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The impact of climate change on storm surges over Irish waters

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ABSTRACT

The Regional Ocean Model System (ROMS) of Rutgers University is used to investigate the influence of anthropogenic climate change on storm surges over Irish waters, particularly on the extreme values. Two experiments were performed to confirm the validity of the approach in the current climate: the first focused on hindcasting the surge generated by a storm in early 2002 while the second provided surge statistics by running the model for the period 1990–2002; in both cases ROMS was driven with ERA-40 forcing fields. The results show that the model is capable of simulating both specific surge events and surge climate statistics with reasonable accuracy (order of 10 cm). Model outputs were also compared spatially against satellite altimetry data, corrected for long wavelength errors, from 1993 to 2001. The ROMS model consistently reproduces the sea level changes in the Irish Sea, and over the waters to the south and west of Ireland. For the investigation of the impact of the climate change on storm surges, the same configuration of ROMS was driven by atmospheric forcing fields downscaled from ECHAM5/OM1 data for the past (1961–1990) and future (2031–2060; SRES A1B greenhouse gas scenario); the downscaled data were produced using the Rossby Centre Regional Atmosphere model (RCA3). The results show an increase in storm surge events around Irish coastal areas in the future projection, except along the south Irish coast; there is also a significant increase in the height of the extreme surges along the west and east coasts, with most of the extreme surges occurring in wintertime.

1. Introduction

Storm surges are occasionally severe enough to lead to a significant loss of life and damage to property in coastal areas (McRobie et al., 2005; Wolf and Flather, 2005). With a warming climate there are concerns that such events may increase in frequency and intensity due a combination of rising sea level and an increase in the frequency of extreme weather, including storms (IPCC, 2007). According to the IPCC report, there is likely to be an increase in the number of intense cyclones and associated strong winds, particularly in winter over the North Atlantic; a slight poleward shift of the storm tracks is also likely. These changes will have a direct impact on storm surges, which are primarily caused by low pressure and strong winds. Rising time-mean sea levels will enhance the impact of surges. In the same report, global sea level is projected to rise 18–59 cm towards the end of this century,excluding the scaled-up ice discharge, although some researchers argue that the range is underestimated and that the rise could reach 1.4 m, based on a proposed linear relationship between global surface temperatures and the rate of global mean sea level change over the timescales relevant to humans-decades to centuries (Rahmstorf, 2007). Due to the changes in ocean density structure and circulation, local sea level changes will be more difficult to predict but any rise in sea level will exacerbate the impact of storm surges.

In Ireland, flooding is associated mainly with heavy rainfall which can lead to enhanced river-flow and over-topping of river banks. However, coastal flooding events also cause devastating effect, particularly those associated with storm surge events that occur in combination with spring tides. The effects may be enhanced locally by the coastal topography (Wells, 1997).

Several early studies on storm surge have been carried out over the NE Atlantic area. The WASA project (Waves and Storms in the North Atlantic; WASA, 1998), for example, analyzed available storm data and found that the climate has undergone significant variation on time scales of several decades. Flather and Smith (1998) found that under enhanced greenhouse gas conditions extreme wind speeds could increase by 10% in the North Sea resulting in a similar increase in the extreme storm surge. Lowe et al. (2001) employed a dynamical approach similar to Flather and Smith (1998) with some improvements, including longer time slices, higher temporal (3-h) and spatial resolutions (35 km) of the atmosphere forcing fields. Their results found a statistically significant increase in extreme storm surge along the UK coastline under assumed future climate conditions. Woth et al. (2005) applied an ensemble method for the surge study, using 6-h atmospheric

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forcing fields from four different regional climate models (horizontal resolution around 50 km) to drive a high resolution surge model (horizontal resolution around 10 km). Their results suggest that storm surge extremes may increase along the North Sea coast towards the end of this century; based on a comparison between the results of the different ensemble members, it was found that the increase is significantly different from zero at the 95% confidence level for most of the North Sea coast. All of the studies confirm the dependence on the underlying driving fields: in order to reach reliable conclusions regarding the impact of climate change, it is necessary to run long time-slice experiments to cover the natural variability of the Atlantic weather.

While the above studies show the uncertainties in predicting future storm surges, nevertheless the numerical storm surge models, driven with accurate atmospheric fields, can produce surge information in good agreement with observed data. They can also be used to generate information at arbitrary locations and for periods without observation. However, the atmospheric forcing fields must also be available with high temporal resolution; the 12- or 6-h data typically available from global models are insufficient to capture rapid storm developments associated with surge extremes. Because of the local characteristic of the surge, a high spatial resolution is also required of the surge model, particularly near complex coastlines (e.g. in the Irish Sea). Jones and Davies (2006) have suggested that the wind-induced circulation, which is important for the surge generation, can be adequately resolved on a 7-km mesh except in estuary area. The integration area must also be large enough to capture the major Atlantic cyclone systems. Flather (2000), for example, points out that the tides in shelf and coastal seas are responses to oscillations generated primarily in the deep oceans and that changes in sea level can also modify the dynamics of the tides and surges. To allow the least constrained resonant response to the lateral tidal forcing, the model domain should also be large enough to accommodate the major Atlantic cyclone systems that move over the area, while capturing the shallow-water characteristics of the Irish Sea.

In previous climate change studies of storm surge in the Atlantic Ocean, most of the research has focused on the North Sea. In Irish coastal areas and the Irish Sea most of the studies have used two-dimensional surge models driven with relatively coarse spatial or temporal resolution data (Flather et al., 1998; Flather and Williams, 2000). Kauker and Langenberg (2000) compared the performance of a 3D ocean model and 2D storm surge model; they found that the 2D surge model produces less variability than the 3D ocean model. The 2D studies could also be viewed as deficient either through the lack of sufficient resolution in the basic model or driving data, or the lack of a proper treatment of the inverted barometer effect in the lateral boundaries. In our study, we follow and extend the approach used in previous studies. A high resolution regional climate model (25 km horizontal resolution) is run to generate the hourly atmosphere forcing field for the surge model. Considering Flather's experience, a large domain was selected, covering an area from the middle of the Atlantic Ocean to the North Sea and including the Rockall Trough and the Bay of Biscay (Fig. 1). The 3D ROMS model also includes the interaction due to the non-linear dynamical processes in shallow water.

Li et al. (2006) used the ROMS model to study the storm surge induced by a hurricane in a semi-enclosed bay. Their results show that the model has excellent predictability for the storm surge as verified against the real-time data recorded on the observation systems. However, compared to a semi-enclosed bay, the Irish Sea is a much more complex shelf area, prompting an initial validation of the model over the area before the climate change simulations were performed.

The layout of the paper is as follows: following the methodology and model setup in Section 2, the validation of the ROMS model is presented in Section 3 and the impact of the climate change study on the storm surge is given in Section 4.

2. Methodology

2.1. The GCM scenario data and regional climate model

The climate change scenario used in this downscaling experiment was obtained from ECHAM5/OM1 model (Roeckner et al., 2003), with the future simulations based on the SRES A1B emission scenario (IPCC, 2000). This scenario is characterized by low population growth, rapid economic growth and rapid introduc-

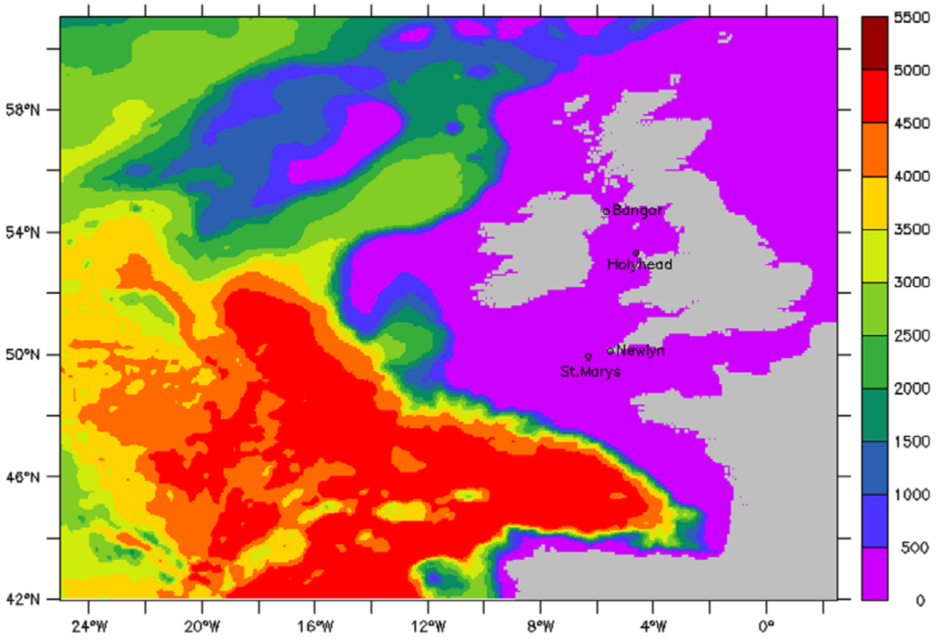

Fig. 1. The model domain and bathymetry.

tion of new and efficient technologies using a balanced emphasis on all energy sources. The atmospheric CO_2 concentration in this scenario reaches 720 ppm at the end of 21th century and the global mean temperature will rise about 3.8 degrees Celsius by the end of this century (relative to the mean temperature between 1961 and 1990). The regional climate model used to downscale the GCM data is the Rossby Centre Regional Atmospheric Model (RCA3) developed from the High Resolution Limited Area Model (HIRLAM). Most HIRLAM parameterisations have been retained in RCA3. However, RCA3 hosts a new land surface scheme and some extra hydrological processes are included (Rummukainen et al., 2001; Jones, 2001), which improve the simulation of precipitation and evaporation; these two parameters are used to calculate the fresh water fluxes for the ocean model. In order to cover the selected domain areas for the ocean modelling, the RCA3 model domain was set up on a 0.22° (25 km), rotated latitude/longitude grid, covering a slightly bigger area than that shown in Fig. 1. RCA3 has been validated extensively using ECMWF ERA-40 reanalysis data (Uppala et al., 2005) to simulate the present day climate; it has also been used to simulate the future climate using ECHAM4 (Roeckner et al., 1996) and ECHAM5 (Roeckner et al., 2003) scenario data. The results suggest that the model is well able to capture the characteristics of the present day climate and is suitable for dynamical downscaling of future climate scenarios (Wang et al., 2006; McGrath et al., 2005).

In this study, the downscaling was performed for two 30-year time-slice periods (1961–1990 and 2031–2060) using boundary data at 6-h intervals from ECHAM5/OM1. In order to drive the storm surge model and to catch the fast moving cyclone systems, the meteorological forcing fields were saved every hour; these included the 10-m u and v component of wind speed, mean sea level pressure, net long-wave and short-wave radiation fluxes, precipitation, evaporation, latent and sensible heat fluxes.

2.2. The surge model

The ROMS model is a three-dimensional, hydrostatic, primitive equation ocean model originally developed by Rutgers University (Shchepetkin and McWilliams, 2003; Shchepetkin and McWilliams, 2005). It incorporates a non-linear free surface in the barotropic mode, enabling simulation of surface elevation changes due to tides and surges. Stretched, terrain-following, coordinate transformations are used in the vertical, while orthogonal curvilinear coordinate transformations are used in the horizontal.

As mentioned in the introduction, the model domain enclosed a large part of the north-west European continental shelf with a horizontal resolution of 4 min (about 7 km) and 16 vertical levels. As a large part of the North Atlantic Ocean is included in our model domain, open boundary conditions are used in the horizontal. For the sea surface elevation boundary condition, the inverted barometer effect (the change in sea level related to the atmospheric pressure, calculated using the hydrostatic assumption) was used. This gives a reasonable approximation to the sea level on the open ocean where coastal effects are not felt, and was used as a boundary condition to approximate changes to sea level related to pressure changes associated with atmospheric systems approaching the model domain. In this set up, the model does not include the direct effects of global sea level rise due to the thermal expansion of seawater or fresh water influx from melting ice or glaciers; the changes in sea level and storm surge are primarily due to the impact of the atmospheric wind and mean sea level pressure. Sea level rise associated with climate change may affect surge heights in shallow water due to changes in bathymetry, but the impact is likely to be small (Lowe et al., 2001; de Ronde, 1993).

A Flather boundary condition (Flather, 1976) was used for the tidal currents and a radiation condition for the momentum, salinity and temperature. The salinity and temperature data are taken from the monthly ECHAM5/OM1 data sets. For the tidal forcing, data were derived from the barotropic tidal data assimilation system of Oregon State University (TPXO6.2) (Egbert and Erofeeva, 2002); it includes eight primary (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1) and two long period (M_f, M_m) harmonic constituents. These data are mainly assimilated from 364 cycles of Topex/Posedon satellite data.

Because surges are superimposed on the normal astronomical tides generated by variations in the gravitational attraction of the Moon and Sun, the surge height was computed following Flather and Williams (2000):

$$\text{Sea level elevation} = \text{predicted tide level} + \text{storm surge height} \tag{1}$$

In order to include the effects of interactions due to non-linear dynamical processes in shallow water, two simultaneous simulations were run on separate, but identical, grids. One was driven with all the forcings (tides, inverted barometer effect and wind forcing); the other was driven with tidal forcing only. The surge heights were determined by subtracting the tide-only run from the tide plus meteorological forcing run.

2.3. Validation run

On 1 February, 2002, an intense cyclone formed over the northwest of Ireland with a central pressure of about 928 hPa recorded at 18 UTC (Burt, 2007). The low pressure, in combination with strong surface winds and coinciding with high tides, caused serious coastal flooding, particularly along the east and south coasts of Ireland and the west coast of the UK. This storm was chosen to evaluate the performance of the ROMS model in hindcasting extreme surge events. To reduce the time for model to reach balance, the temperature and salinity data taken from the World Ocean Atlas 1998 datasets (Antonov et al., 1998; Boyer et al., 1998) were used as the initial fields. The model simulation was run for a total of 45 days from 00 UTC on 1 January, 2002 to 00 UTC on 15 February, 2002. The first 15 days of results were disregarded to allow for model spin-up.

To assess the stability of the ROMS model to simulate multidecadal climate runs, a second and much longer validation run (1990–2002) was carried out. In both cases the model was driven with 6-h ERA40 reanalysis data.

For an independent assessment of the performance of ROMS, satellite altimetry data, corrected for long wavelength errors by SSALTO/DUACS (Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation précise/Data Unification and Altimeter Combination System) using a 2D gravity wave model (MOG2D-G), were used (Carrere and Lyard, 2003). This dynamic atmospheric correction (DAC) data are available from the SSTALTO/DUACS system at 6-h intervals on a 0.25° × 0.25° global grid.

2.4. Surge extreme analysis

The surge elevations are fitted using a Generalized Extreme Value distribution GEV (μ,σ,κ), where μ is the location parameter, σ the scale parameter and κ the shape parameter. All these parameters are estimated by the maximum likelihood method. For reliable estimates of the parameters long terms series are required (Martins and Stedinger, 2000). In this study, as the 30-year time slice is still relatively short for the long-term return period estimation, the 5 largest maxima per year are used in the analysis. To make sure these data are independent, a 48-h time window was applied for the selection of the yearly maxima.

2.5. Statistical analysis

A key purpose for this study is to establish the significance level of any changes for the extreme events in the future projection. Considering that extreme events in the control and future run are generally not normally distributed, the Wilcoxon rank sum test is applied to the future and present day of annual extreme events. The null hypothesis is that the present day and future extreme events are drawn from the same population. A lower value of the confidence level (*P*-value) (10%) means that this null hypothesis is rejected and the difference between the future and present day extreme events are statistically significant.

3. Validation of the storm surge using reanalysis winds

3.1. Station data analysis

For the 2002 storm surge event, Fig. 2 shows the simulated and observed surge for 4 selected stations (St. Mary's, Newlyn, Holyhead and Bangor – see Fig. 1). The model is clearly reproducing both the magnitude and time of surge events in general. Agreement is better at the Newlyn and St. Mary's stations, which are less influenced by the topographic and dynamical effects of the semi-enclosed Irish Sea basin. However, some extreme surges, in particular a large event on the 22–23 January, were underestimated by up to 20 cm in the simulation, even at these stations. For Holyhead and Bangor, there is still a high degree of consistency between the modelled and observed time series, but the amplitude of the surge is systematically underestimated at both stations.

The accuracy of the simulation may be compromised by the use of 6-h ERA-40 data to drive the ocean model; this frequency is too low to capture the full effects of fast-moving cyclone systems across the narrow Irish Sea basin. Another factor is the accuracy of the ERA-40 10-m wind speed. From Flather et al. (1998), the model was found to be capable of capturing the extreme storm surge events when the precise wind forcing was used at 6-h resolution. The coarse resolution of ERA40 data is sufficient for the general large scale system. However, the coarse resolution ERA40 data lack detailed local information, particularly for the strong wind speed events. Caires and Sterl (2003) validated the ERA40 wind speed against buoy, ERS-1, and Topex altimeter measurements. They found that the high wind speed is underestimated. Comparing the ERA-40 data with synoptic surface observations, we find that the reanalysis wind strengths in this case are biased low, in general, but the bias is particularly evident for the strongest winds. Both of these factors will lead to weaker surges in the simulation compared with the observations. Another issue is the resolution of the ocean model; at approximately 7 km it is too coarse to capture the detailed flow in the Irish Sea inshore region, particularly in the North Channel (Jones and Davies, 2006).

According to the research of Lowe et al. (2001), along the south Irish Sea coast the surge height is dominated by the inverted barometer effect, with the wind forcing providing only 16% of the surge height. In the north Irish Sea, on the other hand, the wind forcing contributes 72% of the surge height. A sensitivity study was carried out in which the ERA-40 winds were modified to provide better agreement with synoptic observations; the results confirmed that the wind bias is the main reason that the model performs better in the south Irish Sea (not shown).

For the 12-year simulation run (1990–2002), the hourly observed surge data from the British Oceanographic Data Center for 8 stations were used for validation. Summary statistics are listed in Table 1: the standard deviation error (STD), the root-mean-square error (RMSE), the RMS difference between the observed and simulated surges, and the correlation coefficient.

$$\mathrm{STD} = \sqrt{\frac{\sum_{i=1}^{N}((Y_i - \bar{Y}) - (X_i - \bar{X}))^2}{N}} \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - X_i)^2}{N}} \tag{3}$$

$$\text{RMS difference} = \sqrt{\frac{\sum_{i=1}^{N}Y_i^2}{N}} - \sqrt{\frac{\sum_{i=1}^{N}X_i^2}{N}} \tag{4}$$

where Y is the modeled series, X is the observed series, $\bar{Y}$ and $\bar{X}$ are the mean value of simulated and observed series, N is the number of the data of the series. For Bangor, the hourly data only cover about 5 years; data for the other stations cover at least 7 years.

In the Irish Sea, the simulated surges have a relatively large error in the northern end compared to the south. The correlation

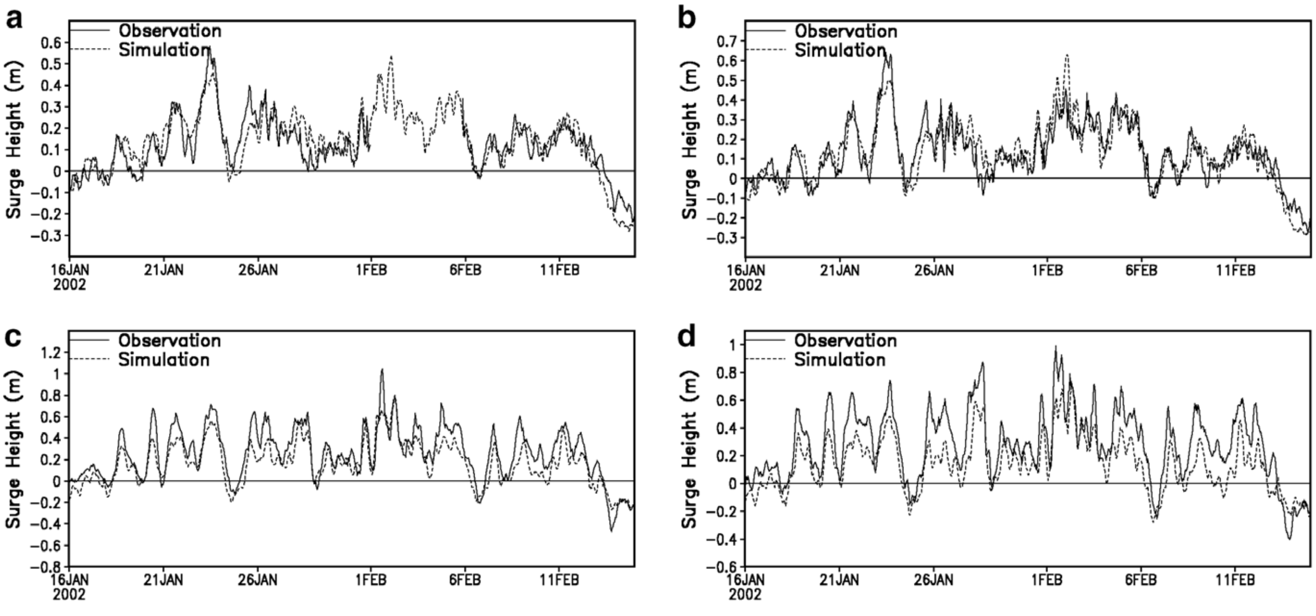

Fig. 2. The simulated and observed surge for (a) St. Mary's, (b) Newlyn, (c) Holyhead and (d) Bangor.

Table 1
Error statistics of the simulated and observed surge elevation at different stations (heights are in cm)

	Sample size	RMSE	STD	RMS difference	Correlation
St. Mary's	70494	9.42	9.41	−1.16	0.75
Portpatrick	103280	12.83	12.6	4.07	0.75
Port Erin	62069	12.25	12.03	3.7	0.73
Port Ellen	97514	13.01	12.85	4.8	0.75
Fishguard	106900	9.05	8.7	0.77	0.84
Newlyn	108646	9.52	9.36	−0.48	0.76
Holyhead	79716	10.31	10.23	2.15	0.80
Bangor	46738	12.32	12.07	3.3	0.71

coefficients are generally high for all the stations. Both the RMSE and STD figures show that the model is able to reproduce the surge variability for the decade simulated here with reasonable accuracy (order of 10 cm) in this region. The small difference between the RMSE and STD indicate that the mean values of observation and simulation for the whole simulation period are very close, the simulation results have a good agreement with the observation.

To investigate extreme surge events, Fig. 3 shows the histogram distributions for the same four stations. For moderate surges, the model simulation is quite reasonable, while for the maximum surge there is an underestimation for all stations although agreement with observations is quite good for Newlyn. This is not surprising, in view of the underestimated wind speed and spatial bias of ERA40 data, but the relatively coarse horizontal resolution of the ocean model may also be a factor, as discussed above. The simulation of the higher storm surge events in the south Irish Sea area (Fig. 3a and b) is much better than in the north Irish Sea area (Fig. 3c and d).

3.2. Spatial variation comparison

The aim of the 12-year simulation was to evaluate the capability of the model to perform long climate simulations. To facilitate comparison with the satellite altimetry data for the period 1993–2001, ROMS output from a small inner domain (49–55°N and 1–12°W) was saved. As the satellite data are weekly averages the ROMS output was similarly converted.

The spatial and temporal variability of both sets of data were compared for the period 1993–2001 over the ocean area adjacent to Ireland, stratified into latitude/longitude bins as indicated in Table 2. Time series for the western area are shown in Fig. 4. The ROMS model is in good agreement with the satellite-derived data in this domain. In the southern area the results are similar but agreement is poor for the northern domain (not shown). These results are also confirmed in the scatterplots shown in Fig. 5.

The correlation coefficient and RMS difference fields (Fig. 6a and b) show similar features from year to year. High correlations are observed in the southern part of the domain, with values exceeding 0.7 around much of Ireland, and more than 0.9 off the southwest coast. The RMS difference fields show a similar pattern, with values of 4–12 cm around the coasts and over most of the area, apart from the extreme north and northwest.

Low correlations and high RMS values north of Ireland indicate a systematic difference between the two sets of data in this area.

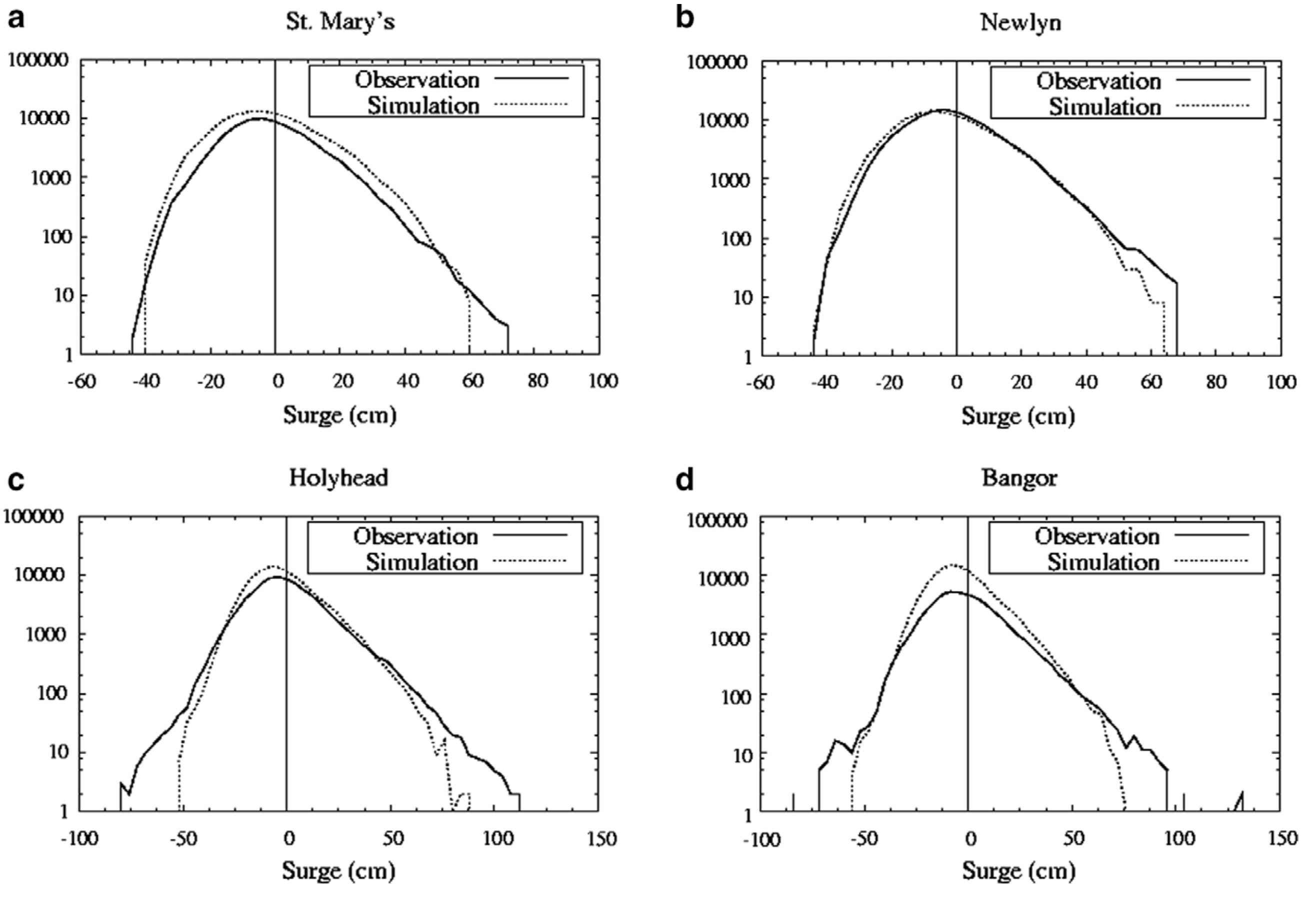

Fig. 3. Histogram distribution of the surge events for (a) St. Mary's, (b) Newlyn, (c) Holyhead and (d) Bangor.

Table 2
Differences between ROMS and satellite-derived data (units are in cm)

Area	Latitude (°N)	Longitude (°W)	RMS difference	R^2	Bias
North	56.6–57.1	8–9	13.0	0.25	4.1
West	51.6–52.3	10.6–11.6	4.4	0.87	4.3
South	50–50.6	8–9	8.1	0.70	−0.4

The consistency of the spatial patterns from year to year points towards a bathymetric effect. This may be due to the bathymetry in the ROMS model having insufficiently high resolution or accuracy in the area adjacent to the Erris–Slyne trough off the north-west of Ireland. It could also be due to inconsistencies in the bathymetry used in the models.

Generally, the above analysis shows that the ROMS model is capable of reproducing storm surge events with reasonable accuracy, supporting its use as a suitable tool in climate change studies.

4. The impact of climate change on storm surge

4.1. Station data analysis

Ireland is particularly exposed to Atlantic storms due to its location on the west of Europe. To evaluate the impact of a changing climate on future storm surges, statistics of original time series were created for 13 coastal sites. The results for these sites are summarized in Table 3, which shows the simulated changes (2031–2060 relative to 1961–1990) in surge heights. The range 50–100 cm is chosen as being typical of surges associated with coastal flooding in Ireland (Flather et al., 1998). The results show increases in the frequency of such occurrences in all cases in the future simulation, especially along the west coast of Ireland (more than 30% increase in some cases). There are similar changes in the extremes (99% percentile); with the exception of Cork all show increases. For the maximum surge height, the changes are more variable but some sites show a large increase (e.g. Galway). To investigate the significance of the high surge events, the Wilcoxon rank sum test is applied to the high surge events (surge height higher than 50 cm) between the control run and future projection. The P values indicate that the changes of a few the stations are significant at 10% level, while most of stations are non-significant.

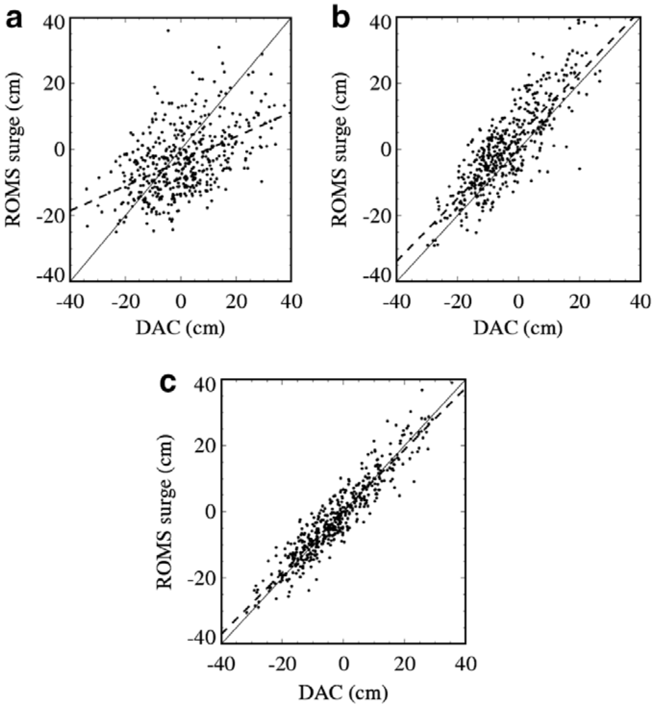

Fig. 5. Scatterplots of ROMS surge and DAC data for the north (a), south (b) and west (c) regions defined in Table 2.

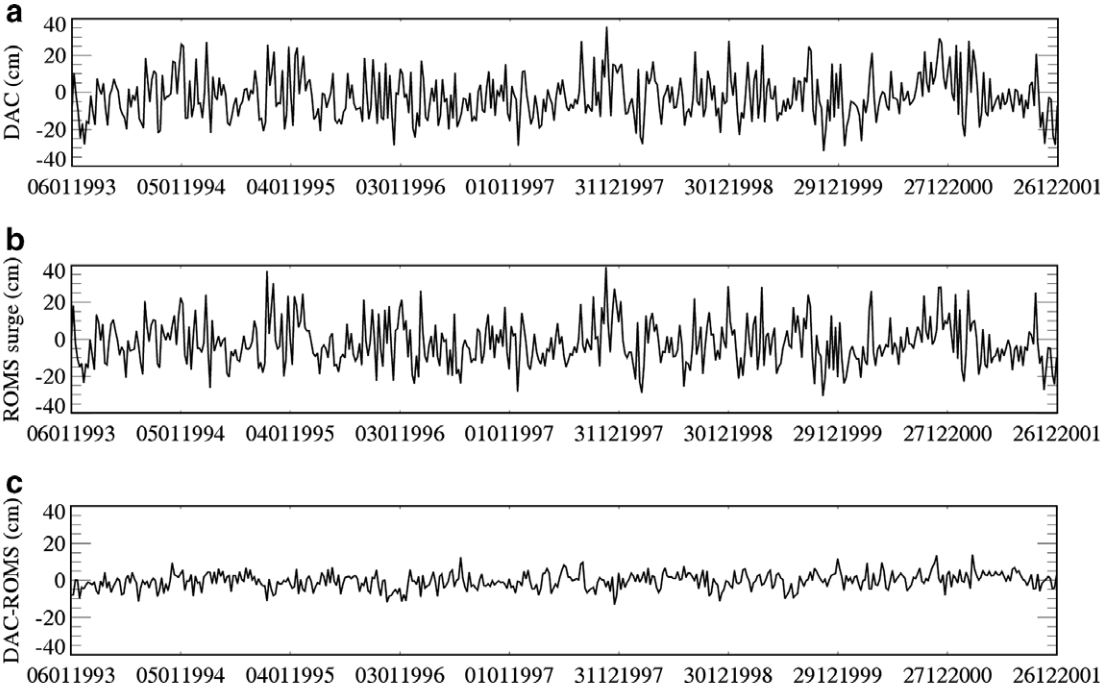

Fig. 4. Time series of (a) dynamic atmospheric correction (DAC), calculated by the MOG2D-G model for correction of altimetric sea level anomalies; (b) surge generated by ROMS model; (c) DAC-ROMS residuals. Data shown are weekly data from the West region (see Table 3) from January 1993 to December 2001.

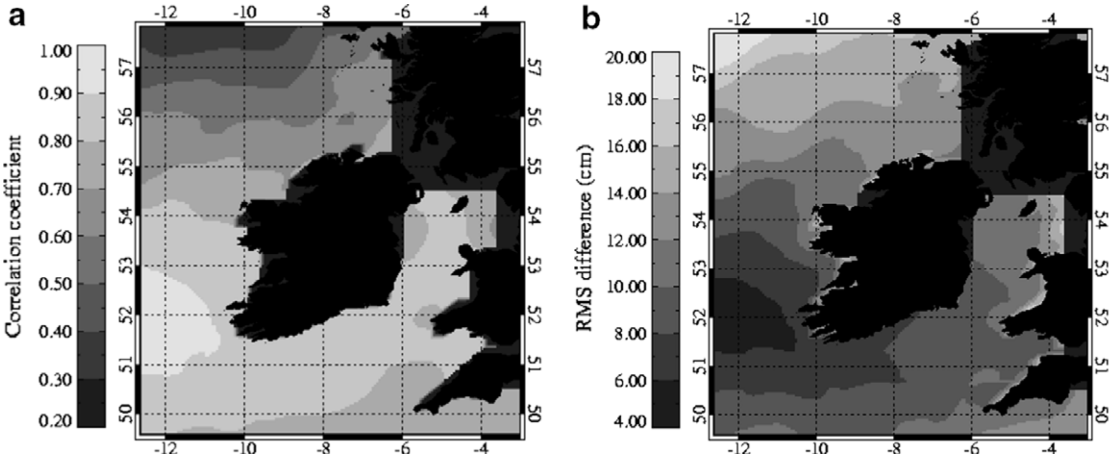

Fig. 6. (a) Correlation coefficient between the DAC and ROMS surge data calculated for all weekly data between 1993 and 2001 and (b) RMS difference.

Table 3
Statistics analysis of the surge elevation between the future (2031–2060) and control (1961–1990) run

Station name	50 cm < Hsurge < 100 cm % change	99 Percentile % change	Maximum surge % change	P values of the Wilcoxon rank sum test
Dublin Bay	14.7	5.45	5.6	0.19
Wicklow	21.9	2.22	13.98	0.44
Arklow	20.1	2.27	11.1	0.08
Wexford Bay	18.98	2.44	12.36	0.03
Waterford	20.6	2.44	−7.69	0.90
Cork Harbour	10.6	0.01	−17.76	0.12
Dingle Bay	24.93	2.33	20.88	0.24
Shannon Estuary	25.50	4.76	10	0.67
Sligo Entrance	30.53	6.38	−5.08	0.02
Lough Swilly	19.2	3.7	−10.88	0.78
Donegal Bay	24.80	6.12	6.87	0.03
Clew Bay	31.20	6.38	6.42	0.11
Galway Bay	25.93	6.52	73.2	0.29

Histogram plots of the surge heights for Dublin Bay, Cork Harbor and Galway Bay are shown in Fig. 7 and generally confirm the findings in Table 3. The increase in extreme surges is consistent with an increase in the frequency of intense cyclones over the area (McGrath et al., 2005; Sweeney, 2000; Lozano et al., 2002). Bijl (1997) showed that an increase in the storm intensity would have a relatively large effect on the surge maxima.

To further investigate the extreme events, the cumulative probability of the Generalized Extreme Value (GEV) distribution was calculated for Dublin, Cork and Galway (Fig. 8). Note that this probability is based on the annual maximum surge heights. These three stations are representative of the extremes for Ireland and are consistent with the histogram plots in Fig. 7. The data confirm the local character of the surge climate, especially in shallow water where the surge events are strongly affected by the local bathymetry.

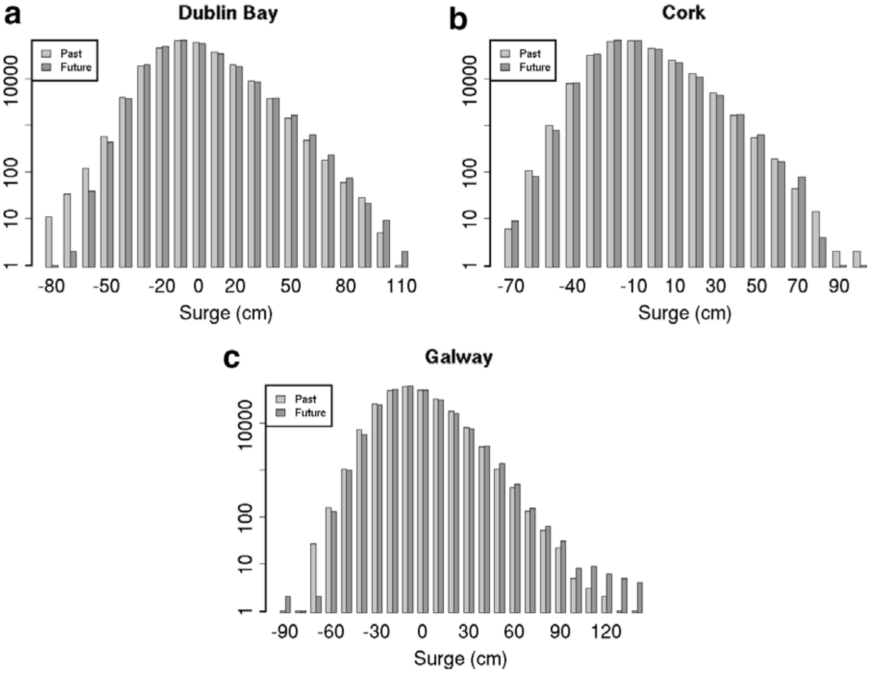

Fig. 7. Histogram distribution of the surge events for (a) Dublin Bay, (b) Cork Harbor, (c) Galway Bay.

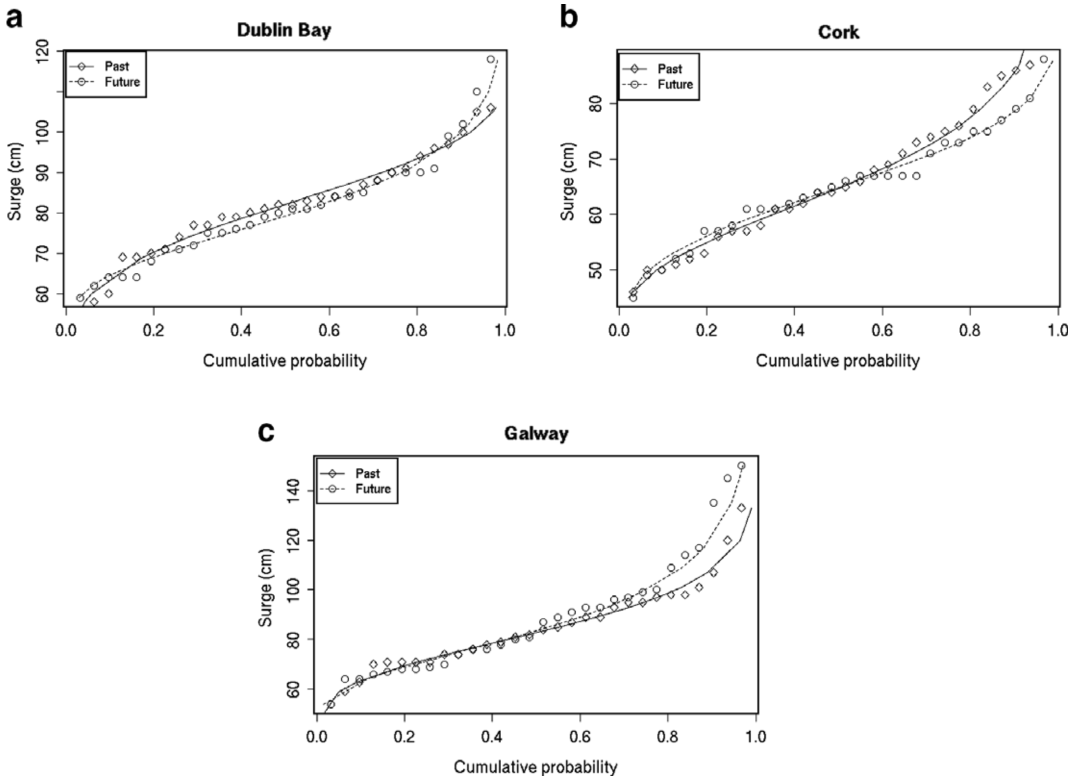

Fig. 8. Cumulative probability distribution of the annual extreme surge for (a) Dublin Bay, (b) Cork Harbor, (c) Galway Bay.

4.2. The spatial distribution analysis

4.2.1. The wind speed and mean sea level pressure

As discussed above, the wind speed and mean sea level pressure are two main factors for generating the storm surge. Changes (%) in the annual mean wind speed (Fig. 9) are relatively small; there is an increasing tendency along the west and north-west coast of Ireland and part of the UK coast, but a decrease over the open sea in the ROMS integration area. These results are similar to the findings in Debernard et al. (2002), which concludes that the largest changes are expected in high latitude areas.

For the difference changes of mean sea level pressure (PMSL) (Fig. 10), the distribution pattern shows an increase around Ireland and to the south, and a decrease to the northwest. This is consistent with an increase in the frequency of intense cyclones over the area in the future.

While the annual mean wind speed does not change much, it is interesting to investigate the variation in the maximum speeds, which are often implicated in the strongest surges. Fig. 11 shows the relative change in the 10-year and 50-year return values. Around the northern coast of Ireland, the 10-year return value has increased 6–10% (Fig. 11a). For the 50-year return value (Fig. 11b), the spatial pattern is similar, with a slightly higher increase around the northern area. In both cases there is a slight decrease along the south coast. Stratification of the data by season shows that the increase in winds occurs mainly in winter; summer values show a slight decrease. The significant test also reveals that there are rather small significant changes in the annual extreme wind

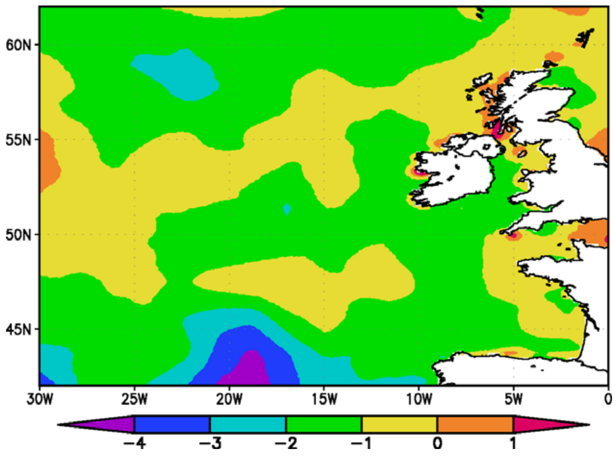

Fig. 9. Relative changes between future and control run periods for the annual mean wind speed (%).

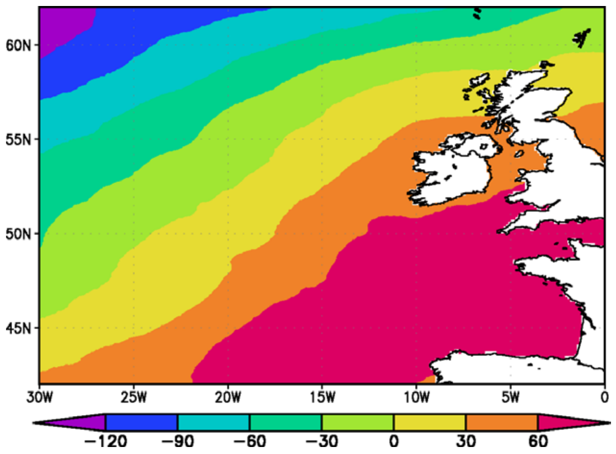

Fig. 10. Bias between future and control run for the annual mean sea level pressure (Pa).

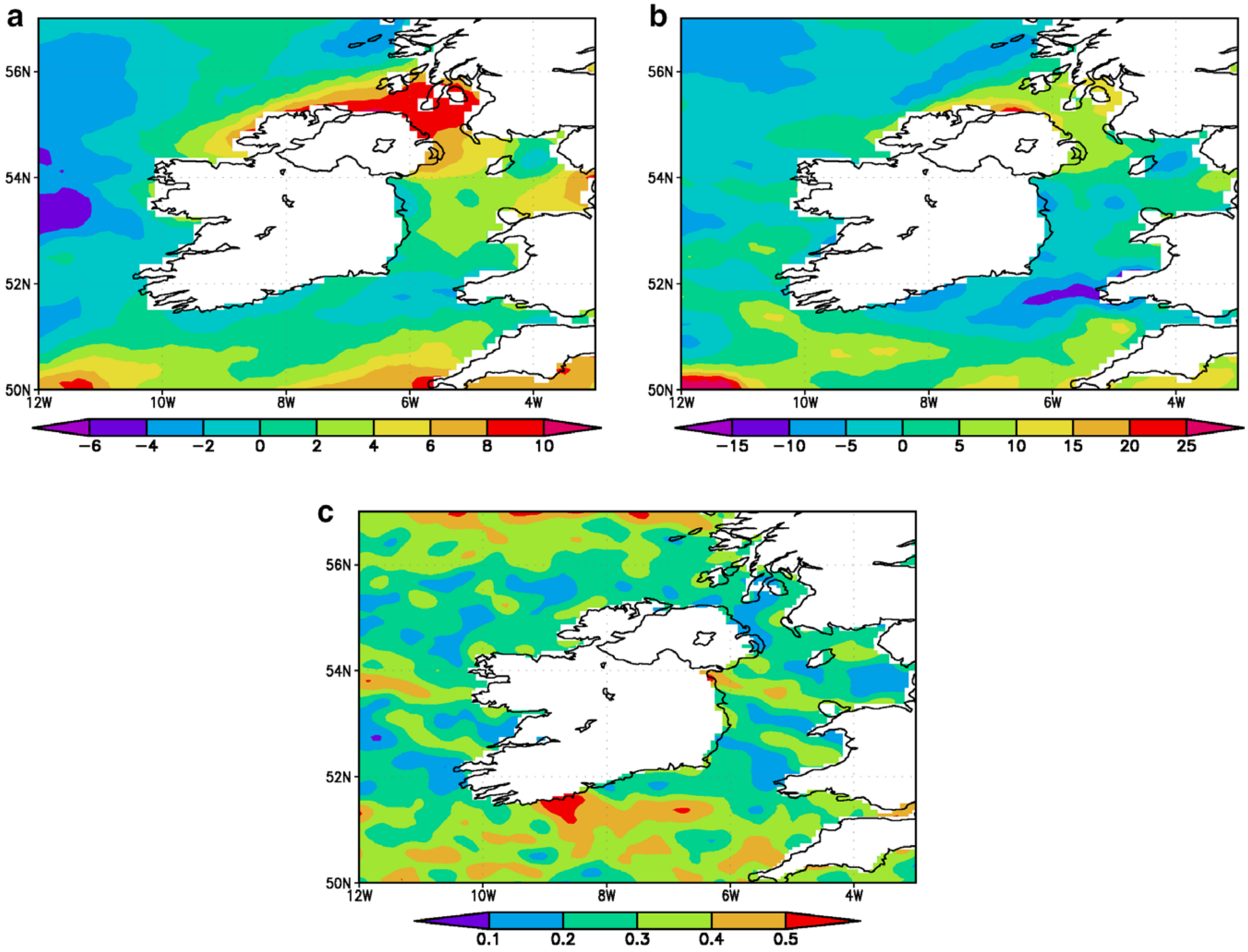

Fig. 11. Relative change in the 10-year (a) and 50-year (b) return values of annual maximum wind speed between the future and past control run (%). The *P* values of the Wilcoxon rank sum test between the control and future extreme wind speed simulations are shown in (c).

speed (Fig. 11c). Only a few locations along west Irish coast are significant at the 10% level.

4.2.2. The extreme value analysis of the surge height from the control run

Apart from the wind speed, the wind direction is also a very important factor in the generation of extreme surges. Along the west coast of Ireland the prevailing westerly and southwesterly winds are associated with the strongest surges. However, over the Irish Sea, the tidal streams are propagated from both the north and south and meet southwest of the Isle of Man, enhancing surge heights around this area. The 10-year return value of the extreme storm surge from the control run shows that the maximum surge heights occurred in the Solway Firth area (Fig. 12a), similar to

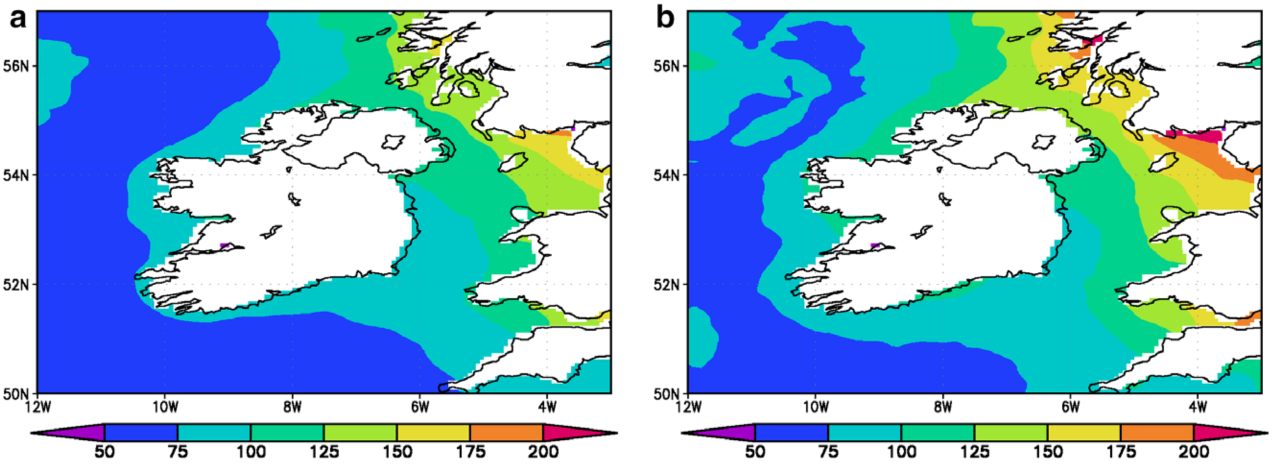

Fig. 12. The 10-year (a) and 50-year return values of the annual maximum surge height for the control run.

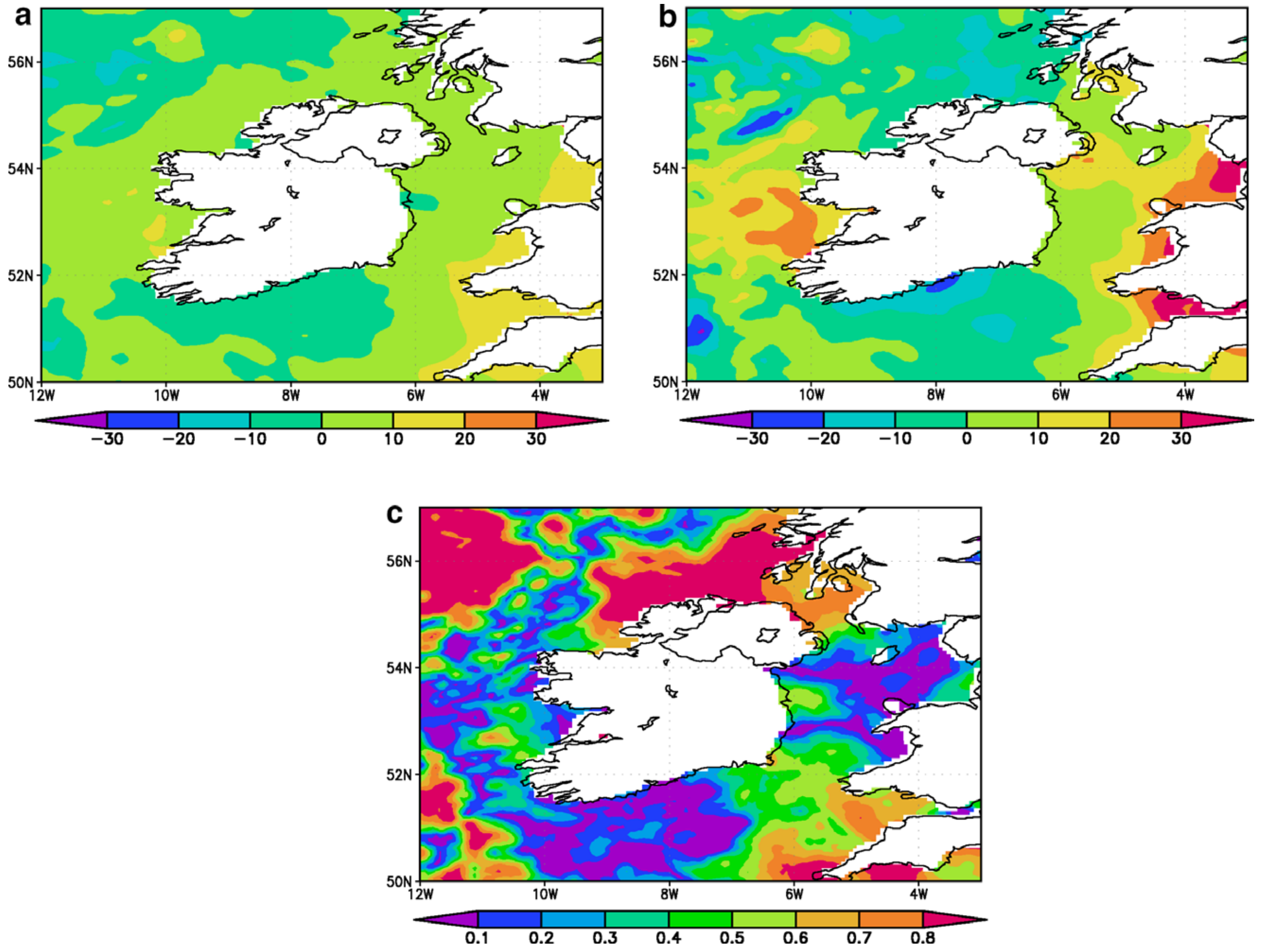

Fig. 13. Relative change in the 10-year (a) and 50-year (b) return values of annual maximum storm surge between the future and past control run (%). The *P* values of the Wilcoxon rank sum test between the control and future extreme surge height simulations are shown in (c).

the findings of Flather et al. (1998). The 50-year return value of surge heights from the ROMS simulation is shown in Fig. 12b. The spatial distribution is very similar to Flather's equivalent map (Flather, 1987) which is based on a sample of 16 storms constrained by observations. These results show that the ROMS model is capable of producing reliable surge extremes when it is forced by suitable meteorological fields.

4.2.3. The effect of future scenario changes on the storm surge extremes

The relative changes of the 10-year and 50-year return period of the surge heights between the future and control simulation show that along most of the Irish coastline the trend is for increasing surge height (Fig. 13a and b). However, the spatial pattern of the change is far from uniform. It is interesting to compare the changes with the corresponding changes in extreme wind speed (Fig. 11). There is some correlation between changes in the maximum wind speed and changes in extreme surge heights but this does not apply everywhere; in the 50-year return values (Fig. 13b) the extreme storm surge heights decreased along the north coast while the maximum wind speed increased; changes in the wind direction may be a factor in this case. Due the complex bathmetry in the continental shelf area, some non-local surge propagating along the coast also caused the discrepancy between the surge height and wind speed. The significant test results show that large fraction of the extreme surge heights in the southern Irish sea area are significant at 10% level, while almost non-significant in the northern area, which is totally different from the extreme wind speed distribution.

As discussed before, there is a strong seasonal variation for the maximum wind speed. This will have a strong impact on the extreme storm surges. Fig. 14a–d show the 10-year return value of the annual extreme storm surge distribution for the four seasons. In general these show increases in winter and spring, and decreases in summer and autumn.

5. Conclusions and discussion

Coastal flooding and coastal erosion are issues with serious economic and social impacts. Recent studies have aimed at understanding and quantifying changes in the surge climatology and, in particular, surge extremes. Such studies usually require model simulations extending over many decades. An initial requirement is to validate the capability of the model to realistically reproduce the storm surges and to evaluate whether the model performance is robust over runs of decadal duration.

In this study, a regional ocean model ROMS was firstly validated against observation in a short and long term study. For the short term validation, the ROMS model is capable of reproducing the general surge variation, especially in the south Irish Sea. However, due to the systematic under-prediction of the wind strengths in the ERA-40 data and the coarse temporal frequency (6-h) of the driving data, the simulated surge in the north Irish Sea has a relatively large error. To improve the accuracy of the simulations, and especially to cap-

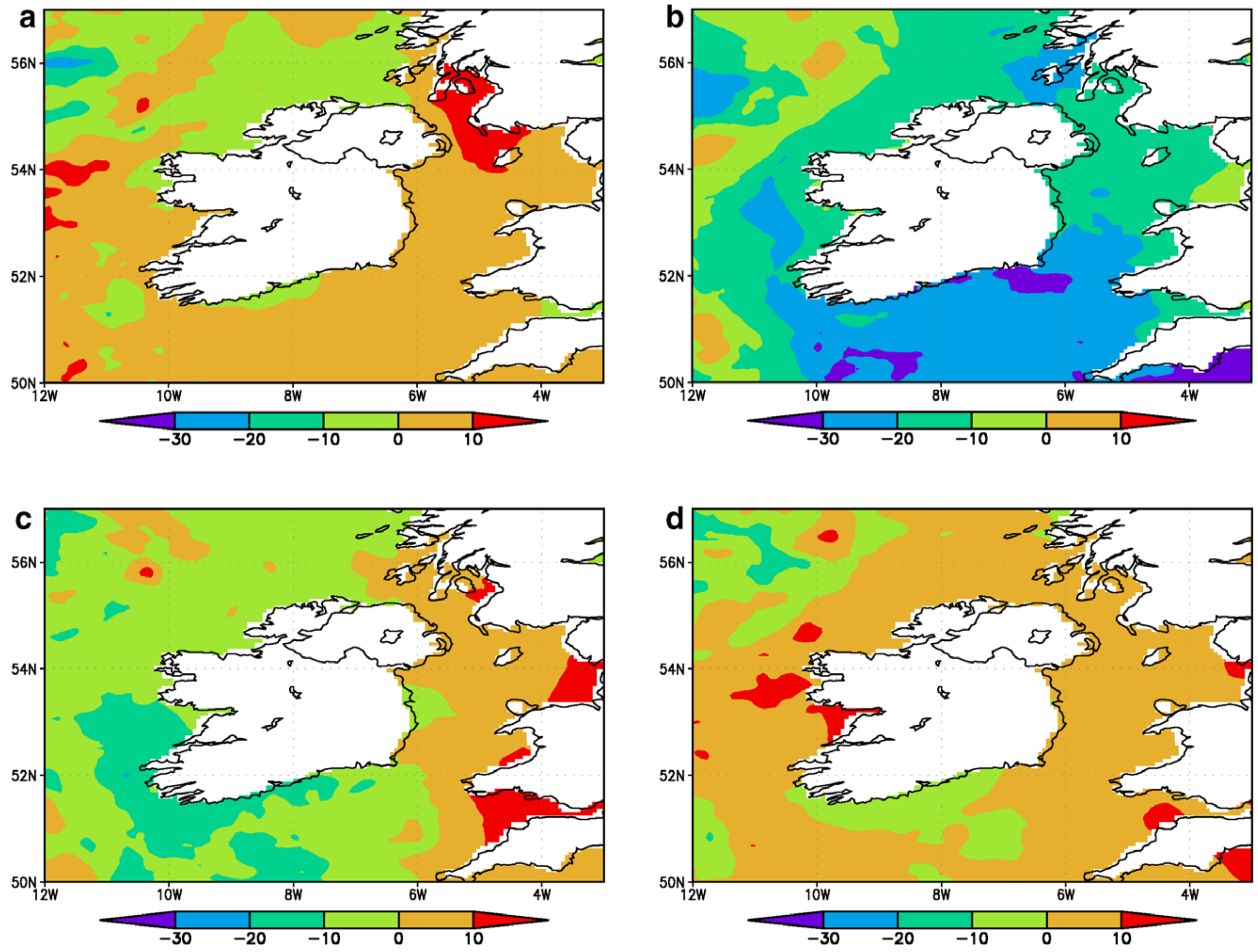

Fig. 14. Relative change of 10-year return value of seasonal maximum storm surge between the future and past control run (%). (a) Spring, (b) Summer, (c) Autumn, (d) Winter.

ture the peak values, it is important to have accurate wind data for driving the model.

For the long-term validation run, comparison against station data show that the model is able to reproduce the surge variability with reasonable accuracy (order of 10 cm) over the chosen area. It also performs well when validated against satellite altimetry data corrected with the MOG2D-G model; time series values from both data sets show high correlation around Irish coastal areas and the Irish Sea, except in the northwest region. These results show that the ROMS model is reliable and suitable for studies of surge climatology in Irish waters.

For the climate change study, the ROMS model was run for two 30 year time-slice periods (1961–1990 and 2031–2060), forced by hourly meteorological data produced by dynamically downscaling ECHAM5/OM1 A1B scenario data using the Rossby Center Regional climate model.

Analysis of the results shows that storm surge heights in the range 50–100 cm are increasing in frequency around all Irish coastal areas; up to 20% in the west and northwest. There is also a significant increase in the height of the extreme surges along the west and east coasts, with most of the extreme surges occurring in wintertime. Changes in extreme surge heights also appear to be related to changes in extreme wind speeds and mean sea level pressure. There are also significant changes in the return values of surge heights.

This study has been based on a single future scenario from a GCM. One single simulation only can provide one possible basic information set. However, SRES A1B scenario is one of the reasonable IPCC scenarios. Therefore, this single simulation still can provide us with some useful information. We can get basic idea about how the storm surge changes under future projection. Considering that the uncertainty in the atmospheric forcing data will be reflected in the surge outputs, the study needs to be repeated using other GCM scenario data to qualify this uncertainty.

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References

Antonov, J.I., Levitus, S., Boyer, T.P., Conkright, M.E., O'Brien, T.D., Stephens, C., 1998. World Ocean Atlas 1998 Vol. 1: Temperature of the Atlantic Ocean. NOAA Atlas NESDIS 27. US Government Printing Office, Washington, D.C.

Boyer, T.P., Levitus, S., Antonov, J.I., Conkright, M.E., O'Brien, T., Stephens, C., 1998. World Ocean Atlas 1998 Vol. 4: Salinity of the Atlantic Ocean. NOAA Atlas NESDIS 30. US Government Printing Office, Washington, DC.

Bijl, W., 1997. Impact of wind climate change on the surge in the Southern North Sea. Climate Res. 8, 45–59.

Burt, S., 2007. The lowest of the lows: extremes of barometric pressure in the British Isles, Part 1- the deepest depressions. Weather 62 (1), 4–14.

Caires, S., Sterl, A., 2003. Validation of ocean wind and wave data using triple collocation. J. Geophys. Res. C 108 (3), 3098. doi:10.1029/2002JC001491.

Carrere, L., Lyard, F., 2003. Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing – comparisons with observations. Geo. Res. Lett. 30 (6), 1275.

Debernard, J., Satra, O., Roed, L.P., 2002. Future wind, wave and storm surge climate in the northern North Atlantic. Climate Res. 23, 39–49.

de Ronde, J.G., 1993. What will happen to the Netherlands if sea level rise accelerates. In: Warrick, R.A., Barow, E.M., Wiegley, T.M.L. (Eds.), Climate and sea level change: observation, projection and implication. Cambridge University Press, Cambridge, pp. 322–335.

Egbert, G.D., Erofeeva, S.Y., 2002. Efficient inverse modeling of barotropic ocean tides. J. Atmos. Oceanic Technol. 19, 183–204.

Flather, R.A., 1976. A tidal model of the northwest European continental shelf. Mem. Soc. Roy.Sci. Leige, Ser. 6 (10), 141–164.

Flather, R.A., 1987. Estimates of extreme conditions of tide and surge using a numerical model of the Northwest European continental shelf. Estuarine Coast. Shelf Sci. 24, 69–93.

Flather, R.A., 2000. Existing operational oceanography. Coastal Eng. 41, 13–40.

Flather, R.A., Smith, J.A., 1998. First estimates of changes in extreme storm surge elsvations due to the doubling of CO_2. Global Atmos. Ocean Syst. 6, 193–208.

Flather, R.A., Williams, J.A., 2000. Climate change efffects on the storm surge: methodologies and results. In: Beersma, J., Agnew, M., Viner, D., and Hulme, M., (Eds.), Climate scenarios for water-related and coastal impact. Norwich:CRU, ECLAT-2 Workshop Report No. 3. pp. 66–78.

Flather, R.A., Smith, J., Richards, J., Bell, C., Blackman, D., 1998. Direct estimates of the extreme surge elevation from a 40 year numerical model simulation and from observation. Global Atmos. Ocean Syst. 6, 165–176.

IPCC, 2000. Special Report on Emission Scenarios. Cambridge University Press, UK.

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

Jones, C., 2001. A brief description of RCA2. SWECLIM Newsl. 11, 9–14.

Jones, J.E., Davies, A., 2006. Application of a finite element model (TELEMAC) to computing the wind induced response of the Irish sea. Continental Shelf Res., 1519–1541.

Kauker, F., Langenberg, H., 2000. Two models for the climate change related development of sea levels in the North Sea – a comparison. Climate Res. 15, 61–67.

Li, M., Zhong, L., Boicourt, W.C., Zhang, S., Zhang, D., 2006. Hurricane-induced storm surges, currents and destratification in semi-enclosed bay. Geophys. Res. Lett. 33, L02604. doi:10.1029/2005GL024992.

Lozano, I., Devoy, R., May, W., Andersen, U., 2002. Storminess and associated cyclone tracks along the Atlantic Coastlines of Europe: evolution during the last six decades and modelling an CO2-induced climate scenario. American Geophysical Union.

Lowe, J.A., Gregory, J.M., Flather, R.A., 2001. , 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. Climate Dyn. 18, 179–188.

Martins, E.S., Stedinger, J.R., 2000. Generalized maximum-likelihood extreme-value quantiule estimators for hydrological data. Water Resorce Res. 36, 737–744.

McGrath,R., Nishimura, L., Nolan, P., Ratnam, J.V., Semmler, T., Sweeney, C.,Wang, S., 2005. Community climate change consortium for Ireland (C4I) 2004 annual report, Met Eireann, Dublin, Ireland, pp. 1–118.

McRobie, A., Spencer, T., Gerritsen, H., 2005. The big flood: North Sea storm surge. Phil. Trans. R. Soc. Lond. A 363, 1263–1270.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science 315, 368–370.

Roeckner, E., Arpe, K., Bengsson, L., Christoph, M., Claussen, M., Duemenil, L., Esch, M., Giorgetta, M., Schlese,U., Schulzweida,U., Giorgetta, M., Schlese, U., 1996. The Atmospheric General Circulation Model ECHAM-4: Model Description and Simulation of Present-Day-Climate, Max-Planck Institute for Meteorology, Report No. 218, Hamburg, Germany, pp. 1–90.

Roeckner, E., Bauml, G., Bonaventura, L., Brokopf, R., Esch, M.,Giorgetta, M., Hagemannn, S., Kirchner, I., Kornblueh, L, Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., Tompkins, A., 2003.The Atmospheric General Circulation Model ECHAM5 Part I: Model Description, Max-Planck Institute for Meteorology, Report No. 349, Hamburg, Germany, pp. 1–127.

Rummukainen, M., Räisänen, J., Bringfelt, B., Ullerstig, A., Omstedt, A., Willén, U., Hansson, U., Jones, C., 2001. A regional climate model for northern Europe: model description and results from the downscaling of two GCM control simulations. Climate Dyn. 17, 339–359.

Shchepetkin, A.F., McWilliams, J.C., 2003. A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. J. Geophys. Res. 108 (C3), 3090. doi:10.1029/2001JC001047.

Shchepetkin, A.F., McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic models. Ocean Modell. 9, 347–404.

Sweeney, J., 2000. A three century storm climatology of Dublin. Irish Geogr. 33, 1–14.

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

Wang, S., McGrath, R., Semmler, T., Sweeney, C., 2006. Validation of simulated patterns over Ireland for the period 1961–2000. Int. J. Climatol. 26, 251–266.

WASA, 1998. changing waves storms in the northeast Atlantic ocean. Bull. Am. Meteorol. Soc. 79, 741–760.

Wells, N., 1997. Atmosphere and Ocean: A Physical Introduction. John Wiley and Sons Ltd.

Woth, K., Weisse, R., Storch, H., 2005. Climate change and North Sea storm surge extreme: an ensemble study of storm surge extremes expected in an changed climate projected by four different regional climate model, Ocean Dyn doi:10.1007/s10236-005-0024-3.

Wolf, J., Flather, R.A., 2005. Modelling waves and surges during the 1953 storm. Phil. Trans. R. Soc. A, 1572.