Projections of waves in the North Atlantic under high-end emissions scenarios

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Abstract

The EU-funded RISES-AM- project is examining the projections of coastal impacts and resilience under high-end climate change scenarios. In practice this means where global average warming is projected to exceed 2°C with respect to pre-industrial temperatures. We are using the RCP4.5 (medium emission) and RCP8.5 (high emission) projections from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) climate model results to force global and regional models of waves which will then feed into coastal impacts models.

Our particular area of interest is the Atlantic-facing NW European coast. We have set up global and regional implementations of WaveWatchIII® wave model, using the latest climate model forcing available through the CMIP5 and CORDEX (Coordinated Regional Climate Downscaling Experiment) projects (http://wcrp-cordex.ipsl.jussieu.fr; particularly EURO-CORDEX: http://www.euro-cordex.net). We have obtained Euro-CORDEX downscaled wind forcing at ~11km resolution as well as global winds for the present day to 2100 period, selecting the EC-EARTH Earth System Model model as the preferred model forcing. We have explored the change in storm climate in the North Atlantic over this period and ultimately how this affects the coastal wave climate. Results from this study will then allow an assessment of the potential impacts and novel methods of coastal adaptation on a European and local scale.

1. Introduction

Coastal areas (less than 100m above sea level) are the most densely populated on earth - currently, more than 35% of the world’s GDP and 40% of the population (e.g. Lichter et al., 2011) is located there. The relevant physical variables which may produce coastal flooding in these areas in a warmer future climate are global/regional sea level rise, extreme sea levels, storminess and waves. The RISES-AM- project (**R**esponses to coastal climate change: **I**nnovative **S**trategies for high **E**nd **S**cenarios **-A**daptation and **M**itigation**-)** aims to address coastal impacts of climate change for high-end emissions scenarios, i.e. where global average warming is projected to exceed 2°C with respect to pre-industrial temperatures.

The dynamic response of the Earth’s global climate system is now known to be strongly affected by interactions between the various subsystems (Lenton et al., 2003)and so recently progress is being made in Earth System modelling, going beyond atmosphere-ocean global climate models (AOGCMs), which are the present state of the art. These Earth System Models (ESMs) will include additional climate components such as ocean biochemistry, dynamic vegetation, atmospheric chemistry, carbon cycle components and dynamic ice sheets, allowing us to study the Earth's climate system and its response to perturbations in the broadest sense. It is anticipated that the interactions between the various subsystems will ultimately result in increased accuracy of climate predictions as well as in valuable new insights in climate variability and interactions. Also, there is increasing interest in predicting both anthropogenic climate change and natural climate variability beyond seasonal to inter-annual time scales. In this project we are looking at a downscaling of global to regional (European) wave projections, forced by a developing Earth System model (EC-EARTH) in order to examine the projected changes in coastal wave impacts due to high-end climate change. Waves on the western coasts of Europe are an integrator of the winds over the North Atlantic (Brown et al., 2010; Wolf and Woolf, 2006). Thus understanding the projected changes in storminess over the North Atlantic will give us better projections of wave impact (Woolf and Wolf, 2013).

Previous work has included using Coupled Model Inter-comparison Project Phase 3 (CMIP3) models to force wave models on a regional scale (e.g. Wolf et al., 2015, using the HadCM3 GCM/RCM) and local scale (Brown et al., 2012). These have been used to make assessments of the changes in wave climate on the NW European shelf and eastern Irish Sea due to global warming, especially around the UK (Lowe et al., 2009). The results from the HadCM3 forcing indicate that the future storm tracks move south, producing higher waves in the SW of UK and lower waves to the north of Scotland. Here we are using the latest climate model results (CMIP5) to force global and regional (European) models of waves which will then feed into coastal impacts models.

The EURO-CORDEX initiative has produced an ensemble of downscaled European Regional Climate Models (RCM) forced by Global Climate Models (GCM) from CMIP5 project through the Earth System Grid Federation (ESGF: http://esgf-index1.ceda.ac.uk/esgf-web-fe/), which provides an infrastructure to disseminate model output and currently supports CMIP5 activities.

The wave modelling results are not yet available, so this paper explores the philosophy behind the study and the likely outcomes based on analysis of the forcing and earlier projections, particularly looking at changes in storminess over the North Atlantic and recent results from global wave modelling. It is important to examine the biases in the CMIP5 storm projections to understand the likely uncertainty in the wave projections and we are already looking forward to the CMIP6 projections (Meehl et al., 2014).

2. Wave Model

Both global and regional versions of the WaveWatchIII® model have been implemented. The extent of the regional model, with 0.11° resolution (~12km) is shown in Figure 1, nested within a global model.

WAVEWATCH III® (Tolman, 2009) is a third generation (3-G) wave model (Komen et al. 1994) developed at NOAA/NCEP. It is a further development of the model WAVEWATCH, as developed at Delft University of Technology (Tolman 1989, 1991a) and WAVEWATCH II, developed at NASA, Goddard Space Flight Center (Tolman 1992). WAVEWATCH III® differs from other 3-G models in various ways including the governing equations, the model structure, the numerical methods and the physical parameterisations. In the latest version 3.14, WAVEWATCH III® is evolving into a wave modelling framework, which aims to allow for easy development of additional physical and numerical approaches to wave modelling. This model has been adopted by the UK Met Office as its operational wave model and is being used in new developments of coupled wave and hydrodynamic models such as the NEMO-WAVE working group, following theoretical developments in understanding coupled waves and hydrodynamics (Tolman, 1991b; Wolf et al., 2002; Wolf, 2008; Wolf, 2009; Brown and Wolf, 2009; Bolaños et al., 2011). Thus it is one of the best developed and well-validated wave models presently available.

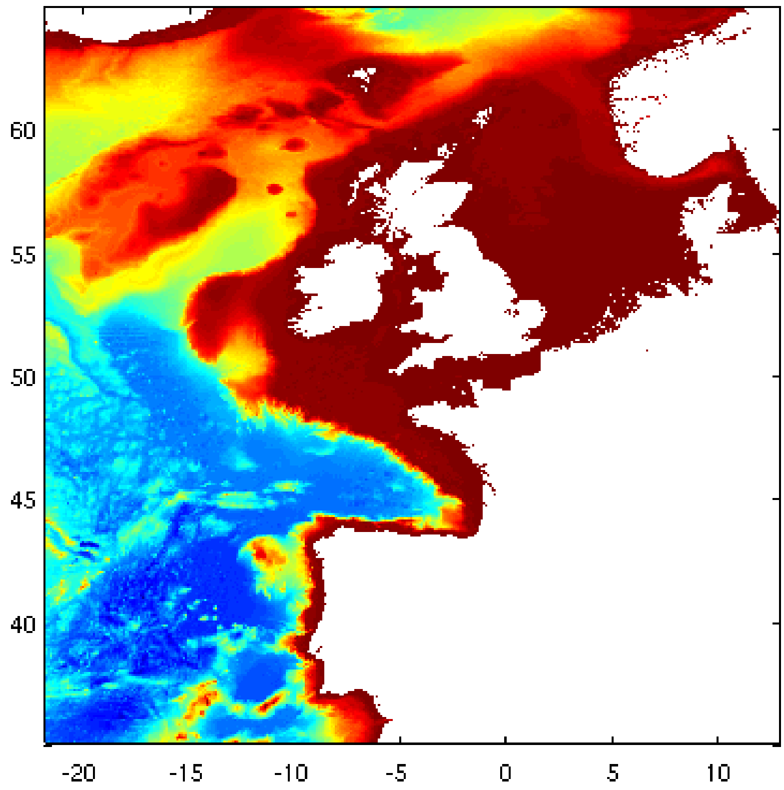

Figure 1: Extent of Euro-CORDEX and regional wave model

2.1 Model Forcing

There are 19 GCM's in various configurations which have been run for CMIP5 simulations (see Table 1), although there are only a limited number of down-scaled EURO-CORDEX RCM simulations. Two of the objectives defined at the outset of EURO-CORDEX were that the GCMs with weak performances over Europe should be avoided and that the spread of CMIP5 simulations should be adequately sampled. In addition to the CMIP5 simulations available through ESGF, Table 1 also lists the associated EURO-CORDEX data available for each CMIP5 GCM. These RCM data are only publically available at a temporal resolution of daily means for the atmospheric surface variables, but higher frequency output may be available through project partners. The RCM simulations listed in Table 1 all have a horizontal resolution of 0.11° however there is an additional EURO-CORDEX 44 experiment, which has an increased number of RCM simulations, but at a cost of a reduced resolution of 0.44°. We have acquired 6-hourly wind forcing from the EC-EARTH GCM and RCM, for the RISES-AM- project, via the Swedish Meteorological and Hydrological Institute (SMHI).

Table 1: CMIP5 Models

	Ensemble Members			2006-2100 / 0.11° / 1 day			
CMIP 5 Model	**RCP4.5**	**RCP8.5**	**Resolution**	**EURO-CORDEX RCM**	**Scenario**	**Ensemble Driver**	**Note**
ACCESS1.0	1	1					
ACCESS1.3	1	1		WRF331A	RCP8.5	r1i1p1	2006-2050
BCC-CSM1.1	1	1	2.8x2.8				
BCC-CSM1.1(m)	1	2	1.12x1.12				
CCSM4	1	1	1.25x0.94				
CMCC-CM	1	1	0.75x0.75				
CNRM-CM5	1	1	1.4x1.4	CCLM4-8-17	RCP4.5/8.5	r1i1p1	
				ARPEGE52	RCP4.5/8.5	r8i1p1	
				ALADIN53	RCP4.5/8.5	r1i1p1	
				RCA4	RCP4.5/8.5	r1i1p1	
CSIRO-Mk3.6.0	10	10	1.8x1.8				
CanESM2	1	1	2.8x2.8				
EC-EARTH	9	9	1.12x1.12	CCLM4-8-17	RCP4.5/8.5	r12i1p1	
				HIRHAM5	RCP4.5/8.5	r3i1p1	
				RACMO22E	RCP4.5/8.5	r1i1p1	
				RCA4	RCP4.5/8.5	r12i1p1	
FGOALS-g2	2	2	2.8x2.8				
GEOSCCM	3	0					
GFDL-CM3	3	1	2.5x2.0				
GFDL-ESM2G	1	1	2.5x2.0				
GFDL-ESM2M	1	1	2.5x2.0				
GISS-E2-H	1	2	2.5x2.0				
GISS-E2-R	2	2	2.5x2.0				
HadGEM2-CC	1	2	1.88x1.25				
HadGEM2-ES	2	2	1.88x1.25	CCLM4-8-17	RCP4.5/8.5	r1i1p1	
				RCA4	RCP4.5	r1i1p1	
INM-CM4	1	1	2.0x1.5				
IPSL-CM5A-LR	5	4	3.75x1.8				
IPSL-CM5A-MR	1	1	2.5x1.25	WRF331F	RCP4.5/8.5	r1i1p1	
				RCA4	RCP8.5	r1i1p1	
IPSL-CM5B-LR	1	1	3.75x1.8				
MIROC-ESM	1	1	2.8x2.8				
MIROC-ESM-CHEM	1	1	2.8x2.8				
MIROC4h	1	0					
MIROC5	5	5	1.4x1.4	CCLM4-8-17	RCP4.5/8.5	r1i1p1	
MPI-ESM-LR	3	3	1.88x1.88	CCLM4-8-17	RCP4.5/8.5	r1i1p1	
				WRF331A	RCP4.5	r1i1p1	2006-2050
				REMO2009	RCP4.5/8.5	r1i1p1	
				REMO2009	RCP4.5/8.5	r2i1p1	
				RCA4	RCP8.5	r1i1p1	
MPI-ESM-MR	3	1	1.88x1.88				
MRI-CGCM3	1	1	1.1x1.1				
MRI-ESM1	0	1					
NorESM1-M	1	1	2.5x1.9				

EC-EARTH is the name given to the ESM being developed at ECMWF, based on the ECMWF weather prediction model (Integrated Forecasting System, IFS) and the NEMO ocean model. There is a goal to produce a 'seamless' Earth System prediction system (Hazeleger et al., 2010). Three scientific and practical common goals have been identified: (i) to investigate Earth system feedbacks e.g. currently there is significant spread in climate sensitivity among climate models, which can be attributed to inaccurate knowledge of the main climate feedbacks such as cloud feedbacks, the lapse-rate feedback and the snow/ice albedo feedback; (ii) to study inter-annual to multi-decadal climate fluctuations and predictability, which is currently not understood very well; and (iii) to develop an advanced modelling tool for making climate scenarios i.e. to make projections for future change. While the current version of EC-EARTH is essentially a state-of-the-art AOGCM, a number of additional components are currently under development and will be added to EC-EARTH in the coming years.

In general the climate model outputs are compared against reanalysis datasets for the historical period to assess any consistent biases, so that the future projections can be treated with some confidence. The different models have also compared to see how consistent the results are and CMIP5 results are checked against CMIP3. Although there has been extensive model development and increasing complexity since CMIP3, the recent CMIP5 simulations have led to similar projections in global temperature, with consistent spatial patterns in both precipitation and temperature (Knutti and Sedláček, 2013). Knutti and Sedláček (2013) argue that while the spread in modelled projections persists on the local scales, improved process representation implies greater confidence in the results. Zappa et al. (2013) note that while the winter-time North Atlantic storm tracks still tend to be either too zonal or displaced southwards, there have been improvements both in the number and the intensity of North Atlantic cyclones in the higher resolution CMIP5 models. The shortcomings in representing these storm tracks are illustrated in Figure 2 of the zonal-mean zonal wind-stress in the CMIP3 and CMIP5 models (IPCC, 2013), with the peak in zonal wind stress to the south of the observations in the northern hemisphere.

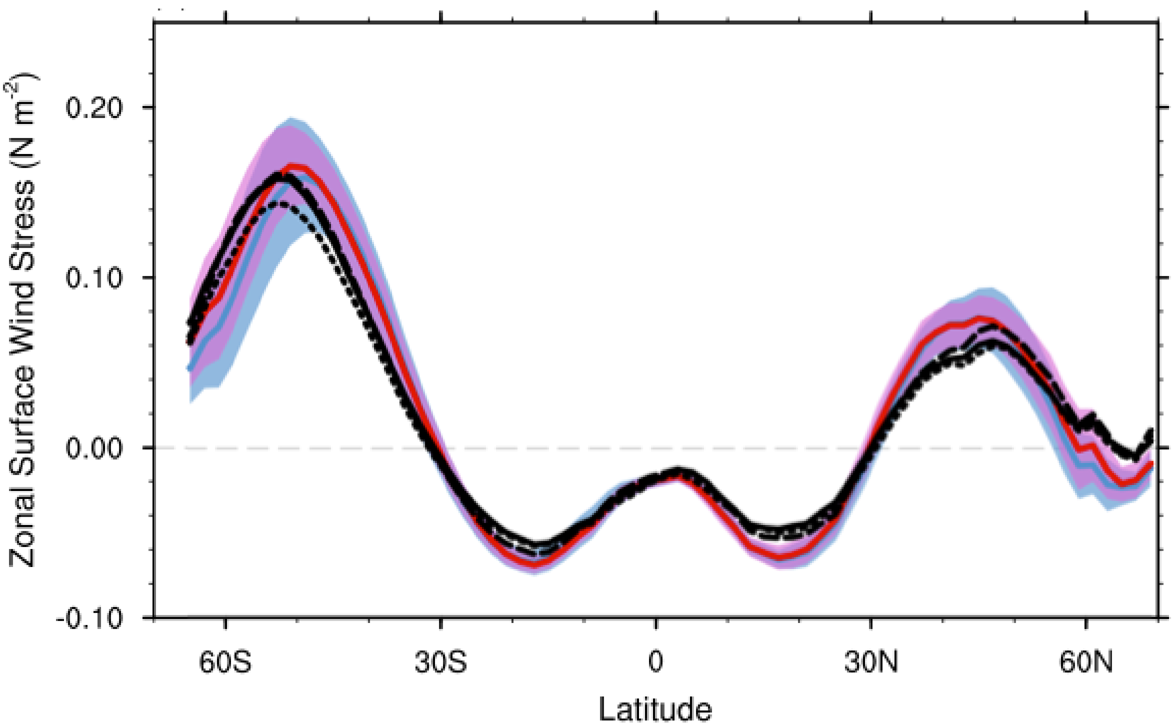

Figure 2: Zonal-mean zonal wind stress over the oceans in a multi-model mean from CMIP3 (blue) and CMIP5 (red) models. Shown is the time-mean of the period 1970–1999 from the historical simulations. The black solid, dashed, and dotted curves represent ECMWF reanalysis NCEP/NCAR reanalysis, and QuikSCAT satellite measurements, respectively. Shading indicates the inter-model standard deviation (figure reproduced from Fig. 9.19b in IPCC AR5)

Due to the large spread in the North Atlantic storm track position, Zappa et al. (2013) split the CMIP5 models into 3 groups of similar behaviour. The first exhibited small biases in winter-time position and had the median latitude consistent with reanalysis data. These models included: EC-EARTH, GFDL-CM3, HadGEM2 and MRI-CGCM3. The second group, with southern displacement of the winter-time storm track, included: BCC-CSM, CMCC-CM, CNRM-CM5, CSIRO, FGOALS-g2, IPSL-LR, and MIROC-ESM. The third group contained the remaining CMIP5 models, which exhibited a storm track that was too zonal. The authors note, however, that even if a model has a small winter-time bias in the storm track position, it does not necessarily mean it performs well during the summer months. They cite the example of HadGEM2, which has a small bias in the winter-time, but exhibits a poleward bias during the summer months. Zappa et al. (2013) conclude that the winter-time southward displacement of the North Atlantic storm track leads to too few and weaker cyclones over the Norwegian Sea and too many cyclones in central Europe, while, in the summer months the CMIP5 models generally perform better.

In an evaluation of GCMs to provide forcing data for RCMs in the European region, Jury (2012) assessed various atmospheric variables over the EURO-CORDEX region. It was found that GCMs that simulated surface parameters better, did not necessarily manage to reproduce the upper atmospheric state better. For example, they found that while MIROC4h and HADGEM2 performed well with respect to most surface fields, they underperformed higher up in the atmosphere. They concluded that the GCM selection for RCM simulations should not be based on observed biases in surface parameters alone, as this may not reflect its ability to provide correct forcing data at the lateral boundaries. In summary they found that the CMIP5 GCMs had a positive bias in precipitation and negative bias in sea-level pressure over Northern Europe during winter months, with shortcomings in modelling extreme months and large deviations and model spread within the southern lateral boundary of the EURO-CORDEX domain.

As part of the EURO-CORDEX experiment design, GCMs from the CMIP5 project have been chosen on their performance and spread. As only these RCM simulations have the resolution required to carry out local surge and wave projections in the European region, the choice of GCM from those available will be dictated accordingly. Of these, EC-EARTH and CNRM-CM5 have the largest ensemble of RCMs available.

The use of better climate model forcing should aid the development of adaptation and mitigation policies in the EU RISES-AM- project.

3. Results

The wave model results are not yet available due to various technical issues. However it is anticipated that the EC-EARTH model will give the best available wave model projections available at present due to its performance with respect to North Atlantic storm tracks, even though these still have some limitations. It is to be hoped that future developments of the ESM will continue to produce further model improvements. A review of existing work is given below.

A lot of uncertainty is associated with future European climate projections due to the variability in climate model predictions and the strong influence of physical processes (storm tracks and jet streams) that are known to be poorly represented within models (Woollings, 2010). The European climate is unique with one of the world's most variable climates due to its location at the end of the Atlantic jet stream and its storm track configuration, making blocking events an important phenomenon (Woollings, 2010). The translation of global climate studies to coastal impacts is still in its infancy (de Winter et al., 2012) with regional climate studies often focusing on rainfall and temperature patterns rather than storm winds, which drive surges and waves (e.g. Gaslikova, et al., 2013; Hemer et al., 2013). For coastal studies it is not only the extreme values of winds but also directional changes that are important for simulation of shoreline evolution, in addition to the influence of sea level rise on wave and water levels (Hemer et al., 2013).

Winter trends in the Northern Hemisphere storm tracks over the North Atlantic and North Pacific have also been found to show a poleward shift (Wang et al., 2013). Between 40° and 60°N there is an increase in the meridional wind variability at 300 hPa that extends from the Atlantic across Eurasia. At 700 hPa a smaller regional increase occurs at 50°N extending from the eastern Atlantic to Europe. For this region, increases in sea level pressure variance are also projected, but by less than 80% of the CIMP5 models. For Europe the projected changes in the winter (December, January, February) cyclone storm track indicate a poleward (northward) shift near 20°E and a significant decrease in frequency. The summer (June, July, August) cyclone tracks show a projected equatorward shift over a small region of Europe and decrease in frequency for Eurasia (Chang et al., 2012). Biases in storm track simulations suggest the CMIP5 models tend to simulate tracks that are too weak and too equatorward. Over Northern Europe trends in strong cyclone activity seem to have increased in numbers and mean lifespan during winter and autumn when considering the periods 1871-2010 and 1951-2010. In summer the storm counts decrease. For this 140-year period the trends are considered statistically significant. For Western Europe (high latitude North Atlantic) a significant increase in cyclone activity occurs in all seasons, although a slightly greater increase has been found in the cold season. This increase is related to both the cyclone count and mean intensity (Wang et al., 2013).

Blocking events divert extra-tropical cyclones either north or south and are often responsible for extreme weather events, such as a cold winter or hot dry summer spells. Blocking events over Greenland are often associated with a southerly-shifted jet stream regime that characterises a negative NAO phase (Zappa et al., 2014). A common feature in relatively coarse global climate models is an underestimate of European blocking episodes and a tendency to over-predict the North Atlantic jet stream strength, which also overestimates NAO regimes (Cattiaux et al., 2013). The tilt of the North Atlantic storm track and Mediterranean cyclone density seem to be related to biases in the European blocking frequency, particularly in winter, but less so to the cyclone track density in summer (Zappa et al., 2014). Future changes in blocking activity over the European Atlantic show a reduction over the Atlantic and an eastward shift in autumn and winter. However, there is still debate as to whether global climate models such as CMIP5 are able to meaningfully represent future changes in blocking activity as they are unable to represent the current climate sufficiently accurately (de Vries et al., 2013). Assessment of the CMIP5 model performance suggests EC-EARTH, MIROC, MOHC perform best over Europe for winter and NCAR in summer (Masato et al., 2013). Using the RCP8.5 concentration pathway to represent the 21st century a decrease in European winter and summer blocking maximum in an ensemble of 12 CMIP5 models is found. A winter poleward shift in high latitude blocking and an eastward summer shift are identified. In summer, the decrease in blocking is accompanied by a poleward storm track shift into the high-latitude blocking region. This may mean that the incidence of blocked storms may increase. By the end of the 21st century model analysis over Europe indicates a 30% decrease in blocked days during winter, although not over Eastern Europe, and a 35% increase in blocked days during summer for the Europe-western Russia region (Masato et al., 2013).

To identify changes in coastal conditions analysis of the wind climate is required. Studies have shown that the 12 CMIP5 models do not project changes in North Sea annual maximum surface wind speeds or wind speeds with lower return frequency for both the medium RCP4.5 and high-end RCP8.5 emission scenarios. Maximum differences for the ensemble-mean annual maximum are projected to be around 1 m/s. The majority of the models predict no significant change in the annual maximum wind speeds or corresponding 1:500 year return value. There is however, an indication that extreme wind events will be more frequently from a westerly direction, as there is a decrease in annual maximum values from south-easterly directions and an increase in south-westerly and westerly directions. This may again be related to a poleward shift in storm track (de Winter et al., 2013). The models available in CMIP5 have a coarse resolution and do not resolve tropical cyclones (de Winter et al., 2013). EC-EARTH has therefore been used at high resolution (~25km, 91 vertical levels) to investigate changes in mid-latitude storms in response to greenhouse warming (Haarsma et al., 2013). The occurrence of hurricane-force winds (>32.6 m/s) has been found to increase over Western Europe and occur earlier in the season, from August to October. This is in consequence of a rise in Atlantic tropical sea surface temperatures extending the breeding ground of tropical cyclones eastward. In addition to more frequent and intense hurricanes following a path to Europe, the shorter travel distance will increase the likelihood of these storms maintaining their “tropical” strength characteristics (Haarsma et al., 2013).

A preliminary assessment of changes in global wave climate due to CMIP5 results was shown, e.g. using RCP8.5 and RCP4.5 in the EC-Earth model and modelling resulting waves, by Dobrynin et al., (2012). Both scenarios indicate a future increase of wind speed and wave height in the Arctic and Southern Ocean and a decrease in the Pacific Ocean. In the North Atlantic there is a change of sign from currently positive to negative trends in the 21st century.

Wang et al. (2014) made statistical projections of changes in ocean wave heights using sea level pressure (SLP) information from 20 CMIP5 global climate models for the 21st century. The results show significant wave height increases in the tropics (especially in the eastern tropical Pacific) and in Southern Hemisphere high latitudes (south of 45◦S). Under the projected 2070–2099 climate condition of the rising high concentration pathway—the RCP8.5 scenario, the occurrence frequency of the present-day one in 10 year extreme wave heights is likely to double or triple in several coastal regions around the world. These wave height increases are primarily driven by increased SLP gradients and hence increased surface wind energy.

4. Conclusions

We are at an early stage of evaluating new wave projections for NW Europe based on CMIP5 model outputs. There is not much difference between the CMIP3 and CMIP5 models, so it remains to be seen whether there are substantial differences in wave projections for NW Europe. There are still uncertainties in the climate model prediction of North Atlantic storm tracks. Some previous work suggest reduced wave heights for the North Atlantic but locally there may be increased wav heights so this area is still uncertain.

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