SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	An extreme wind climatology for Dutch Water Defences
Computer Project Account:	spnlburg
Start Year - End Year :	2012 - 2015
Principal Investigator(s)	Gerrit Burgers (Reinout Boers after september 2013) Henk van den Brink
Affiliation/Address:	KNMI PO 201 3730 AE De Bilt Netherlands
Other Researchers (Name/Affiliation):	Peter Baas, KNMI Fred Bosveld, KNMI Jan Barkmeier, KNMI Ine Wijnand, KNMI Jacco Groeneweg, Deltares Sofia Caires, Deltares

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The objective of the special project is to make high-resolution simulations of all major storms over the Netherlands from the period 1979-2012 using the Harmonie-Arome model (2.5km grid) for dynamical downscaling the ERA-Interim re-analysis.
The special project contributes to a joint project of KNMI and Deltares that is funded by the Netherlands National Water Authority RWS and has the following objectives:

- Assessment how well high-resolution models can represent storm fields.
- Production of a long-term (~ 30 year) storm data set that can be used for deriving extreme wind statistics needed for the design of Dutch water defenses.
- Extreme value analysis of storm fields, including a proper space and time dependence.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

None

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

No particular problems encountered

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

For the determination of the Hydraulic Boundary Conditions (HBC) extreme directional wind speeds over open water are required, as they serve as input for surge- and wave-models. In this study reliable directional extreme wind estimates have been determined in more than 7,500 locations covering all Dutch water systems. These are available digitally along with the data and scripts needed to reproduce them.

The return value estimates of the directional wind speeds were determined by applying the Gumbel distribution to the annual maxima of the 1979-2013 period computed by HARMONIE and ERA-Interim. The output of the high-resolution meteorological model HARMONIE is used for the region south of 57°N in the North Sea and over the Netherlands. Outside this area in the northern North Sea and Atlantic Ocean, the much coarser ERA-Interim model is used. Over open water the wind speeds are represented as pseudo-wind, which is directly related to the surface stress. Over mixed land-water regions a simple downscaling is applied to obtain the wind over the water fraction, the open water potential wind.

The following remarks should be born in mind:
• The extreme value analysis of the data indicates that the Gumbel distribution fitted to omni-directional annual maxima provides the best representation of the extreme wind speeds. This makes the choice of a threshold in a peak-over-threshold approach superfluous.
• Seasonal variations seem to play a role in the distributions of the annual maxima, especially in the most inland locations and for wind blowing from the East. However, the effect of such variations in homogeneity of the annual maxima still needs to be investigated.
• In order to force the omni-directional estimates to be higher than the directional estimates, a compound omni-directional estimate is constructed from the directional estimates. However, this compound estimate yields 10,000-yr return values of wind speed maxima that are mostly conservative because they have not yet been corrected for correlation between sectors.
• We presume that the depressions that are mostly outside the HARMONIE area are not well represented in HARMONIE, leading to underestimations of the extreme wind speeds. For this reason the HARMONIE output is used only south of 57°N.

Enclosed as a separate file is an accepted final report of the project.

List of publications/reports from the project with complete references

Baas, P., 2014: *Final report of WP1 of the WTI2017-HB Wind Modelling Project*. KNMI Scientific Report; WR 2014-02 (http://www.knmi.nl/bibliotheek/knmipubWR/WR2014-02.pdf), August 2014.

Baas, P. and H. van den Brink, 2014:*The added value of the high-resolution HARMONIE runs for deriving the HBCs. Contribution to WP 1 of the WTI2017-HB Wind Modelling Project*. KNMI Report, February 2014.

Van den Brink, H.W., Baas, P., and Burgers, G. 2013. `*Towards an approved model set-up for HARMONIE Contribution to WP 1 of the SBW-HB Wind modeling*.', Technical report KNMI.

Van den Brink, H.W. and Caires, S. 2015, `*Extreme wind statistics for the Dutch primary water defenses*', Technical Report 1220082-007 KNMI/Deltares. *Final Report of WP3 of the WTI2017-HB Wind Modelling project*

Van den Brink & I. Wijnant, 2016 *A 35-year high-resolution meteorological dataset for The Netherlands Final Report of WP2 of the WTI2017-HB Wind Modelling project*. Technical Report KNMI/Deltares.

Baas P., Bosveld F. C., and Burgers G. (2015) *The impact of atmospheric stability on the near-surface wind over sea in storm conditions,* Wind Energ., doi: 10.1002/we.1825.

The paper '*A verification of the high-resolution NWP model HARMONIE for 18 historical storms*' by Peter Baas was accepted in 'Journal of Wind Engineering and Industrial Aerodynamics', precise ref. not yet available

Conference papers:

The paper '*High resolution modelling improves the simulation of extreme winds in the coastal zone*' by Boers, Baas, vd Brink, Barkmeijer, Bosveld, Wijnand, Groeneweg en Caires was presented on 26 September 2014 at the conference 'Deltas in a time of climate change II' in Rotterdam

A paper on high resolution modelling of wind fields by P. Baas and F. Bosveld was presented on 07 October, 2014 at the 14th European Meteorological Society annual meeting in Praag.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

There are no immediate plans for continuation of this project. However, results from the project will be used to define other policy and water-safety relevant research projects in the Netherlands.

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Deltares
Enabling Delta Life

Extreme wind statistics for the Dutch primary water defenses

Deltares

Extreme wind statistics for the Dutch primary water defenses

Henk van den Brink
Sofia Caires

1220082-007

Deltares

Title
Extreme wind statistics for the Dutch primary water defenses

Client	Project	Reference	Pages
Rijkswaterstaat – WVL	1220082-007	1220082-007-HYE-0006	39

Keywords
Pseudo-wind speed, extreme climate, hydraulic boundary conditions, Netherlands, WTI, HARMONIE, ERA-interim

Summary
For the determination of the Hydraulic Boundary Conditions (HBC) wind direction-dependent extreme wind speeds over open water are required, as they serve as input for surge- and wave-models. The required wind direction-dependent estimates of the wind speeds with return periods of up to 100,000-yr are based on analyses for the period 1979-2013 of the high-resolution meteorological model HARMONIE.

For the area where HARMONIE is not available or appeared to be unreliable, the ERA-Interim data for the same period are used.

For the grid points over sea of HARMONIE and ERA-Interim, the pseudo-wind is used, which is a measure of the surface wind stress. For grid points above inland waters, grid points that represent (a fraction of) land, a transformation to potential wind speed over open water is made, using a roughness that corresponds to a roughness that follows from a Charnock relation with a Charnock parameter of 0.0185.

The analysis per grid point of the most extreme omni-directional wind speeds in 35 year indicate that, in the used HARMONIE domain, wind speeds are expectable with return periods up to approximately 10,000 years. Up to these return periods, the Gumbel distribution is the optimal distribution for extrapolation purposes.

For a depression which has its centre outside the HARMONIE domain, the extreme winds are underestimated. For this reason, the HARMONIE data are only used south of 57°N.

References
Groeneweg, J. G. Burgers, S. Caires and A. Feijt, 2011. Plan of approach SBW wind modelling. SBW – Belastingen. Deltares, Report 1202120-003, Deltares.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1	Oct. 2015	Henk van den Brink		Chris Geerse		Marcel van Gent	
		Sofia Caires					
2	Nov. 2015	Henk van den Brink		Chris Geerse	b.a.	Marcel van Gent	
		Sofia Caires					

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Contents

Nederlandstalige samenvatting

Voor het bepalen van de Hydraulische Randvoorwaarden (HR) zijn extreme open water windsnelheden nodig, die als invoer dienen voor onder meer waterbewegings- en golfmodellen. De benodigde windrichtingsafhankelijke schattingen met herhalingstijden tot orde 100,000-jaar windsnelheden zijn gebaseerd op analyses voor de periode 1979-2013 van het hoge-resolutie meteorologische model HARMONIE. Voor het gebied waar HARMONIE data niet beschikbaar is of niet betrouwbaar bleek, is de ERA-Interim data gebruikt voor dezelfde periode.

Voor de roosterpunten op zee van HARMONIE en ERA-Interim is de pseudo-wind gebruikt, wat een maat is voor de wind stress. Voor roosterpunten boven binnenwateren die (gedeeltelijk) land representeren is een vertaling gemaakt naar de potentiele wind over open water met een ruwheid die correspondeert met de Charnock relatie met een Charnock-parameter van 0.0185.

De analyse van de meest zeldzame windsnelheden in 35 jaar per roosterpunt laat zien dat men omni-directionele extremen in het gebruikte HARMONIE domein kan verwachten tot herhalingstijden van ongeveer 10,000 jaar. Tot deze herhalingstijd blijkt de Gumbel-verdeling de meest geschikte verdeling om te extrapoleren.
Als de kern van een depressie buiten het HARMONIE domein ligt, wordt de extreme wind onderschat. Daarom zijn de HARMONIE gegevens alleen zuidelijk van 57°N gebruikt.

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1 Introduction

1.1 Background

In compliance with the Dutch Water Act ("Waterwet, 2009") the strength of the Dutch primary water defences must be assessed periodically[1] for the required level of protection, which, depending on the area, varies from 250 to 10,000 year loads; see Figure 1.1. These loads are determined on the basis of Hydraulic Boundary Conditions (HBC). The HBC and the Safety Assessment Regulation ("Voorschrift op Toetsen op Veiligheid", VTV), play the crucial role in the assessment of the primary water defences. Until 2011, the safety assessment was based on the failure probability of a dike section. In the future, assessments will be based on the probability of flooding of a dike ring or dike ring segments. The corresponding normative return periods will probably vary between 300 and 100,000 years, but they still have to be established. This means that not only will the values in Figure 1.1 change, but so will the interpretation of the normative values, due to the probabilities of failure being different from the probability of exceedence of hydraulic loads presently used. The knowledge underlying the presently available HBC and VTV will be incorporated in a new instrumentation for assessing the safety of dike rings, or at least parts of a dike ring. Most probably this new instrumentation will be Hydra-Ring (Van Balen, 2014).

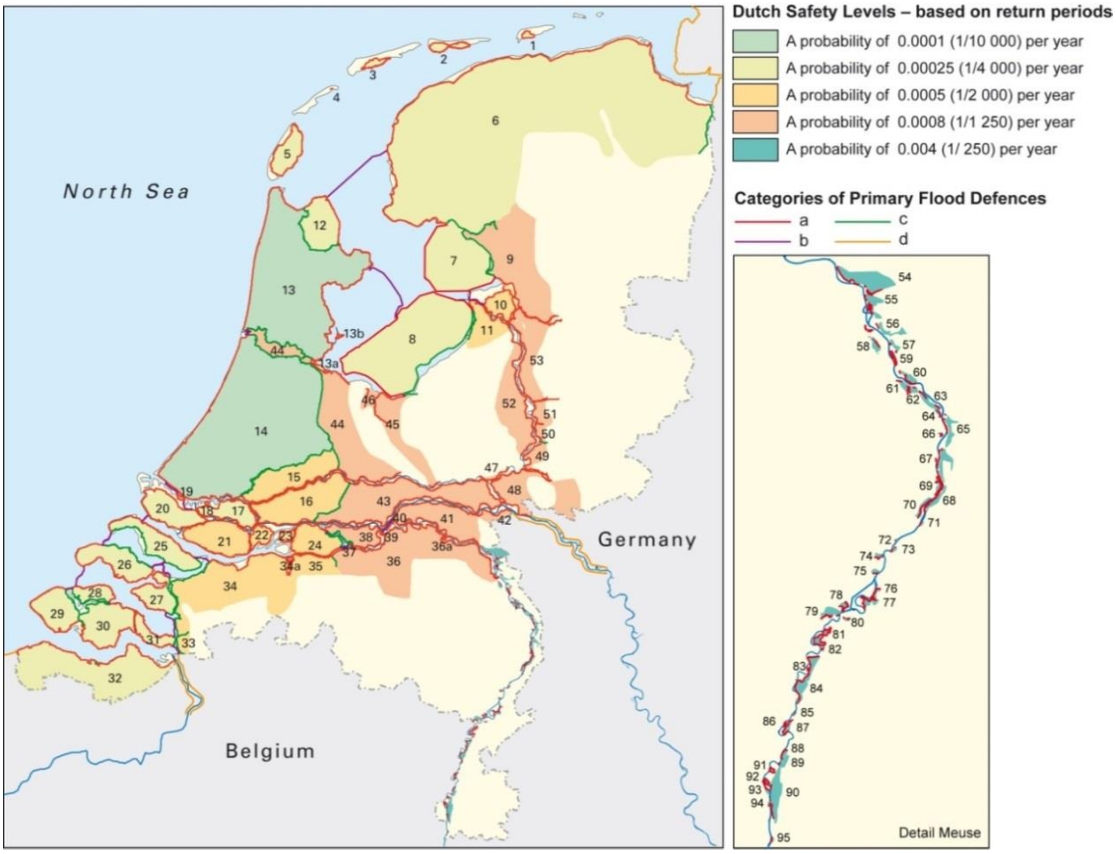

Figure 1.1 The safety standard of the Dutch primary water defences.

1. *Previous assessments took place in 1996, 2001, 2006 and 2011. The date of the next assessment is 2017. According to the "Nieuwe Waterwet" after 2017 the assessment will be made on a continuous basis.*

With the aim of delivering legal assessment instruments to be used in the fourth assessment period, starting in 2017, Rijkswaterstaat – WVL is funding the long-term project WTI 2017. One of the projects of the WTI 2017 program is the Hydraulic Loads project and focusses on HBC in particular and more generally on subjects related to hydraulic loads. The goals of the project are twofold:

1. To determine Hydraulic Boundary Conditions for all water systems (although new production runs will only be carried out for river areas).
2. To fill in the most important knowledge gaps concerning Hydraulic Loads in such a way that from 2017 on more reliable HBC can be determined for the Dutch primary sea and flood defences, either by the conventional approach of “probability of exceedence” or by the future approach of “probability of flooding”.

In line with its two goals, the project is divided in two parts; one is related to the determination of HBC and in particular to the production runs in the river areas, and the other is concentrated on filling in the knowledge gaps in order to improve the quality of the HBC. The present report, whose motivation is given in the next section, focuses on the knowledge gap regarding “Determination of extreme open water winds”.

1.2 Motivation

In order to determine the HBC, extreme open-water winds are needed to drive the wave and flow models. However, there exist no sufficiently long and reliable in-situ (i.e. open water) wind data available for that purpose. Instead, there is a rich dataset of decades of measurements at certain coastal and relatively close by inland stations. A commonly used two-layer model (Caires et al., 2012) for neutral atmospheres was thought to provide reasonably accurate open-water winds from the available dataset, on the grounds that the model assumptions seemed plausible within the range of extreme winds of interest. However, it turned out that the model results were deemed inaccurate and, after reviewing the KNMI-Deltares joint research, the experts of the SBW Hydraulic Review Team have recommended that *high-resolution atmospheric models* be used in the determination of the HBC.

The identified limitations of the two-layer model along with the need for having more precise estimates of temporally and spatially evolving extreme wind fields for the determination of the HBC were the main motivation of the joint KNMI-Deltares wind modelling research project (Groeneweg et al., 2011), referred to as the WTI2017 wind modelling project. In broad terms, the objective of this project is to

I) support the inclusion of the dimensions “time” and “space” in the determination of the Hydraulic Boundary Conditions, and
II) address the knowledge gap regarding “Determination of open water winds”.

The project is divided into three work packages:

1 Assessment of how well high-resolution atmospheric models can represent storm wind fields, and investigation of how high-resolution models can be used to represent the space-time structure of extreme storms.
2 Production of a long-term wind/stress hindcast dataset that can be used to derive the extreme wind statistics needed for the determination of HBC.
3 Extreme value analysis of the surface wind/stress fields, including a proper time and space dependence.

Work packages 1 is completed (Baas, 2014) and work package 2 are is nearing its completion. The high resolution atmospheric model HARMONIE (HIRLAM ALADIN Research on Mesoscale Operational NWP in Euromed) has been chosen to model the surface stress (τ), 10-m wind speed (U_{10}) and mean sea level pressure (MSLP) fields leading to hydraulic loads in the Dutch primary water defences and used to hindcast the period from 1979 until 2013. These fields are now available for the analyses of extremes in work package 3. The preliminary analysis of these data in work package 3 was reported in Caires and Van Nieuwkoop (2015). This follow up study gives a comprehensive and detailed determination of the directional extreme wind statistics for all water systems.

1.3 Objectives

The objective of this study is to determine directional extreme wind statistics over open water in all Dutch regions containing primary water defences. These are to be used in the determination of future (after 2017) WTI HBC. Because reproducibility of such statistics that have been derived for a total of 7,589 locations is needed, a second objective of this study is the creation of a data base with extreme wind estimates, the input data and the scripts used in the determination of the estimates.

1.4 Approach

We determine the return values of the directional extreme wind for the inland waters and a large part of the North Sea. The return values are based on the area of HARMONIE that reproduces realistic extreme wind fields (i.e. south of 57°N) from the driving ERA-Interim model. Outside this area, the ERA-Interim data (which has a much coarser resolution) is used. For consistency reasons, the wind speeds are represented as pseudo-wind, that is directly related to the surface stress, i.e. as the wind corresponding to a Charnock parameter of 0.0185. Over mixed land-water points, a simple downscaling is applied to obtain the wind over the water fraction. In this way, inconsistencies between the meteorological and hydrodynamical models can be avoided (Van Nieuwkoop et al, 2015) as well as inconsistencies between ERA-Interim and HARMONIE.

We first determine the preferable distribution for extrapolation, which points out to be the Gumbel distribution, as the fit to this distribution is unbiased for extrapolation of wind speeds up to return periods of the order of 10,000 years.

Then we apply the Gumbel distribution to all records of directional annual wind speed maxima. The omni-directional wind speed estimates are derived from the directional estimates.

1.5 Project team

The project team consists of KNMI and Deltares employees with expertise in wind modelling, hydrodynamics and extreme value analysis. The team is referred to as the WTI2017 – Hydraulic Loads wind modelling team and includes, in alphabetical order, Jan Barkmeijer (KNMI), Reinout Boers (KNMI), Fred Bosveld (KNMI), Henk van den Brink (KNMI), Gerrit Burgers (RWS, former KNMI), Sofia Caires (Deltares), Jacco Groeneweg (Deltares), Joana van Nieuwkoop (Deltares), Hans de Waal (Deltares) and Ine Wijnant (KNMI).

The analyses and reporting presented here were carried out by Henk van den Brink and Sofia Caires with critical advice and help from the rest of the team.

1.6 Acknowledgment

We would like to express our appreciation to Dr Chris Geerse, the reviewer of this study, for his valuable comments and suggestions on an earlier version of this report.

2 Water systems and data

2.1 Introduction

As said in the previous chapter, the objective of this study is to determine directional extreme wind statistics to be used in the assessment of all Dutch primary water defences. In order for these to be determined the locations where they are needed need to be identified. These are located in the Dutch water systems, which are described next. The most suitable dataset and the wind variable to be used in the determination is also dealt with in this chapter. The chapter ends with a description of all locations where the statistics are to be determined.

2.2 Water systems

We apply the approach of Probabilistic Tool Box for WTI2017 (Van Balen, 2014) and consider sixteen Dutch water systems. These are

1 non-tidal river reaches Rhine,
2 non-tidal river reaches Meuse,
3 tidal river reaches Rhine,
4 tidal river reaches Meuse,
5 IJssel delta,
6 Vecht delta,
7 lake IJssel,
8 lake Marken,
9 Wadden Sea east,
10 Wadden Sea west,
11 the northern part of the Dutch coast,
12 the central part of the Dutch coast,
13 the southern part of the Dutch coast,
14 Easternscheldt,
15 Westernscheldt,
16 the Dutch sandy coasts (dunes).

We shall refer to water systems 1 to 6 as small water systems or river water systems and to the other as large water systems. To give an overview of their geographic location the locations used as water defence test locations in Van Balen (2014, Appendix F) for these water system are show in Figure 2.1. These water systems are subdivided into reaches, cf. Van Balen (2014, Appendix D), but given that such amount of detail is not needed for the illustrations given in this report, such division is not considered here. Furthermore, as in Van Balen (2014), the Europoort area (system 17), is not considered separately but as part of the Rhine tidal river system (system 3).

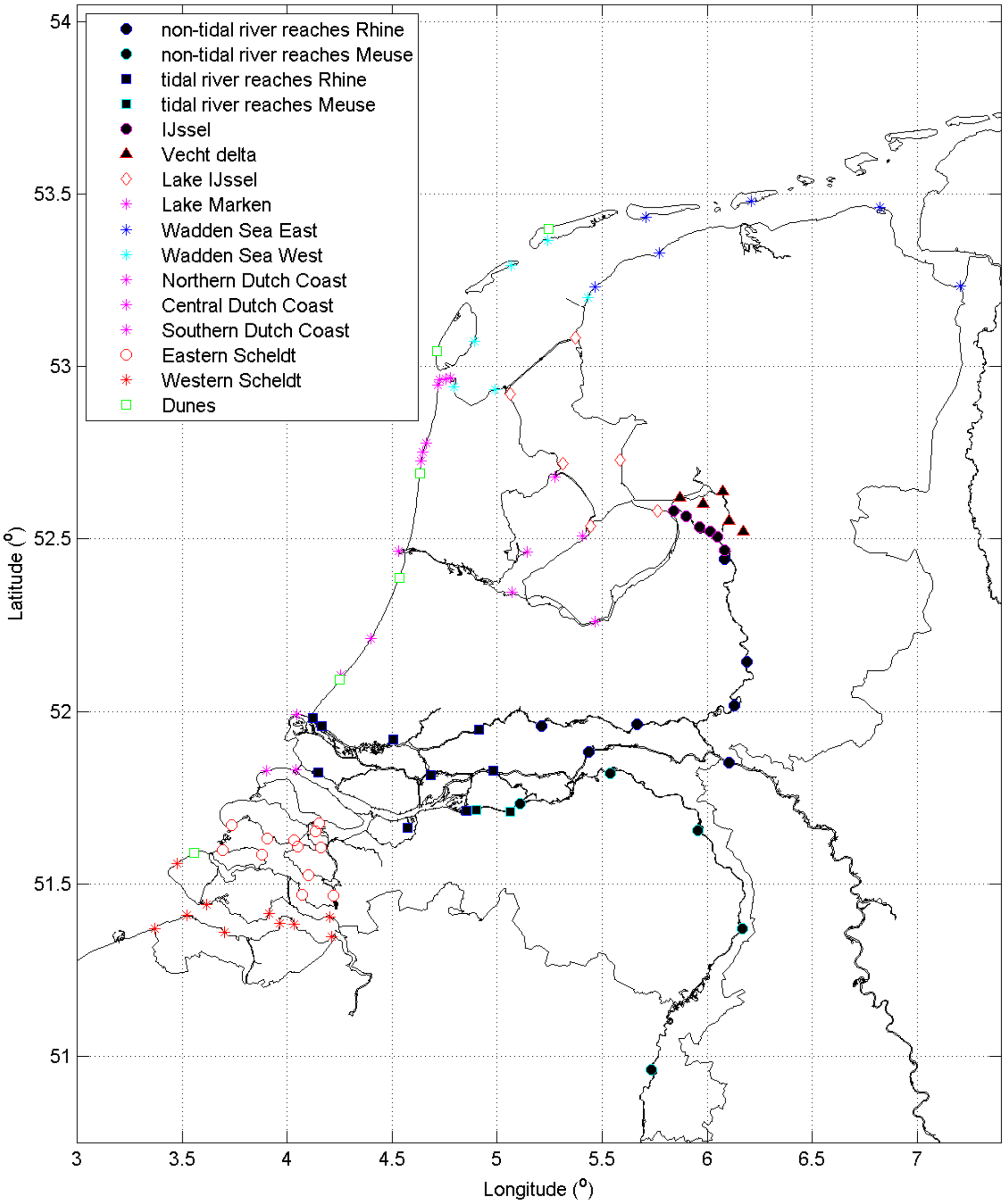

Figure 2.1 Overview of the Dutch Water systems. A few test locations used in Van Balen (2013) are marked for each water system.

Extreme open water winds relevant for the determination of the HBC in all these water systems are needed. Depending on the water system the suitable wind data sources and variable have been considered. These are described next.

2.3 HARMONIE data

HARMONIE is the operational Numerical Weather Prediction (NWP) model of KNMI. It is a limited-area model that has been developed in a consortium involving many European countries. HARMONIE is the successor of the HIRLAM and the ALADIN models. Major differences between HARMONIE and its predecessors are that HARMONIE is intended to run on a very high resolution and that it is a non-hydrostatic model. The latter means that instead of employing the hydrostatic approximation, which often breaks down in severe-weather events, that the vertical momentum equation is solved explicitly. In the framework of the WTI2017 wind modelling project, a local HARMONIE model has been setup, calibrated and validated (Baas and Van den Brink, 2014; Baas, 2014). After its successful calibration, the model has been used to hindcast the relevant atmospheric variable in the period from 1979 until 2013 with a time resolution of 1 hour on a grid with a spacing of 2.5 km and covering the region show in Figure 2.2. The period from 1979 until 2013 was chosen because it is the period in which the ERA-Interim data, needed to force the model at the boundaries and to provide initial conditions for the HARMONIE runs, are available. ERA-Interim is the most reliable reanalysis dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF). The strength of the ERA-Interim dataset is that it combines one of the leading numerical weather prediction models (the ECMWF model) with an advanced data assimilation system (Dee et al., 2011) that systematically feeds observations into the model analysis. The resulting data can be considered a best estimate of the state of the atmosphere, given the model information and the observations.

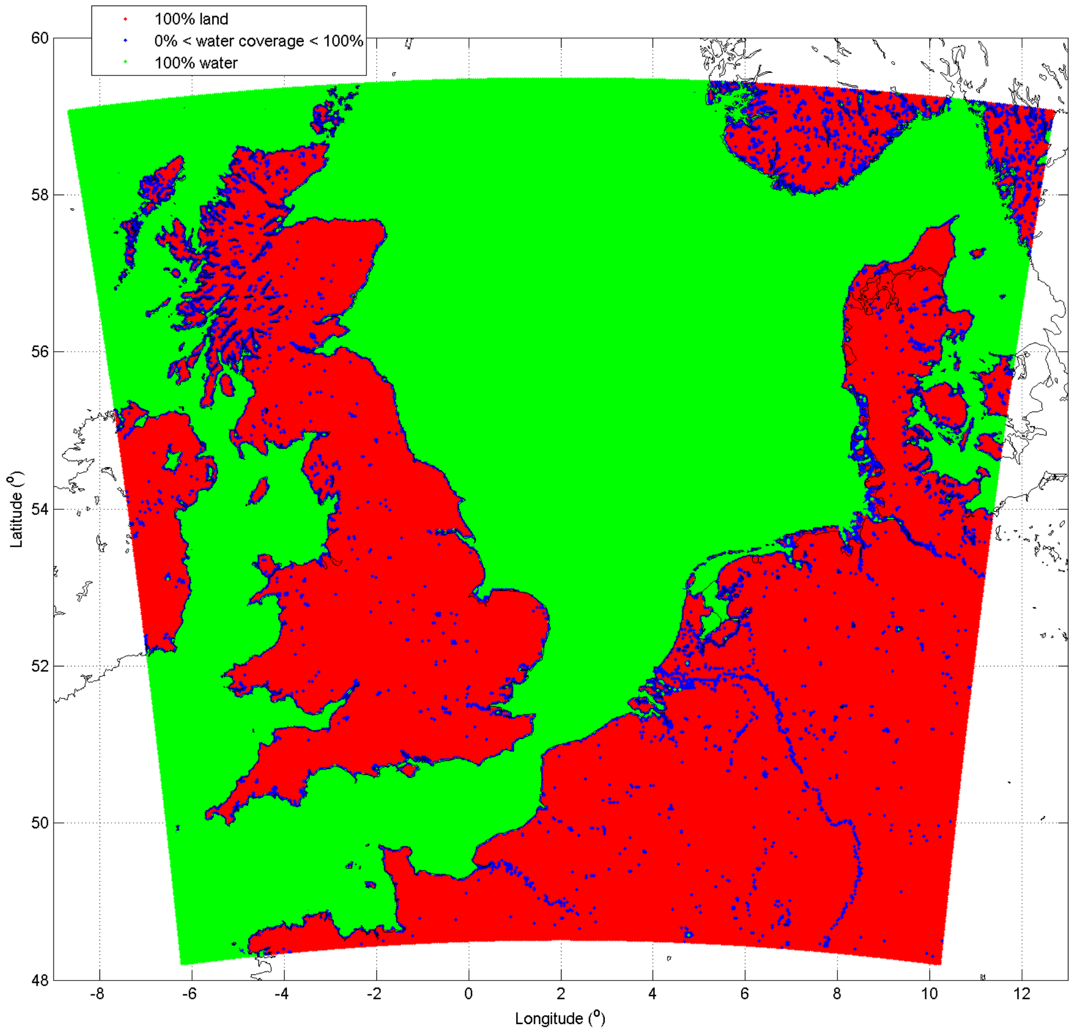

Figure 2.2 Grid of the HARMONIE model setup. A Lambert conformal conical projection is used; the grid is centred at 54°N 2°E, consists of 489x489 grid points and the grid-spacing is 2.5 km. The water coverage of each grid cell is indicated in colour.

Relevant to note is that the hydrodynamic and wave models used in the determination of the HBC should be forced with open water winds. However, the considered water coverage of the HARMONIE grid locations may be less than 100%, cf. Figure 2.2. Therefore, the wind speeds at those locations needs to be downscaled to represent open water wind speeds. Furthermore, although the input for the hydrodynamic and wave models generally consists of 10-m wind speeds, these are converted internally in these models to surface stress by applying a particular drag relation and using

$$\tau = \rho_a C_d U_{10}^2, \tag{2.1}$$

where ρ_a is the density of the air and C_d the drag coefficient. When wind fields from an atmospheric model are used, this procedure leads to inconsistencies and errors if the hydrodynamic, wave and atmospheric models apply different drag relations.
This is also of relevance because HARMONIE does not use a simple functional relationship to determine the drag, which makes off-line transformations of raw HARMONIE wind fields into surface stress difficult.
There is, therefore, a need to post-process the HARMONIE data above the water systems to avoid inconsistencies between models and to convert wind data from grid cells with a water coverage of less than 100% into open water winds. The processing of the data depends on the water system:

- In large water systems, where the relevant HARMONIE grid cells have a water coverage of 100% the pseudo-wind is used.
- In small or river water systems, where the relevant HARMONIE grid cells have a water coverage of less than 100% the potential open water wind is used.

How these wind speeds are computed is described in the next two sections separately.

2.3.1 Pseudo-wind

In order to avoid inconsistencies between the stress applied in the hydrodynamic and wave models on the one hand and that determined in the atmospheric models on the other hand, we recommend that above water (both above sea and above lakes) the HARMONIE surface stress be used instead of the HARMONIE 10-m wind speed. However, instead of using the stress directly, we recommend the use of a synthetic wind which we refer to as the *pseudo-wind,* $U_{10,ps}$. The motivation for using the pseudo-wind instead of the surface stress is that the latter offers a less intuitive interpretation of the wind and that the stress can always be easily derived from the pseudo- wind.

The computations of the pseudo-wind have been done assuming local neutral atmospheric stability as follows:

1 The friction velocity is computed using

$$u_* = \sqrt{\tau / \rho_a}\ , \tag{2.2}$$

and assuming a constant air density $\rho_a = 1.21$ kg/m^3 (considered as characteristic of a winter depression).

2 The water roughness length, z_w, is calculated using the standard Charnock relation (1955)

$$z_w = \alpha u_*^2 / g, \tag{2.3}$$

where $g = 9.81$ m/s^2 is the acceleration due to gravity and α is the Charnock parameter which has been set at $\alpha = 0.0185$. This value of the Charnock parameter was chosen because, besides being widely accepted, is also the value used in the default implementation of the wave model used to compute the HBC.

3 The roughness length is then used to calculate the drag coefficient assuming a logarithmic wind profile (neutral stability)

$$C_d = \left(\frac{\kappa}{\ln(10 / z_w)} \right)^2, \tag{2.4}$$

where $\kappa = 0.41$ is the Von Karman constant.

4 Finally, the latter is also used to calculate the pseudo-wind as

$$U_{10,ps} = u_* / \sqrt{C_d}, \tag{2.5}$$

which for simplicity we also denote as U_{10}.

2.3.2 Open water potential wind

For grid points where the water coverage is not 100% the HARMONIE surface stress cannot be used directly to determine the open water wind because it is affected by the local land coverage of the grid cell, and the surface stress over the water part of the grid cell is lower than the average surface stress over the grid cell. We, therefore, resort to the potential wind concept (see e.g. Caires et al., 2012) to determine the open water wind speed.

Open water potential wind speed time series were computed assuming local neutral atmospheric stability from the HARMONIE data by:

1 Determining the hourly roughness length applied in HARMONIE using the HARMONIE surface stress and 10-m wind speed. This is done using Eq. (2.2) to compute u_*, next compute the drag coefficient from

$$C_d = \left(u_* / U_{10} \right)^2, \tag{2.6}$$

and then

$$z_0 = 10 \big/ \exp\left(\kappa \big/ \sqrt{C_d} \right). \tag{2.7}$$

2 Downscaling the HARMONIE 10-m wind speed to open water wind assuming a logarithmic wind profile (neutral stability) and a blending height of 60 m. This is done iteratively starting with an initial estimate of 0.001m for the water roughness z_w and repeating the following five steps (a-e) sequentially until the value of z_w converges:

2.a Compute the Exposure Correction Factor (ECF),

$$ECF = \frac{U_p}{U_{10}} = \frac{U_p}{U_{60}} \frac{U_{60}}{U_{10}} = \frac{\ln(10/z_w)}{\ln(60/z_w)} \frac{\ln(60/z_0)}{\ln(10/z_0)}, \tag{2.8}$$

2.b compute the open water potential wind speed

$$U_{pw} = U_{10} ECF \ , \tag{2.9}$$

2.c compute C_d using Eq. (2.4),
2.d compute

$$u_* = U_{pw}\sqrt{C_d} \ , \text{ and} \tag{2.10}$$

2.e compute a new estimate of z_w using (2.3).

Note that the potential wind speed is not a pseudo-wind speed assuming a local open water roughness, but a downscaling of the HARMONIE 10-m wind speed to a local open water roughness.

The effect of the transformations are illustrated in Figure 2.3, which shows the average annual wind for the original HARMONIE wind (green), the open water potential wind (black) and the pseudo-wind (yellow). The open water potential wind is higher than the original wind over land, due to the transformation to a lower surface roughness, and practically equal over open water. The differences between the three representations are negligible over open water.

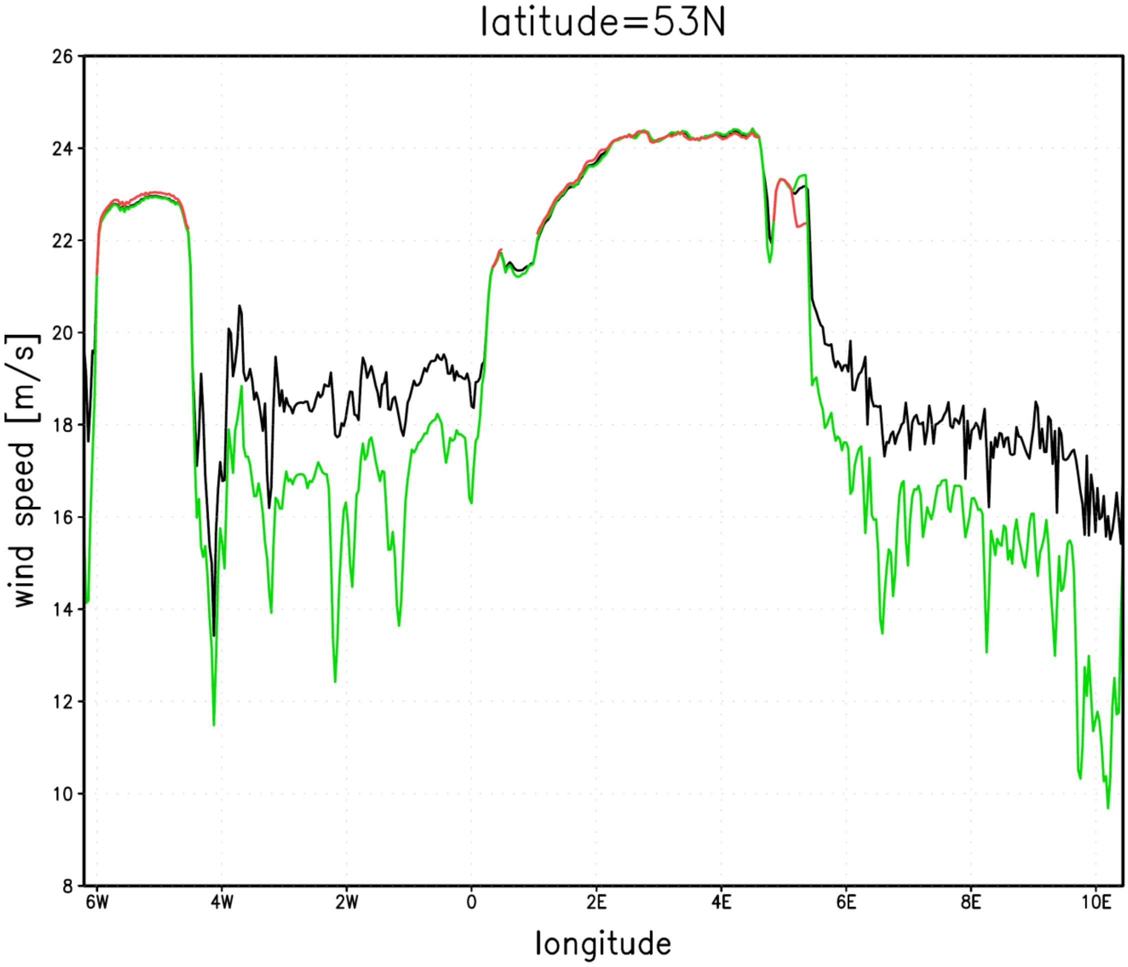

Figure 2.3 Average annual wind speed at 53N of the original HARMONIE wind (green), the open water potential wind (black) and the pseudo-wind (red). The pseudo-wind is only defined over sea.

2.4 ERA-Interim data

Because the winds blowing in the North Atlantic are also relevant from the hydraulic conditions in the Dutch coast, the HARMONIE grid does not cover the full domain of the North Sea hydrodynamic model, DCSMv6 (Zijl, 2013) that is to be used in the determination of the HBC for the large water systems. Therefore, we also resort to ERA-Interim pseudo-wind data to complement the HARMONIE data in the domain of the North Sea hydrodynamic model, the region between 16°W to 14°E and 42°N to 65°N. The considered ERA-Interim data have a spatial resolution of 0.5° x 0.5°, is 6-hourly and cover the same period as the HARMONIE data, 1979 to 2013. Only open water ERA-Interim locations are considered and at these locations pseudo-wind time series are computed from the ERA-Interim 10-m wind speed,$U_{10,ERA}$, and the sea state dependent Charnock parameter, α_{ERA}, time series. The computations of the pseudo-wind have been done follows:

1 The friction velocity is computed iteratively starting with an initial estimate of 0.001 and repeating the following three steps sequentially until the value of u_* converges:
  a. compute z_w using Eq. (2.3) and α_{ERA},
  b. compute C_d using Eq. (2.4) and
  c. compute a new estimate of

$$u_* = U_{10,ERA}\sqrt{C_d}\ . \tag{2.11}$$

2 The friction velocity is subsequently used to compute z_w using Eq. (2.3), u_* and fixing $\alpha = 0.0185$.
3 The roughness length is then used to calculate C_d using Eq. (2.4).
4 Finally, the latter with u_* from the first step to calculate the pseudo-wind using Eq. (2.5).

2.5 Considered locations

The extreme value analyses are to be carried out in only a subset of the 239,121 HARMONIE grid points. In fact two sets of HAMONIE locations have been defined:

- Set 1 – a set of HARMONIE grid locations in open water, relevant for the large water systems;
- Set 2 – a set of HARMONIE grid locations along small or river water systems.

Furthermore, in order to be able to force the DCSMv6 model, the extreme value analyses also need to be carried out in

- Set 3 – a set of ERA-Interim grid locations in open water.

The first and third set of locations should cover the open water regions of the DCSMv6 model. A strategy has therefore been developoed to obtain data in a grid covering the DCSMv6 model area using a spatially thinned set of the HARMONIE data and ERA-Interim data (cf. Caires van Nieuwkoop, 2013).

The following considerations where taken into account in the definitions of the first set:

1. Consider only grid points with a 100% water coverage. With this aim a mask was made using the HARMONIE land-sea mask and the HARMONIE inland waters mask to get all grid points over sea, in the Western Scheldt, Eastern Scheldt, Wadden Sea, Lake Marken and in Lake IJssel.
2. The Irish Sea and Baltic Sea lie outside the area of interest, in these areas it is sufficient to use the coarser ERA-Interim data. Therefore, HARMONIE grid points in these areas are not considered.

3. A spatial resolution of 2.5 km x 2.5 km is not needed everywhere in open sea. The fine resolution is mainly important near the coast. Therefore, the 2.5 km x 2.5 km is only maintained in a zone near the Dutch coast, the Wadden Sea, Lake Marken and Lake IJssel. For the remaining areas a thinning factor of 4 is used, which gives the remaining areas a resolution of 10 km x 10 km.
4. The HARMONIE data at latitudes above 57°N is of less quality due to boundary effects (cf. §3.4) and is, therefore, excluded.

This led to a set of 5,653 locations. These are marked with red dots (.) in Figure 2.4 .

Set 3 was defined by filling up with ERA-Interim grid points the area inside the DCSMv6 domain that is not covered by Set 1 of HARMONIE grid points. This complementary set of grid point is obtained by removing from all ERA-Interim grid points inside the DCSMv6 domain:

- those covered by Set 1,
- those inside the Mediterranean Sea, and
- those above land or inland waters, using a land mask based on the bathymetry of the DCSMv6 model.

The resulting set of 1,463 locations is marked with blue pluses (+) in Figure 2.4 (left panel).

Set 2 was defined by considering HARMONIE grid points along the river water systems (water systems 1 to 6, cf. Figure 2.4). The resulting 473 locations are marked with blue dots (.) in Figure 2.4 (right panel).

The extreme values analyses are therefore to be carried out in a total of 7,598 (5,653+1,463+473) locations.

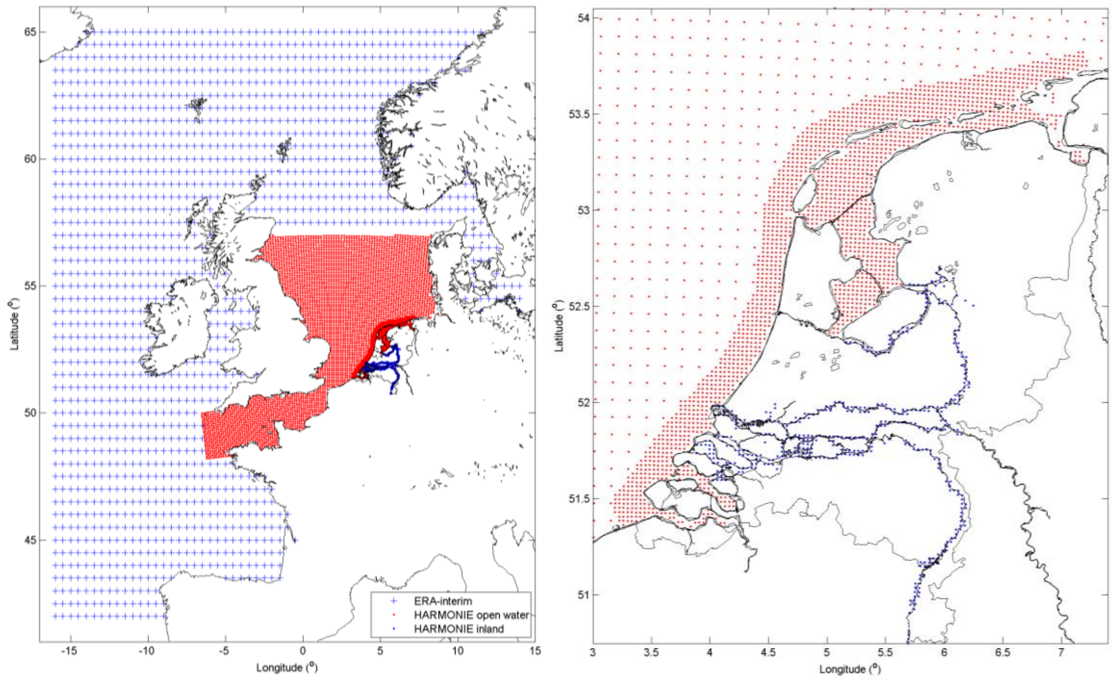

Figure 2.4 Left panel: Selected HARMONIE open water, inland and ERA-Interim grid points. Left panel: Zoom in of the left panel in the region of the Netherlands. Note the higher density of HARMONIE points in the Dutch waters.

3 Methodology

3.1 Selection of statistical approach

3.1.1 Introduction to extreme value analysis

In order to explain the basic ideas of extreme value theory, let us write $M_n = \max\{X_1, \ldots, X_n\}$, where $X_1, X_2 \ldots$ is a sequence of independent and identically distributed (i.i.d) random variables with distribution function *F*. In its simplest form, the *extremal types theorem* states the following: If there exist sequences of constants $\{\sigma_n > 0\}$ and $\{\mu_n\}$ such that $\mathrm{P}\{\sigma_n M_n + \mu_n \le z\} \to G(z)$ as $n \to \infty$, where *G* is a *non-degenerate distribution function*[2], then *G* must be a Generalized Extreme Value (GEV) distribution, which is given by

$$G(z) = \begin{cases} \exp\left\{-\left[1+\xi\left(\dfrac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}, \text{ for } \xi \ne 0 \\ \exp\left\{-\exp\left[-\left(\dfrac{z-\mu}{\sigma}\right)\right]\right\}, \quad \text{for } \xi = 0, \end{cases} \tag{3.1}$$

where z takes values in three different sets according to the sign of the shape parameter ξ: $z > \mu - \sigma/\xi$ if $\xi > 0$ (the domain of z has a lower bound), $z < \mu - \sigma/\xi$ if $\xi < 0$ (the domain of z has an upper bound), and $-\infty < z < \infty$ if $\xi = 0$.

In other words, if the distribution function of (a normalization of) the maximum value in a random sample of size *n* converges to a distribution function as *n* tends to infinity, then that distribution function must be a GEV distribution. Moreover, this and other results of extreme value theory *holds true even under general dependence and some non-stationary conditions* (Coles, 2001).

In Eq. (3.1) the parameters *μ*, *σ* and ξ are called the location, scale and shape parameters, and they satisfy $-\infty < \mu < \infty$, $\sigma > 0$ and $-\infty < \xi < \infty$. For $\xi = 0$ the GEV is the *Gumbel distribution*; for $\xi > 0$ it is the *Fréchet distribution*; and for $\xi < 0$ it is the *(reverse) Weibull distribution*. For $\xi > 0$ the tail of the GEV is “heavier” (i.e., decreases more slowly) than the tail of the Gumbel distribution, and for $\xi < 0$ it is “lighter” (decreases more quickly and actually reaches 0) than that of the Gumbel distribution. The GEV is said to have a *type II tail* when the shape parameter is positive ($\xi > 0$) and a *type III tail* when the shape parameter is negative ($\xi < 0$, the domain of z has an upper bound)[3]. The tail of the Gumbel distribution ($\xi = 0$) is called a *type I or exponential tail*.

---

2. *A distribution function is said to be degenerate if it allocates probability 1 to a single point.*
3. *Note that some articles (e.g. Hosking and Wallis, 1987) use another convention for the sign of the shape parameter: a negative shape parameter in those references corresponds to a type II distribution.*

Since the distribution function F of the variables $X_1, X_2 \ldots$ in the extremal types theorem is associated with a unique (i.e. independent of the particular sequences $\{\sigma_n > 0\}$ and $\{\mu_n\}$) value of ξ, the parameter ξ is called the *tail index* of F.

The extremal types theorem gives rise to the *annual maxima* (AM) method of modelling extremes, in which the GEV distribution is fitted to a sample of block maxima (e.g. to annual maxima).

One of the main applications of extreme value theory is the estimation of the *once per m year (m-yr) return value*, the value which is exceeded on average once every *m* years. The *m*-yr return value (for *m*>1) based on the AM method/GEV distribution, z_m, is given by[4]

$$z_m = \begin{cases} \mu - \dfrac{\sigma}{\xi}\left(1 - \left\{-\ln\left(1 - \dfrac{1}{\mathrm{m}}\right)\right\}^{-\xi}\right), & \text{for } \xi \neq 0 \\ \mu - \sigma \ln\left\{-\ln\left(1 - \dfrac{1}{\mathrm{m}}\right)\right\}, & \text{for } \xi = 0. \end{cases} \tag{3.2}$$

3.1.2 Choice for type 1 tail.

Suppose we have *m* independent records, each containing *n* years, then we may expect to find *m n*-yr events, *n m*-yr events, and 1 *m·n*-yr return value in one of the records. As this *m·n*-yr event must occur in one of the *m* records, this requires an extrapolation of order *n* for the specific location. By inter comparing the estimated return value (based on the distribution fitted to the data of the specific location) to this theoretical return value for all locations, it can be judged whether the fitted distribution is appropriate for extrapolation purposes. Van den Brink and Können (2008, 2011) generalized this concept, and proved that the horizontal distance (called ΔX_n) on a Gumbel plot between the highest event in a record and its estimated return period according to the fit, is exactly described by the standardized Gumbel distribution, i.e. with location parameter μ=0 and scale parameter σ=1. The value of ΔX_n is given by:

$$\Delta X_n = -\ln\left(-\ln\left(F\left(y_n\right)\right)\right) - \ln\left(n\right) \tag{3.3}$$

in which y_n is the maximum value of the n-yr record, and F the fitted distribution. It is thus shown that:

$$\Pr\left(\Delta X_n \leq x\right) = \mathrm{Gumbel}\left(x, 0, 1\right) \tag{3.4}$$

in which Gumbel(x,0,1) is the standardized Gumbel distribution.

Van den Brink and Können (2008) used this result to investigate how well the GEV distribution, fitted to time series of limited length, is appropriate for extrapolation purposes. They showed that the determination of 3 parameters from short time series (< 100 years) leads to overfitting, resulting in biased estimates (most often overestimations) for large return periods. In many cases with meteorological data, the 2-parameter Gumbel distribution turns out to be the best choice.

---

4. *The natural logarithm of x is written as ln(x).*

Here we apply the methodology of Van den Brink and Können (2008) by calculating ΔX_n for all the 489x489 grid points of the HARMONIE omni-directional open water potential wind speeds. We assume independence if the moments of maximum winds differ by more than 5 days. The 489x489=239121 dates (belonging to the maximum wind speed for every grid point), can be clustered into 297 sets that have mutually a temporal distance of at least 5 days. From every cluster, we take the maximum value of ΔX_n. This yields *m*=297 independent values of ΔX_n. From the dependent grid points, only the one for which ΔX_n is maximal, is considered. All records have a length of *n*=35 year, so a *m·n*=10395-yr event can be expected somewhere in the HARMONIE domain.

A detailed depiction is given in Figure 3.1, in which the distribution of ΔX_n is shown. According to Van den Brink and Können (2008), a correct extrapolation of the fit would result in a standardized Gumbel distribution, which is represented by the black line. The figure shows the results for ΔX_n if a (2-parameter) Gumbel distribution is fitted to all 35-yr records (red) or to a (3-parameter) GEV distribution (blue). Also the distribution of ΔX_n is shown (green) for an Exponential distribution fitted to all independent peaks (with a window of 48 hours) above the 97% threshold. It clearly shows that the Gumbel distribution is in better agreement with the theory (black line) than the GEV distribution, while the Exponential distribution performs visually as good as the Gumbel distribution.

The goodness-of-fit can be quantified with the Kolmogorov-Smirnov statistic[5] which is summarized in Figure 3.2.

It shows that the Gumbel distribution performs better than both the GEV distribution and the Exponential distribution, the latter of which was applied to the peak-over-threshold values for different thresholds.

The Exponential distribution yields the best results provided a threshold of 97% is chosen, in which case the extrapolation is almost as good as the fit based on the Gumbel distribution.

[5] The Kolmogorov-Smirnov statistic quantifies a distance between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution - in our case the standardized Gumbel distribution. A lower value for this statistic indicates a better agreement between the empirical and theoretical distribution.

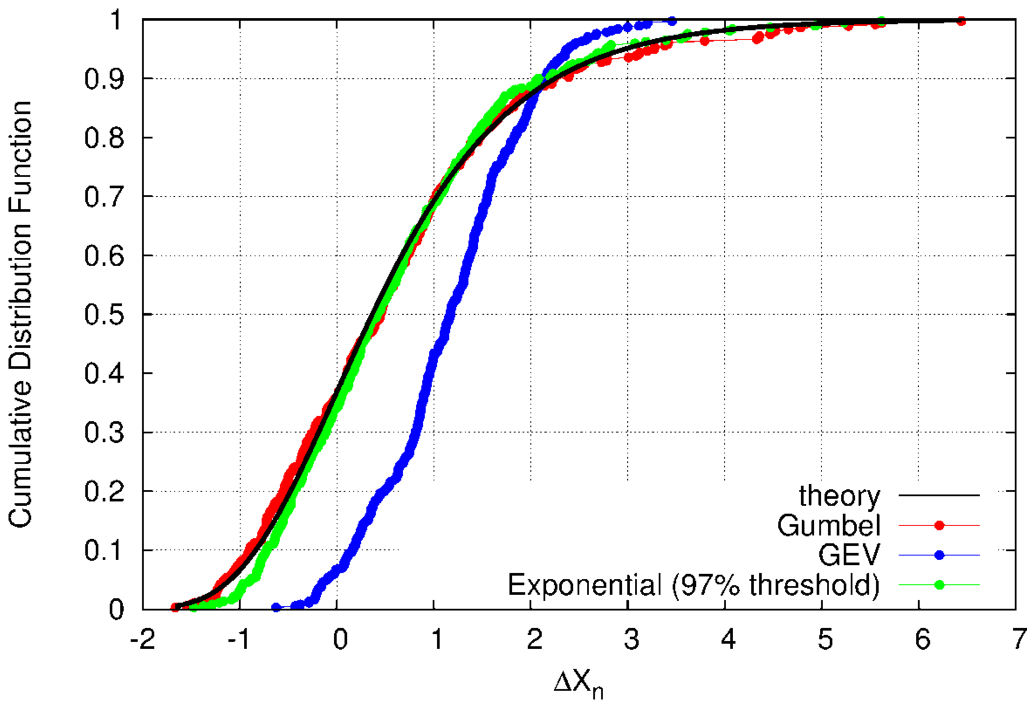

Figure 3.1 Cumulative distributions of ΔX_n, based on the 297 independent HARMONIE grid points for which the Gumbel distribution is fitted to the annual maxima (red), the GEV distribution (blue), or the Exponential distribution to all independent peaks above the 97% threshold (green). The black line shows the theoretical line of the standardized Gumbel distribution.

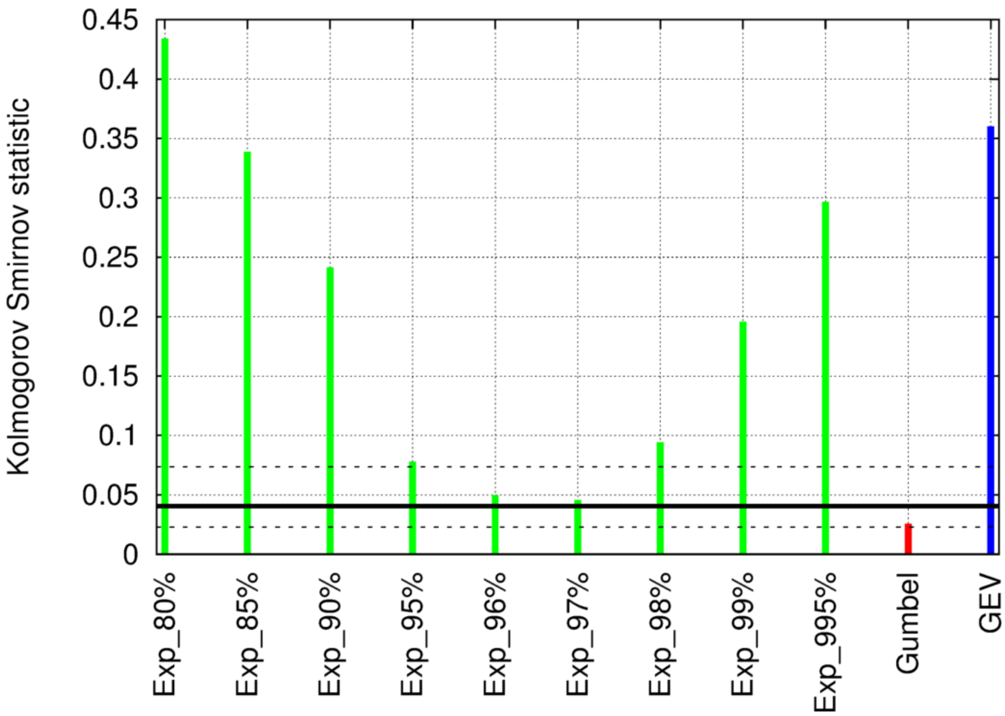

Figure 3.2 Kolmogorov-Smirnov statistic for the distribution of ΔX_n *compared with the standardized Gumbel distribution for the Pareto-distribution (for different threshold levels, given as a quantile, green), the GEV distribution (blue) and Gumbel distribution (red). The horizontal lines give the median (solid black) and 2.5% and 97.5% percentiles (dashed black) of the Kolmogorov-Smirnov statistic.*

We conclude that the extrapolation of the omni-directional open water potential wind speed is optimally performed by applying the Gumbel distribution to the annual maxima. A fit of similar quality (based on the Kolmogorov-Smirnov test for extrapolation) is obtained by applying the Exponential distribution with a 97% threshold for the sampling of the Peaks-Over-Threshold (POT). We prefer the Gumbel distribution over the Exponential distribution for the following reasons:

1. The Gumbel distribution has a solid theoretical basis, without the extra choice for a threshold.
2. The Kolmogorov-Smirnov test shows optimal agreement with the Gumbel distribution for HARMONIE and ERA-Interim.
3. The POT approach is more sensitive for seasonal variations in the wind climate than the annual maxima approach, as the less extreme events may originate from different seasons than the most extreme, which makes the dataset inhomogeneous.

3.1.3 Gumbel fits

For most water system the determination of HBC requires that wind statistics be available over 12 directional sectors (each 30º wide). These 12 sectors of wind direction are 345ºN-15ºN, 15ºN-45ºN, …, 285ºN-315ºN and 315ºN-345ºN and are the sectors for which the annual maxima have been sampled and estimates have been obtained. The method of Maximum Likelihood was used to obtain the Gumbel parameter estimates. Confidence intervals were computed using the adjusted bootstrap method.

3.1.4 Calculation of omni-directional wind

In many cases, the extrapolation of wind speed maxima from one or more of the 12 wind directions result in higher 10,000-yr return values of the wind speed than the extrapolation of the omni-directional wind speed maxima. This is partly due to statistical uncertainty, and party due to incomplete convergence of the directional winds to the asymptotic extreme value distribution.

In order to remove this inconsistency, we calculate an alternative omni-directional wind speed estimate from the directional estimates using (see e.g. also Verkaik et al., 2003):

$$G_{omni} = \prod_{i=1,12} G_i \;, \qquad (3.5)$$

where G_i is the Gumbel distribution for wind sector i, and G_{omni} the *compound* distribution of the omni-directional wind speed. The compound omni-directional wind speed return value estimates are always higher or equal to the highest directional wind speed return value estimate.

As a single event may generate annual maxima in multiple wind directions, the directional wind maxima are mutually correlated. This effect is not accounted for Eq. (3.5), which implies that it gives higher return values than the annual omni-directional winds indicate. A second effect which makes Eq. (3.5) higher than the omni-directional winds is statistical uncertainty in the directional wind estimates. The random uncertainties in the directional estimates are accumulated in the the omni-directional estimate, which makes estimate based on Eq. (3.5) biased towards higher values.

Figure 3.3 shows the omni-directional return values based on the omni-directional maxima (left panel) and based on the directional estimates according to Eq. (3.5) (right panel). Figure 3.4 shows the absolute differences between these estimates; as can be seen in the figure, Eq. (3.5) results in estimates that are can be up to 10 m/s higher than those based on the Gumbel fit to the omni-directional annual maxima.

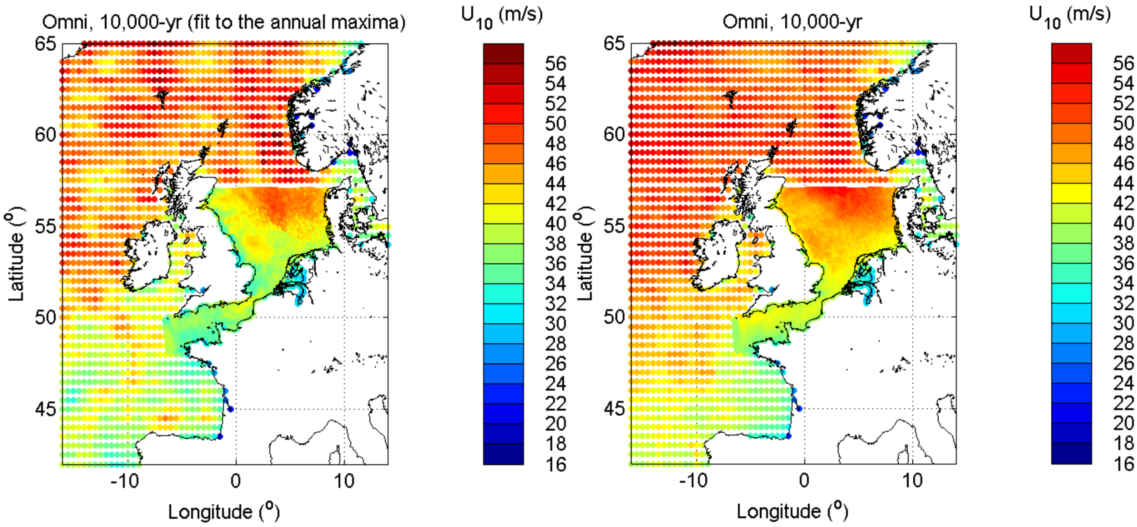

Figure 3.3 Omni-directional 10,000-yr return value estimates of the wind speeds based on the the Gumbel fit to the omni-directional annual maxima (left) and based on the directional estimates according to Eq. (3.5) (right).

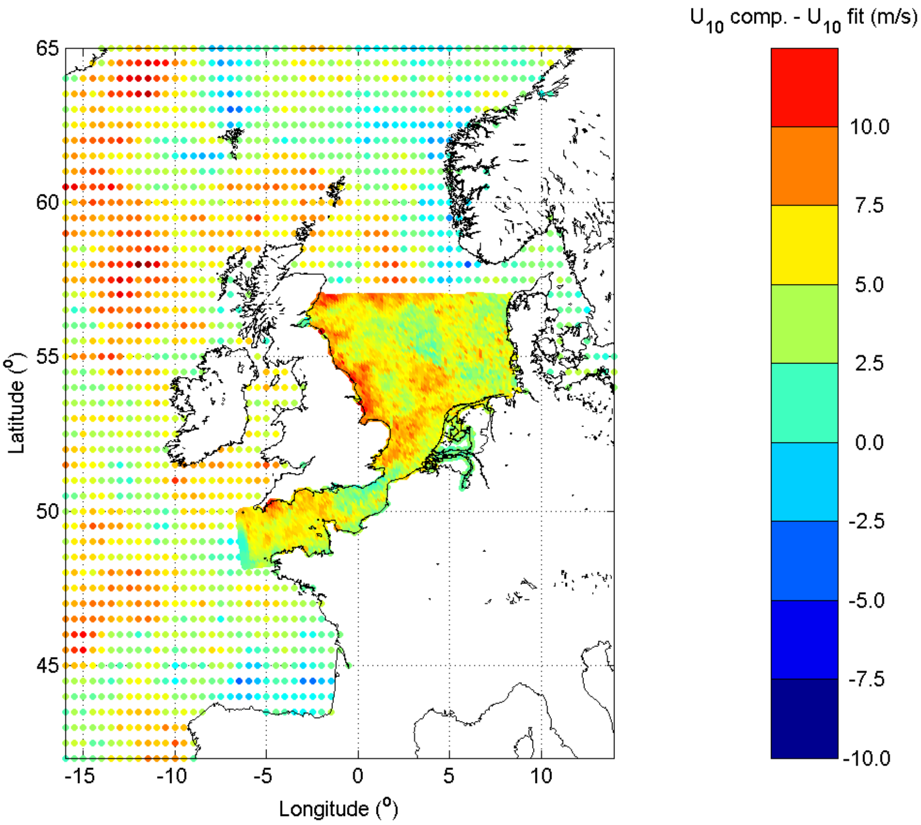

Figure 3.4 Absolute differences between the omni-directional 10,000-yr return value estimates based on the directional estimates according to Eq. (3.5) and on the Gumbel fit to the omni-directional annual maxima.

3.1.5 Smoothing

In order to reduce the effect of the statistical noise on the calculation of the directional estimates, as well as on the compound omni-directional wind, following a suggestion of the reviewer of this report and in line with Roskam et al. (2000), the directional return value estimates have been smoothened using the following filter:

$$x_{s,dir} = 0.25x_{dir-1} + 0.50x_{dir} + 0.25x_{dir+1} \, . \tag{3.6}$$

This smoothing was applied to the 10- and 10,000-yr return values based on the Gumbel fits. Subsequently, the smoothed Gumbel parameters were obtained per sector by fitting a line through these two return values. These smoothed estimates were then used for determining compound omni-directional 10- and 10,000-yr return values according to Eq. (3.5). The Gumbel parameter estimates of the compound fit being also derived by fitting a line through the compound omni-directional 10- and 10,000-yr return values.

3.2 Illustrations

The extreme value estimates of the wind speed have been determined at all 7,589 locations indicated in §2.5. The obtained results are illustrated at 15 locations spread over all water systems.

	Longitude (°)	Latitude (°)
1 non-tidal river reaches Rhine	6.177	52.149
2 non-tidal river reaches Meuse	6.175	51.361
3 tidal river reaches Rhine	4.515	51.927
4 tidal river reaches Meuse	5.047	51.712
5 IJssel delta	5.884	52.564
6 Vecht delta	6.178	52.532
7 Lake Ijssel	5.311	52.807
8 Lake Marken	5.213	52.495
9 Wadden Sea east	6.502	53.511
10 Wadden Sea west	5.191	53.193
11 Northern part of the Dutch coast and dunes	4.447	53.976
12 Central part of the Dutch coast	3.644	53.000
13 Southern part of the Dutch coast	3.461	52.013
14 Eastern Scheldt	3.810	51.626
15 Western Scheldt	3.693	51.403

Table 3.1 Coordinates of the reference locations used to illustrate the analyses.

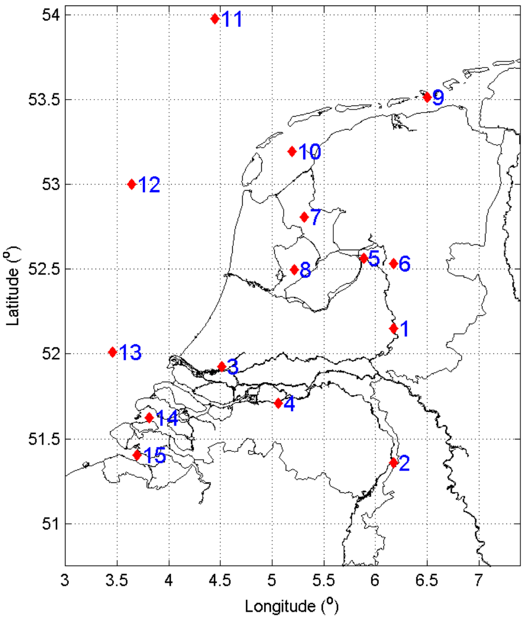

Figure 3.5 Reference locations.

The coordinates of these reference locations used to illustrate the analyses are given in Table 3.1 along with the water system they belong to and in Figure 3.5. The annual maxima of the omni-directional wind speed, as well as the directional maxima (divided in 30°-wide sectors) are shown in Figure 3.6 for reference location 2 in Figure 3.5 (similar plots for the other locations are supplied in Appendix A). The figure clearly illustrates the wide spread in directional estimates. It also shows that the most extreme wind speeds are dominated by a single wind direction (255°-285° in this case), and that the compound omni-directional wind speed asymptotically approaches this directional estimate. The omni-direction 10,000-yr wind speed estimate based on the omni-directional annual maxima is about 2 m/s lower than the compound omni-directional estimate, cf. Table 3.2.

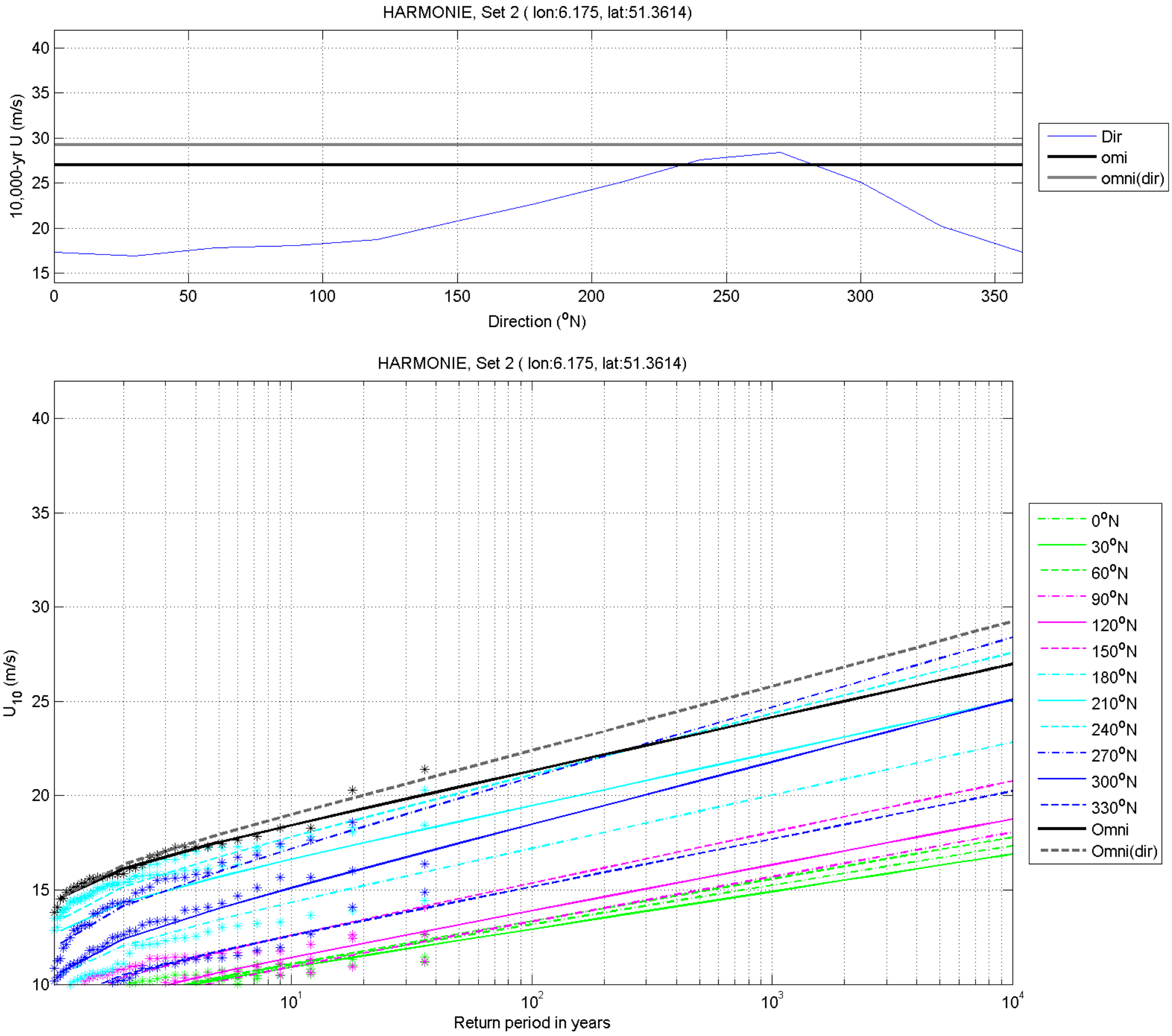

Figure 3.6 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates and the compound omni-directional estimate (based on the directional estimates). The annual maxima data are represented by the asterisks.

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	15.67 (15.26,16.12)	1.47 (1.11, 1.87)	29.2 (26.2, 32.8)
Omni (AM fit)	15.67 (15.26,16.12)	1.23 (0.93, 1.56)	27.0 (24.1, 30.3)
345°-015°	9.01 (8.67, 9.34)	0.90 (0.71, 1.09)	17.3 (15.5, 19.1)
015°-045°	8.95 (8.68, 9.24)	0.86 (0.71, 1.02)	16.9 (15.3, 18.4)
045°-075°	8.91 (8.57, 9.27)	0.97 (0.68, 1.17)	17.8 (15.5, 19.8)
075°-105°	8.61 (8.17, 9.04)	1.03 (0.85, 1.22)	18.1 (16.2, 20.1)
105°-135°	9.04 (8.73, 9.37)	1.06 (0.82, 1.36)	18.8 (16.5, 21.5)
135°-165°	9.94 (9.48,10.40)	1.18 (1.01, 1.34)	20.8 (19.2, 22.3)
165°-195°	11.59 (11.13,12.08)	1.22 (0.96, 1.49)	22.8 (20.1, 25.5)
195°-225°	13.89 (13.51,14.28)	1.21 (0.89, 1.49)	25.1 (22.3, 27.6)
225°-255°	14.65 (14.25,15.12)	1.41 (1.11, 1.72)	27.6 (24.8, 30.6)
255°-285°	13.57 (12.94,14.22)	1.61 (1.26, 1.97)	28.4 (24.9, 32.1)
285°-315°	11.87 (11.42,12.41)	1.44 (1.14, 1.75)	25.1 (22.1, 28.3)

Table 3.2 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 2. The associated 95% confidence intervals are given in brackets.

3.2.1 Omni-directional estimates

In Table 3.3 the differences between the omni-directional and the maximal directional estimates of the 10,000-yr return values are summarised for all reference locations. For WTI only the directional estimates are needed and the differences between these estimates is therefore of second importance in this study. In case omni-directional estimates are need we advise that those based on Eq. (3.5) be used. These are, however, on the conservative side and we recommend that a study to estimate the directional correlation correction factors that should added to Eq. (3.5) be carried out in case unbiased omni-directional estimates are needed.

		Maximal directional estimate		Omni (AM fit)	Omni (Eq. (3.5))
Nr.	Description	Sector	m/s	m/s	m/s
1	Non-tidal river reaches Rhine	225°-255°	30.9 (27.3, 34.8)	30.7 (27.1, 34.4)	31.9 (28.2, 35.8)
2	Non-tidal river reaches Meuse	255°-285°	28.4 (24.9, 32.1)	27.0 (24.1, 30.3)	29.2 (26.2, 32.8)
3	Tidal river reaches Rhine	225°-255°	30.0 (26.8, 33.2)	29.4 (26.1, 32.8)	30.8 (27.4, 34.3)
4	Tidal river reaches Meuse	225°-255°	31.1 (27.8, 34.5)	30.6 (27.5, 34.1)	32.3 (28.9, 35.9)
5	IJssel delta	255°-285°	33.2 (29.4, 37.5)	32.7 (28.6, 37.2)	35.1 (30.7, 39.9)
6	Vecht delta	255°-285°	30.0 (26.0, 34.0)	28.3 (25.6, 31.2)	31.3 (28.3, 34.5)
7	Lake IJssel	225°-255°	35.2 (32.1, 38.7)	34.4 (31.0, 37.6)	37.6 (33.8, 41.0)
8	Lake Marken	225°-255°	34.4 (30.9, 38.0)	32.4 (29.3, 35.3)	36.2 (32.7, 39.4)
9	Wadden Sea East	255°-285°	38.8 (34.8, 42.9)	35.4 (32.3, 38.6)	40.8 (37.2, 44.5)
10	Wadden Sea West	225°-255°	40.5 (36.4, 44.9)	36.0 (33.0, 39.1)	42.3 (38.8, 45.8)
11	Northern part Dutch coast and dunes	195°-225°	41.6 (35.9, 45.7)	38.9 (34.9, 42.5)	44.3 (39.7, 48.4)
12	Central part of Dutch coast	255°-285°	40.8 (36.7, 44.7)	38.2 (34.8, 41.6)	43.0 (39.3, 46.9)
13	Southern part of Dutch coast	225°-255°	38.9 (33.1, 44.4)	37.1 (33.6, 41.0)	41.0 (37.1, 45.3)
14	Eastern Scheldt	255°-285°	36.9 (33.0, 41.2)	34.5 (30.4, 38.5)	38.4 (33.9, 42.9)
15	Western Scheldt	255°-285°	35.4 (31.0, 39.7)	35.0 (31.4, 38.8)	36.9 (33.1, 40.9)

Table 3.3 Omni-directional and maximal directional 10,000-yr return value estimates.

3.2.2 Seasonal and directional effects

As expected, most of the omni-directional extremes occur in winter. However, the directional extremes can also occur in spring or summer, which means that the requirement of homogeneity may not be fulfilled, and deviations from the Gumbel distribution can be expected.

The figures in Appendix A.2 show how often the annual maxima originate from a certain calendar month. As can be seen in the figures, especially in the most inland locations and for wind blowing from the East, the annual maxima can originate in the period from April to September. Given that there is a seasonal dependence in the physics of the generation of extreme winds, this seasonal variation may lead to a violation of the assumption of homogeneity that is being made when fitting the Gumbel distribution to these annual maxima. The effect of such a violation is due to a number of constrains outside the scope of this study, but should be investigated further.

3.3 Calibrations

A detailed validation of the HARMONIE data is given in Baas (2014). This validation is enhanced in this study by validating the 10-yr return value estimates from the data against those from observations.

Figure 3.7(a) shows the relative difference in the 10-yr wind speed estimates between HARMONIE and the observations. It shows that most of the locations have lower wind speeds in HARMONIE than observed. However, the gridbox-averaged roughness of HARMONIE is mostly larger than that of the measurement locations (which is ideally equal to 0.03 m). The HARMONIE winds are therefore not representative for the circumstances at the measurement locations.

To make a fair intercomparison, we transformed both the HARMONIE winds and the observations to the so-called potential wind, which is defined as a standardized speed corrected for local roughness effects, representing the 1 hour averaged wind speed at 10 metres height at a location with a local roughness of 3 cm, corresponding to short grass (Wieringa 1986, 1996). The difference between HARMONIE and observations of potential wind is shown in Figure 3.7(b). The HARMONIE potential wind clearly has a considerably smaller (negative) bias (-2%) than the raw wind (-6%). Apparently, most of the difference between HARMONIE and observations can be attributed to the difference in the (representation) of the local roughness.

Taking into account that the bias of -2% in the potential wind intercomparison is removed if the average HARMONIE roughness over land would have been only 5 cm higher, we conclude that the extreme wind speeds in HARMONIE do not differ significantly from the observations, and no further correction of the HARMONIE wind is needed.

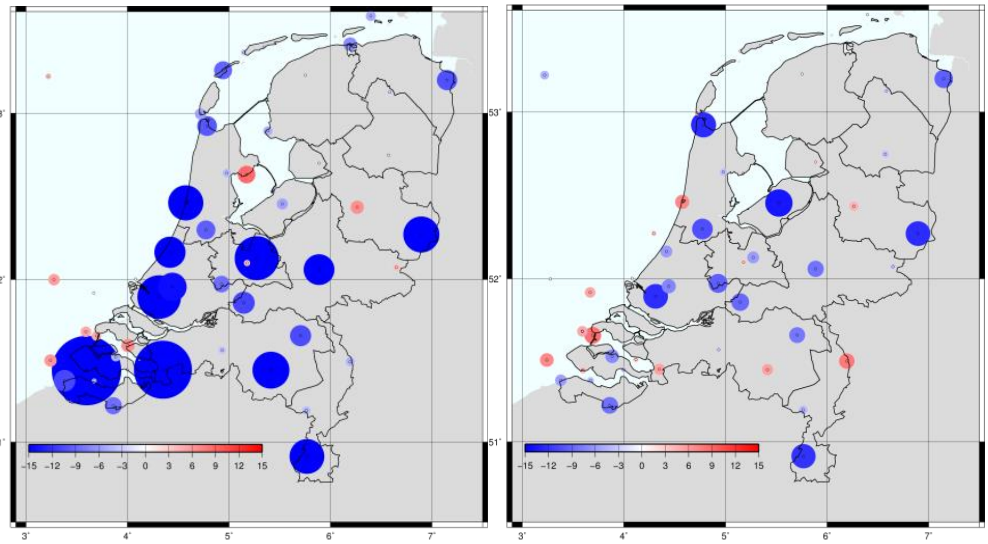

Figure 3.7 Relative difference in the 10-yr extreme wind between HARMONIE and the observations for the raw wind (a) and the potential wind (b). Blue dots indicate underestimation by HARMONIE, red overestimation. The size of the dots indicates the amplitude of the bias.

3.4 Transitions between the HARMONIE and the ERA-Interim estimates

Figure 3.8 shows the 10,000-yr return values of the pseudo-wind for ERA-Interim (left) and HARMONIE (right). While the ERA-Interim 10,000-yr wind field is rather constant in northern direction, HARMONIE indicates a maximum at 57°N.

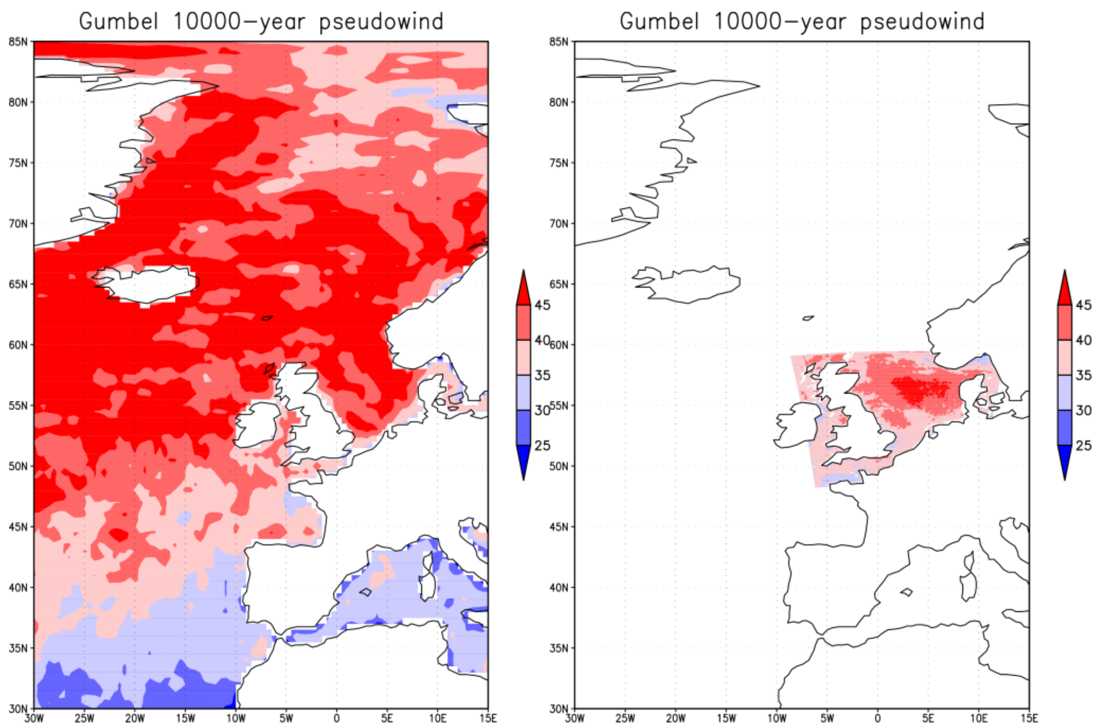

Figure 3.8 10,000-yr return values for the pseudo-wind for ERA-Interim (left) and HARMONIE (right).

Figure 3.9, showing the 10,000-yr wind speed averaged over longitudes between 0°E and 6°E, illustrates the same point more clearly. The agreement of HARMONIE with ERA-Interim is rather good up till 57°N. However, for the area north of 57°N HARMONIE drops down, whereas ERA-Interim remains high.

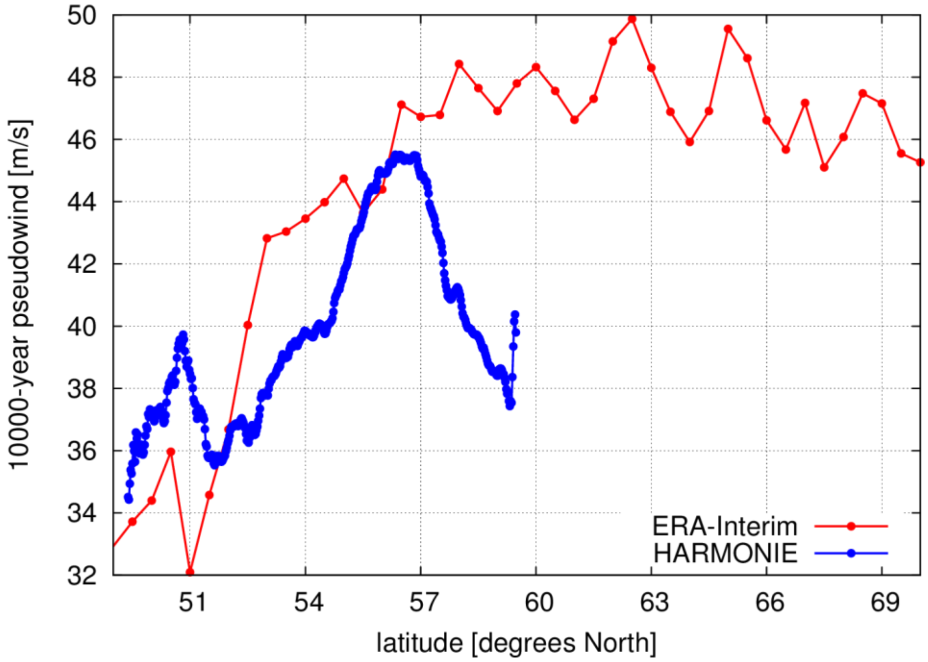

Figure 3.9 10,000-yr return values for the pseudo-wind, averaged between 0°E and 6°E, for ERA-Interim (red) and HARMONIE (blue).

As there are no climatological reasons to expect a decline in the extreme wind speed north of 57°N, we decided to use the HARMONIE data up to 57°N, and the ERA-Interim data north of 57°N. We presume that the depressions that are mostly outside the HARMONIE area are not well represented in HARMONIE, leading to underestimations of the extreme wind speeds.

4 Extreme wind statistics

Here we present some graphs of the 10,000-yr return value estimates of the wind speed[6]. The graphs show the ERA-Interim pseudo-winds, the HARMONIE pseudo-winds, and the HARMONIE open water potential winds. Plots for each direction and location are given, along with the raw data and MATLAB scripts used to produce them, in the 'deliverables' directory accompanying this report, cf. Appendix C.

4.1 Surface plots

The compound omni-directional 10,000-yr return values of the wind speed are shown in Figure 4.1 and Figure 4.2. The omni-directional wind speed is derived from the directional wind speed estimates according to Eq. (3.5). It shows return value estimates up to 58 m/s. These values are expected to have a positive bias (cf. §3.1.4) and are given for indicative purposes only.

[6] The 10,000-yr return period is chosen for illustration. Another return period could have been chosen as well.

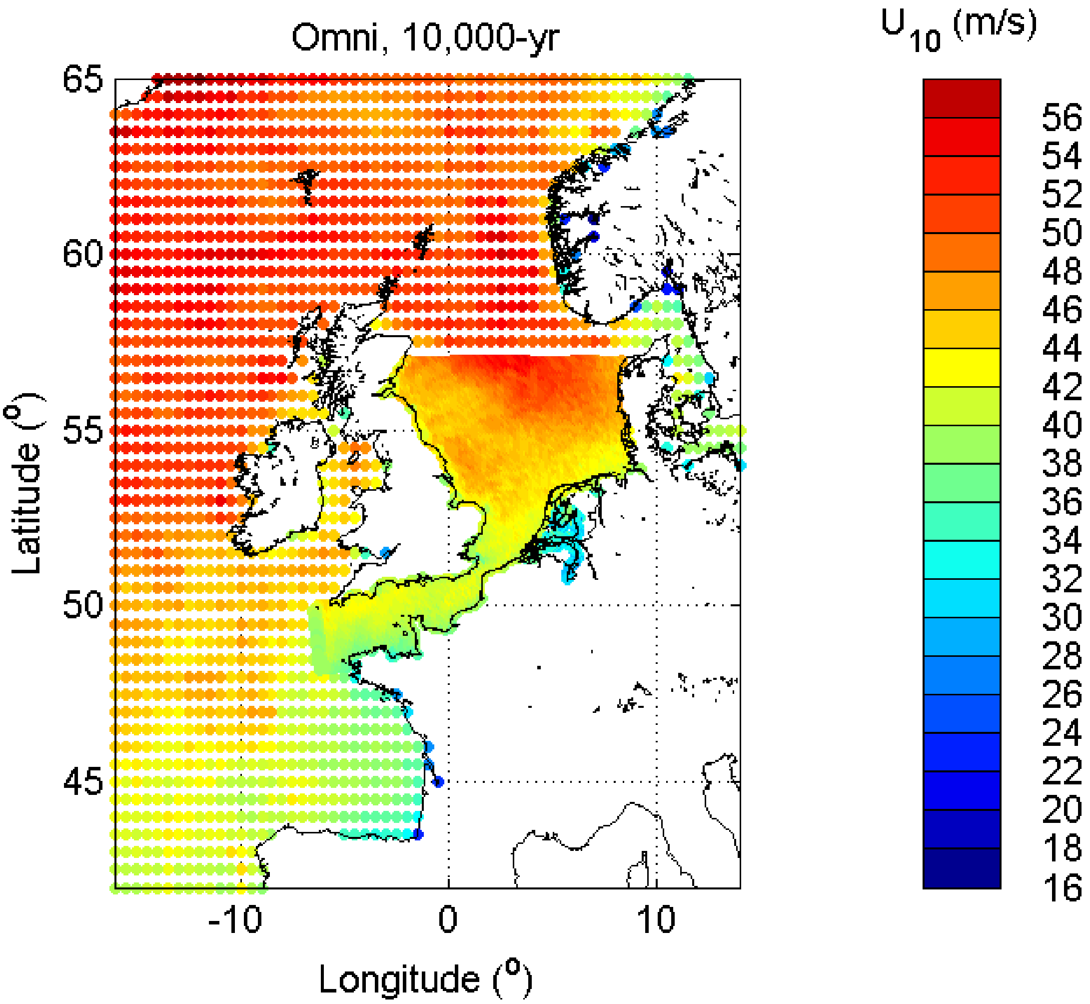

Figure 4.1 Omni-directional 10,000-yr return value estimates of the wind speed. The omni-directional wind speed is derived from the directional wind speed estimates according to Eq. (3.5). The outer region contains the ERA-Interim pseudo-wind, the North Sea (south of 57°N) the HARMONIE pseudo-wind, and the inland waters the potential open water wind speed.

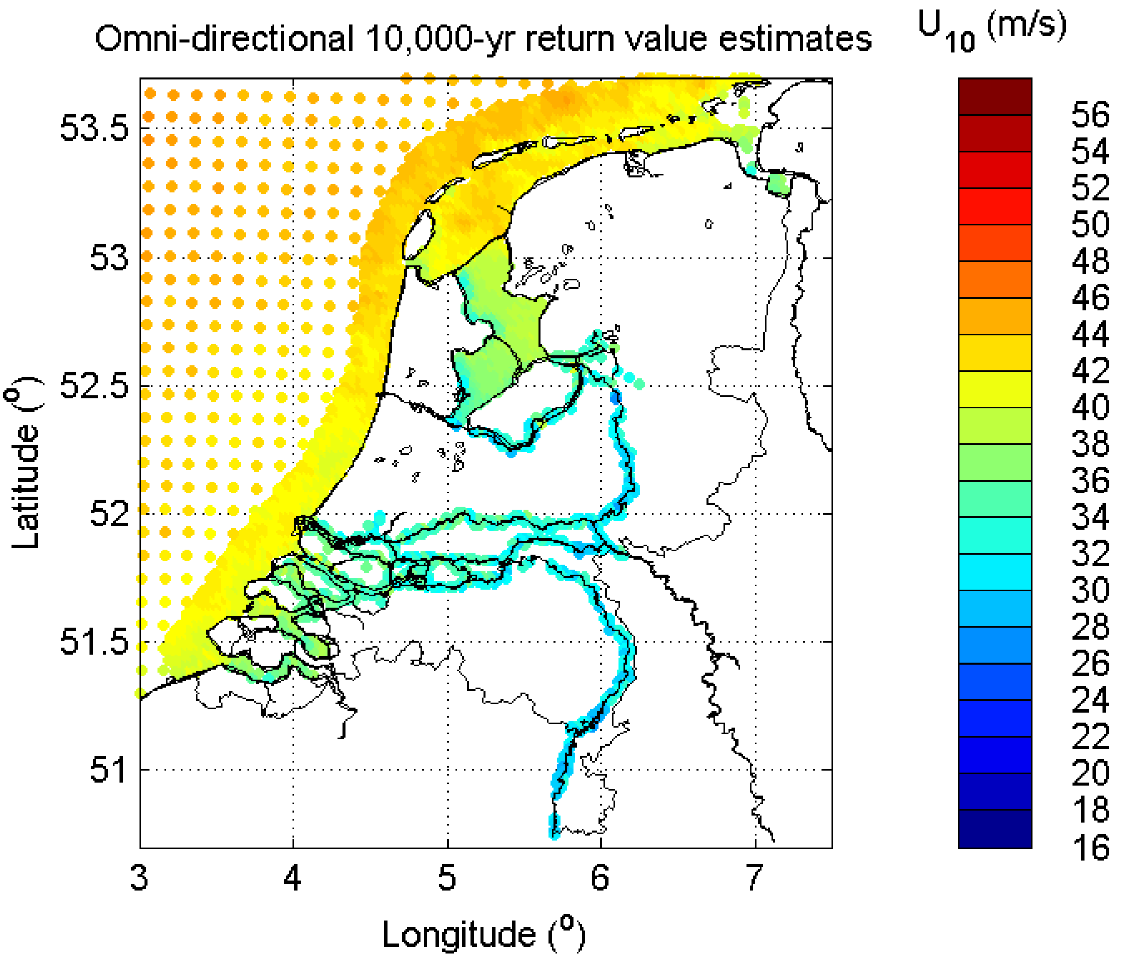

Figure 4.2 Zoom in of Figure 4.1 above the Netherlands.

gives an example of the directional 10,000-yr return values for four 30-degrees sectors around 0, 30, 60 and 90°N. The maps for the other wind directions and also zooming in into the Dutch waters are given in Appendix B.

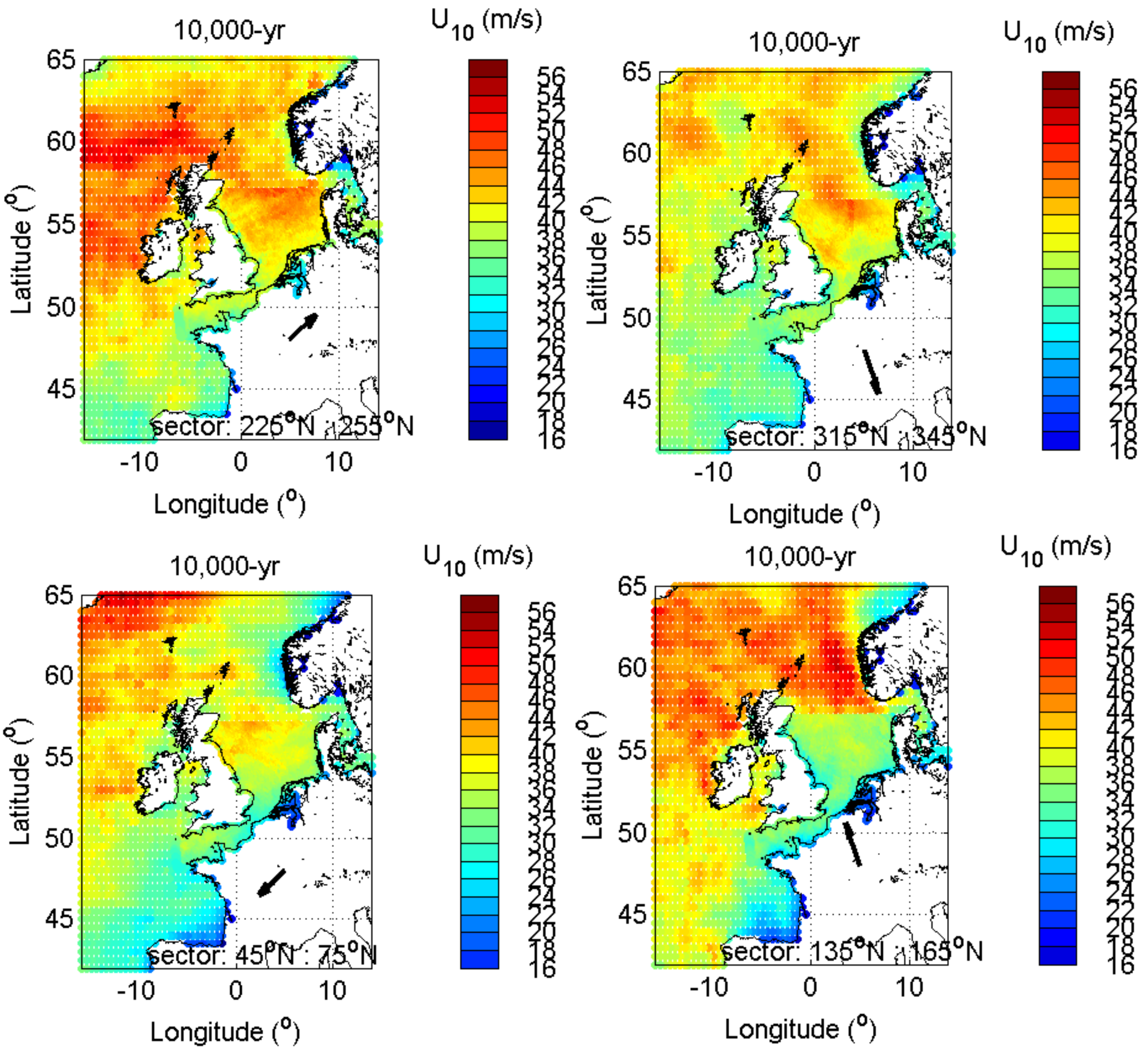

Figure 4.3 Directional 10,000-yr return value estimates of the wind speed for Southwest, Northwest, Northeast and Southeast directions.

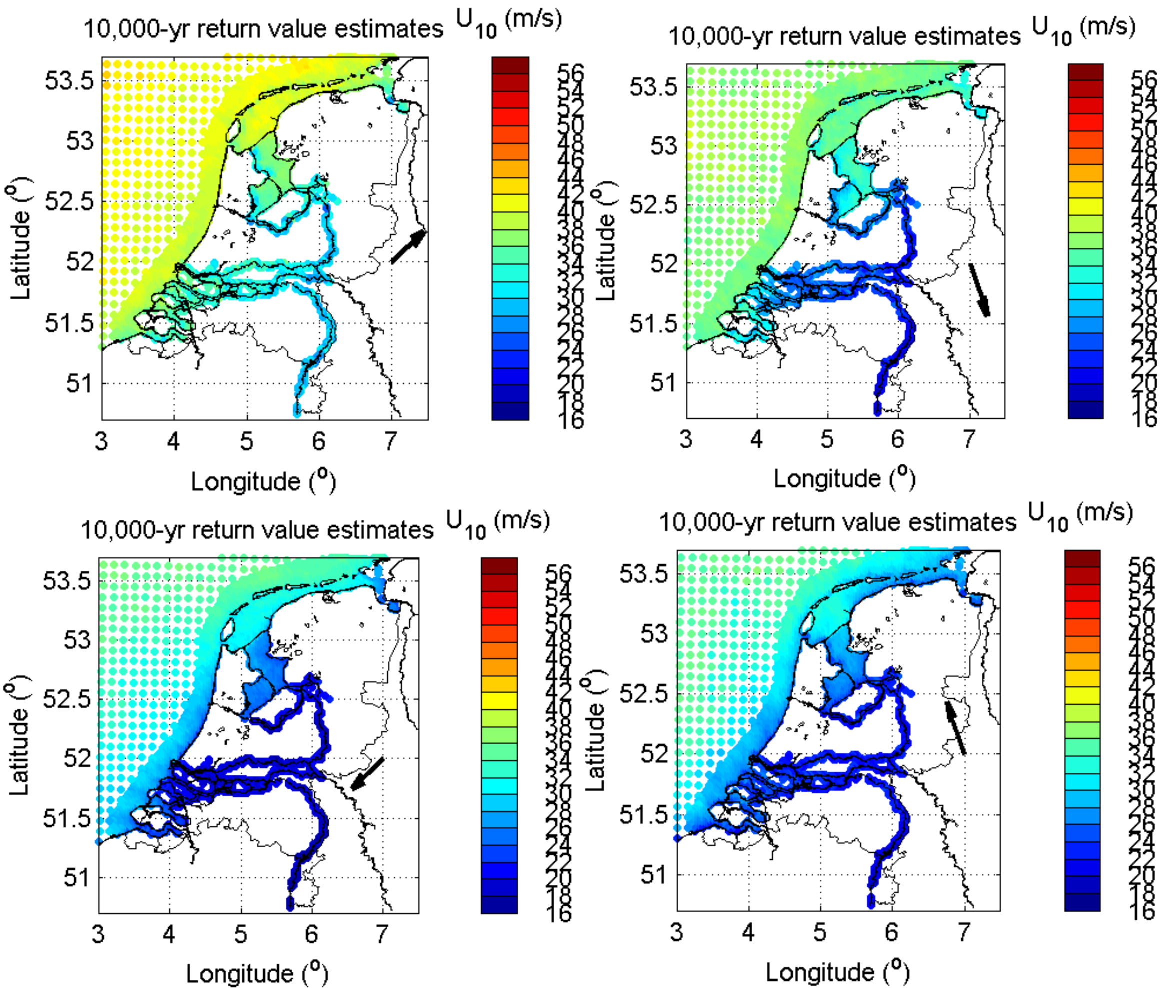

Figure 4.4 Zoom in of Figure 4.3 above the Netherlands.

5 Concluding remarks

For the determination of the Hydraulic Boundary Conditions (HBC) extreme directional wind speeds over open water are required, as they serve as input for surge- and wave-models. In this study reliable directional extreme wind estimates have been determined in more than 7,500 locations covering all Dutch water systems. These are available digitally along with the data and scripts needed to reproduce them.

The return value estimates of the directional wind speeds were determined by applying the Gumbel distribution to the annual maxima of the 1979-2013 period computed by HARMONIE and ERA-Interim. The output of the high-resolution meteorological model HARMONIE is used for the region south of 57°N in the North Sea and over the Netherlands. Outside this area in the northern North Sea and Atlantic Ocean, the much coarser ERA-Interim model is used. Over open water the wind speeds are represented as pseudo-wind, which is directly related to the surface stress. Over mixed land-water regions a simple downscaling is applied to obtain the wind over the water fraction, the open water potential wind.

The following remarks should be beard in mind when considering the given estimates:

- The extreme value analysis of the data indicates that the Gumbel distribution fitted to omni-directional annual maxima provides the best representation of the extreme wind speeds. This makes the choice of a threshold in a peak-over-threshold approach superfluous.
- Seasonal variations seem to play a role in the distributions of the annual maxima, especially in the most inland locations and for wind blowing from the East. However, the effect of such variations in homogeneity of the annual maxima still needs to be investigated.
- In order to force the omni-directional estimates to be higher than the directional estimates, a compound omni-directional estimate is constructed from the directional estimates. However, this compound estimate yields 10,000-yr return values of wind speed maxima that are mostly conservative because they have not yet been corrected for correlation between sectors.
- We presume that the depressions that are mostly outside the HARMONIE area are not well represented in HARMONIE, leading to underestimations of the extreme wind speeds. For this reason the HARMONIE output is used only south of 57°N.

6 Recommendations

A number of choices and assumptions have been made in this study. In order to study the effects of such choices and assumptions we recommend the following:

- The European Centre for Medium-Range Weather Forecasts (ECMWF) generates every month a 51-member weather ensemble of 7 months length. For calibration purposes, this dataset is hindcasted from 1981 onwards, resulting in a 3,500-yr dataset of 6-hourly wind speeds. This dataset is very appropriate to explore some of the issues of this report, e.g., the extrapolation assumptions and the scalability of the extreme depressions. However, for issues concerning the seasonal inhomogeneity, this dataset lacks sufficient resolution to resolve the small-scale events that cause the summer extremes.
- The ECMWF has recently finished an extended re-analysis project, called ERA-CLIM, in which the weather back to 1900 is re-analysed on a 3-hourly resolution. It has the same spatial resolution as ERA-Interim. This dataset may be used to extend the current 35-yr ERA-Interim period to over 100 years, which will include severe (flooding) events like 1953 and 1916.
- The given compound omni-directional estimates are conservative. A directional correlation correction should be added to the equation used for the compound omni-directional fit if unbiased estimates are needed. Suggested is to derive this directional correlation correction by counting how often omni-directional annual maxima events return in the directional events. Preliminary results indicate an average value in the HARMONIE region that is close to the value of 1.67. This value was also been found in other studies, cf. Geerse et al., (2002). Some regional dependence may be expected for such a correction.
- Replace the approach applied in §2.3.2 to determine the open-water (potential) wind with a 1D or 2D model for short fetches. This can be done either in an analytical or in a numerical way. It is expected that this will lead to lower wind speed values, as the current open-water approach can be considered as the asymptotic value for large fetches.
- For winds blowing from sectors where the wind is lower, the physics for the generation of extreme winds seem to be seasonal dependent. Most likely the distribution of extremes of these data is non-homogeneous and a study into the consequences of such seasonality in the data should be carried out.
- For a better confidence in the directional fits and the compound omni-directional fit, we suggest to explore and apply the *XIMIS* - approach as suggested by Cook et al. (2003) and Harris (2009). This means that the assumptions of the extreme value theory are explicitly explored, and *pen-ultimate distributions* are applied if the assumptions are not fulfilled. The cited authors have intensively explored the application to wind data, with promising results. The suggestions in Harris (2009) about handling mixed climates are relatively easy applicable to the different wind directions, as well as for the seasonal variations. The challenge here is to find the appropriate transformation that should be applied to the data (see e.g. Caires, 2009).

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A Estimates at the reference locations

This appendix contains figures like Figure 3.6 and tables like Table 3.2 for each reference location. Furthermore, in Section A.2 the monthly percentage of the annual maxima per sector are given. These figures support the statements made in Section 3.2.2.

A.1 Extreme value estimates

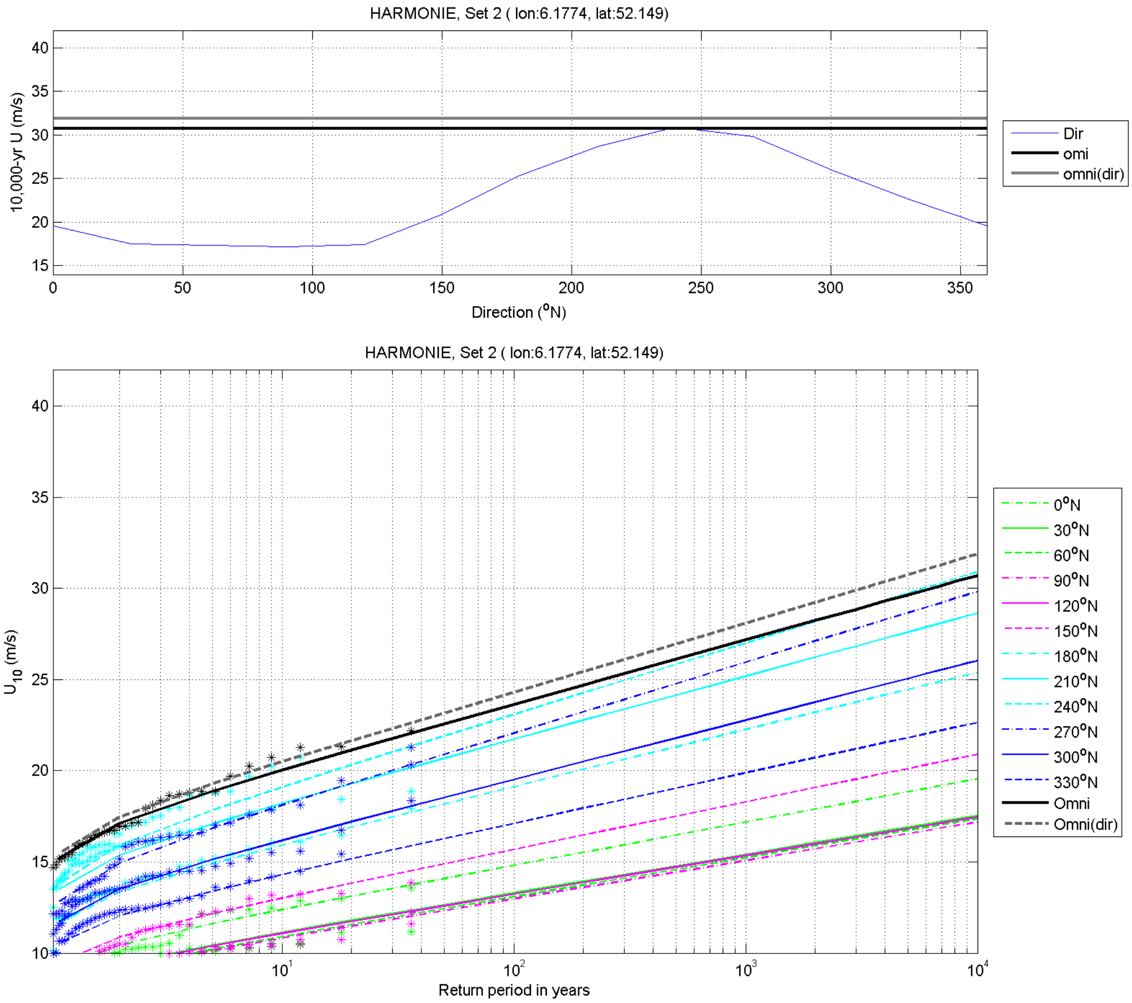
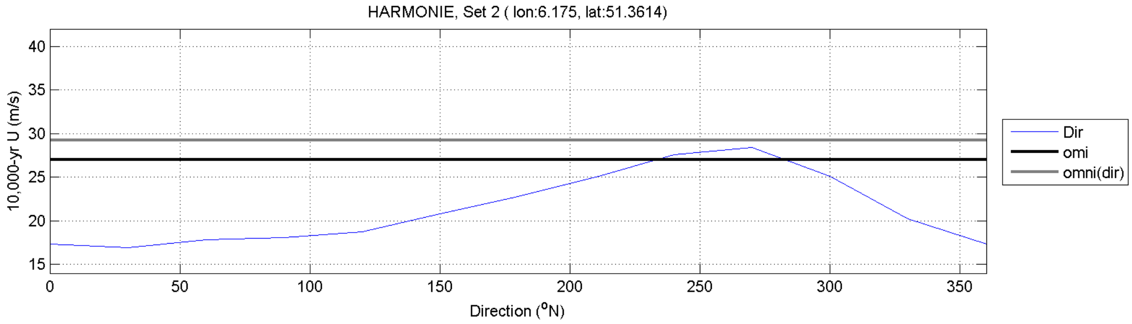


Figure A.1 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 1 (Non-tidal river reaches Rhine).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	16.79 (16.27,17.39)	1.64 (1.24, 2.04)	31.9 (28.2, 35.8)
Omni (AM fit)	16.55 (16.04,17.14)	1.54 (1.17, 1.92)	30.7 (27.1, 34.4)
345°-015°	10.06 (9.73,10.44)	1.03 (0.75, 1.32)	19.6 (16.9, 22.4)
015°-045°	9.05 (8.77, 9.39)	0.92 (0.75, 1.09)	17.5 (15.8, 19.2)
045°-075°	8.82 (8.47, 9.15)	0.93 (0.66, 1.17)	17.4 (15.0, 19.5)
075°-105°	8.76 (8.39, 9.12)	0.91 (0.62, 1.18)	17.2 (14.5, 19.6)
105°-135°	9.00 (8.73, 9.31)	0.92 (0.64, 1.19)	17.5 (15.1, 19.9)
135°-165°	10.47 (10.07,10.90)	1.13 (0.87, 1.40)	20.9 (18.3, 23.6)
165°-195°	12.86 (12.33,13.35)	1.36 (0.95, 1.76)	25.4 (21.6, 29.2)
195°-225°	14.83 (14.35,15.30)	1.50 (1.05, 1.90)	28.6 (25.0, 32.0)
225°-255°	15.29 (14.71,15.95)	1.70 (1.32, 2.06)	30.9 (27.3, 34.8)
255°-285°	14.32 (13.70,15.01)	1.68 (1.38, 2.02)	29.8 (26.5, 33.4)
285°-315°	12.99 (12.55,13.47)	1.42 (1.10, 1.73)	26.0 (23.3, 28.9)

Table A.1 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 1.



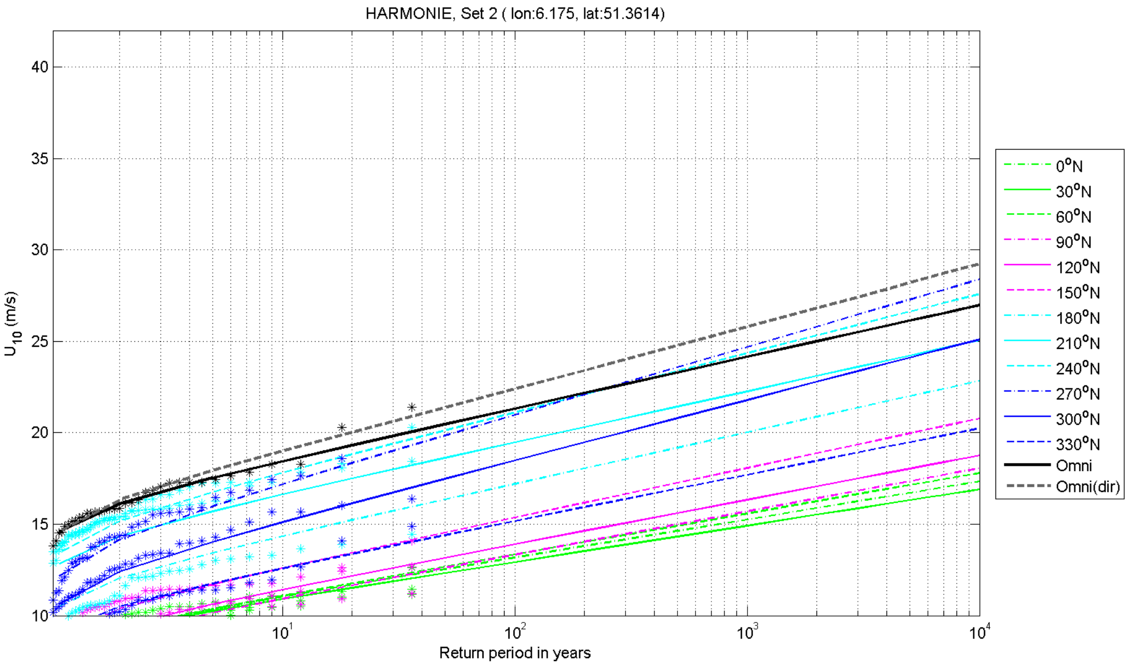


Figure A.2 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 2 (Non-tidal river reaches Meuse).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	15.67 (15.26,16.12)	1.47 (1.11, 1.87)	29.2 (26.2, 32.8)
Omni (AM fit)	15.67 (15.26,16.12)	1.23 (0.93, 1.56)	27.0 (24.1, 30.3)
345°-015°	9.01 (8.67, 9.34)	0.90 (0.71, 1.09)	17.3 (15.5, 19.1)
015°-045°	8.95 (8.68, 9.24)	0.86 (0.71, 1.02)	16.9 (15.3, 18.4)
045°-075°	8.91 (8.57, 9.27)	0.97 (0.68, 1.17)	17.8 (15.5, 19.8)
075°-105°	8.61 (8.17, 9.04)	1.03 (0.85, 1.22)	18.1 (16.2, 20.1)
105°-135°	9.04 (8.73, 9.37)	1.06 (0.82, 1.36)	18.8 (16.5, 21.5)
135°-165°	9.94 (9.48,10.40)	1.18 (1.01, 1.34)	20.8 (19.2, 22.3)
165°-195°	11.59 (11.13,12.08)	1.22 (0.96, 1.49)	22.8 (20.1, 25.5)
195°-225°	13.89 (13.51,14.28)	1.21 (0.89, 1.49)	25.1 (22.3, 27.6)
225°-255°	14.65 (14.25,15.12)	1.41 (1.11, 1.72)	27.6 (24.8, 30.6)
255°-285°	13.57 (12.94,14.22)	1.61 (1.26, 1.97)	28.4 (24.9, 32.1)
285°-315°	11.87 (11.42,12.41)	1.44 (1.14, 1.75)	25.1 (22.1, 28.3)

Table A.2 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 2.

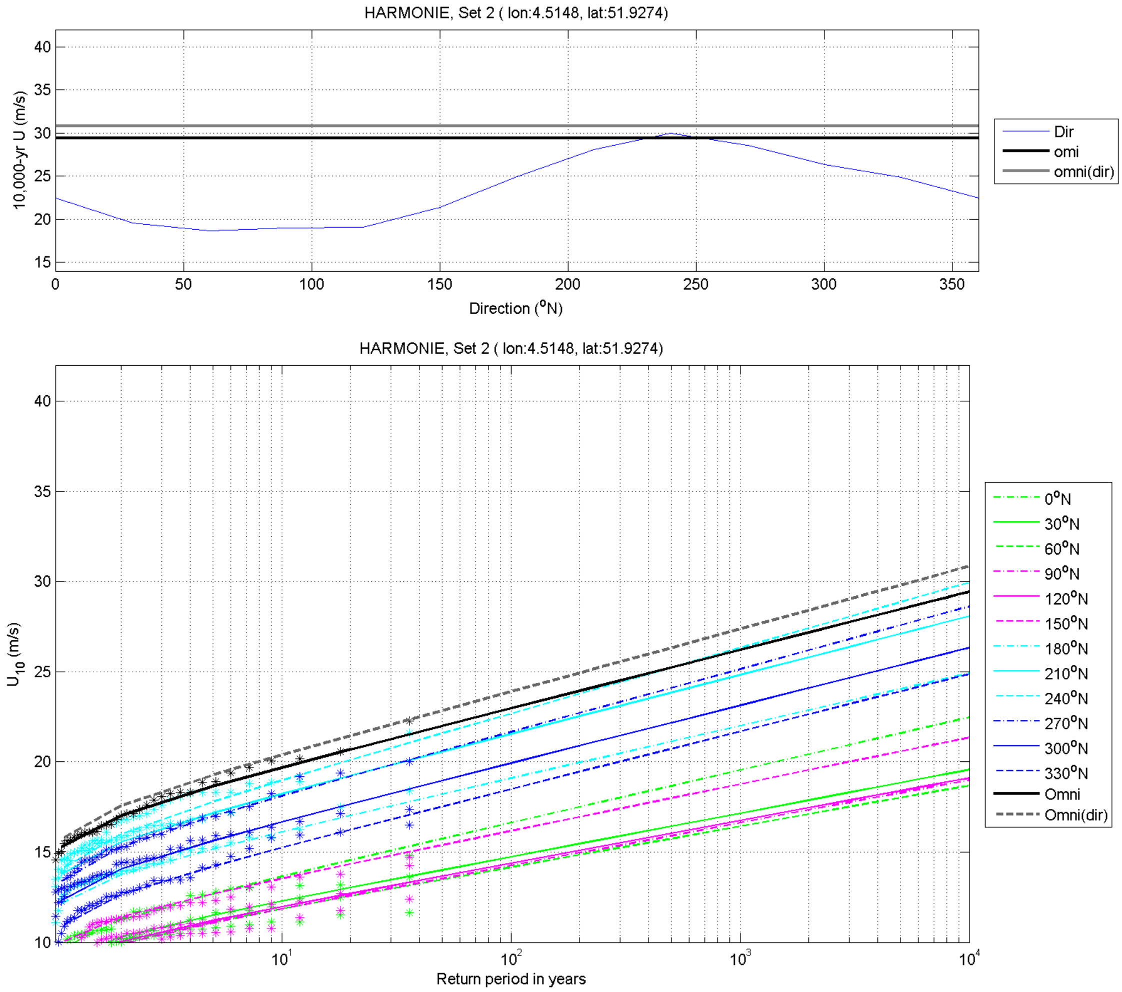


Figure A.3 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 3(Tidal river reaches Rhine).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	16.97 (16.49,17.51)	1.51 (1.14, 1.87)	30.8 (27.4, 34.3)
Omni (AM fit)	16.51 (16.04,17.03)	1.40 (1.06, 1.74)	29.4 (26.1, 32.8)
345°-015°	10.78 (10.34,11.26)	1.27 (0.93, 1.54)	22.5 (19.5, 25.1)
015°-045°	9.91 (9.57,10.29)	1.05 (0.82, 1.30)	19.6 (17.3, 22.0)
045°-075°	9.64 (9.31, 9.96)	0.98 (0.75, 1.24)	18.7 (16.6, 20.9)
075°-105°	9.53 (9.14, 9.93)	1.03 (0.81, 1.26)	19.0 (16.9, 21.3)
105°-135°	9.66 (9.35,10.01)	1.03 (0.83, 1.23)	19.1 (17.2, 21.1)
135°-165°	11.00 (10.60,11.43)	1.12 (0.92, 1.31)	21.4 (19.2, 23.4)
165°-195°	13.28 (12.84,13.73)	1.26 (0.84, 1.64)	24.9 (21.1, 28.3)
195°-225°	15.04 (14.59,15.50)	1.42 (0.98, 1.85)	28.1 (24.2, 31.9)
225°-255°	15.43 (14.84,16.06)	1.58 (1.26, 1.88)	30.0 (26.8, 33.2)
255°-285°	14.72 (14.24,15.27)	1.51 (1.20, 1.86)	28.6 (25.5, 32.1)
285°-315°	13.54 (13.09,14.01)	1.39 (1.04, 1.71)	26.3 (23.3, 29.3)

Table A.3 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 3.

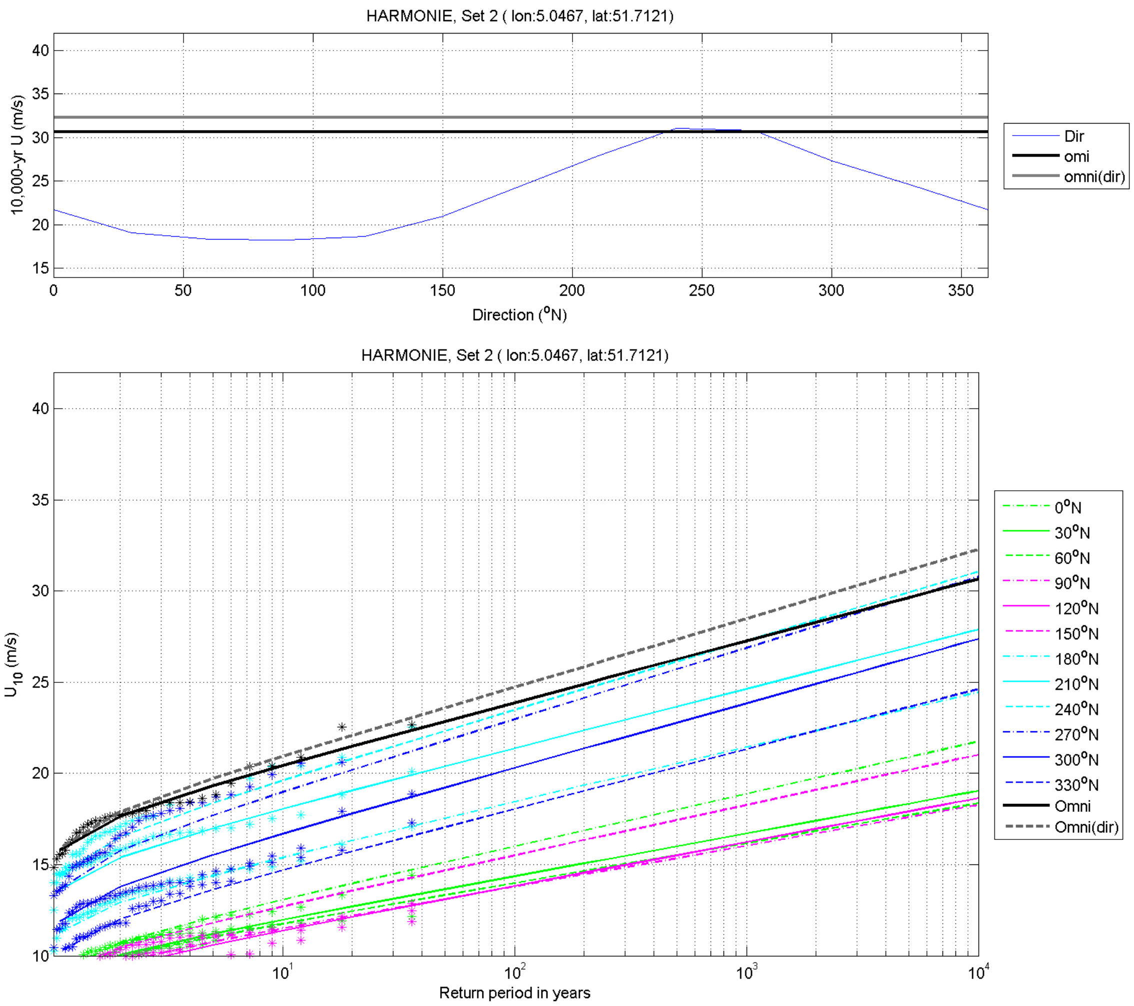


Figure A.4 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 4 (tidal river reaches Meuse).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	17.24 (16.70,17.78)	1.63 (1.26, 2.03)	32.3 (28.9, 35.9)
Omni (AM fit)	17.10 (16.57,17.64)	1.47 (1.14, 1.83)	30.6 (27.5, 34.1)
345°-015°	10.26 (9.82,10.72)	1.25 (0.94, 1.53)	21.8 (19.1, 24.4)
015°-045°	9.68 (9.35,10.04)	1.02 (0.81, 1.23)	19.0 (17.0, 21.2)
045°-075°	9.62 (9.31, 9.93)	0.95 (0.75, 1.16)	18.4 (16.6, 20.2)
075°-105°	9.30 (8.93, 9.68)	0.97 (0.69, 1.23)	18.3 (15.7, 20.7)
105°-135°	9.03 (8.70, 9.36)	1.04 (0.78, 1.27)	18.6 (16.4, 20.6)
135°-165°	10.02 (9.52,10.52)	1.19 (1.00, 1.38)	21.0 (19.1, 22.9)
165°-195°	12.45 (12.00,12.90)	1.30 (0.98, 1.62)	24.4 (21.4, 27.6)
195°-225°	14.86 (14.39,15.31)	1.42 (0.97, 1.86)	27.9 (24.0, 31.5)
225°-255°	15.90 (15.33,16.49)	1.65 (1.32, 1.99)	31.1 (27.8, 34.5)
255°-285°	15.15 (14.55,15.83)	1.70 (1.39, 2.06)	30.8 (27.4, 34.5)
285°-315°	13.23 (12.70,13.73)	1.54 (1.10, 1.96)	27.4 (23.7, 31.2)

Table A.4 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 4.

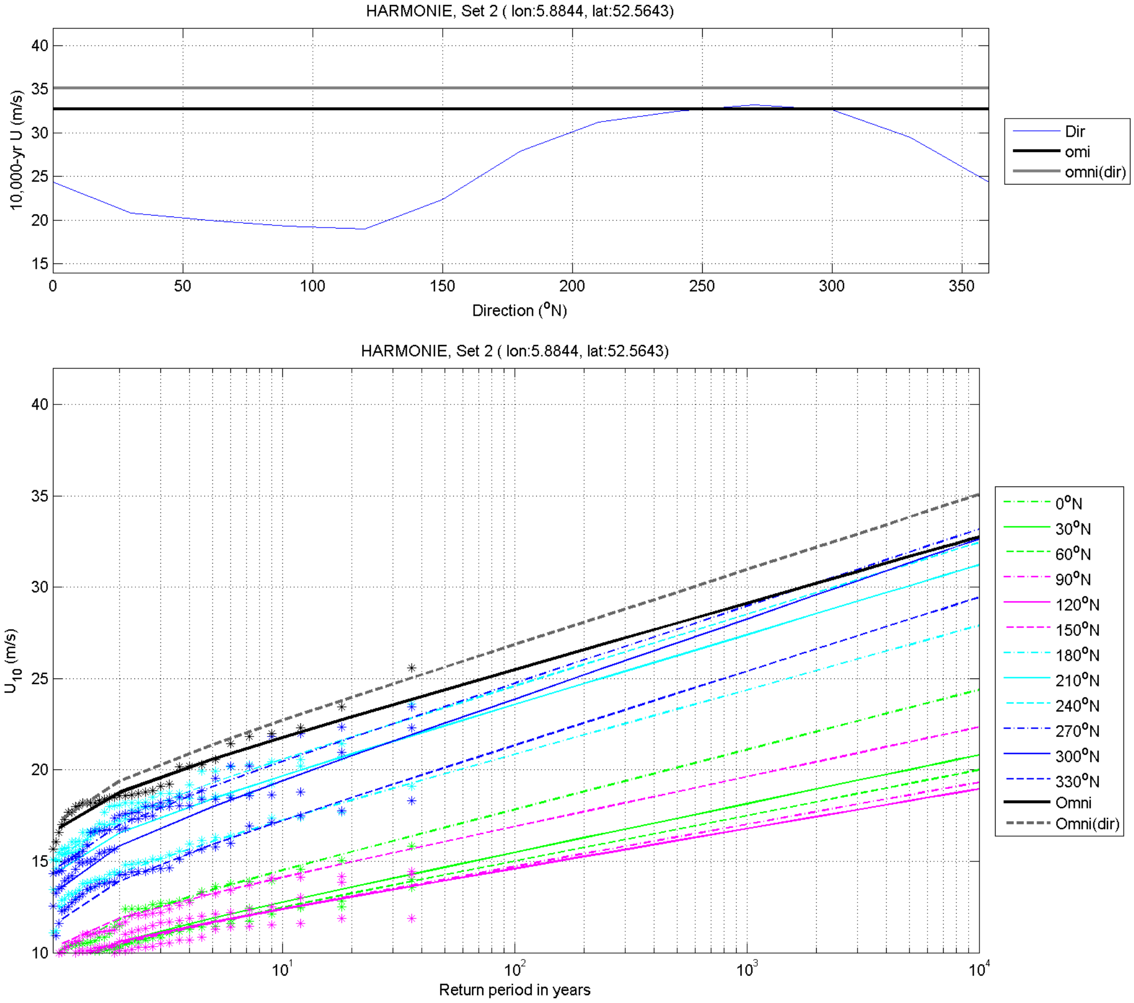


Figure A.5 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 5 (IJssel delta).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	18.69 (18.13,19.30)	1.78 (1.28, 2.32)	35.1 (30.7, 39.9)
Omni (AM fit)	18.20 (17.65,18.79)	1.58 (1.14, 2.07)	32.7 (28.6, 37.2)
345°-015°	11.31 (10.88,11.82)	1.42 (1.07, 1.75)	24.4 (21.0, 27.7)
015°-045°	10.15 (9.77,10.57)	1.16 (0.93, 1.40)	20.8 (18.5, 23.2)
045°-075°	10.04 (9.65,10.44)	1.08 (0.79, 1.34)	20.0 (17.4, 22.5)
075°-105°	10.13 (9.76,10.53)	1.00 (0.76, 1.26)	19.3 (17.0, 21.9)
105°-135°	10.25 (9.97,10.54)	0.95 (0.71, 1.17)	19.0 (17.0, 20.9)
135°-165°	11.46 (11.06,11.91)	1.18 (0.92, 1.42)	22.3 (19.8, 24.7)
165°-195°	13.80 (13.21,14.38)	1.53 (1.06, 1.91)	27.9 (23.6, 31.6)
195°-225°	15.94 (15.37,16.54)	1.66 (1.22, 2.13)	31.2 (27.2, 35.7)
225°-255°	16.75 (16.22,17.30)	1.70 (1.37, 2.06)	32.4 (29.2, 35.9)
255°-285°	16.33 (15.70,17.03)	1.83 (1.46, 2.26)	33.2 (29.4, 37.5)
285°-315°	15.14 (14.48,15.83)	1.90 (1.49, 2.31)	32.6 (28.6, 36.7)

Table A.5 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 5.

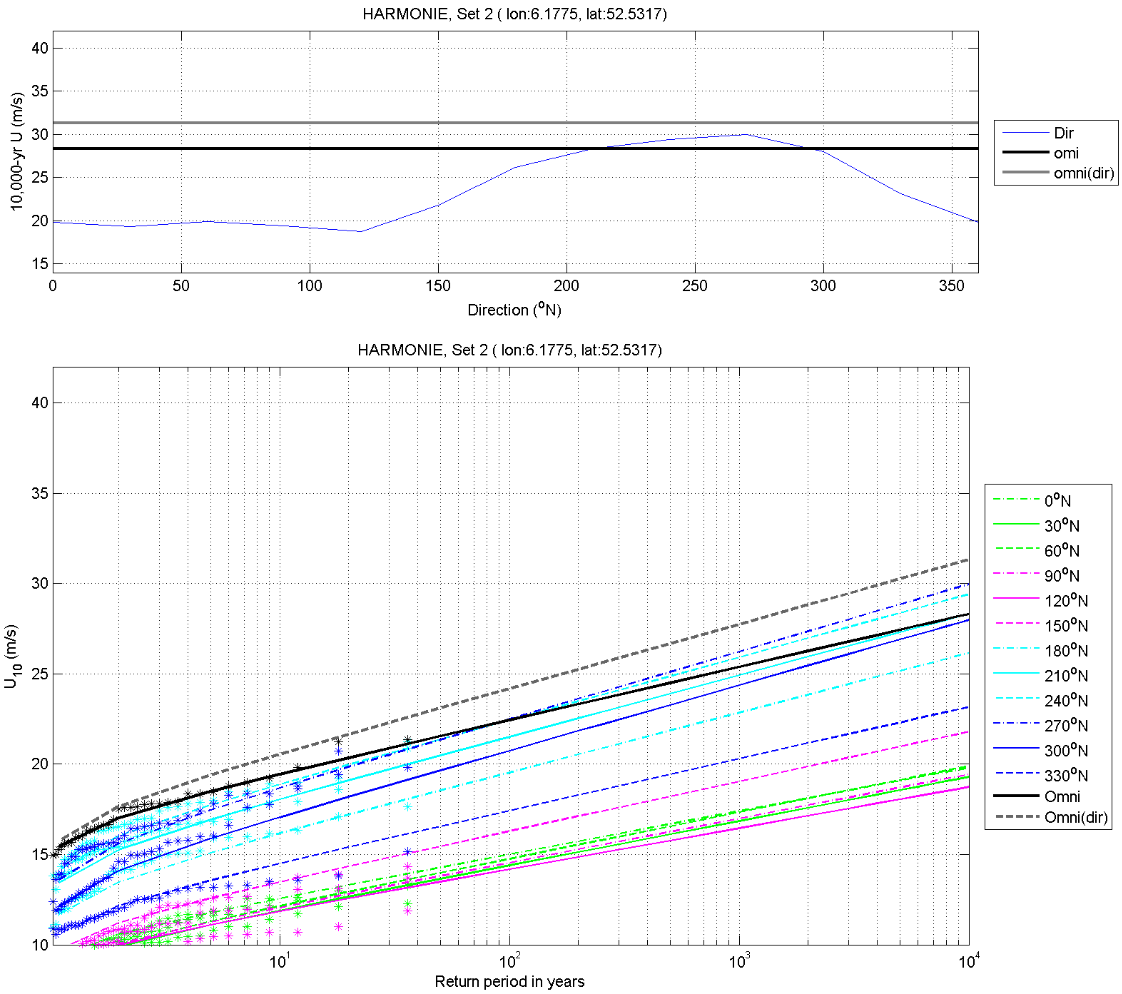


Figure A.6 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 6 (Vecht delta).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	17.06 (16.62,17.56)	1.55 (1.22, 1.91)	31.3 (28.3, 34.5)
Omni (AM fit)	16.56 (16.14,17.04)	1.28 (1.00, 1.57)	28.3 (25.6, 31.2)
345°-015°	10.21 (9.90,10.60)	1.04 (0.81, 1.28)	19.8 (17.6, 22.1)
015°-045°	9.50 (9.12, 9.91)	1.06 (0.81, 1.31)	19.3 (16.8, 21.7)
045°-075°	9.63 (9.27,10.01)	1.12 (0.83, 1.40)	19.9 (17.4, 22.5)
075°-105°	9.66 (9.22,10.11)	1.06 (0.76, 1.31)	19.4 (16.6, 21.9)
105°-135°	9.62 (9.37, 9.88)	0.99 (0.76, 1.21)	18.7 (16.8, 20.6)
135°-165°	10.79 (10.34,11.27)	1.20 (0.90, 1.47)	21.8 (18.9, 24.5)
165°-195°	12.94 (12.43,13.44)	1.44 (1.15, 1.74)	26.2 (23.4, 29.2)
195°-225°	14.72 (14.19,15.22)	1.48 (1.10, 1.84)	28.3 (25.0, 31.6)
225°-255°	15.47 (14.97,15.98)	1.51 (1.22, 1.82)	29.4 (26.6, 32.3)
255°-285°	15.03 (14.48,15.57)	1.62 (1.17, 2.06)	30.0 (26.0, 34.0)
285°-315°	13.52 (12.91,14.16)	1.57 (1.19, 1.95)	28.0 (24.1, 32.0)

Table A.6 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 6.

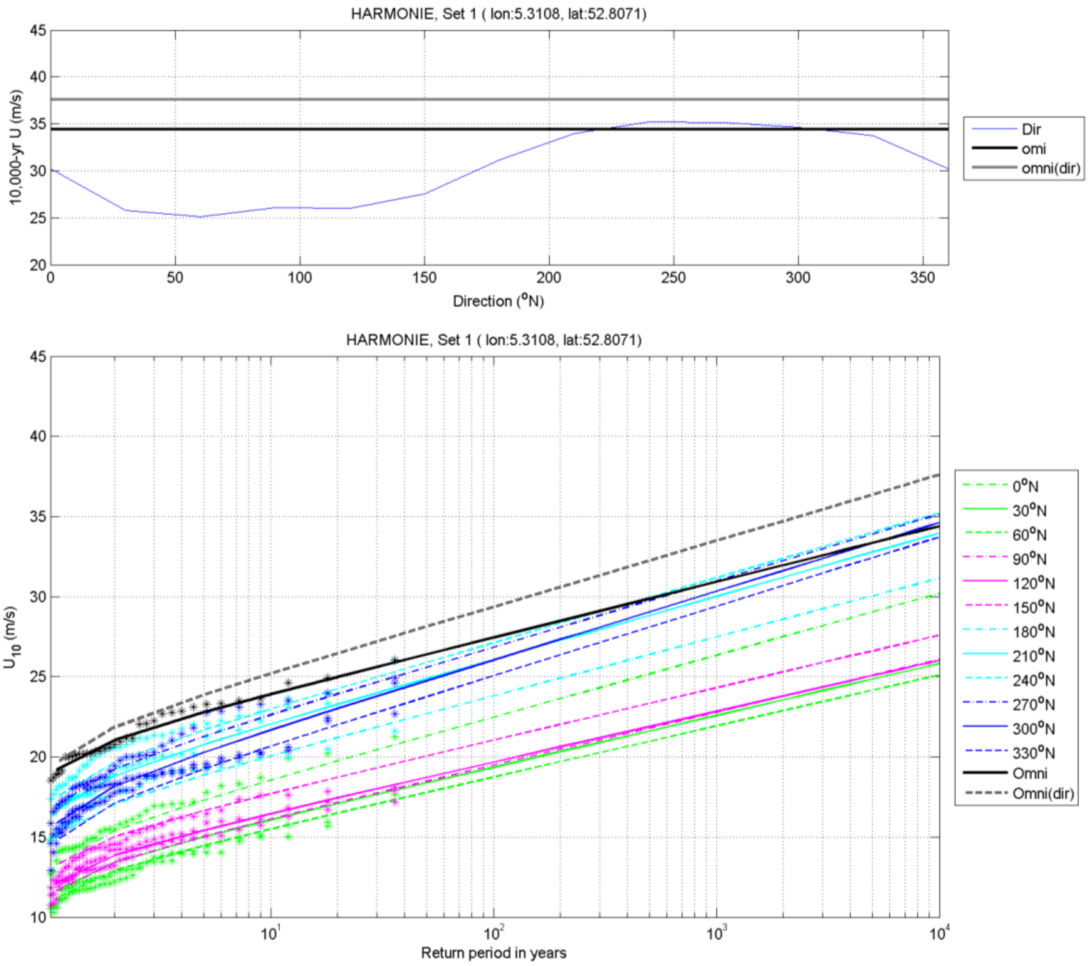


Figure A.7 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 7 (Lake Ijssel).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	21.17 (20.66,21.72)	1.78 (1.37, 2.16)	37.6 (33.8, 41.0)
Omni (AM fit)	20.51 (20.01,21.04)	1.51 (1.16, 1.83)	34.4 (31.0, 37.6)
345°-015°	14.77 (14.24,15.39)	1.68 (1.27, 2.08)	30.2 (26.4, 34.1)
015°-045°	12.90 (12.40,13.39)	1.40 (0.99, 1.74)	25.8 (22.2, 29.0)
045°-075°	12.40 (11.96,12.92)	1.38 (1.03, 1.74)	25.1 (21.7, 28.7)
075°-105°	12.90 (12.34,13.48)	1.43 (1.10, 1.71)	26.1 (22.9, 28.9)
105°-135°	13.36 (12.97,13.78)	1.37 (1.05, 1.70)	26.0 (23.0, 29.0)
135°-165°	14.51 (13.99,15.10)	1.42 (1.14, 1.69)	27.6 (24.8, 30.3)
165°-195°	16.48 (15.99,17.03)	1.59 (1.29, 1.89)	31.2 (28.2, 34.0)
195°-225°	18.20 (17.54,18.88)	1.71 (1.23, 2.17)	34.0 (29.2, 38.7)
225°-255°	19.03 (18.47,19.57)	1.76 (1.43, 2.12)	35.2 (32.1, 38.7)
255°-285°	18.58 (17.94,19.29)	1.80 (1.39, 2.23)	35.1 (31.0, 39.6)
285°-315°	17.50 (16.82,18.20)	1.86 (1.48, 2.28)	34.6 (31.2, 38.6)

Table A.7 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 7.

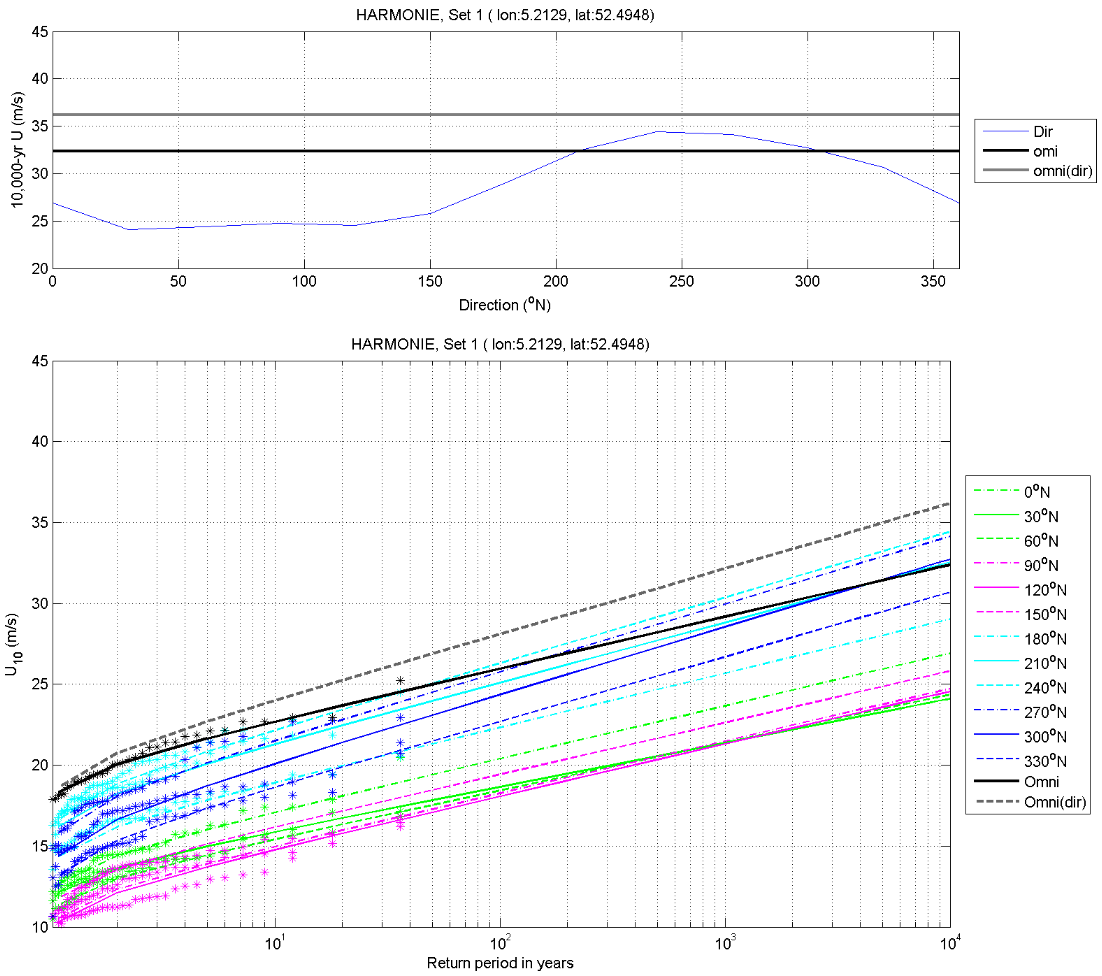


Figure A.8 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 8 (Lake Marken).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	20.06 (19.59,20.62)	1.75 (1.37, 2.12)	36.2 (32.7, 39.4)
Omni (AM fit)	19.54 (19.08,20.09)	1.39 (1.09, 1.69)	32.4 (29.3, 35.3)
345°-015°	13.90 (13.48,14.39)	1.41 (1.08, 1.79)	26.9 (23.7, 30.5)
015°-045°	13.21 (12.85,13.57)	1.18 (0.91, 1.47)	24.1 (21.7, 26.7)
045°-075°	12.52 (12.07,13.02)	1.29 (1.03, 1.55)	24.4 (21.9, 27.0)
075°-105°	11.80 (11.32,12.31)	1.40 (1.11, 1.70)	24.7 (22.1, 27.6)
105°-135°	11.59 (11.08,12.13)	1.41 (0.93, 1.82)	24.6 (20.1, 28.5)
135°-165°	13.04 (12.56,13.58)	1.39 (1.14, 1.61)	25.8 (23.5, 28.0)
165°-195°	15.65 (15.21,16.12)	1.45 (1.09, 1.81)	29.0 (25.9, 32.2)
195°-225°	17.65 (17.04,18.25)	1.62 (1.16, 2.01)	32.5 (28.4, 36.4)
225°-255°	18.19 (17.62,18.76)	1.76 (1.41, 2.14)	34.4 (30.9, 38.0)
255°-285°	17.41 (16.76,18.15)	1.82 (1.41, 2.21)	34.1 (30.1, 38.2)
285°-315°	15.99 (15.35,16.63)	1.82 (1.40, 2.20)	32.7 (29.2, 36.1)

Table A.8 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 8.

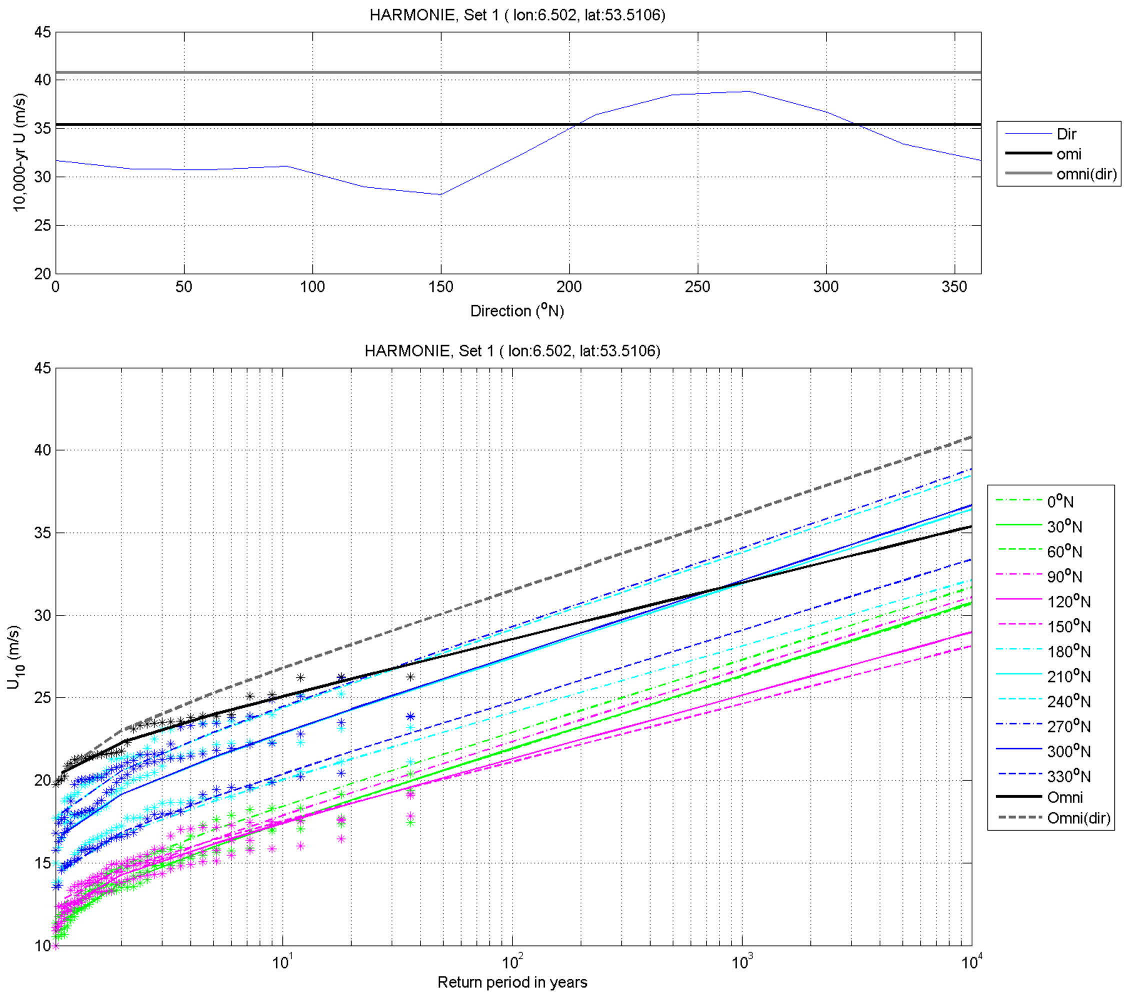


Figure A.9 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 9 (Wadden Sea east).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	22.26 (21.73,22.80)	2.01 (1.58, 2.44)	40.8 (37.2, 44.5)
Omni (AM fit)	21.74 (21.22,22.27)	1.48 (1.16, 1.79)	35.4 (32.3, 38.6)
345°-015°	14.13 (13.43,14.89)	1.91 (1.53, 2.29)	31.7 (27.7, 35.7)
015°-045°	13.10 (12.41,13.86)	1.92 (1.50, 2.30)	30.8 (26.9, 34.4)
045°-075°	13.11 (12.50,13.81)	1.91 (1.48, 2.35)	30.7 (26.6, 35.1)
075°-105°	13.60 (12.85,14.39)	1.90 (1.47, 2.29)	31.1 (27.0, 34.8)
105°-135°	13.66 (13.12,14.19)	1.66 (1.21, 2.08)	29.0 (25.0, 32.8)
135°-165°	14.11 (13.58,14.65)	1.52 (1.20, 1.82)	28.1 (25.1, 31.1)
165°-195°	16.11 (15.48,16.75)	1.74 (1.40, 2.08)	32.1 (28.9, 35.3)
195°-225°	18.46 (17.77,19.20)	1.95 (1.46, 2.39)	36.4 (31.9, 40.6)
225°-255°	19.83 (19.12,20.51)	2.03 (1.61, 2.42)	38.5 (34.5, 42.4)
255°-285°	19.82 (19.10,20.63)	2.07 (1.63, 2.48)	38.8 (34.8, 42.9)
285°-315°	18.43 (17.77,19.16)	1.98 (1.63, 2.33)	36.7 (33.3, 39.9)

Table A.9 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 9.

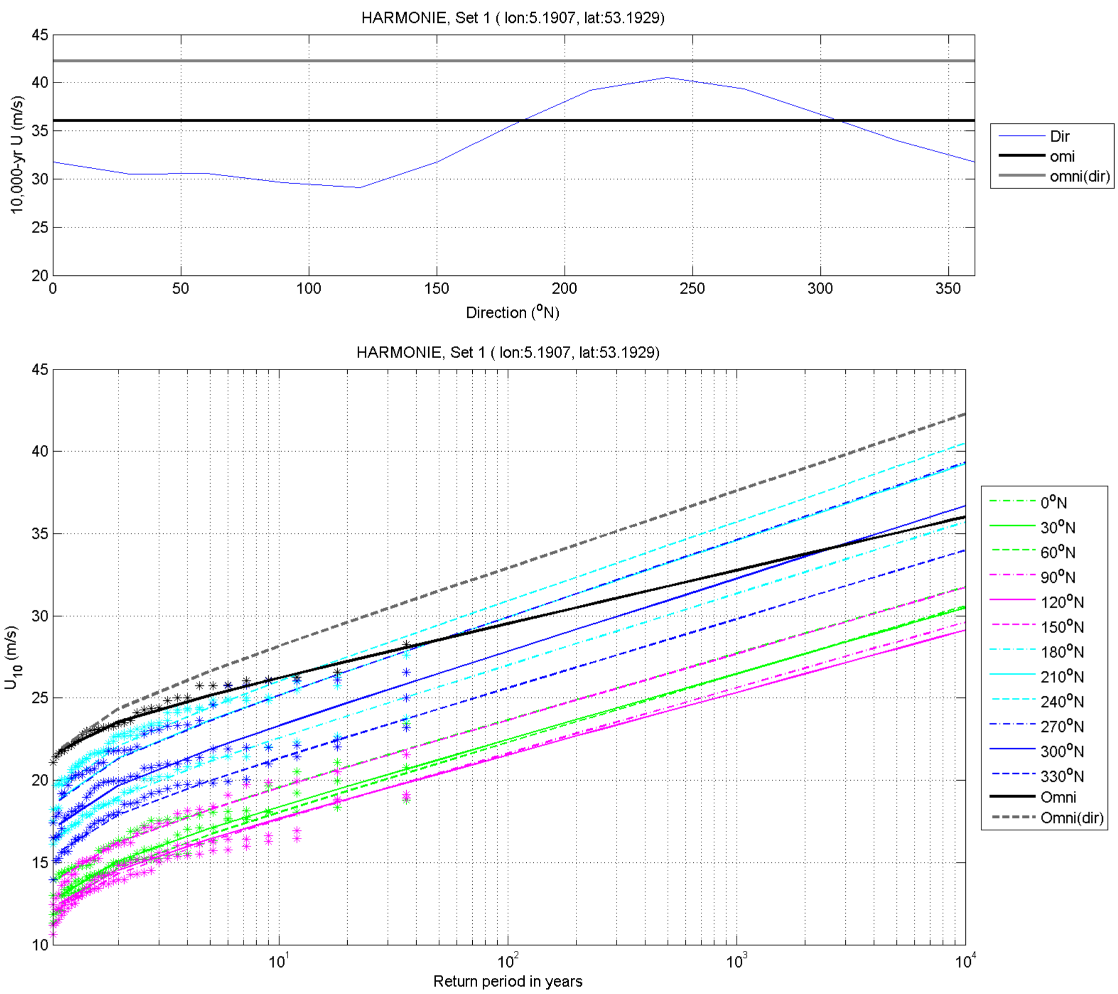


Figure A.10 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 10 (Wadden Sea west).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	23.59 (23.10,24.12)	2.03 (1.60, 2.47)	42.3 (38.8, 45.8)
Omni (AM fit)	23.04 (22.56,23.55)	1.41 (1.11, 1.72)	36.0 (33.0, 39.1)
345°-015°	15.60 (15.07,16.24)	1.75 (1.30, 2.21)	31.8 (27.4, 36.1)
015°-045°	14.47 (13.84,15.09)	1.74 (1.26, 2.11)	30.5 (26.3, 34.1)
045°-075°	14.00 (13.39,14.68)	1.80 (1.42, 2.22)	30.6 (26.8, 34.8)
075°-105°	13.70 (13.07,14.43)	1.73 (1.41, 2.04)	29.6 (26.4, 32.6)
105°-135°	13.95 (13.46,14.48)	1.65 (1.23, 2.07)	29.1 (25.5, 33.2)
135°-165°	15.59 (14.94,16.37)	1.75 (1.39, 2.11)	31.7 (27.9, 35.5)
165°-195°	18.30 (17.74,18.88)	1.89 (1.51, 2.31)	35.7 (32.2, 39.6)
195°-225°	20.63 (19.83,21.42)	2.02 (1.47, 2.46)	39.2 (34.3, 43.4)
225°-255°	21.33 (20.62,21.99)	2.08 (1.61, 2.56)	40.5 (36.4, 44.9)
255°-285°	20.56 (19.80,21.44)	2.04 (1.58, 2.47)	39.3 (35.0, 43.7)
285°-315°	18.99 (18.35,19.68)	1.92 (1.55, 2.24)	36.7 (33.5, 39.7)

Table A.10 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 10.

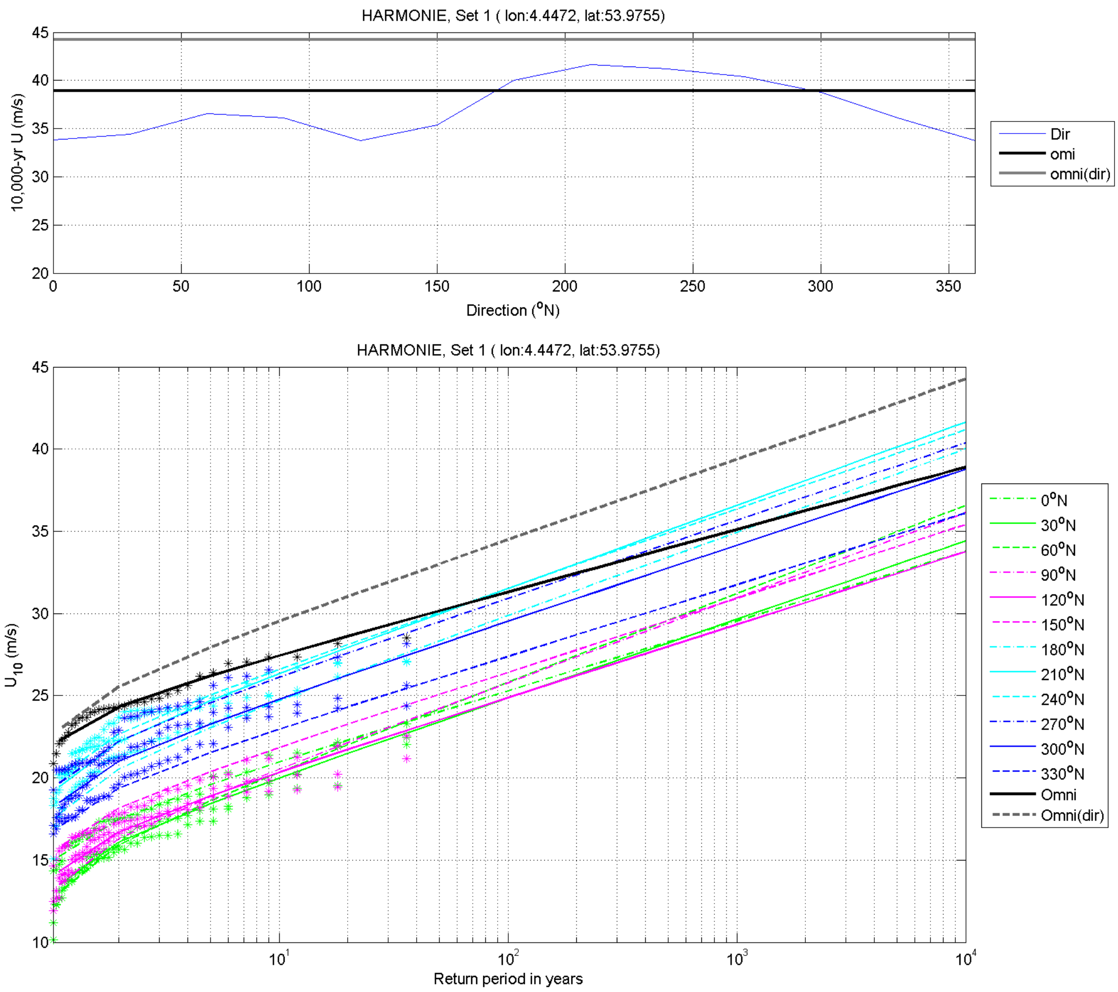


Figure A.11 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 11 (Northern part of the Dutch coast and dunes).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	24.74 (24.14,25.38)	2.12 (1.57, 2.62)	44.3 (39.7, 48.4)
Omni (AM fit)	23.71 (23.13,24.32)	1.65 (1.22, 2.04)	38.9 (34.9, 42.5)
345°-015°	16.82 (16.22,17.47)	1.84 (1.42, 2.24)	33.8 (30.0, 37.7)
015°-045°	15.31 (14.55,16.06)	2.07 (1.51, 2.62)	34.4 (29.2, 39.4)
045°-075°	15.08 (14.14,15.98)	2.33 (1.69, 2.95)	36.6 (30.5, 42.4)
075°-105°	15.47 (14.68,16.31)	2.24 (1.80, 2.62)	36.1 (32.1, 39.8)
105°-135°	16.00 (15.33,16.70)	1.93 (1.48, 2.34)	33.8 (29.7, 37.7)
135°-165°	17.46 (16.88,18.12)	1.95 (1.49, 2.38)	35.4 (31.1, 39.4)
165°-195°	19.73 (18.81,20.59)	2.20 (1.57, 2.76)	40.0 (33.9, 45.5)
195°-225°	21.38 (20.68,22.06)	2.20 (1.52, 2.67)	41.6 (35.9, 45.7)
225°-255°	21.90 (21.07,22.70)	2.09 (1.71, 2.44)	41.2 (37.7, 44.7)
255°-285°	21.48 (20.85,22.21)	2.05 (1.60, 2.51)	40.4 (35.9, 44.8)
285°-315°	20.27 (19.48,21.04)	2.01 (1.64, 2.38)	38.8 (34.9, 42.5)

Table A.11 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 11.

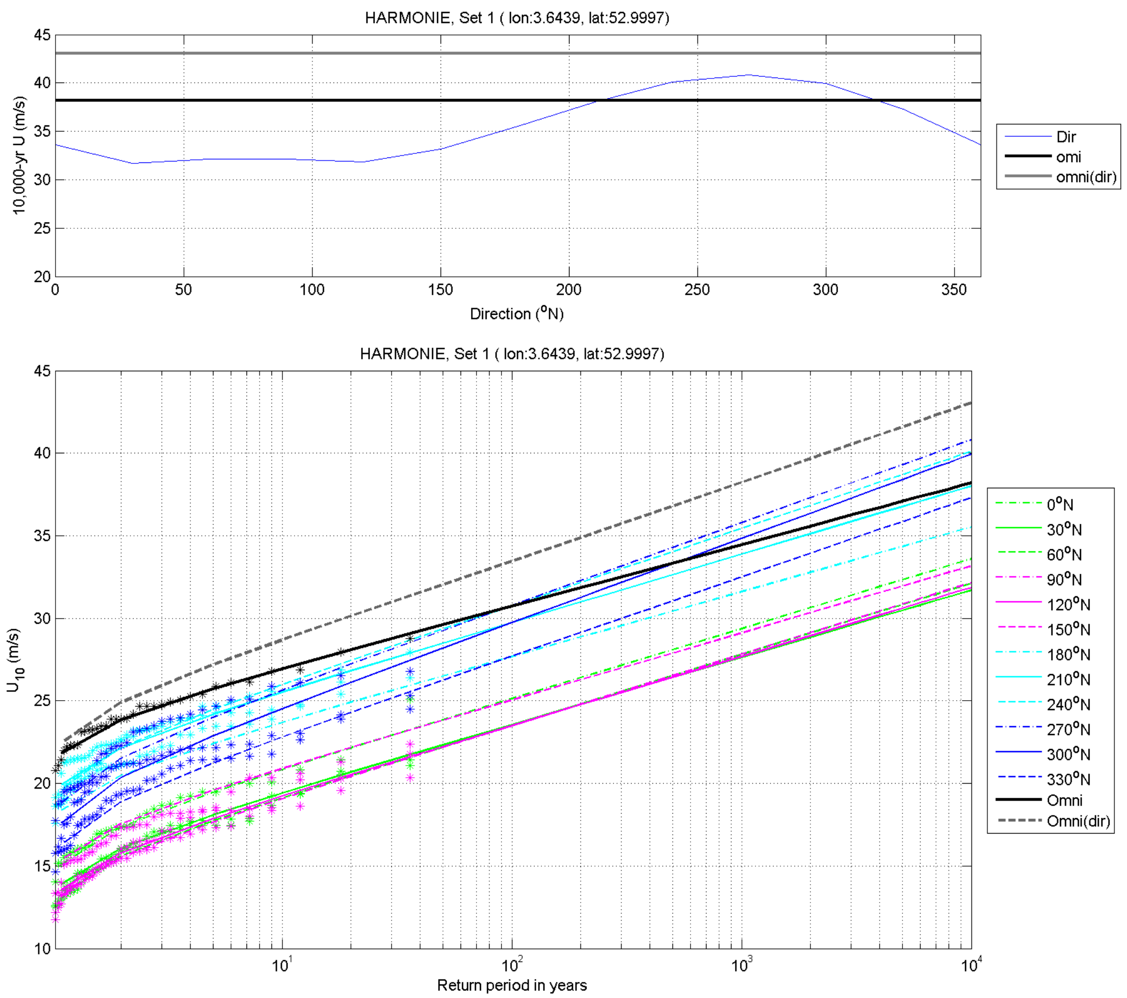


Figure A.12 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 12 (Central part of the Dutch coast).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	24.04 (23.46,24.68)	2.06 (1.59, 2.49)	43.0 (39.3, 46.9)
Omni (AM fit)	23.26 (22.70,23.88)	1.62 (1.25, 1.96)	38.2 (34.8, 41.6)
345°-015°	16.69 (16.15,17.31)	1.84 (1.37, 2.35)	33.6 (29.2, 38.3)
015°-045°	15.45 (14.84,16.07)	1.76 (1.38, 2.14)	31.7 (27.9, 35.4)
045°-075°	14.91 (14.23,15.67)	1.87 (1.48, 2.22)	32.1 (28.1, 35.8)
075°-105°	14.83 (14.16,15.55)	1.88 (1.48, 2.26)	32.2 (28.1, 36.0)
105°-135°	15.14 (14.58,15.79)	1.82 (1.39, 2.25)	31.9 (27.8, 36.1)
135°-165°	16.93 (16.23,17.70)	1.76 (1.32, 2.14)	33.2 (28.8, 36.9)
165°-195°	19.86 (19.30,20.46)	1.70 (1.33, 2.10)	35.5 (32.2, 39.2)
195°-225°	21.49 (20.88,22.09)	1.79 (1.22, 2.23)	38.0 (33.0, 41.9)
225°-255°	21.43 (20.67,22.18)	2.03 (1.57, 2.48)	40.1 (35.9, 44.5)
255°-285°	20.75 (19.97,21.62)	2.18 (1.78, 2.58)	40.8 (36.7, 44.7)
285°-315°	19.54 (18.68,20.41)	2.21 (1.72, 2.61)	39.9 (35.7, 43.6)

Table A.12 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 12.

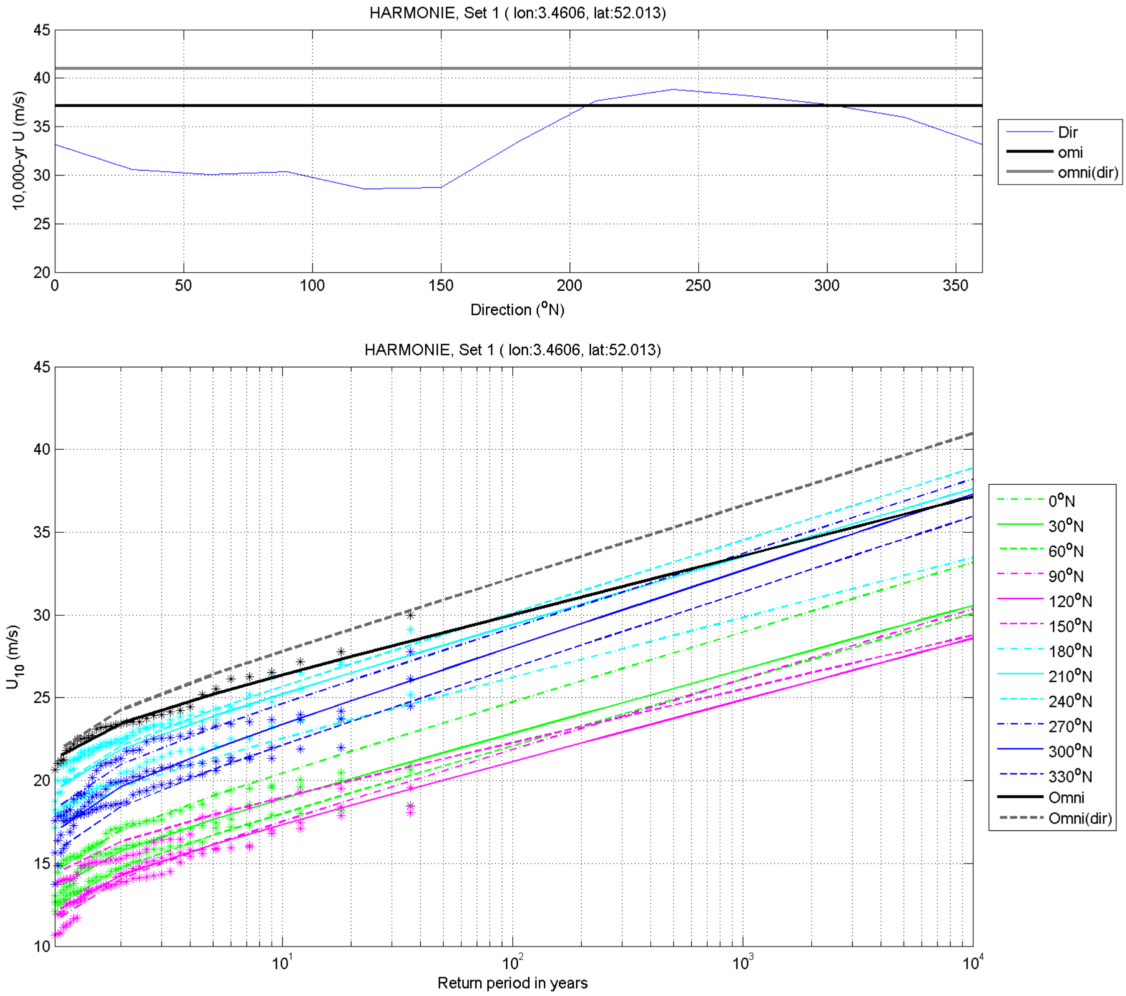


Figure A.13 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 13 (Southern part of the Dutch coast).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	23.53 (23.00,24.13)	1.89 (1.44, 2.39)	41.0 (37.1, 45.3)
Omni (AM fit)	22.88 (22.37,23.47)	1.55 (1.18, 1.95)	37.1 (33.6, 41.0)
345°-015°	16.34 (15.79,16.93)	1.83 (1.35, 2.28)	33.2 (29.0, 37.2)
015°-045°	15.13 (14.56,15.74)	1.68 (1.32, 2.01)	30.6 (27.2, 34.0)
045°-075°	14.10 (13.58,14.70)	1.74 (1.38, 2.09)	30.1 (26.8, 33.4)
075°-105°	13.38 (12.54,14.20)	1.84 (1.44, 2.24)	30.4 (26.4, 34.1)
105°-135°	13.70 (13.18,14.26)	1.62 (1.18, 2.05)	28.6 (24.8, 32.6)
135°-165°	15.80 (15.38,16.33)	1.41 (1.05, 1.81)	28.8 (25.3, 32.8)
165°-195°	19.00 (18.47,19.56)	1.57 (1.20, 1.95)	33.5 (29.8, 37.2)
195°-225°	21.21 (20.54,21.86)	1.78 (1.39, 2.17)	37.6 (34.0, 41.3)
225°-255°	21.40 (20.75,22.04)	1.90 (1.24, 2.51)	38.9 (33.1, 44.4)
255°-285°	20.25 (19.54,21.02)	1.95 (1.64, 2.29)	38.2 (35.0, 41.6)
285°-315°	18.90 (18.25,19.57)	2.00 (1.54, 2.44)	37.3 (33.3, 41.3)

Table A.13 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 13.

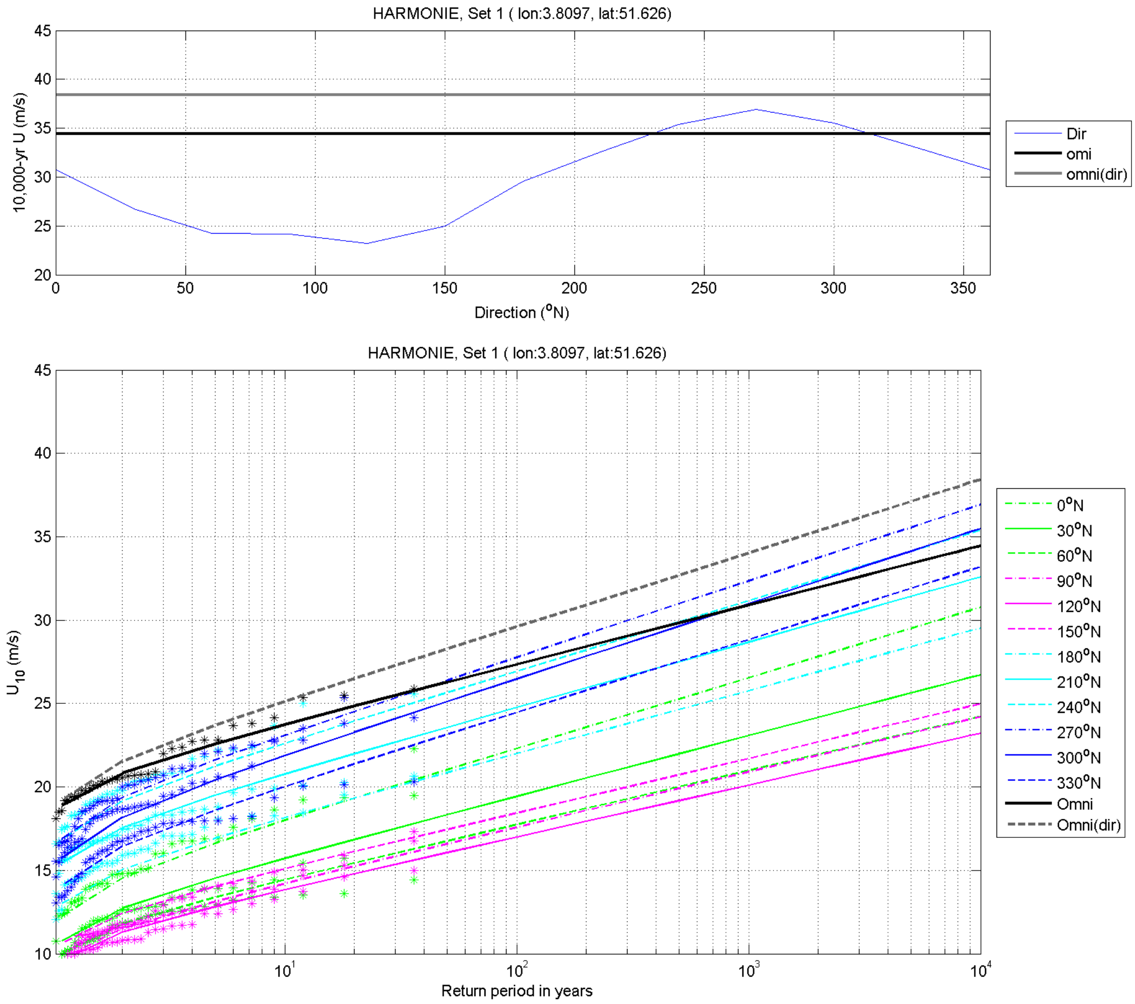


Figure A.14 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 14 (Eastern Scheldt).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	20.80 (20.28,21.35)	1.91 (1.40, 2.41)	38.4 (33.9, 42.9)
Omni (AM fit)	20.24 (19.74,20.79)	1.54 (1.13, 1.95)	34.5 (30.4, 38.5)
345°-015°	13.87 (13.25,14.52)	1.83 (1.40, 2.28)	30.8 (26.6, 35.2)
015°-045°	12.15 (11.58,12.78)	1.58 (1.22, 2.08)	26.7 (23.1, 31.6)
045°-075°	11.26 (10.88,11.69)	1.41 (1.16, 1.67)	24.2 (22.0, 26.5)
075°-105°	10.97 (10.39,11.60)	1.44 (1.09, 1.74)	24.2 (20.8, 27.4)
105°-135°	10.79 (10.39,11.27)	1.35 (1.01, 1.71)	23.2 (20.2, 26.4)
135°-165°	11.90 (11.42,12.40)	1.42 (1.09, 1.81)	25.0 (21.7, 28.9)
165°-195°	14.47 (13.85,15.12)	1.63 (1.20, 2.01)	29.5 (25.6, 33.2)
195°-225°	16.94 (16.36,17.49)	1.70 (1.18, 2.18)	32.6 (28.2, 36.8)
225°-255°	18.48 (17.85,19.16)	1.84 (1.41, 2.27)	35.4 (31.3, 39.5)
255°-285°	18.63 (17.93,19.37)	1.99 (1.57, 2.41)	36.9 (33.0, 41.2)
285°-315°	17.47 (16.85,18.17)	1.96 (1.53, 2.40)	35.5 (31.5, 39.5)

Table A.14 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 14.

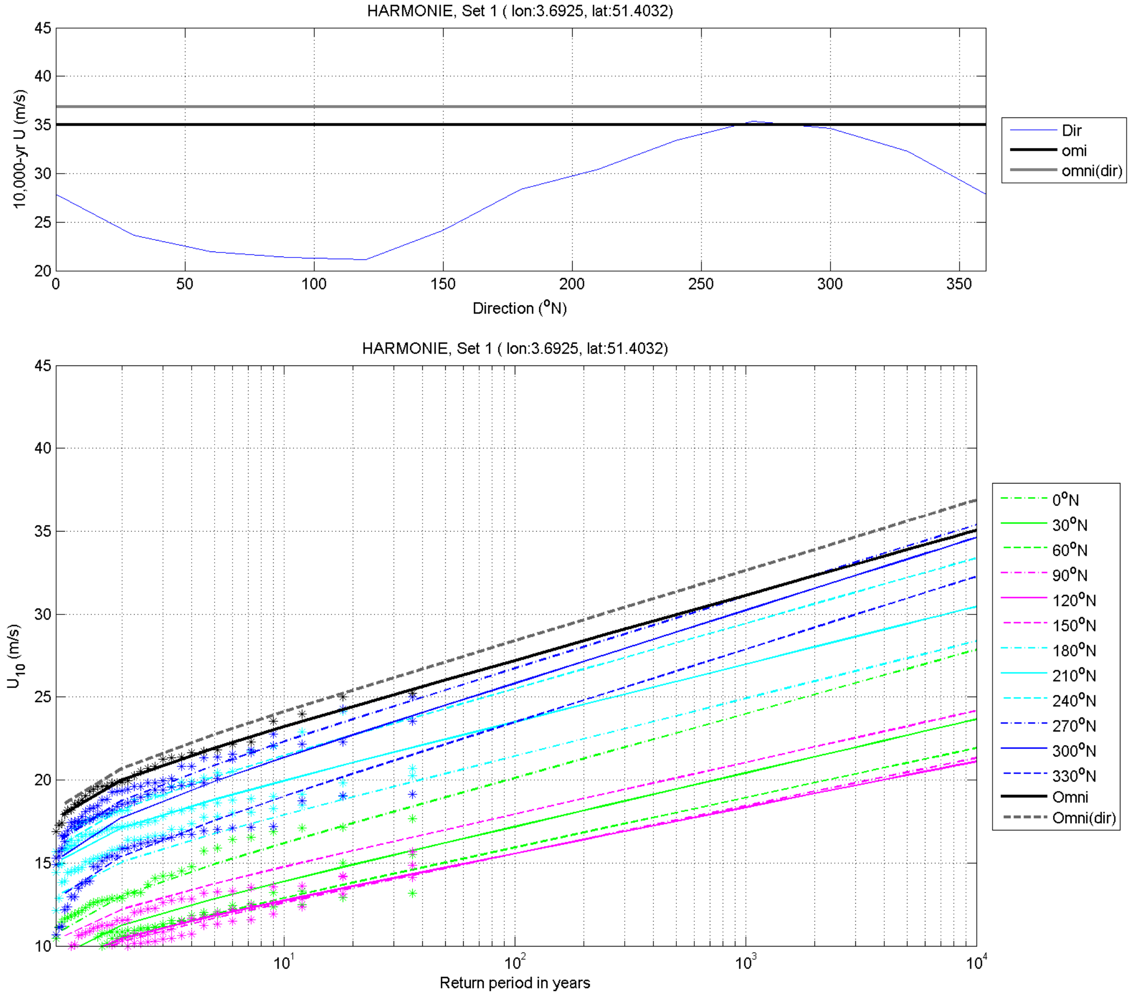


Figure A.15 Top panel: Omni-directional and directional 10,000-yr return value estimates. Bottom panel: Return value plot for the directional estimates, the omni-directional estimates (black) and the omni-directional estimate based on the directional estimates (grey). The annual maxima data are represented by the asterisks. Location 15 (Western Scheldt).

Sector	μ (m/s)	σ (-)	10,000-yr value (m/s)
Omni (Eq. (3.5))	19.97 (19.38,20.60)	1.84 (1.42, 2.25)	36.9 (33.1, 40.9)
Omni (AM fit)	19.37 (18.80,19.98)	1.70 (1.32, 2.08)	35.0 (31.4, 38.8)
345°-015°	12.43 (11.94,12.96)	1.67 (1.26, 2.09)	27.9 (24.0, 31.8)
015°-045°	10.72 (10.19,11.34)	1.40 (1.10, 1.71)	23.7 (20.7, 26.8)
045°-075°	9.96 (9.55,10.38)	1.30 (1.03, 1.54)	21.9 (19.5, 24.2)
075°-105°	9.79 (9.30,10.32)	1.25 (0.97, 1.55)	21.3 (18.4, 24.4)
105°-135°	10.03 (9.65,10.42)	1.20 (0.81, 1.55)	21.1 (17.8, 24.2)
135°-165°	11.72 (11.24,12.25)	1.35 (1.10, 1.61)	24.2 (21.7, 26.7)
165°-195°	14.52 (13.95,15.09)	1.50 (1.08, 1.88)	28.4 (24.5, 32.0)
195°-225°	16.56 (16.08,17.02)	1.51 (1.11, 1.83)	30.5 (27.3, 33.3)
225°-255°	17.63 (17.05,18.29)	1.71 (1.32, 2.13)	33.4 (29.5, 37.7)
255°-285°	18.09 (17.41,18.82)	1.88 (1.40, 2.31)	35.4 (31.0, 39.7)
285°-315°	17.06 (16.54,17.64)	1.91 (1.48, 2.33)	34.6 (30.9, 38.4)

Table A.15 Directional and omni-directional Gumbel parameters and 10,000-yr wind speed estimates for location 15.

A.2 Monthly percentages of the annual maxima

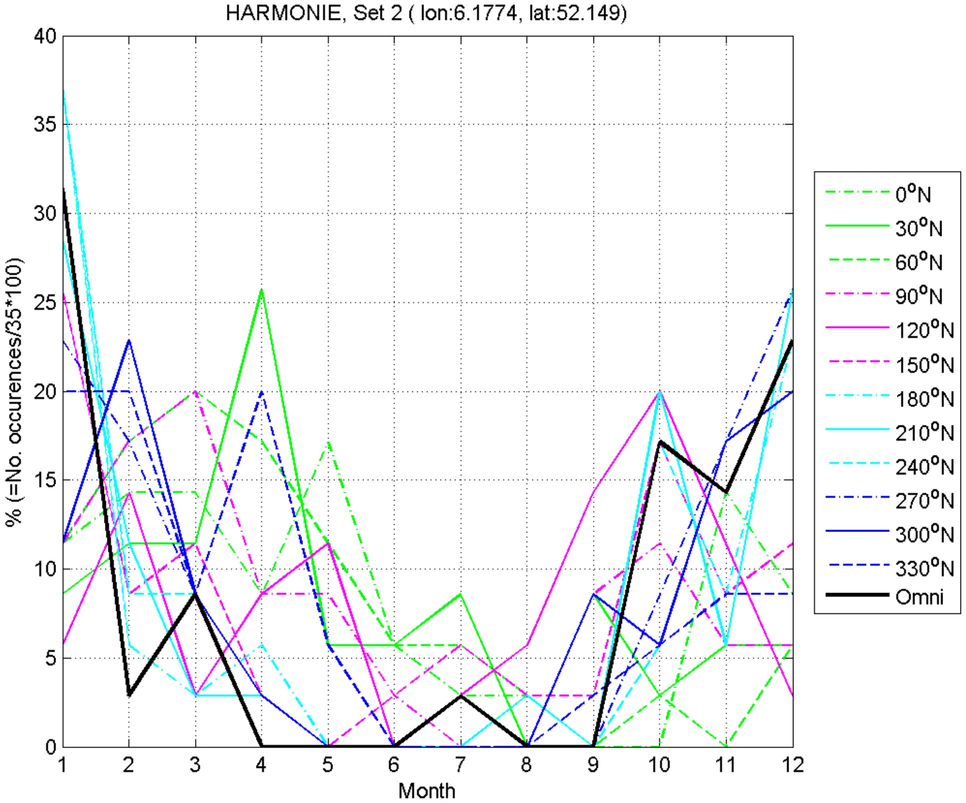


Figure A.16 Monthly percentages of the directional and omni-directional annual maxima of location 1.

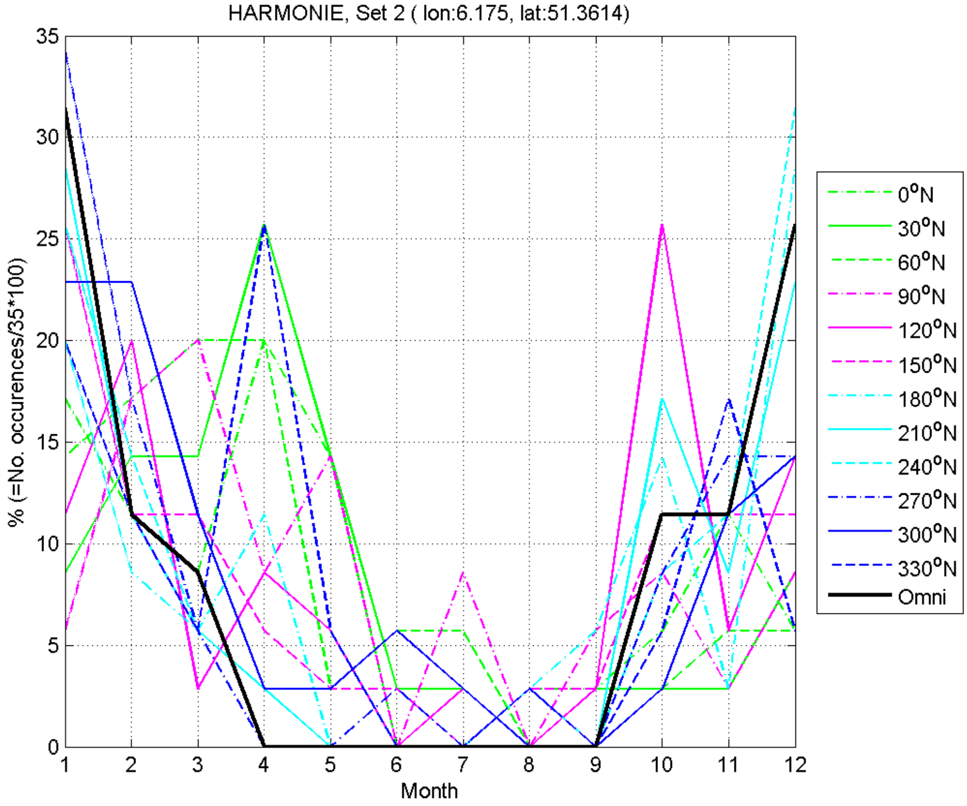


Figure A.17 *Monthly percentages of the directional and omni-directional annual maxima of location 2.*

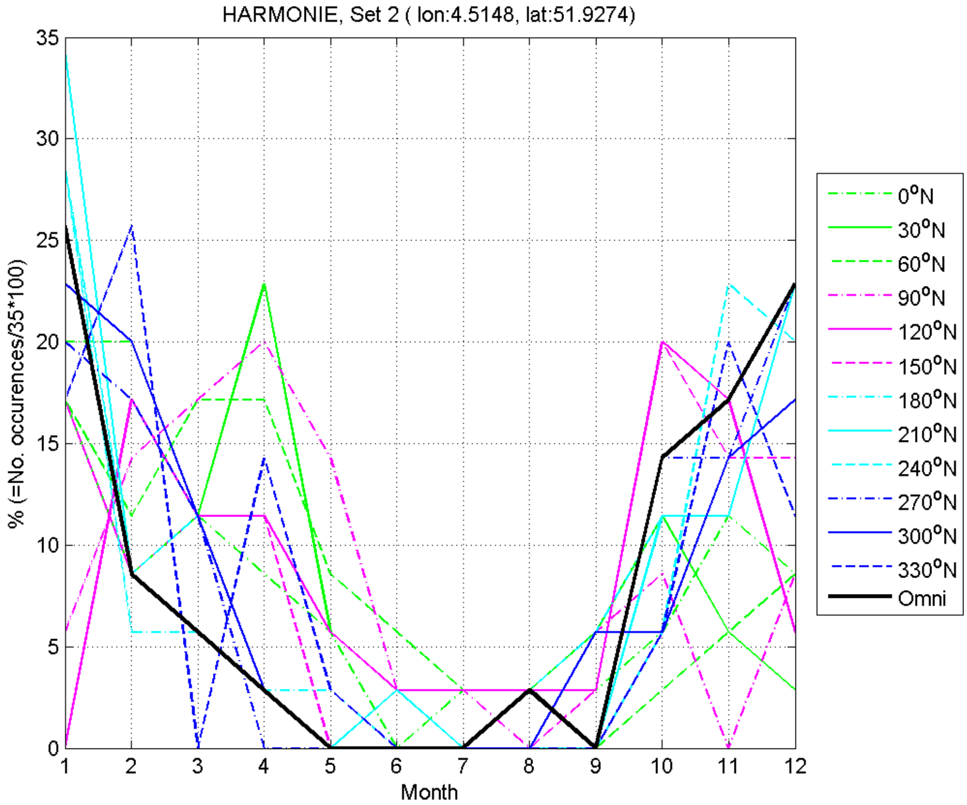


Figure A.18 *Monthly percentages of the directional and omni-directional annual maxima of location 3.*

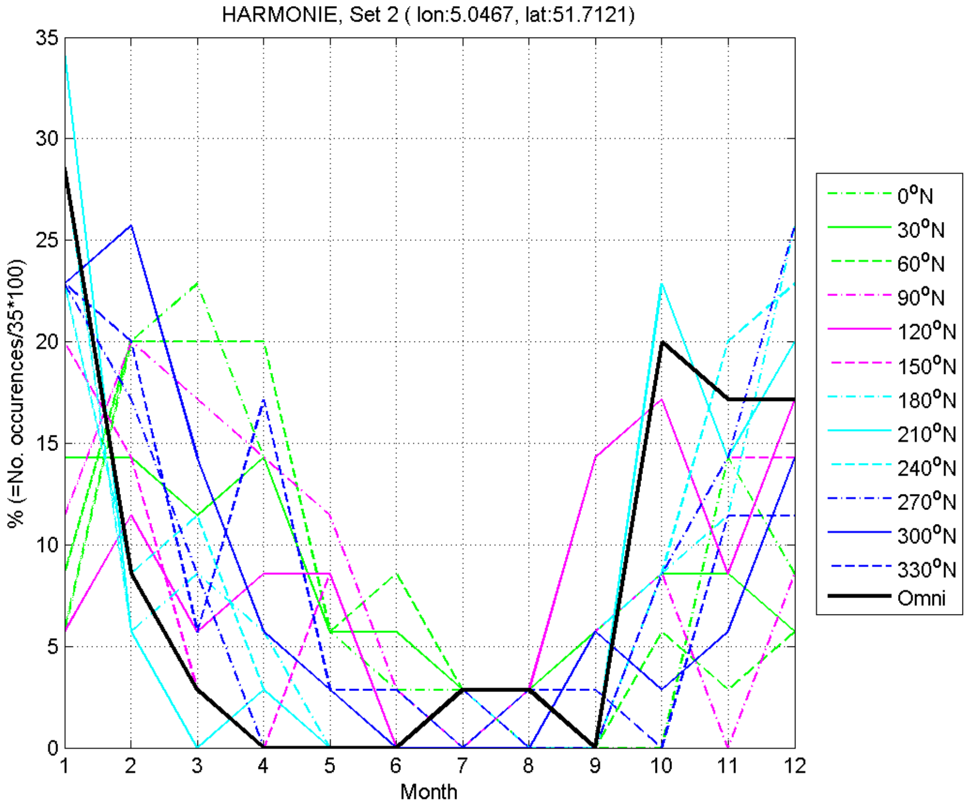


Figure A.19 *Monthly percentages of the directional and omni-directional annual maxima of location 4.*

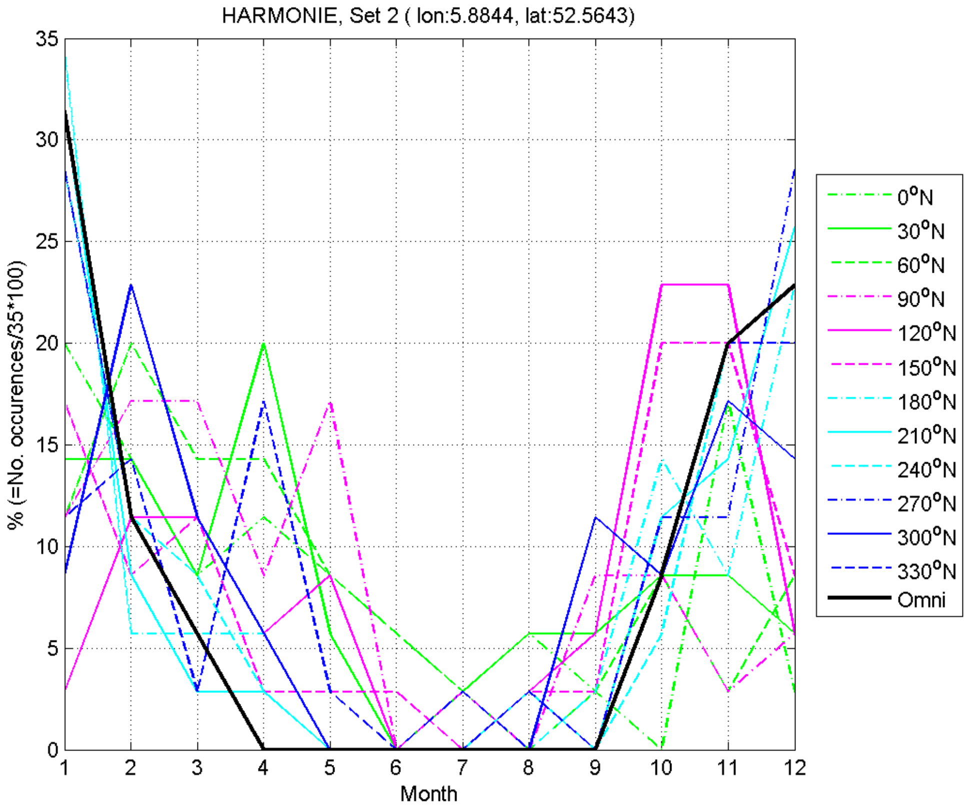


Figure A.20 *Monthly percentages of the directional and omni-directional annual maxima of location 5.*

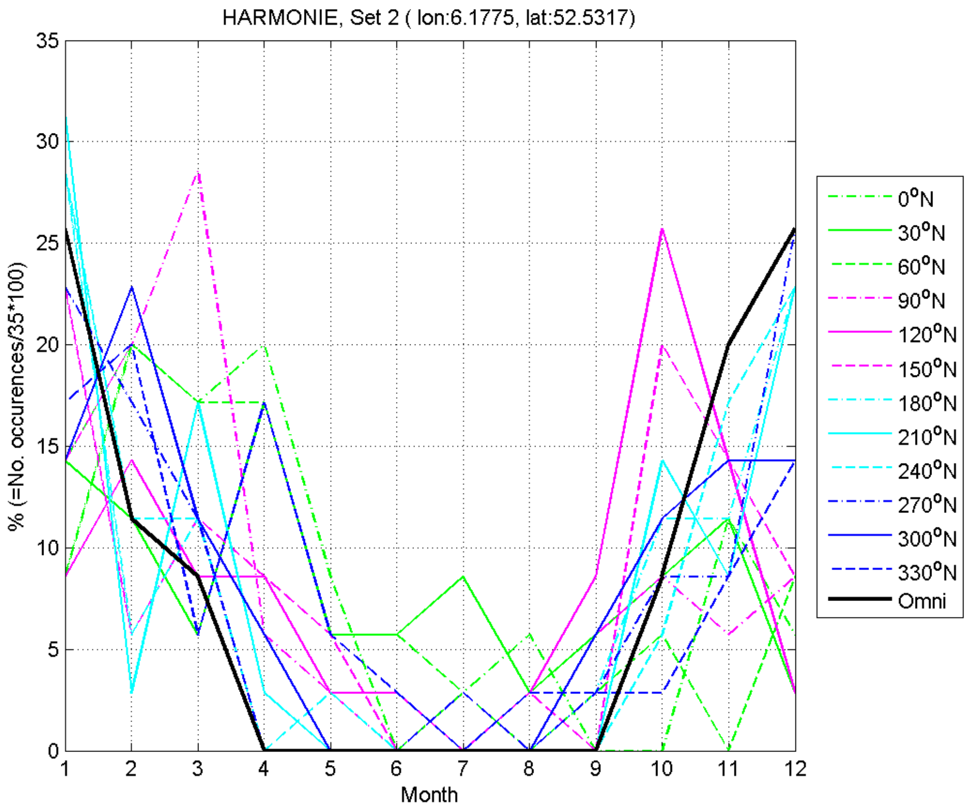


Figure A.21 *Monthly percentages of the directional and omni-directional annual maxima of location 6.*

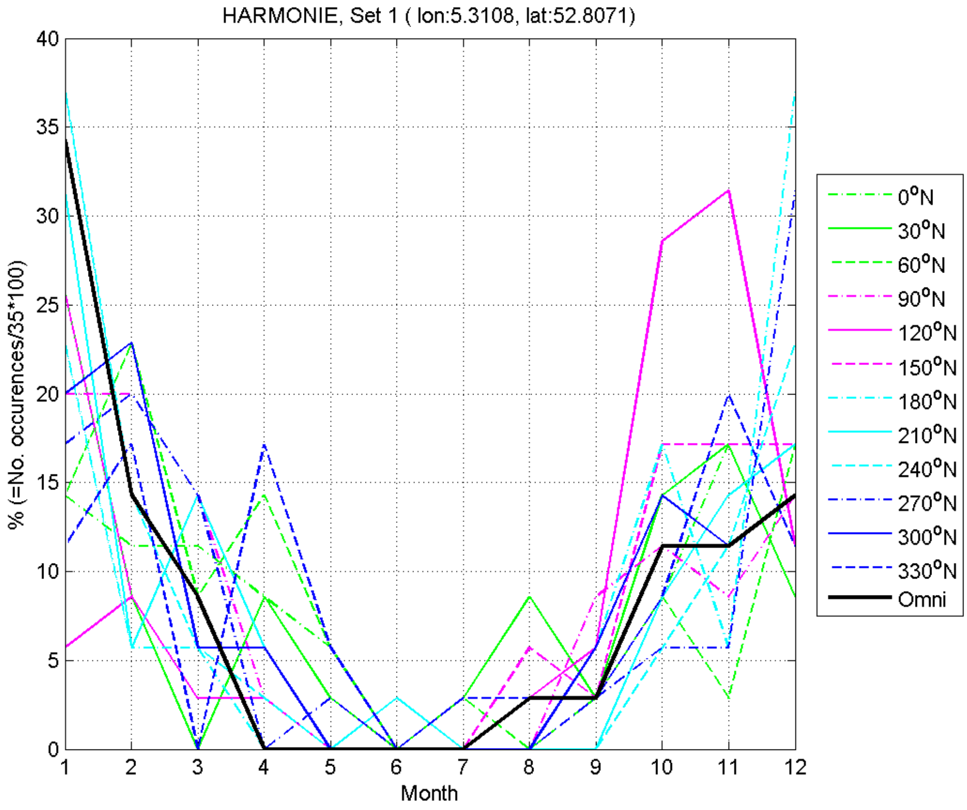


Figure A.22 *Monthly percentages of the directional and omni-directional annual maxima of location 7.*

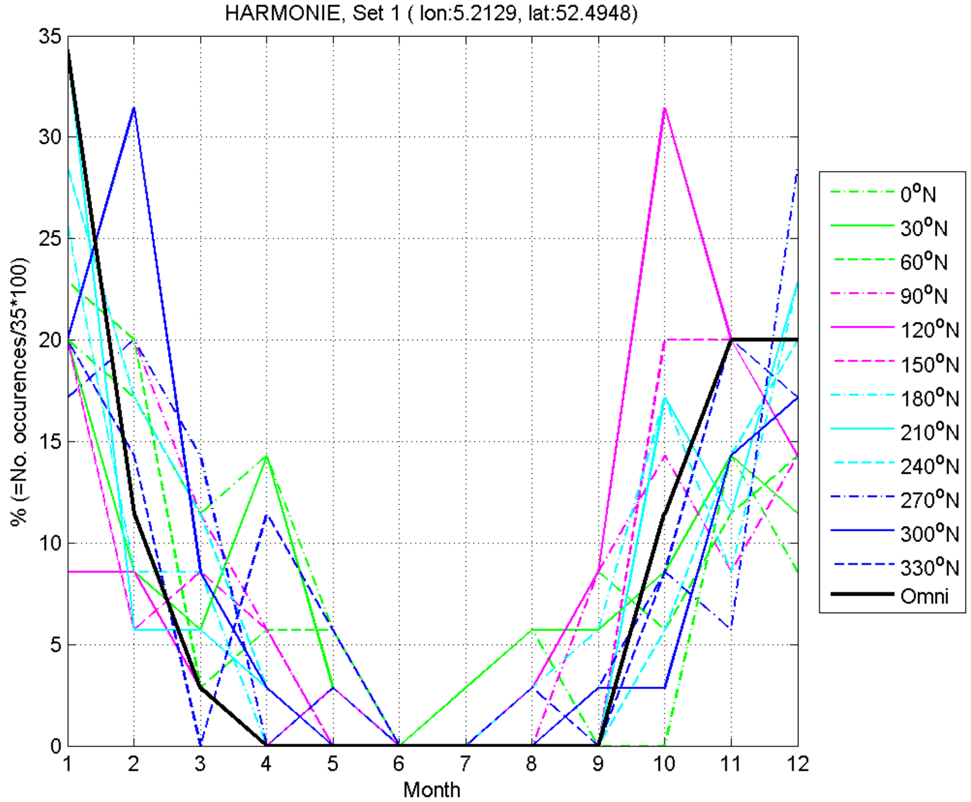


Figure A.23 *Monthly percentages of the directional and omni-directional annual maxima of location 8.*

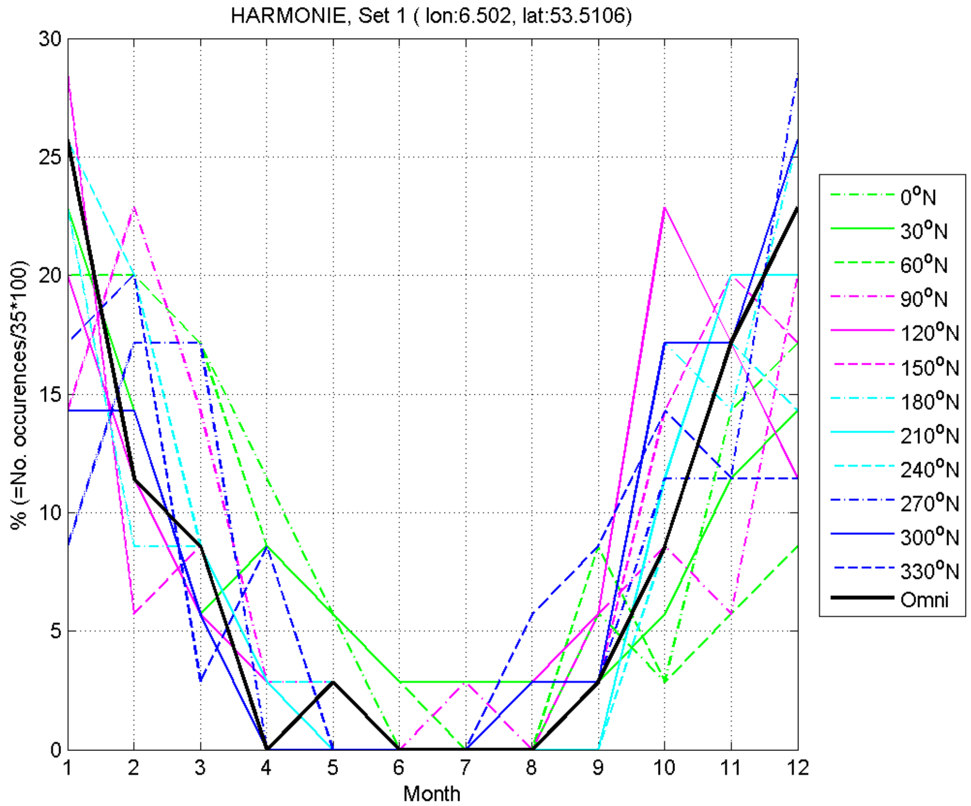


Figure A.24 *Monthly percentages of the directional and omni-directional annual maxima of location 9*

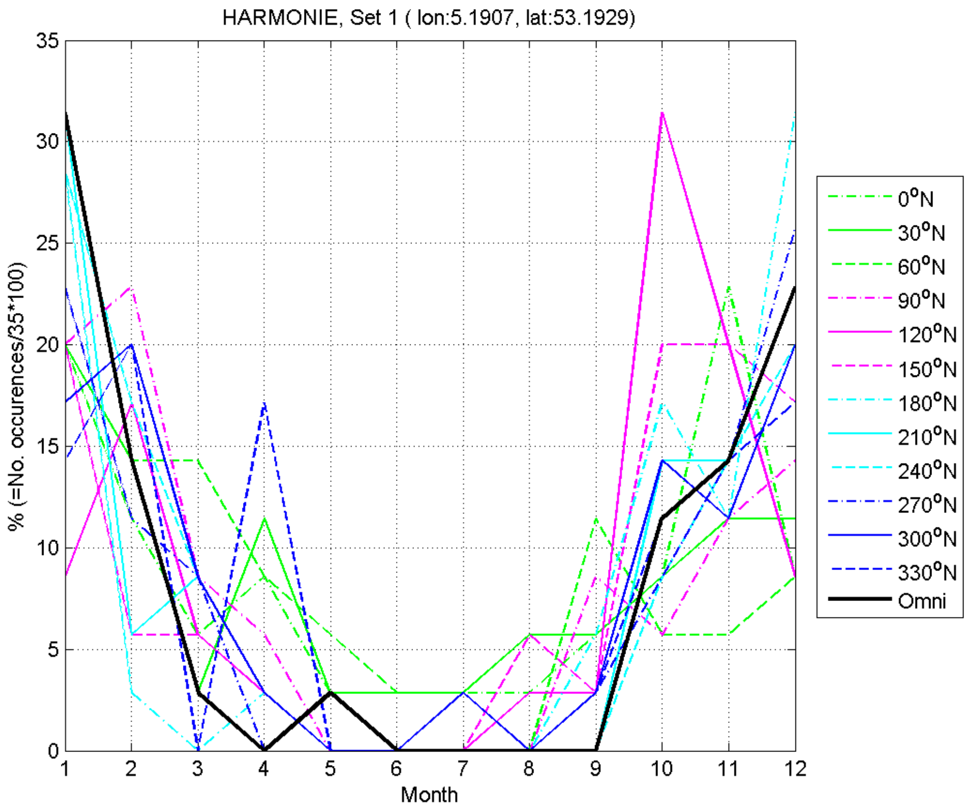


Figure A.25 *Monthly percentages of the directional and omni-directional annual maxima of location 10.*

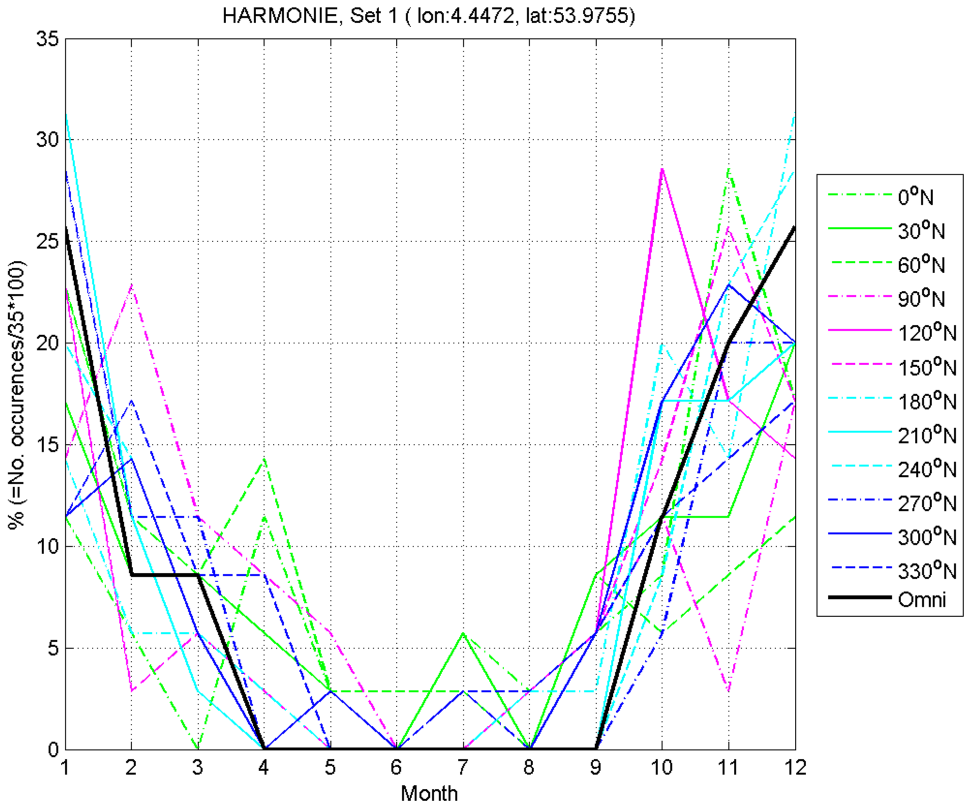


Figure A.26 *Monthly percentages of the directional and omni-directional annual maxima of location 11.*

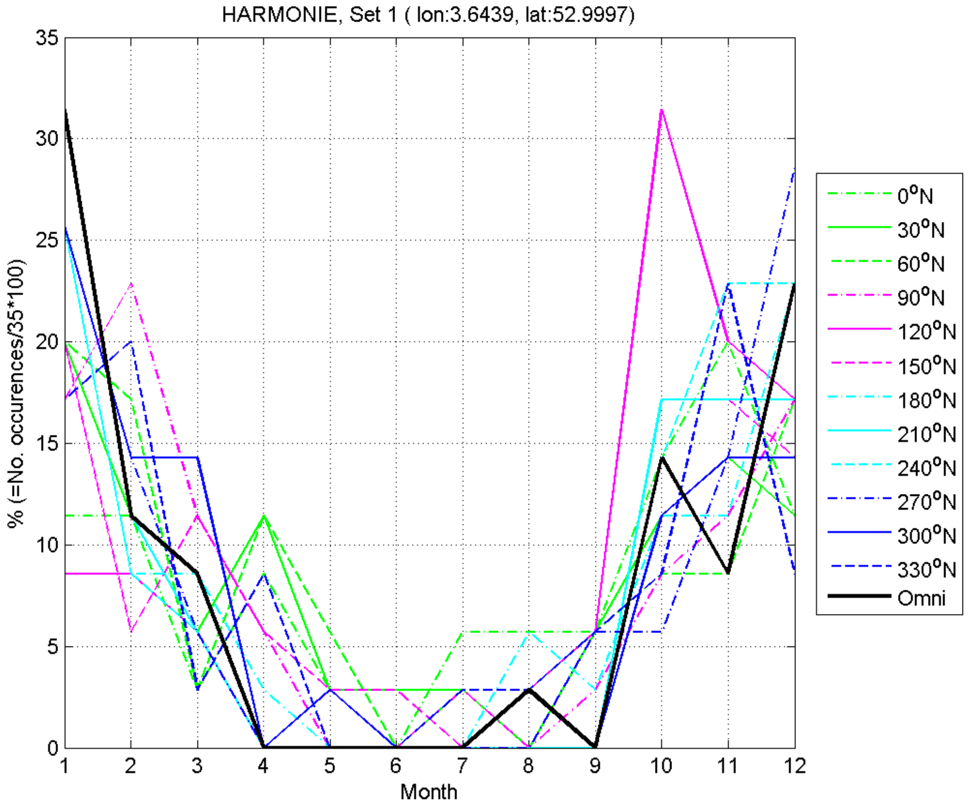


Figure A.27 *Monthly percentages of the directional and omni-directional annual maxima of location 12.*

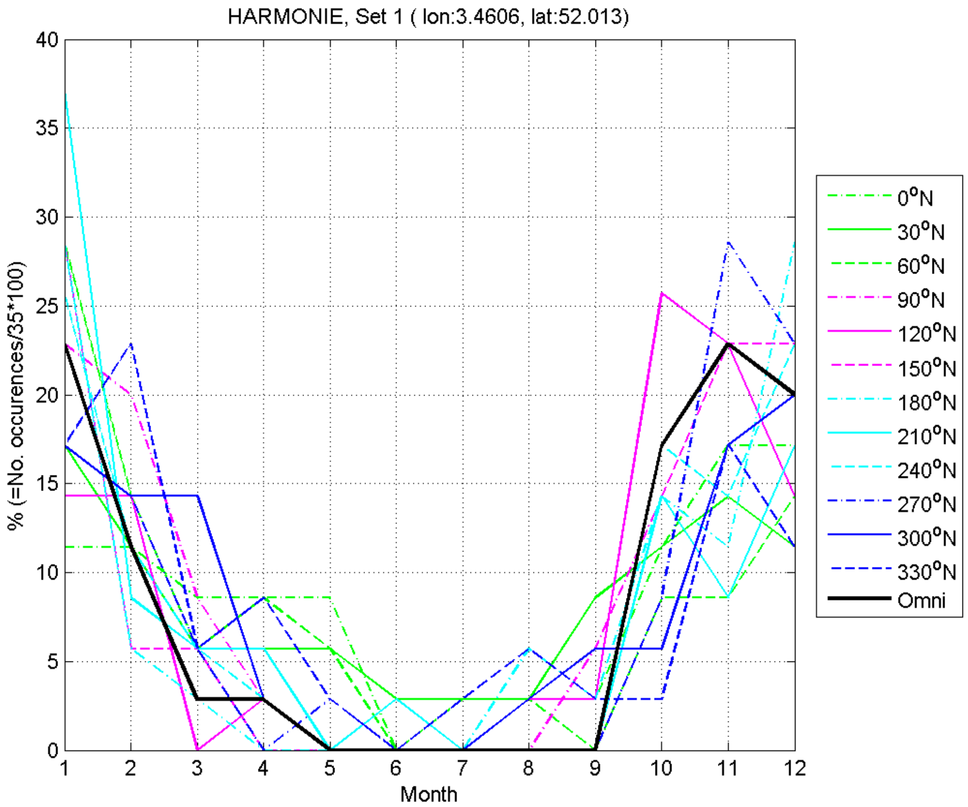


Figure A.28 *Monthly percentages of the directional and omni-directional annual maxima of location 13.*

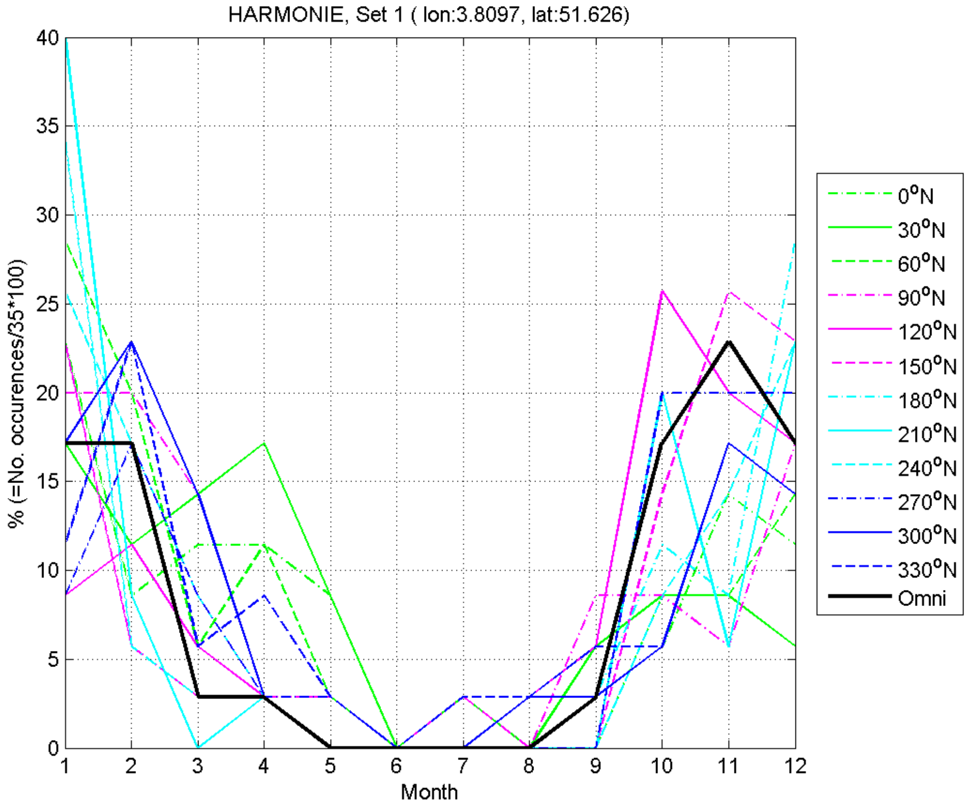


Figure A.29 Monthly percentages of the directional and omni-directional annual maxima of location 14.

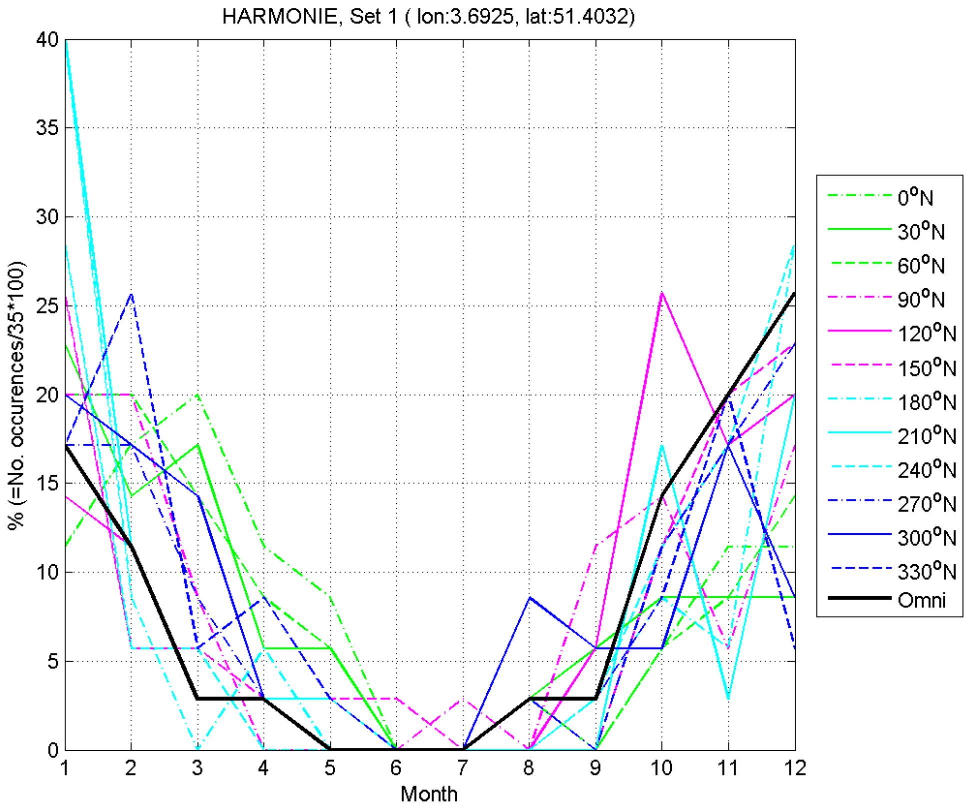


Figure A.30 Monthly percentages of the directional and omni-directional annual maxima of location 15.

B Spatial 10,000-yr return values estimates

Here we present the omni-directional (compound) wind speed estimates of the 10,000-yr wind speeds, based on Eq. (3.5), as well as the directional wind speed estimates. As Eq. (3.5) tends to over-estimations, the omni-directional 10,000-yr return value estimates are for indicative purposes only. The first set of figures shows all considered locations. The second set is a zoom into the Dutch water systems of the figures in the first set.

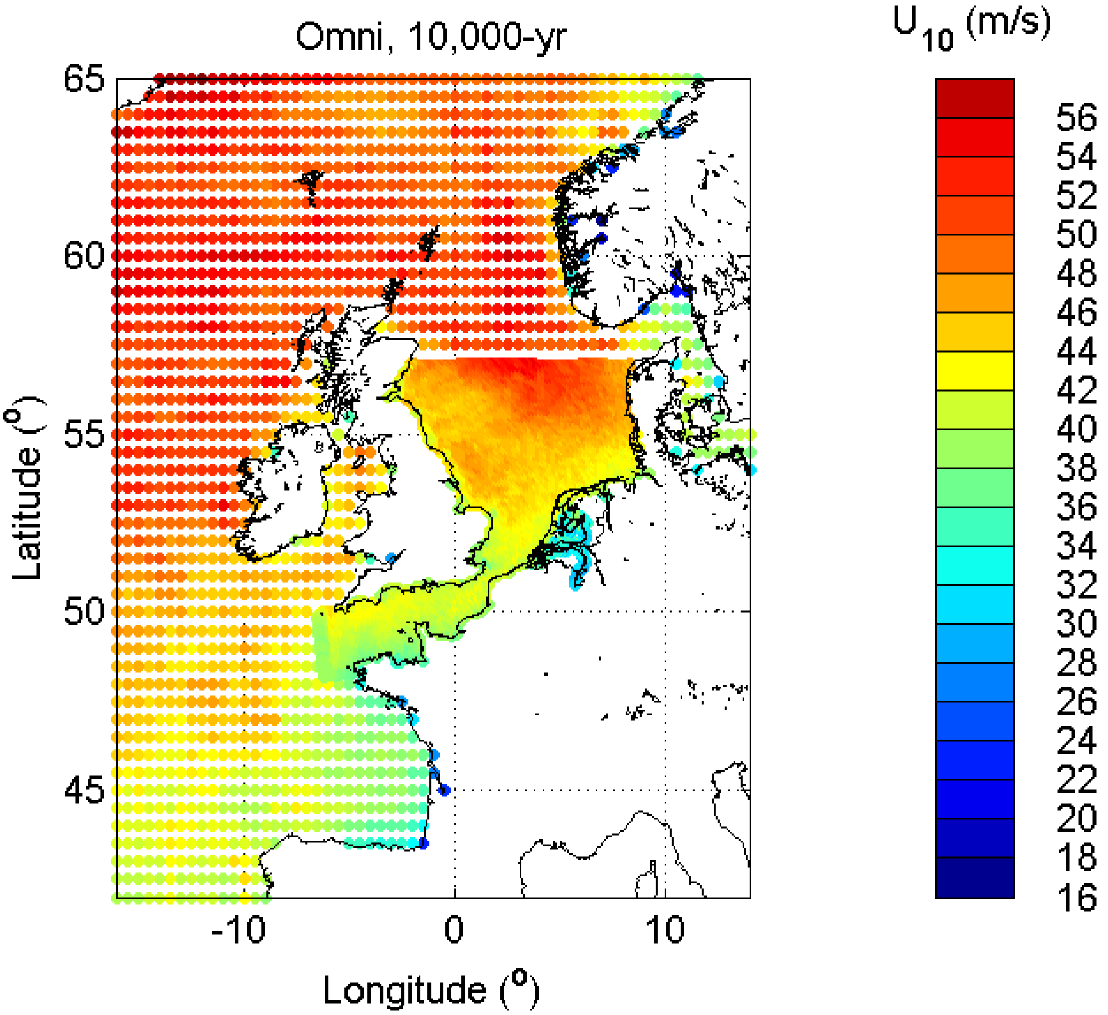


Figure B.1B.2 Omni-directional 10,000-yr return value estimates of the wind speed. These compound omni-directional estimates are based on the directional wind speeds according to Eq. (3.5).

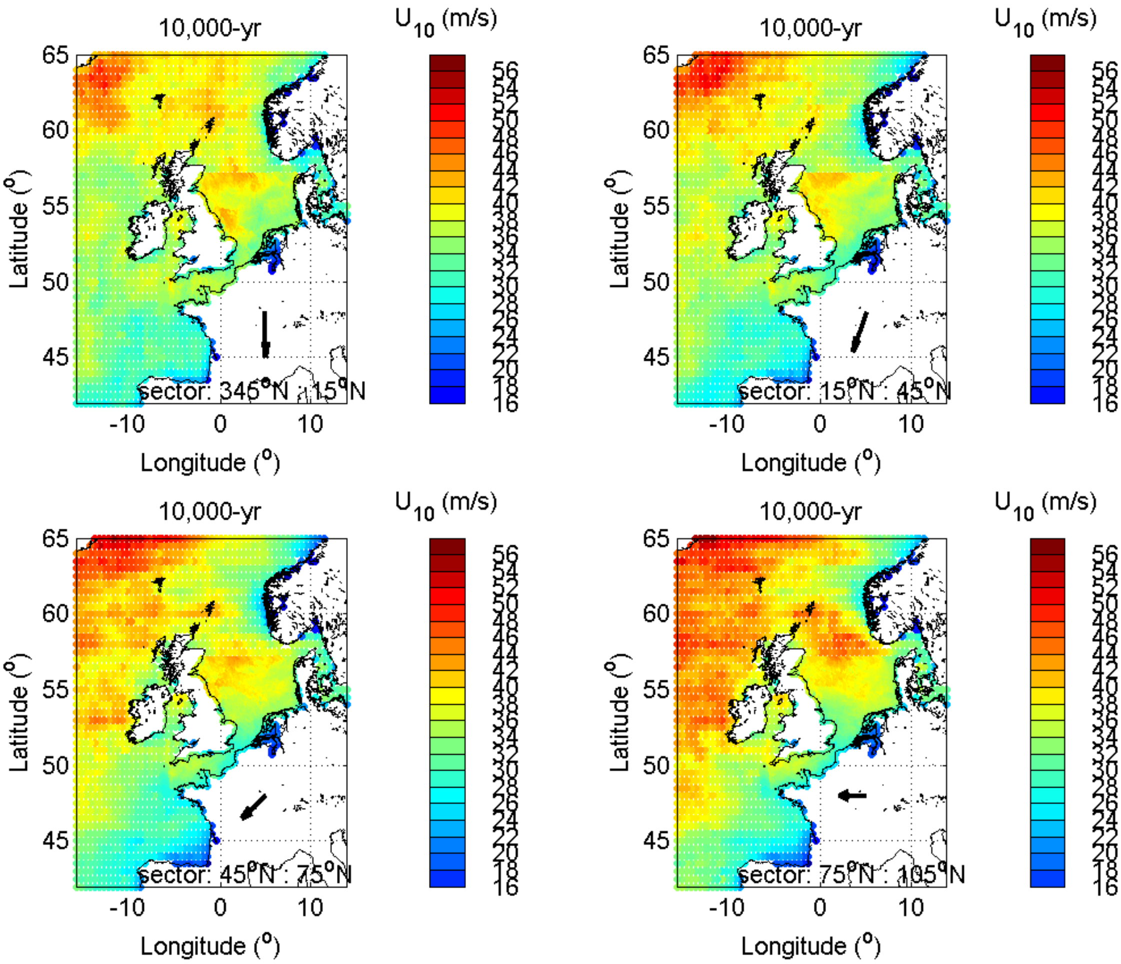


Figure B.3B.4 10,000-yr return value estimates for the 0, 30, 60 and 90 degrees directional wind. The wind directions are indicated with the black arrows.

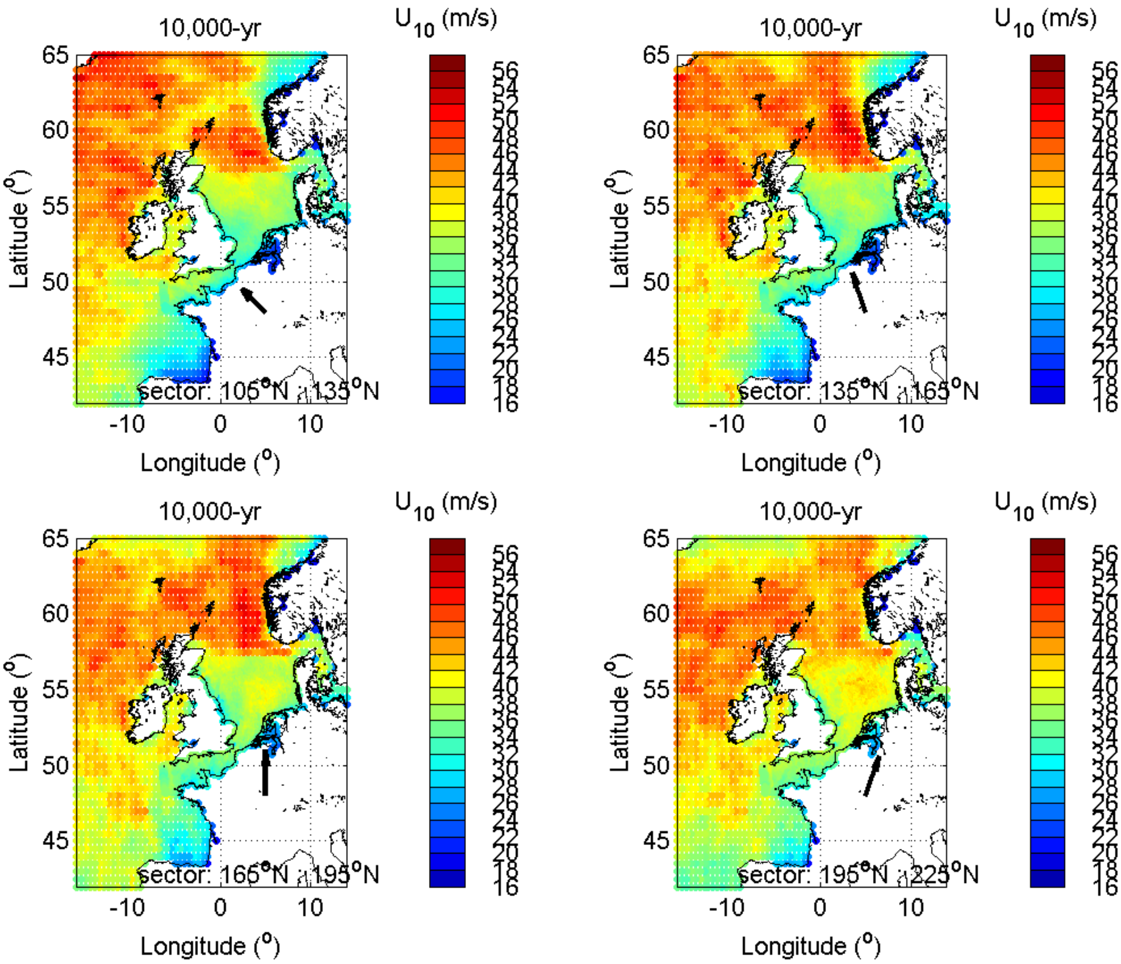


Figure B.5B.6 *10,000-yr return value estimates for the 120, 150, 180 and 210 degrees directional wind. The wind directions are indicated with the black arrows.*

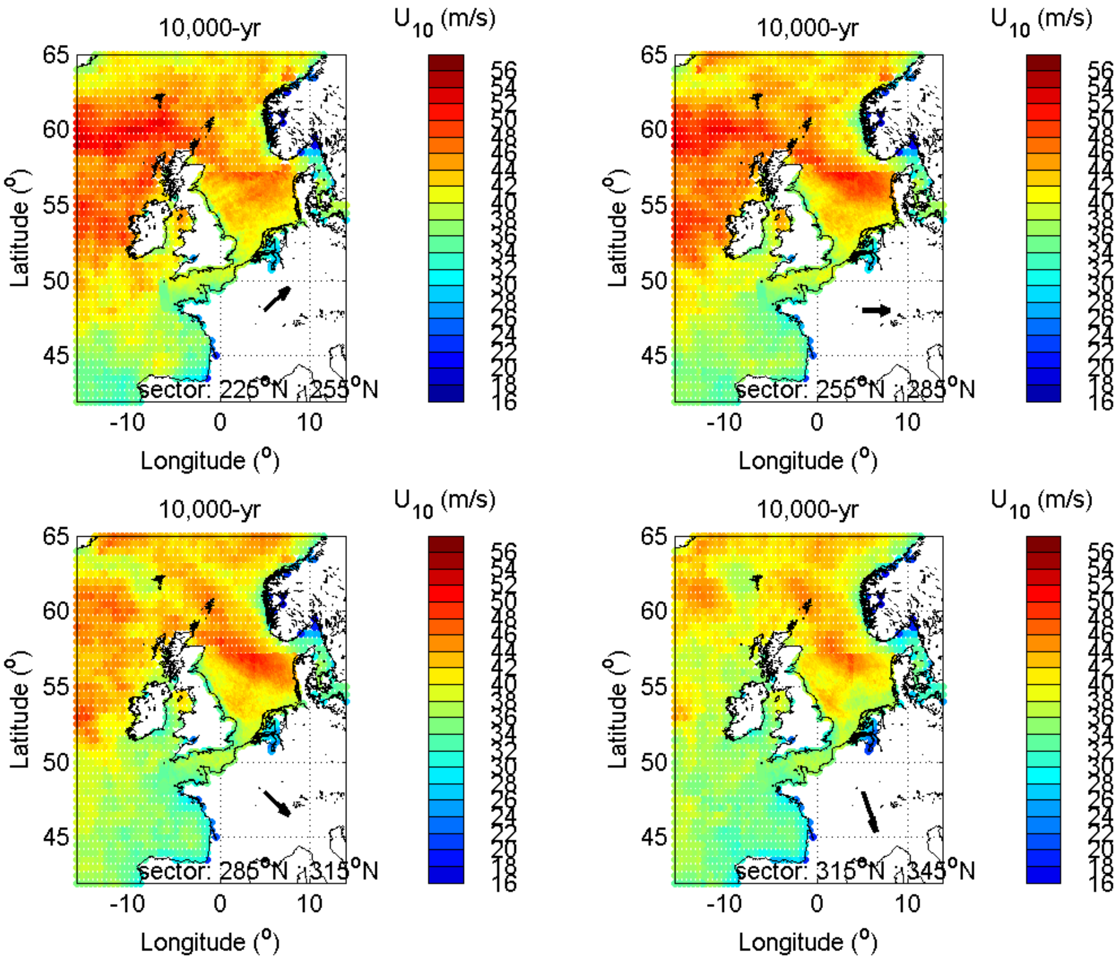


Figure B.7B.8 *10000-yr return value estimates for the 240, 270, 300 and 330 degrees directional wind. The wind directions are indicated with the black arrows.*

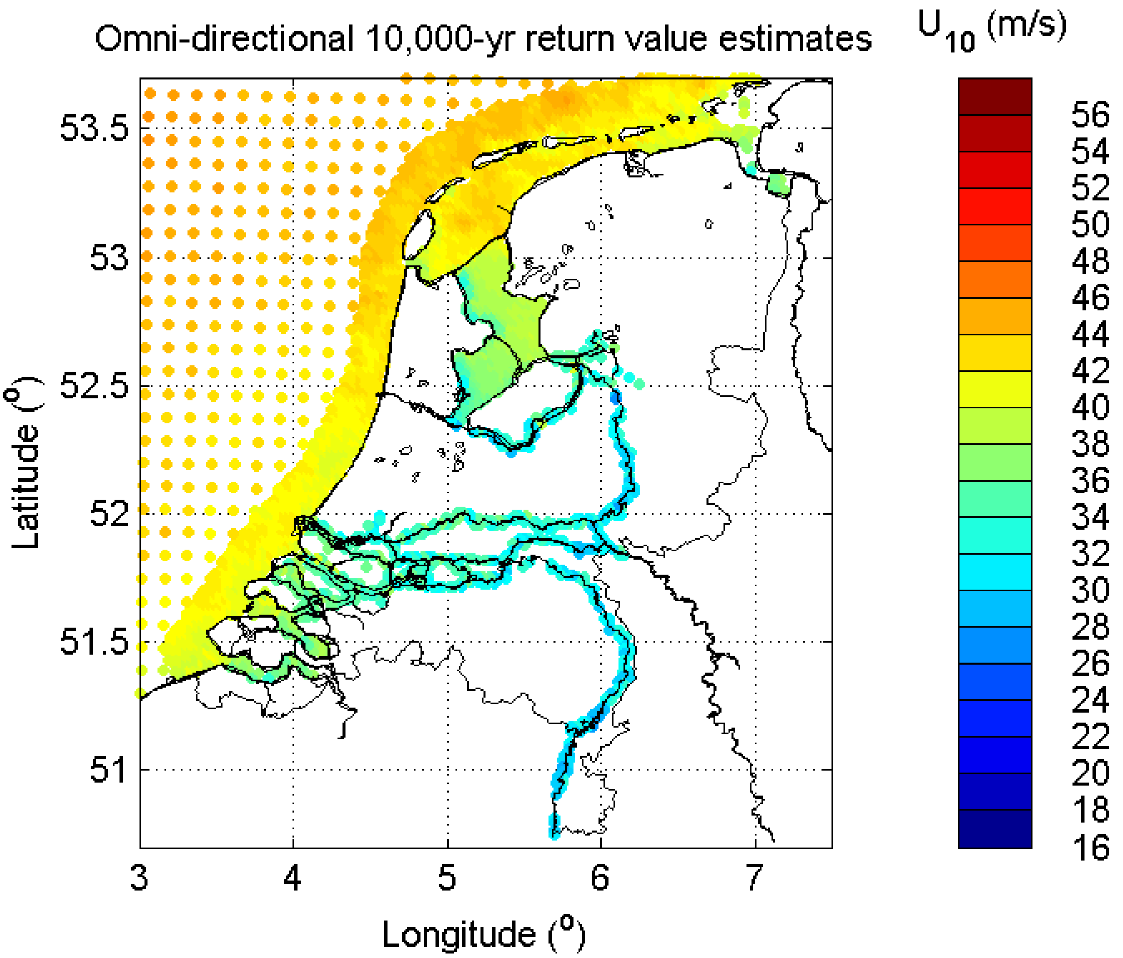


Figure B.9 Omni-directional 10,000-yr return value estimates of the wind speed. These compound omni-directional estimates are based on the directional wind speeds according to Eq. (3.5). Zoom in into the Dutch water systems.

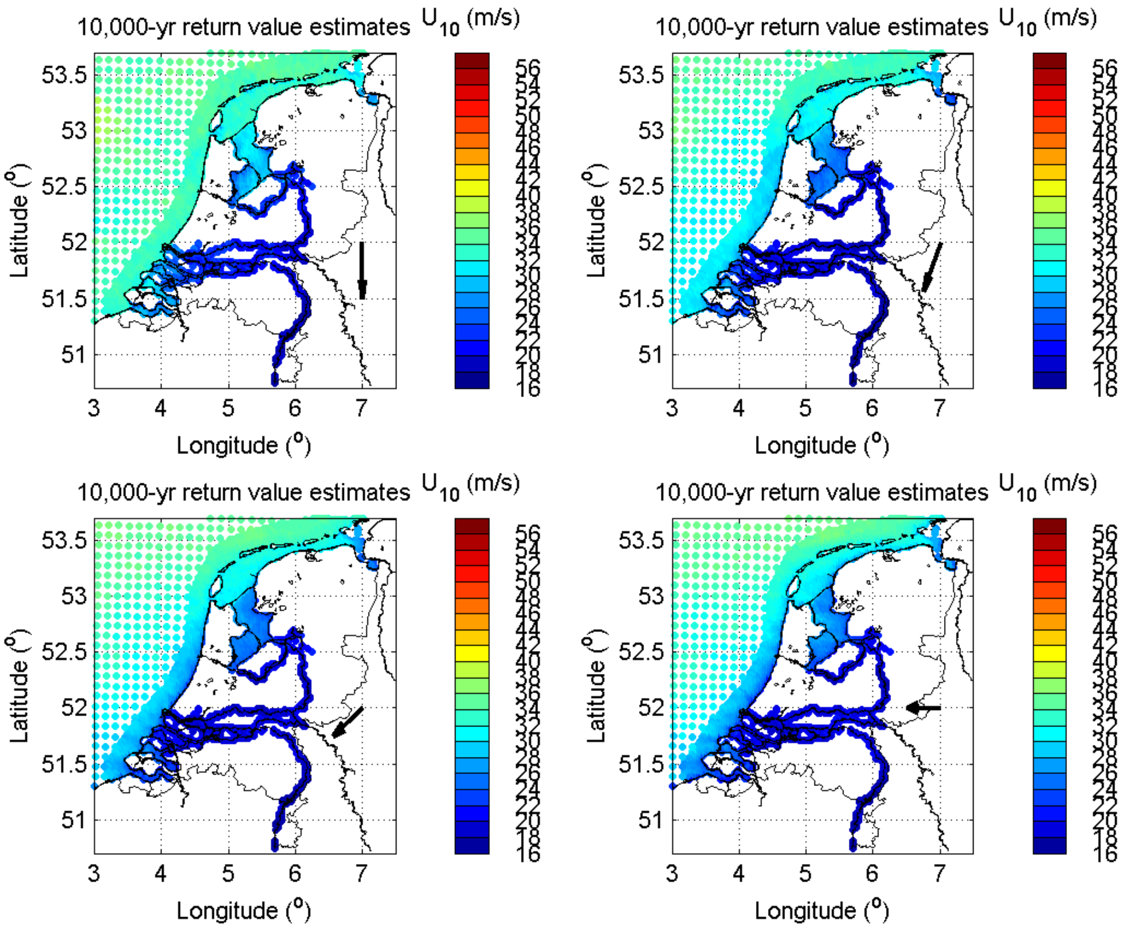


Figure B.10 10,000-yr return value estimates for the 0, 30, 60 and 90 degrees directional wind. The wind directions are indicated with the black arrows. *Zoom in into the Dutch water systems.*

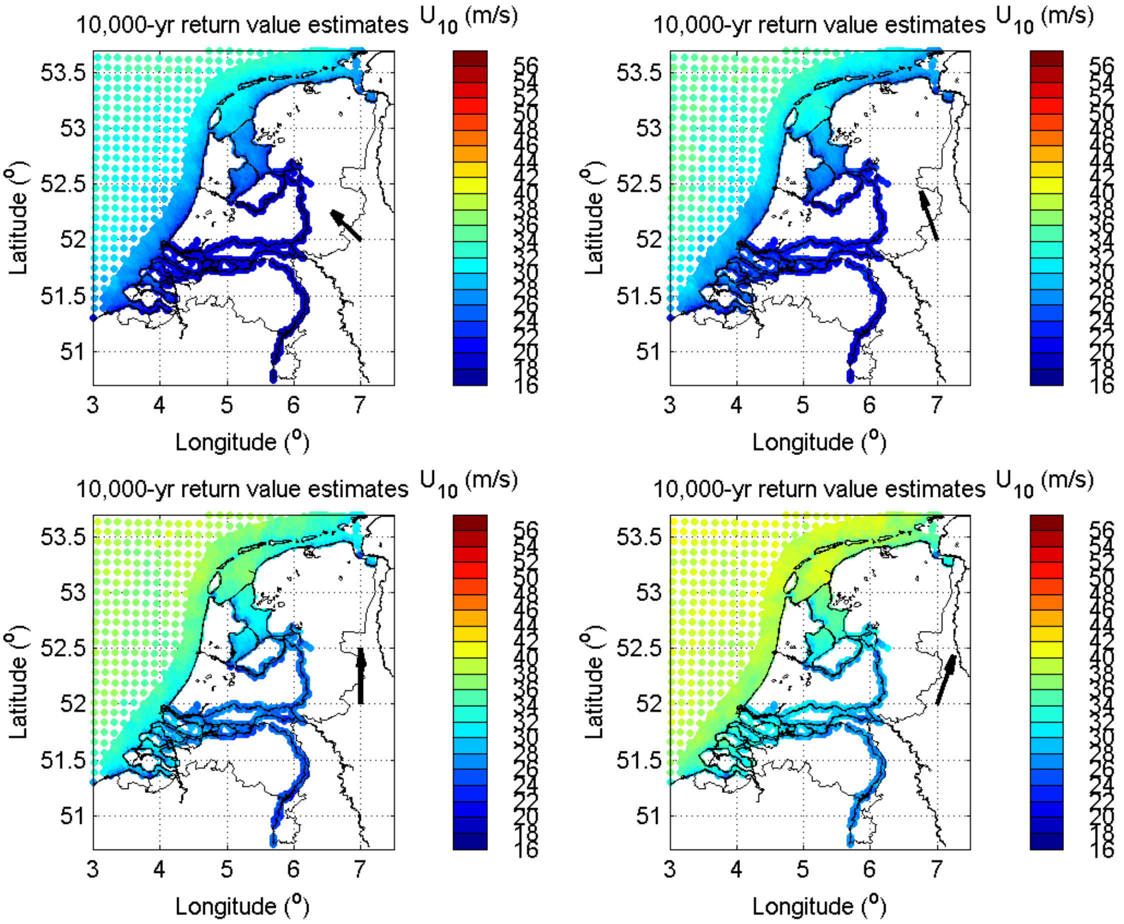


Figure B.11 *10,000-yr return value estimates for the 120, 150, 180 and 210 degrees directional wind. The wind directions are indicated with the black arrows. Zoom in into the Dutch water systems.*

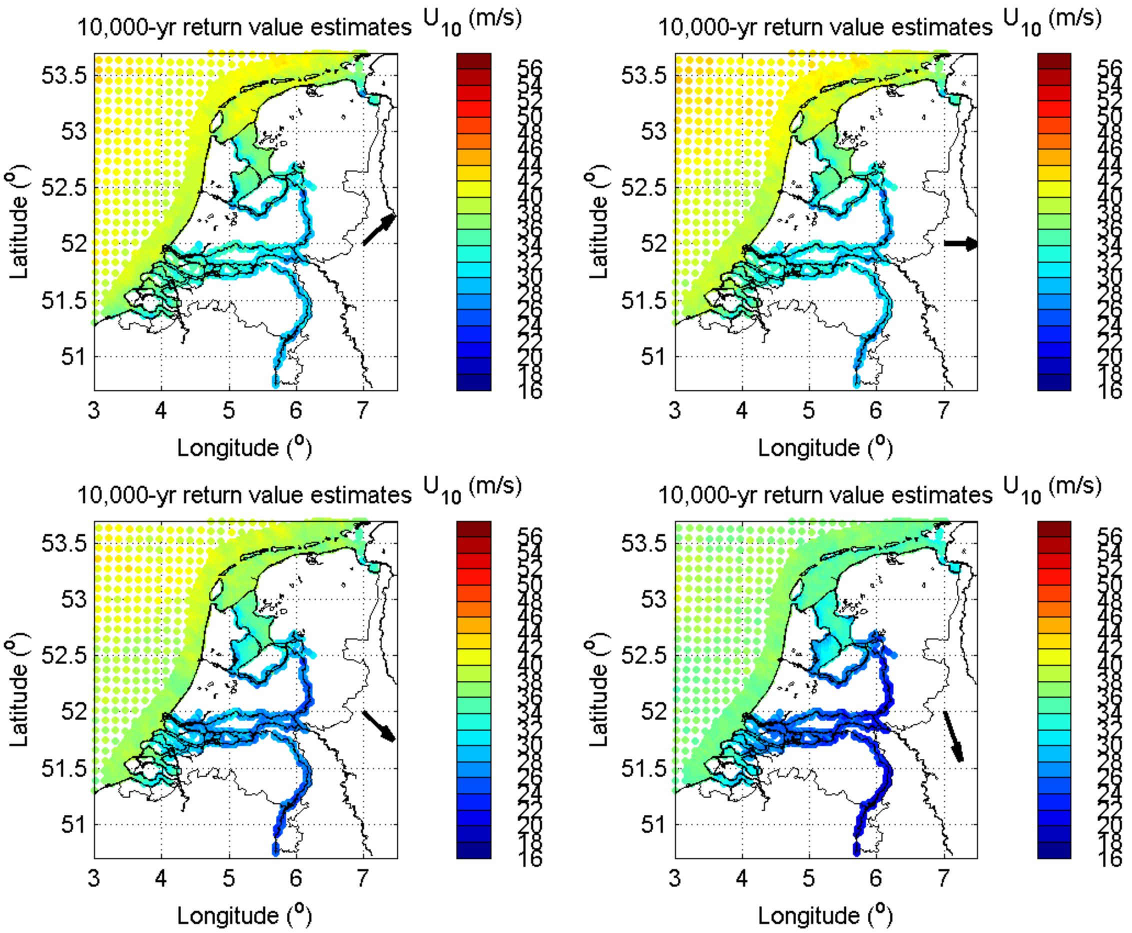


Figure B.12 *10000-yr return value estimates for the 240, 270, 300 and 330 degrees directional wind. The wind directions are indicated with the black arrows. Zoom in into the Dutch water systems.*

C Digital deliverables

Along with this report a directory called 'deliverable' and occupying about 35GB is available. The contents of this directory allow the reproducibility in MATLAB of the estimates given in the report.

The data are distributed in the directory as given in

Directory	Contents	Examples
deliverable	Scripts to be used in reproducing the estimates	loc_eva_HAR_land_smoothing.m – script for the analysis of HARMONIE data from (Set 2) grid locations along small or river water systems. loc_eva_HAR_sea_smoothing.m – script for the analysis of HARMONIE data from (Set 1) grid locations in open water, relevant for the large water systems. loc_eva_ERAi_sea_smoothing.m – script for the analysis of ERA-interim data (Set 3).
deliverable\subs\	Support functions of the scripts	omni_Gumbel.m - function used in the computation Gumbel omni-directional return value estimates from the directional fits.
deliverable\input\	• Files with the coordinates on the considered locations. • Land boundary files.	xy_selection_HARMONIE_land.txt – coordinates of the (Set 2) grid locations along small or river water systems.
deliverable\input\data\	MATLAB files with the original HARMONIE or ERA-Interim time series.	HARMONIEo_lonE005.1732_lat051.9560.mat – time series of HARMONIE U10 and stress for location with coordinates 5.1732°E 51.956°N. There is one file for each location.
deliverable\output\figs	Figures generated by the scripts.	RVP_*.png – plots like report's Figure 3.5 for each location.
deliverable\output\tables	Tables generated by the scripts.	HARMONIEo_lonE005.1732_lat051.9560_l00208.eva – Omni-directional and directional extreme wind speed statistics for location with coordinates 5.1732°E 51.956°N. There is a file for each location. loc_eva_HAR_land.mat – MATLAB files with directional extreme wind speed statistics for all (Set 2) grid locations along small or river water systems. There is one file per set.

Table C.1 Contents of the 'deliverable' directory.