Ocean Sci., 5, 369–378, 2009
www.ocean-sci.net/5/369/2009/

Ocean Science

An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate

A. Sterl, H. van den Brink, H. de Vries, R. Haarsma, and E. van Meijgaard

Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, The Netherlands

Received: 8 May 2009 – Published in Ocean Sci. Discuss.: 18 May 2009
Revised: 1 September 2009 – Accepted: 5 September 2009 – Published: 18 September 2009

Abstract. The height of storm surges is extremely important for a low-lying country like The Netherlands. By law, part of the coastal defence system has to withstand a water level that on average occurs only once every 10 000 years. The question then arises whether and how climate change affects the heights of extreme storm surges. Published research points to only small changes. However, due to the limited amount of data available results are usually limited to relatively frequent extremes like the annual 99%-ile. We here report on results from a 17-member ensemble of North Sea water levels spaning the period 1950–2100. It was created by forcing a surge model of the North Sea with meteorological output from a state-of-the-art global climate model which has been driven by greenhouse gas emissions following the SRES A1b scenario. The large ensemble size enables us to calculate 10 000 year return water levels with a low statistical uncertainty. In the one model used in this study, we find no statistically significant change in the 10 000 year return values of surge heights along the Dutch during the 21st century. Also a higher sea level resulting from global warming does not impact the height of the storm surges. As a side effect of our simulations we also obtain results on the interplay between surge and tide.

1 Introduction

Storm surges are a major threat for coastal areas. Especially low-lying countries like The Netherlands are vulnerable as large areas can easily be flooded. During the last great flood in 1953, nearly 4% of the Dutch territory was inundated, and about 1835 people lost their lives. In reaction to that catastrophe the Dutch government adopted the Delta Plan (Deltacommissie, 1960/61). The plan included massive improvements in existing dikes and the damming off of large parts of the Scheldt-Meuse-Rhine delta. As a standard, Dutch law[1] requires the most important parts of the coastal defence system to be able to withstand a water level that on average is reached only once in 10 000 years.

The required 10 000-year return level[2] is determined statistically from past water levels. As the observations only cover a little more than 100 years, this involves an extrapolation over two orders of magnitude, resulting in a large statistical uncertainty. Furthermore, the extrapolation is only possible when the background environment does not change with time. An important aspect of the environment is the changing climate which may affect sea level and storm characteristics. Other aspects are changing bathymetry due to sedimentation and erosion or local water works. We here focus on the impact global warming may have on the storm climate in the North Sea and consequently on storm surges along the Dutch coast. By employing a large model ensemble our results have a low statistical uncertainty.

The first integrated effort to assess possible changes in North Sea climate was the WASA project (WASA-Group, 1998). They concluded that the storm climate did not undergo significant systematic changes in the 20th century, but that large decadal variability exists. This result was confirmed by Alexandersson et al. (1998, 2000). They found that the level of storm activity in the 1990s was comparable to that at the beginning of the 20th century with a minimum around mid-century. Since the mid 1990s storm activity is

Correspondence to: A. Sterl
(sterl@knmi.nl)

---

[1] *Wet op de waterkering*; go to http://wetten.overheid.nl/ and type *waterkering* into the search window

[2] Mathematically, this is a well defined term. However, its actual determination and interpretation is made difficult by climate variability not being strictly "white" (cf. Bunde et al. 2004). The term is conveniently adopted by the Dutch community, but it is not an uncontested concept, and other communities use different design criteria.

decreasing again (update of Alexandersson et al., 1998, 2000 in the recent IPCC report, IPCC, 2007). Considering even longer time periods, Bärring and Von Storch (2004) showed that such decadal variations have not been unusual and that no discernible long term trend in storm activity could be detected so far.

For the future (time of doubled CO_2 concentration) the WASA Group's (1998) results point to a moderate increase of winds, waves and surges in the North Sea. However, these changes are within the range of previously observed variations and therefore cannot be unequivocally ascribed to climate change.

The recent IPCC-report (IPCC, 2007) contains a short section about projected wind changes over Europe (Sect. 11.3.3.5) which does not explicitly address the North Sea. Overall, some models are found to predict an increase in storminess over middle and northern Europe, while others predict a decrease.

In 2006, KNMI presented climate change scenarios for The Netherlands (KNMI, 2006). They are based on an analysis of the CMIP-3 climate model runs (Meehl et al., 2007). From the available models, four were selected that best reproduced the current circulation over Europe (Van Ulden and Van Oldenborgh, 2006[3]). Three of these four models show a slight increase of annual maximum daily-mean wind speed over the southern North Sea, and one shows no changes. Expressed in terms of 50 or 100-year return values of wind speed, the increase amounts to 0.5–1.5 m/s (dependent on model) at the end of this century under an SRES A1b forcing scenario. This small increase is not statistically significant. It is the same for all return times, meaning that percentage changes are lower for long return times than for short ones.

For the height of storm surges not only the wind speed, but also the wind direction is very important. For the Dutch coast northerly winds are most dangerous because they have the longest fetch. An illustration is given in Fig. 2b below. It displays the meteorological situation leading to the highest modelled surge in Hoek van Holland in the ESSENCE-WAQUA/DCSM98 ensemble (see Sect. 2.1). The long fetch is clearly visible.

None of the models used to create the KNMI'06 scenarios exhibits a change to more northerly winds, while three of them show a tendency to westerly winds becoming more frequent. These are the same models that exhibit the small change in annual-maximum daily-averaged wind speeds. All models underestimate the frequency of northerly winds relative to ERA-40. From this one expects climate change not to have dramatic consequences on the surge heights at the Dutch coast. This is backed by forcing a simple parametric surge model (Van den Brink et al., 2004) with the winds from the CMIP-3 models considered above. Despite the small increase in wind speed the surge levels remain centered around their present value because the frequency and strength of northerly winds do not change.

Räisänen et al. (2003) force the Swedish Rossby Centre's regional climate model (RCAO) with data from two different global models and two different emission scenarios. They find an increase (2071–2100 compared to 1961–1990) of the average annual maximum wind speed in the southern North Sea of around 5% (their Fig. 31). However, the exact number and the pattern of the changes strongly depend on the forcing scenario and the global model used to force RCAO. Therefore results may not be very robust but could simply be the result of sampling uncertainty. Woth (2005) uses the winds from the RCAO integrations to force a surge model. She finds small increases of the 99%-ile of surge heights. The increase is significant in the German Bight and along the Danish coast, but not along the Dutch coast. The results for the different forcing scenarios and driving GCMs are statistically not distinguishable. These results were confirmed by Woth et al. (2006), where four different regional climate models were used.

Debernard and Røed (2008) performe a similar exercise and dynamically downscale GCM results using RACM, their regional climate model, as well as the WAM wave model and a surge model. In the south-eastern North Sea they find a slight (≈2%) increase of the mean and the 99%-ile of wind, but no significant change for the most extreme winds. Surge heights appear to increase along the continental coasts of the southern North Sea, but variations between different forcing scenarios and driving GCMs are large.

Lowe and Gregory (2008) also use dynamically downscaled winds to drive their surge model. They focus on the 50-year return values of surge height and find small increases along the Dutch coast, which differ widely between climate forcing scenario and driving global GCM used. This uncertainty is stressed by the fact that the results "differ considerably" from those reported in an earlier paper by the same authors (Lowe et al., 2001), in which they use an earlier version of the same climate model to find the climate-change signal.

In summary, all model studies agree in that projected changes in North Sea storm climate, and consequently surge heights, are small compared to natural variability. However, due to the limited amount of data (typically one integration over 30 years), this conclusion only holds for extremes with rather short return periods (years). We here report on results obtained from a 17-member ensemble of surge model runs. This gives enough data to estimate the 10 000-year return surge height with a statistical uncertainty that is small enough to allow conclusions on its possible change in a future climate. Of course, this conclusion relies on the used model's ability to correctly represent the impact of climate change on wind speeds.

---

[3] Actually, Van Ulden and Van Oldenborgh (2006) identified five models. However, one of them could not be used to assess the storm climate because data with adequate time resolution (at least daily) were not available.

2 Model and forcing data

2.1 WAQUA/DCSM98

To infer surge heights and their possible future development in the North Sea we use WAQUA/DCSM98 (Gerritsen et al., 1995). This model solves the two-dimensional shallow-water equations on a $\frac{1}{12}^\circ \times \frac{1}{8}^\circ$ (approximately 8 km×8 km) grid on the northwest European shelf region. It is operationally used at KNMI (www.knmi.nl/~jwdv/WAQUA) to predict the water levels along the Dutch coast. Meteorological input are mean sea level pressure and 10-m wind. The latter is translated into wind stress using a drag coefficient based on the parameterization of Charnock (1955), with a Charnock parameter of 0.032. River run-off is not taken into account in this paper. The astronomical tide is prescribed at the open boundaries in ten harmonic constituents (O_1, K_1, N_2, M_2, S_2, K_2, Q_1, P_1, ν_2, and L_2) and propagates from there into the model domain. This is sufficient to capture the first-order effect of the tide-surge interaction (see Sect. 5). For day-to-day forecasts in coastal stations the astronomical tide from the model is replaced by a harmonic analysis with 94 components based on several years of observed water levels.

Given the high spatial and temporal resolution, saving of the whole model fields would generate large amounts of data. In operational mode results are therefore only saved at some pre-defined stations, usually harbours. Following this practice we retained a list of 19 stations (Table 1; see also Fig. 9 below) along the coasts of the southern North Sea for which output is available at the model resolution of 10 min. In this paper we focus on the Dutch station Hoek van Holland. Results for the other stations are qualitatively identical.

The model output consists of total water level and the height of the astronomical tide in the absence of meteorological forcing. The total water level results from the non-linear interplay between the meteorologically driven *surge* and the astronomically driven *tides*. We analyze the model results in terms of total water level as this is the quantity relevant for coastal defence. The interplay between tides and surge is investigated in some detail in Sect. 5.

2.2 ESSENCE

In the ESSENCE project (Sterl et al., 2008) the ECHAM5/MPI-OM climate model (Jungclaus et al., 2006) has been used to simulate the climate from 1950 to 2100, assuming future greenhouse gas concentrations to follow the SRES A1b scenario (Nakicenovic et al., 2000). To assess the full range of internal variability and to obtain good statistics for extreme cases, 17 integrations have been done, each starting from slightly different initial conditions. Winds and sea level pressures from these integrations are used to drive WAQUA/DCSM98. This yields 17 realizations of North Sea water levels, giving a good basis for a statistical assessment of extreme surges.

Table 1. List of stations and their position for which output from the ESSENCE-WAQUA/DCSM98 runs is available. The stations are ordered north-to-south and east-to-west. See also map in Fig. 9 below.

Station Name	Longitude	Latitude
Cuxhaven	8.75	53.92
Delfzijl	7.00	53.33
Huibertgat	6.38	53.58
Harlingen	5.38	53.25
Texel Noordzee	4.75	53.17
Den Helder	4.62	53.00
IJmuiden	4.50	52.42
Meetpost Noordwijk	4.25	52.33
Scheveningen	4.25	52.17
Hoek van Holland	4.12	52.00
Goeree	3.62	51.92
Roompot Buiten	3.62	51.67
West Kapelle	3.38	51.50
Vlissingen	3.50	51.42
Lowestoft	1.75	52.50
Dover	1.38	51.17
Zeebrugge	3.12	51.33
Oostende	2.88	51.25
Duinkerken	2.38	51.08

Note that we directly use the coarse-resolution (about 2° lat/lon and 3 h in time) output of a global climate model and interpolate it to the $\frac{1}{12}^\circ \times \frac{1}{8}^\circ$, 10 min resolution needed to drive WAQUA/DCSM98, while most papers cited in the Introduction employ a regional climate model to downscale the results form a global model. Downscaling was not possible for the ESSENCE ensemble due to the lack of computer resources. Furthermore, water level is the integral result of the forcing over the whole North Sea. We therefore anticipated that the water level is primarily determined by the large-scale pressure and wind fields, which are well represented in global models, and that the fine structure of the wind field is only important for individual cases, but not for the long-term statistics. In Sect. 3.2 we show that WAQUA/DCSM98 is indeed capable of handling coarse resolution forcing adequatly.

2.3 ERA-40

In the ERA-40 atmospheric reanalysis (Uppala et al., 2005) the numerical weather forecasting model of the European Centre for Medium Range Weather Forecasting (ECMWF) has been run for the period September 1957 to August 2002. During the integration the model has been constrained by all available meteorological data. The result is a complete description of the atmosphere with a temporal resolution of six hours and a spatial resolution of nominally 1.3°. Being a model result, this data set is physically and dynamically consistent, and due to the constraint by observations it is as close as possible to the real state of the atmosphere. We use wind and pressure fields from ERA-40 to (i) compare wind statistics from ERA-40 with those of ESSENCE, and (ii) to show that WAQUA/DCSM98, which is usually driven by output form a high-resolution (≈11 km) regional weather model, is capable of dealing with the coarse-resolution (≈200 km) of ESSENCE. To do so we interpolate ERA-40 data to the coarse ESSENCE resolution and use it to drive WAQUA/DCSM98. As the driving represents the real atmospheric conditions, the resulting water levels can be verified against observations.

2.4 Method

To determine the 10 000-year return surge height, simulated and observed annual maxima, y, are fitted to a Generalized Extreme Value (GEV) distribution, the theoretical distribution for block maxima (Coles, 2001),

$$G(y) = \exp\{-[1 + \xi\,(\frac{y-\mu}{\sigma})]^{-1/\xi}\}. \tag{1}$$

Here μ, σ and ξ are called the location, scale and shape parameter, respectively. $G(y)$ is defined for $\{y\colon 1+\xi\,(\frac{y-\mu}{\sigma})>0\}$, so that for negative ξ the distribution has a hard upper limit of $\mu-\sigma/\xi$. The return time $T(y)$ for level y is given by the $1-1/T(y)$ percentile of G, i.e.,

$$T(y) = \frac{1}{1-G(y)}. \tag{2}$$

The fits are performed by the maximum likelihood method. Using the profile likelihood a confidence limit for the resulting parameters and therefore for the return period is obtained (Coles, 2001).

The modelled or observed annual maxima are rank-ordered. The highest data point is associated with a return period of $N+1$ years, where N is the number of years in the data, the second highest with $(N+1)/2$, etc. According to Eq. (2) this corresponds to an empirical distribution function $G(y_i)=\frac{i}{N+1}$, where $y_i \le y_{i+1}$ for $1<i<N-1$.

The statistical comparisons in this paper are presented in the form of Gumbel plots, in which the annual maxima are plotted as function of the Gumbel variate $x=-\ln(-\ln(G(y)))$. In case of a Gumbel distribution (GEV with $\xi=0$) this results in a straight line. Through Eq. (2) the Gumbel variate is directly related to the return time, which we label on the upper horizontal axis of the plots.

3 Evaluation

3.1 Winds

Before we investigate the simulated surge heights, we assess the ESSENCE 10 m winds which are used to drive WAQUA/DCSM98. Of particular importance is the question whether the model correctly represents extreme wind speeds. The lack of long time series of reliable extreme wind measurements at sea hampers answering this question. For the ESSENCE ensemble we here put forward two pieces of evidence suggesting that the model correctly represents extreme winds.

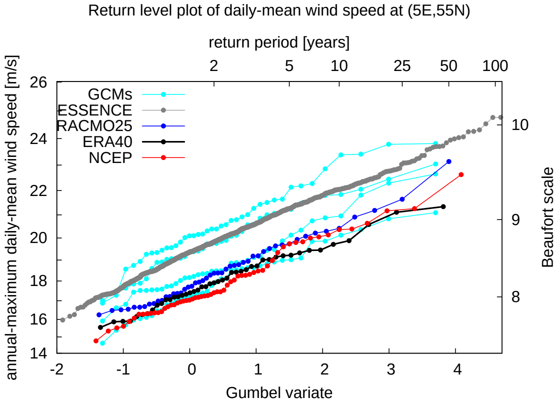

Fig. 1. Gumbel plot of annual-maximum daily-mean wind speed at 5° E, 55° N. The cyan lines labeled GCMs refer to the four GCMs used in the KNMI'06 scenarios (KNMI, 2006), and the blue line labeled RACMO25 to a run with the regional climate model RACMO at 25 km resolution, driven by ERA-40 boundary conditions. Values from the ERA-40 and the NCEP/NCAR reanalyses are represented by the black and red symbols, respectively. The Gumbel variate (lower horizontal axis) is a transformed rank variable. It is directly related to the return time (upper horizontal axis), the average time between two occurrences of a given value. Note that the vertical axis is linear in u^2 instead of u (see main text).

Figure 1 is a Gumbel plot of annual-maximum daily-mean winds at 5° E, 55° N in the southern North Sea from different models for the present climate. The models are the four GCMs that have been used in the KNMI'06 scenarios (KNMI, 2006), the ESSENCE ensemble, and a run using the regional climate model RACMO (Van Meijgaard et al., 2008), driven by boundary conditions from ERA-40. Furthermore, the values from ERA-40 (Uppala et al., 2005) and from the NCEP/NCAR reanalysis (Kalnay et al., 1996) are included. The vertical axis is linear in u^2 because the annual maxima of u^2, rather than of u alone, follow a Gumbel distribution (Van den Brink and Können, 2008). This is reflected in Fig. 1 by the fact that the values for each model fall on straight lines.

These lines are not only straight, but also parallel, meaning that all models have the same relation between *changes* of the intensity and *changes* of the frequency of extreme winds. They show no sign of divergence at the highest extremes, indicating that even in the coarsest model the winds have not yet reached a strength that cannot be resolved any more. From this we conclude that these models should be able to reliably simulate *changes* in extreme values.

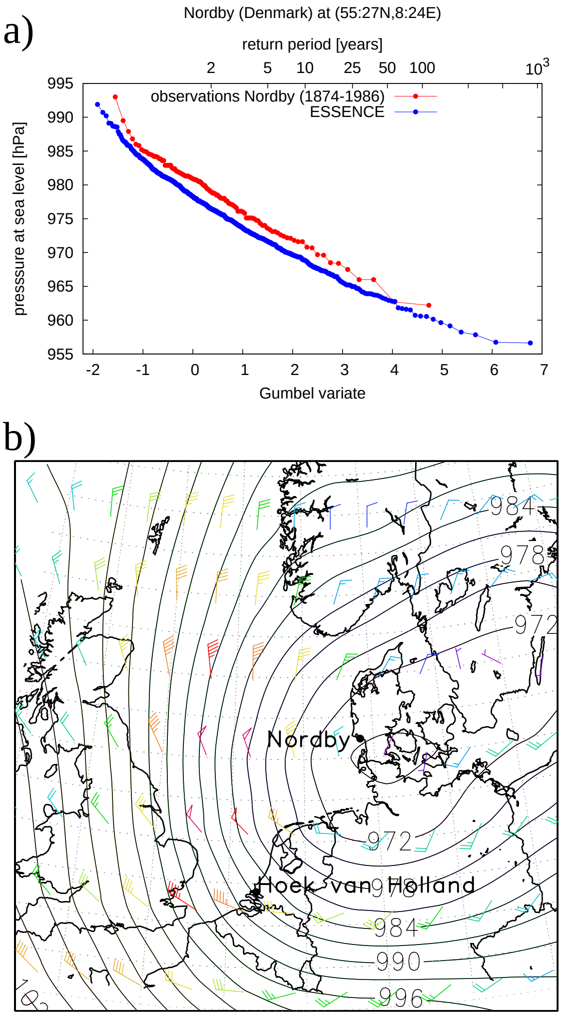

Fig. 2. (a) Gumbel plot of observed annual-minimum sea level pressure in Nordby, Denmark (8.2° E, 55.3° N) (red) and as simulated at the nearest ESSENCE grid point (blue), and **(b)** wind and pressure fields for the situation leading to the highest surge in Hoek van Holland that occurred in the ESSENCE-WAQUA/DCSM98 ensemble.

The fact that the curves in Fig. 1 have different offsets is considered to be of less importance. 10 m winds depend on surface roughness. As different models employ different parameterizations of surface roughness, they can, under otherwise identical circumstances, come up with different wind speeds. This is particularly evident for the ERA-40 and the RACMO results. While the large-scale pressure field of the latter is constrained by the former, the wind speeds are different. This is mainly due to a lower surface roughness in the high wind speed regime in RACMO as compared to ERA-40. The second piece of evidence comes from Fig. 2. Figure 2a is a Gumbel plot of annual-minimum sea level pressure as observed in Nordby, Denmark (8.2° E, 55.3° N), together with the simulated values at the nearest grid point of the ESSENCE ensemble. This point was chosen because a pressure minimum in this area leads to long wind fetches over the North Sea and therefore to high surges at the Dutch coast. This is illustrated in Fig. 2b, which depicts the pressure and the wind field related to the highest surge that occurred in Hoek van Holland in the ESSENCE-WAQUA/DCSM98 ensemble (see next section). In the Gumbel plot (Fig. 2a) observed and simulated values yield parallel curves. Modelled pressures are slightly lower than the observed ones, but the model has the same relation between intensity and frequency of low pressures as do the obseration. There is no sign of an artificial lower limit on pressure in the model.

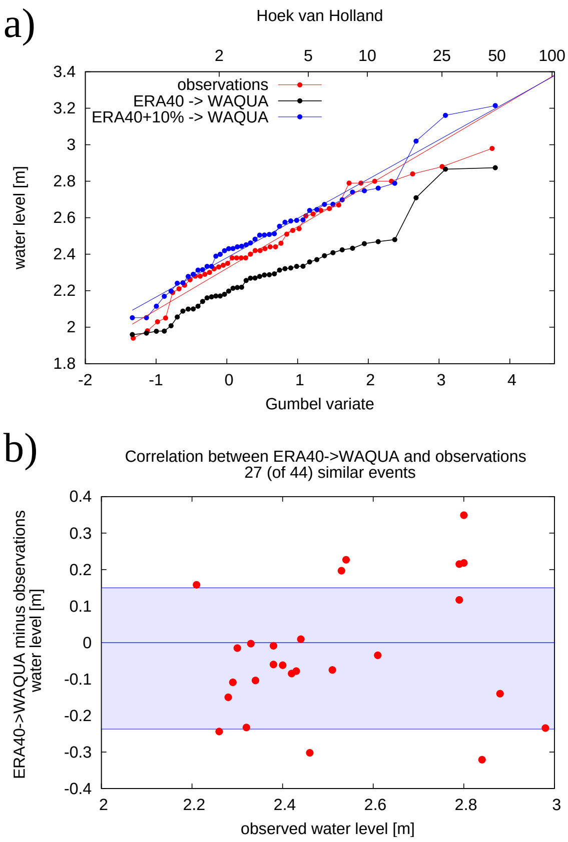

Fig. 3. (a) Gumbel plot of annual-maximum water levels in Hoek van Holland for the period 1958–2002. Compared are observations and results from WAQUA/DCSM98 forced by the original ERA-40 winds and by ERA-40 winds increased by 10%. The thin lines are the fits to a GEV. **(b)** Dependence of model-data difference on observed water levels for the 27 events that caused the highest annual water level in both the observations and the model.

3.2 Water levels

As explained in Sect. 2.3 we use ERA-40 winds, interpolated to the ESSENCE grid, to verify whether the low-resolution ESSENCE winds are a suitable forcing for WAQUA/DCSM98. Two runs have been conducted, one

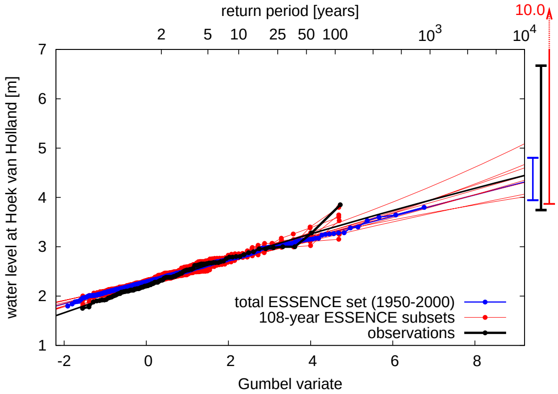

Fig. 4. Gumbel plot for water levels at Hoek van Holland. Black: 118 years of observations (1888–2005, thick) and GEV fit (thin). Red: data from eight 108-year chunks of ESSENCE-WAQUA/DCSM98 (thick) and corresponding fits (thin) for the present climate (1950–2000). The choice of 108 was motivated by the fact that 8×108=864 is as close as possible to 17×51=867, the total number of years available. Blue: All 867 years of ESSENCE-WAQUA/DCSM98 data together. The bars at the right margin indicate the 95% confidence intervals for the 10 000-year return value. The red bar corresponds to the curve with the highest best estimate of 5.1 m.

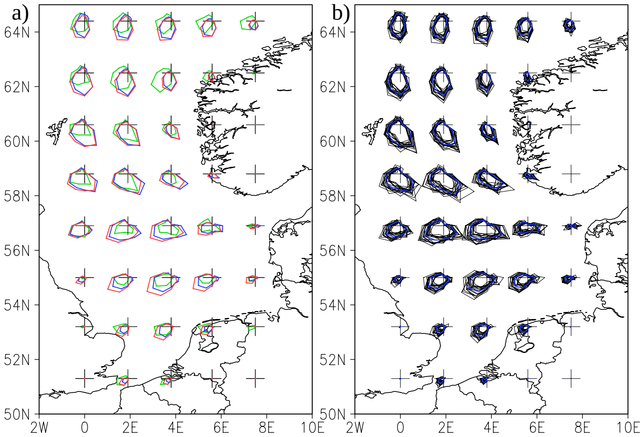

Fig. 5. Fraction of 6-hourly winds exceeding 8 Bf (17 m/s) per 30-degree sector for all grid points in the North Sea. **(a)** Means over all ESSENCE members for the present (1950–2000, blue) and future (2050–2100, red) climates. For comparison, ERA-40 is added in green. **(b)** All 17 members for the present climate and their mean (blue).

with the original ERA-40 winds, and one in which these winds were increased by 10% to compensate for the underestimation of surface winds in ERA-40 relative to other model data sets that was noted in Fig. 1. The modelled annual maximum water levels follow the same distribution as the observed levels (Fig. 3a), and in 27 of the 44 years the same event was responsible for the annual maximum in the model and in the observations. The model-observation difference shows no systematic dependence on water level (Fig. 3b). Summarizing, we conclude that the coarse resolution of the driving data does not impact negatively on the results of the water level model, and thus that the combination ESSENCE-WAQUA/DCSM98 is suitable to study extreme storm surges.

3.3 Uncertainty

Dutch law requires coastal defence systems to withstand a water level with a return period of 10 000 years. This level has to be estimated from the existing 118 years of observations. Not surprisingly, extrapolating over two orders of magnitude yields a large error bar. This is illustrated in Fig. 4 for the station Hoek van Holland, where black denotes observations. The GEV-fit yields a best estimate of 4.5 m for the 10 000 year return value, but the 95% confidence interval ranges from 3.8 m to 6.8 m.

This uncertainty is stressed by the results from the ESSENCE-WAQUA/DCSM98 ensemble. The red dots and lines in Fig. 4 are for eight arbitrary 108-year segments of the ensemble for present-day climate conditions (years 1950–2000). They were generated by concatenating all 17 runs and cutting the resulting time series into chunks of 108 years (8×108=864, which is as close as possible to 17×51, the number of years available). The respective GEV fits yield best estimates ranging from 4 m to more than 5 m, and the 95% confidence interval for the latter value ranges from 3.9 m to 10 m. From these results it is obvious that the impact of climate change on water levels cannot reliably be inferred from short time series. The sampling error would be much larger than the signal, which in the light of Sect. 3.1 we anticipate to be small. Only the whole ensemble (17×51 years, blue) yields a confidence interval that may be small enough to detect a climate change signal.

4 Projections

4.1 Winds

For the grid points on the North Sea, Fig. 5 shows the fraction of 6-hourly wind speeds exceeding 8 Bf (17 m/s) for 30-degree sectors for the present (1950–2000) and future climates (2050–2100). In the left panel the averages over the ensemble are plotted together with the values derived from the ERA-40 reanalysis (Uppala et al., 2005). Winds in the ESSENCE ensemble tend to be higher than those from ERA-40. As explained in Sect. 3.1 this is a consequence of the surface roughness parameterizations being different between ERA-40 and ESSENCE. The higher winds are due to more south-easterly winds in the northern part of the domain and more south-westerly winds in the southern

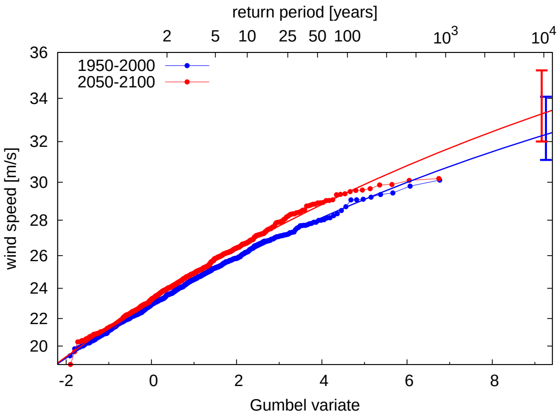

Fig. 6. Gumbel plot for ESSENCE annual maximum 3-hourly wind speeds for the same location as used in Fig. 1 (5° E, 55° N). Blue refers to the present (1950–2000), red to the future (2050–2100) climate. The lines are the fits to a GEV distribution. The error bars at the right margin indicate the 95% confidence intervals for the 10 000-year return values. The vertical axis is linear in u^2.

part. Both directions are not important for surges along the Dutch coast, where the highest surges are reached for north-westerly winds.

The differences between the present and the future climate are small. Changes are only seen for grid points along the rows at 53° N and 55° N, where strong south-westerly winds increase. A comparison with the right panel, in which all 17 members of the ensemble are plotted separately for the present-day climate, shows that the differences are smaller than the natural variability. It can be anticipated that an increase of south-westerly winds will not change surge heights greatly at the Dutch coast.

In Fig. 6 the annual maxima of 3-hourly wind speed at the grid point 5° E, 55° N are presented in a Gumbel plot. In accordance with Fig. 5 the values for the future climate are higher than those for the present one, but the increase is small and statistically insignificant as the respective 95%-confidence intervals for the 10 000-year return values overlap.

4.2 Water levels

Figure 7a shows a Gumbel plot of modelled annual-maximum water levels at Hoek van Holland for the present (1950–2000) and the future climate (2050–2100). The simulated values for the two periods are nearly identical, the fits are close together and the confidence intervals for the 10 000-year return value overlap. Within the limits of natural variability (Fig. 4) there is no change in the height of the water levels due to global warming along the Dutch coast. This result not only holds for Hoek van Holland, but also for other stations along the southern North Sea (Fig. 7b).

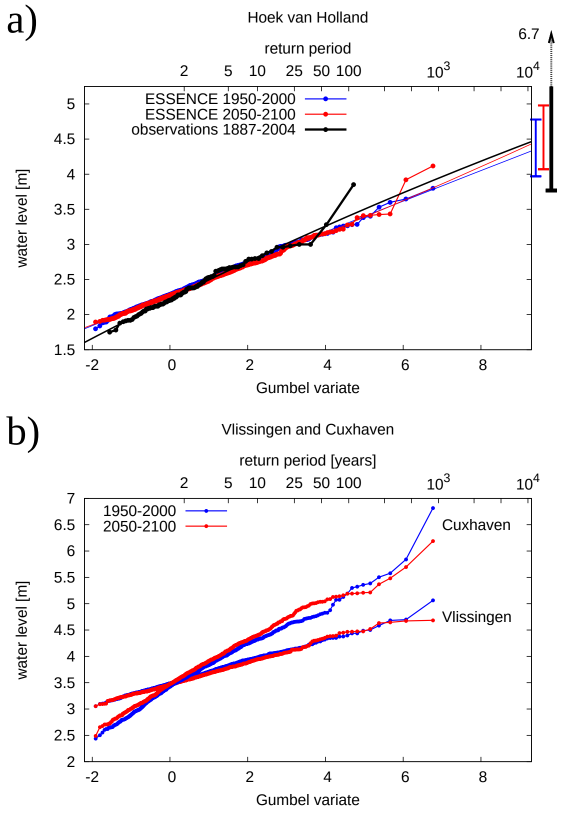

Fig. 7. Gumbel plot for water levels at **(a)** Hoek van Holland and **(b)** Vlissingen and Cuxhaven from the ESSENCE-WAQUA/DCSM98 ensemble. Black: observations, blue: present-day climate (1950–2000), red: future climate (2050–2100). For Hoek van Holland the observed data and present-day simulations are the same as in Fig. 4. The thin lines are the fits to a GEV, and the bars in the right margin indicate the 95% confidence interval of the 10 000-year return value.

In a warming climate the sea level will rise due to the thermal expansion of the sea water and the melting of land ice, and the deeper water might have an effect on surge heights, too. We therefore performed some test experiments in which the water depth was uniformly increased by 2 m in the whole domain of WAQUA/DCSM98. The coastlines, however, were not changed. The differences in the height of the water level (except for the constant increase of 2 m) from this run and the run with unchanged water depth are negligible, confirming results from Lowe et al. (2001).

5 Impact of tides

To investigate the impact of the tide on the water levels we have repeated the WAQUA/DCSM98 runs (all-forcing runs) without imposing the tides at the boundary of the model domain (no-tide runs). The tidal component has been calculated separately in a run without meteorological forcing, but tide imposed (tide-only run).

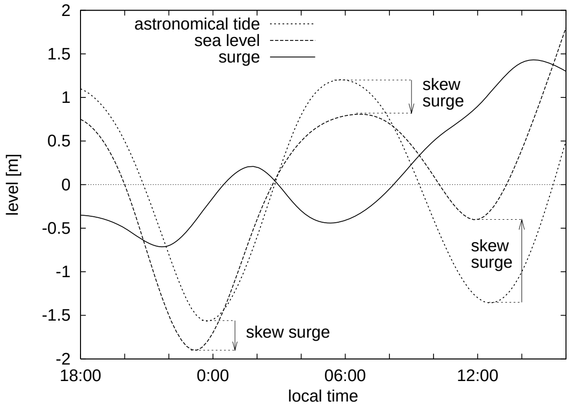

Fig. 8. The *surge* (solid line) or *tidal residual* is the difference between observed water level and astronomical tide at each moment. The *skew surge* is the difference between the maximum (minimum) water level and the closest high (low) astronomical tide, which need not to take place at the same moment. In the figure the skew surges at the first low tide (00:00) and the high tide (06:00) are negative, whereas the second low tide skew surge (12:00) is positive (indicated by arrows). Shown is the situation at Delfzijl from 21 February 2002 18:00 to 22 February 2002 16:00 local time (reproduced from Van den Brink et al., 2003).

The evaluation is done in terms of the *skew surge* (Fig. 8). The skew surge at high (low) tide is the difference between the highest (lowest) water level and the closest astronomical high (low) tide (e.g. Van den Brink et al., 2003). We prefer this measure of surge height above the straightforward and often-used tidal residual, the instantaneous difference between water level and astronomical tide (sometimes also called storm surge residual). The skew surge better separates the astronomical from the meteorological impact on the water level, as, in general, the maximum of the wind-driven part of the water level (surge) does not coincide with the maximum of the astronomically-driven part (tide). For the runs without tide we first add the water levels from the no-tide runs to the water level of the tide-only run and then calculate the skew surge. This assumes independence of surge and tide.

The comparison of the two sets of runs confirms the result of Horsburgh and Wilson (2007) that the tide has a dampening effect on surge heights. Figure 9a shows that the difference between the location parameters of GEV-fits to the skew surges of the two sets of runs, $\Delta\mu=\mu_{\text{tide}}-\mu_{\text{no tide}}$, is negative everywhere. In accordance with the results of Horsburgh and Wilson (2007) the largest tidal residual systematically occurs *before* the high tide. In general, this time difference is larger for stations with a larger $\Delta\mu$ (not shown), which in turn is larger for places with a higher tidal amplitude (Fig. 9b). Dover is a notable exception from this general trend. Clearly, tide and surge are *not* independent.

The interaction between surge and tide is a dynamical effect. As mentioned at the end of Sect. 4.2 modelled water levels are not changed by increasing the water depth of the whole North Sea, and neither are the skew surges. The only effect is a slightly faster propagation of both the tidal wave and the surge. Both are to first order shallow water waves with a phase speed depending in the same way on water depth (Horsburgh and Wilson, 2007). Uniformly increasing the water depth impacts both of them in the same way with no net effect.

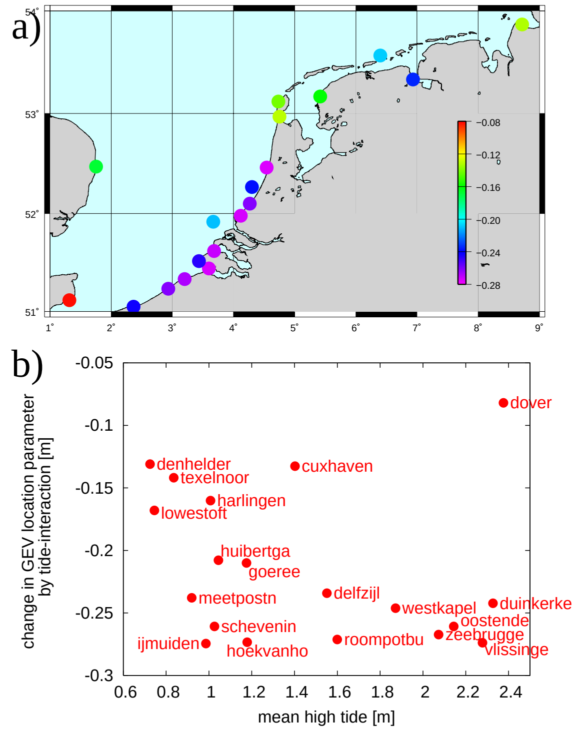

Fig. 9. **(a)** Difference of location parameter of GEV fits to annual maximum skew surge from runs with and without tides along the southern North Sea (in m). **(b)** Scatter plot of $\Delta\mu$, the difference in location parameter, (y-axis) and the mean high tide (x-axis).

6 Summary and conclusion

To investigate possible changes in storm surge characteristics along the Dutch coast as a consequence of global warming, we have forced WAQUA/DCSM98, a comprehensive 2-D storm surge model of the Northwest European shelf, by output from ESSENCE, a large-member ensemble of climate change simultions. In these simulations the ECHAM5/MPI-OM climate model was run 17 times for the period 1950–2100 under an SRES A1b forcing scenario. It is shown that it is possible to drive WAQUA/DCSM98 directly with the output of the climate model without employing a downscaling step using a regional climate model.

Dutch law requires a safety level of the coastal defence system of once-in-10 000 years. Estimating this level from the order 100 years of observations leads to a large statistical uncertainty. Only with the large ESSENCE ensemble is it possible to reduce this uncertainty to a level suitable to make inferences about possible changes in a changing climate.

The results of ESSENCE feature a small increase in maximum wind speeds over the southern North Sea. However, this increase is due to winds from the south-west, which do not lead to high surges along the Dutch coast. Consequently, no changes in surge heights are simulated by WAQUA/DCSM98. Likewise, no changes in surge height resulting from an increased sea level are found. We like to stress that this result is based on only one climate model, and that a large ensemble using another model or a large multi-model ensemble is needed to confirm it. However, the investigations reviewed in the Introduction, although focusing on much shorter return times, back our result.

As a by-product of our simulations we find that surge and tide interact non-linearly, with the tide having a damping effect on total water level. This is a dynamic effect. Uniformly increasing the depth of the North Sea in order to simulate sea level rise has no effect on the combined surge+tide level. The deeper water affects the propagation of the surge and the tide in the same way with no net effect.

Acknowledgements. This work was initiated and partly funded by the Dutch Delta Committee ("Commissie Veerman"). We like to thank Ralf Weisse (GKSS, Germany) and Jason Lowe (Hadley Centre, UK) for their contributions during the work for the Delta Committee. Parts of the introduction of this paper are taken from Ralf Weisse's contribution to the report for that Committee. The ESSENCE project, lead by Wilco Hazeleger (KNMI) and Henk Dijkstra (UU/IMAU), was carried out with support of DEISA, HLRS, SARA and NCF (through NCF projects NRG-2006.06, CAVE-06-023 and SG-06-267). We thank the DEISA Consortium (co-funded by the EU, FP6 projects 508830/031513) for support within the DEISA Extreme Computing Initiative (www.deisa.org). The authors thank Camiel Severijns (KNMI) as well as HLRS and SARA staff for technical support.

Edited by: E. J. M. Delhez

References

Alexandersson, H., Schmith, T., Iden, K., and Tuomenvirta, H.: Long-term variations of the storm climate over NW Europe, Global Atmos. Oc. System, 6, 97–120, 1998.

Alexandersson, H., Tuomenvirta, H., Schmidth, T., and Iden, K.: Trends of storms in NW Europe derived from an updated pressure data set, Climate Res., 14, 71–73, 2000.

Bärring, L. and von Storch, H.: Scandinavian storminess since about 1800, Geophys. Res. Lett., 31, L20202, doi:10.1029/2004GL020441, 2004.

Bunde, A., Eichner, J. F., Havlin, S., and Kantelhardt, J. W.: Return intervals of rare events in records with long term persistence, Physica A, 342, 308–314, 2004.

Charnock, H.: Wind stress on a water surface, Q. J. Roy. Meteorol. Soc., 81, 639–640, 1955.

Coles, S.: An Introduction to Statistical Modeling of Extreme Values, Springer-Verlag, Berlin, London, Heidelberg, 208 pp., 2001.

Debernard, J. B. and Røed, L. P.: Future wind, wave and storm surge climate in the Northern Seas: a revisit, Tellus, 60A, 472–438, doi:10.1111/j/1600-0870.2008.00312.x, 2008.

Deltacommissie: Rapport Deltacommissie, 's-Gravenhage; Staatsdrukkerij- en Uitgeverijbedrijf, 6 Delen, 1960-61. Deel I: Eindverslag en interimadviezen. Deel II-IV: Beschouwingen over stormvloeden en getijbeweging. Deel V: Onderzoekingen betreffende de opzet van het Deltaplan en de gevolgen van de werken. Deel VI: Onderzoekingen van belang voor het ontwerpen van dijken en dammen; sociaal-economische aspecten van het Deltaplan. Dutch only, 1960/61.

Gerritsen, H., de Vries, H. and Philippart, M.: The Dutch Continental Shelf Model, in: Quantitative Skill Assessment for Coastal Ocean Models, edited by: Lynch, D. and Davies, A., Coastal and Estuarine Studies, 47, AGU, 1995.

Horsburgh, K. J., and Wilson, C.: Tide-surge interaction and its role in the distribution of surge residuals in the North Sea, J. Geophys. Res., 112, C08003, doi:10.1029/2006JC004033, 2007.

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK, and New York, NY, 2007.

Jungclaus, J. H., Keenlyside, N., Botzet, M., Haak, H., Luo, J. J., Latif, M., Marotzke, J., Mikolajewicz, U., and Roeckner, E.: Ocean Circulation and Tropical Variability in the Coupled Model ECHAM5/MPI-OM, J. Climate, 19, 3952–3972, 2006.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: The NCEP/NCAR reanalysis project, B. Am. Meteorol. Soc., 77, 437–471, 1996.

KNMI: KNMI Climate Change Scenarios 2006 for The Netherlands, KNMI Scientific report WR 2006-01. Available from KNMI, P.O. Box 201, 3730 AE De Bilt, The Netherlands, 2006.

Lowe, J. A., Gregory, J. M., and Flather, R. A.: Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models, Clim. Dynam., 18, 179–188, 2001.

Lowe, J. A. and Gregory, J. M.: The effects of climate change on storm surges around the Unitied Kingdom, Philos. T. Roy. Soc., A363, 1313–1328, doi: 10.1098/rsta.2005.1570, 2008.

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., and Taylor, K. E.: The WCRP CMIP3 multi-model dataset: A new era in climate change research, B. Am. Meteorol. Soc., 88, 1383–1394, 2007.

Nakicenovic, N. and Swart, R. (Eds.): Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 599 pp., online available at: http://www.grida.no/climate/ipcc/emission/index.htm, 2000.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L., Jones, C., Meier, H., Samuelsson, P., and Willén, U.: GCM driven simulations of recent and future climate with the Rossby Centre coupled atmosphere-Baltic Sea regional climate model RCAO, SMHI, Norrköping, Rossby Centre, 61 pp., 2003.

Sterl, A., Severijns, C., Dijkstra, H., Hazeleger, W., van Oldenborgh, G. J., van den Broeke, M., Burgers, G., van den Hurk, B., van Leeuwen, P. J., and van Velthoven, P.: When can we expect extremely high surface temperatures?, Geophys. Res. Lett., 35, L14703, doi:10.1029/2008GL034071, 2008.

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., V. da Costa Bechtold, Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J.-F., Morcrette, J.-J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P., and Woollen, J.: The ERA-40 re-analysis, Q. J. Roy. Meteorol. Soc., 131, 2961–3012, 2005.

Van den Brink, H. W., Können, G. P., and Opsteegh, J. D.: The reliability of extreme surge levels, estimated from observational records of order hundred years, J. Coast. Res., 19, 376–388, 2003.

Van Den Brink, H. W., Können, G. P., Opsteegh, J. D., van Oldenborgh, G. J., and Burgers, G.: Improving 10^4-year surge level estimates using data of the ECMWF seasonal prediction system, Geophys. Res. Lett., 31, L17210, doi:10.1029/2004GL020610, 2004.

Van den Brink, H. W. and Können, G. P.: The statistical distribution of meteorological outliers, Geophys. Res. Lett., 35, L2370, doi:10.1029/2008GL035967, 2008.

Van Meijgaard, E., van Ulft, L. H., van de Berg, W. J., Bosveld, F. C., van den Hurk, B. J. J. M., Lenderink, G., and Siebesma, A. P.: The KNMI regional atmospheric climate model RACMO, version 2.1, KNMI Technical Report TR-302, available from KNMI, P.O. Box 201, NL-3730 AE De Bilt, The Netherlands, 43 pp., 2008.

Van Ulden, A.P., and Van Oldenborgh, G.J.: Large-scale atmospheric circulation biases and changes in global climate model simulations and their importance for climate change in Central Europe, Atmos. Chem. Pys. 6, 863–881, Sref-ID: 1680-7324/acp/2006-6-863, 2006.

The WASA-Group: Changing waves and storms in the Northeast Atlantic?, B. Am. Meteorol. Soc., 79, 741–760, 1998.

Woth, K.: North Sea storm surge statistics based on projections in a warmer climate: How important are driving GCM and the chosen emission scenario?, Geophys. Res. Lett., 32, L22708, doi:10.1029/2005GL023762, 2005.

Woth, K., Weisse, R., and von Storch, H.: Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models, Ocean Dynam., 56, 3–15, doi:10.1007/s10236-005-0024-3, 2006.