Koninklijk Nederlands
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Deltares
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Interim report on the validation of Harmonie

SBW-HB Wind modelling

Final

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Keywords
Harmonie, model evaluation, two-layer model, extreme wind

Summary
For the derivation of the Hydraulic Boundary Conditions, information of extreme winds over open-water areas is required. Because previous methodologies provided contradictory results, a new method is being developed that relies on the results of a high-resolution atmospheric model rather than on the spatial interpolation of sparse point measurements. The Harmonie model, which has a grid spacing of 2.5 km, has been selected to perform the simulations. To test the model, Groen and Caires (2011) composed a test set of 17 historical storms to be simulated with the model. In this report, model results for two of these storms are compared with observations.

The results of the high-resolution model are encouraging. For both simulated storms, the model is able to reproduce the large-scale structure of the wind fields both in space and time. The extreme wind velocities of the storm peaks are well represented, especially over open water areas. The benefit of the high-resolution model simulations is most obvious in areas with large roughness transitions like coastlines.

Drawing general conclusion based on only two cases is impossible. In order to give additional and more specific conclusions there is need to i) simulate the remaining storms of the test set composed by Groen and Caires (2011), ii) further test and (if desirable) modify the model set-up, iii) include more measurements in the evaluation, and iv) consider surface wind-stress in more detail.

References
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Plan of approach SBW wind modelling. Deltares Report 1202120-003-HYE-0001.

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Executive summary

General

According to the Dutch Water Act ('Waterwet, 2009') the safety of the Dutch primary water defenses must be assessed periodically. This assessment is based on the Hydraulic Boundary Conditions (HBC), consisting of water levels and wave conditions under normative conditions. To obtain reliable HBC's accurate wind fields are required. This report presents first results on a new method to derive extreme open-water winds using high-resolution atmospheric model simulations.

To guarantee the quality of the HBC's, Rijkswaterstaat is funding the long-term project 'Strengths and Loads of Water Defenses' (in Dutch: Sterkte en Belastingen Waterkeringen, SBW).

Problem statement

For the determination of the HBC's, information of above open-water winds is required to drive 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 (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 explore the capabilities of the new method, Groen and Caires (2011) composed a test set of 17 historical storms to be simulated with a high-resolution model. To perform the simulations, the Harmonie model (www.hirlam.org) was selected. This model has been developed by the HIRLAM and ALADIN consortia, an international cooperation comprising 24 countries. Harmonie will be the next KNMI weather forecasting model from 2012 onwards. It is run at a high resolution of 2.5 km grid size. So far, two storms of the test set have been simulated with the model. This report compares the results with available observations. Simulation of the remaining storms is scheduled for 2012. Because only results for two of the storms are presented, the current report should be considered as an interim report.

Approach

A Harmonie model environment has been set up to enable the simulation of historical storms. Choices have been made on model version, forecast strategy, model domain, and boundary conditions. The storms of January 1990 and November 2006 have been simulated. The results are compared with observations from the network of KNMI stations.

To compare the results of the high-resolution model to the previously applied method based on spatial interpolation of point measurements, ratios of wind speed over land to wind speed over water are compared to observed ratios.

Conclusions

The results of the high-resolution model are encouraging. For both simulated storms, the model is able to reproduce the large-scale structure of the wind fields in both space and time. The extreme wind velocities of the storm peaks are well represented in the numerical model, especially over open water areas where representativeness errors due to roughness differences play a minor role. For the 1990 storm, modelled peak velocities over land are underestimated, which appear to be (at least partly) caused by an underestimation of the pressure gradient. The timing of air-mass transitions (the passage of warm and cold fronts) is accurately captured by the model.

The benefit of the high-resolution model simulations is most obvious in areas with large roughness transitions. For both storms, Harmonie accurately resolves the wind speed variations near coastlines and edges of e.g. IJsselmeer and major urban areas. In areas with complex topography like the Eems-Dollard estuary, Harmonie calculates a much more realistic wind field than the 11-km resolution model Hirlam, which is beneficial for surge level predictions by hydrodynamic models.

The average ratio between inland and open water stations as calculated by the 2-layer model is realistic for the present storms. The temporal variations in the ratios are typically underestimated. Harmonie captures these variations much better, although their amplitude is still too low.

Follow-up steps

Drawing general conclusions based on only two cases is impossible. In order to give additional and more specific conclusions there is need to i) simulate the remaining storms of the test set composed by Groen and Caires (2011), ii) further test and (if desirable) modify the model set-up, iii) include more measurements in the evaluation, and iv) consider surface wind-stress in more detail.

Contents

1 Introduction

1.1 Framework

According to the Dutch Water Act ('Waterwet, 2009') the safety of the Dutch primary water defenses must be assessed periodically. This assessment is based on the Hydraulic Boundary Conditions (HBC), consisting of water levels and wave conditions under normative conditions.

The government funded program WTI ("Wettelijk Toets Instrumentarium": legal assessment instruments) produces the required safety assessment instruments. This program is supported by the SBW ("Sterkte en Belastingen Waterkeringen": strengths and loads of water defences) program, also funded by the government, which addresses relevant knowledge gaps and guarantees the quality of the HBC's.

To obtain reliable HBC's accurate (especially open-water) wind fields are required. This report presents first results on a new method to derive extreme open-water winds using high-resolution atmospheric model simulations.

1.2 Problem statement

For the determination of the HBC's, information of above open-water winds is required to drive hydrodynamic models. The presently used (WTI 2011) wind fields are based on spatial interpolation of point measurements from the network of KNMI wind stations using simple versions of a 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 (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 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 and to assess how this method compares to the current practice of interpolating sparse point measurements. An overview of this project is given in Groeneweg et al. (2011) and will not be reproduced here. This report is part of Work Package 1 (WP1) of the project. The main focus of WP1 is setting 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.

This report contributes to reaching the following Milestones of WP1 as defined in the project overview: i) Approved model set-up, ii) Simulation of 17 storms completed, and iii) Evaluation of high-resolution simulation of 17 storms with observations. Since these Milestones are foreseen in June, September, and December of 2012, respectively, the current report only presents preliminary results: it is an interim report.

1.3 Objectives

As part of the SBW Wind Modelling project, Groen and Caires (2011) selected and described 17 storm periods that can be used for testing the capability of the model to simulate extreme wind events. So far, simulations of the storms of January 1990 and November 2006 have been made. The 1990 storm was selected for its high hydraulic loads along the western Dutch coast and extremely high wind velocities. The 2006 storm was primarily selected for its record-breaking surge levels in the Delfzijl area. The aim of the present report is to evaluate these first two simulated storms using available observations.

1.4 Overview of activities in the reporting period

The reporting period is November – December 2011. This report presents interim results concerning the following subjects:

1. Set-up of the high-resolution atmospheric model (WP1, activity 1)
2. Assessment of the high-resolution model results using available wind measurements (WP1, activity 3)
3. Comparison of storm wind fields from high-resolution model simulations with storm wind fields from interpolating measurements (WP1, activity 5)

Sub 1. Set-up of the high-resolution atmospheric model

To perform high-resolution numerical simulations the Harmonie model (www.hirlam.org) has been selected. It has been developed by the HIRLAM and ALADIN consortia, an international cooperation comprising 24 countries. Harmonie will be the next KNMI weather forecasting model from 2012 onwards. It is run at a high resolution of 2.5 km. As such, it is capable of resolving sharp gradients like coastlines and modelling the impact of urban areas on wind. For the present study choices have been made on model version, the forecast strategy, the model domain, and boundary conditions. More details on the model set-up are given in Section 2.2.

Sub 2. Assessment of the high-resolution model results using available wind measurements

One of the aims of the SBW Wind Modelling project is to obtain reliable stresses above open water. Since a direct evaluation of stress is not possible, (surface) wind observations from the network of KNMI stations will be used as a proxy. Hence, parameter of primary interest is the 10-m wind speed. Unfortunately, the number of observations above open-water areas is limited. While using the available observations at sea as much as possible, we analyze observations above land to derive a more complete picture. For a more in-depth analysis other variables will be considered at some locations like wind direction, temperature and pressure.

Sub 3. Comparison of storm wind fields from high resolution model simulations with storm wind fields from interpolating measurements

In earlier studies, wind speed above open water were estimated from wind speed measurements over land by using a two-layer model (2LM) (e.g. Verkaik et al., 2003; Caires et al., 2009). Here, we compare ratios of wind speed over land to wind speed over water as provided by the 2LM to wind-speed ratios derived from the high-resolution model and observations (see Section 2.3 for details). In this way, we aim to identify strengths and weaknesses of both methods.

1.5 Report outline

Section 2 describes the measurement data, the Harmonie model and the basic characteristics of the 2LM. In Section 3, the Harmonie results for the two selected storms are discussed and compared to observations. The results for the 2LM are discussed in Section 4. Section 5 discusses challenges and issues that need further attention. Conclusions and follow-up steps are summarized in Section 6.

1.6 Acknowledgements

We thank our colleagues Sofia Caires, Gerrit Burgers (KNMI), Jan Barkmeijer (KNMI), and Fred Bosveld (KNMI) for their support and constructive comments. Jan Barkmeijer is acknowledged for performing the Harmonie simulations. Finally, we thank Douwe Dillingh for reviewing our work.

2 Data source description

2.1 Measurement data

2.1.1 KNMI stations

Figure 2.1 shows the locations of KNMI wind measurement stations in the Netherlands. Most stations are located above land; the open-water stations concern mostly oil platforms. The periods for which data are available varies between the different stations (see Wever and Groen (2009) for an overview). For the two storm periods examined in the present report, we use observations from the stations listed in Table 2.1. The data were extracted from the KNMI climatological database. Note that in the present study we use measured wind rather that potential wind.

WMO standards stipulate that wind observations are performed above short grass (if over land), in open terrain, and at height of 10 m above the surface. While most measurement stations above land meet these criteria, some coastal stations measure at a different height. This is also true for the offshore platforms. In compliance with the KNMI climatological database, for this interim report we apply the Benschop correction (Benschop, 1996) for stations with deviating measurement heights (Table 2.1). The Benschop correction transforms the observed wind at the measurement height to the reference 10-m level using a logarithmic wind profile and the local roughness. Over sea, the Benschop correction applies a fixed roughness length of 0.0016 m. This value originates from applying a Charnock relation with a Charnock constant of 0.032 and a normative 10-m wind of 15 m/s.

For the evaluation, data from the KNMI climatological database have been used. Detailed information on measurement systems, procedures and algorithms can be found in the *Handboek Waarnemingen* (Royal Netherlands Meteorological Institute, 2001). For wind speed the hourly averaged values are archived, together with the average over the last 10 minutes of each hour and the maximum gust that occurred during the hour. For wind direction the average value over the last 10 minutes of each hour is archived. For temperature, humidity, and pressure the hourly values represent 1-minute averaged values.

2.1.2 RWS stations at IJsselmeer

As an additional data source, observations from various stations operated by Rijkswaterstaat in the IJsselmeer and Slotermeer are utilized for the 2006 storm. In 1990, these data were not available yet. The site locations are added to Figure 2.1. The measurement height is 10 m above (the slightly varying) water level. For consistency with the KNMI stations described above, we utilize hourly averaged values of wind speed. Details on the instrumentation can be found in Bottema (2007).

2.2 Harmonie

2.2.1 Model characteristics

In this study, the model Harmonie is used for numerical simulations. In principle it could be used for horizontal scales of the order of 100 m, thereby resolving mesoscale circulations such as cumulus convection. However, due to computational constraints, we use a horizontal resolution of 2.5 km, similar to the resolution of the version that will be used at KNMI for operational weather forecasts. For this resolution, the Hirlam-Aladin consortium has extensively tested the model.

Harmonie is a limited area model. Its computational domain is a restricted geographical area and at the boundaries data must be provided by another model. We use a domain of roughly 1000 km x 1000 km, and use boundary data from ERA-Interim re-analysis simulations, see next Section (2.2.2.).

Harmonie is a so-called non-hydrostatic model. This means that instead of employing the hydrostatic approximation, which often breaks down in severe-weather events, the vertical momentum equation is solved explicitly. 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 (De 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 surface and soil processes. Part of it are the 1-D column model CANOPY, which describes the interaction between the boundary layer and the canopy (Masson, 2009), and the so-called Town Energy Budget urban canyon model (Masson, 2000). In addition to the standard Harmonie CY36h1.3 version, the latest update to the mass-flux convection scheme (EDMF-M) was used. For the time being, the ECUME module, which takes into account effect of atmospheric convection, precipitation and gustiness on surface fluxes over sea, was switched off. Further experiments must point out if ECUME can be included and gives better results than a simple parameterization of ocean surface roughness. In the present study, the wind speed dependent Charnock relation was used:

$$z_0 = \alpha \frac{u_*}{g},$$

where z_0 represent the roughness length for momentum, u_* is the friction velocity, g is the acceleration due to gravity, and α is the Charnock constant taken as 0.015.

The Harmonie model 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 .

2.2.2 Set-up of simulations

In this project, the following initial configuration has been used. The horizontal integration domain was defined in such a way that it encompasses the ZUNO (ZUidelijk NOordzee model) domain, which is frequently used in studies with hydrodynamic models. To satisfy this constraint, a 489 x 489 grid point domain at 2.5 x 2.5 km^2 grid resolution was constructed. In the vertical, 60 model levels are employed with the lowest model levels situated at around 10, 30, and 60 m. The model time step is 1 minute.

The lateral boundary conditions are provided by the ERA-Interim reanalysis dataset from the ECMWF (European Centre for Medium-Range Weather Forecasts, www.ecmwf.int). It comprises full 3D analyses at a spectral resolution T255, corresponding to a grid resolution of approximately 80 km. The temporal resolution is 6 h. Starting from each available ERA-Interim analysis (at 0, 6, 12, and 18 UTC) 6-h forecasts are performed with Harmonie. Lateral boundary conditions are obtained by interpolating ERA-Interim analyses at initial time and at T+6 h to a grid resolution of 0.5 degree (lat-lon projection). The sea-surface temperature is prescribed from ERA-Interim as a bottom boundary condition. Values are obtained by interpolating consecutive ERA-Interim analyses in time to the Harmonie grid.

Parameters like albedo and roughness length above land are prescribed from ECOCLIMAP, which is a global dataset at a 1km 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).

The storm periods specified in Section 1.2 have been simulated with Harmonie. For the 2006 storm the hindcast period starts at 28 October and ends 3 November (7 days). The January 1990 hindcast starts at 21 January and ends 3 February (14 days). The latter period has a longer duration in order to capture a second (minor) storm depression that passed the Netherlands at 28 January.

2.2.3 Model output

For the current simulations, the model state is archived every hour. Full 3D fields of, for example, zonal (*u*) and meridional (*v*) component of wind, temperature, rain, and cloud-ice, together with an extensive set of 2D fields are stored.

To enable a comparison with station data, Harmonie output is required at measurement locations, which in general do not coincide with grid points of the model. In the present analysis, Harmonie output at the grid point that is nearest to the measurement location is taken as representative for the model output at the measurement location. As the resolution of Harmonie is only 2.5 km, we expect that this procedure is accurate enough.

2.3 The two layer model for spatial interpolation

2.3.1 Model characteristics

Since the work of Wieringa and Rijkoort (1983), the concept of a simple two-layer model (2LM) has frequently been used in the analysis of Dutch wind measurements (e.g. Verkaik et al., 2003; Caires et al., 2009). Its basic formulas are presented in (Caires et al., 2009) and will not be reproduced here. These formulas have been implemented in several (unofficial) Matlab scripts that may be applied in other Matlab scripts for analysis purposes.

The type of application of the 2LM in this report is rather basic: it consists of the translation of an observed local 10-m wind at a single location (at land) to another single location (having a large area of water in the upwind direction), similar to the analysis reported in Section 5.2 of (Caires et al., 2009). See also Figure 2.2.

Additional assumptions applied in the present analysis are:

- Directional roughness length information at the measurement locations is taken from tables applied in earlier SBW studies. An example of the applied information is presented in Figure 2.3.
- The 10-m wind speed and direction at the land location are the measured values.
- The wind direction at the water location is assumed to be equal to the wind direction at the land location.
- Only for wind directions at the water location for which the local roughness length in the roughness table is smaller than 0.0002 m, the upwind area is regarded to be water. For other wind directions, a dummy value is attributed to the wind speed at the water location.
- Only at time steps for which all[1] wind speeds exceed a threshold of 8 m/s the water-land wind speed ratio is computed.

2.3.2 Set-up of simulations

The analysis is performed for the full time windows of the storms of January 1990 and November 2006, for several pairs of water-land stations. For presentation purposes, only a small set of pairs of water-land stations is selected. These pairs are presented in Figure 2.4.

Schiphol (240) is selected as the (only) land station, since this has been the main reference wind location for the HBC assessment up to now. IJmuiden (225) is relatively nearby Schiphol and therefore these two make a pair for which neglecting the spatial variation in weather systems is relatively justifiable. Hoek van Holland (330) is a coastal station like IJmuiden, but at a larger distance from Schiphol. Rotterdamse Hoek (902) is situated more inland, but in a large lake (IJsselmeer) and Slotermeer (929) in a relatively small lake.

2.3.3 Model output

The output of the 2LM is the local wind speed at the water location for every time step. However, the analysis will be performed on the 10-m water-land wind speed *ratio* for all time steps.

1. *I.e. at both the land location and the water location, and from measurement, Harmonie and 2LM results.*

3 Analysis of Harmonie results

As described in Section 1.2, two storm periods have been simulated with HARMONIE so far. Here, we compare the model results with observations. Focus is on the temporal and spatial evolution of the magnitude and the direction of the 10-m wind. To augment the understanding of these observations, also model results for other variables like pressure, temperature (at various levels) and elevated winds will be shown.

Section 3.1 described the results for the November 2006 storm, Section 3.2 for the January 1990 storm. In both cases, first the synoptic situation is briefly described. Then, time series of the 10-m wind during the main event for selected stations are presented. The choice for these stations is inspired by the specific characteristics of the storms. This analysis is followed by a more statistical analysis of the complete reanalysis period. Each section concludes with some additional results, which provide further insight in the model's behaviour.

3.1 The storm of 1 November 2006

3.1.1 Large-scale situation

Between 30 October and 2 November 2006 a storm depression moved from Scotland via Norway to Denmark. At the south side of the depression an area with a strong pressure gradient developed. Around 18 UTC the back-bent occlusion passed the Dutch coast, as illustrated in the analysis of Figure 3.1. Behind the occlusion, the stormy wind veered from west to northwest, leading to a long fetch over the complete North Sea. In the early morning of 1 November this gave rise to record-breaking surge levels at Delfzijl (+4.83 NAP).

Along the Dutch coast, maximum wind velocities were observed in the early morning of 1 November at the passage of a sharp trough. To illustrate the general Harmonie model analysis, Figure 3.2 presents mean sea level pressure (p_s) and the 10-m wind (U_{10}) for 6 UTC. As in the Hirlam analysis of 12 h earlier (Figure 3.1), the long fetch over the North Sea is clearly visible in the pressure field. The wind field shows a narrow band of Bft 9 winds over the North Sea. Near the Dutch coast some patches with Bft 10 can be distinguished.

3.1.2 Analysis of 10-m winds

Figure 3.3 presents time series of 10-m wind speed and direction for a selection of stations (see Figure 2.1 for the location of the stations) for the 24 hours following 31 October 12 UTC, which coincides with the peak of the storm. Since the storm mainly affected the northern Dutch coast, most of the selected stations are located here. The stations F3, K13 and Huibertgat are located in open water, while Lauwersoog is located at the coast. Leeuwarden and Nieuw Beerta are located about 20 km inland. The stations Marknesse and RWS-FL2n are added to highlight the contrast between the open water of the IJsselmeer and the surrounding land.

For all stations, the marked veering of the wind on the passage of the occlusion in the afternoon is clearly visible in both the observations and the model. The accompanying increase in wind speed is also well-represented in the model. Highest wind speeds are recorded at Platform F3, about 150 km north of the Wadden Islands. Shortly after midnight, hourly values of 26 m/s, Bft 10, are observed. The timing and magnitude of the maximum agrees well with the model results, although the observations show a stronger decrease after the peak than the model suggests. Two hours after Platform F3, U_{10} at Huibertgat reaches its maximum of 23 m/s, Bft 9. The wind speed at K13, which is located about 200 km west of Huibertgat, is constantly between 16 and 19 m/s, Bft 7-8. Contrary to F3 and Huibertgat, a clear storm peak does not occur. The platform is not located in the main band of high wind speed (cf. Figure 2.1 and 3.2), illustrating the small spatial scale of the extreme wind field. The temporal evolution at Lauwersoog, which experiences open water wind for northerly wind direction, is very similar to Huibertgat. The modelled U_{10} is slightly lower than observed, but the temporal evolution is well captured. At Leeuwarden and Nieuw-Beerta both modelled and observed U_{10} are clearly lower than at the Lauwersoog and Huibertgat. For both stations the model captures the temporal evolution of the wind rather well.

Both modelled and observed U_{10} at RWD-FL2n, located only 2 km off the coast of the Noordoostpolder, are persistently higher than at Marknesse. These results suggest that Harmonie is well-capable of simulating representative winds above the open water of the IJsselmeer. The discontinuities between the consecutive 6-h simulations (in particular the low values of U_{10} for the initial time of each run) indicate that these details are not present in the coarse resolution ERA-Interim. The discontinuities are the result of the specific model set-up, and are further discussed in Section 5 (Discussion).

As mentioned before, the storm mainly affected the northern part of The Netherlands. In the remainder of the country the 5 Bft threshold was hardly exceeded. For example, at Vlissingen and De Bilt the observed U_{10} did not exceed 10 m/s, at Eindhoven the average wind over the considered 24 h was only 5 m/s. This north-south gradient is well-represented in the model.

So far, only model results for the main storm event have been analyzed. As indicated in Section 2.2.2, the complete Harmonie hindcast covered 7 days, starting at 28 October, 0 UTC. To give an impression of the model performance over the complete period, simple statistics have been calculated based on observed and modelled U_{10}. Table 3.1 presents bias and root mean square error (rmse) scores for a wider selection of stations spread over the entire country. The results are discussed in Section 5 together with the results of the 1990 storm.

Figure 3.4 presents scatter plots of p_s and U_{10} for Leeuwarden for the complete hindcast period. The model captures the variations in p_s extremely well, which is true for most other stations where pressure data are available. Since pressure differences drive the large-scale winds, this puts confidence in the model's ability to reproduce the large-scale structure of the storms. The correlation in the U_{10} panel is lower than for p_s. Still, de model is able to capture the temporal evolution of U_{10}. This seems to be especially true for higher wind speeds of, say, above 10 m/s. The larger scatter for lower wind speeds may be related to roughness and/or stability issues.

3.1.3 Additional results

Surge in the Eems-Dollard estuary

For Delfzijl, forecasts with a hydrodynamic model predicted a maximum surge level of +4.00 m. However, in reality a water level of +4.83 m occurred. Den Heijer et al. (2007) suggest that part of the discrepancy is due to the relatively coarse resolution of the Hirlam wind field (11 km) that served as input for the surge model. The small-scale topography of the Eems-Dollard estuary would require a higher resolution.

Figure 3.5 shows the Hirlam wind field that was fed into the hydrodynamic model. It shows a strong decrease of U_{10} when moving from the North Sea into Eems-Dollard estuary where Delfzijl is located. Especially for northerly winds, it is questionable whether the wind speed decreases so strongly. Den Heijer et al. (2007) show that Hirlam underestimates U_{10} for the station of Nieuw Beerta, which is located just south of the Dollard. Figure 3.5 shows that this is not the case for the current 2.5-km resolution HARMONIE forecast, suggesting that the winds in the basin decrease not as fast as in Hirlam. This is confirmed in Figure 3.5, which shows a map of U_{10} for the HARMONIE model. The wind speeds above the open water of the basin are much higher than in the Hirlam forecast, which seems to be more realistic.

When Den Heijer et al (2007) used Hirlam winds from the open-water station Huibertgat for all water areas, they obtained an increase in storm surge of 0.33 m. Luijendijk et al. (2011) obtained comparable results when driving a hydrodynamic model with wind fields from the present Harmonie simulation. Although the modelled surge levels still underestimate the observed water level, this example clearly demonstrates the added value of a high-resolution model for making surge forecasts in areas with complex topography.

Modelling surface stress and momentum roughness

This report focuses on the representation of the near-surface wind field. However, in the end the surface-stress field drives the evolution of the surge. Hydrodynamic models use 10-m winds as an input variable and convert them to surface stress. However, surface stress is also directly computed by Harmonie. As such, it would be interesting to provide stress fields obtained from Harmonie directly to a hydrodynamic model. To illustrate the capability of Harmonie to model surface stress, Figure 3.6a shows the modelled stress at 1 November, 6 UTC. Not surprisingly, stress levels are highest in the area of maximum winds.

For completeness, the calculated z_0 above water is show in Figure 3.6b. Clearly, the roughness increases for increasing wind speeds. The Benschop correction applied to open-water observations with deviating measurement height utilizes a fixed value of z_0 (0.0016 m, see Section 2.1), which is too large in calm areas and too small in areas of high wind speeds.

3.2 The storm of 25 January 1990

3.2.1 Large-scale situation

On 25 January 1990 a rapidly developing storm depression moves from the Irish Sea towards the Skagerrak. During the day, an area with Bft 11 winds moves from the British Channel along the Dutch coast towards Denmark. In the warm sector of the depression very mild air is transported northerly. Three days after this main event a second low-pressure area is passing with a strong southerly wind field, a few days later followed by a weaker third system.

To capture all these variations, a 14-day Harmonie hindcast has been performed. In The Netherlands, the main storm reached its maximum intensity around 18 UCT. For this moment in time, Figure 3.7 shows various model fields. The top-left panel shows p_s. Around a deep low-pressure off the British coast, the isobars are packed closely together. The top-right panel shows the temperature at 850 hPa (around 1300 m). The very mild air that has been transported northward in the warm sector is clearly visible. The tongue with maximum temperatures has passed The Netherlands already a few hours earlier and, while getting progressively narrower, extends now over Germany and Denmark and than curves into the Central North Sea. The bottom panels both show U_{10} for a subsection of the domain: the left panel gives the analysis from ERA-Interim (resolution 0.5°), the right panel shows the 6-h forecast with HARMONIE valid at the same time. While in ERA-Interim sharp gradient along the coasts and the IJsselmeer are smoothed out, they are clearly resolved in the Harmonie run. Furthermore, large urban areas like London, Amsterdam, and Rotterdam show lower wind velocities, as does the forested area of de Veluwe.

3.2.2 Analysis of 10-m winds

Figure 3.8 presents time series of wind speed and direction for a selection of stations for 25 January 1990. The two platforms K13 and Europlatform are located west of the west coast. Huibertgat is also located in open water, but this station is located close to the island of Schiermonnikoog. The coastal stations Vlissingen and IJmuiden are selected because the storm moves in from the west. Earlier analysis has shown that wind speeds above land were remarkably high (Caires et al., 2009). Therefore, two stations relatively close to the coast were selected, i.e. Schiphol and Rotterdam. Soesterberg is situated more inland.

For all selected stations the evolution of the wind direction is very well represented by the model. Highest wind speeds are observed at open water: K13 and Europlatform record a maximum hourly wind of 30 m/s (11 Bft). The model reproduces these values reasonably well. At the two stations along the west coast, the storm peak is lower than above open water. This is especially true for Vlissingen. While the model follows the course of the observations quite well, it underestimates the strength of the storm peak. The model represents the sharp increase of U_{10} around 15 UTC at Huibertgat rather well. Contrary to the rest of the country, in the northeastern part the storm peak is rather broad in time: high wind velocities persist for multiple hours. Again, the model is capable of reproducing this feature. The three inland stations show comparable behaviour. Most of the time model and observations are closely together, but, as for the coastal stations, the peak of the storm is underestimated.

The hindcast of the January 1990 storm covered 14 days. Figure 3.9 shows scatter plots of modelled versus observed values of hourly wind speed for four selected stations for the complete 14 days. At Platform K13 the correlation seems largest: de data spreads nicely around the 1:1 line. This is also true for U_{10} values of over 25 m/s. The wind speed at IJmuiden appears to be biased low in the model for the period considered (see Section 5.2). At the more inland stations Soesterberg and Schiphol the model represents U_{10} reasonably well, but the extreme wind velocities are underestimated. For the complete 14-day hindcast bias and rmse scores for a broader selection of stations are summarized in Table 3.1.

3.2.3 Additional results

Wind and temperature in the lowest 2 km

As mentioned in Section 3.2.1, in the warm sector of the storm very mild air is advected northward. The changing air mass may change the stability of the lower atmosphere and impact on the vertical transfer of momentum. In earlier reports, it was suggested that this might explain the relatively high values of U_{10} observed inland in comparison with values observed at the coast. Here, we present the modelled wind and temperature structure of the lowest 2000 m of the atmosphere. Figure 3.10 gives time series of modelled temperature at various vertical levels for IJmuiden and Schiphol. At 850 hPa the arrival of the warm air really starts at around 6 UTC at both stations. Somewhat later, at 9 UTC, the temperature in the boundary layer exhibits a marked jump. At Schiphol the 2 m temperature follows the increase in temperature aloft. At IJmuiden the situation is different. Because the sea surface temperature is rather low (around 280 K), a large gradient arises in the air layer adjacent to the water surface. This is reflected in the IJmuiden 2 m temperature, which is clearly lower than the temperature at 10 m. It appears that the boundary layer at Schiphol is well-mixed from the surface upward. At IJmuiden the boundary layer is also well-mixed, apart from a very shallow stably-stratified layer just above the sea surface of only a couple of meters thickness. Further research is needed to investigate the impact of this type of process on U_{10}.

Figure 3.11 presents vertical profiles of wind and temperature for 25 January 1990 for De Bilt and Europlatform. Some notable differences can be pointed out between the land station and the open-water station. First, the increase of wind speed with height. At Europlatform the wind speed increases much faster with height than at De Bilt. The impact of surface roughness is apparent in a layer of about 1000 m. The temperature profiles show the arrival of the mild air between 6 and 12 UTC. At 6 UTC the temperature near the surface is lower inland than at sea, while at midday the opposite is true. In future studies, the relation between the vertical temperature structure of the lower atmosphere on the wind profile will be examined in more detail.

Evolution of mean sea level pressure gradient

Because a widespread underestimation of the storm peak has been identified, we also examined the surface pressure field. To a large extent, it is the gradient in p_s that determines the wind velocity. Figure 3.12 shows the pressure distribution over The Netherlands for 25 January 1990, 18 UTC. The left panel show the +6 h Harmonie forecast that was initialized from ERA-Interim at 12 UTC, the right panel shows the pressure distribution as obtained from a spatial interpolation of pressure observations from KNMI stations. The model clearly underestimates the observed pressure gradient: between De Kooy and Gilze-Rijen: the observed pressure difference amounts to 12.7 hPa, while the difference in the model remains limited to 10 hPa. As the distance between the two stations is 150 km, this corresponds to a difference in geostrophic wind speed of 74 – 58 = 16 m/s (taking a latitude of 52°). The geostrophic wind is the theoretical wind that would result from an exact balance between the Coriolis force and the pressure gradient force. Although geostrophic wind velocities cannot be directly translated to U_{10} (especially for extreme storm events), the numbers indicate that the underestimation of the modelled pressure gradient is quite significant.

Thanks to its highly advanced data assimilation system, in the ERA-Interim analysis valid at 18 UTC the pressure values are closer to the observed values. This can be seen from the lower panels of Figure 3.12, which show time series of observed and modelled p_s at De Kooy and Gilze-Rijen. As a result, the 10-m winds in the Harmonie run initialized by this analysis shows slightly increased wind speeds compared with the simulation that was started at 12 UTC. This can be inferred from Figure 3.8, most notably for the stations, Europlatform, IJmuiden, Schiphol and Rotterdam. The underestimation of the surface pressure gradient clearly contributes to the underestimation of the storm peak wind speeds in the western part of The Netherlands. Apparently, for the present storm the model has difficulties in correctly reproducing the large-scale dynamical evolution.

4 Analysis of land-water wind speed ratios

The results for the water-land wind speed ratios are presented per pair of water-land station and per storm. For every combination a set of three graphs is presented:

- The top graph shows the measured wind speed in time at both the land and the water location. This indicates the most extreme (and thus interesting) time windows within the overall time window. Moreover, the graph provides information about the fluctuations (noise?) in the measured signal. For measuring heights other than 10 m the Benschop correction has been applied.
- The bottom left graph shows the water-land U_{10} ratio in time for the three different sources: measurements, Harmonie and 2LM. For convenience, the time scale is in line with the time scale of the top graph.
- The bottom right graph shows the correlation between the computed (Harmonie and 2LM) water-land wind speed ratios and the measured ratios. For convenience, the (computed) ratio axis is in line with the ratio axis in the bottom left graph.

The basic results are presented in Figure 4.1 to 4.6. The following observation can be noted:

- The measured ratio shows the largest variation (0.9-2.2), the ratio from 2LM the smallest (1.3-1.7) and the ratio from Harmonie lies in between (1.0-1.7).
- Although the scatter is rather large, the agreement between Harmonie and the measurements is in most cases better than the agreement between 2LM and the measurements.
- In many cases the 2LM ratios are higher than the Harmonie ratios, especially for Schiphol - Hoek van Holland (January 1990) and Schiphol - Slotermeer (November 2006).

Most of these observations are quite well in agreement with the expectations:
The ratios from the 2LM show the effect of difference in roughness only, whereas the ratios from Harmonie may - in addition - show effects of spatial variation of weather systems and atmospheric stability. For Slotermeer the 2LM ratios are probably too high due to the assumption of a meso roughness governed by water; this assumption is invalid for this relatively small lake.

For the Schiphol/IJmuiden combination, the effect of increasing the threshold for wind speeds to be analyzed to 10 m/s is presented in Figure 4.7. The reduction in number of high values of the measured ratio (for which the agreement with the computed ratios was rather poor) is remarkable (cf. figures 4.1 and 4.7). This may be explained by the fact that mostly nocturnal points are excluded. During the night, the boundary layer at Schiphol is probably stably stratified, which leads to an underestimation of the wind speed at the blending height. As a result, the estimate for U_{10} at IJmuiden will also be too low. Thus, for these conditions, the water-land ratios obtained by the 2LM will also be lower than observed. Comparison of Figure 4.1 and 4.7 suggests that Harmonie is better capable of including this stability effect.

The effect of applying an 3-hr moving average (using the original wind speed threshold of 8 m/s) is presented in Figure 4.8. The scatter is significantly reduced and the agreement between Harmonie and measurements is quite good (cf. figures 4.7 and 4.8).

5 Discussion

In previous Sections, two Harmonie hindcasts were evaluated using available wind observations. Although the results are quite promising, several topics have been identified that need further attention. Here, we discuss issues on the model set-up, the impact of terrain roughness, and some directions for future evaluation.

5.1 Model set-up

5.1.1 Model domain

The present model domain measures 1220 x 1220 km, centred over The Netherlands. Using Harmonie, Jacobs et al. (2011) conclude that the choice of the domain size is crucial for a correct representation of severe weather phenomena like intense precipitation and squall-lines. Earlier research with limited area models indicated that the domain size has relatively little impact on the simulation of storms (Van Meijgaard, 2011). Experiments with various domain settings should point out the optimal size.

5.1.2 Forecast cycle

As apparent in many of the presented time series, discontinuities arise at transitions between the consecutive 6-h HARMONIE runs. This is especially true for stations that are located close to significant changes in terrain roughness as, for example, the RWS-FL2n station (see Figure 3.3), which is located in the IJsselmeer. In the host model (ERA interim) small scale features like coastlines are not realistically represented. Consequently, they are not present in the initialization fields of the 6-h HARMONIE forecasts. After initialization, the HARMONIE model quickly develops finer structures. To allow for smoother transitions between the consecutive runs, experiments with the modelling set-up should be performed. Not only to avoid the unwanted ‘jumps’ in the time series, but also to reduce the impact of ERA-Interim on the first few hours of the simulations (in other words: to allow some spin-up time for the HARMONIE model) (see also Frank and Majewski, 2006). Probably, a balance exists between allowing for enough spin-up time at the one hand and a decrease in forecast quality (due to increasing lead times used in the analysis) at the other hand.

5.1.3 Post processing

The frequency at which the model state is archived should be considered. For this interim study, only instantaneous (i.e. 1-minute averaged) values at each hour were available. These were compared with hourly averaged observations. Since the model is run at a high resolution, it is expected that, just as in reality, the variability within an hour is substantial. To enable a more straightforward comparison between model results and observations, we suggest constructing both hourly averaged and 10-minute averaged model output. Note that 10-minute averaged observations for most stations are only available from 2003 onwards (for some stations as from 1995) (Wever and Groen, 2009).

5.1.4 Marine boundary layer

For the time being, the ECUME module of the marine boundary layer was switched off, and a simpler parameterization was used. Later it will be investigated if ECUME can be included and gives better results than the presently used simple parameterization of ocean-surface roughness.

5.1.5 Quality of the forcing data set

Apart from the modelling strategies for the high-resolution model, the quality of the host model plays a crucial role in the hindcasting of case studies (especially when the hindcast time is only 6 h). The results of the present study suggest that the ERA interim dataset is of high quality. This is best illustrated in the accurate representation of the mean sea level pressure. The performance of the ERA interim reanalysis is extensively described by Dee et al. (2011). As a case study on severe weather, they study the representation of a major storm event that occurred in 1987. After stressing the crucial role of data assimilation, they conclude that ERA interim performs better than its predecessor ERA40 in terms of the storm intensity.

5.2 Representativeness of observations and model roughness

As commonly known, U_{10} is very sensitive to local terrain roughness, which is often wind direction dependent. Numerical weather prediction models utilize grid boxes in which one values for the roughness length is assumed. Correlating point observations to grid-averaged wind velocities is an extremely difficult task. Since Harmonie operates at a resolution of only 2.5 km, it is expected to be less vulnerable to these issues than models that run on resolutions of 10, 25 or even 100 km are utilized. Still, differences in real and modelled roughness length are likely to induce differences in U_{10}. Further research is needed to compare the roughness map used in Harmonie with roughness lengths based on, for example, gustiness analysis (e.g. Wever and Groen, 2009). In this respect, the work of De Rooy and Kok should be mentioned, who downscale grid-box mean model results using information from detailed local roughness maps.

In Section 3.2.2 a low bias in the modelled U_{10} for the station of IJmuiden was identified for the storm of 25 January 1990. Careful analysis of Table 3.1 shows that this is also the case for the storm of 1 November 2006. It turns out that for most stations, the sign of the bias is equal for the two events; as shown in Figure 5.1 there appears to be fair correlation between the biases at various stations. This again suggests that model roughness and station representativeness play a decisive role in the evaluation of wind observations with model data. Note that apart from roughness issues also systematic model deficiencies could play a role.

5.3 Model evaluation

For the evaluation of the remaining storms of the test set composed by Groen and Caires (2011), comparison of the model results with 10-m wind observations from KNMI stations will comprise a significant part of the analyses. In addition, other relevant meteorological parameters like, for example, temperature and humidity will be examined to assess the model's ability to model air mass transitions. The network of surface pressure observations in The Netherlands can be used to assess whether a mismatch between the model and the observations is probably due to the large-scale dynamics rather than to, for example, roughness length issues. Observations from high measurement towers and from regular atmospheric soundings can be used to assess the model's stability characteristics. As an addition to the network of observational stations, we will explore the use of scatterometer data for the evaluation, which may be helpful in investigating the spatial structure of extreme wind fields. The scatterometer is a satellite instrument that provides information on wind above sea by analyzing the interference of a radar beam with capillary waves at the water surface.

Measures should be defined that enable a quantitative evaluation of model performance. For example, criteria on the time that certain wind speed thresholds are exceeded or on the surface area in which the winds are stronger than a particular value. The rates at which storm winds intensify and weaken provide valuable information on their temporal evolution. Further analysis of simple statistics measures like the biases and root mean square errors can indentify areas in which the model systematically over- or underestimates the wind speeds. Analysis of the evolution of pressure (gradient) can be used to evaluate modelled pressure gradients, which provides insight in the storms spatial structure.

When, in the end-phase of the project, a 30-year hindcast with HARMONIE becomes available, additional analyses of more statistical character can be performed. For example, frequency distributions of modeled wind speed and diurnal and daily cycles can be compared with climatology. Also relations between wind ratio's at different levels and stability can be related to measurement sites with long records of vertical profiles like Cabauw.

6 Conclusions and follow-up steps

6.1 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 (Groeneweg et al., 2011). While in the past open-water winds were derived from spatially interpolating sparse point observations, the current project investigates the application of a high-resolution atmospheric model. As a starting point, this interim report presents a comparison of model results and observations for two of the selected storms, i.e. the November 2006 storm and the January 1990 storm. Modelling of the remaining storms of the test set will follow in the future. Furthermore, a comparison has been made between observations, high-resolution model outcomes and results of a simple two-layer model (Wieringa and Rijkoort, 1983; Caires et al., 2009) to interpolated near-surface winds in space.

The two storms were simulated with the Harmonie model, the semi-operational high-resolution (grid spacing of 2.5 km) forecasting model of KNMI. The forecasts are driven from ECMWF ERA-Interim reanalyses. The model gives encouraging results. Based on a comparison with wind observations we conclude that

1) the model is well-capable of simulating the characteristics of the two storms in time and space and
2) that the temporal variations of wind speed ratios between inland and coastal stations is more realistic in the high-resolution numerical model than in the previously applied 2-layer model.

For both storms, the extreme wind velocities of the storm peaks are well-represented in the numerical model, especially over open water areas where representativeness errors due to roughness differences play a minor role. For the 1990 storm, peak velocities over land are too low, which appear to be (at least partly) caused by an underestimation of the pressure gradient. The timing of air mass transitions (the passage of warm and cold fronts) is accurately captured by the model.

Drawing general conclusions based on only two cases is impossible. From the simulations of the two storms, indications exist that Harmonie, in the present set-up, underestimates wind speeds over land. This is in line with previous results and experiences with model simulations in general. Therefore, we should address this aspect carefully in the simulations of all 17 storms.

The benefit of the high-resolution model simulations is most obvious in areas with large roughness transitions. For both storms, we find that wind velocities near coastlines and edges of e.g. IJsselmeer and major urban areas are accurately resolved by Harmonie, while they are not present in the host model ERA-Interim. In areas with complex topography like the Eems-Dollard estuary, Harmonie calculates a much more realistic wind field than the 11-km resolution model Hirlam.

For the two simulated storms, we find systematic biases in 10-m wind for various stations. This points to a misrepresentation of the surface roughness at these stations. Other possible causes may be the apparent measurement height due to high water levels, inaccurate interpolation towards the 10-m level in case the measurements are performed at a deviating height above the surface, or yet unknown systematic model deficiencies.

The average ratio between open water and land stations as calculated by the 2LM is realistic for the present storms. The temporal variations in the ratios are typically underestimated. Harmonie captures these variations much better, although their amplitude is still too low. Since the spatial scale of the investigated storms is limited, the 2LM assumption of a constant macro wind is questionable. When the boundary layer at the land-point is stably stratified, the 2LM will underestimate the 10-m wind at the open-water point.

As final remark, note that, although only considering two storm periods, the assessed quality of Harmonie wind velocity fields is high in open-water areas. The model gives a better representation of the temporal and spatial evolution of the storm wind fields than previously used interpolation models. Being able to produce higher quality open-water winds is the main aim of the SBW Wind modelling project, since these (not those above land) are the winds affecting the quality of the HBC. This is why the related SBW knowledge gap focuses specifically on the computation of accurate open-water winds. These preliminary results are, therefore, rather encouraging in terms of the long-term goals of the SBW Wind modelling project, in particular for the derivation of the HBC for WTI 2017.

6.2 Follow-up steps

Although the modelling results of the present study are promising, during the analysis some aspects were encountered that need more attention in future analysis.

- In order to arrive at additional and more general conclusions there is need to simulate the remaining storms of the selection made by Groen and Caires (2011).

- Efforts should be made to further improve the model set-up. Here, we utilized subsequent 6-h forecasts. Consequently, jumps arise between the 6-h lead-time of one forecast and the analysis of the following run. This problem would be avoided when allowing an overlap between the consecutive runs. It also ensures sufficient spin-up time for the high-resolution model.

- The comparison of model results with point observations is hampered by the surface roughness. Comparison of the roughness used by the model with the observed roughness characteristics can explain differences between the model and the observations. Note that above open water the impact of surface roughness on model evaluation is of minor importance. If the difference in roughness characteristics between model and observations appear to be large, we suggest to correct modelled and observed wind speeds using a common local roughness lengths.

- To avoid the impact of surface roughness on the analysis we plan to utilize data from high measurement towers. This also enables an evaluation of the stability characteristics of the model. For the platforms on the North Sea we intend to evaluate the model at the height of the measurements besides interpolating the measurements to the 10-m level.

- In the framework of this interim report, instantaneous model results (1 minute averages) were compared with hourly averaged observations. To enable a more direct comparison of model results with observations, we strongly recommend to experiment with varying model output averaging times. Note that the present results suggest that the current approach gives valuable insights in the performance of the model, as well.

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Figures

Figure 2.1. Locations of KNMI wind measurement sites. Numbers indicate station codes. Rijkswaterstaat stations are given in red. (Adopted with modifications from Wever and Groen, 2009.)

Figure 2.2. Cartoon illustrating the procedure to transform local wind speeds from one location to another location. (Adopted from Caires et al., 2009.)

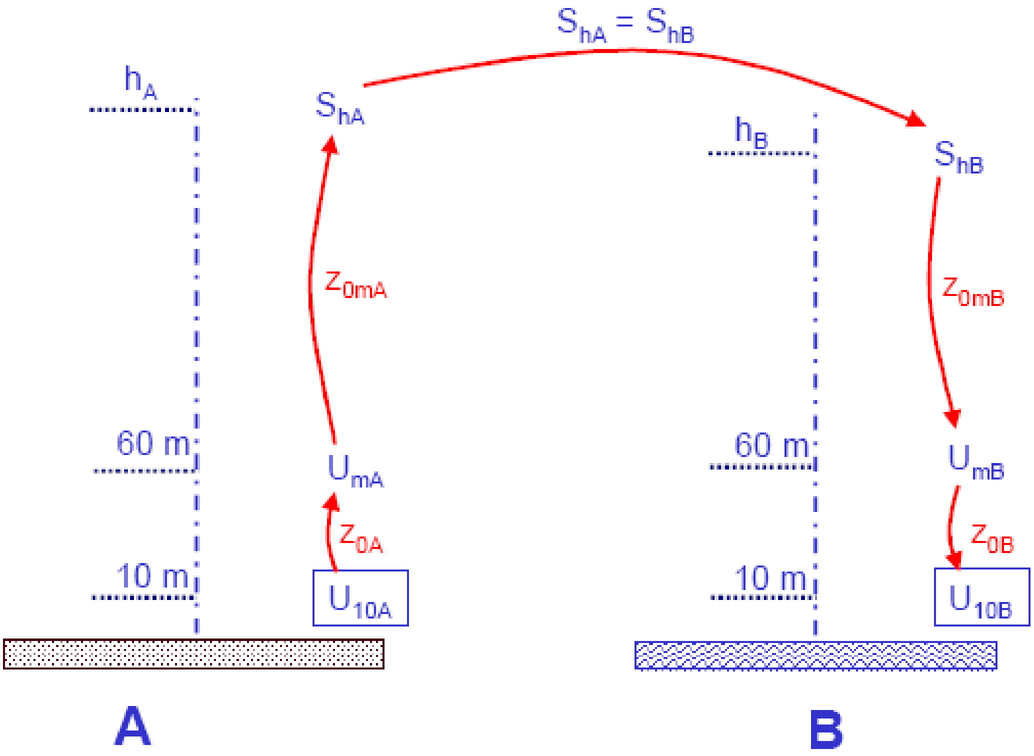


Figure 2.3. Directional information on local and meso roughness (per 2.5°) at Schiphol (240) as applied in the 2LM.

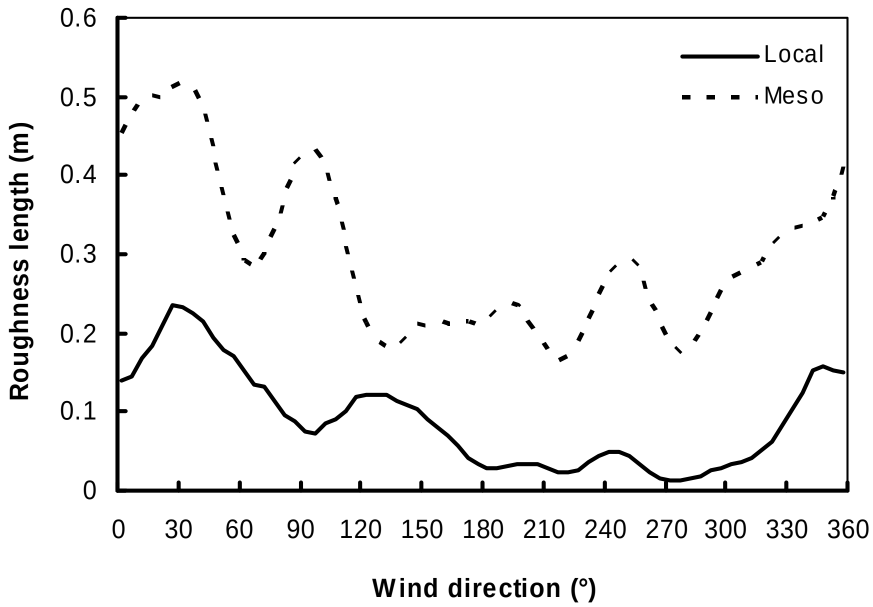


Figure 2.4. Pairs of water-land locations used in the 2LM.

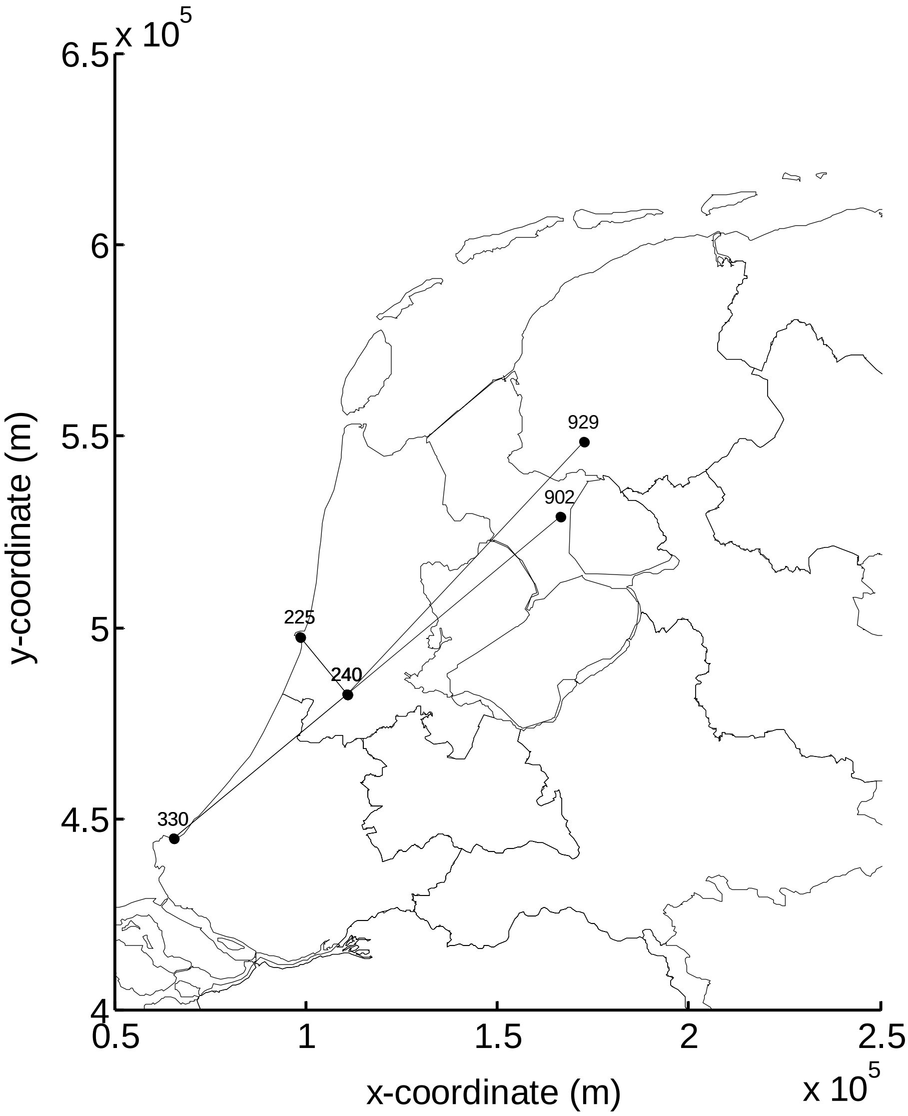


Figure 3.1 Synoptic analysis based on Hirlam model output.

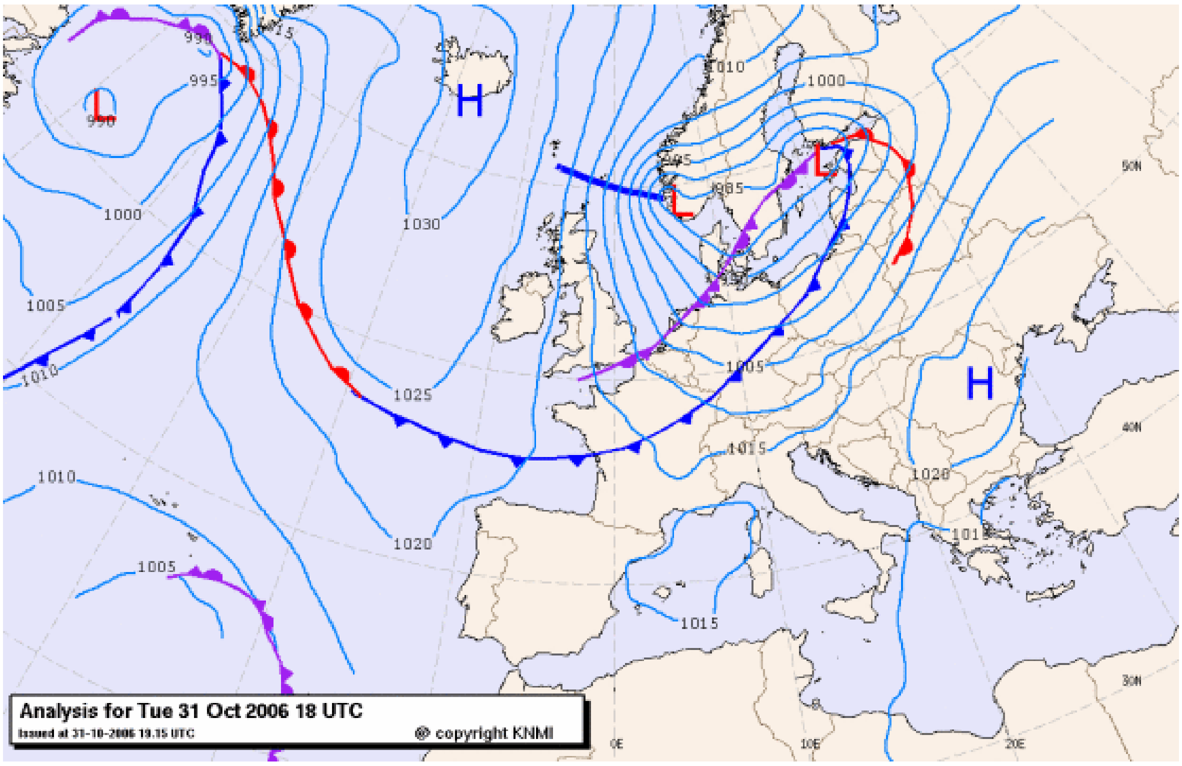


Figure 3.2. Harmonie fields of p_s (hPa) (left) and U_{10} (Bft) (right) valid at 1 November, 6 UTC.

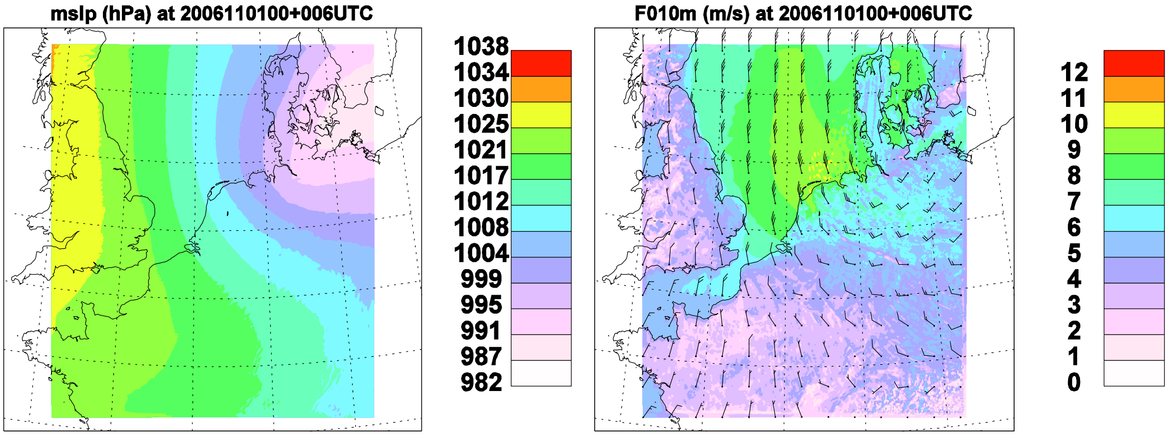


Figure 3.3. Wind speed and direction for selected stations for 2006103112 – 2006110112. Solid lines and crosses represent modelled and observed wind speed, dashed lines and plus-signs represent wind direction.

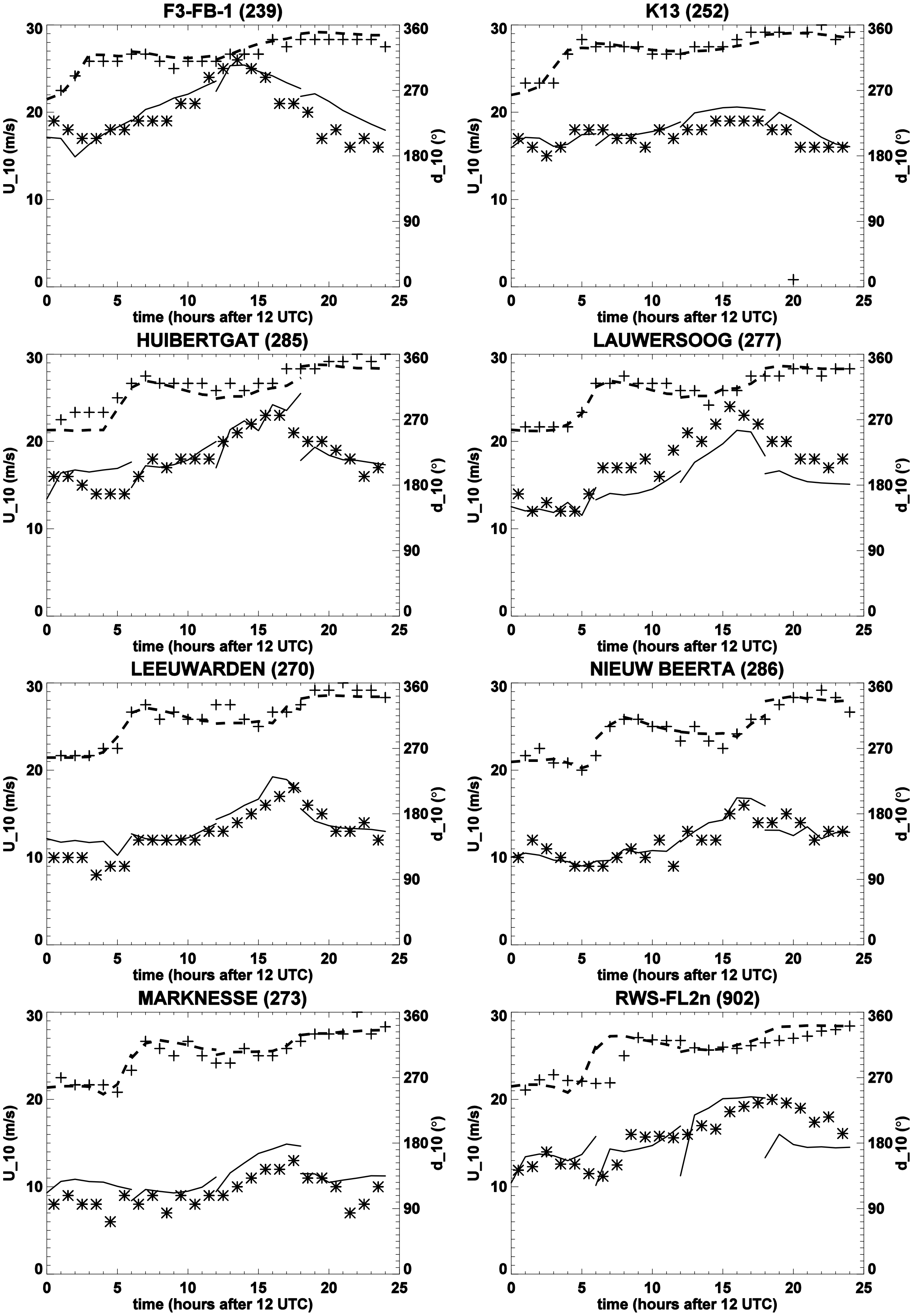


Figure 3.4. Modelled versus observed p_s and U_{10} for Leeuwarden for the full 7-day 2006 hindcast (+0 h forecasts are omitted).

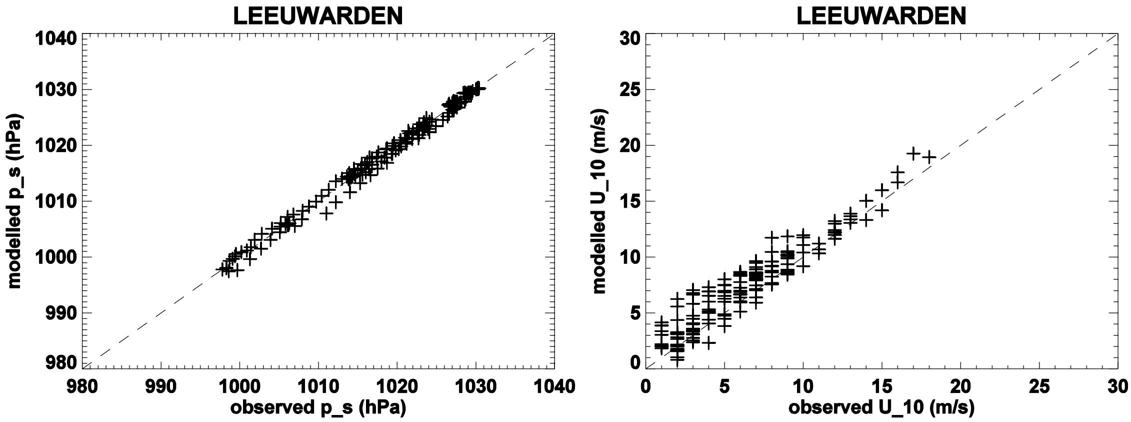


Figure 3.5. Detailed maps of the modelled 10-m wind field (in m/s) around the Eems-Dollard estuary for Hirlam (adopted from Den Heijer et al., 2007) (top) and the present Harmonie simulation (bottom).

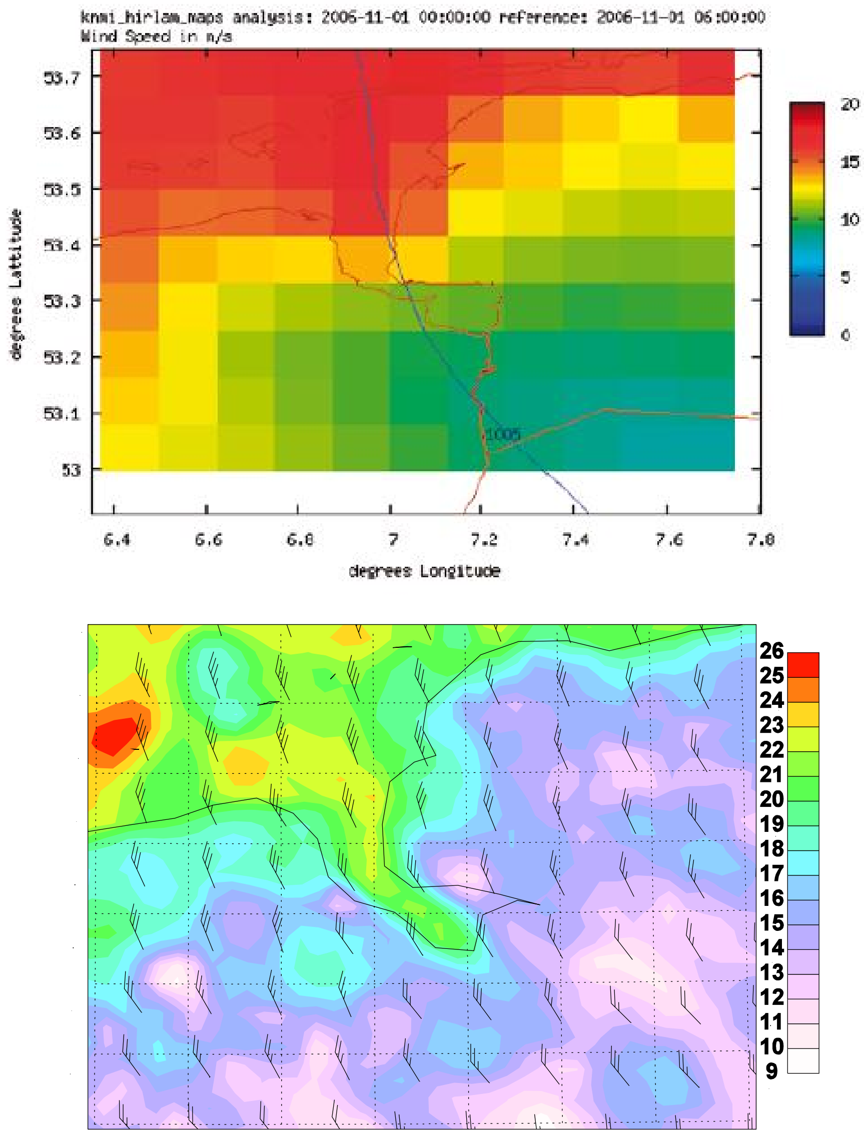


Figure 3.6. Examples of surface stress (N/m^2) (left) and roughness (mm) (right) fields as simulated by Harmonie (valid at 1 November, 6 UTC).

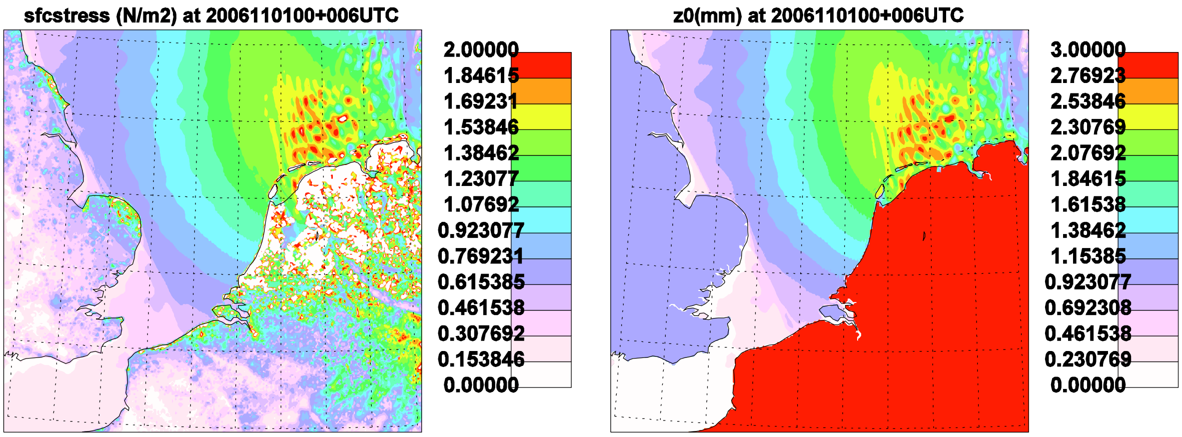


Figure 3.7. Overview of Harmonie model fields, valid at 25 January 1990, 18 UTC. The top panels show p_s (hPa) (left) and the T (K) at 850 hPa. The bottom panels show U_{10} (m/s) from the ERA interim analysis (left) and from a +6 h Harmonie forecast (right).

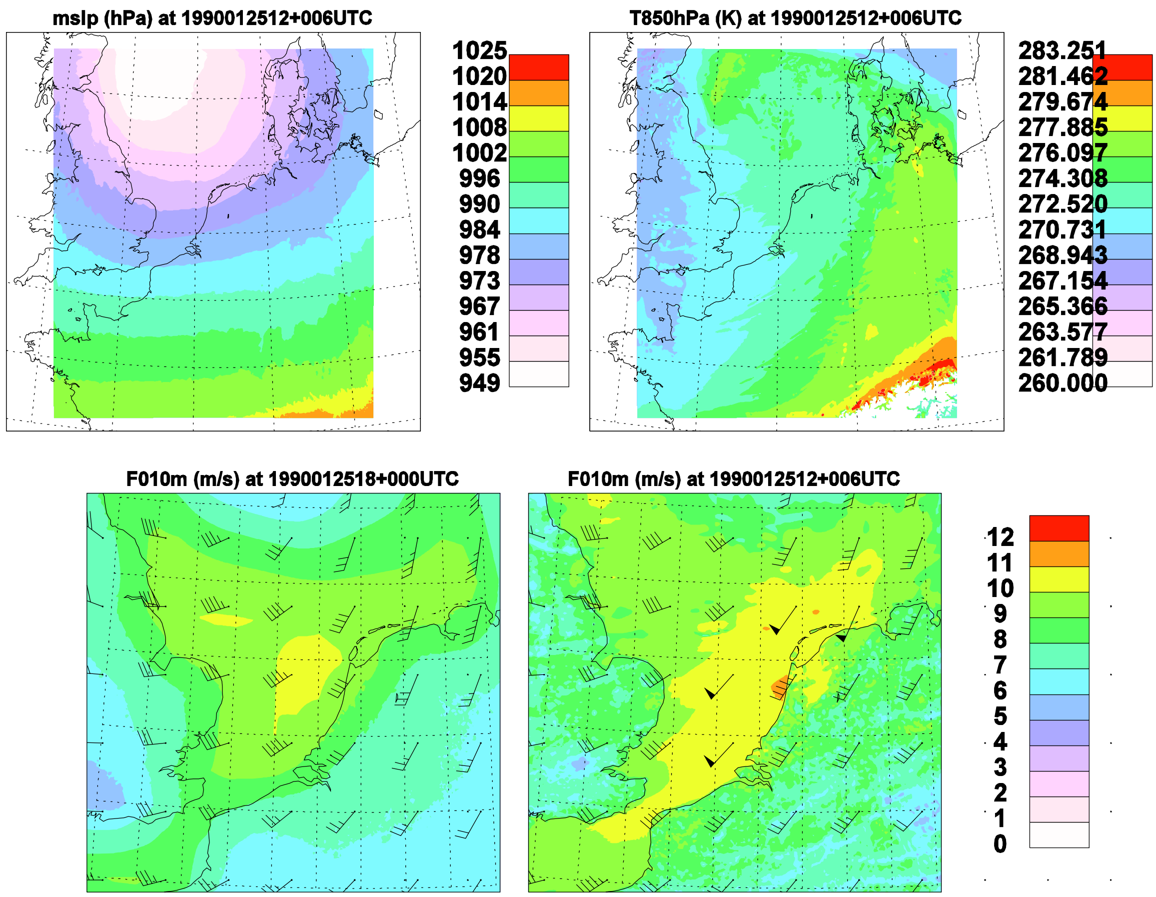


Figure 3.8. As Figure 3.3 but for 19900125.

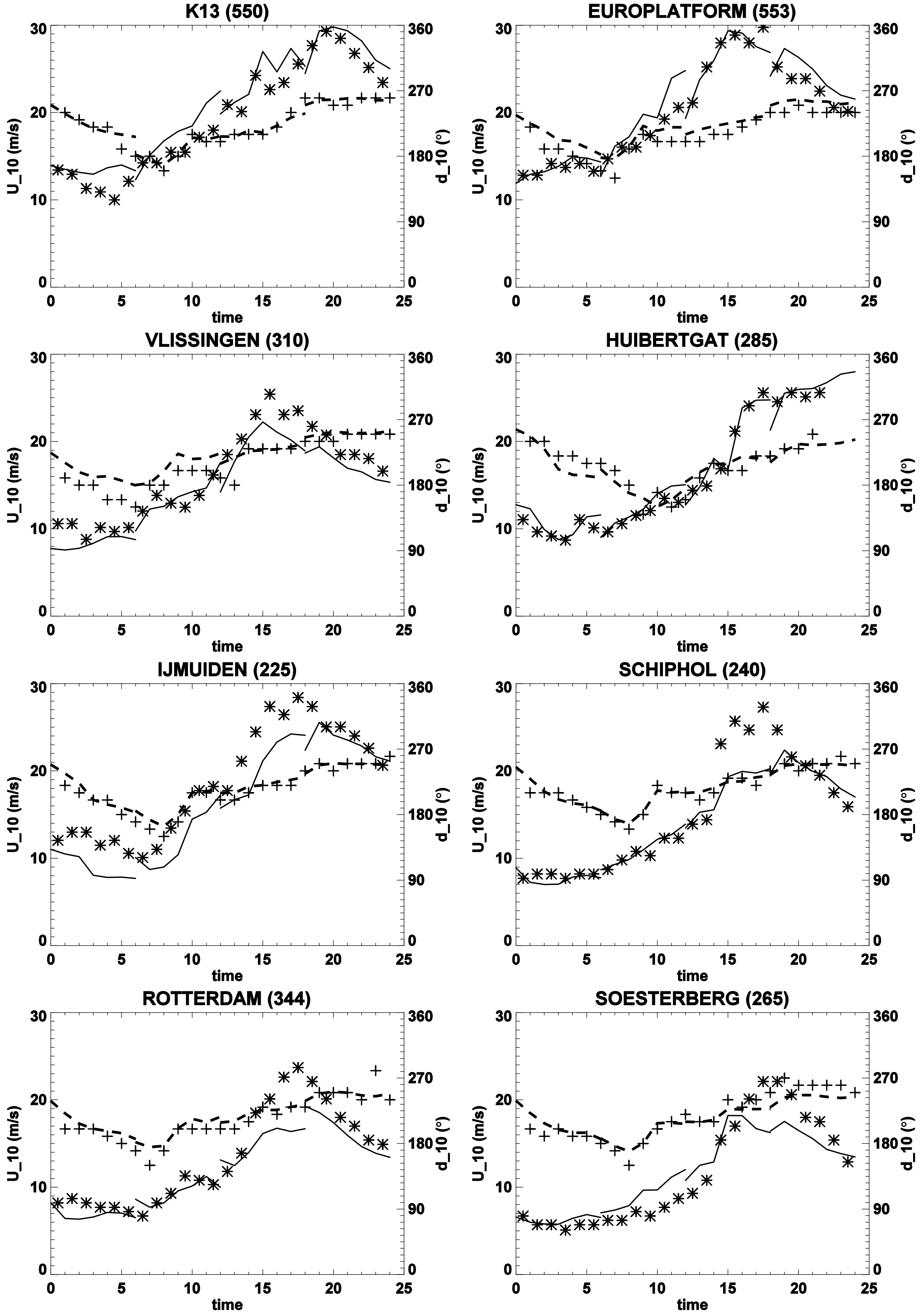


Figure 3.9. Modelled versus observed U_{10} for selected stations for the complete 14 day 1990 hindcast (+0 h forecasts are omitted).

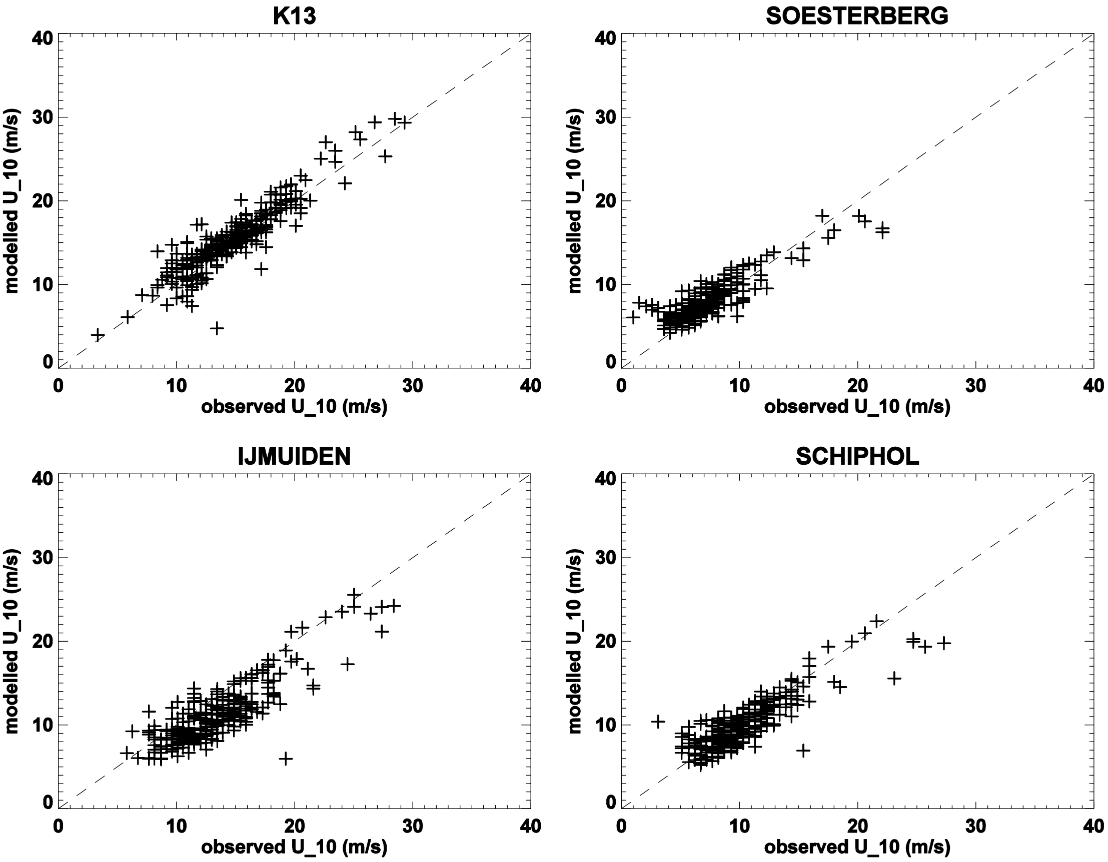


Figure 3.10. Modelled temperature (K) evolution at 2, 10, 200 and 500 m, as well as at 850 hPa (approx. 1300 m) for IJmuiden and Schiphol. For the latter, 2 m temperature observations are added.

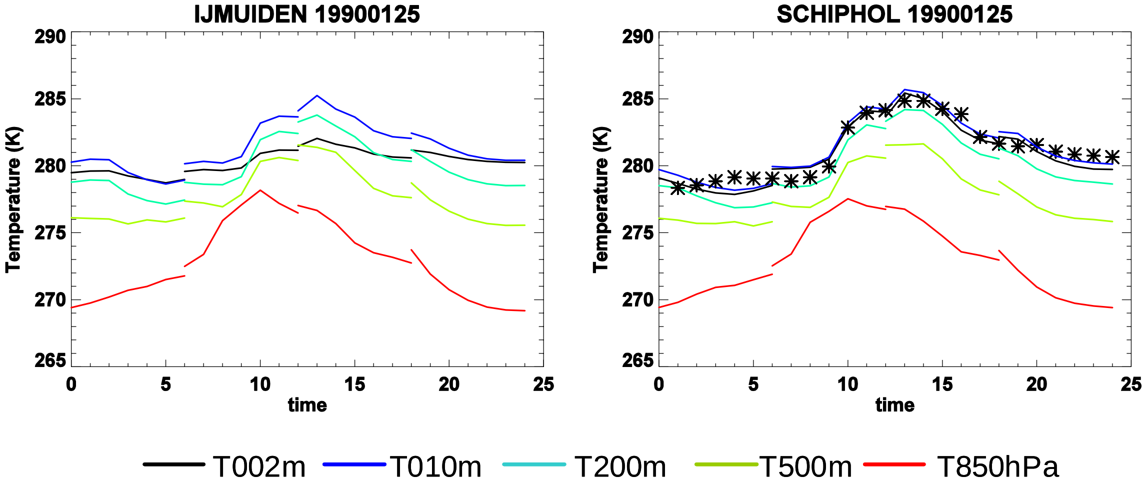


Figure 3.11. Modelled vertical profiles of wind speed (m/s) and temperature (K) for De Bilt en Europlatform for 25 January 1990.

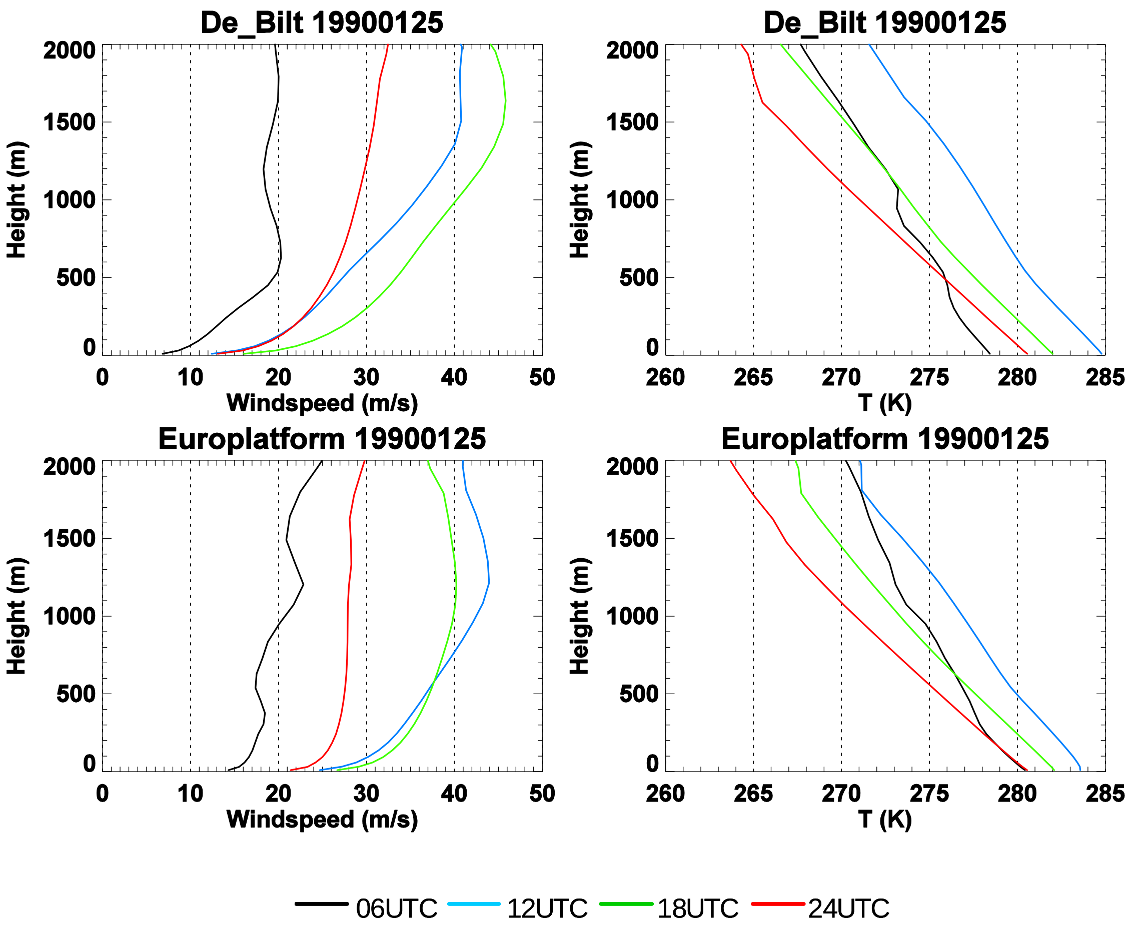


Figure 3.12. Modelled and observed p_s (hPa) fields at 25 January 1990, 18 UTC (upper panels). (Note that near the edges of the observation plot the interpolation becomes unrealistic). Modelled (solid lines) and observed (crosses) time series of p_s for De Kooy and Gilze-Rijen for 25 January 1990 (lower panels).

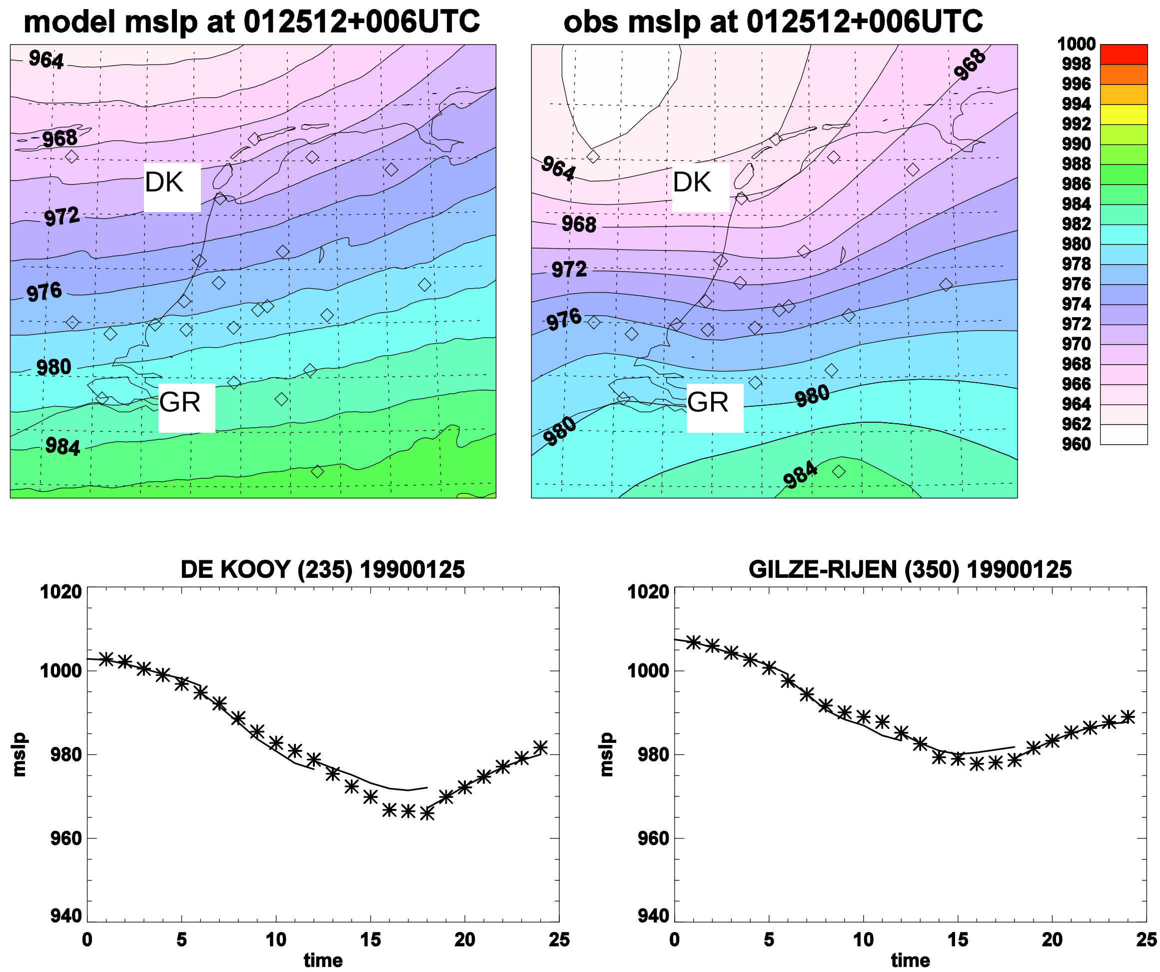


Figure 4.1. Water-land 10-m wind speed ratio for January 1990 for Schiphol (240) and IJmuiden (225)

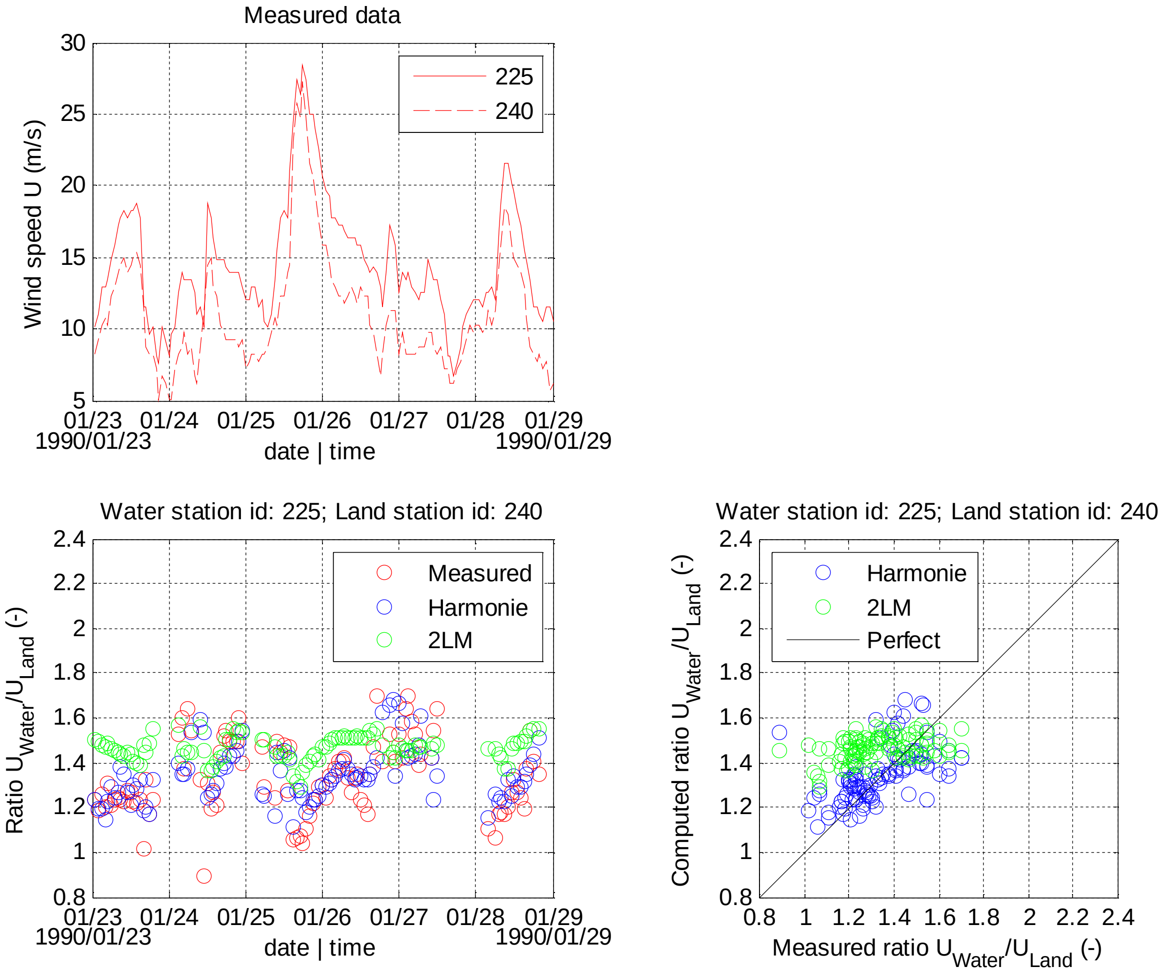


Figure 4.2. Water-land 10-m wind speed ratio for January 1990 for Schiphol (240) and Hoek van Holland (330)

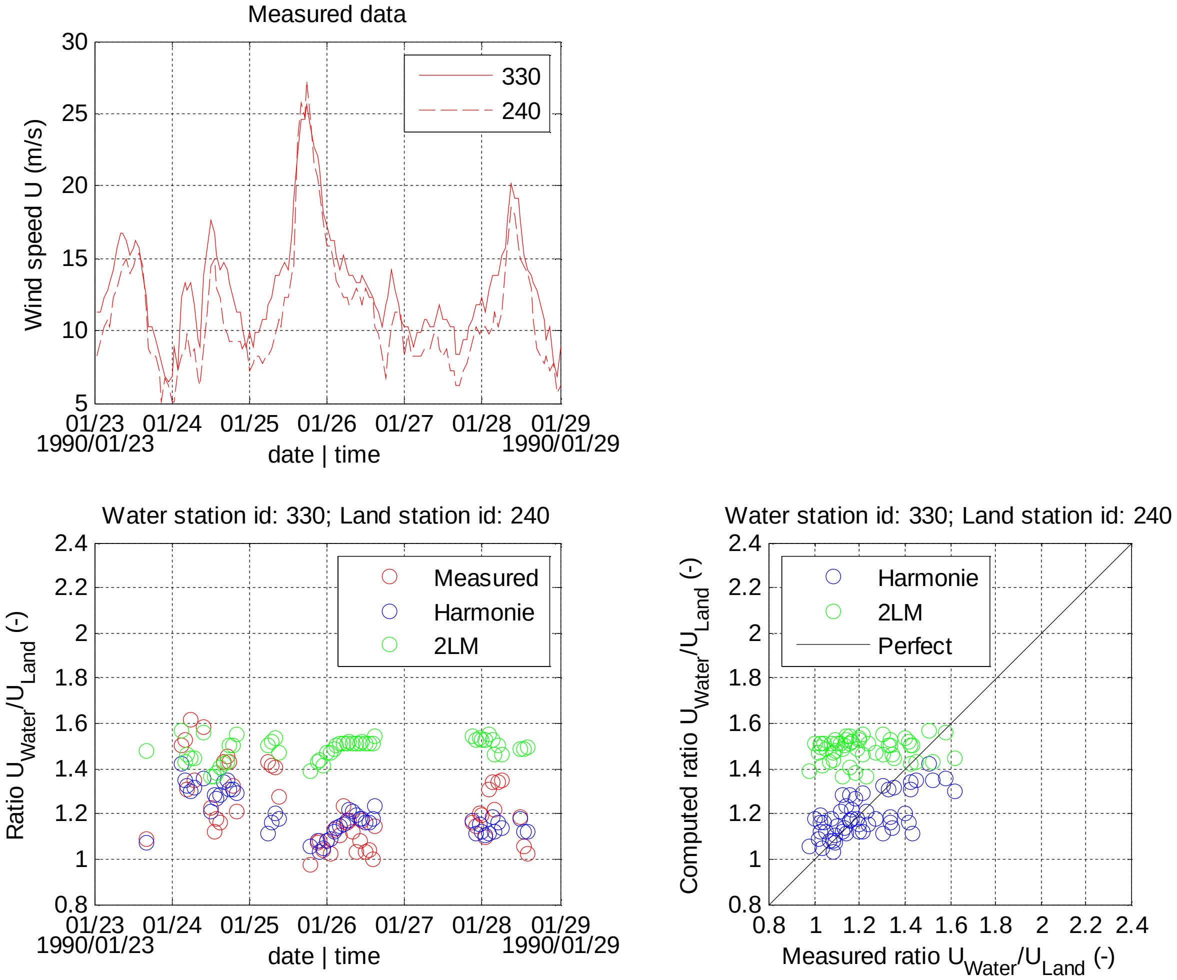


Figure 4.3. Water-land 10-m wind speed ratio for November 2006 for Schiphol (240) and IJmuiden (225)

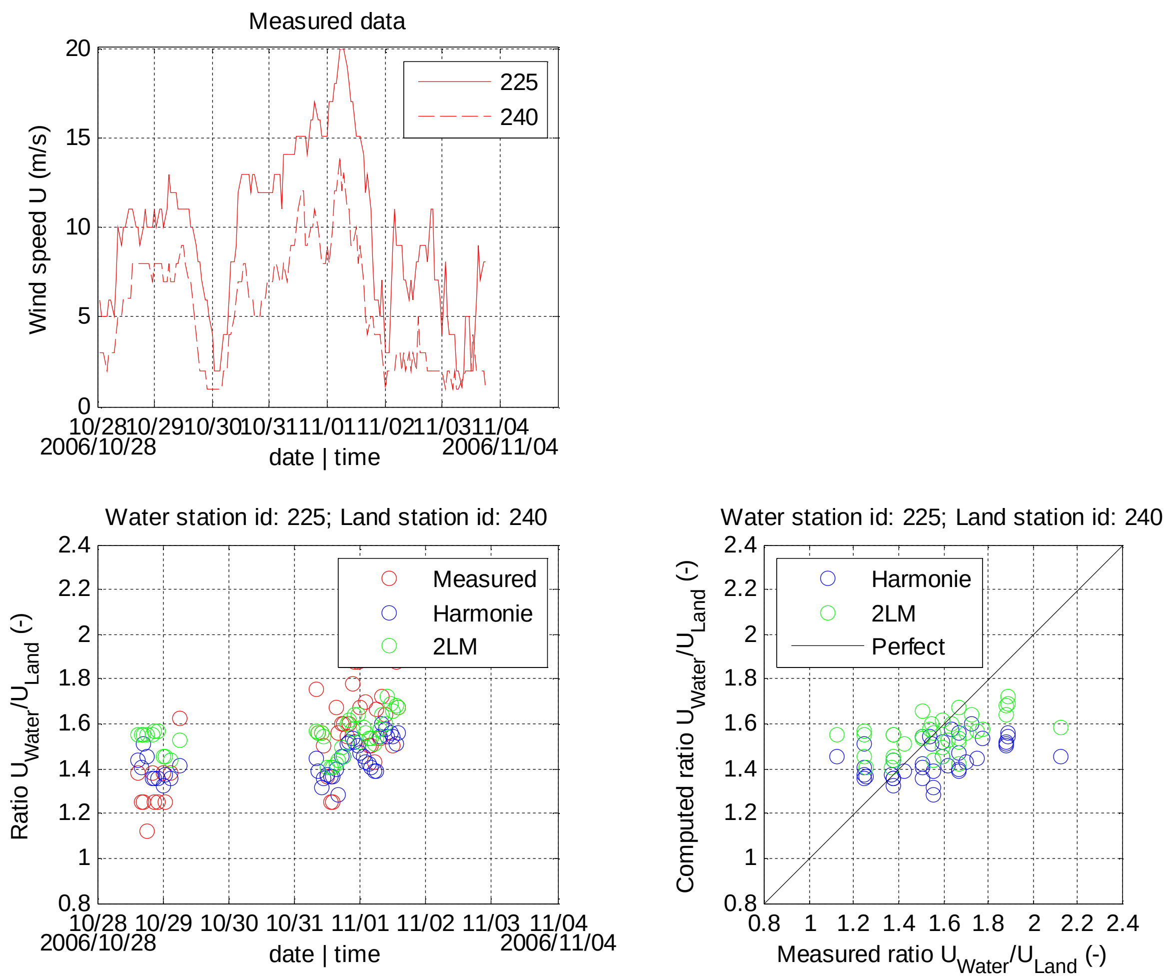


Figure 4.4. Water-land 10-m wind speed ratio for November 2006 for Schiphol (240) and Hoek van Holland (330)

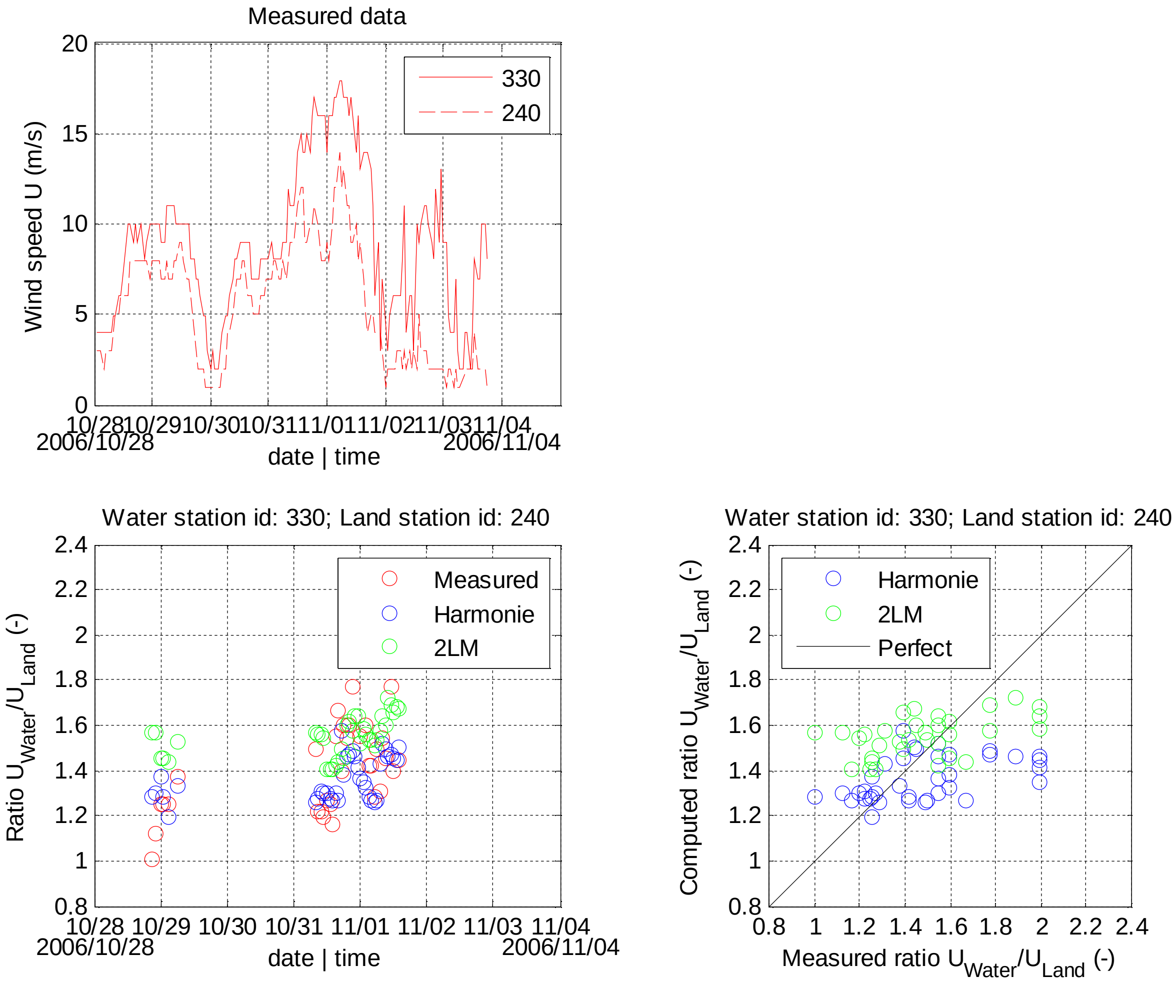


Figure 4.5. Water-land 10-m wind speed ratio for November 2006 for Schiphol (240) and Rotterdamse Hoek (902)

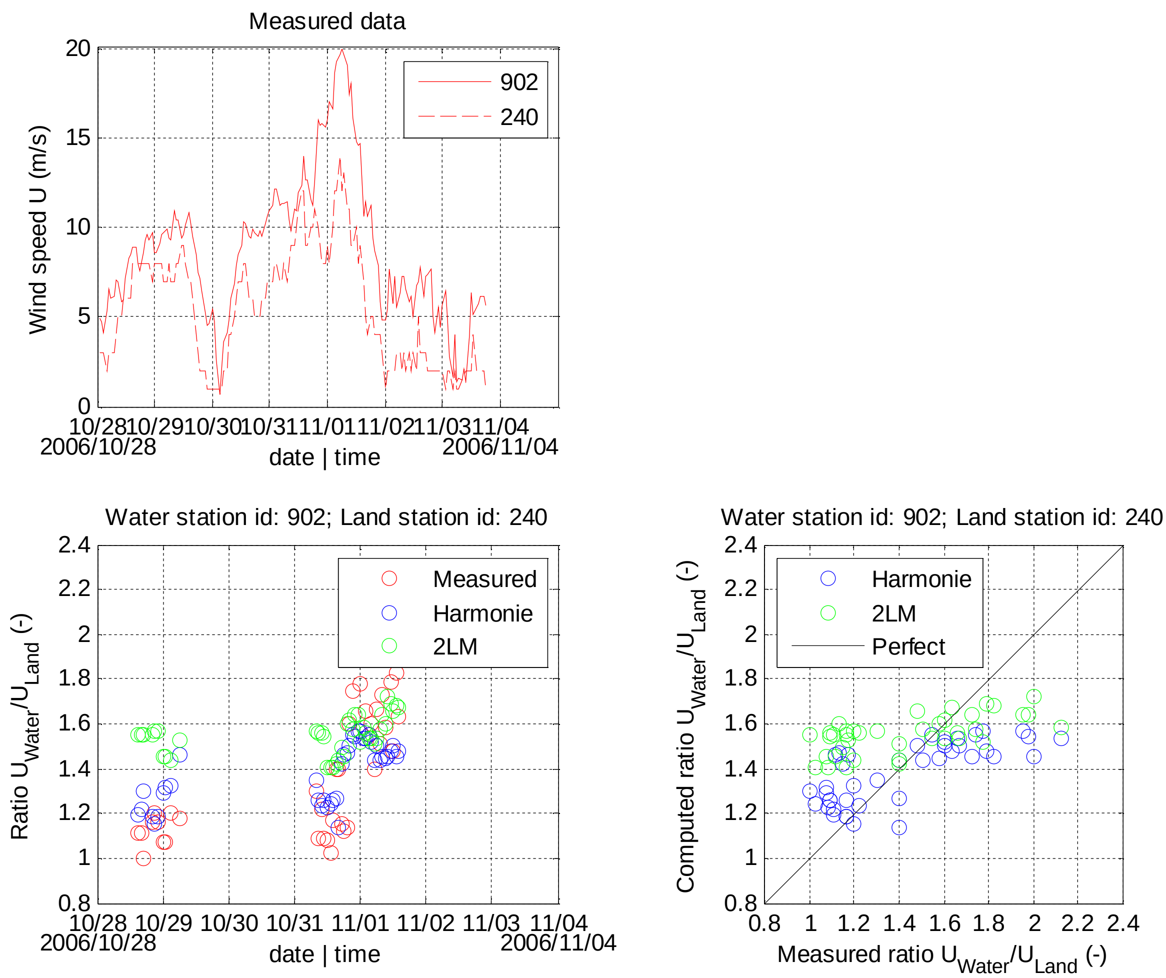


Figure 4.6. Water-land 10-m wind speed ratio for November 2006 for Schiphol (240) and Slotermeer (929)

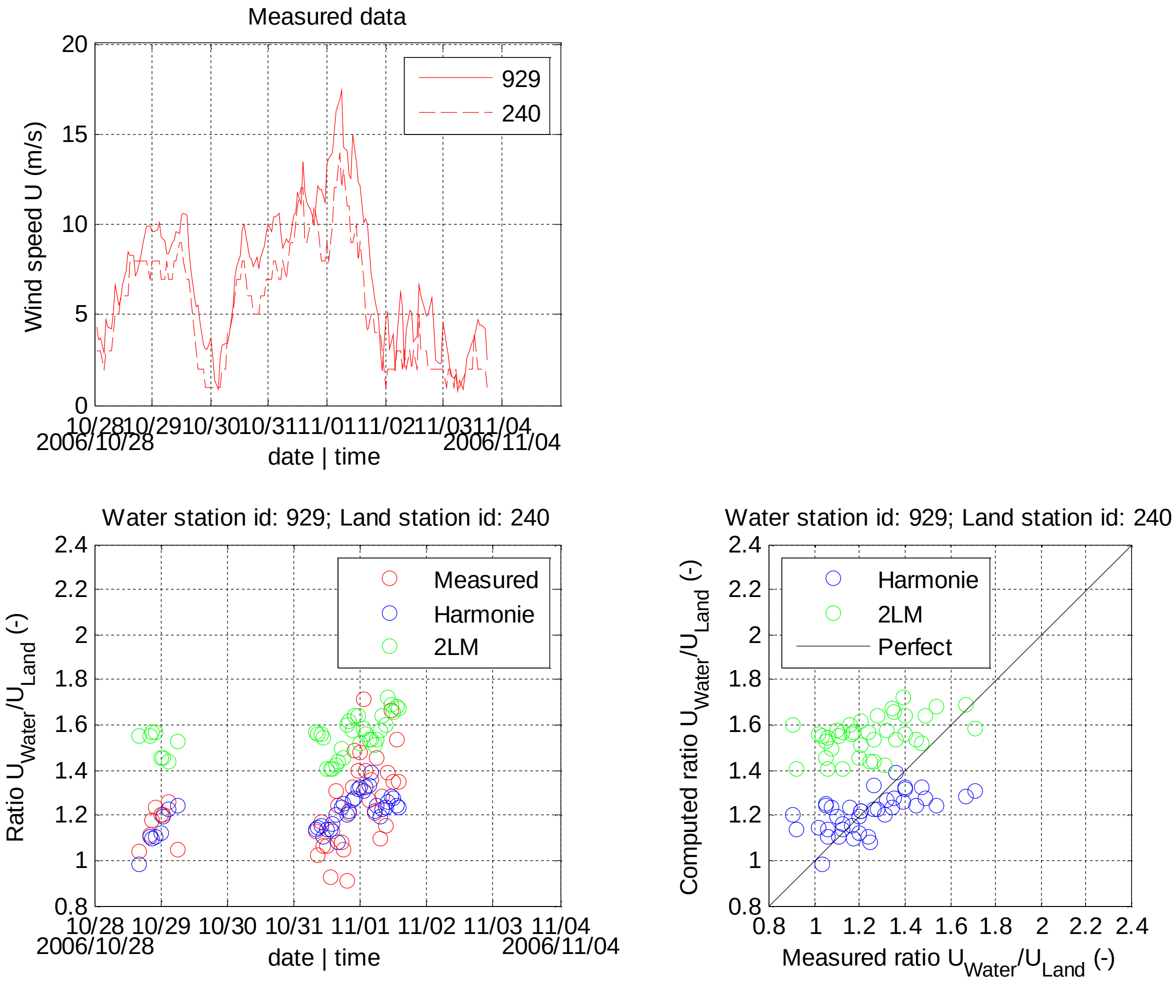


Figure 4.7. Water-land 10-m wind speed ratio for January 1990 for Schiphol (240) and IJmuiden (225), using a wind speed threshold of 10 m/s instead of 8 m/s.

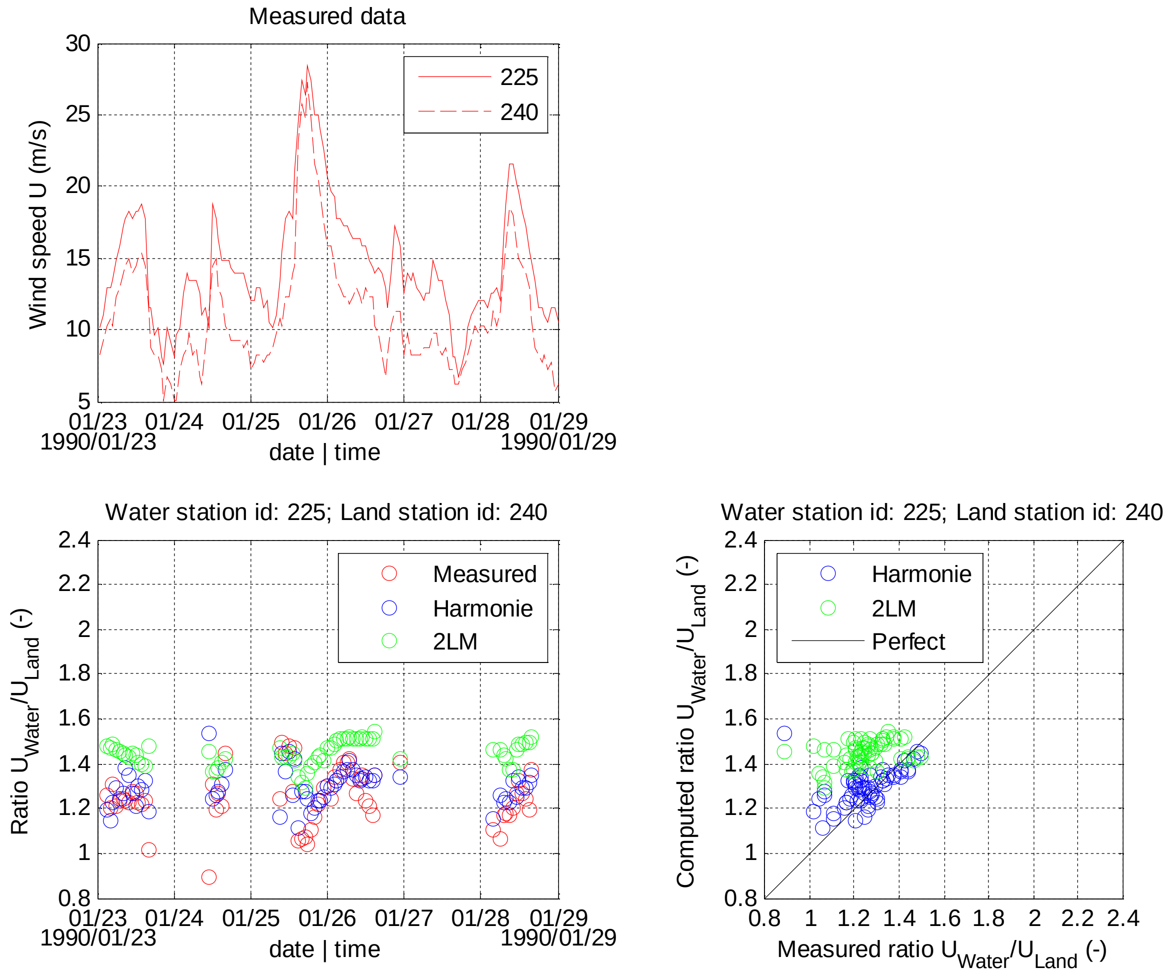


Figure 4.8. Water-land 10-m wind speed ratio for January 1990 for Schiphol (240) and IJmuiden (225), using a 3-hr moving average.

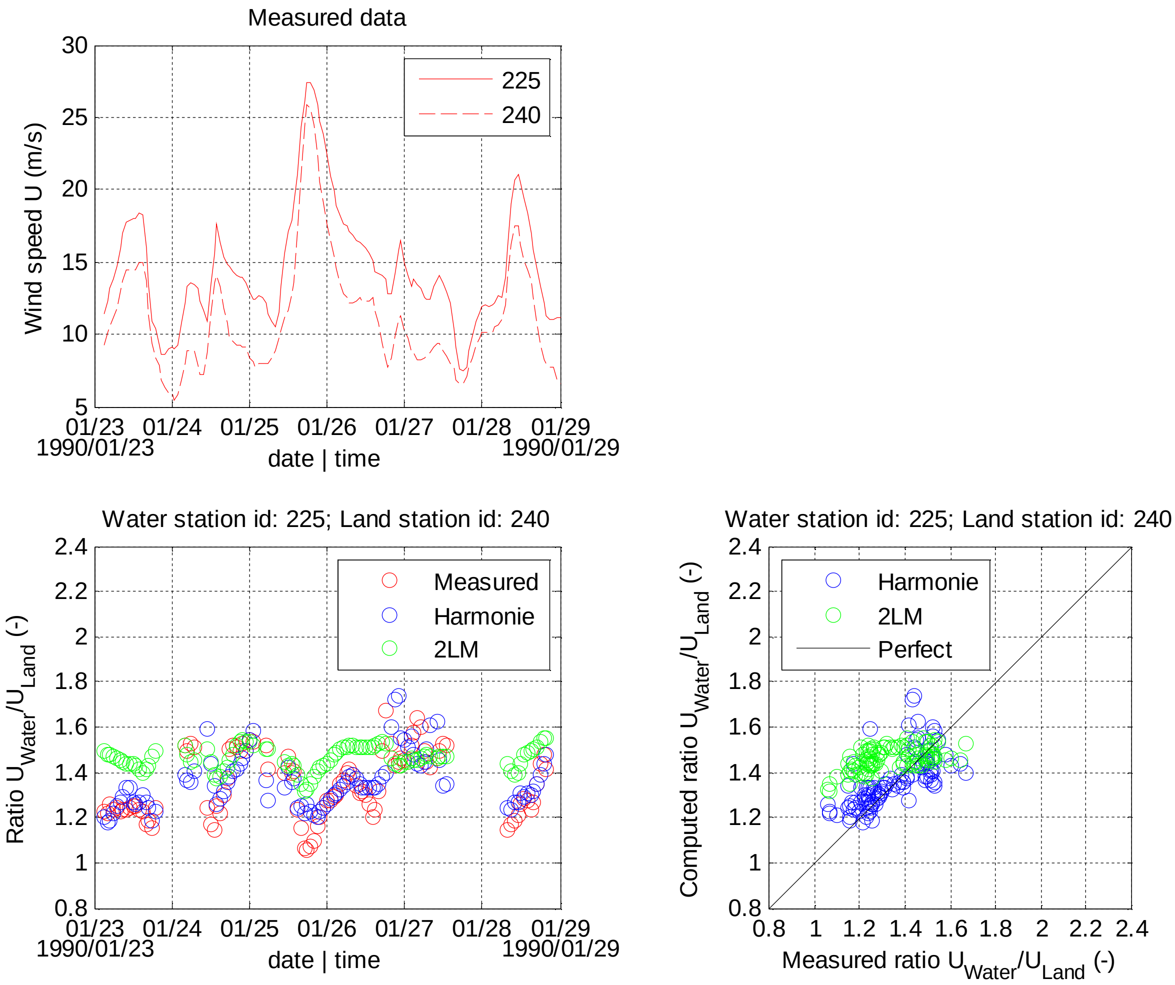
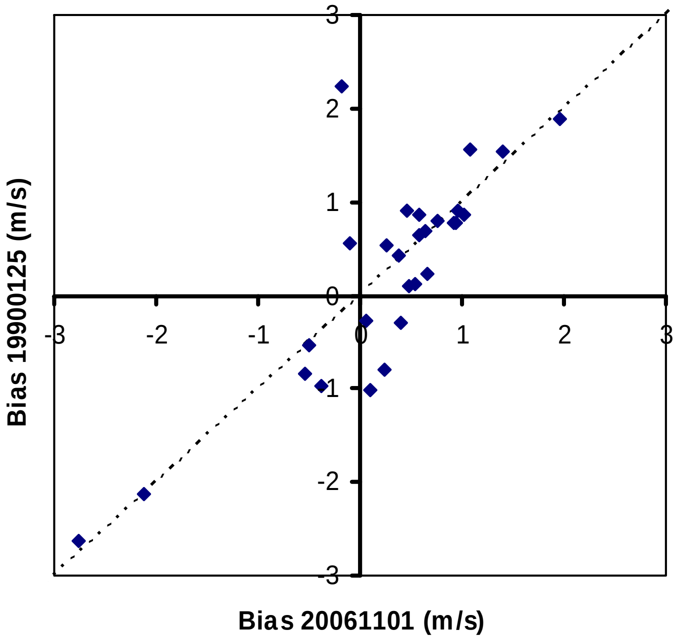


Figure 5.1. Relation between bias (per station) in U_{10} for the two hindcast periods.



Tables

Table 2.1. Overview of utilized wind-speed observations. Crosses indicate data availability. Sensor heights other than 10 m are indicated.

	210 VALKENBURG	225 IJMUIDEN	235 DE KOOY	239 F3-FB-1	240 SCHIPHOL	242 VLIELAND	248 WIJDENES	251 HOORN-TERSCHELLING	252 K13	260 DE BILT	265 SOESTERBERG
deviating sensor height (m)		18.5		59.2					73.8	10.0 | 20.0	
1990	x	x	x		x				x	x	x
2006	x	x	x	x	x	x	x	x	x	x	x

	267 STAVOREN	269 LELYSTAD	270 LEEUWARDEN	273 MARKNESSE	275 DEELEN	277 LAUWERSOOG	279 HOOGEVEEN	280 EELDE	285 HUIBERTGAT	286 NIEUWBEERTA	290 TWENTHE	310 VLISSINGEN
deviating sensor height (m)			6.0						18.0			27.0
1990		x	x	x	x	x	x	x	x	x	x	x
2006	x	x	x	x	x	x	x	x	x	x	x	x

	313 VLAKTE V.D. RAAN	319 WESTDORPE	320 LICHTEILAND GOEREE	321 EUROPLATFORM	330 HOEK VAN HOLLAND	340 WOENSDRECHT	344 ROTTERDAM	348 CABAUW	350 GILZE-RIJEN	356 HERWIJNEN
deviating sensor height (m)	16.5		38.3	29.1	15.0					
1990			x	x	x		x	x	x	x
2006	x	x	x	x	x	x	x	x	x	x

	370 EINDHOVEN	375 VOLKEL	377 ELL	380 MAASTRICHT	391 ARCEN	551 AUK	902 RWS-FL2n	925 RWS-FL25	929 RWS-SL29
deviating sensor height (m)									
1990	x	x		x		x			
2006	x	x	x	x	x		x	x	x

Table 3.1. Bias and rmse scores (in m/s) for the 10-m wind speed for various measurement stations for the two full Harmonie hindcast periods.

		2006		1990	
		bias	*rmse*	*bias*	*rmse*
VALKENBURG	*210*	-0.49	1.61	-1.15	1.80
IJMUIDEN	*225*	-2.14	2.67	-2.35	2.82
DE KOOY	*235*	1.89	2.34	1.94	2.31
F3-FB-1	*239*	0.56	1.52	N/A	N/A
SCHIPHOL	*240*	0.32	1.32	-0.30	1.38
VLIELAND	*242*	-2.25	2.57	N/A	N/A
WIJDENES	*248*	2.18	2.89	N/A	N/A
HOORN-TERSCHELLING	*251*	1.55	1.95	N/A	N/A
K13	*252/550*	0.31	1.14	0.10	1.51
DE BILT	*260*	1.35	1.86	1.49	1.85
SOESTERBERG	*265*	0.90	1.53	0.77	1.53
STAVOREN	*267*	0.33	1.63	N/A	N/A
LELYSTAD	*269*	0.25	1.37	-0.74	3.62
LEEUWARDEN	*270*	1.00	1.55	1.49	1.87
MARKNESSE	*273*	1.00	1.55	1.02	1.59
DEELEN	*275*	0.78	1.51	0.94	1.50
LAUWERSOOG	*277/605*	-0.51	2.00	-0.63	1.59
HOOGEVEEN	*279*	0.48	1.35	1.01	4.13
EELDE	*280*	0.58	1.49	0.19	1.28
HUIBERTGAT	*285*	0.69	1.66	0.10	1.35
NIEUW BEERTA	*286*	0.36	1.50	0.46	4.90
TWENTHE	*290*	0.69	1.28	0.79	1.30
VLISSINGEN	*310*	-0.58	1.35	-1.00	1.81
VLAKTE V.D. RAAN	*313*	0.41	1.64	N/A	N/A
WESTDORPE	*319*	0.49	1.23	N/A	N/A
LICHTEILAND GOEREE	*320*	0.02	1.55	2.16	2.56
EUROPLATFORM	*321*	-0.01	1.38	N/A	N/A
HOEK VAN HOLLAND	*330*	-2.81	3.31	-2.84	3.16
WOENSDRECHT	*340*	0.57	1.30	N/A	N/A
ROTTERDAM	*344*	0.01	1.26	-1.14	1.75
CABAUW	*348*	0.59	1.46	0.78	1.58
GILZE-RIJEN	*350*	1.06	1.56	1.01	1.56
HERWIJNEN	*356*	0.64	1.36	1.09	1.92
EINDHOVEN	*370*	0.04	1.03	-0.29	1.13
VOLKEL	*375*	0.99	1.65	0.90	1.61
ELL	*377*	0.33	0.92	N/A	N/A
MAASTRICHT	*380*	0.50	1.32	0.25	1.39
ARCEN	*391*	0.95	1.39	N/A	N/A
AUK	*551*	N/A	N/A	-3.39	4.09
EUROPLATFORM	*553*	N/A	N/A	0.41	1.41
RWS-FL2n	*902*	0.31	1.83	N/A	N/A
RWS-FL25	*925*	0.90	1.95	N/A	N/A
RWS-SL29	*929*	0.00	1.49	N/A	N/A