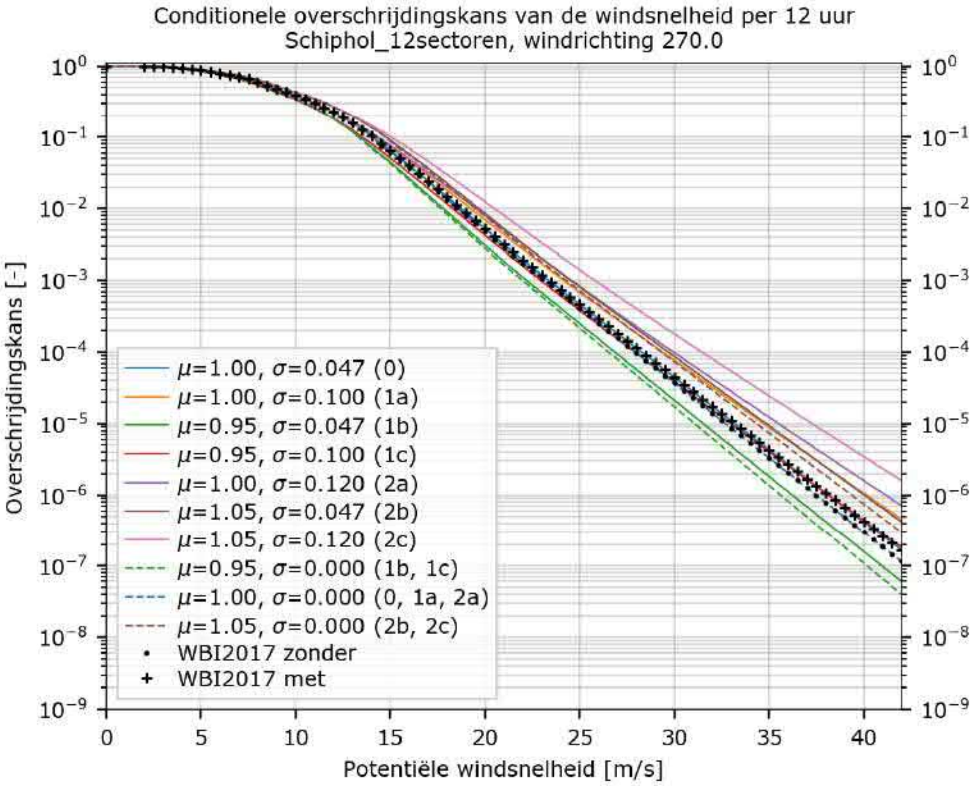
Figuur 42 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor Schiphol (12 sectoren).



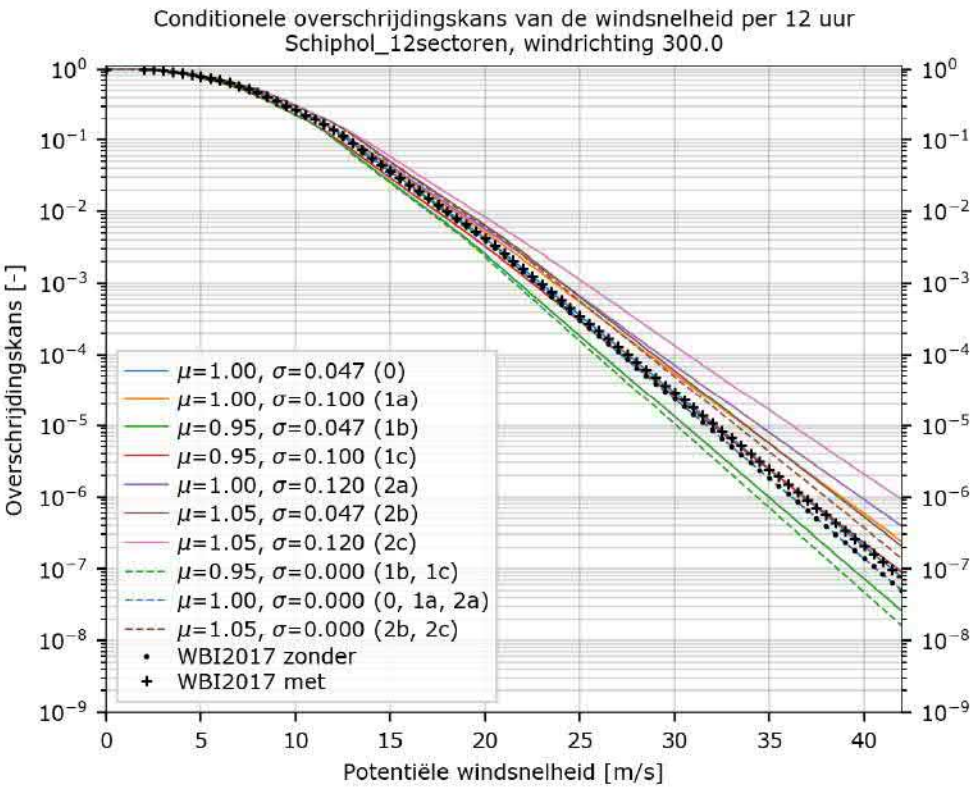
Figuur 43 Overschrijdingsfrequentielijnen voor windrichting 210.0 voor Schiphol (12 sectoren).



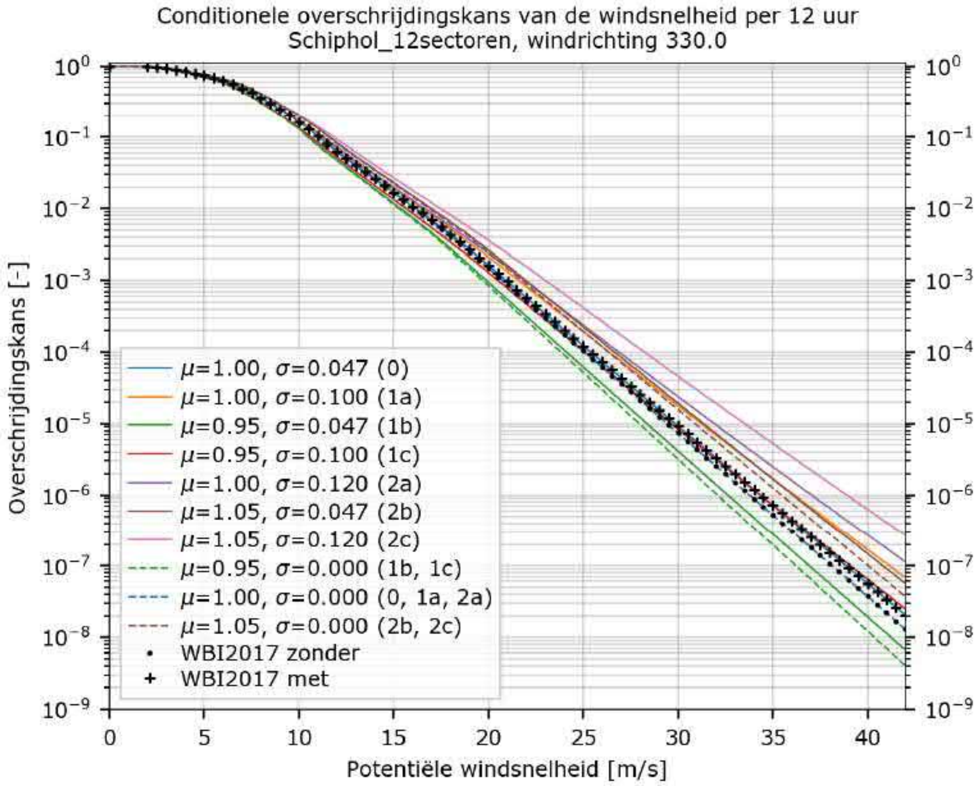
Figuur 44 Overschrijdingsfrequentielijnen voor windrichting 240.0 voor Schiphol (12 sectoren).



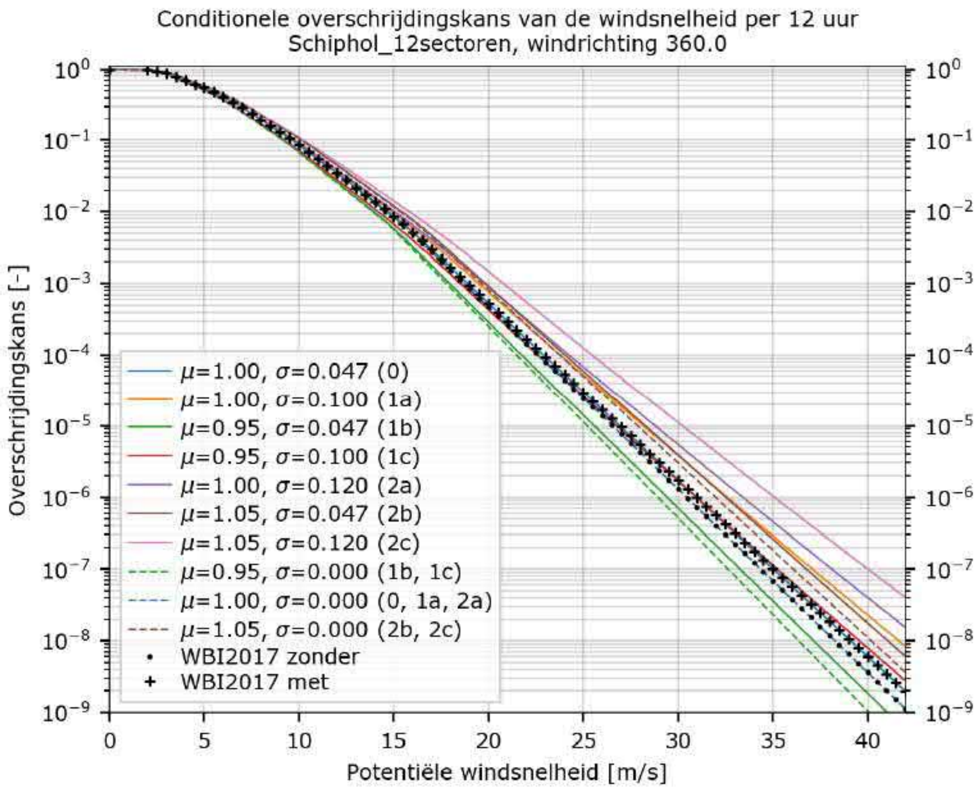
Figuur 45 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor Schiphol (12 sectoren).



Figuur 46 Overschrijdingsfrequentielijnen voor windrichting 300.0 voor Schiphol (12 sectoren).

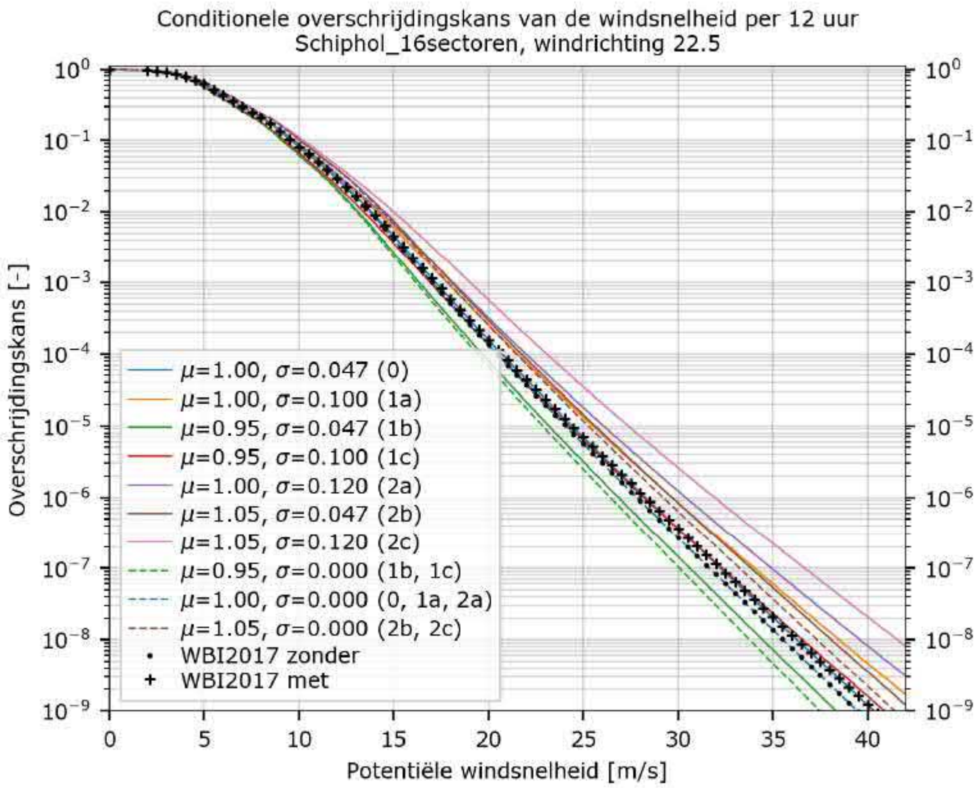


Figuur 47 Overschrijdingsfrequentielijnen voor windrichting 330.0 voor Schiphol (12 sectoren).

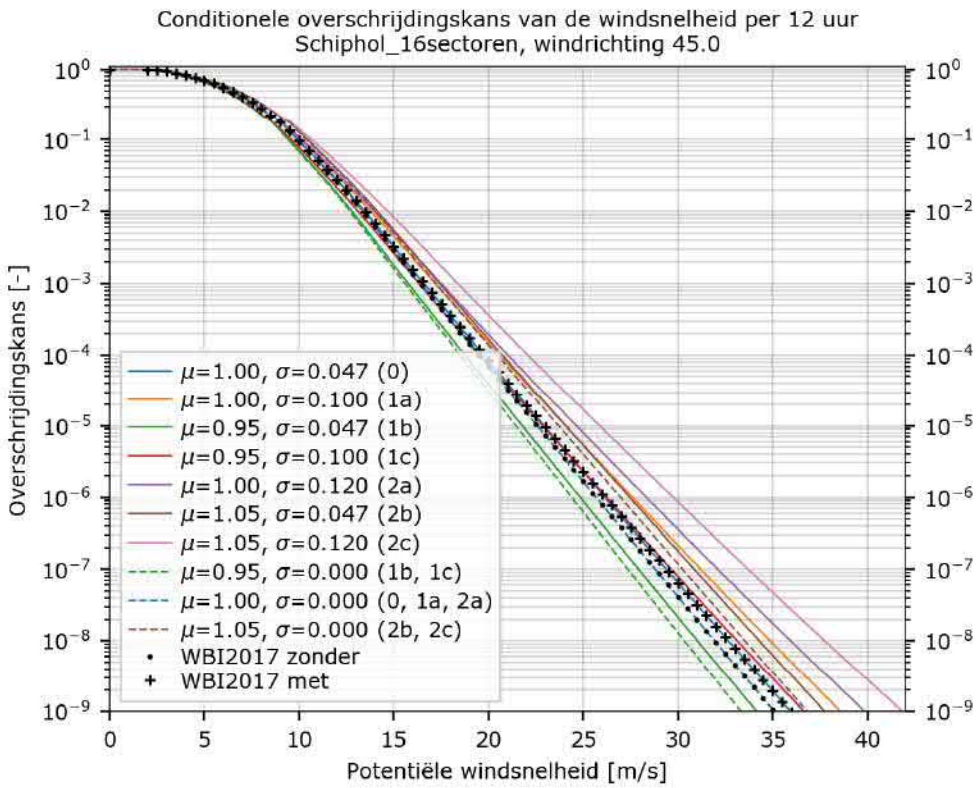


Figuur 48 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor Schiphol (12 sectoren).

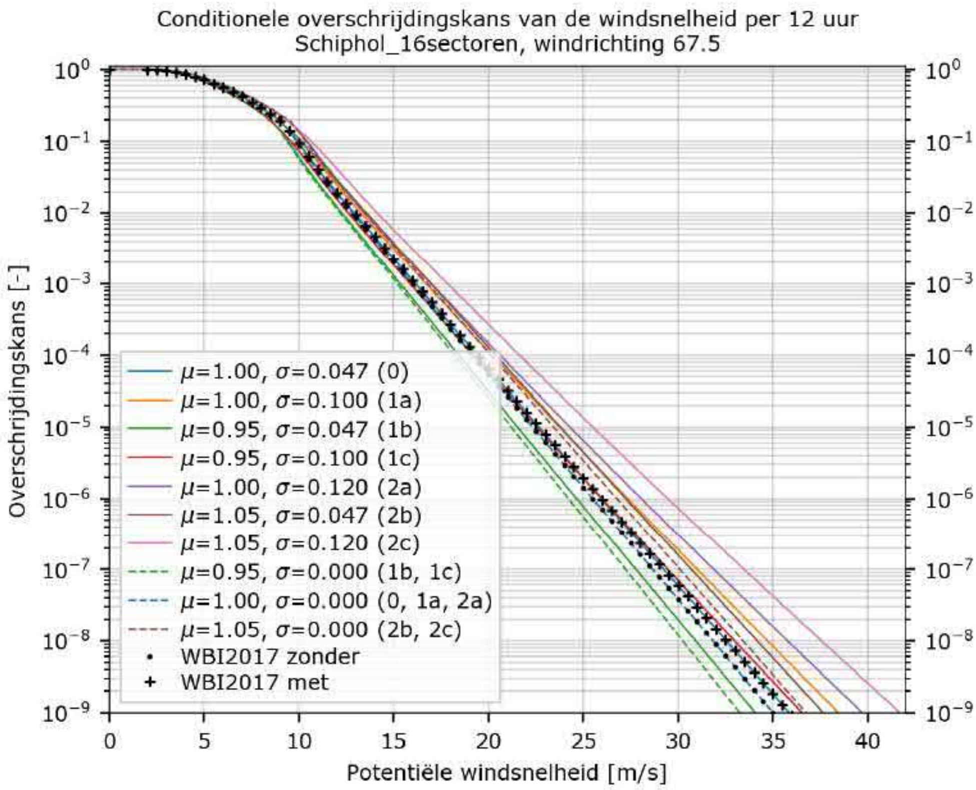
3.5 Schiphol (16 sectoren)



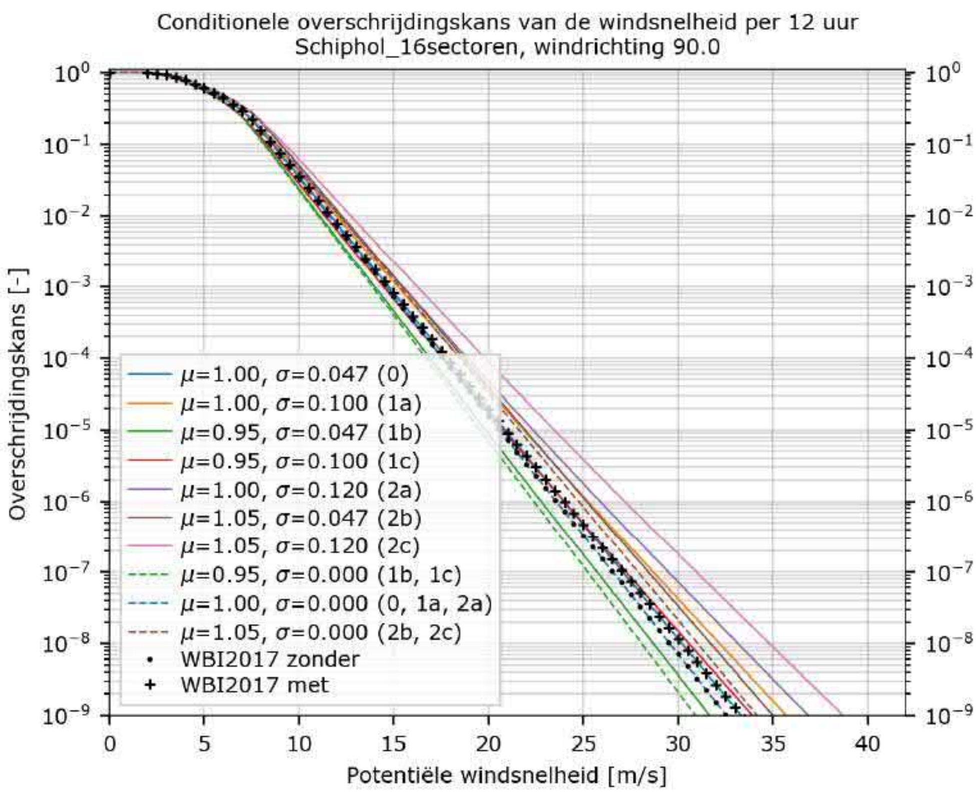
Figuur 49 Overschrijdingsfrequentielijnen voor windrichting 22.5 voor Schiphol (16 sectoren).



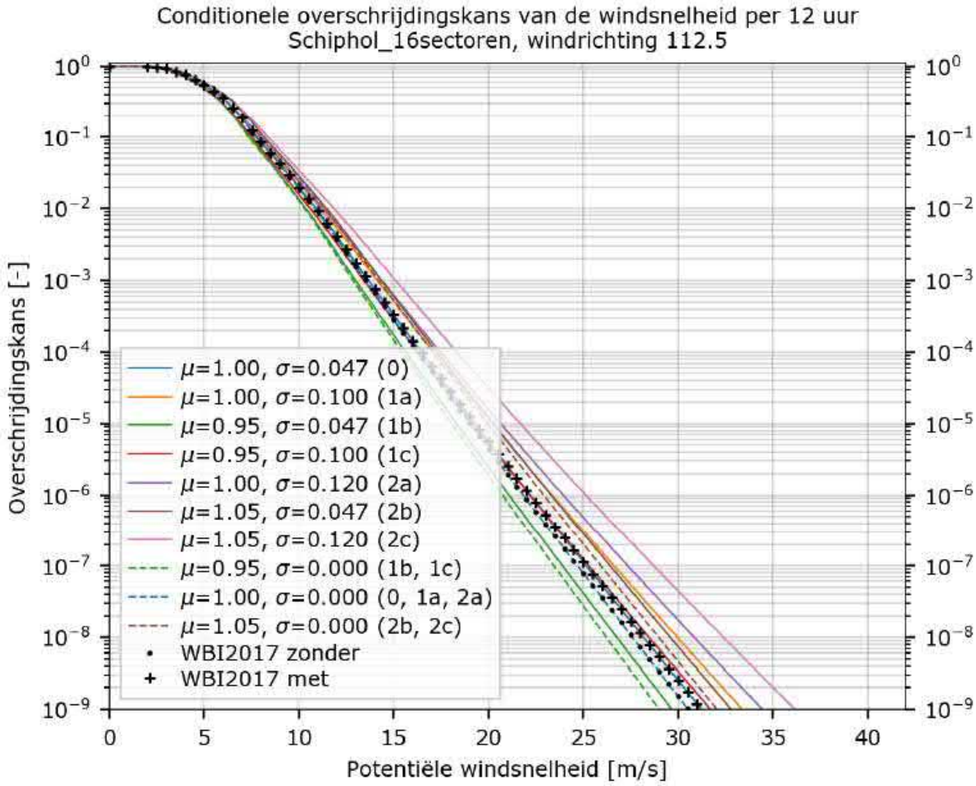
Figuur 50 Overschrijdingsfrequentielijnen voor windrichting 45.0 voor Schiphol (16 sectoren).



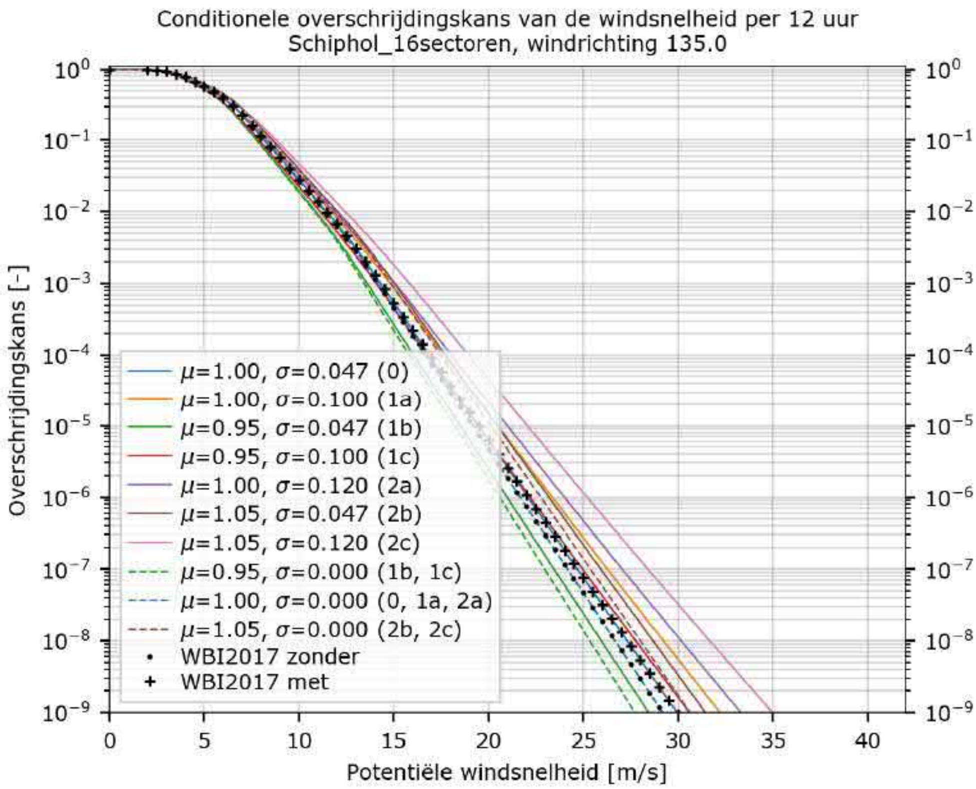
Figuur 51 Overschrijdingsfrequentielijnen voor windrichting 67.5 voor Schiphol (16 sectoren).



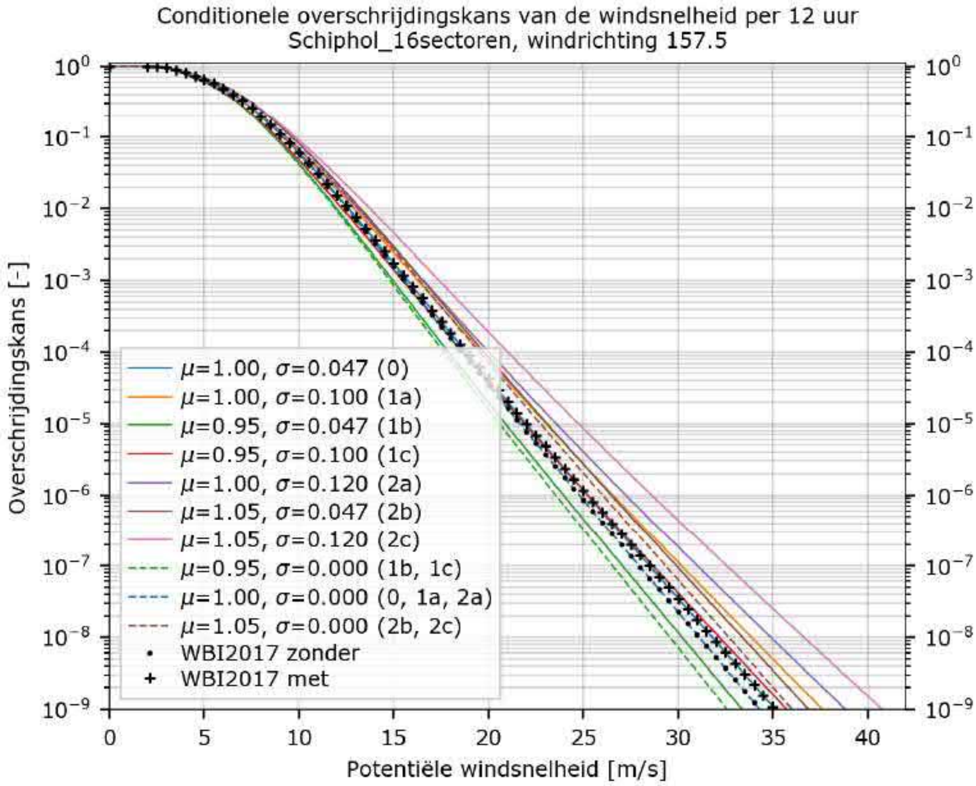
Figuur 52 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor Schiphol (16 sectoren).



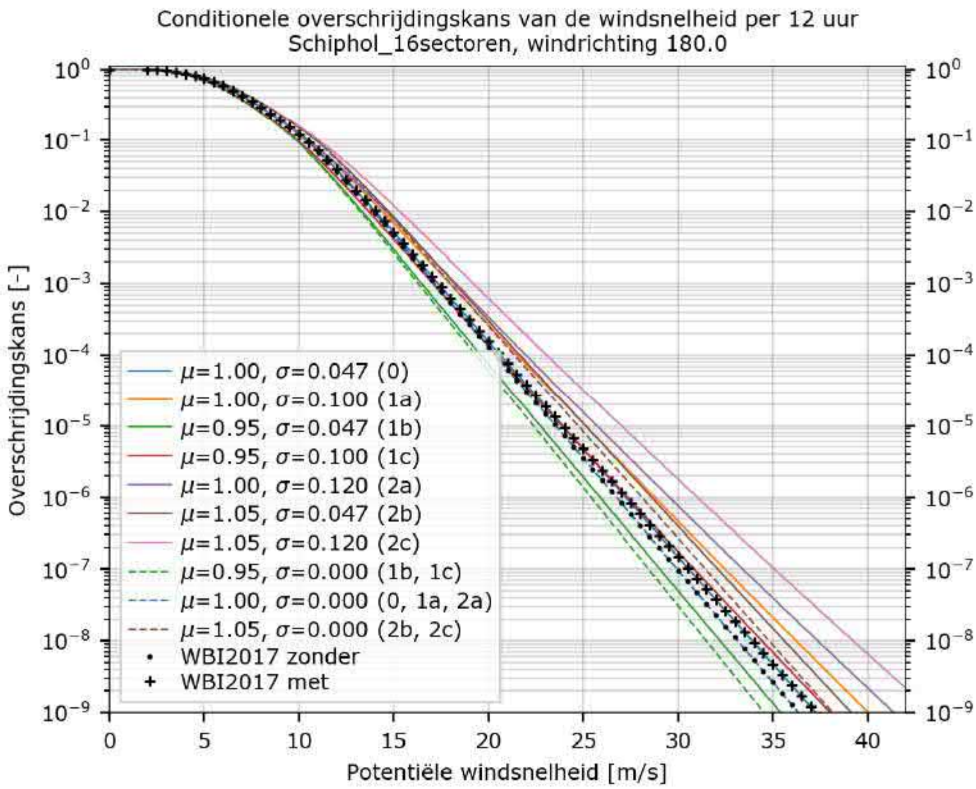
Figuur 53 Overschrijdingsfrequentielijnen voor windrichting 112.5 voor Schiphol (16 sectoren).



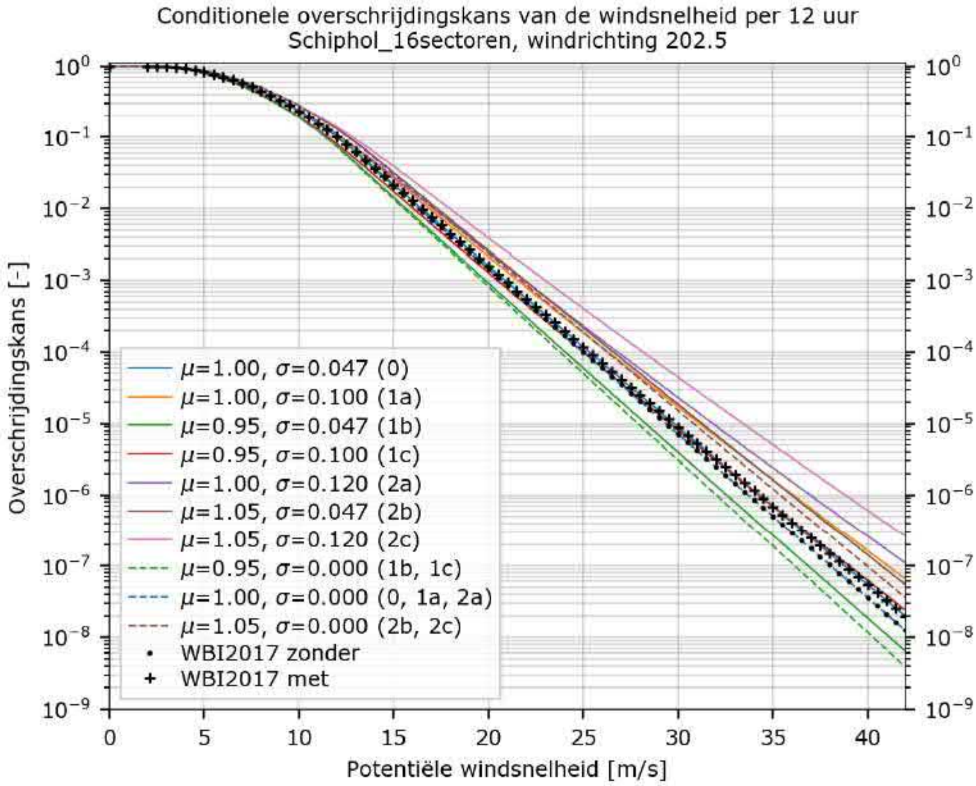
Figuur 54 Overschrijdingsfrequentielijnen voor windrichting 135.0 voor Schiphol (16 sectoren).



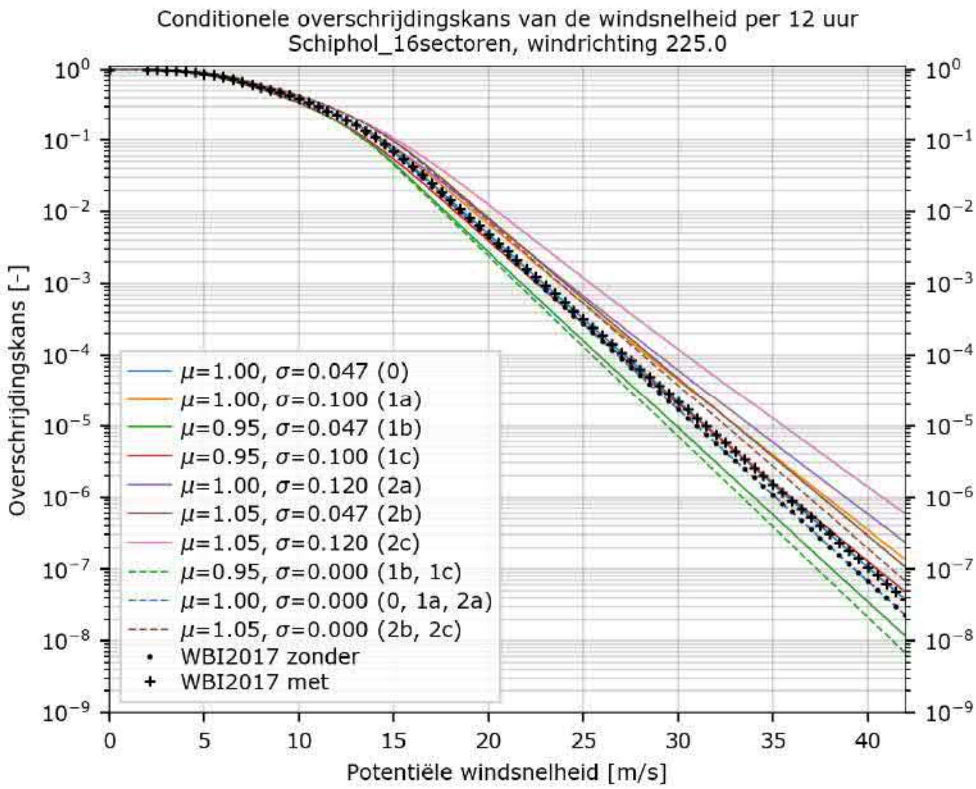
Figuur 55 Overschrijdingsfrequentielijnen voor windrichting 157.5 voor Schiphol (16 sectoren).



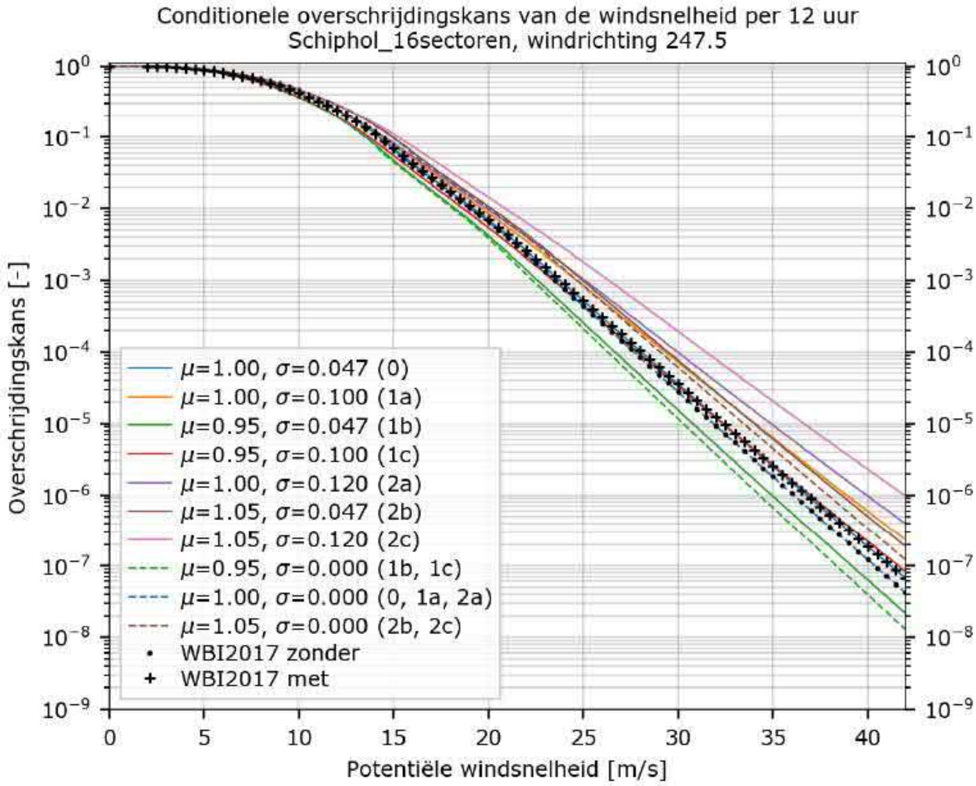
Figuur 56 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor Schiphol (16 sectoren).



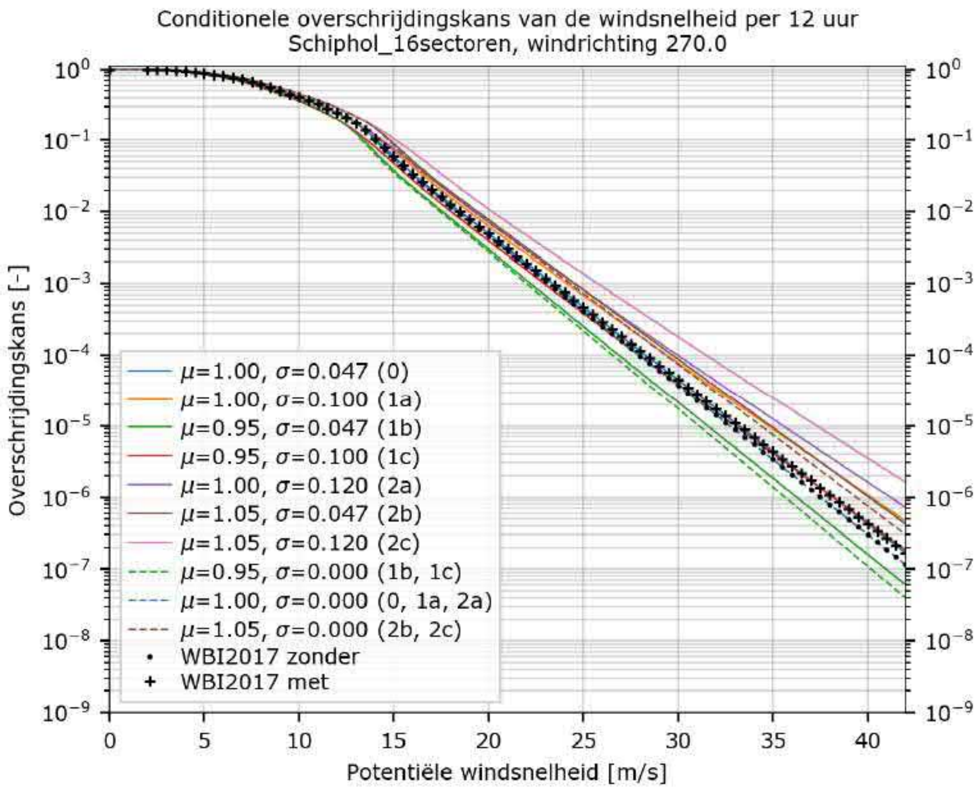
Figuur 57 Overschrijdingsfrequentielijnen voor windrichting 202.5 voor Schiphol (16 sectoren).



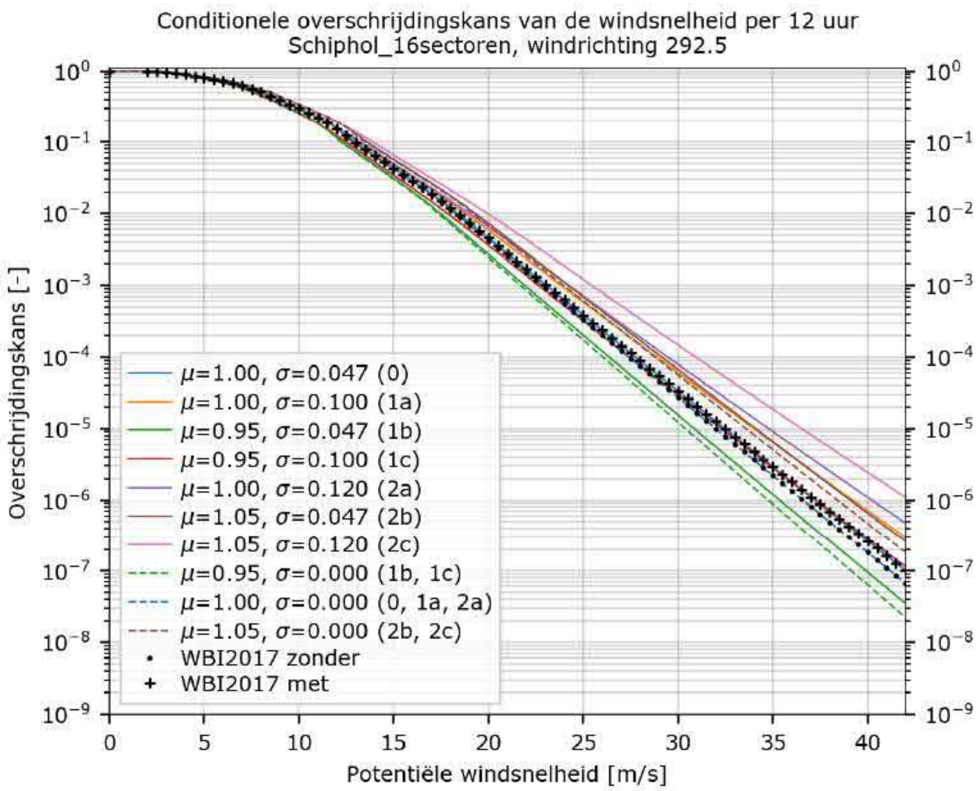
Figuur 58 Overschrijdingsfrequentielijnen voor windrichting 225.0 voor Schiphol (16 sectoren).



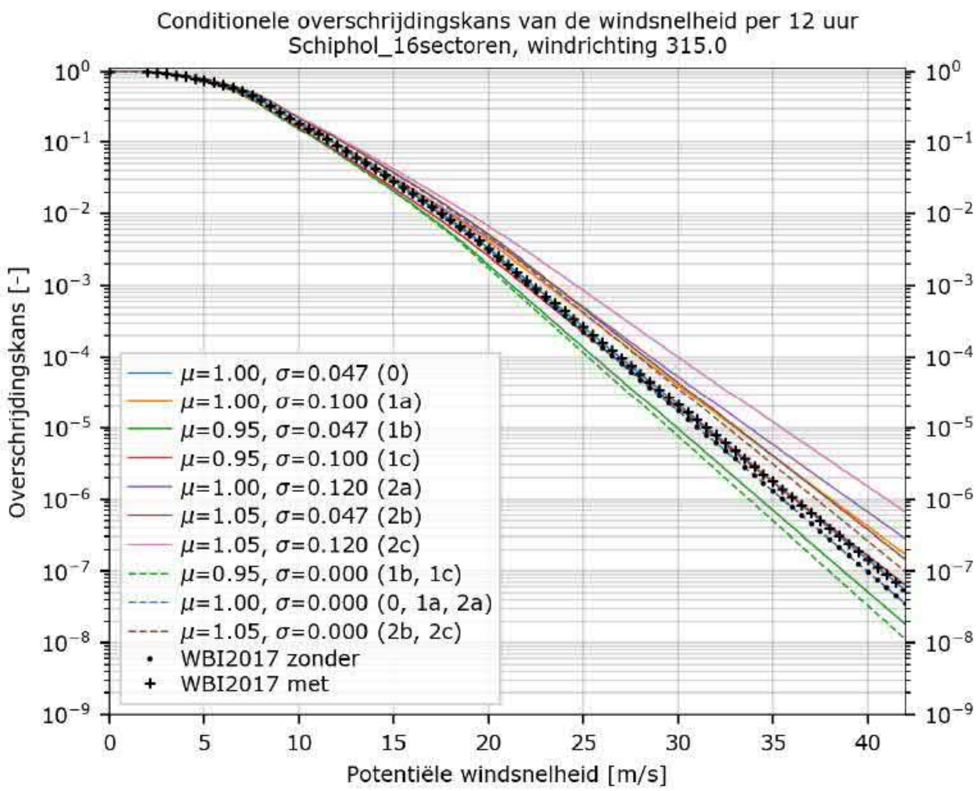
Figuur 59 Overschrijdingsfrequentielijnen voor windrichting 247.5 voor Schiphol (16 sectoren).



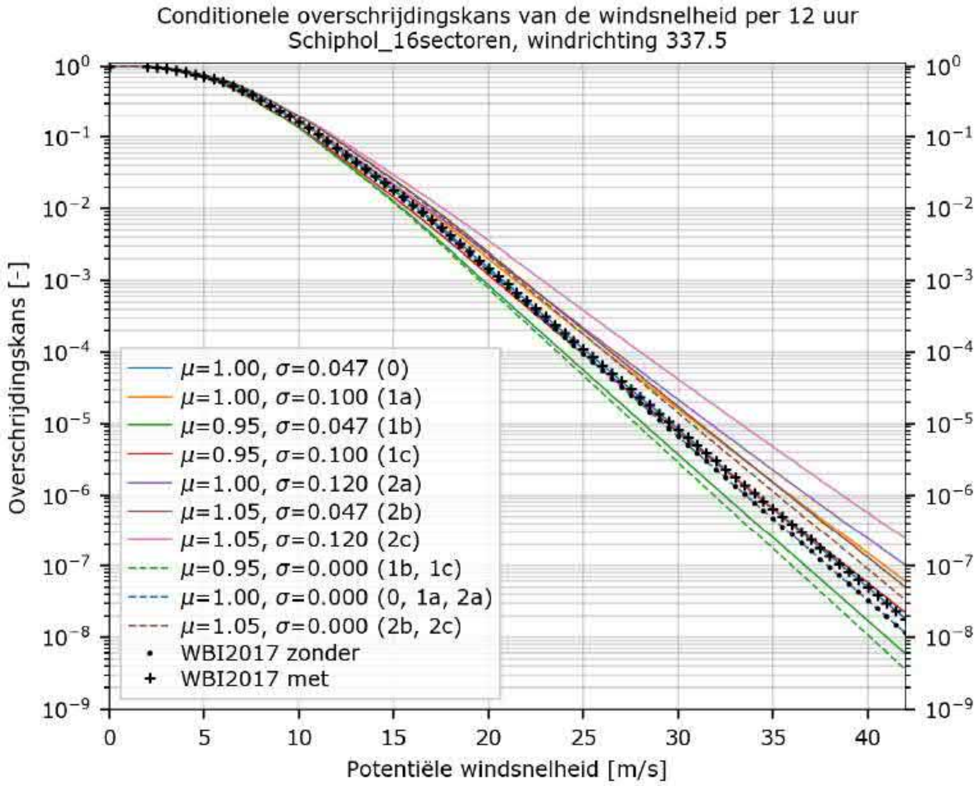
Figuur 60 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor Schiphol (16 sectoren).



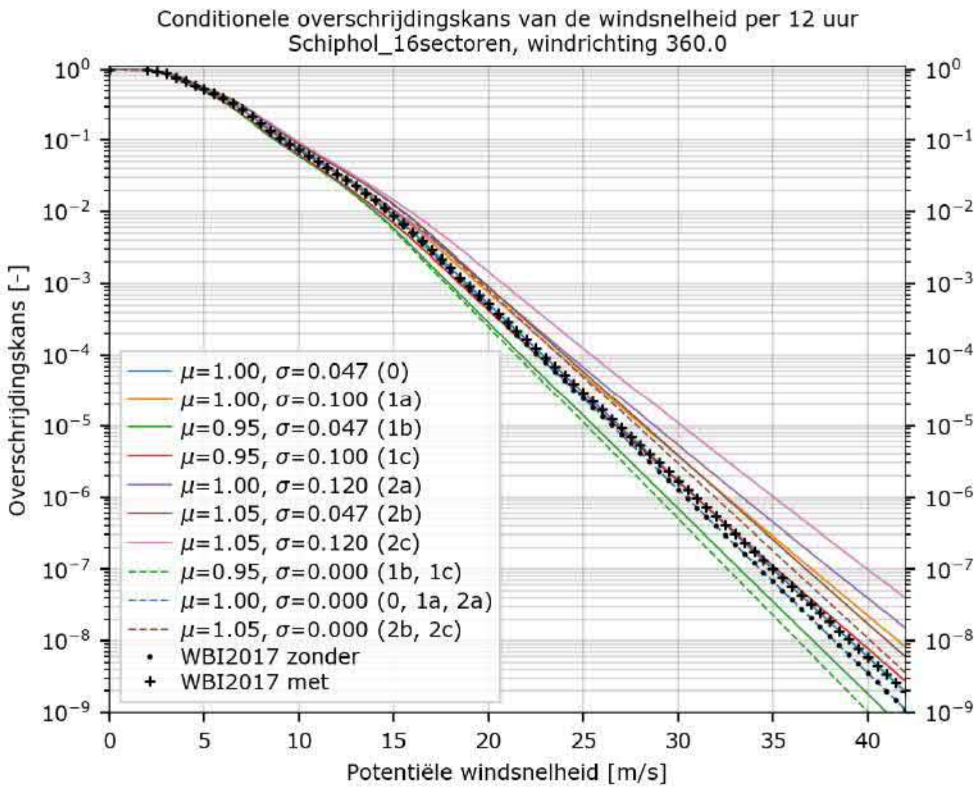
Figuur 61 Overschrijdingsfrequentielijnen voor windrichting 292.5 voor Schiphol (16 sectoren).



Figuur 62 Overschrijdingsfrequentielijnen voor windrichting 315.0 voor Schiphol (16 sectoren).

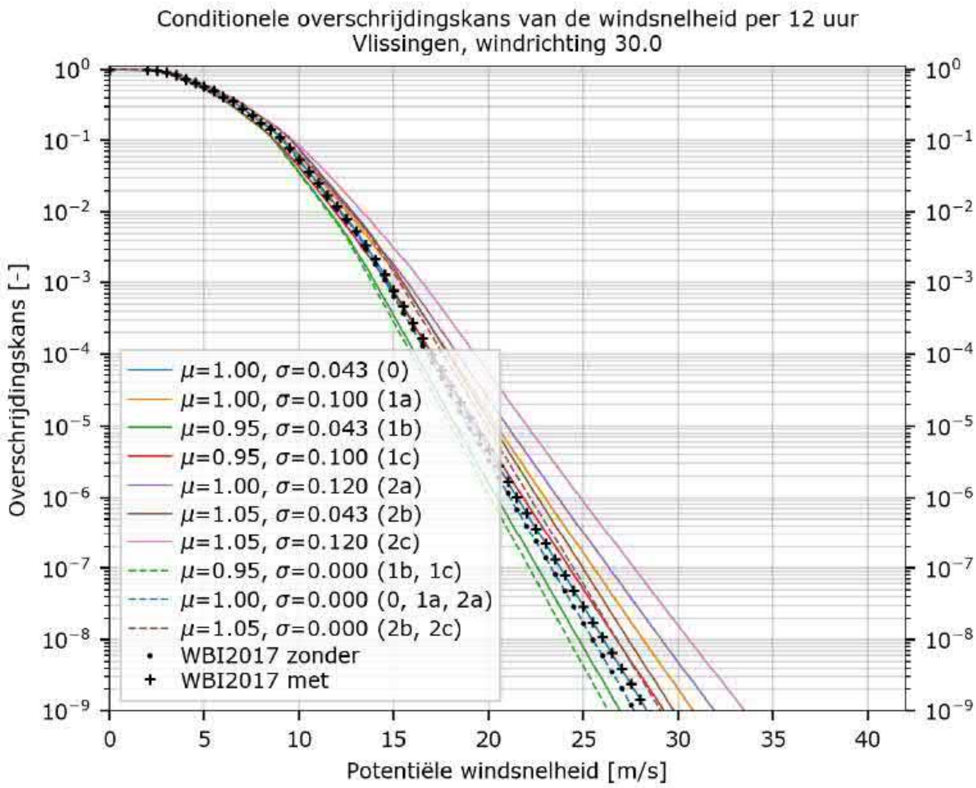


Figuur 63 Overschrijdingsfrequentielijnen voor windrichting 337.5 voor Schiphol (16 sectoren).

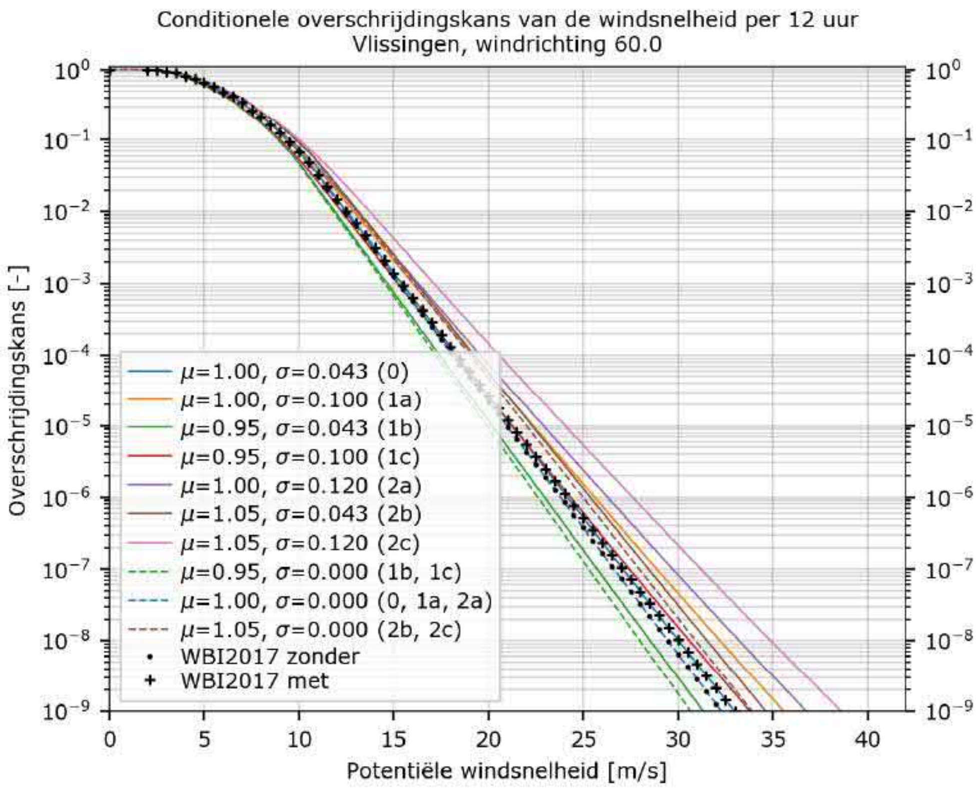


Figuur 64 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor Schiphol (16 sectoren).

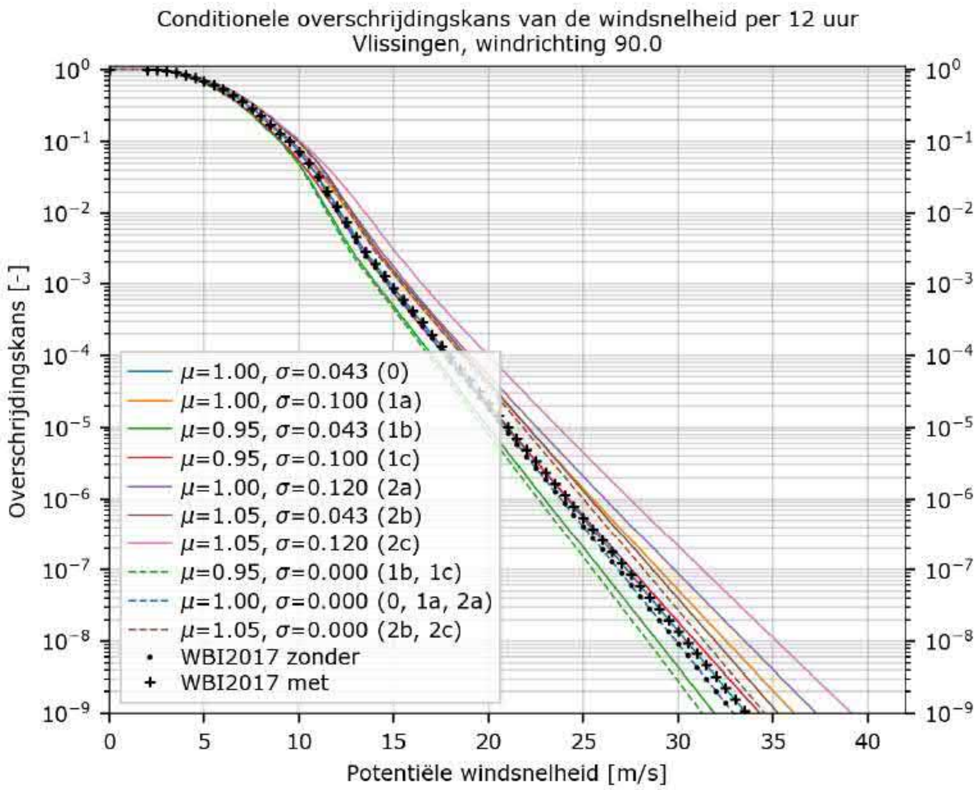
3.6 Vlissingen



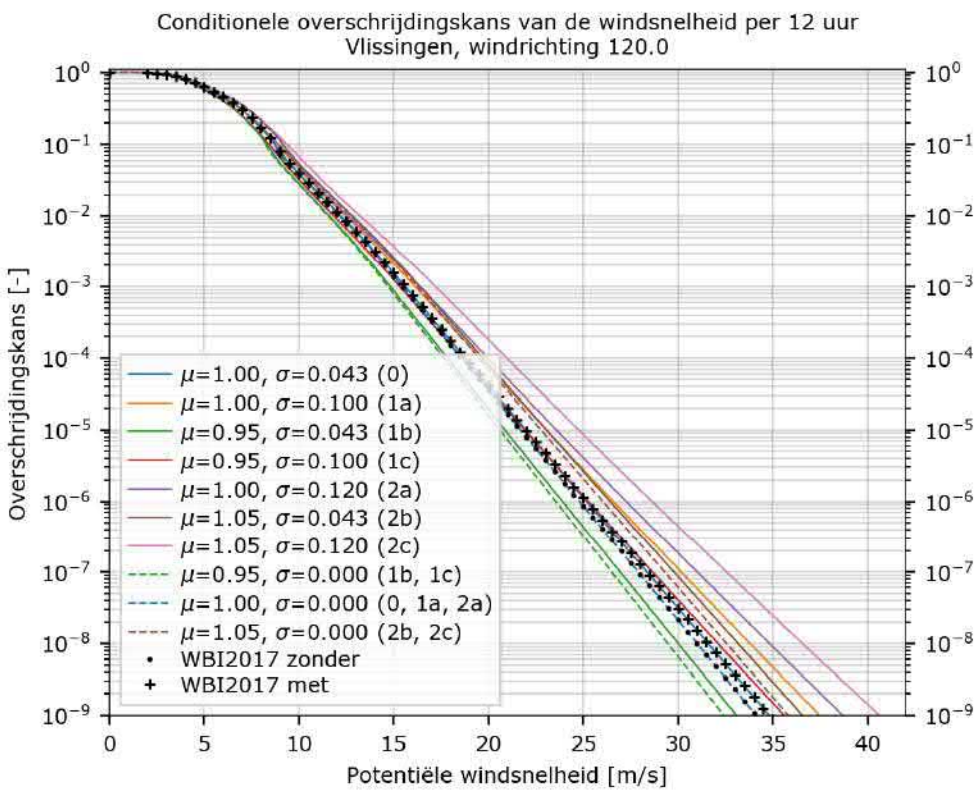
Figuur 65 Overschrijdingsfrequentielijnen voor windrichting 30.0 voor Vlissingen.



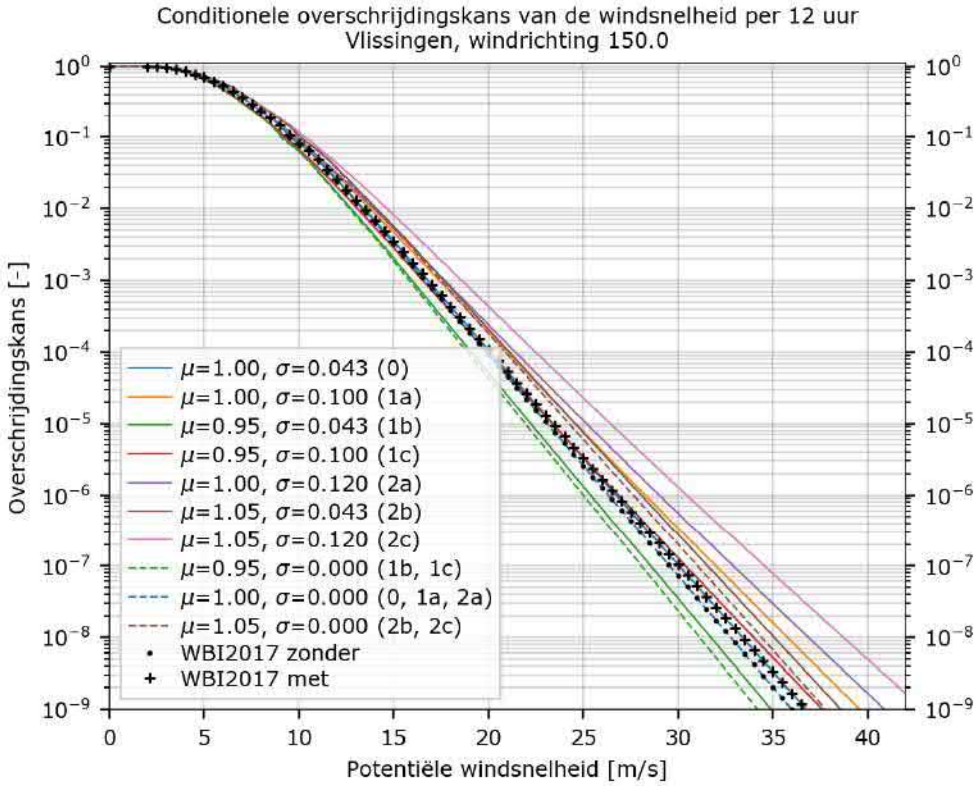
Figuur 66 Overschrijdingsfrequentielijnen voor windrichting 60.0 voor Vlissingen.



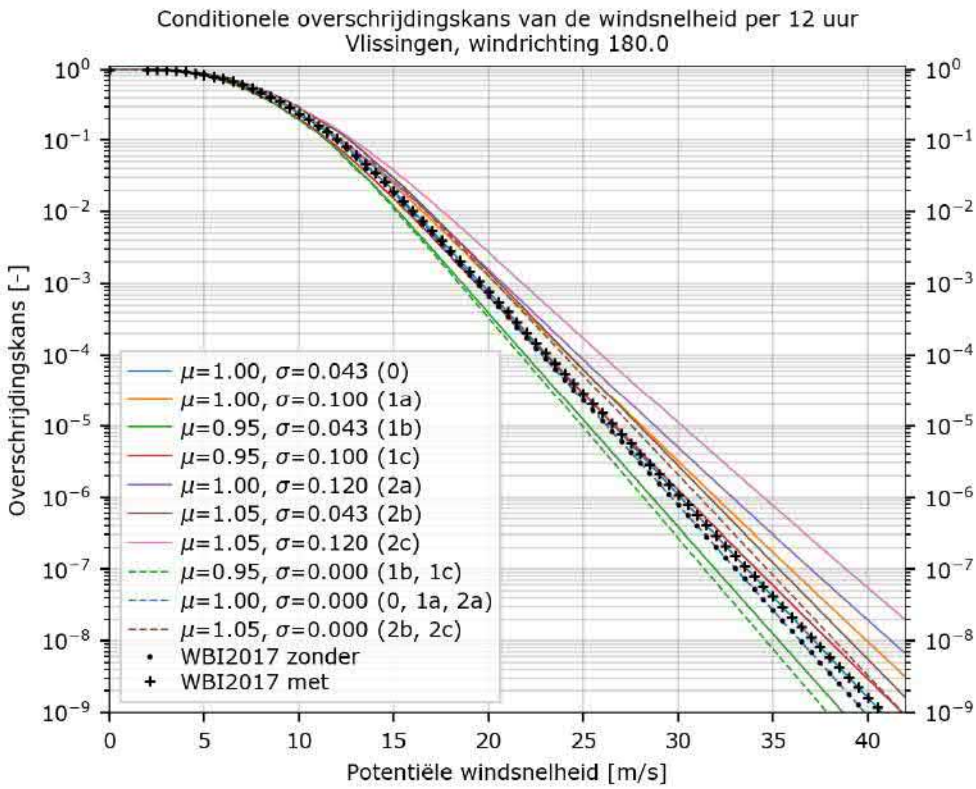
Figuur 67 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor Vlissingen.



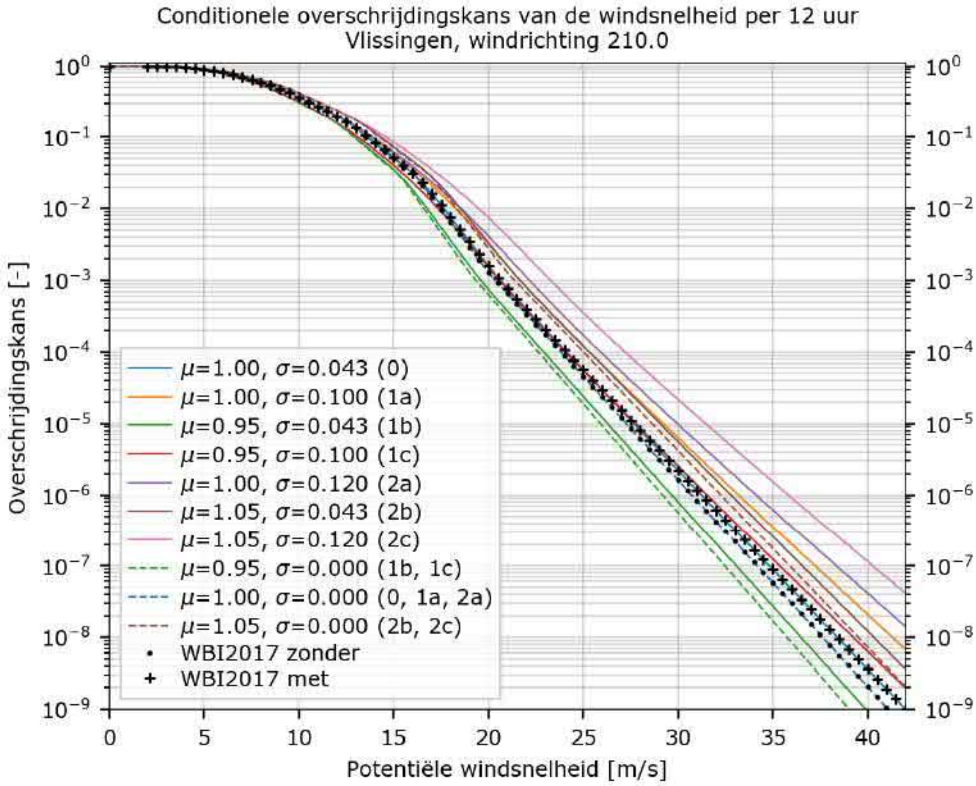
Figuur 68 Overschrijdingsfrequentielijnen voor windrichting 120.0 voor Vlissingen.



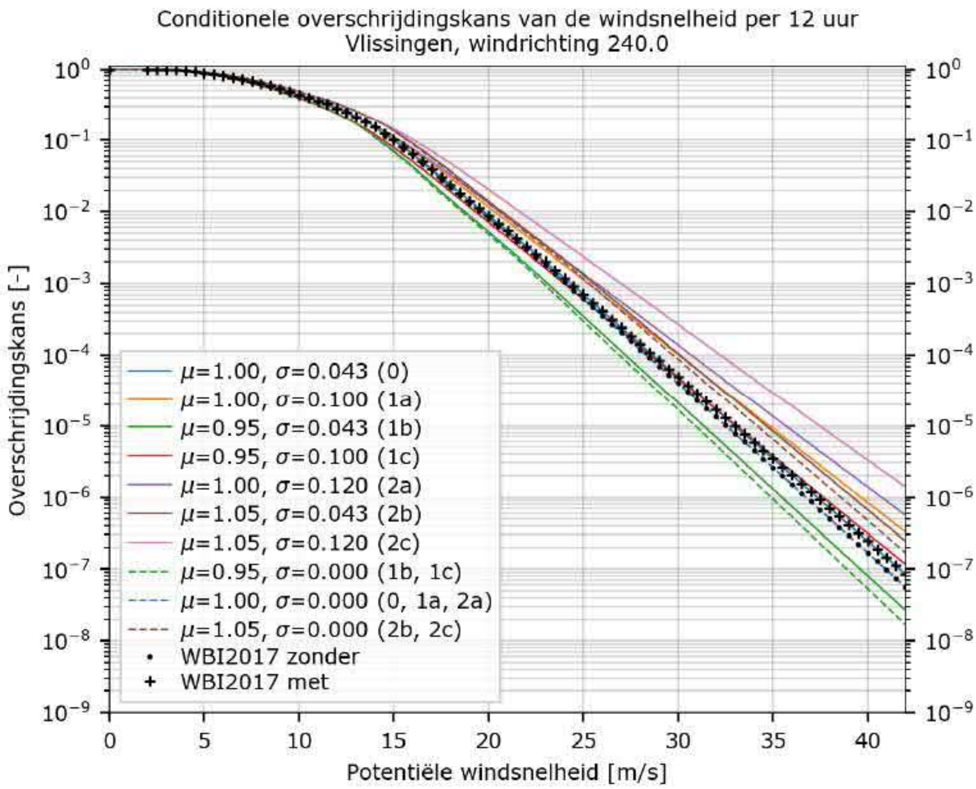
Figuur 69 Overschrijdingsfrequentielijnen voor windrichting 150.0 voor Vlissingen.



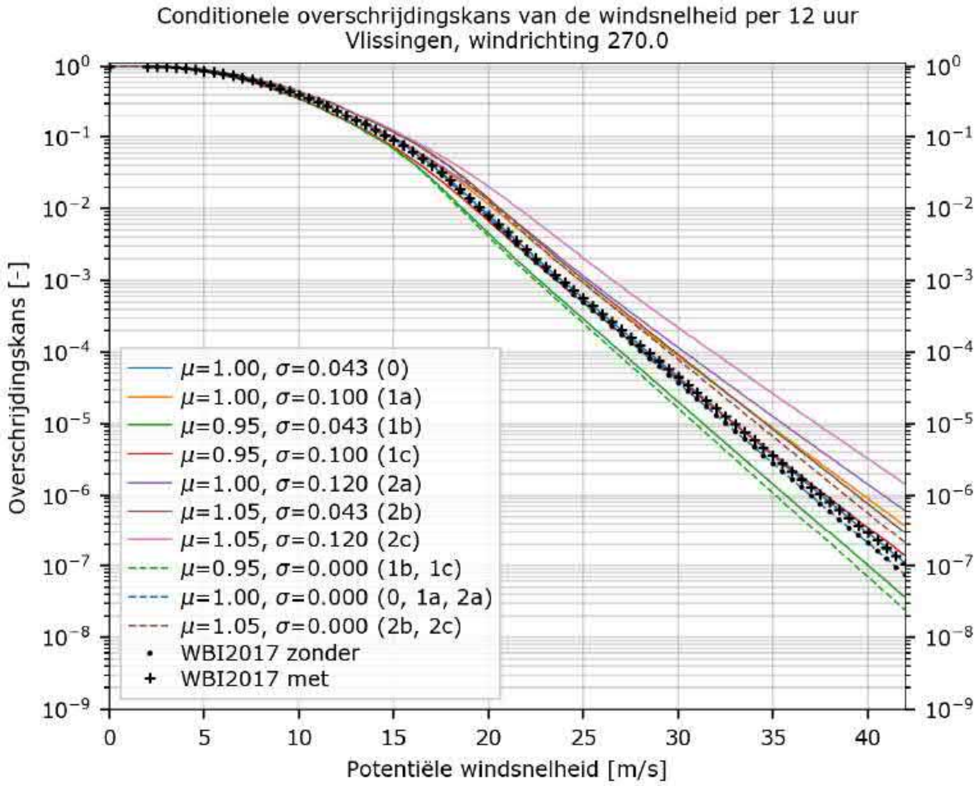
Figuur 70 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor Vlissingen.



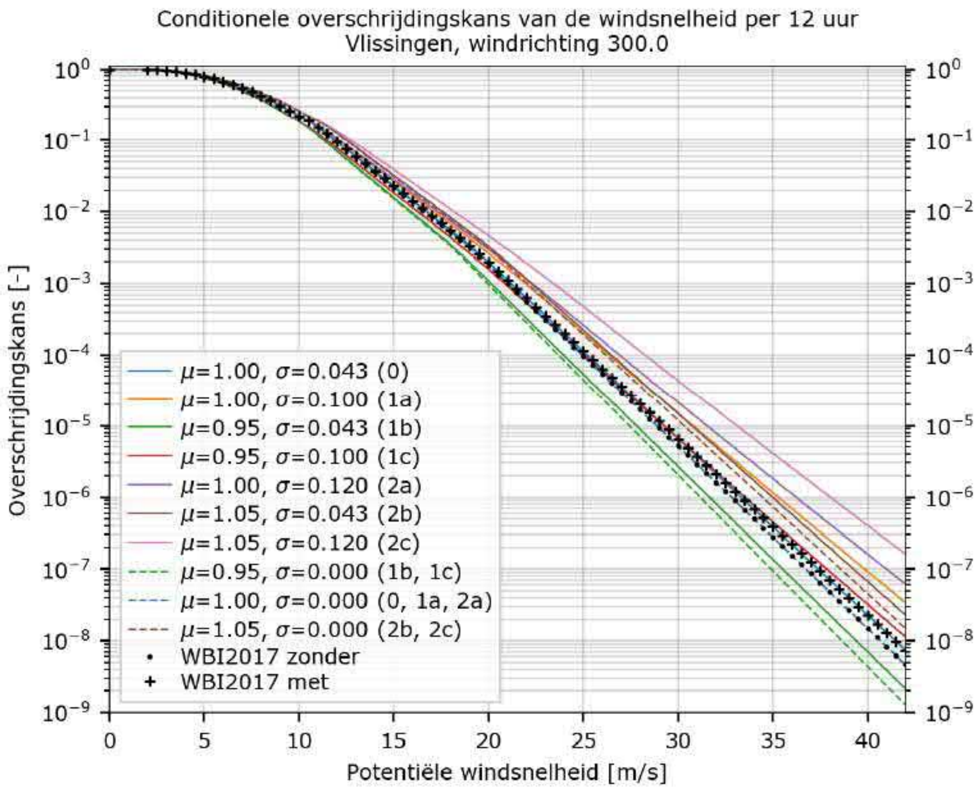
Figuur 71 Overschrijdingsfrequentielijnen voor windrichting 210.0 voor Vlissingen.



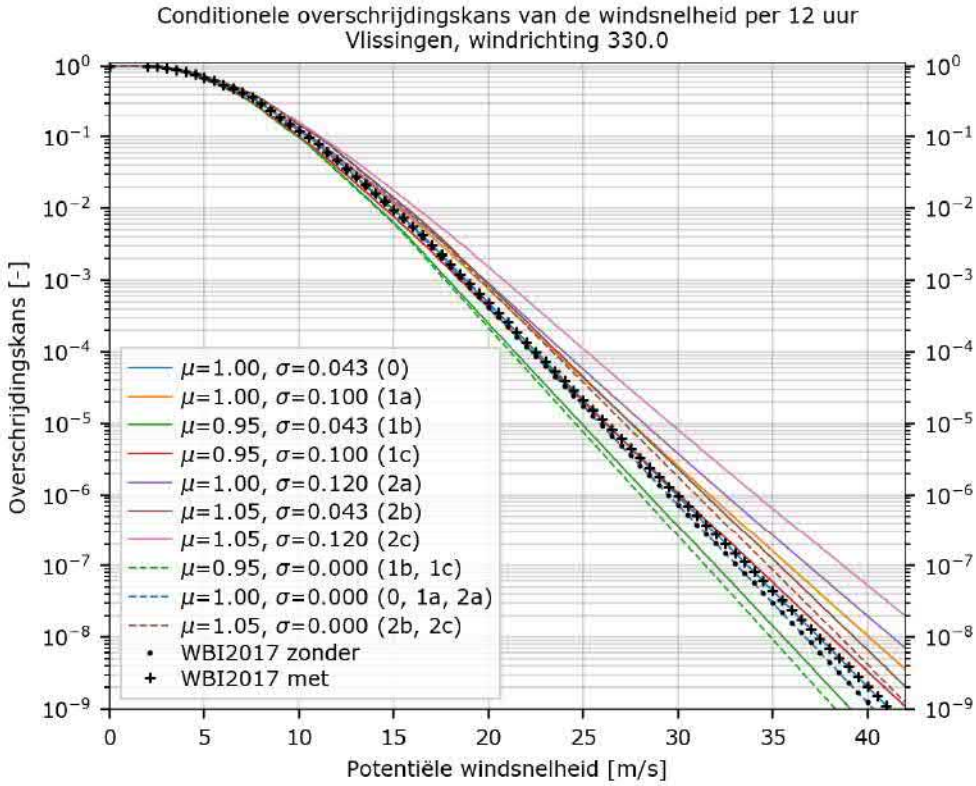
Figuur 72 Overschrijdingsfrequentielijnen voor windrichting 240.0 voor Vlissingen.



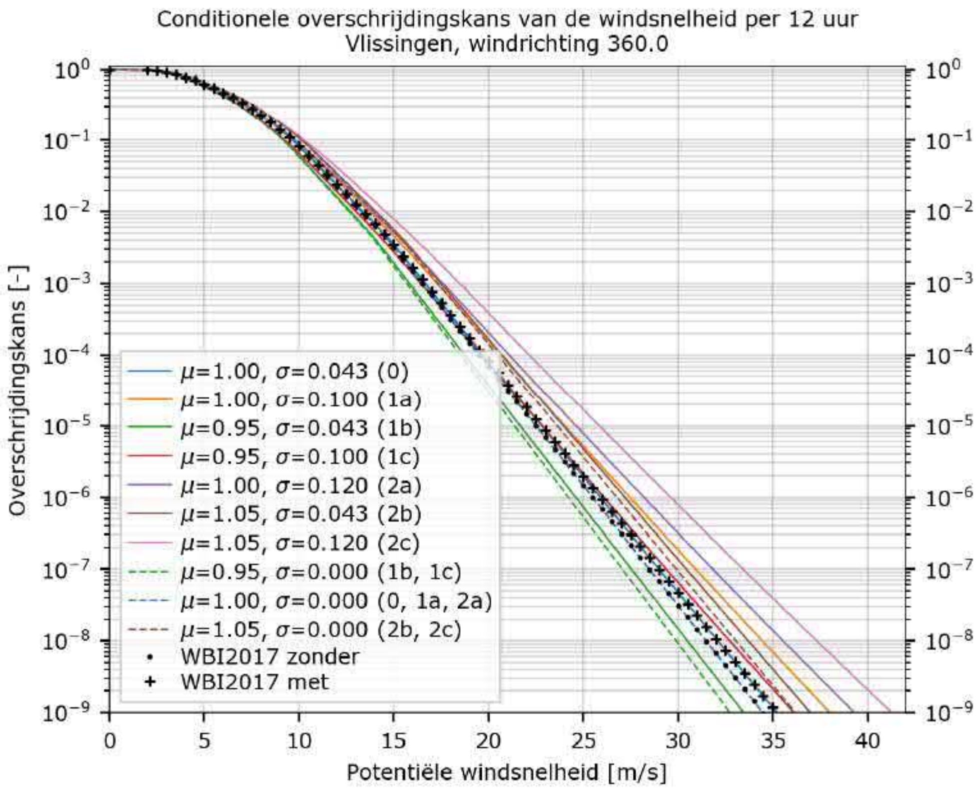
Figuur 73 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor Vlissingen.



Figuur 74 Overschrijdingsfrequentielijnen voor windrichting 300.0 voor Vlissingen.

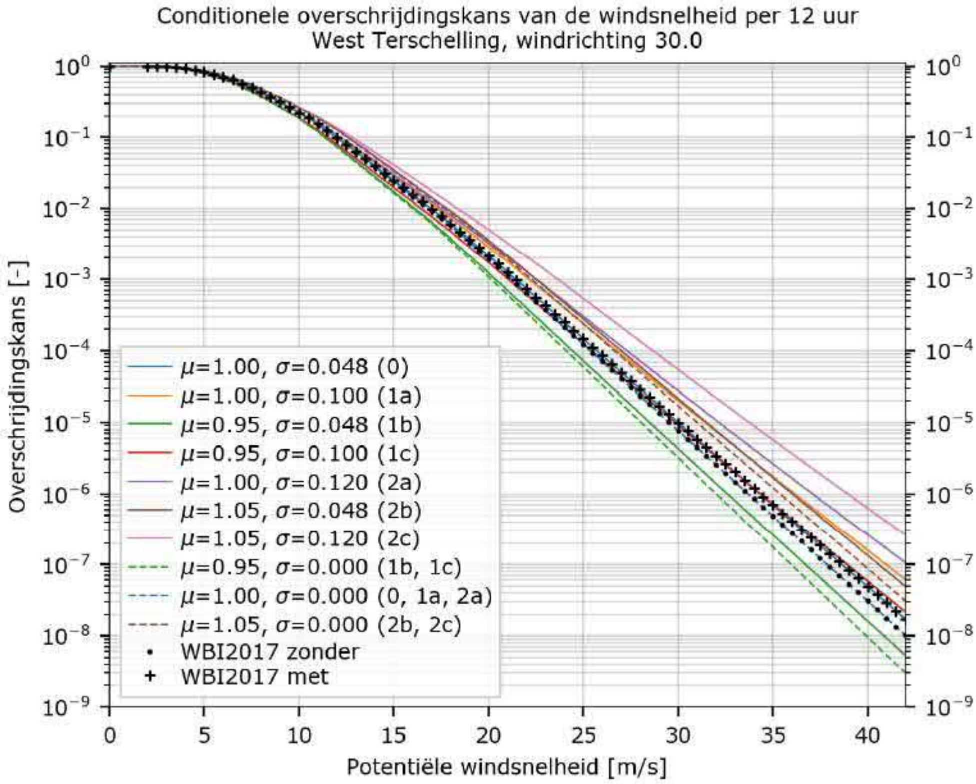


Figuur 75 Overschrijdingsfrequentielijnen voor windrichting 330.0 voor Vlissingen.

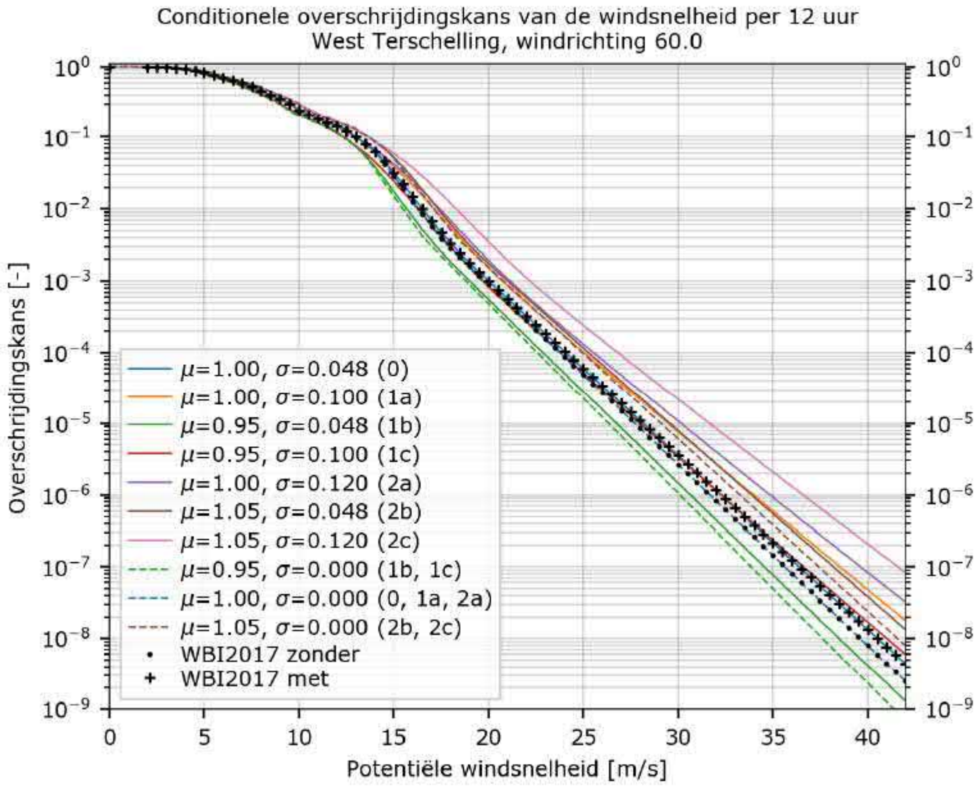


Figuur 76 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor Vlissingen.

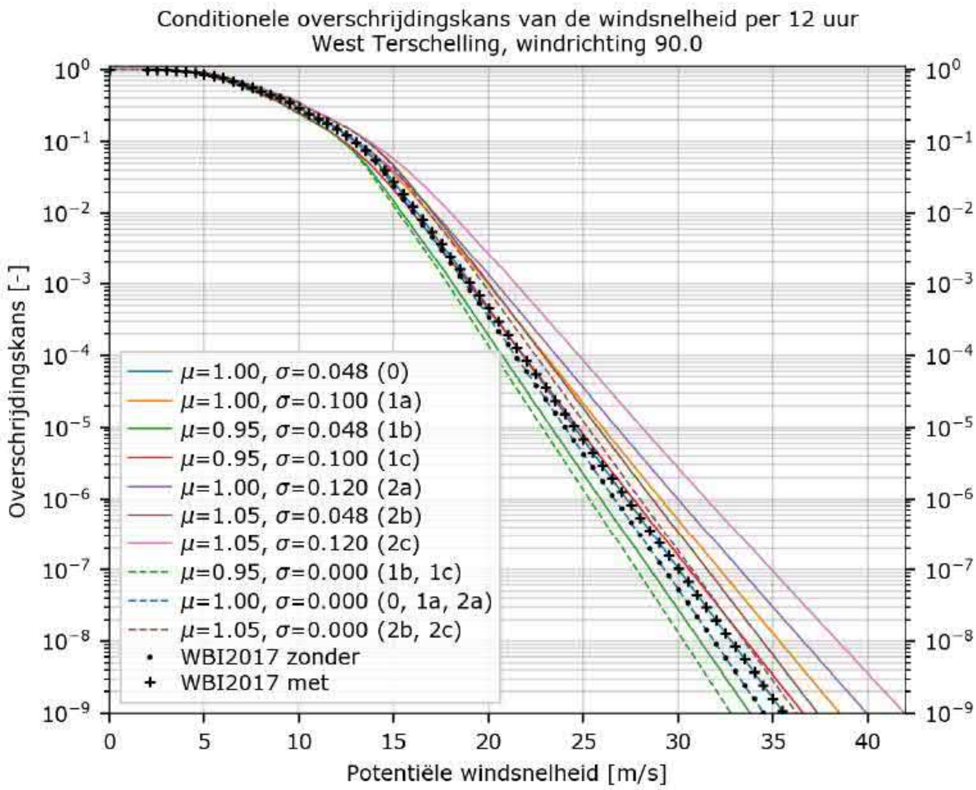
3.7 West Terschelling



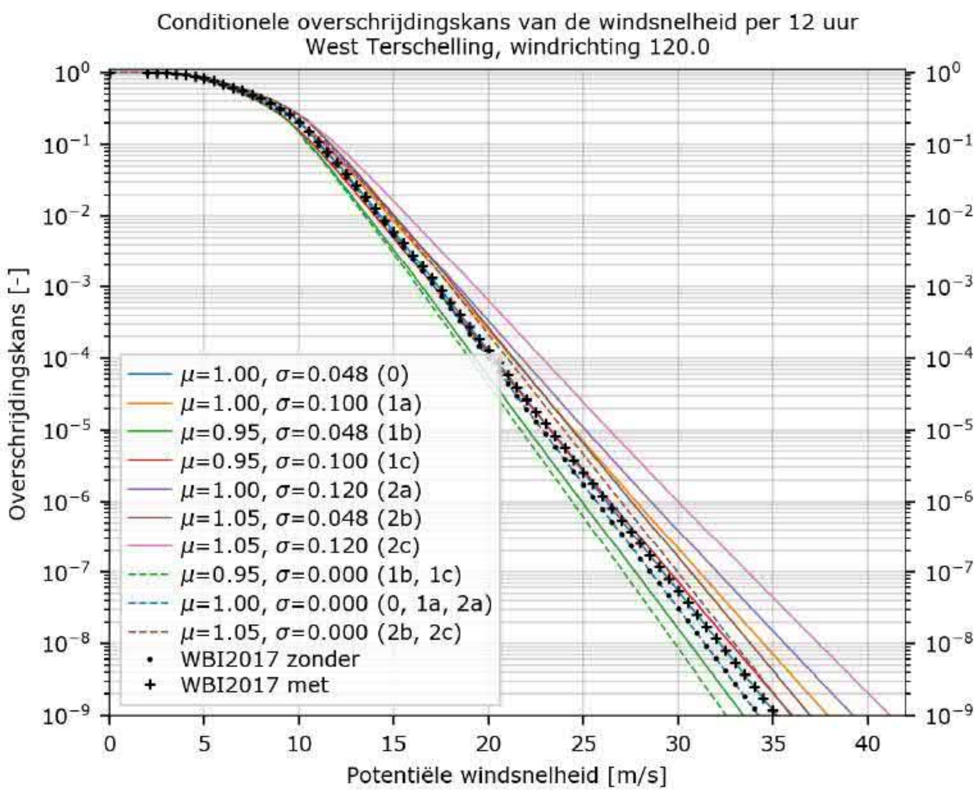
Figuur 77 Overschrijdingsfrequentielijnen voor windrichting 30.0 voor West Terschelling.



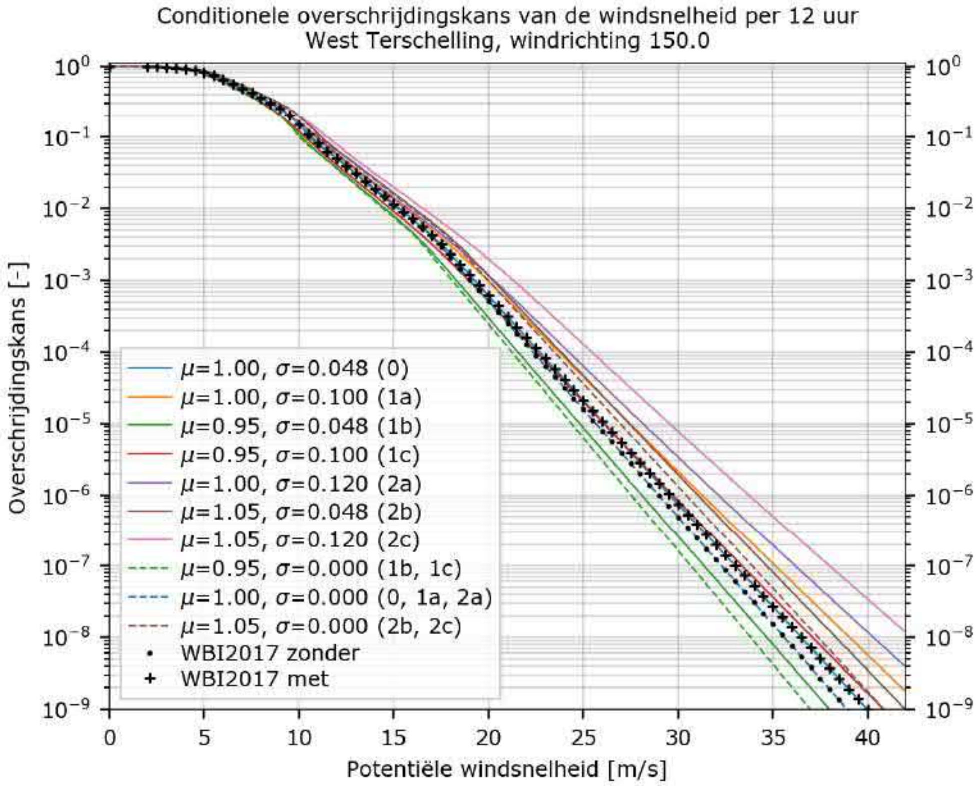
Figuur 78 Overschrijdingsfrequentielijnen voor windrichting 60.0 voor West Terschelling.



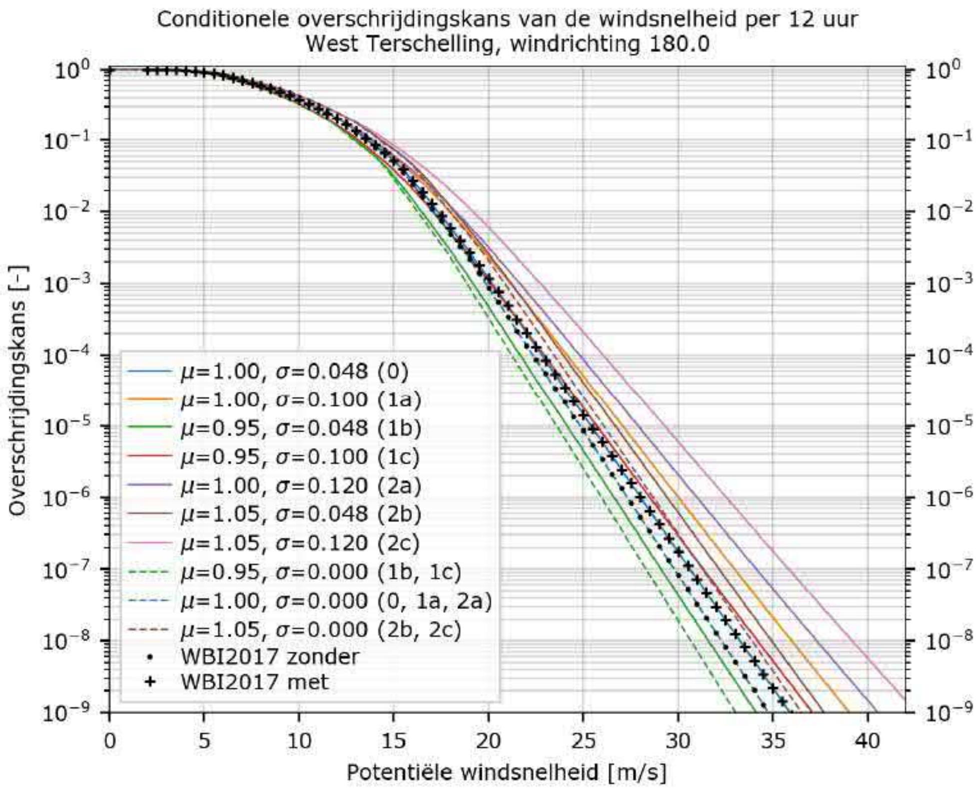
Figuur 79 Overschrijdingsfrequentielijnen voor windrichting 90.0 voor West Terschelling.



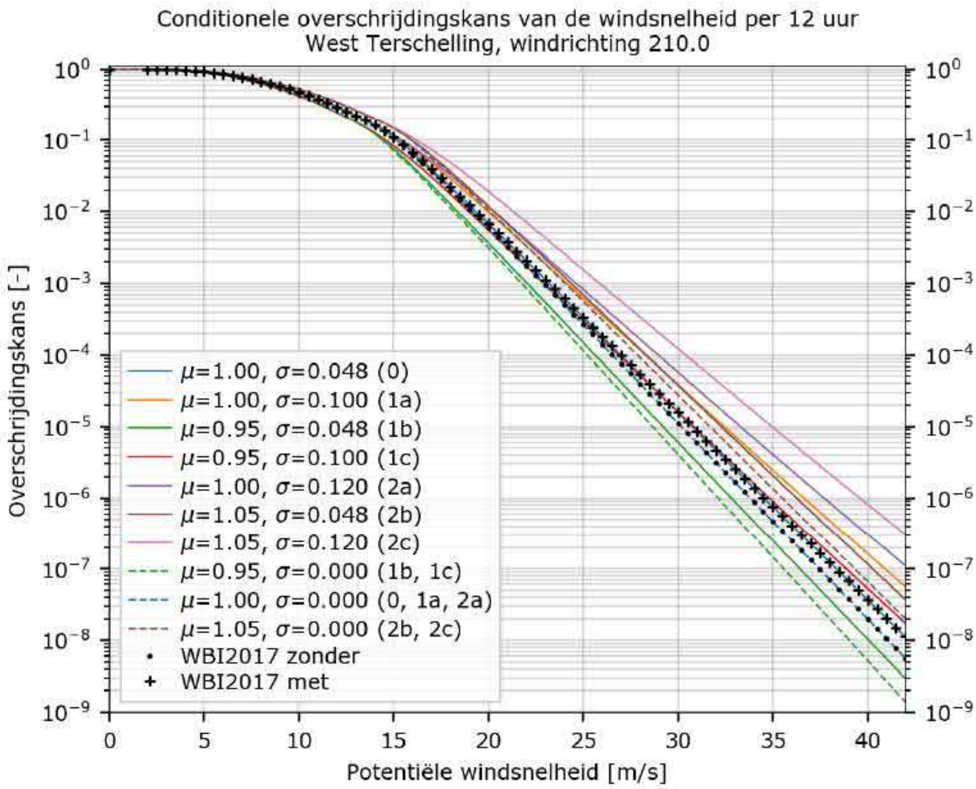
Figuur 80 Overschrijdingsfrequentielijnen voor windrichting 120.0 voor West Terschelling.



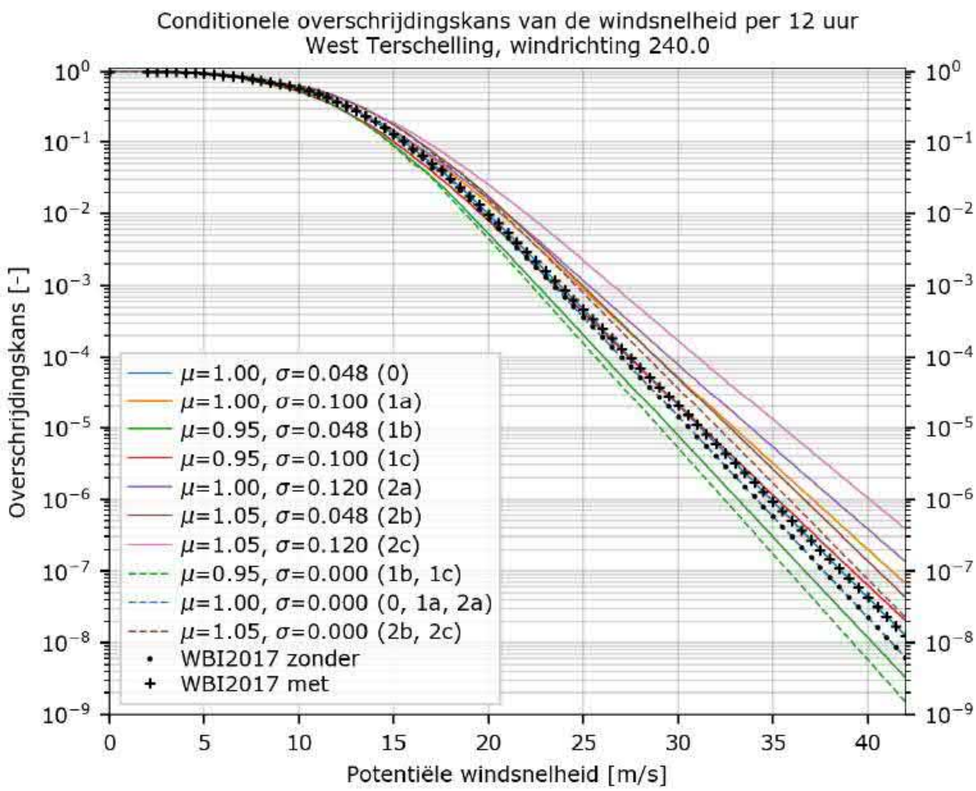
Figuur 81 Overschrijdingsfrequentielijnen voor windrichting 150.0 voor West Terschelling.



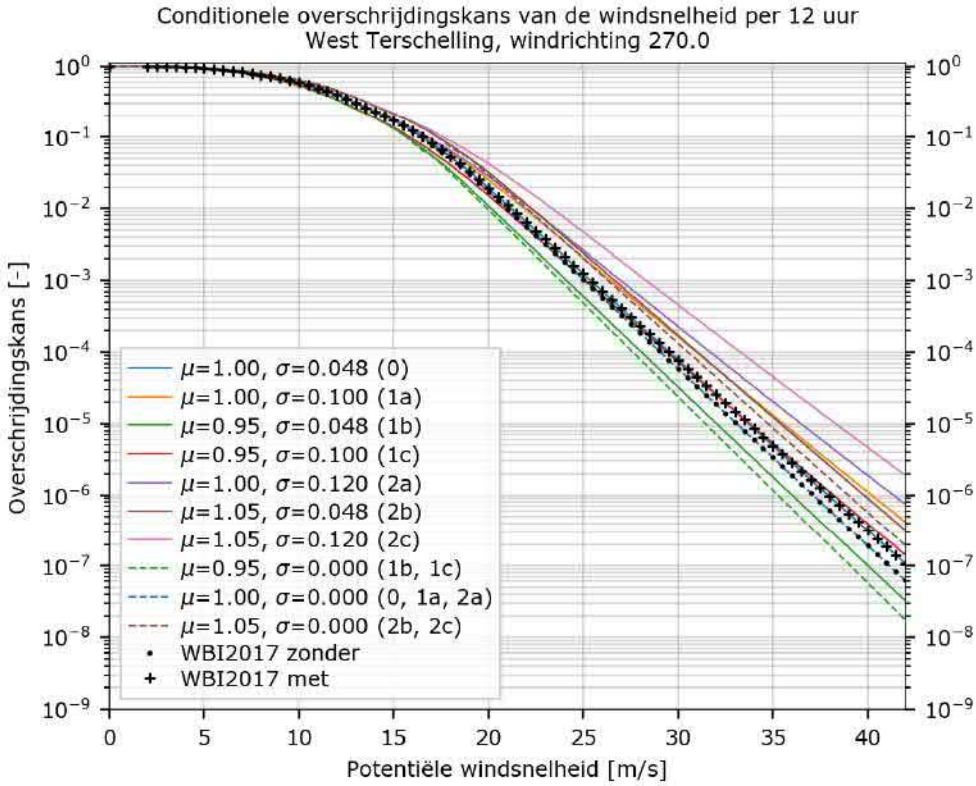
Figuur 82 Overschrijdingsfrequentielijnen voor windrichting 180.0 voor West Terschelling.



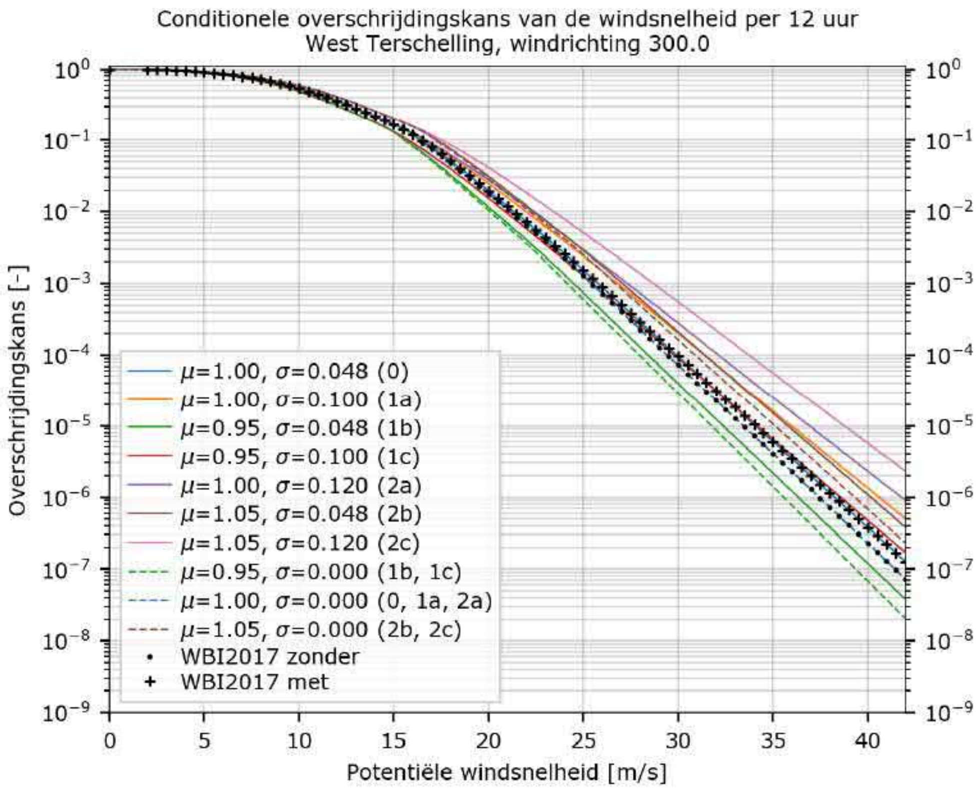
Figuur 83 Overschrijdingsfrequentielijnen voor windrichting 210.0 voor West Terschelling.



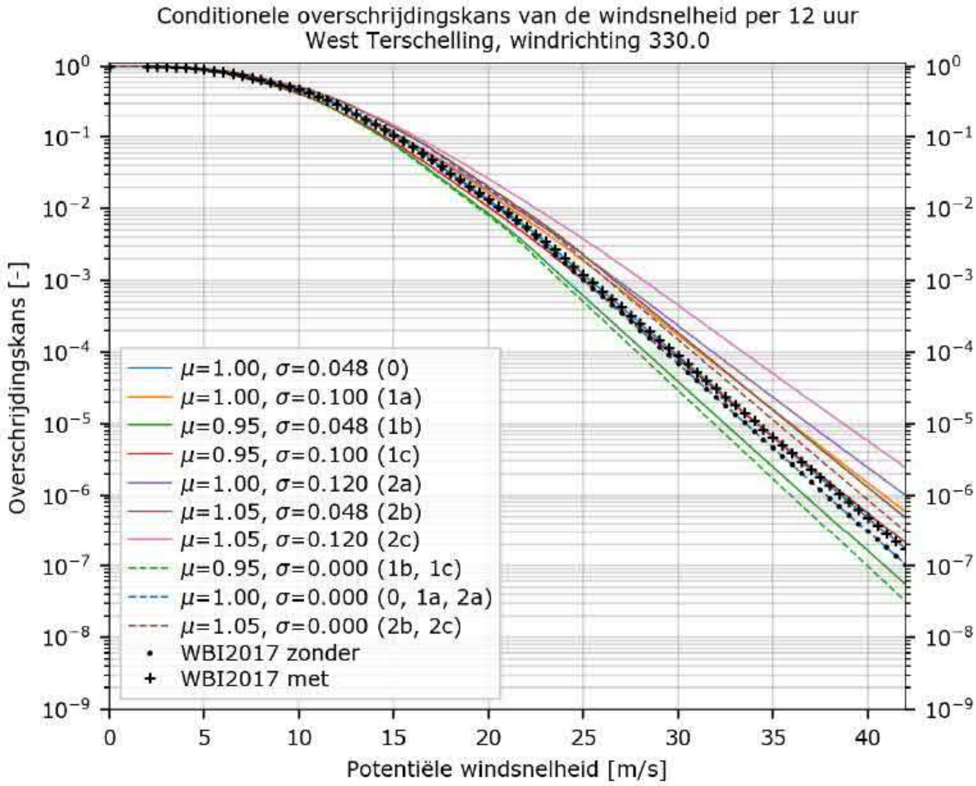
Figuur 84 Overschrijdingsfrequentielijnen voor windrichting 240.0 voor West Terschelling.



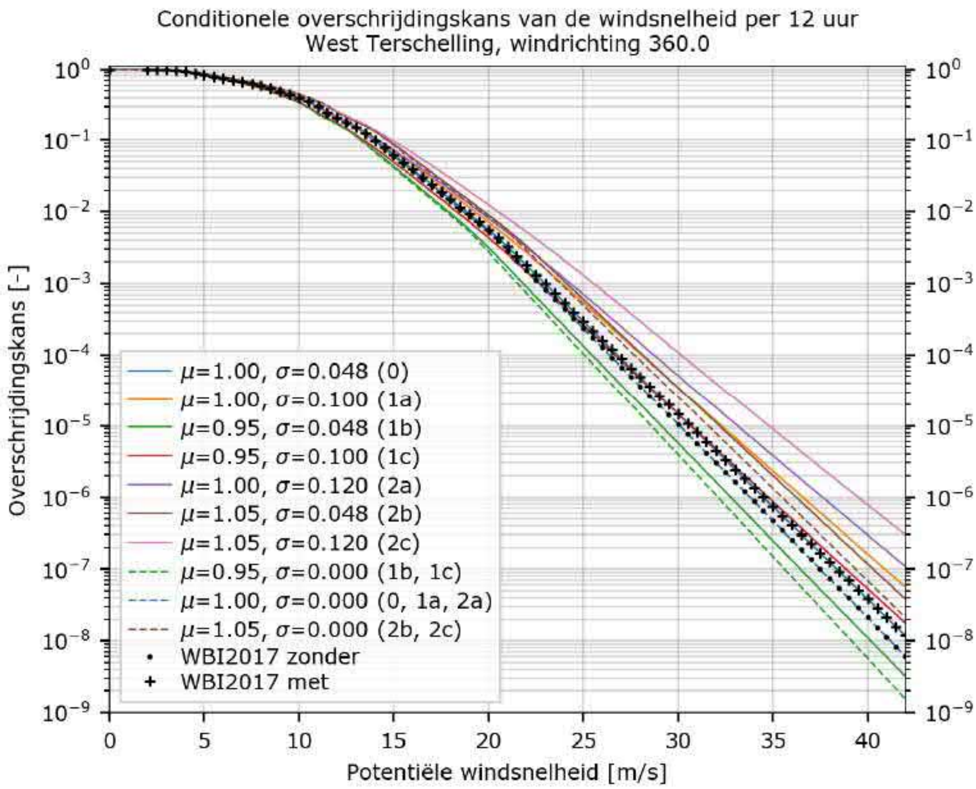
Figuur 85 Overschrijdingsfrequentielijnen voor windrichting 270.0 voor West Terschelling.



Figuur 86 Overschrijdingsfrequentielijnen voor windrichting 300.0 voor West Terschelling.



Figuur 87 Overschrijdingsfrequentielijnen voor windrichting 330.0 voor West Terschelling.



Figuur 88 Overschrijdingsfrequentielijnen voor windrichting 360.0 voor West Terschelling.

4 Referenties

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C Hydraulic loads in coastal region

For the selected locations in the Wadden Sea, the Western Scheldt and along the Holland Coast the required crest level (HBN) has been determined for all scenarios. For the reference wind climate the HBN levels, corresponding to the profile norm, along with the values of water level, wind speed and wind direction have been presented in the table below. Based on the estimate given in Section 3.3.2 the contribution of the storm surge to the water level has been estimated (last column).

				Illustration point			
Location	Traject norm	Profile norm	HBN (m+NAP)	Water level (m+NAP)	Wind speed (m/s)	Wind direction (degN)	Strom surge (m)
WZ_1_2-2_dk_00041	1000	8330	5.81	4.18	33	270	4.58
WZ_1_6-4_dk_00020	1000	12500	6.236	5.09	36.1	330	5.49
WZ_1_1-2_dk_00010	1000	4170	6.329	4.84	34.3	300	5.24
WZ_1_6-6_dk_00061	1000	12500	7.881	5.5	34.9	300	5.9
WZ_1_6-6_dk_00211	1000	12500	6.766	6.09	35.3	300	6.49
WZ_1_6-7_dk_00153	3000	37500	9.083	7.4	36.7	300	7.8
WZ_1_13-4_dk_00029	1000	4170	5.531	3.06	25	360	3.46
WZ_1_5-2_dk_00047	3000	25000	6.083	4.34	33.8	330	4.74
WZ_1_4-2_dk_00002	300	2500	4.774	3.72	32.4	270	4.12
WZ_1_201_vk_00084	3000	25000	9.135	5.15	35	330	5.55
WZ_1_3-2_dk_00010	1000	8330	5.614	3.97	32.9	270	4.37
WZ_1_6-3_dk_00096	1000	12500	8.081	4.82	33.6	300	5.22
WS_1_29-3_dk_00024	30000	250000	8.63	5.47	39.5	270	4.47
WS_1_30-3_dk_00067	1000	8330	6.969	6.05	29.1	300	5.05
WS_1_31-1_dk_00007	1000	8330	7.665	6.82	29.6	300	5.82
WS_1_32-4_dk_00160	1000	8330	7.309	6.86	28.8	300	5.86
WS_1_32-4_dk_00060	1000	8330	7.858	6.35	29.8	300	5.35
WS_1_32-2_dk_00039	300	2500	6.611	5.65	28.4	300	4.65
HK_1_13-2_dk_00009	3000	12500	13.713	4.34	31.1	330	3.84
HK_1_13-2_dk_00031	3000	12500	13.748	4.36	31.1	330	3.86
HK_1_211_dk_00003	1000	8330	10.339	5.04	32.3	330	4.54
HK_1_25-1_dk_00046	1000	dune					
HK_2_13-4_dk_00010	1000	4170	7.105	3.74	32.7	270	3.24
HK_3_hd02-00005	10000	41670	14.052	5.41	35.2	300	4.91
HK_3_hd03-00008	10000	41670	12.943	5.54	33.8	330	5.04
HK_3_hy01-00006	10000	dune					
HK_3_kw03-00044	10000	41670	13.868	5.46	33.2	330	4.96