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Towards an approved model set-up for HARMONIE

Contribution to WP 1 of the SBW-HB Wind modelling project

Final

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Towards an approved model set-up for HARMONIE Contribution to WP 1 of the SBW-HB Wind modelling project

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Abstract

For the derivation of the Hydraulic Boundary Conditions (HBCs), information on extreme winds over open-water areas is required. To this end, a new method is developed that will answer the need for a description of both the strength and the space- and time-characteristics of extreme storms. The method relies on using high-resolution atmospheric model simulations rather than on using spatial interpolation of sparse point measurements of wind speed. The HARMONIE model, which has a grid spacing of 2.5 km, has been selected to perform the simulations. This report documents the configuration of HARMONIE that will be used in the project. The quality of the high-resolution model results depends on the settings of the model. We have tested various domain settings, forcing strategies and model options. On the basis of the results, we selected a standard model set-up. This set-up was used in simulations of 14 storms that are contained in the storm test set recommended by Groen and Caires (2011).

As a first evaluation of the standard model set-up, we compared the maximum attained wind speed in the model with the observations for each storm. Over sea the agreement between the model results and the observations is good. Over land the modelled wind extremes are slightly lower than observed. To establish the value of the high-resolution model for the determination of the HBCs, a comprehensive evaluation of the spatial and temporal characteristics of the selected storms is needed.

In accordance with the Adjusted SBW Wind Modelling project, this work is anticipated for 2013.

Keywords
HARMONIE, model set-up, extreme wind

Executive summary

General

According to the Dutch Water Act (Waterwet, 2009) the safety of the Dutch primary water defences must be assessed periodically. The water defences must offer protection against water levels and wave conditions at normative conditions, known as Hydraulic Boundary Conditions (HBCs). To obtain reliable HBCs, accurate wind fields are required.

To ensure that the quality of the HBCs will meet future needs, Rijkswaterstaat has funded a long-term R&D project, SBW-Hydraulics Loads (SBW-HL). The goal of the SBW-Wind Modelling subproject is to improve on existing methodologies by making use of model simulations.

This report presents the selection and description of a model configuration that is suitable for high-resolution extreme wind simulations.

Problem statement

For the determination of the HBCs, information on open-water surface winds is required for driving hydrodynamic models. The presently used wind fields are based on spatial interpolation of point measurements from the network of KNMI wind stations using a simple 2-layer model. Unfortunately, most of the measurement locations are located over land. Although the current interpolation methods to convert land-based observations to open-water winds are based on well-established theories, contradictory results were obtained for extreme winds (e.g. Caires *et al.*, 2009).

Given the limitations of the applied method, the Hydraulic Review Team advised the use of numerical models instead. It is anticipated that in this way fewer assumptions are needed, and that more physically realistic space-time patterns can be obtained. Recently, the SBW-Wind Modelling project was initiated to set up a new method based on high-resolution atmospheric model simulations for estimating extreme surface wind fields and to assess how this method compares to the current practice of interpolating sparse point measurements.

To perform the simulations, the HARMONIE model (`www.hirlam.org`) was selected. This model was developed by the HIRLAM and ALADIN consortia, an international collaboration comprising 24 countries. Since 2012 HARMONIE has been used by KNMI for high-resolution weather forecasting. It is run at a resolution of 2.5 km grid size. This report documents the model set-up that will be used in the SBW-Wind Modelling project.

Approach

Some model settings were treated as given in advance. This is the case for general settings like, for example, the horizontal resolution. Also, the version of the HARMONIE model has been frozen at version Cy37h1.1 that was released in June 2012. When it comes to settings where no clear default setting exists (e.g. domain configuration, spin-up time) we performed sensitivity experiments to make sure that the model set-up is suitable for our purpose, i.e. the simulation of extreme wind fields over The Netherlands. Results of the sensitivity experiments are discussed, and choices motivated. As a first evaluation of the selected model set-up, modelled peak winds are compared to observations for 14 storms of the 17 storms that were recommended as a storm test-set by Groen and Caires (2011).

Conclusions

A HARMONIE model environment was set up that will be used for simulation of surface wind fields in the SBW-Wind Modelling project. Over sea the agreement between the modelled and observed maximum wind speed per storm is good. Over land the model shows a slight underestimation, especially for stations that are situated in complex terrain.

Follow-up steps

To establish the value of the high-resolution model for the determination of the HBCs in more detail, a comprehensive evaluation of the spatial and temporal characteristics of the selected storms is needed.

Special focus will be on

1. the role of atmospheric stability on the 10-m wind,
2. the way in which point observations should be compared with time- and grid-averaged model values,
3. the coupling between the atmospheric model and the hydrodynamic models.

Additionally, the model output that will be archived will be established.

According to the Adjusted SBW Wind Modelling project, these activities are foreseen for 2013.

Contents

1 Introduction

1.1 Framework

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, may vary 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 Toetsen op Veiligheid", VTV), play a 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 probably be based on the probability of flooding of a dike ring.

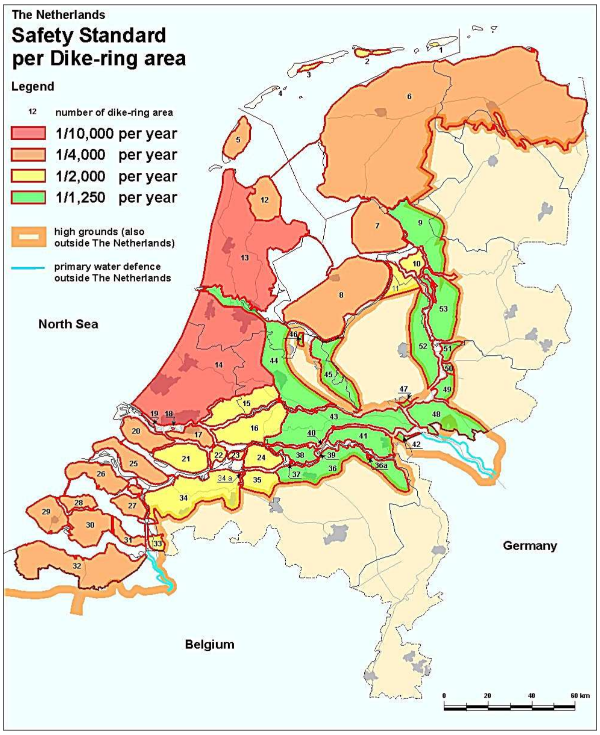


Figure 1.1: The safety standard of the Dutch primary water defences.

With the aim of delivering legal assessment instruments to be used in the performance of the fourth assessment period, starting in 2017, Rijkswaterstaat - Centre for Water Management ("Waterdienst") is funding the long-term project WTI-SBW. Until 2011 WTI and SBW were two separate, strongly related projects. The WTI ("Wettelijk Toets Instrumentarium": legal assessment instruments) project provided the HBC and VTV and other instruments that are necessary to perform the assessment of the primary sea defences. The instrumentation consists of a large set of methods, techniques and rules. Insights have changed over the years and many developments have provided improvements to be made to the instrumentation. Ten years ago the research project Strengths and Loads of Water Defences ("Sterkte en Belastingen

[1] Previous assessments took place in 1996, 2001 and 2006. The date of the next assessment is 2017 and for the period after 2017 the assessment will be on a continuous basis.

Waterkeringen", SBW) started. The SBW project provides expertise and instruments to be used in WTI.

The first SBW program started in 2007 and ended in 2010. That SBW program comprised nine projects, of which seven were related to the strengths and two to the loads of water defences: SBW-Waddenzee and SBW-Belastingen[2]. From 2011 the SBW-Belastingen and SBW-Waddenzee projects have been superseded by the SBW Hydraulic Loads project, in short SBW-HB[3].

The quality of the derived HBC depends on the adequate performance of a number of components in the so-called HBC chain. In this chain, statistical results for waves, wind, water levels and river discharges and simulation results from physical models form the input to probabilistic models. These in turn provide the output of the HBC chain, namely the hydraulic loads, a combination of water level and/or wave height, wave period and wave direction per location, depending on the water system (coastal region, lakes or rivers) and on the failure mechanism under consideration.

The approach of the SBWHydraulic Loads project, presented in Groeneweg *et al.* (2011b), has been based on improving models and methods in the three disciplines in which the knowledge gaps have been clustered, namely:

- Statistical methods
- Models of physics (for instance wave, flow and atmospheric models)
- Probabilistic models

Atmospheric models form an important part of the set of models and techniques used in the WTI instrumentation. The validation and application of an atmospheric model in the WTI cycle is described in (Groeneweg *et al.*, 2011c). The present report is part of Work Package 1 (WP1), as described in Groeneweg *et al.* (2011c), of the Wind Modelling project. This report is specifically concerned with results of the Work Package 1 milestone "Approved model set-up for generating high-resolution simulations of 17 storms" as defined in the project overview.

1.2 Motivation

To obtain reliable HBC's, accurate (especially open-water) wind fields are required. Recently, following the advice of the Hydraulic Review Team, the KNMI-Deltares "SBW-Wind Modelling" project was initiated to set up a new method based on high-resolution atmospheric model simulations for estimating extreme surface wind fields. An overview of this project is given in Groeneweg *et al.* (2011c, 2012) and will not be reproduced here.

As part of the SBW-Wind Modelling project, Groen and Caires (2011) selected and described 17 storm periods that will serve as test events to analyse the capability of the model to simulate extreme wind events. In an interim report Baas and De Waal (2012) described the first results of the high-resolution model based on two of the selected storm periods using a preliminary model set-up. Recommendations were made for improving the modelling strategy and the model set-up. In the present report, most of these recommendations were followed. When appropriate, this is indicated in the text.

[2]Dutch for loads

[3]HB are the initials of Hydraulic Loads in Dutch: Hydraulische Belastingen.

1.3 Objectives

The quality of the high-resolution model results depends on the settings of the model. This report aims to present a model set-up that will serve as a suitable standard for the remainder of the project. Choices are made on the size and location of the domain, the required spin-up time of the high-resolution model, and the boundary conditions.

1.4 Approach

Some model settings were treated as given in advance. This is the case for general settings like, for example, the horizontal resolution. Also, the version of the HARMONIE model has been frozen at version Cy37h1.1 that was released in June 2012.

When it comes to settings where no clear default setting exists (e.g. domain configuration, spin-up time, boundary conditions) we performed sensitivity experiments to make sure that the model set-up is suitable for our purpose, i.e. the simulation of extreme wind fields over The Netherlands.

Results of the sensitivity experiments are discussed, and choices motivated. As a first evaluation of the selected model set-up, modelled peak winds are compared to observations for 14 storms of the 17 storms that were recommended as a storm test-set by Groen and Caires (2011).

1.5 Outline of this report

In Section 2 the HARMONIE model will be described. Section 3 presents the results of the sensitivity experiments. Section 4 presents a basic evaluation of modelled maximum wind speed per storm versus observations. Conclusions and follow-up steps are summarized in Section 5.

2 The HARMONIE implementation

In this section the HARMONIE model is described as it will be used in the remainder of the SBW-Wind Modeling project. Specific settings that were made regarding the model physics, the model set-up and boundary conditions are documented. In some cases these settings were treated as given in advance. This is the case for more general settings like, for example, the horizontal resolution and the model version. When there is no clear default setting (e.g. domain configuration, spin-up time, boundary conditions) we performed sensitivity experiments to make sure that the final model set-up is suitable for our purpose, i.e. the simulation of extreme wind fields over The Netherlands. In this section we only mention the selected model settings. For the motivation of these choices, we refer to the next section which describes the results of the sensitivity experiments.

2.1 General HARMONIE description

HARMONIE (HIRLAM ALADIN Research On Mesoscale Operational NWP in Europe) is the operational Numerical Weather Prediction model of KNMI since summer 2012. It is a limited-area model, that was developed by a consortium involving many European countries. HARMONIE is the successor of the HIRLAM and the ALADIN models. Major differences are that HARMONIE is intended to run on a very high grid resolution (typically with a spacing of 2.5 km) and that it is a so-called non-hydrostatic model. The latter means that instead of employing the hydrostatic approximation, which often breaks down in severe-weather events, the vertical momentum equation is solved explicitly. The HIRLAM-ALADIN consortium tested the model extensively. HARMONIE is also known as the AROME model. More details on HARMONIE / AROME are given by Seity *et al.* (2011), see also the documentation on www.hirlam.org.

HARMONIE is equipped with advanced modules, which, for example, enable the assimilation of high-resolution radar data. In the physics module, the mass-flux convection scheme combines small-scale turbulent and larger-scale convective transport in one consistent framework (Rooy and Siebesma, 2008). Together with a recently improved cloud scheme, already quite realistic examples of cloud formation (including fog) have been observed in HARMONIE runs. The SURFEX model handles the interactions between the atmosphere and the surface and soil processes (Le Moigne, 2012). As such, it calculates fluxes at the air-surface interface, which serve as lower boundary condition for the atmospheric part of the model. Part of SURFEX is the 1-D column model CANOPY, which aims for a more accurate coupling between the atmosphere and the surface (Masson and Seity, 2009). This is done by adding 6 additional levels between the lowest model level and the surface. In fact, when CANOPY is switched 'on', the surface scheme is driven by the lowest level of the CANOPY model (i.e. 0.5 m) instead of by the lowest level of the atmospheric model (10 m).

Over land, the impact of CANOPY on the air in the surface layer is explicitly modelled. In case of very large vertical gradients of wind and temperature the CANOPY model has a beneficial effect. Over sea, the impact of the model is generally small.

Here, we use HARMONIE CY37h1.1 that was released at 13 June 2012.

2.2 Surface drag modelling

Surface drag is the driving meteorological force in hydrodynamic models. It is also a determining factor in the magnitude of the 10-m wind. Therefore, in this section we document the surface drag parameterization in HARMONIE. In HARMONIE the surface is divided into 4 different surface types, called tiles: sea, inland water bodies, nature, and urban areas. Each tile has its own surface drag formulation. Grid boxes in HARMONIE can contain multiple tiles. In section 2.2.1 the water tiles sea and inland water bodies are discussed, section 2.2.2 covers the land tiles nature and towns.

2.2.1 Surface drag modelling over water

HARMONIE makes a distinction between sea and inland water bodies. The latter includes lakes and rivers. First, we review the drag formulation over sea. Over sea, the roughness length z_0 of the surface depends on the wind speed. The interaction between the sea surface and the atmosphere is calculated by the Exchange Coefficients from the Unified Multi-campaigns Estimates (ECUME) module. Being part of the SURFEX model, ECUME is a bulk iterative parameterization developed in order to obtain optimal exchange coefficients for a wide range of atmospheric and oceanic conditions (Weill *et al.*, 2003). ECUME is based on the ALBATROS database that consists of data from five flux measurement campaigns. From this database, the relation between the 10-m wind and the surface fluxes was derived.

The observations cover a wide range of atmospheric conditions in terms of atmospheric stability and wind speed (up to 29 ms^{-1}). In ECUME, the drag coefficient for momentum is calculated directly from the 10-m wind speed using a fourth-order ordinary polynomial. The ECUME drag relation flattens off for wind speeds over 30 ms^{-1}. This is a more realistic behaviour than obtained in the traditional Charnock formulation, where the drag continuously increases even for very high wind speeds. The effect of atmospheric stability is included using Monin-Obukhov similarity theory (see also Appendix A).

Figure 2.1 presents the drag relation modelled by HARMONIE using the default ECUME settings[4]. As illustrated by the dashed line, this relation corresponds well to a Charnock relation with a Charnock constant α of 0.020 for winds between 15 and 30 ms^{-1}. In principle, we will use the ECUME parameterization with default settings. Depending on results of the test with the hydrodynamic models that will be used for WTI-SBW, these settings can be modified. For illustration, in section 3.3 the impact of a rather large modification in the drag formulation on the surface stress and the 10-m wind is shown.

For the inland waters bodies (e.g. the IJsselmeer), HARMONIE uses a Charnock formulation by default. The value of the Charnock constant is set to 0.015. These setting are applied in the present report. For future simulations, it has to be decided whether this is a suitable value for α or that we replace the Charnock relation by the ECUME module that is used over sea. A possible reason for replacing the Charnock relation is that ECUME flattens off for wind speeds over 30 ms^{-1}.

2.2.2 Surface drag modelling over land

Over land, the roughness length z_0 does not depend on the wind speed. HARMONIE distinguishes towns and nature. For the town areas, z_0 is prescribed as a function of the type and characteristics of the buildings (city, industry, airports). Fluxes are calculated by the detailed Town Energy Budget urban canyon model (Masson, 2000). For the nature areas, the

[4] In line with the default HARMONIE configuration, here the CANOPY model is switched 'on'. When the CANOPY model is switched 'off', the effective drag relation will be 5-7% lower. This is because the wind profile as calculated by the CANOPY scheme is slightly different from wind profile that is applied when CANOPY is switched 'off'. Decisions on the final settings will be made after testing with hydrodynamic models.

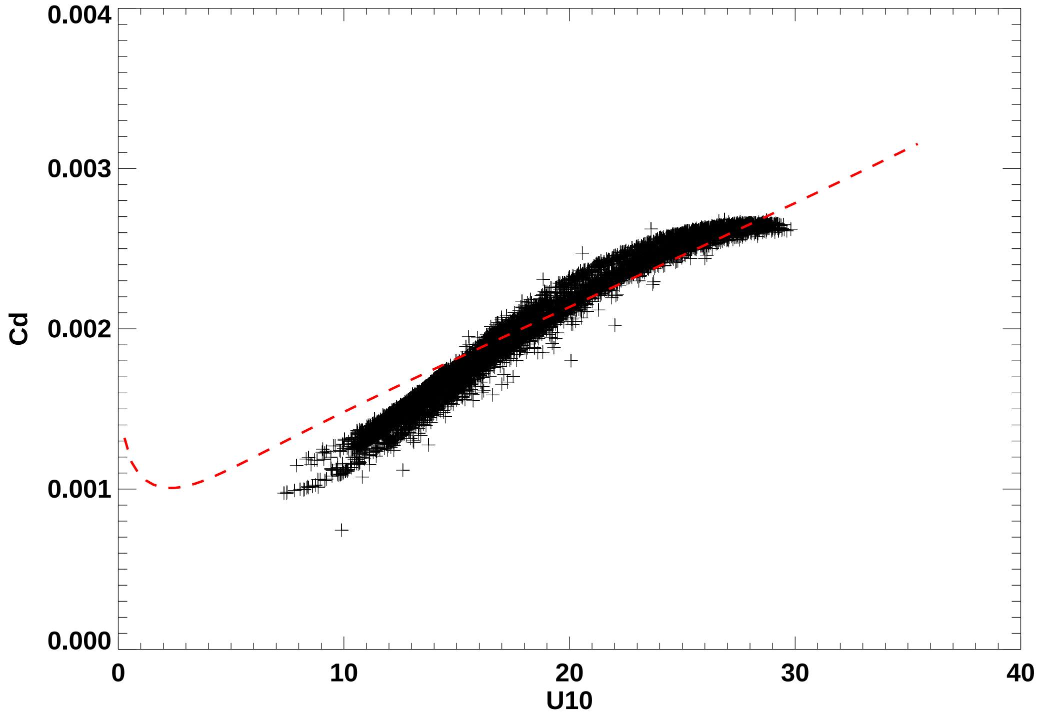


Figure 2.1: The ECUME drag relation as diagnosed from the stress and 10-m wind fields (symbols) and a Charnock relation with α = 0.020 (dashed line).

Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme (Noilhan and Planton, 1989) is used to represent the coupling between the air and the vegetation. Variations in the wind speed over land are largely determined by variations in roughness length. The ISBA scheme has 12 different vegetation types, each having their own roughness length z_0 and other characteristics. Depending on the vegetation type, z_0 is a function of the leaf area index (LAI) or the vegetation height (Table 2.1).

The LAI is obtained via a 10-day look-up table, thus introducing a seasonal cycle in the roughness. Each HARMONIE grid box can contain multiple vegetation types.

The HARMONIE land use map is based on the ECOCLIMAP database, which is a global dataset at a 1 km resolution containing information on land-surface parameters (Masson *et al.*, 2003). It is specifically intended to be used in soil-vegetation-atmosphere-transfer schemes in meteorological and climate models (at all horizontal scales). It consists of 215 land covers for Europe. In HARMONIE, the ECOCLIMAP map is interpolated to the model grid. Then, for each grid box the occurring land covers are transformed to the HARMONIE tiles and vegetation types. For example, the ECOCLIMAP cover airports is treated as 30% urban area and 70% nature. The 70% nature consists of one vegetation type, i.e. grassland.

For each gridbox, one average z_0 is calculated according to

$$z_0 = \max\left(0.001, z_{ref}\exp(-1/\sqrt{(z_{sum})})\right) \tag{2.1}$$

where z_{ref} is a reference height (set to 10 m) and

$$z_{sum} = \sum_i \frac{f_i}{(\ln(z_0/z_{ref}))^2} \tag{2.2}$$

Vegetation type	z_i (m)
Crops	$\min(2.5, \exp((\text{LAI-3.5})/1.3)$
Irrigated crops	$\min(2.5, \exp((\text{LAI-3.5})/1.3)$
Broadleaf forest	HT
Coniferous forest	HT
Grassland	LAI/6
Irrigated parks	LAI/6
Bare ground	0.1
Permanent snow	0.01
Rocks	1

Table 2.1: Height of the HARMONIE vegetation types used to calculate the roughness length. HT is the height of trees in meters and LAI is the leaf-area index. The roughness length z_0 is proportional to the vegetation height (see Eq. 2.3).

where f_i is the fraction of land cover, i, and z_0 the roughness length. The roughness length z_0 is a function of the vegetation height z_i (see Table 2.1):

$$z_0 = 0.13 z_i \tag{2.3}$$

2.3 Grid configuration

HARMONIE runs on a regular grid with a grid spacing of 2.5 km. The vertical grid contains 60 levels, 15 of which are located below 1000 m of height. The lowest model levels are located at about 10, 30, 60, 90, 130, 180, and 240 m above ground level.

2.4 Domain

Because HARMONIE is a limited-area model, a suitable domain must be selected in advance. We use a domain size of 500x500 grid points (effectively 489x489 grid points, after removing the most outward grid points), centered at 54°N,2°E. This corresponds with a domain of 1250x1250 km. The choice for this domain configuration is motivated in section 3.1

2.5 Boundary Conditions

Because HARMONIE is run on a finite domain, information on the state of the atmosphere must be provided at the boundaries.

Initial conditions of the atmosphere and the surface are prescribed from the ERA-Interim reanalysis dataset from the ECMWF (European Centre for Medium-Range Weather Forecasts, (Dee et al., 2011, www.ecmwf.int). It comprises full 3D analyses at a spectral resolution T255, corresponding to a grid resolution of approximately 80 km. The ERA-Interim dataset is of high quality: it is not only generated using a state-of-the-art atmospheric model, it also incorporates many observations (data from the synoptic networks, upper-air information, satellite data) by an advanced data assimilation system. The temporal resolution of the ERA-Interim analyses is 6 h. Starting from each available ERA-Interim analysis a forecast is performed with HARMONIE.

The lateral boundary conditions are obtained by linearly interpolating in time between the 6-hourly ERA-Interim fields, and to a 0.5 degree (lat-lon projection) grid in space.

The HARMONIE time-step is 1 minute.

2.6 Spin-up

As indicated above, every 6 h a new HARMONIE simulation is started, initialized from the ERA-Interim analysis. At the start of each simulation, the model fields consist of ERA-Interim fields which are interpolated to the HARMONIE grid. Consequently, small-scale structures are lacking: the HARMONIE model needs some spin-up time in order to reach a new equilibrium and to develop its own structures. The effect of the number of hours that is used for the spin-up is determined in section 3.2, Figure 3.6.

Small-scale structures over water need 5-10 hours to develop (Figure 3.7). However, shorter spin-up times give better comparisons with observations; the best match is found for a 1 hour spin-up time (Figure 3.8). So we choose 1 hour spin-up time. Given the fact that we make a forecast every 6 hours, we use a forecast length of 7 hours. The sensitivity experiments described in section 3.2 demonstrate that when a spin-up period of 1 h is used (60 time steps) the majority of the small-scale structures is already present.

2.7 Model output

In principle, the complete model state can be archived every time-step. Full 3D fields of, for example, zonal and meridional component of wind, temperature, rain, and cloud-ice, together with an extensive set of 2D fields are stored including surface fluxes. This concerns instantaneous fields; for surface fluxes also accumulated values are stored.

To save disk space and enhance post processing speed, we will archive only a subset of relevant model variables at hourly intervals. Besides the obvious ones like 10-m wind fields, surface stress and mean sea level pressure, variables that are needed to calculate atmospheric stability will be included. The exact list of variables that will be stored has yet to be established and will be documented in a subsequent report.

For the research presented in this report we used hourly instantaneous values, which we assume to be intercomparable with hourly-averaged observations. Whether this assumption is appropriate will be examined in the future. Also the effect of that the model output is more smooth than the observations (not shown) will be examined.

2.8 Selected model setup

The choices of the selected model setup are summarized in Table 2.2:

domain:	size:	489x489 gridpoints
	center:	54°N,2°E
	gridsize:	2.5x2.5km
	boundaries:	ERA-interim
vertical grid:	60 levels	
forecast cycle:	6 hours	
forecast length:	7 hours	
HARMONIE version:	CY37h1.1	
spin-up time:	1 hour	
output time step:	1 hour	
drag relation over sea:	ECUME	
drag relation over inland waters:	to be decided	

Table 2.2: Summary of the selected model setup.

3 Sensitivity experiments

This section describes the results of the sensitivity experiments that were performed in view of model settings for which no clear default setting exists. These experiments have been performed in order to make sure that the selected model set-up is suitable for our purpose, i.e. the simulation of extreme wind fields over The Netherlands. Following recommendations of Baas and De Waal (2012), we explore the impact of the domain choice, the spin-up period, and the sensitivity to the drag relation over water.

3.1 Domain

HARMONIE runs on a pre-defined domain. We experimented with 3 domains, as presented in Figure 3.1, to investigate the effect of the size and center position of the domain on the wind speed.

name	colour	size	center	gridsize
A	red	489x489	52°N,5°E	2.5x2.5
B	green	489x489	54°N,2°E	2.5x2.5
C	blue	289x289	54°N,2°E	2.5x2.5

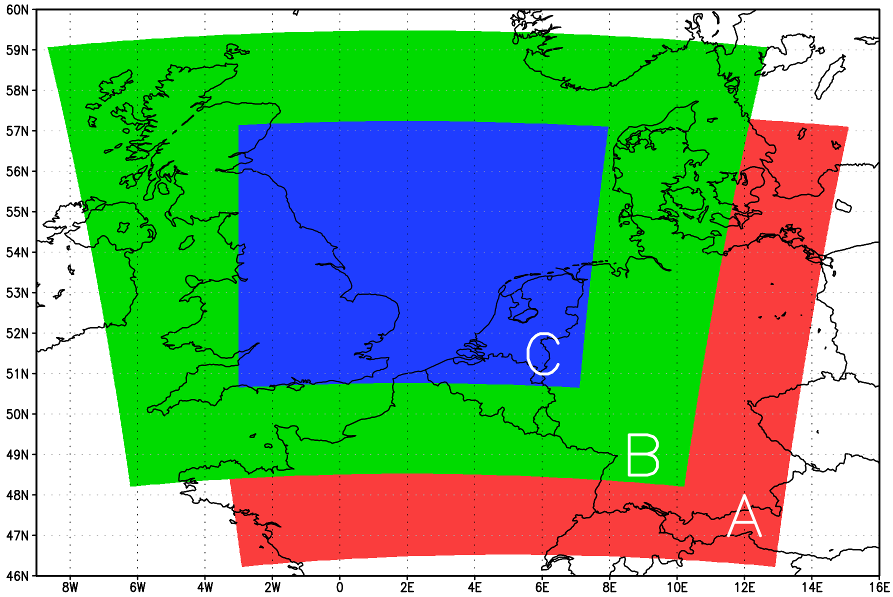


Figure 3.1: Domains to investigate the effect of the size and position of the HARMONIE domains.

Domain A is the domain which was used in the studies carried out in 2011 (Baas and De Waal, 2012). Domain B is shifted North-westward to investigate the effect on deep depressions over Scotland. Domain C is also shifted North-westward, but smaller than domain B, in order to investigate whether a smaller domain (which runs faster) gives similar results.

As an example, the minimum pressure per hour for the area in which the 3 domains overlap (as shown in Figure 3.1) is presented in Figure 3.2 for the January-1990 storm (which is one of the largest depressions over the North Sea in the ERA-interim period). It shows a discontinuity at 25 Jan 12UTC for domains A and C. This is at the moment that a new ERA-interim analysis is used, indicating that the new ERA-interim information is better captured

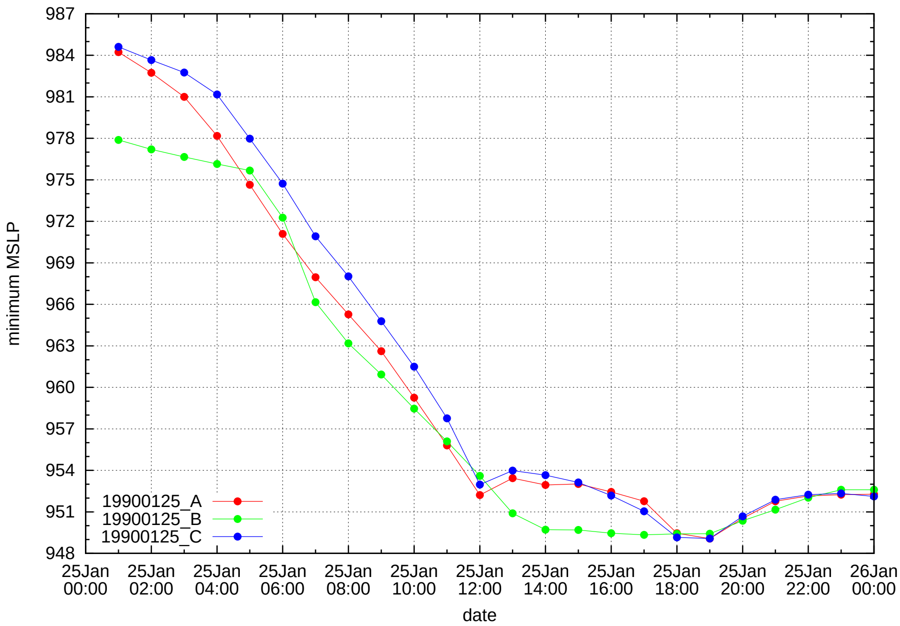


Figure 3.2: Field-minimum MSLP per timestep for the area in which the 3 domains overlap. The colors correspond with those of Figure 3.1 on page 15.

by domain B than by domains A and C. This is further illustrated in Figure 3.3, which shows the pressure at mean sea level (MSLP) of domain A and B, as well as the difference between domain A and B for 25 Jan 1990 14UTC. It indicates that domain B results in a 3 mbar deeper depression. Figure 3.4 shows that the MSLP timeseries of domain B corresponds better with the observations at Hoek van Holland than those of domains A and C (although all domains underestimate the depth of the MSLP). We conclude the wind- and pressure fields are better represented if the center of the depression is within the HARMONIE domain during the timespan of high winds over The Netherlands.

An important part of the hydraulic boundary conditions are related to large surges at the Dutch coast. These large surges are caused by North-Westerly winds over the North Sea, implying a northerly track of the depressions. These northerly depressions are better captured by domain B than by domains A and C. Exploration of a few other depressions sustain these findings. For the more southerly storm track of the May 2000 event, domains A and B behave similarly (not shown).

We expect that domain B is capable to capture almost all depressions that are relevant for the determination of the hydraulic boundary conditions. If during the project it is observed that some depressions are badly captured by domain B, these situations will be rerun with a larger domain (that includes domain B) to improve the representation by HARMONIE of these events.

3.2 Spin-up

Every 6 hours a new HARMONIE forecast is started, with ERA-interim analyses (with a resolution of 0.5°) as initial conditions. Starting from the ERA-interim initial state, the HARMONIE model needs some spin-up time before it reaches a new equilibrium. The first part of the model run is less useful because the model needs time to adjust from the ERA-interim initial

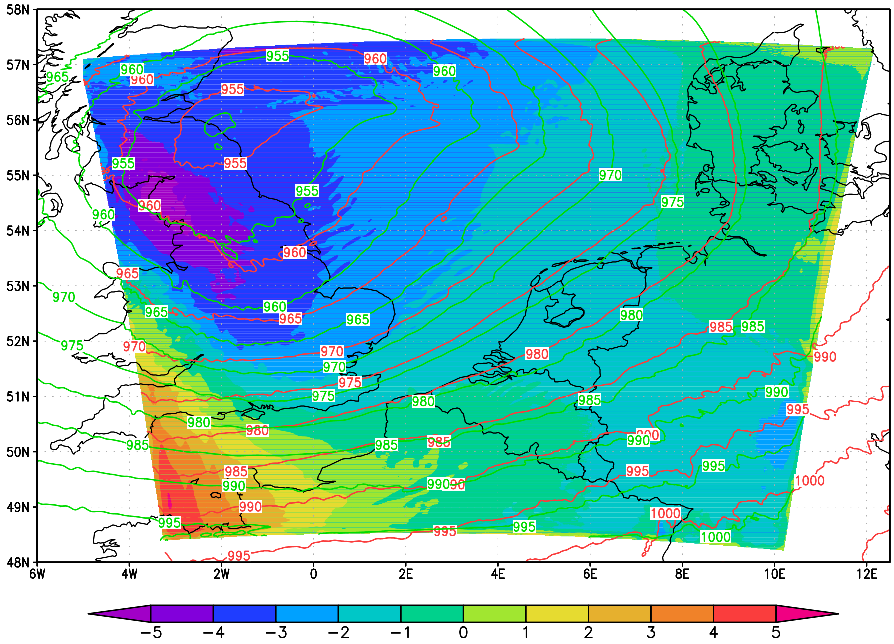


Figure 3.3: MSLP for 25 Jan 1990 14UTC for domain A (red contours) and B (green contours) as well as the difference between B and A (shaded). The colors correspond with those of Figure 3.1. Units are mbar.

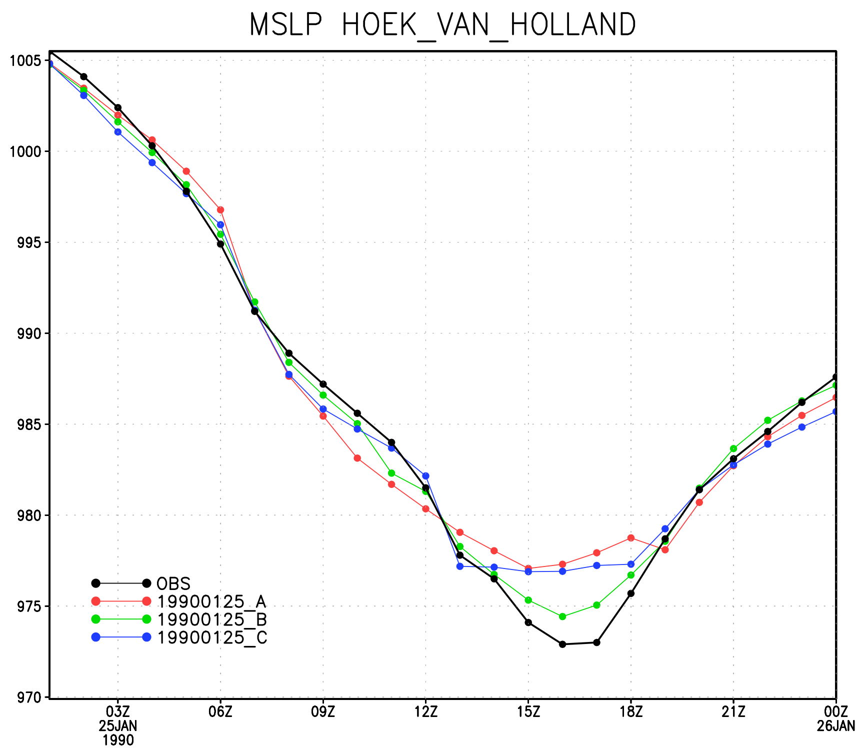


Figure 3.4: MSLP timeseries at Hoek van Holland according to the 3 domains of Figure 3.1 and the observations. Units of the vertical axis is mbar.

state to a state that is natural for the HARMONIE model and contain small-scale structures, and this effect deteriorates the quality of the first part of a HARMONIE run. However, in contrast to the ERA-interim re-analyeses, the HARMONIE run is not directly constrained by observations and will deviate more and more from reality as the run continues. This means that one has to find a compromise between avoiding the spin-up period and avoiding long forecasts times when one selects which 6h-period of a HARMONIE runs one wishes to use. Here we investigate how much spin-up time is needed. Small-scale structures over water need 5-10 hours to develop (Figure 3.7). However, shorter spin-up times give better comparisons with observations; the best match is found for a 1 hour spin-up time (Figure 3.8). So we choose 1 hour spin-up time.

3.2.1 Effect of spin-up on small-scale structures

Figure 3.5 shows the wind fields for several forecast times. The right figures hold for the same verification time as the left ones, but the forecast starts 6 hours later. Comparison of Figures 3.5(a) and (b) show that the 0-hour forecast is too smooth, as it does not show the land-sea effect nor any small-scale spatial structures over sea.

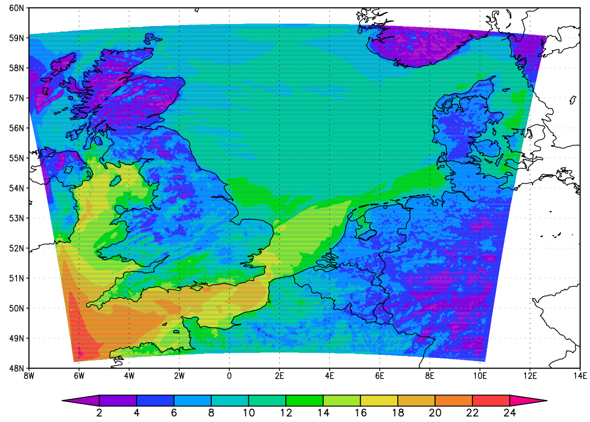
After 1 hour (Figure 3.5(d)), the HARMONIE wind is adjusted to the high-resolution land-sea mask, but the small-scale spatial structures are not yet well developed.

Figure 3.6 shows schematically how the 6-hourly HARMONIE periods can be concatenated to longer timeseries. The red arrows indicate that from every forecast run, the forecast hours 0 to 5 are used, implying no spin-up-time; the green arrows imply a spin-up time of 1 hour, using forecast hours 1 to 6, whereas a spin-up time of 7 hours are indicated by the blue arrows. So, as an example, going from Figure 3.5(a) to (d) is indicated by the green arrow in Figure 3.6.

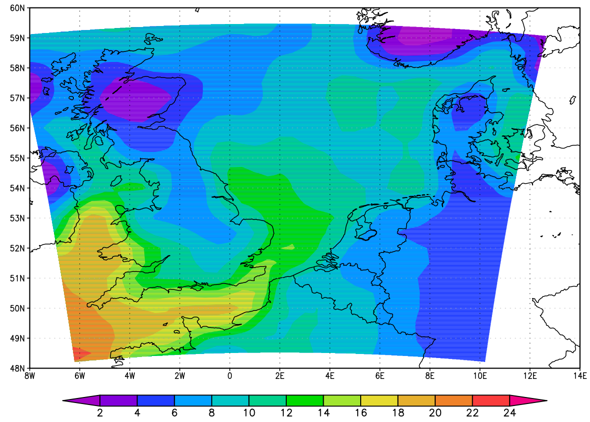
To investigate the effect of the spin-up-time somewhat further, we calculated the field-average (for the complete domain) of the gridpoint-wise standard deviation of the wind speed for succeeding hours for two situations: for succeeding hours in the same forecast run and for succeeding verification hours around the moment of the concatenation of two forecast runs that differ 6 hours in forecast time. Figure 3.7 shows both situations as a function of the forecast time. The blue line shows that the hourly difference is largest at t=1, in which the model develops from the ERA-interim field (based on the ERA-interim roughness parameterization) to the HARMONIE field. The hourly differences become constant after about 10 hours, which implies that the small-scale structures need about 5-10 hours to develop fully. However, the extra development after the first timestep is relatively small. This gives an estimate of the spin-up-time of 2-5 hours. The red line in Figure 3.7 shows the largest standard deviation at t=0, which indicates the transition from forecast hour 5 of the previous forecast run to forecast hour 0 of the next run. Afterwards, the decrease in the standard deviation is relatively small. To clarify the difference between the red and the blue line: The blue line shows the standard deviation between Figure 3.5(a) and (c) at t=7, (c) and (e) at t=8, etc., whereas the red line shows the difference between Figure 3.5(a) and (d) at t=1, (c) and (f) at t=2, etc. The red line is higher than the blue line as it includes (contrary to the blue line) a changes between two different forecasts.

3.2.2 Effect of spin-up on model errors

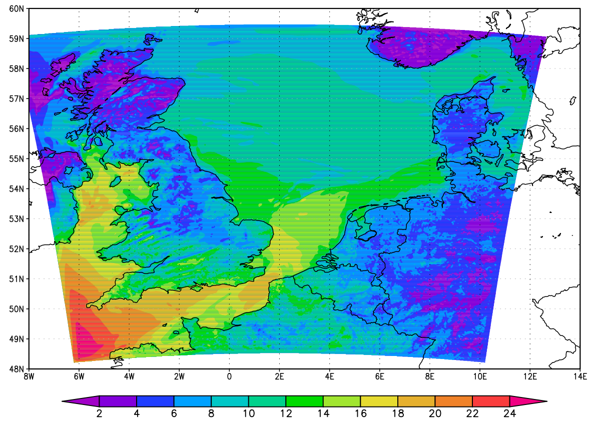
Another consideration is that a longer spin-up leads to growing errors, as HARMONIE drifts away from the actual ERA-interim situation. This is illustrated in Figure 3.8, which shows the Mean Absolute Error (MAE) between model and observations of the wind speed (averaged over all used stations) as a function of the concatenation moment. Apparently, the optimal



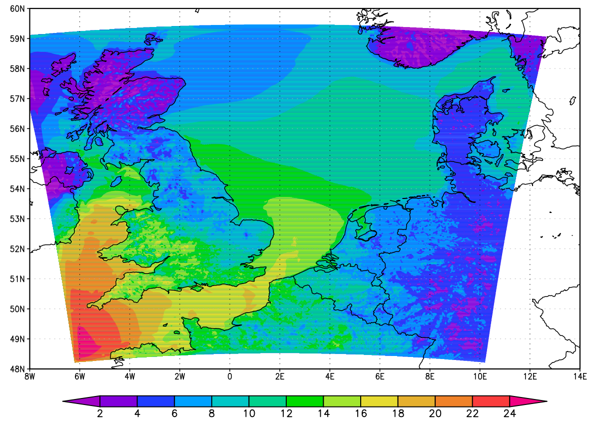
(a) 1990012500+006



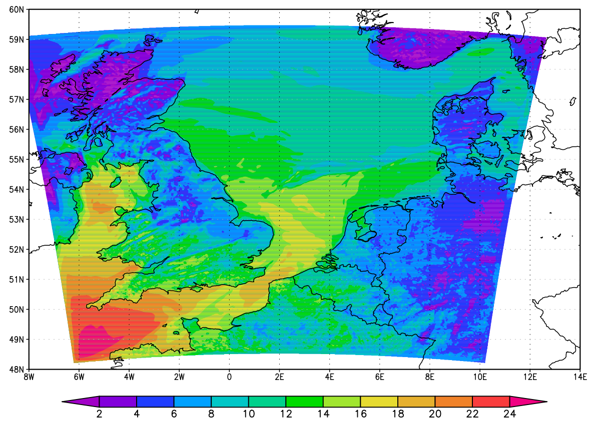
(b) 1990012506+000



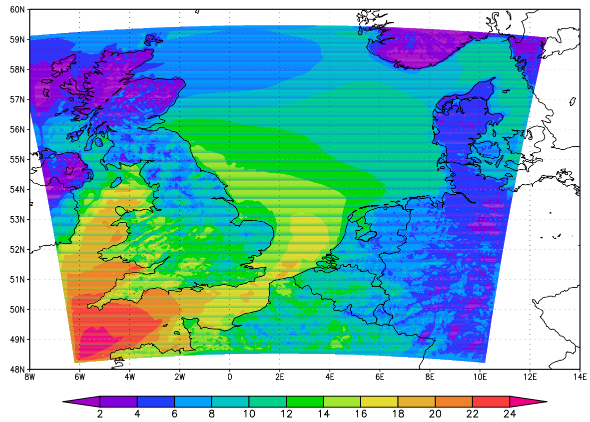
(c) 1990012500+007



(d) 1990012506+001



(e) 1990012500+008



(f) 1990012506+002

Figure 3.5: Windfields for several forecast times. The right figures hold for the same verification time as the left ones, but the forecast time start 6 hours later.

choice for minimizing the MAE is to concatenate the run after 6 hours with the 1st hour of the next forecast, i.e. using forecast hours 1-6. Although the small-scale structures are not yet fully developed after 1 hour spin-up, they are thought to be of minor impact on the hydraulic boundary conditions, and their changes are relatively small after 1 hour spin-up time. So, it is decided to set the spin-up time to 1 hour, taking forecast hours 1-6. A forecast length of

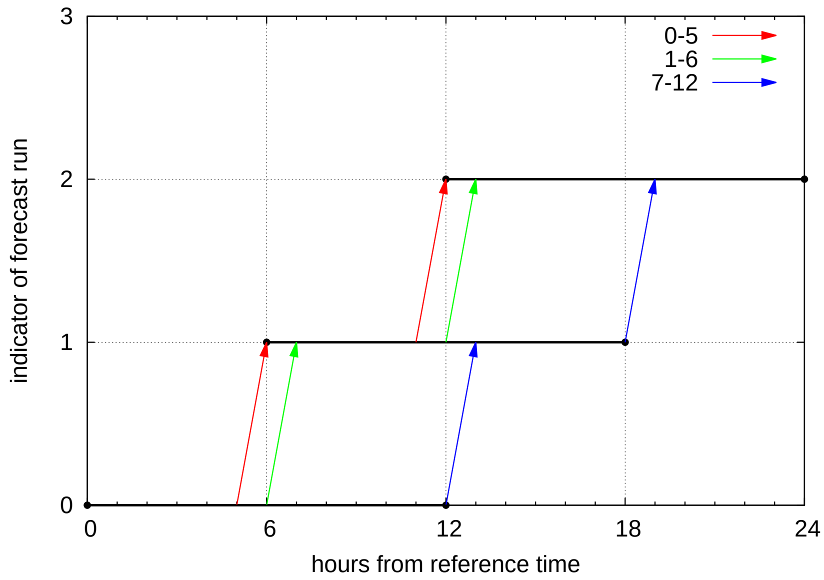


Figure 3.6: Schematic view of the concatenation of 6-hourly HARMONIE forecasts. The red arrows indicate that from every forecast run, the forecast hours 0 to 5 are used, implying no spin-up-time; the green arrows imply a spin-up time of 1 hour, using forecast hours 1 to 6, whereas a spin-up time of 7 hours are indicated by the blue arrows.

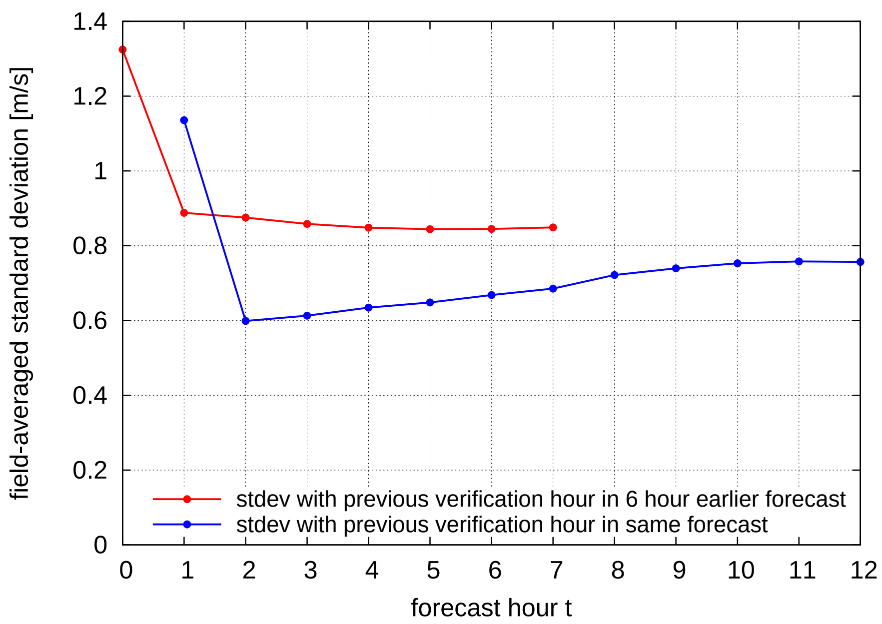


Figure 3.7: Field-averaged standard deviation of the point-wise difference of the wind speed in succeeding verification hours. Blue: based on fields within the same forecast runs; Red: based on fields which differ 6 hours in forecast time.

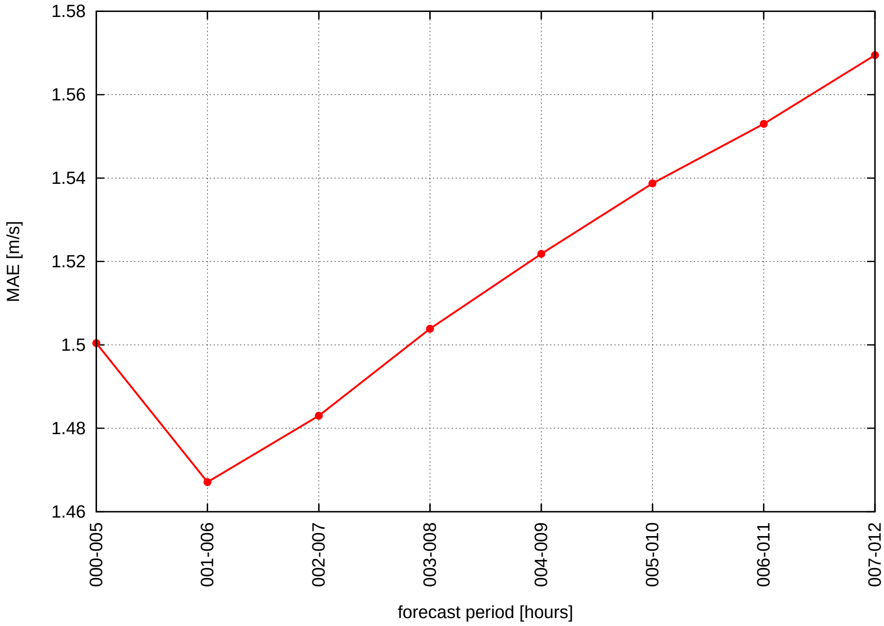


Figure 3.8: Mean Absolute Error (MAE) between model and observations of the wind speed, averaged over 36 stations. The abscissa shows which forecast hours are considered: 001-006 indicates that forecast hour 6 is followed by the 1st hour of the next forecast run.

7 hours will be archived in order to have 1 hour flexibility in future choices.

3.3 Sensitivity to drag formulation

To examine the impact of changing the drag parameterizations on the stress and the 10-m wind a sensitivity experiments was performed with two with different settings of ECUME. Figure 3.9 presents time series of the drag coefficient (left), the surface stress (middle) and the 10-m wind (right) for the platform K13 for 25 January 1990. The black lines represent the reference simulation, the red lines represent a simulation with enhanced drag coefficients. The ECUME drag relation was modified in such a way that it is equivalent to a Charnock relation with α=0.034 for moderate to high wind speeds.

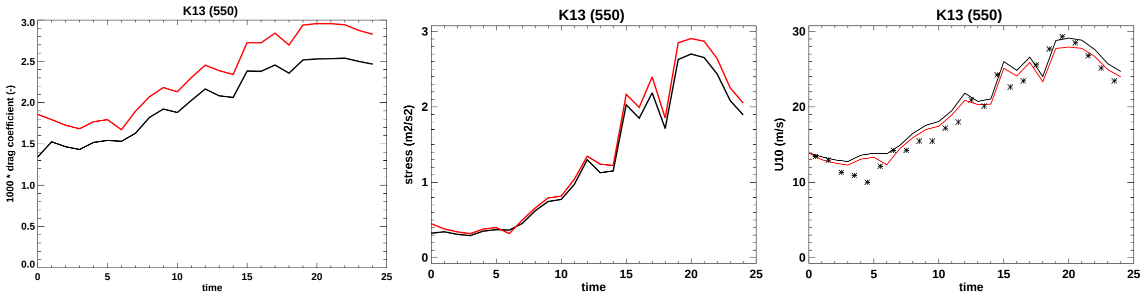


Figure 3.9: HARMONIE timeseries of the drag coefficient (left), surface stress (middle) and 10-m wind speed (right) for K13 for 25 Jan 1990. The black lines represent the reference simulation, the red lines represents a simulation with enhanced drag coefficients. For the wind speed, observations are added (symbols).

On average over the day the drag coefficient is increased by 15.3%. The increase in the surface stress is much less, namely 7.9%, while the wind speed decreases by 3.3%. We conclude that an increase in drag coefficient leads to a smaller increase in surface stress as a result of the negative feedback between the surface drag and the wind speed. As a result, the uncertainty in the surface stress is smaller than in the drag coefficient. Preliminary results with a hydrodynamic model show a difference of 5 cm (2.5%) in the surge for Delfzijl for the November 2006 storm (personal communication Petra Goessen, HHNK).

The feedback mechanism between the surface drag and the wind speed should be kept in mind while fine-tuning the drag relations used in the atmospheric model and the hydrodynamic models. From a physical point of view, the surface stress in the atmospheric model should be the same as the surface stress in the hydraulic model. If this is not the case, e.g. because the hydraulic model is forced by atmospheric wind fields but the hydraulic model uses a drag relation that differs from the one used in the atmospheric model, one should be careful in the interpretation of what one is doing. In particular, increasing the drag in the hydraulic model only, will increase the hydraulic response, while increasing the drag coefficient in the atmospheric model only will decrease surface wind speed and decrease the hydraulic response of a wind-driven hydraulic model.

4 Comparison of selected model setup with observations

In this section we present a first evaluation of the selected model set-up with observations. In the framework of the present report, we suffice with only considering the wind maxima per storm. Simple skill scores are presented for many KNMI wind measurement stations. A comprehensive evaluation of the storms will follow in the course of 2013.

From the test-set of 17 storms (Groen and Caires, 2011), 14 storms are simulated for 24 hours around the storm maximum. In order to investigate how well HARMONIE generates high wind speeds, we intercompared the maximum wind speed during the 14 storm events between the model and observations. The observations are hourly-averaged and Benschop-transformed to 10 m height (Benschop, 1996)[5]. Figure 4.1 shows the scatterplot for Hoek van Holland, both for the gridpoint nearest to the measuring location, as well as for a grid point with a higher seafraction. The linear fits are also shown.

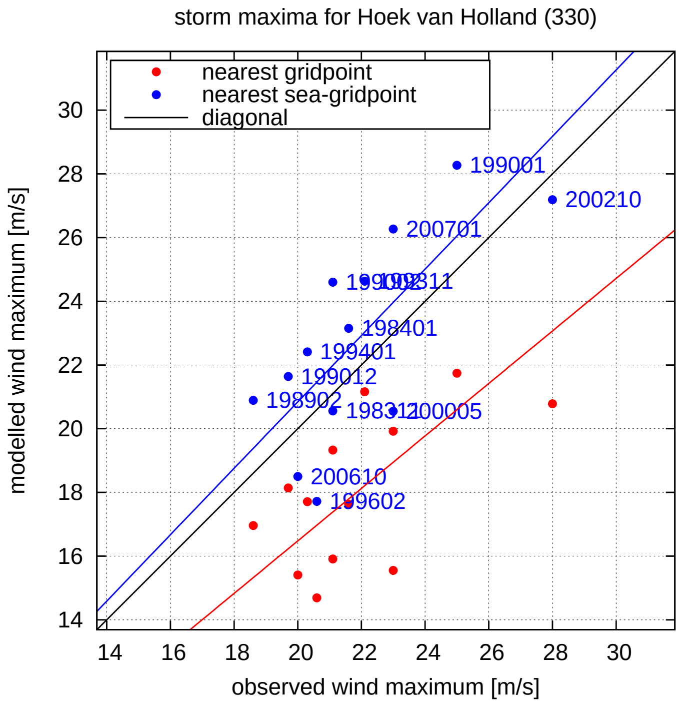


Figure 4.1: Scatterplot of the modelled and observed hourly wind maximum per storm for two grid-points near Hoek van Holland. Red: nearest gridpoint; Blue: nearest sea-gridpoint. The year and month of the storms are plotted. The 197902 event is missing due to lacking observational data.

It points out that the nearest gridpoint underestimates the maxima per storm on average with 18%, whereas the nearest sea-gridpoint has 4% overestimation. The percentual overestimation for all gridpoints in the neighborhood of Hoek van Holland is shown in Figure 4.2. The colors indicate the percentage sea for every gridbox. Apparently, the nearest gridpoint has effectively a lower sea fraction (40%) than the observational location.

[5]The validation of the Benschop approach will be investigated in a future report.

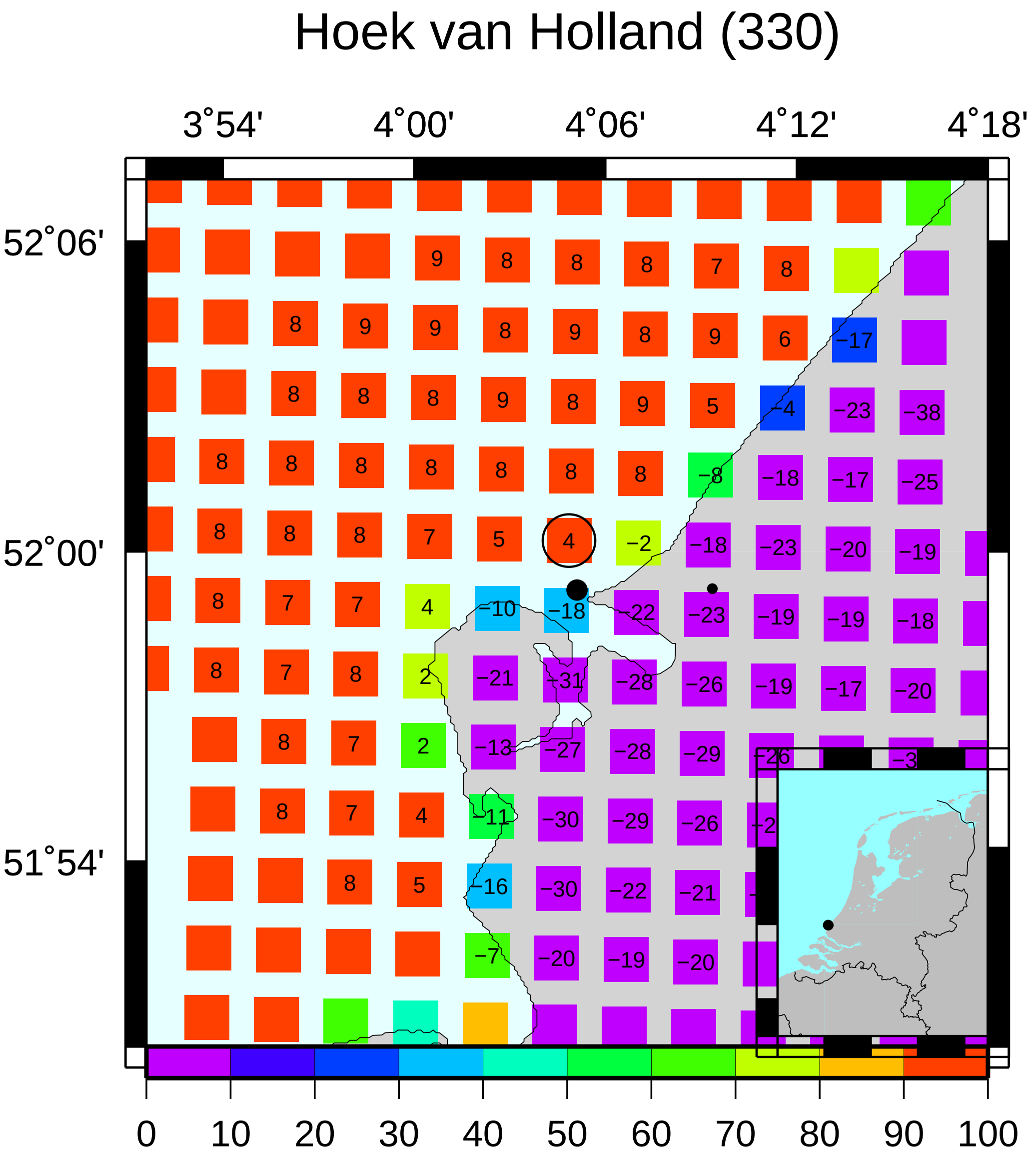


Figure 4.2: Percentual overestimation per gridpoint of the maxima per storm compared with the observations at Hoek van Holland. The colors indicate the percentage sea for every gridbox. The encircled number indicates the gridpoint with the nearest sea-gridpoint.

Figure 4.3 shows the percentual overestimation both for the nearest gridpoint (left) and the optimal gridpoint (right). The optimal gridpoint is the gridpoint within 7.5 km (3 gridpoints) from the observational coordinates with the smallest over- or underestimation. Figure 4.4 shows the histograms of the percentual overestimations both for the nearest and the optimal gridpoints. Figures 4.3 and 4.4 clearly show that for most of the locations (82.5%), a gridpoint can be found for which the modelled maxima per storm are on average within 5% of the observed maxima.

Figure 4.3 hints on a good representation of the extreme wind over sea; over land the grid-box averaged model maxima are slightly lower than the point-values at the measuring locations. This holds especially for stations in complex terrain. In most cases this effect is probably related to the fact that at the measuring location the roughness is generally lower

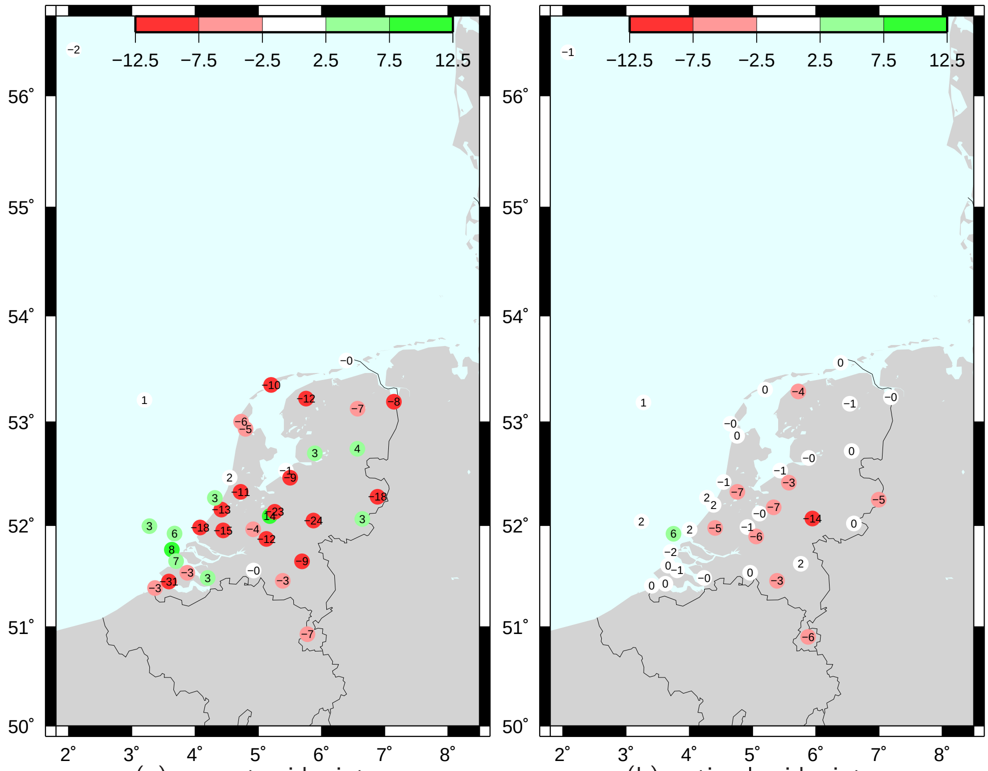


Figure 4.3: Percentual overestimation of the maximum wind speed per storm for the nearest gridpoint (left) and the optimal gridpoint for all measuring locations. The optimal gridpoint is required to be less than 7.5 km (3 gridpoints) from the observational coordinates.

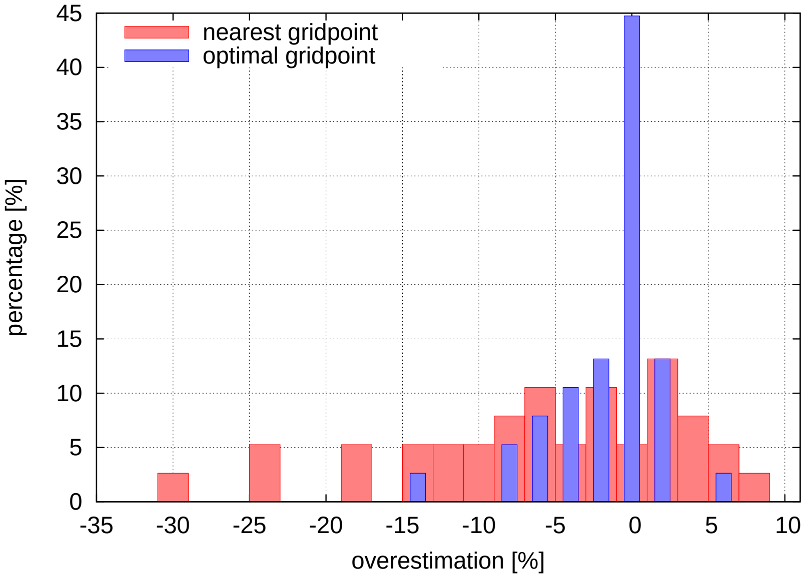
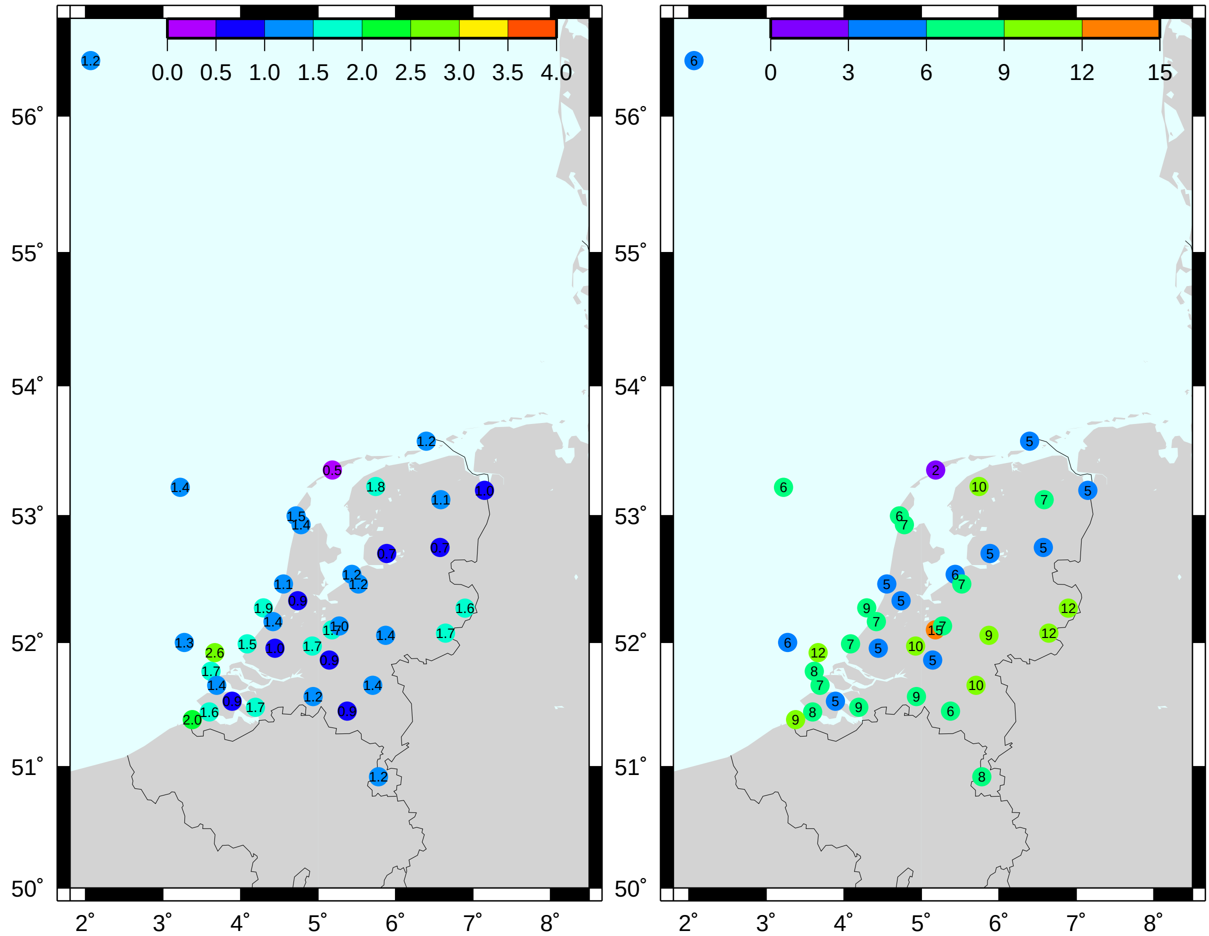


Figure 4.4: Histograms of the percentual overestimation of the maxima per storm for the nearest gridpoint (red) and the optimal gridpoint (blue). The optimal gridpoint is required to be less than 7.5 km (3 gridpoints) from the observational coordinates.



(a) root-mean-square error (m/s) (b) scatterindex (%)

Figure 4.5: Left: Root-mean-square error in m/s (left) and scatterindex in % (right) of the modelled maximum wind speeds for the optimal gridpoint.

than the average of the HARMONIE grid box. This is clearly the case for e.g. Deelen and Soesterberg. Figure 4.5 shows the root-mean-square error of the modelled maximum wind speed per storm for the optimal gridpoint per station, as well as the scatterindices. The scatterindex is defined as the root-mean square errors divided by the mean of the maximum observed wind speeds per storm. Figure 4.6 shows the histogram of the root-mean-square error. Figures 4.5 and 4.6 indicate that 84% of the locations has a root-mean-square error $<$ 2 m/s and a scatterindex $<$ 10%. The largest root-mean-square error belongs to L.E. Goeree. To find out whether this large error is due to the model or due to observational uncertainties, we intercompare in Figure 4.7 L.E. Goeree (3.55°E,51.92°N) with the nearby (26 km westward) station Europlatform (3.28°E,52.00°N). It shows that the agreement between model and observations is much better for Europlatform (root-mean-square error 1.2 m/s) than for L.E. Goeree (2.6 m/s). Due to the small mutual distance between the stations, we expect similar values (which is the case for the model). So, the discrepancy between model and observations for L.E. Goeree might point to an issue with the L.E. Goeree observations.

Figure 4.8 shows for all stations the ratio between the modelled and the observed maxima per storm. Also shown are the mean and standard deviation per storm event. It shows that none of the storms is significantly under- or overestimated; The average ratio (for wind

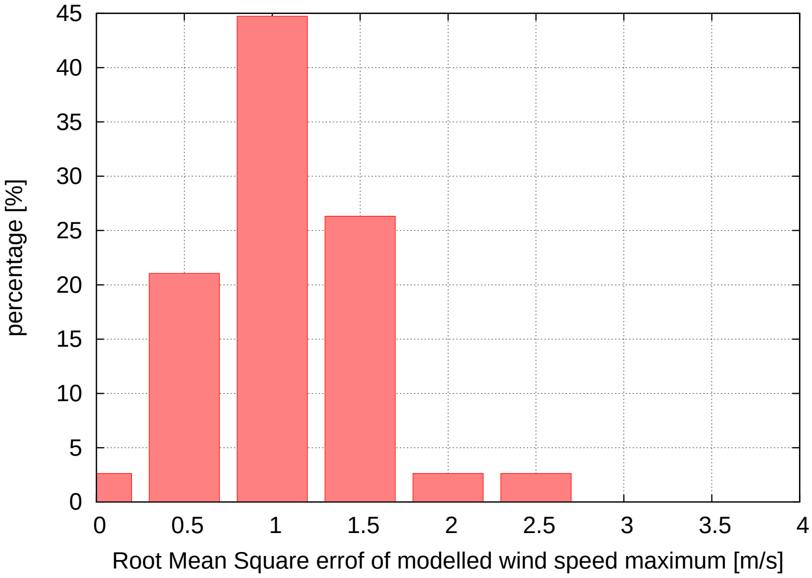


Figure 4.6: Histogram of the root-mean-square errors of the modelled maximum wind speed per storm for the optimal gridpoints.

speeds $>10\,\mathrm{m/s}$) is 96$\pm$11%; all storms are between 90% and 105%. The slight overall underestimation can be attributed to the underestimation over land (Figure 4.3b). There is no temporal trend in the ratio's, indicating that the quality of the HARMONIE runs can be considered to be time-independent.

The spread of 11% is acceptable if it is compared to other sources of uncertainty, e.g. the statistical extrapolation to return period of 10^4 years, and the question how representative the relatively short ERA-interim period is. In addition, as far as we know, all methods that have been applied so far for spatial interpolation of winds in the Netherlands have an uncertainty of at least 11%.

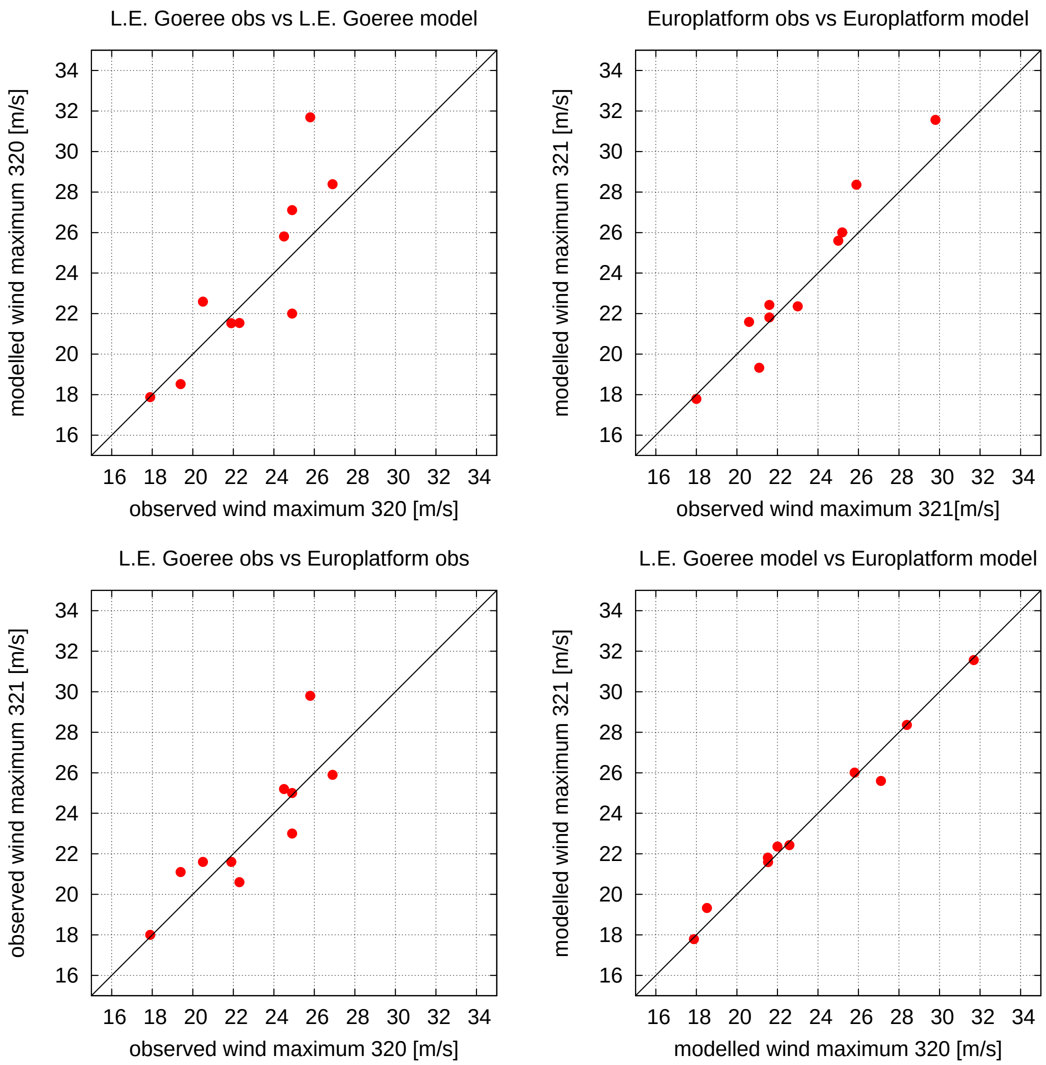


Figure 4.7: Scatterplots for Lichteiland Goeree (320) and Europlatform (321). The upper graphs show the modelled versus the observed maxima per storm for L.E. Goeree and Europlatform respectively; the lower graphs show the intercomparison of the stations for the observations and the model respectively.

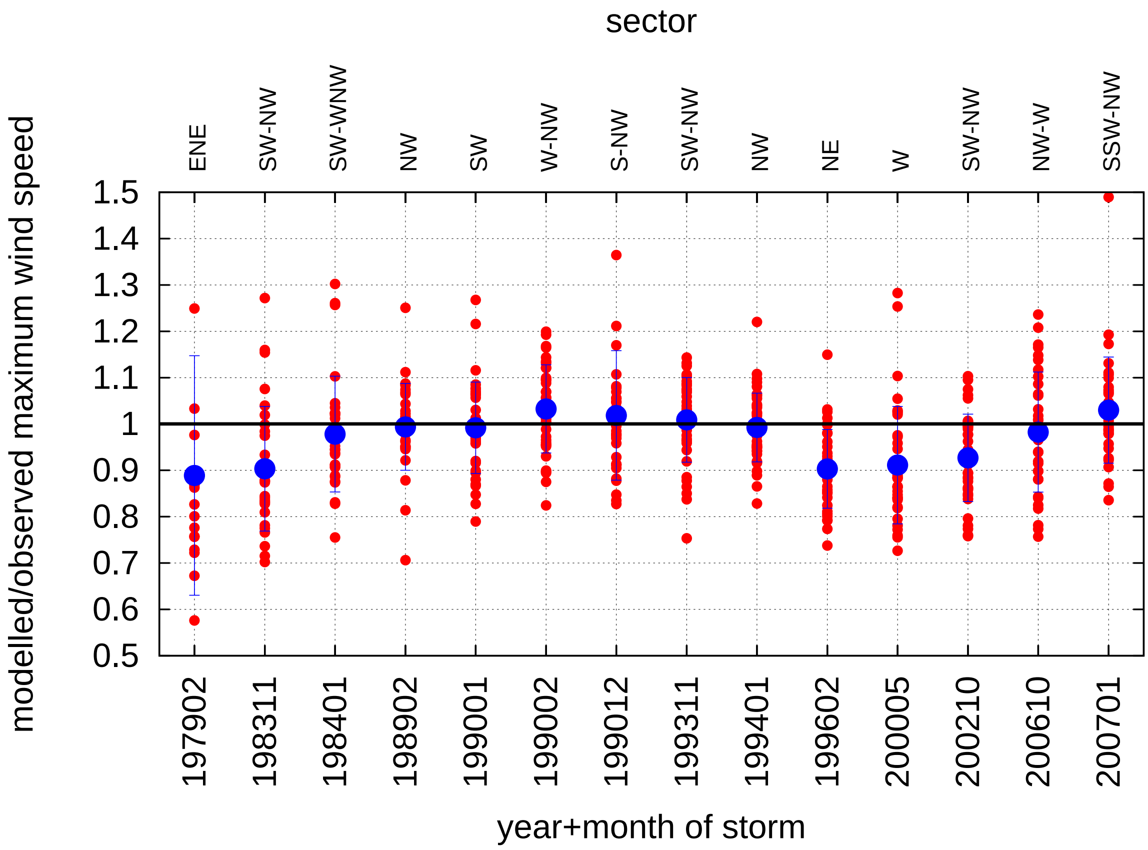


Figure 4.8: Ratio between modelled and observed wind speed per storm and per location (red). The average and standard deviation per storm are indicated in blue. The upper axis shows the dominant wind direction in The Netherlands. These wind directions are obtained from Table 3.1 of Groen and Caires (2011).

5 Conclusions and follow-up steps

5.1 Conclusions

This report is part of the KNMI-Deltares project 'SBW Wind modelling', which aims to determine a reliable (especially above water) and detailed extreme-wind climatology for The Netherlands using a high-resolution atmospheric model (Groeneweg *et al.*, 2011a). The HARMONIE model, which has grid spacing of 2.5 km, was selected to perform the simulations. A HARMONIE model environment has been set up that will be used for the simulation of surface wind fields in the SBW-Wind Modelling project. Some model settings were treated as given in advance. This is the case for general settings like, for example, the horizontal resolution. Also, the version of HARMONIE has been frozen at Cy37h1.1 that was released in June 2012. When it comes to settings for which no clear default setting exists (e.g. domain configuration, spin-up time), choices have been made based on sensitivity experiments. As a first evaluation of the selected model set-up, we compared maximum attained wind speeds in the model with observations for 14 of the 17 historical storms that were selected by Groen and Caires (2011).

Specific conclusions are listed below:

- A spin-up time of 1 hour is suitable for wind (extremes), taking into account the effects of computational effort, growth of errors with longer forecast times, development of small-scale structures and jumps between successive forecasts.
- We have optimized the centre and size of the domain, focusing on The Netherlands and the southern North Sea. The centre is at 54°N,2°E and the size is 500x500 grid points (with a grid distance of 2.5 km).
- The wind maxima per storm of HARMONIE show a good correspondence with the observations over sea, and a slight underestimation over land. The likely cause of the underestimation over land are discrepancies between local and gridbox-averaged roughness.
- There is no temporal trend in how well the storms are reproduced, indicating that the quality of the HARMONIE runs can be considered to be time-independent.
- In HARMONIE, as in any atmospheric model, increasing the drag relation over water leads to an increase in the surface stress that is approximately only half as large. The difference is related to the negative feedback mechanism between the surface drag and the wind speed. This feedback mechanism should be kept in mind while fine-tuning the drag relations used in the atmospheric model and the hydrodynamic models.
- For the drag formulation over sea the default ECUME parameterization of HARMONIE is selected, which corresponds for high wind speeds to a Charnock parameterization with α=0.020. For lakes and rivers we use a Charnock formulation with α=0.015 as in the operational HARMONIE model. Depending on results of hydrodynamic models, the settings for these surface types can be modified.
- The investigations that have been performed so far indicate that HARMONIE simulations provide high-quality wind statistics in strong wind situations, especially over sea. This makes the model potentially appropriate for deriving the Hydraulic Boundary Conditions.

5.2 Follow-up steps

To establish the value of the high-resolution model for the determination of the Hydraulic Boundary Conditions in more detail, a comprehensive evaluation of the spatial and temporal characteristics of the selected storms is needed.

Special focus will be on

1. the role of atmospheric stability on the 10-m wind,
2. the way in which point observations should be compared with time- and grid-averaged model values,
3. the coupling between the atmospheric model and the hydrodynamic models.

Additionally, the model output that will be archived will be established.

A The vertical wind profile and momentum exchange over sea.

For convenience, here some basic theory is presented. We give a short review of the vertical wind profile and the calculation of turbulent fluxes over water surfaces. For background information we refer to Stull (1988).

A.1 The vertical wind profile

In the atmospheric boundary layer the wind speed is reduced by friction due to the presence of the Earth's surface. Ignoring effects of stratification, it can be argued from dimensional analysis that the vertical gradient of the wind is proportional to a friction velocity divided by a height z:

$$\frac{dU}{dz} = \frac{u_*}{kz} \tag{A.1}$$

where U is the horizontal wind speed, k the von Karman constant, z the height above the surface, and $u_* = \sqrt{(\tau/\rho)}$ with τ the surface stress and ρ the air density. Under the assumption that u_* is constant with height, integration of Eq. A.1 between the aerodynamic roughness length, z_0, and z gives the logarithmic wind profile

$$U(z) = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \tag{A.2}$$

An important parameter in Eq. A.2 is z_0. Rougher surfaces are likely to cause more intense turbulence and increase the drag and transfer across the air-sea interface.

When thermal stratification cannot be ignored, the logarithmic wind profile must be corrected. This is done by applying the stability correction function ψ_m:

$$U(z) = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right] \tag{A.3}$$

The parameter z/L is a measure of stability. L denotes the Obukhov length, which is a function of the ratio between the vertical transport of momentum and heat:

$$L = -\frac{\theta_v}{gk}\frac{u_*^3}{\overline{w'\theta_{vs}'}} \tag{A.4}$$

where θ_v denotes the virtual potential temperature, g the acceleration due to gravity, and $\overline{w'\theta_{vs}'}$ the surface turbulent heat flux.

A.2 Momentum exchange over sea

In so-called bulk parameterizations the wind stress is related to the mean wind speed by the drag coefficient for momentum, C_d,

$$\tau = \rho C_d U^2 \tag{A.5}$$

where U, the wind speed at a reference height in the surface layer, is given by the wind profile of Eq. A.3. The drag coefficient C_d is defined by:

$$C_d = \left(\frac{u_*}{U}\right)^2 \tag{A.6}$$

For neutral conditions, C_d can be related to z_0 by combining Equations A.1 and A.6:

$$C_d = \left[\frac{k}{\ln\left(\frac{z}{z_0}\right)}\right]^2 \tag{A.7}$$

Over sea, z_0 is often parameterized according to Charnock (1955):

$$z_0 = \alpha\frac{u_*^2}{g} \tag{A.8}$$

with g the acceleration due to gravity. In the literature, the value of α, which is known as the Charnock constant, varies between 0.010 and 0.035.

The HARMONIE model uses the Exchange Coefficients from the Unified Multi-campaigns Estimates (ECUME) parameterization to calculate the surface fluxes over sea (Weill *et al.*, 2003; Belamari, 2005). In ECUME, the drag coefficient is directly calculated from the 10-m wind by means of a relation that was derived from a database that consists of data obtained from five different flux measurement campaigns.

Determining drag relations over water surfaces is subject to continuous research. For example, in recent years evidence has been put forward that the drag coefficient for momentum levels-off and even decreases for extremely high wind speeds (Powell *et al.*, 2003; Donelan *et al.*, 2004; Holthuijsen *et al.*, 2012). Such a levelling-off is present in the ECUME relation applied by HARMONIE.

Another issue is the drag relation over relatively small and shallow water surface, e.g. lakes like the IJsselmeer (Donelan *et al.*, 1993; Makin and Kudryavtsev, 2002; Bottema, 2007). Arguments can be made that young waves present in these areas are rougher than mature waves that are found in the open ocean. Thus, for the same wind speed the drag coefficient over a lake would be higher than over the open ocean.

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