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LETTER

Large-scale winds in the southern North Sea region: the wind part of the KNMI'14 climate change scenarios

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Abstract

The wind climate and its possible change in a warming world are important topics for many applications, among which are marine and coastal safety and wind energy generation. Therefore, wind is an important variable to investigate for climate change scenarios. In developing the wind part of the KNMI'14 climate change scenarios, output from several model categories have been analysed, ranging from global General Circulation Models via regional climate model (RCMs) to suitably re-sampled RCM output. The main conclusion is that global warming will not change the wind climate over the Netherlands and the North Sea beyond the large range of natural climate variability that has been experienced in the past.

1. Introduction

Wind is an important climate parameter. High winds can cause safety problems, either directly trough wind damage, or indirectly via waves or storm surges. Low winds can cause air pollution problems, and, due to the growing wind energy production, affect electricity supply. As climate warms due to anthropogenic greenhouse gas emissions, the wind climate may change, too. Therefore, wind is one of the key parameters investigated for the recently published KNMI'14 climate change projections for the Netherlands (van den Hurk *et al* 2014b). The present paper summarizes the main findings of the research that led to the wind part of these scenarios.

The main source of information are the Coupled Model Intercomparison Project, phase 5 (CMIP5; Taylor *et al* 2012) model runs, and especially the runs of EC-Earth (Hazeleger *et al* 2012). To improve the representation of small-scale features, especially along the coast, and of extremely high wind speeds, output from the EC-Earth run (resolution ≈125 km) was downscaled using the regional climate model (RCM) RACMO2 (van Meijgaard *et al* 2008) with a resolution of ≈11 km. Many CMIP5 models simulate circulation changes over Europe as the climate warms. The corresponding changes as simulated by EC-Earth do not span the whole CMIP5 range (van den Hurk *et al* 2014a), and consequently the same is true for the RACMO2 runs. To create time series that span 60–80% of the CMIP5 simulated spread of changes of a set of temperature and precipitation characteristics, the RACMO2 runs have been suitably subsampled (Lenderink *et al* 2014). With this procedure spatial detail is retained and physical consistency is not significantly affected. As precipitation is strongly linked to circulation characteristics (van den Hurk *et al* 2014a), the precipitation criterion essentially selects different circulation regimes.

Hazeleger *et al* (2012) show that differences of sea level pressure between EC-Earth and ERA-Interim (Dee *et al* 2011) are smaller than 2 hPa, making EC-Earth better than any CMIP3 (the predecessor of CMIP5) model in this respect. Especially the North Atlantic Oscillation, the dominant pressure pattern over the North Atlantic, is reproduced well, albeit with too low variability. de Winter *et al* (2013) show that the characteristics of high wind speeds compare well with those of ERA-Interim (their Figure 2), and Zappa *et al* (2013) show that the characteristics of extratropical cyclones in EC-Earth are very close to those of several reanalyses. This makes us confident that EC-Earth is a suitable model to investigate global-warming induced changes of the wind climate in the North Sea region.

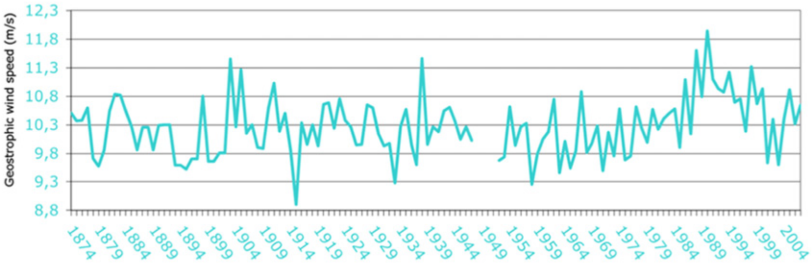

Figure 1. Annual-mean geostrophic wind (as a measure of windiness) for the pressure triangle Aberdeen–Tyborøn–De Bilt, which covers the whole southern North Sea.

2. Observations—past changes

2.1. Over the North Sea

Storminess (climate of high winds) and windiness (climate of mean wind) in the North-East Atlantic Ocean and the North Sea have shown large, spatially highly correlated variations during the 20th century. The driving force for these low-frequency variations is not fully understood (Bakker *et al* 2013). Any projected future changes must be compared with these natural fluctuations.

Long-term direct wind observations are sparse, prone to errors and not available over the open sea. An indirect measure of storminess can be obtained by calculating the average geostrophic wind within a triangle from surface pressure measurements at the corner points. Pressure has been measured for a long time with great precision at several locations. Following earlier work by Alexandersson *et al* (2000) and Wang *et al* (2009), who investigated the whole North-East Atlantic, Bakker and van den Hurk (2012) investigated several pressure triangles covering the North Sea. Their results confirm those of the earlier work. Large interannual variations are superimposed on a low-frequency variation that is characterized by high values at the beginning and end of the 20th century, and low values at mid-century (figure 1). Since the 1950s, storminess and windiness rose until the beginning of the 1990s, when a maximum was reached, which, however, was not exceptional when compared to the late 19th century. Since then both wind indicators have been declining. There is no discernible trend over the whole period of ≈140 years.

Using 140 years (1871–2010) of wind output from the *Twentieth Century Reanalysis* data set (Compo *et al* 2011), Bett *et al* (2013) arrive at essentially the same result. Their analysis is not confined to the North Sea but covers the whole of Europe. Also over land they find no indications for a long-term trend in wind climate.

2.2. Over land

Smits *et al* (2005) notice that surface winds (10 m height) over land in the Netherlands exhibit a decreasing trend between 1962 and 2002, while geostrophic winds based on a pressure triangle covering the country show no trend. Vautard *et al* (2010) show that this decrease is not limited to the Netherlands, but a widespread phenomenon of the Northern Hemisphere. They ascribe between 25% and 60% of the decrease between 1979 and 2008 to increased surface roughness over land. For the Netherlands, Wever (2012) estimates that surface roughness increase accounts for up to 70% of the observed wind speed reduction over the 1981–2009 period. He finds negative trends in annual-mean winds of typically $-0.25\ \mathrm{m\ s^{-1}}$ per decade for inland stations, but no significant trends for coastal ones. Bakker *et al* (2013) investigated several indices related to wind-power production over the period 1988–2010 and found that they were decreasing. However, they found no convincing evidence for surface roughness changes being a major cause. This difference with the results of Vautard *et al* (2010) and Wever (2012) can partly be explained by the different periods used.

It is important to note that Vautard *et al* (2010) find no or even a positive wind speed trend away from the surface, where the influence of the roughness is small. This has implications for wind energy generation, as modern wind turbines have a hub height of about 100 m. However, Bakker *et al* (2013) show that also indices based on actual wind power generation show a decreasing trend.

Cusack (2013) analysed 101 years (1910–2010) of wind measurements at five stations in the Netherlands. He focuses on potentially damaging storms, defined as storms in which the daily maximum wind speed, U_{10}^{dmx}, exceeds its climatological 99%-ile. Both the number of potentially damaging storms per year and their loss index, which is proportional to $(U_{10}^{\mathrm{dmx}})^3$, show high inter-annual variability and decadal-scale variations, but no long-term trend. Both variables reach their highest values at the beginning and the end of the 20th century, showing that the low-frequency variations found in the pressure triangle results (figure 1) over sea extend onto land. The *number* of potentially damaging storms reaches an additional maximum in the middle of the century, which is mainly due to relatively weak storms, and an absolute minimum at the beginning of the 21st century.

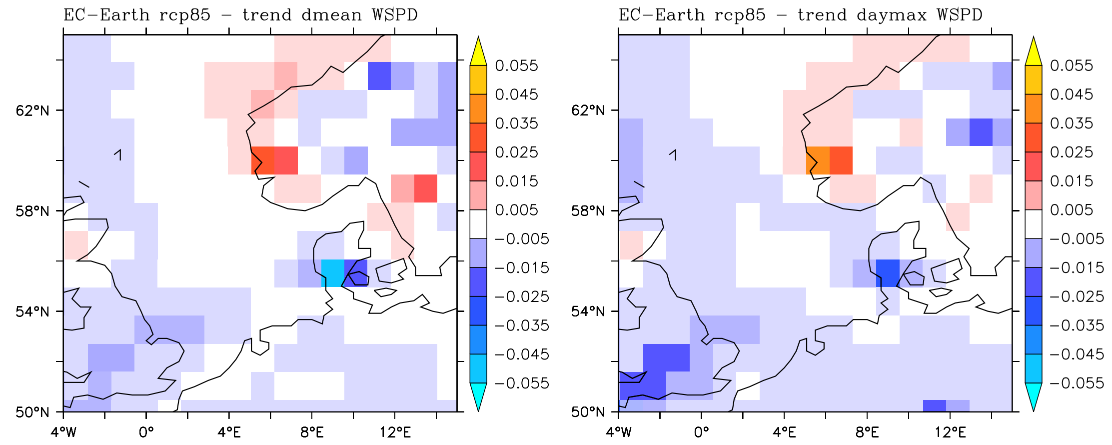

Figure 2. Linear trends (in (m s^{-1} /decade) of (left) daily-mean and (right) daily-maximum wind speeds over the North Sea area from the EC-Earth rcp8.5 runs. Grid cells in which the trends are significant at the 95% level (t-test) are indicated by full colours. They are all over land.

3. Projections for the future

3.1. Literature survey

Wind climate and its possible changes have been studied extensively using output from the CMIP3 and CMIP5 model runs, either directly, or downscaled by RCMs. Based on the CMIP3 model runs, the main result concerning the wind in the older KNMI'06 climate change scenarios (van den Hurk *et al* 2006) was that 'the wind scenarios give small changes compared to the typical interannual variability of the scenario variable' (p 49). Sterl *et al* (2009) presented a literature survey in which they reinforce these conclusions: Modelled wind speed changes in the North Sea differ between models and are usually small when compared to natural variability. These results are confirmed when using RCMs. Using output from an ensemble of RCMs, driven by various General Circulation Models (GCMs), Nikulin *et al* (2011) find no significant changes in the 20 year return wind speed over the North Sea, and Pryor *et al* (2012) find no changes in the strength of wind gusts.

Using output from the newer CMIP5 models (Taylor *et al* 2012) does not change the picture. Harvey *et al* (2012) and Chang *et al* (2012) conclude that wind speed changes over western Europe are smaller than natural variability. Mizuta (2012) uses the CMIP5 models to investigate extratropical cyclone numbers and cyclone growth rates. He finds that changes in these variables are small in the North Atlantic, and that they differ between models. Eichler *et al* (2013) find a decrease of storm frequency, but an increase of storm intensity in the North Atlantic, which, however, does not extend into the North Sea region. Zappa *et al* (2013) analyse storm tracks in 22 CMIP5 models. While they find decreasing trends in cyclone number and frequency in most of the North Atlantic and Europe, they find a small region over the British Isles and the southern North Sea with an increasing trend. Although the signal is small (less than 1% in wind speed!), they find it to be significant as it is consistent among models.

Concluding, papers published so far suggest no substantial changes of the wind climate in the North-East Atlantic under climate warming. Natural variability is large and dominant and will remain so for the century to come.

3.2. The North Sea area in CMIP5 models

We are interested in possible changes of the most extreme wind speeds as these cause the largest damage. Naturally, wind speeds averaged over a short period can reach higher values than those averaged over a longer period, but *changes* in annual-maxima of hourly and of daily-mean winds are comparable (figure 2). In order to have an appreciable impact on water level (surge height) or wave height on the North Sea, high winds have to last for at least several hours. Therefore, de Winter *et al* (2013) analysed the output of daily-mean 10 m wind (U_{10}) from twelve CMIP5 models. They find that the patterns of change between the two 50-year periods 2051–2100 and 1951–2000 in the average annual-maximum daily-mean wind speed differ widely between models, but that in all cases the changes are small. In general, they are not significant over the open North Sea. Over land some models show statistically significant changes, but without agreeing on their sign. These results carry over to estimated wind speeds with long return times (>100 years). Differences between the models are much larger than projected changes. While their findings on wind speed changes are equivocal, de Winter *et al* (2013) find indications for maximum winds coming more often from westerly directions and less often from South-Easterly ones, confirming the results of van den Hurk *et al* (2006) and Sterl *et al* (2009). Winds from westerly directions are less dangerous for the Dutch coast as their fetch is shorter, resulting in smaller storm surges,

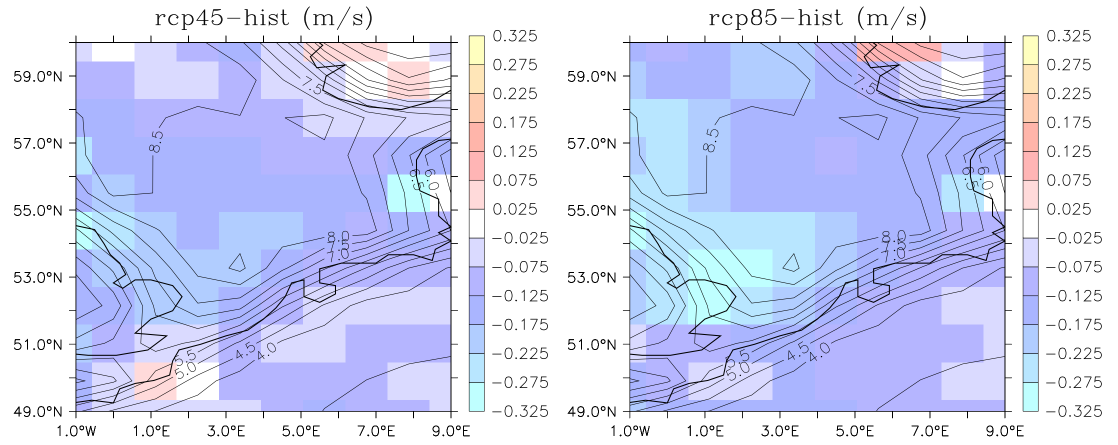

Figure 3. Differences in annual-mean wind speed between 2071–2100 and 1976–2005 from the EC-Earth runs for (left) rcp4.5 and (right) rcp8.5 (color shading) in the North Sea region. Superimposed as contours is the climatology 1976–2005.

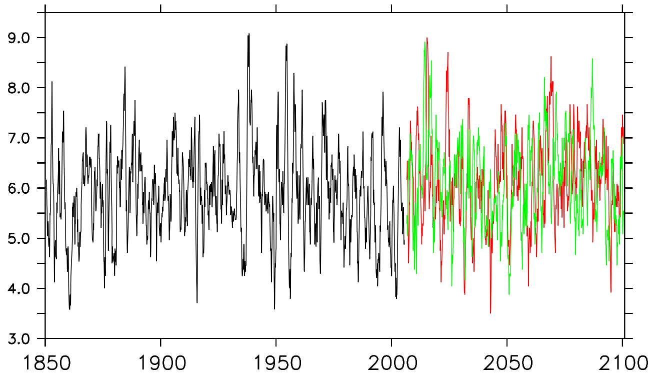

Figure 4. Number of low-wind days (daily-mean $U_{10} < 5$ m s^{-1}) per month according to EC-Earth historic (black), rcp4.5 (green) and rcp8.5 (red) scenario runs for the point (4°E, 54°N) on the North Sea. A 12 month running-mean filter has been applied to the data to enhance visibility.

than north-westerly winds, the frequency of which is found by de Winter *et al* (2013) not to change.

Figure 3 shows the annual-mean wind speed change (2071–2100—1976–2005) from the KNMI EC-Earth runs for the rcp4.5 and the rcp8.5 scenarios (respectively 4.5 W m^{-2} and 8.5 W m^{-2} radiative heating in 2100; van Vuuren *et al* 2011). Note that the data for the period 1976–2005 are from the historic EC-Earth run, not from observations. The changes are all negative, but according to a t-test they are not significant at the 95% level. Splitting the results into months (not shown) reveals that the mean wind speed decreases in almost all months. Only in late summer and early autumn (September/October) some increases do appear. However, a t-test shows that neither the positive nor the negative changes are significant at the 95% level for any month.

Prolonged periods of low wind can be a problem for the wind energy sector. We here present the—to our knowledge—first assessment of possible changes of the frequency of low-wind events. As a wind turbine does not produce energy for wind speeds below 5 m s^{-1}, we define a *low wind day* as a day with a mean U_{10} of less than 5 m s^{-1}. Figure 4 shows the number of such days for a location in the Southern North Sea (4° E, 54°N) as derived from the EC-Earth CMIP5 runs. The frequency of low-wind days varies around six per month, with large inter-annual and inter-decadal variations, but no long-term trend. The two future scenarios show no signs of a systematic difference between each other or with the historical period. Repeating the same analysis for a threshold of 3 m s^{-1} or a land point gives a similar picture. Of course, the mean frequency changes (≈1.4 d/mon for the sea point and ≈9 d/mon for the land point (5°E, 51°N), both for a 3 m s^{-1} threshold), but the variability remains large, and no long-term trend can be discerned. We therefore conclude that systematic changes in the frequency of low-wind days are not to be expected.

3.3. Downscaling

To obtain information on smaller scales than resolved by GCMs we use RACMO2 (van Meijgaard *et al* 2008), an RCM developed and maintained at KNMI, to dynamically downscale results from EC-Earth. Due to

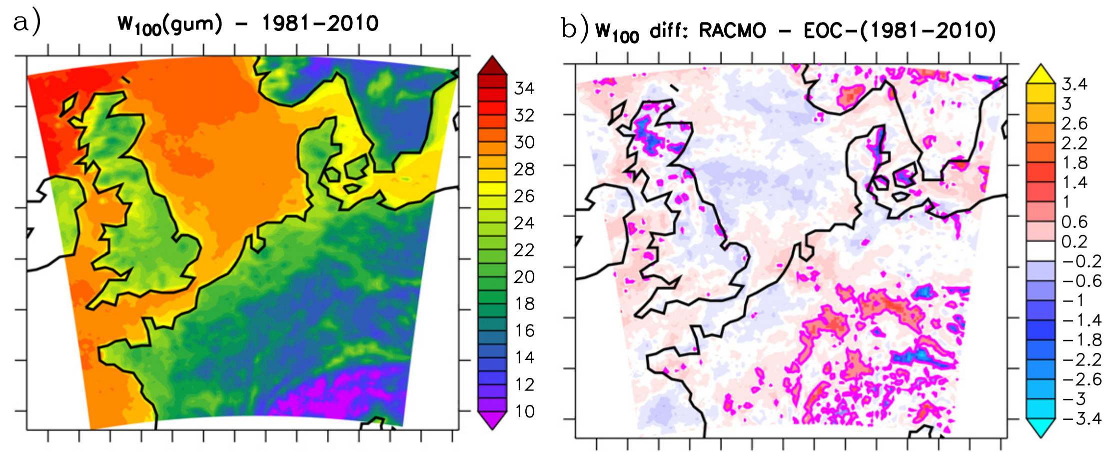

Figure 5. 100-year return values (in m s^{-1}) of daily-maximum wind speed as obtained from a Gumbel fit to the RACMO2 output. (a) Values for the historical period (1981–2010), and (b) difference between the last 30 years of the 21st century (2071–2100) and the historical period. Differences that are (not) significant at the 95% level (see text) are in full (pale) colours and surrounded by a pink line.

their higher resolution (RACMO2 has a resolution of ≈0.1° on a domain covering most of western and northern Europe), RCMs can generate higher extremes, as extremes are usually confined to small spatial areas. Eight EC-Earth runs have been downscaled. They were forced according to the CMIP5 protocol with rcp8.5 forcing for the 21st century. The downscaling period is 1960–2100. These eight runs are lumped together to determine 100-year return values (U_{100}) of wind speed.

Surface winds are influenced by surface roughness (see section 2.2). The RACMO2 runs are performed with constant present-day surface roughness, so the possible effect of its changes (e.g., due to more or less trees or more or higher buildings) on surface wind speed is not included.

In figure 5 we present U_{100} and its changes for the RACMO2 output. The 100-year return values were determined from a Gumbel fit (Coles 2001) to the annual-maxima of daily-maximum 10 m wind speeds. Note that this is different from de Winter *et al* (2013), who used annual-maxima of daily means. This, together with the effect of the higher resolution in RACMO2, leads to the 100-year return values from RACMO2 shown in figure 5 being higher than those given in de Winter *et al* (2013). However, daily-mean and daily-max values show the same (insignificant) trends in EC-Earth (figure 2). The difference pattern (figure 5(b)) is noisy and consists of patches of increasing or decreasing U_{100}, suggesting that the changes are not significant. To formally estimate the significance of the changes we divide the differences by an estimate of their uncertainty. The following uncertainty measure is used. For each of the two periods we generate 1000 U_{100} values by bootstrapping and take the 95% interval of these 1000 values, σ_{95}. The σ_{95} values for the two periods are then added quadratically, $\sigma_{95}^{\mathrm{tot}} = (\sigma_{95,1}^2 + \sigma_{95,2}^2)^{1/2}$. The uncertainty (spread of bootstrapped values) turns out to be the same for the two periods (not shown), indicating that the variability does not change. In figure 5(b) full colours (plus pink contour) are used for grid points at which the simulated change between the two periods is larger than the uncertainty. Clearly, in most places the simulated differences in U_{100} are not significant.

3.4. Re-sampling

The KNMI'14 scenarios are organized along two dimensions, one representing global-mean temperature rise, and the other regional precipitation/circulation change. For global-mean temperature rise the two values 1.5 K and 3.5 K for the 2071–2100 mean are considered (G and W scenarios, respectively). Circulation change can be strong (labelled with subscript H), with wetter winters and drier summers due to respectively more westerly and more easterly winds, or relatively weak (subscript L), with small precipitation changes in both seasons. To generate conditions for these four KNMI'14 scenarios (W_L/W_H and G_L/G_H), the RACMO2 runs have been re-sampled (Lenderink *et al* 2014). The re-sampling involves the sea-level pressure, and thus indirectly the wind, as a selection criterion. It is therefore not surprising that in the re-sampled output changes in wind characteristics are larger than in the original RACMO2 output. However, even then changes in annual-mean and annual-maximum wind speeds are not significant.

Consistent with the selection criterion, the number of days with southerly to westerly wind directions, the prevailing wind direction, will increase (decrease) in the H (L) scenarios in winter, while all scenarios show a decrease in summer, with the largest decrease occurring in the H scenarios. The winter changes are statistically significant for the G_H (increase) and W_L (decrease) scenarios for the 2071–2100 period.

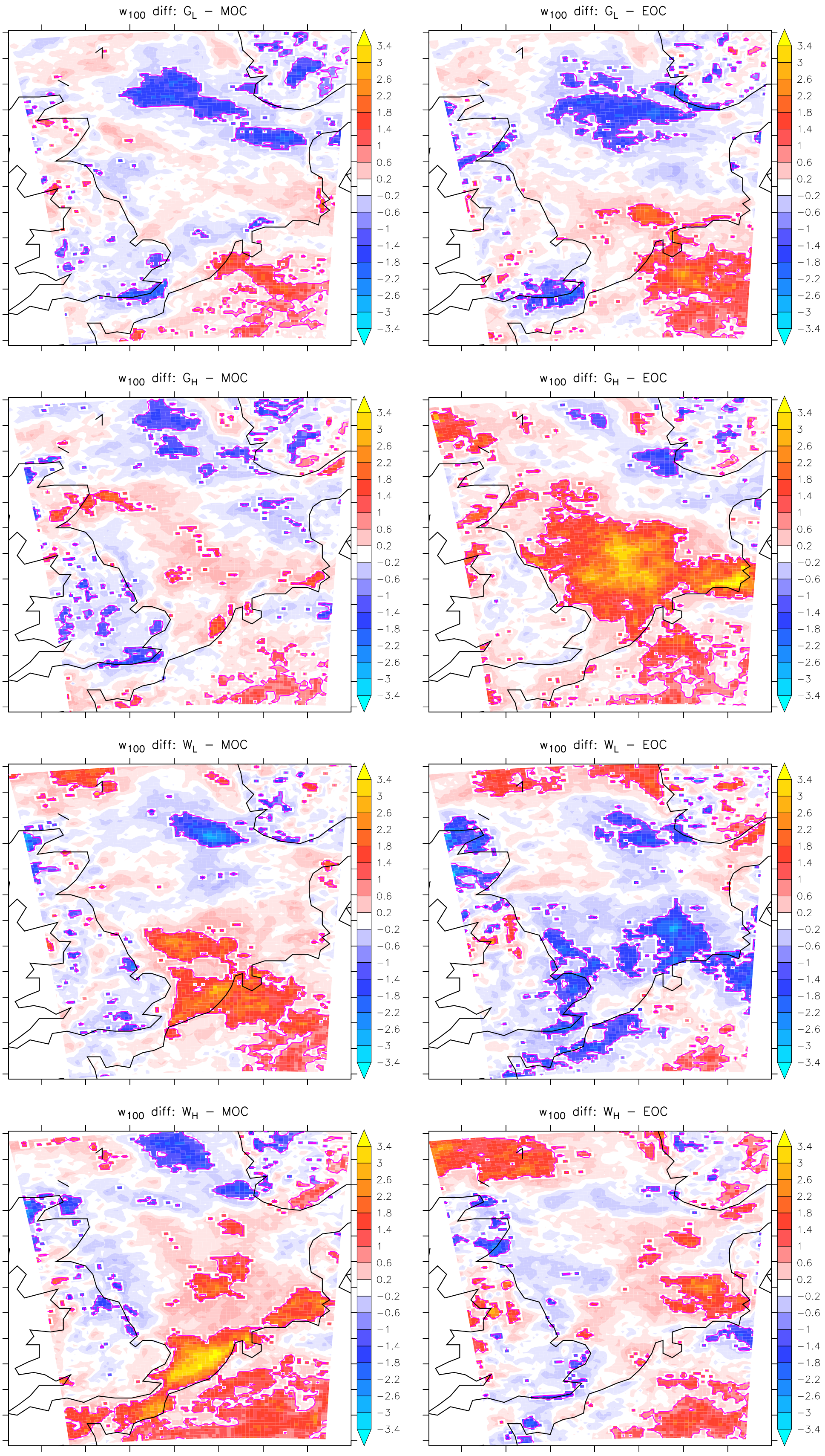

Figure 6. Changes of 100-year return values (in m s^{-1}) of daily-maximum wind speed as obtained from a Gumbel fit to the re-sampled RACMO2 output for the four KNMI'14 scenarios and two time-horizons (MOC = middle of century = 2036–2065; EOC = end of century = 2071–2100). Differences that are (not) significant at the 95% level (see text) are in full (pale) colours and surrounded by a pink line.

Figure 6 shows the projected changes of U_{100} for all scenarios and two time periods. Although they are significant over larger areas than in the original RACMO2 output (figure 5), their patterns are relatively small-scaled and noisy. The changes are inconsistent between scenarios and time periods. For instance, in the W_L scenario an area with a large increase shows up between the Netherlands and England for the 2036–2065 period, which is totally absent for the later (2071–2100) period. Finally, the changes seem to be smallest for the situation with the largest forcing (W_H in 2071–2100). Repeating the calculation with a GEV fit (Generalized Extreme Value; Coles 2001) instead of a Gumbel fit, or using daily-mean instead of daily-maximum values, gives a similar picture. Furthermore, the change patterns obtained from the different combinations (GEV or Gumbel, mean or max) do not agree (not shown). We conclude that there is no robust statistical evidence for a change in extreme wind conditions in the North Sea region.

4. Conclusions

The storm climate in and around the North Sea is very variable. Observations show decadal-scale variations, but no long-term trend over the past 130+ years. Results from recent state-of-the-art climate models as well as RCM studies do not suggest changes in the wind climate to occur as a response to increased global warming. This is true for mean wind conditions, low wind conditions and extreme wind speeds. Modelled changes are statistically insignificant. The climate models point to an increasing frequency of extremes coming from westerly directions. To construct the four KNMI’14 scenarios, RACMO2 output has been re-sampled, taking into account a possible systematic change of the pressure pattern. Consequently, the scenarios display larger changes than the raw RACMO2 output, but even in that case most changes are statistically insignificant.

The new results presented in this paper are based on only one modelling chain (EC-Earth—RACMO2), and the re-sampling covers only 60–80% of the CMIP5 simulated spread of *changes* of a set of *temperature* and *precipitation* characteristics. Wind is not used directly. While this seems to limit somewhat the general validity of our results it should be kept in mind that the literature survey (sections 3.1 and 3.2) shows that the spread of changes of *wind* indicators in CMIP5 is small and mainly insignificant.

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