CLIMATE CHANGE: MEETING THE CHALLENGE OF ADAPTATION

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ACRONYMS

C4I: Community Climate Change Consortium For Ireland
CCCma: Canadian Centre for Climate Modelling and Analysis
CMRC: Coastal and Marine Resources Centre
CSIRO: Commonwealth Scientific and Research Organisation
ECHAM: European Centre Hamburg Model
GCM: Global Climate Model
HadCM: Hadley Centre Coupled Model
ICARUS: Irish Climate Analysis and Research UnitS
IPCC: Intergovernmental Panel on Climate Change
RCM: Regional Climate Model
SNIFFER: Scotland and Northern Ireland Forum For Environmental Research
SRES: Special Report on Emissions Scenarios
UKCIP: United Kingdom Climate Impacts Programme

SUMMARY OF LIKELY CHANGES IN KEY PARAMETERS

Work on climate change in Ireland to date has been successful in refining the likely impacts of climate change over the course of the coming century. However, significant uncertainty and challenges remain and it is essential that researchers in this critical area work closely with end-users of data to ensure best possible information is used for decision making and designing for the future. While acknowledging the uncertainty that remains the following is a summary of likely changes in key parameters.

- Temperatures are likely to increase everywhere relative to the present with greatest increases suggested for the summer and autumn of up to 3.4^{o}C by the end of the century.
- With increases in average temperatures a change in extreme events is to be expected with an increase in the intensity and duration of heatwaves and a decrease in frost occurrence likely.
- Precipitation remains an uncertain variable with differences in the extent and spatial distribution of changes between different modelling approaches. A robust signal of increased seasonality is evident with wetter winters and drier summers likely. No clear direction of change is evident for spring and autumn.
- As changes in average climate progress, changes in extremes can be expected with the magnitudes likely to increase and the occurrence of extreme events for all climate

variables (with the exception of minimum temperatures) likely become more frequent.

- Increases of 8-11% in 60m height average wind speeds are likely in winter by mid-century, with decreases of 14-16% in summer, but assessment of this variable to date has been subject to high levels of uncertainty.
- In relation to stream flow, robust increases in winter and spring flows in the order of 20% in winter are likely by mid to late century. Reductions in summer and autumn months of over 40% are likely in many catchments. Catchments show different signatures of change depending on characteristics determining runoff response.
- Flood events are likely to become more frequent with the current 50 year event likely to be associated with a ~10 year return period by mid to late century. While uncertainty remains low flow events are also likely to become more frequent.
- IPCC scenarios suggest a likely sea level rise of between 0.28 to 0.43m by the end of the century relative to 1980-1999. However, recent thinking suggests that this may be too conservative with increase of over 1m suggested. Localised rises will depend on characteristics such as isostatic rebound and topography.
- The likelihood of increased storminess, higher sea levels and wind speeds will result in a subsequent enhancement of wave heights and storm surges, when combined with riverine flooding will pose serious flood risks in many of our coastal cities and for key infrastructure.

Even if greenhouse gas emissions were capped at 2000 levels some degree of climate change can be expected due to the inertia in the climate system. In light of these findings there is a requirement to urgently review the security of critical infrastructure; to prioritise adaptation measures for existing infrastructure as well as incorporate provisions for adaptation in all new infrastructure. Failure to do so would place unacceptable risk on the wellbeing of society.

PURPOSE OF THIS PAPER

The purpose of this paper is to provide information to the engineering community on where we currently stand in our knowledge of the impacts of climate change in Ireland. It seeks to identify what we know and where the key uncertainties lie in relation to climate variables and impacts that are critical to designing robust engineering strategies for the future. Rather than trawl the substantial literature in the limited time available it provides some of the important findings from the key reports produced for Ireland in recent years, particularly Sweeney et al., 2008, McGrath et al., 2008 and Hulme at al., 2002. The thrust behind these reports has been to inform policy development in adapting to climate change. It is hoped that these findings will serve as a starting point for dialogue between the climate change research community and the engineering community about where we need to go from here in order to refine and provide the best information as possible for a profession with a substantial degree of responsibility in ensuring successful adaptation to climate change for this and future generations in Ireland.

1. INTRODUCTION

The need to adapt to the impacts of climate change in Ireland has become increasingly recognised in recent years. For many engineering projects, plans and programmes a medium to long term view of climate change impacts is essential so that appropriate designs, resilience and robustness to future changes in climate can be achieved. Climate change impact assessment in Ireland has been on the research agenda for over eighteen years now with the first comprehensive approach dating back to the McWilliams report in 1991 which set prescribed climate scenarios for impact modellers to use. The second main assessment; Climate Change, Impacts and Scenarios for Ireland (Sweeney et al., 2003) occurred in 2003 using downscaled global climate data as input to models in several key sectors. While this report marked a significant advance in understanding the impacts of climate change and provided strong signals regarding spatial variations in impacts throughout Ireland it is limited in that key uncertainties are omitted, with results being based on output from only one Global Climate Model.

Progress since then has been significant in developing capacity to produce climate change scenarios and impact assessments in an increasingly sophisticated manner. Over this time capacity in Regional Climate Modelling has been developed at a number of centres nationwide, while increasingly sophisticated approaches to manipulating output from climate models has enabled multiple runs of numerous models to be employed in attempts to capture and quantify the cascade of uncertainty that exists in assessing climate change impacts, thereby providing endusers with more appropriate information for adapting to climate change. Key reports publishing results from this period of significant growth include Climate Change; Refining the Impacts for Ireland (Sweeney et al., 2008), Ireland in a Warmer World: Scientific Predictions of the Irish Climate in the Twenty-First Century (McGrath et al., 2008), Implications of the EU climate protection target for Ireland (McElwain, and Sweeney, 2006) and Climate Change: Regional Climate Model Predictions for Ireland (McGrath et al., 2005). In Northern Ireland additional information has been derived through the continually evolving generations of UKCIP reports (most recently, Hulme et al. 2002) which have informed key policy documents such as the SNIFFER Report of 2002 and 'Preparing for Climate Change in Northern Ireland' (Arkell et al., 2007). In addition, the international standing of research on climate change in Ireland has been reflected in the number of papers published in leading academic journals and the increasingly important contributions that Irish researchers are making to the international agenda, particularly in informing different generations of the reports from the Intergovernmental Panel on Climate Change (IPCC).

2. SOURCES OF UNCERTAINTY

Producing future climate scenarios and future impacts is by no means an exact science. Despite advances in modelling chaotic behaviour and natural variability in the climate system, it is clear that climate models will never be able to provide a singular prediction of future climate (Jones, 2000). Giorgi (2005) highlights three major sources of uncertainty in GCM simulations: model configuration uncertainty, uncertainty due to internal model variability and uncertainty due to the stochastic nature of natural forcing.

Of these, uncertainty in model configuration is by far the most significant. Wilby and Harris (2006) highlight the fact that over reliance on a single GCM in impact assessment could lead to inappropriate planning or adaptation responses. Indeed to do so would be to suppress a key source of uncertainty in climate impacts modelling (Hulme and Carter, 1999).

Additionally, projections intended to represent plausible transient climate change due to anthropogenic forcing must rely heavily on future projections of population growth, economic activity and technological change which are inherently uncertain. (Webster *et al.* 2002). An overview of the SRES emissions scenarios used in climate modeling is given at the end of the paper.

Despite the high degree of sophistication of GCMs, their output is generally too coarse to be useful for regional or local scale impacts analysis as important processes which occur at sub grid scale are not at present resolved by these models (Wilby *et al.*, 1999). Due to computational limitations, the grid box output from GCMs is generally in the order of 100s kms. While this is adequate to capture large scale variability, many important process in the climate system occur at much smaller spatial scales and thus are too fine to be resolved in the modelling process. Therefore regionalisation or downscaling of GCM outputs is required for meaningful impact assessment with uncertainty associated with the approaches taken. In terms of approach uncertainty two categories of downscaling have come to the fore, namely, dynamic approaches, in which the physical dynamics of the system are solved explicitly, and empirical or statistical downscaling. Both approaches are subject to benefits and limitations in terms of computational costs and assumptions made, with neither emerging as entirely preferable over the other.

Finally, uncertainty exists in the models used to conduct impact assessments. From a hydrological perspective conceptual rainfall-runoff models have been most widely used for impact assessment. Such models are subject to limitations in parameter stability, parameter identifiability and equifinality, each of which gives rise to uncertainty in model output. Wilby and Harris (2006) and Murphy et al. (2008) show that uncertainty in future flow changes due to equifinality is comparable in magnitude to the uncertainty in emissions scenario

In dealing with these uncertainties it is important to note that the key reports on which this paper is based use different climate models, emissions scenarios, downscaling techniques, impact models, time period of simulation in the future and control periods from which future changes are derived. Therefore they provide a good indication of the ranges of uncertainty associated with climate change in Ireland, but also challenges as to how we provide information to users of the data. Table 1 characterises the range of approaches taken by these reports in producing future climate scenarios.

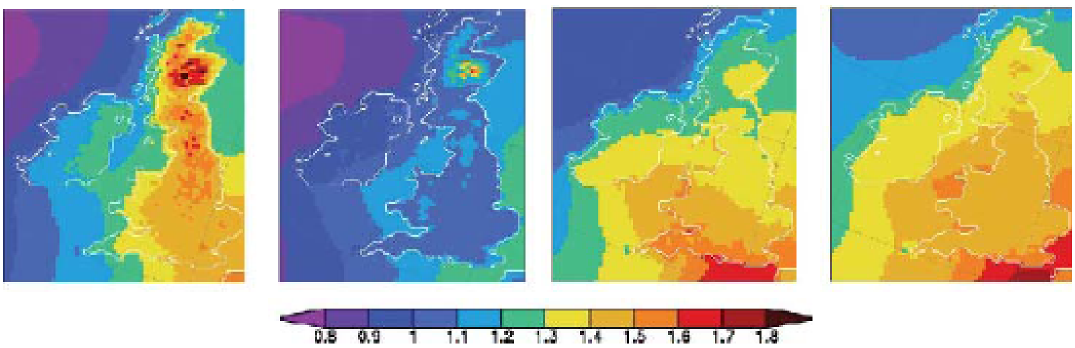
Scenarios	GCMs	Emissions Scenarios	Downscaling Approach	Control and future time periods
C4I	ECHAM4 ECHAM5 HadCM3L HadCM3H	A2 SRES A1B SRES B1 SRES B2 SRES	Regional Climate Modelling & Statistical Downscaling	1961-2000 2021-2060
UKCIP02	HadCM3 HadAM3H	Constructed 4 scenarios from low to high representing the SRES Range	Regional Climate Modelling Pattern Scaling	1961-1990 thirty year time period centred around the 2020s, 2050s, 2080s
ICARUS	HadCM3 CCCma CSIRO (Mark2)	A2 B2	Statistical Downscaling	1961-1990 thirty year time period centred around the 2020s, 2050s, 2080s

Table 1: Approaches used in the key reports used in compiling paper

3. TEMPERATURE PROJECTIONS

Future projections in temperature are attributed with higher confidence levels than many other variables projected by GCMs. However, while there is a good degree of consistencey between the different projections made for Ireland, uncertainties exist depending on the GCMs, emission scenarios, downscaling methods, and baselines used.
From the simulation results derived for Ireland from the C4I project (McGrath et al., 2008) (Figure 1) temperature projections for mid-century show warming everywhere relative to the present, the warming being accentuated in summer and autumn (1.2 to 1.4 °C warmer). The warming shows a spatial gradient, with the greatest temperature increases projected for the south and east. For the latter part of the century warming of up to 3.4^{o}C is expected with greatest increases again evident for the east and south east.

Figure 1 Seasonal warming: mean of 8 ensemble simulations showing the temperature change (°C) between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). The warming is greatest in the summer/autumn (1.2-1.4°C) (Caption and Figure after McGrath et al., 2008).



Based on the multi-model ensemble simulations (based on 3 GCMs and 2 emissions scenarios) derived by Fealy and Sweeney (2008), results for seasonal changes in temperature and precipitation are presented for three 30-year time slices centered on the 2020s, 2050s and 2080s. Regional climate model projections for Ireland suggest that, over the present century, this warming rate is likely to increase to between 0.2-0.3^{o}C/decade. As a consequence, an increase of between 0.7-1.0^{o}C is likely to occur in all seasons by the 2020s (Fealy and Sweeney, 2008). This increase is projected to be more or less uniform across Ireland (Figure 2). By the 2050s, mean seasonal Irish temperatures are projected to increase by between 1.4 to 1.8^{o}C, with the greatest warming in the autumn months. This increase is likely to be associated with a greater warming of the interior of the island resulting in an enhanced 'continental effect'. Coastal areas are likely to be slightly cooler than inland areas in summer due to the presence of sea breezes during the summer months. This continental effect becomes further enhanced by the 2080s, with temperature increases of between 2.0^{o}C to 2.7^{o}C. On a seasonal basis summer and autumn show likely temperature increases of between 2.5-3.0^{o}C, very much in line with C4I projections, although direct comparison is not fully justified.

In comparison with the UKCIP02 scenarios for Northern Ireland annual mean temperatures are likely to increase by between 0.5-2.0^{o}C by mid century and by 1.0-3.5^{o}C by the end of the century. On a seasonal basis the UKCIP02 scenarios also show warming in all seasons with the greatest increases in summer and autumn of between 1.0-3 .5^{o}C and 1.5 to 4.0^{o}C respectively. In line with current trends winter and spring are also likely to become reliably warmer. Figure 3 shows temperature changes for Northern Ireland for the low and high emissions scenarios used in UKCIP02.

Such changes in temperature also have implications for future water temperatures and energy requirements. In relation to the latter McGrath et al. (2008) highlight a clear trend of decreasing heating energy demand, while a weak demand for air conditioning may develop in the southeast of the island during summer months.

4. TEMPERATURE EXTREMES

Little work has been completed on the impact of climate change on future extreme events. Of the work that has been completed, the frequency, intensity and duration of temperature extremes, which can have a negative effect on human societies and ecosystems, are projected to change. The prolonged heat wave that occurred in Europe in 2003, one of the hottest on record, resulted in an excess of 35,000 deaths, while in Ireland during the summer months of 2006, above average mean temperatures, which were over 1^{o}C higher than the 'normal' 1961-1990 period (nearly 2^{o}C higher than 'normal' in the midland stations of Clones and Kilkenny), combined with below average precipitation, resulted in significant soil moisture deficits through out much of the southern part of Ireland with resultant impacts on agriculture (Met Éireann, 2006).

While such extreme events are consistent with the natural variability of the climate system, evidence from the observational records suggests there is a tendency towards an increase in frequency of occurrence and intensity of extreme events. A significant increase was found to have occurred in both maximum and minimum temperatures over the 1961-2005 period (McElwain & Sweeney, 2007). This increase in minimum temperatures has resulted in a shortening of the frost season and a significant decrease in the annual number of frost days (by more than half at a number of stations) (McElwain & Sweeney, 2007). While the number of consecutive cold days has been decreasing over the same period at a number of stations in Ireland, the duration of heat waves has also been increasing,

Fealy and Sweeney (2008), in an analysis of likely future changes in extremes based on the A2 (Medium-high) scenario, found that significant changes are likely to occur in the four key indices of extreme events, namely:

- hot-day threshold (T_{max} 90th percentile),
- cold-night threshold (T_{min} 90th percentile),
- number of frost days ($T_{min} < 0^oC$)
- longest heat wave (Heat wave duration).

Trends were found to be significant (0.01 significance level) at all synoptic stations analysed for all the temperature indices employed in their analysis. An increase in the intensity of extreme temperatures (the hot day threshold) is indicated for all stations, rising by a rate of more than 0.2^{o}C/decade, particularly for inland stations. An increase in the duration of heat waves is also projected by between 3-4 days per decade, while a decrease in the number of frost days per decade, especially at inland stations, is also likely due to the cold night threshold rising by 0.2-0.3^{o}C/decade. These projected changes are consistent with the observational records, indicating that a good degree of confidence can be placed in these findings.

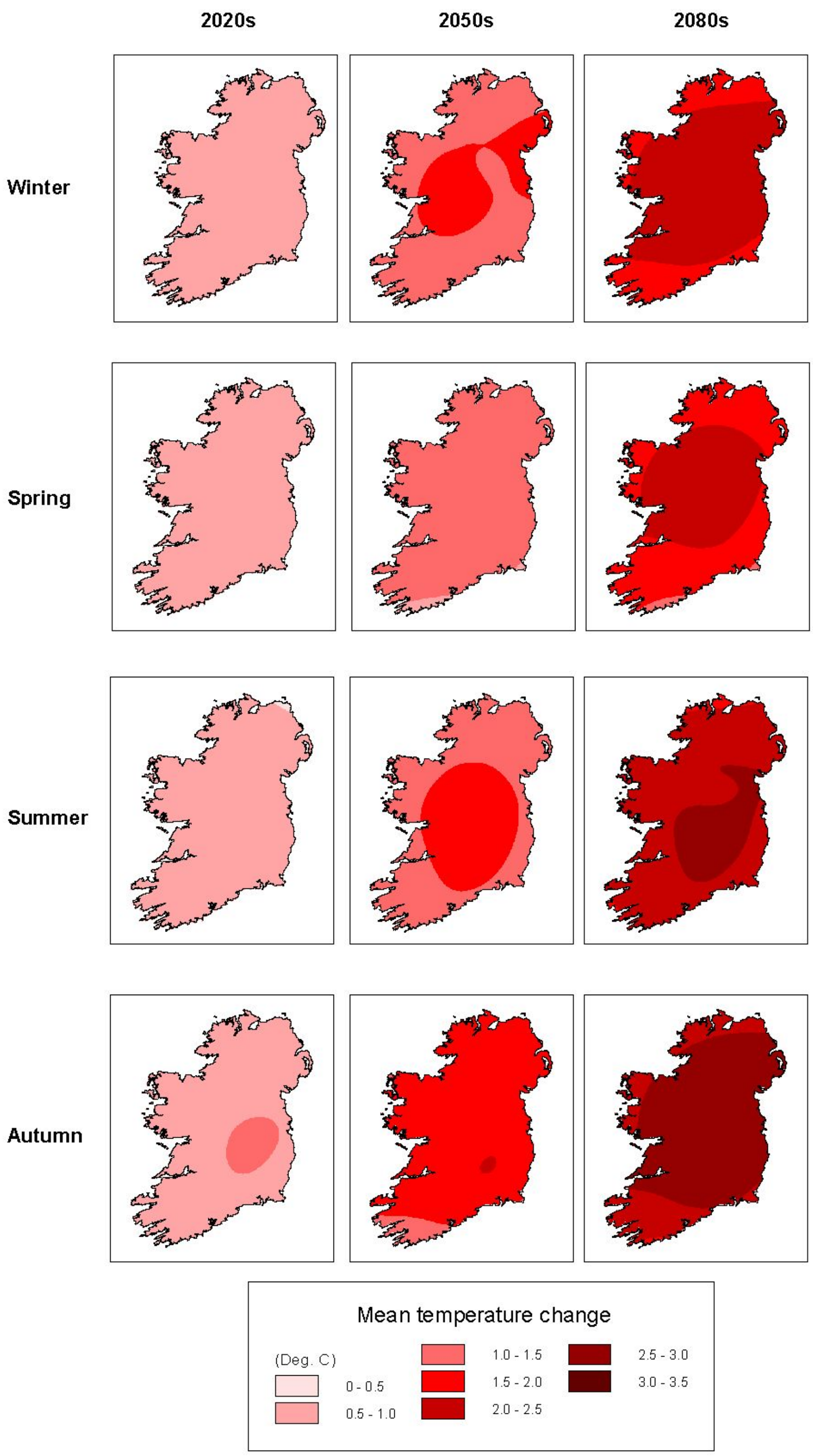


Figure 2 Changes in temperature by Fealy and Sweeney (2008). Results based on a mean ensemble of output from three GCMs forced with two emissions scenarios.

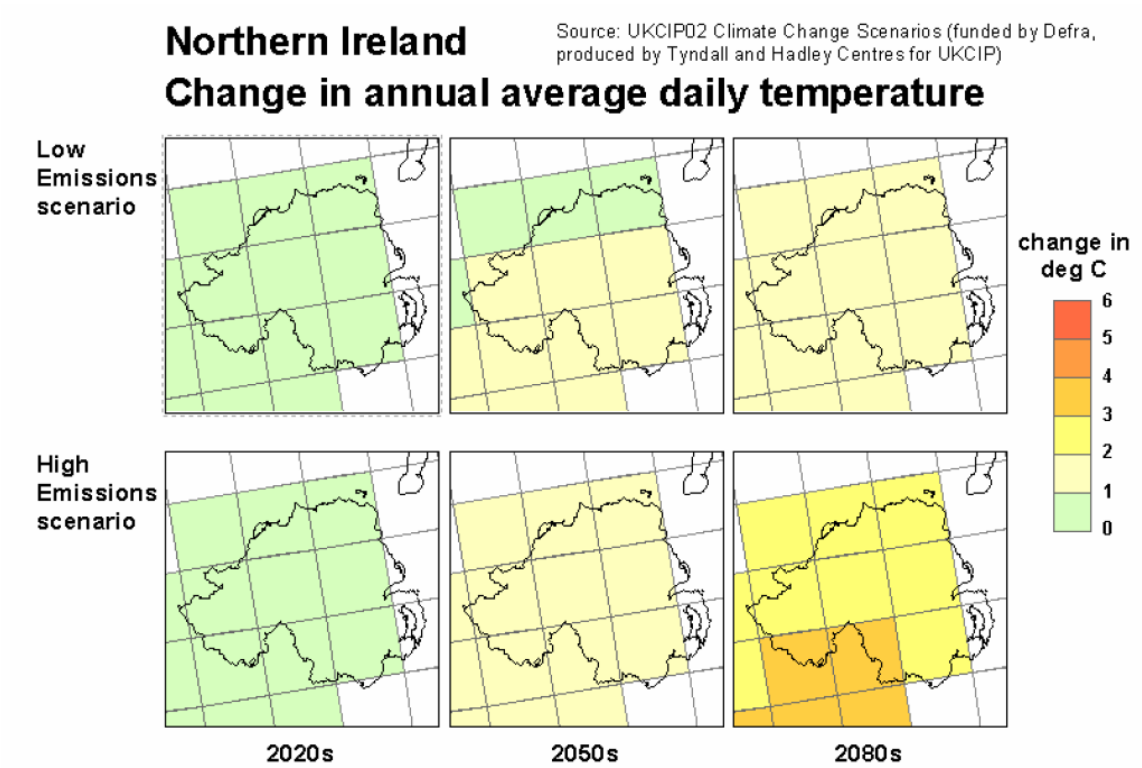


Figure 3 Percent change in annual average daily temperature for Northern Ireland for the UKCIP02 Low and High Emissions Scenarios (Arkell et al., 2007).

5. PRECIPITATION PROJECTIONS

Changes in precipitation over the course of the present century are likely to have a greater impact on Ireland than changes in mean temperature, due to the potential of increased flooding during the winter months and reductions in stream flow during the summer months. Projected changes in precipitation suggest that an increased seasonality with wetter winters and drier summers and a change in the spatial distribution are likely for all future time periods. Dealing firstly with the ICARUS scenarios produced by Fealy and Sweeney (2008) mean ensemble changes by the 2020s suggest that winter precipitation is likely to increase by approximately 3%. A similar magnitude decrease in national precipitation is projected to occur during the summer months, although a large regional decrease, of the order of 10-16%, is projected to occur along the south and east coast.

Greater seasonality of precipitation becomes evident during the 2050s, with an increase in the order of 12% projected to occur during the winter months. A similar reduction is projected to occur during the summer months. Regional decreases of between 20-28% are projected for locations along the south and east coasts (Figure 4).

These seasonal and spatial changes are further enhanced by the 2080s. An increase in winter precipitation of 15% is projected to occur nationally, with above average increases projected for the midlands. Nationally, summer reductions of 19% are likely, with decreases of between 30-40% along the east and south coasts.

Increases in winter precipitation are projected to occur for all time periods, while reductions are consistently projected to occur for all other seasons. If realised, these changes in the seasonal and spatial distribution of precipitation are likely to result in an increased likelihood of flooding, particularly in the midlands and west of Ireland, while water availability and quality are likely to be adversely affected during the late summer and autumn months in all regions, but particularly along the south and east coasts.

While not directly comparable due to the difference in simulated time periods, spatial differences in projected precipitation are apparent between both the C4I (McGrath *et al*., 2008) and Fealy and Sweeney (2008) simulations for the middle of the century. The C4I simulations (McGrath *et al*., 2008) project a greater decrease in summer precipitation along the west coast of Ireland, with reductions in the order of 6 to 9%, while the Fealy and Sweeney (2008) projections suggest the greatest decrease in summer precipitation will be experienced along the east and south coast.

UKCIP02 scenarios for Northern Ireland also suggest an increased seasonality with increases in winter rainfall of up to 10% for the 2020s, up to 15% for the 2050s and up to 25% for the 2080s, depending on emission scenario. It is worth keeping in mind that the upper limit of the UKCIP02 scenarios is a high emission scenario, equivalent A2 SRES scenario, again highlighting the importance of uncertainties and methodologies employed.

While there are differences in the extent and spatial distributions of changes in winter and summer, there is agreement in the overall direction of change. This however cannot be said for the shoulder seasons of spring and autumn with no clear and robust changes forthcoming. Both ICARUS and C4I scenarios suggest decreases in spring precipitation for mid-century while the UKCIP02 scenarios suggest an increase of up to 10%. In autumn both the ICARUS and UKCIP02 scenarios suggest decreases while the C4I scenarios suggest increases. These differences largely reflect uncertainties in the different models and approaches employed and the greater uncertainty associated with modelling precipitation, as compared to temperature, and stress the importance of employing multiple model simulations in order to develop robust adaptation strategies for the future.

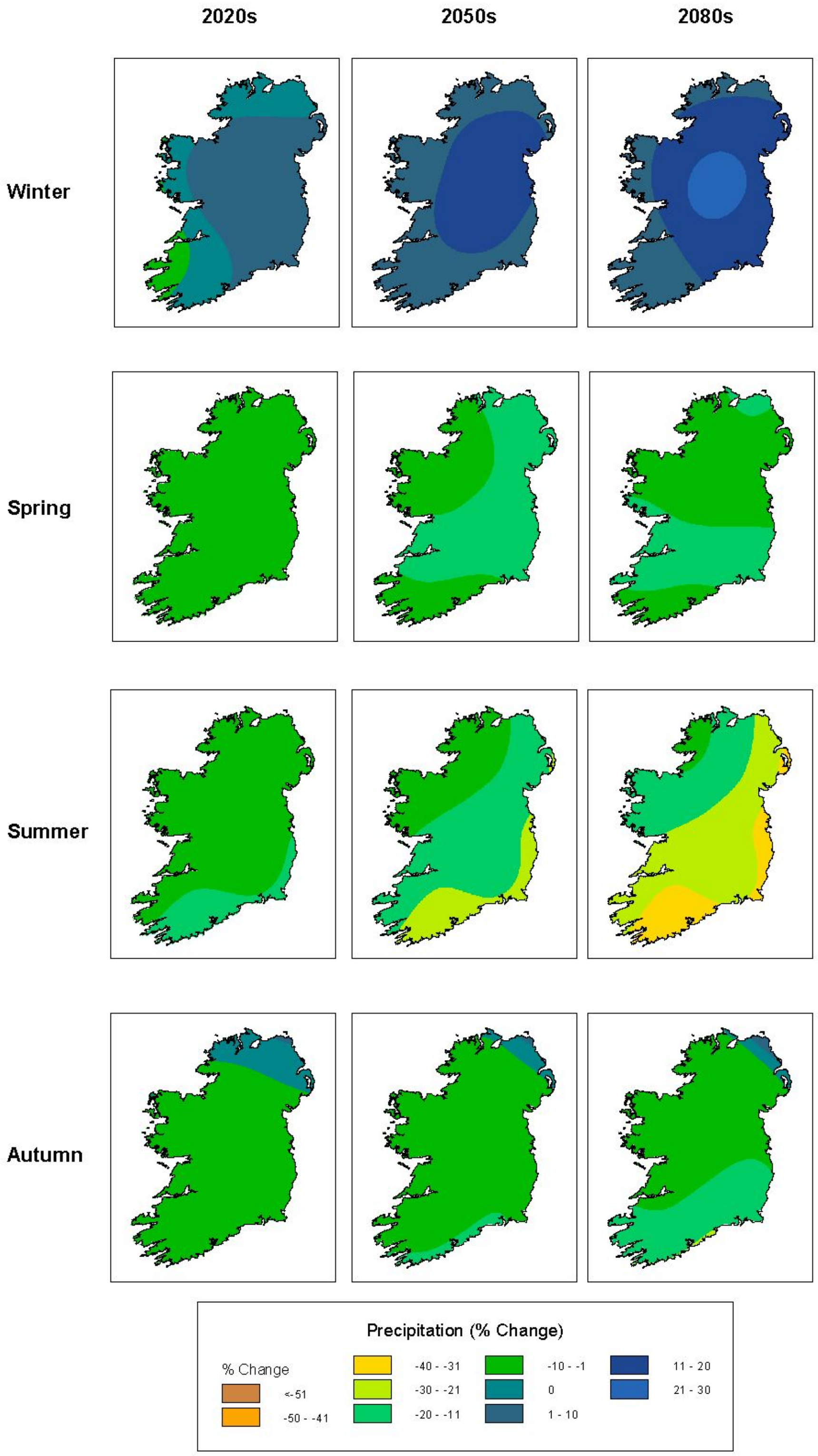
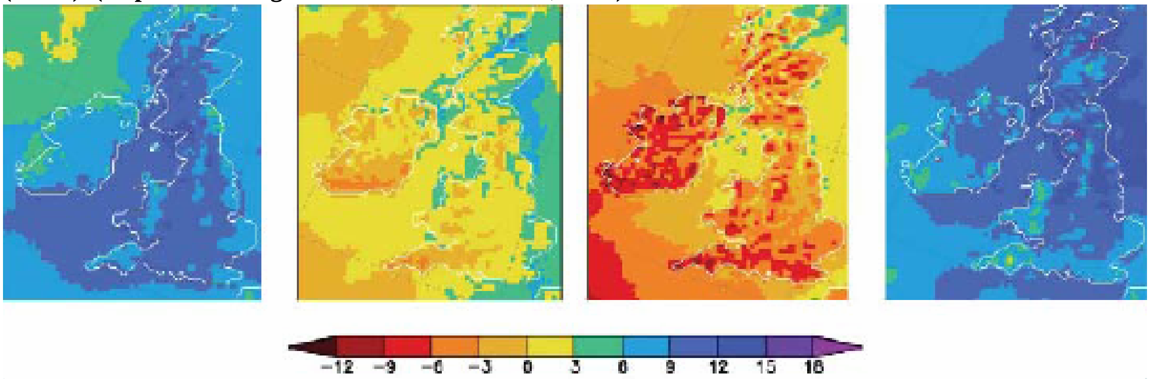


Figure 4 Percent changes in precipitation by Fealy and Sweeney (2008). Results based on a mean ensemble of output from three GCMs forced with two emissions scenarios.

Figure 5Seasonal changes in precipitation: mean of 8 ensemble simulations showing the percentage change between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). Autumn and winter are wetter (5-10%), summer drier (5-10%); spring is also slightly drier (2-5%). (Caption and Figure after McGrath et al., 2008).



6. EXTREMES OF PRECIPITATION

Due to the difficulties and uncertainties involved in modeling precipitation, confidence in estimates of changes in extreme events is very low. As global temperatures increase, the hydrological cycle will likely become more intense and will result in more extreme precipitation events. Changes in intensity or duration are likely to result in an increase in flood frequency and magnitude, while water shortages or drought conditions are likely due to reductions in precipitation. Analysis of extreme precipitation events by Fealy and Sweeney (2008) suggests a significant and increasing trend in the highest 5-day rainfall totals at eight synoptic weather stations analysed. These stations are located in the midlands and along the east coast. An increase in the longest number of consecutive dry days was found to be significant at all stations, with the greatest increases for stations in the east and midlands. These changes suggest that Irish precipitation, typically characterised as low intensity long duration, is likely to become more intense resulting in increased surface runoff.

McGrath et al. (2008) in modeling the sensitivity of the climate system to Atlantic sea surface temperatures suggest that there will be an increase in the frequency of very intense cyclones with associated increases in extremes of precipitation, translating into an increased risk of storm damage and flooding. However, there remains considerable uncertainty in these projections and further research is required (McGrath et al., 2008).

In the UK, Hulme et al. (2002) suggest that extreme winter precipitation will become more frequent. By the 2080s, winter daily precipitation intensities that are experienced once every two years on average may become up to 20 per cent heavier. Very dry summers - like 1995 – may occur in half the years by the 2080s, while very wet winters like 1994/95 may occur on average almost once a decade for the Medium-High Emissions scenario.

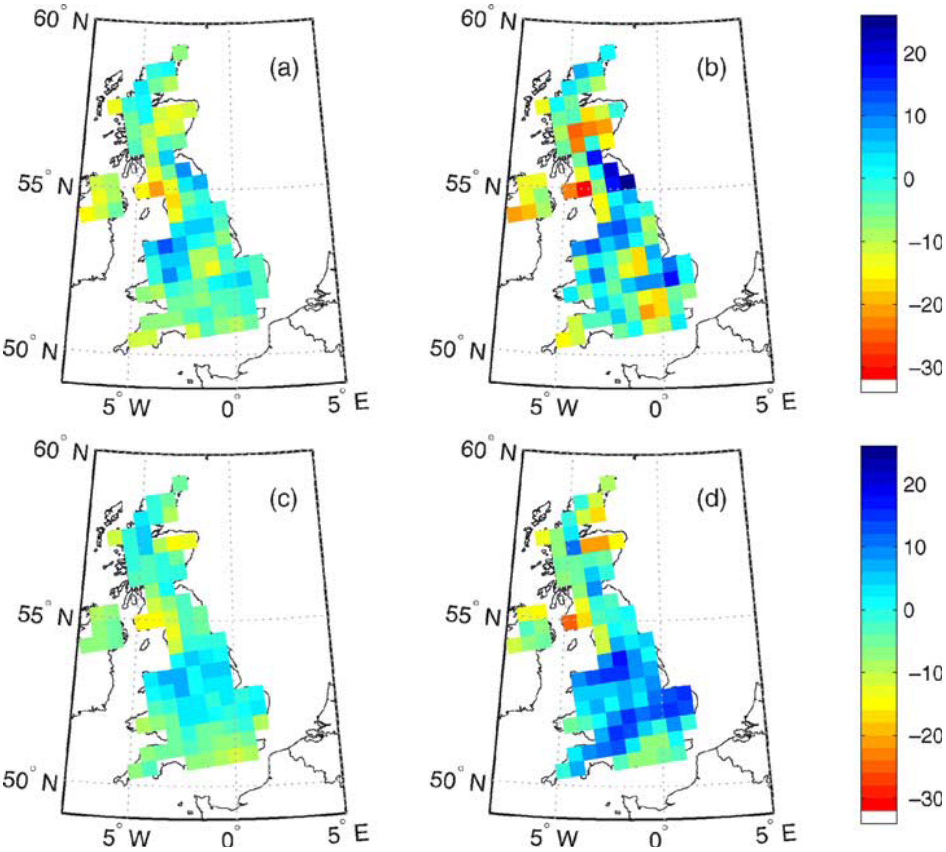


Figure 6 Percentage change in 1-day rainfall event magnitudes between control and future simulations for (a) HadRM3H, 10-year return period, (b) HadRM3H, 50-year return period, and for 10-day rainfall event magnitudes, (c) HadRM3H, 10-year return period and (d) HadRM3H, 50- year return period. (Ekstrom et al. 2005).

More recently Ekstrom et al (2005) used a regional climate model (HadRM3H) to estimate the impact of climate change on design storm depths to examine climate change impacts on various structures. Their work showed that the HadRM3H model may be used with some confidence to estimate extreme rainfall distributions, showing good predictive skill in estimating statistical properties of extreme rainfall during the baseline period, 1961–1990. The authors used HadRM3H (following the IPCC SRES scenario A2 for 2070–2100) to assess possible changes in extreme rainfall across the UK. Results indicate that for short duration events (1–2 days), event magnitude at a given return period will increase by 10% across the UK. For longer duration events (5–10 days), event magnitudes at given return periods show large increases in Scotland (up to ~30%), with greater relative change at higher return periods (25–50 years). The results presented for Northern Ireland show decreases in the order of 10% for 1-day rainfall totals with a 10-year return period and greater reductions ranging up to 20% for the 50-year return period. Reductions in the order of 5-10% are also evident for corresponding recurrence intervals of 10-day rainfall magnitudes. Data for the Republic was not available.

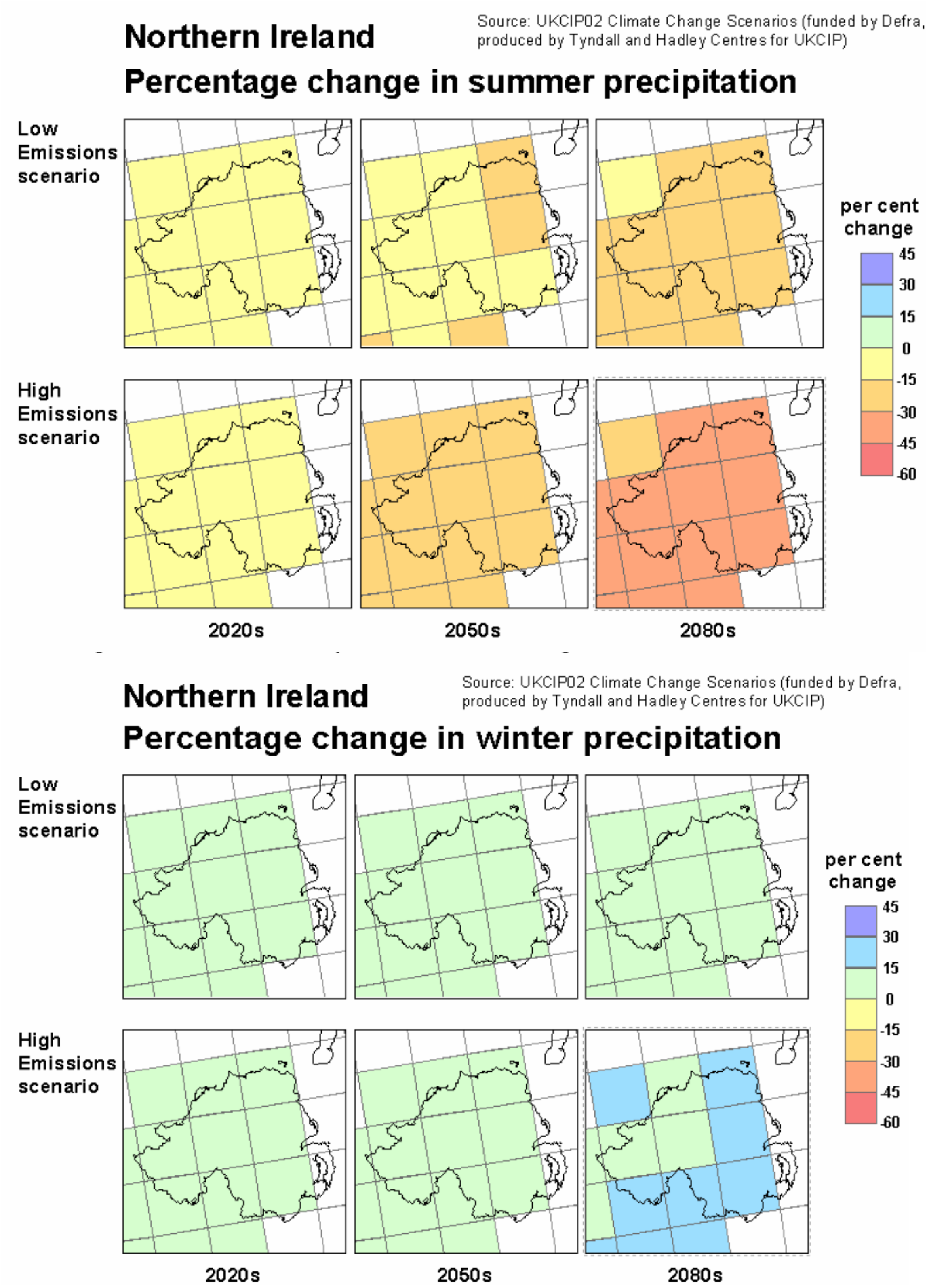


Figure 7 Percent changes in summer and winter precipitation for Northern Ireland. Results based on the UKCIP02 Low and High emissions scenarios. (Arkell et al., 2007)

7. WIND SPEED

An understanding of changes in windspeeds is important from an energy perspective as well as in terms of assessing the future integrity of physical structures. In a preliminary study, McGrath et al. (2008) have studied the impacts of climate change on wind speeds from a wind energy perspective. Using a regional climate modelling approach a small ensemble of wind predictions were produced at 60m level for Ireland. The idea of the modelling experiment was to quantify changes in future wind speeds and to evaluate the ability of dynamical downscaling to describe near surface winds at the local level. The results of these simulations for Ireland for the period 2021-2060 in comparison to current are shown in Figure 8. On a seasonal basis increases of between 8-11% (ECHAM5 A1B simulation) are shown for winter. In contrast summer decreases of as much as 14-16% are suggested for the ECHAM5 B2 simulation, with the modelling exercise indicating a decrease in the likelihood of useful windspeeds during summer months.

In terms of the above results, McGrath et al highlight that the results should be treated with caution in light of the uncertainty in emission scenarios, the reliability of AOGCM simulations and the coarse grid (~13km horizontal resolution) used for downscaling. In order to increase confidence in projections for future wind speeds the quantification of uncertainty will require an ensemble approach and higher resolution downscaling, with significant computational costs. Nonetheless basic uncertainty in the raw data for modelling windspeeds will remain problematic.

In modelling future daily mean windspeed Hume et al. (2002) find the largest changes in wind speed in the winter and summer seasons with spring and autumn speeds changing little from today. From the simulations produced for Ireland for the 2080s changes in windspeed are within natural variability for the low emissions scenario in winter for the majority of the island, in contrast the high emissions scenario suggest little change for Northern Ireland, while increases in the order of 7% are likely for parts of the midlands. During the summer in the 2080s average wind speed in Northern Ireland decreases quite substantially with greatest reductions of up to -11% for the east coast. In the South the UKCIP02 simulations show similar scale changes continuing along the east coast with greater reductions for the south east of greater than 11%. Reductions in the midlands and west as suggested by UKCIP02 range between -3% and -5% for the 2080s under the same high emissions scenario. In line with McGrath et al, Hulme et al also note the large uncertainties involved in modeling future wind speeds. The consistency between different models and the coarse physical representation within HadRM3 are not sufficient to be able to attach any level of confidence to wind speed and highlight that more caution should be taken when using these results than when using those for temperature and precipitation.

In getting a handle on extremes Hulme et al. suggest the use of empirical relationships to obtain statistics at a shorter time-scale than the daily- averages. They suggest that the maximum hourly-average wind speed is about 30 per cent higher than the daily-average wind speed, while the maximum gust, which may occur only for a few seconds, is typically about twice the daily-average wind speed. The authors highlight that there is no evidence to suggest that these empirical relationships will change greatly in the future.

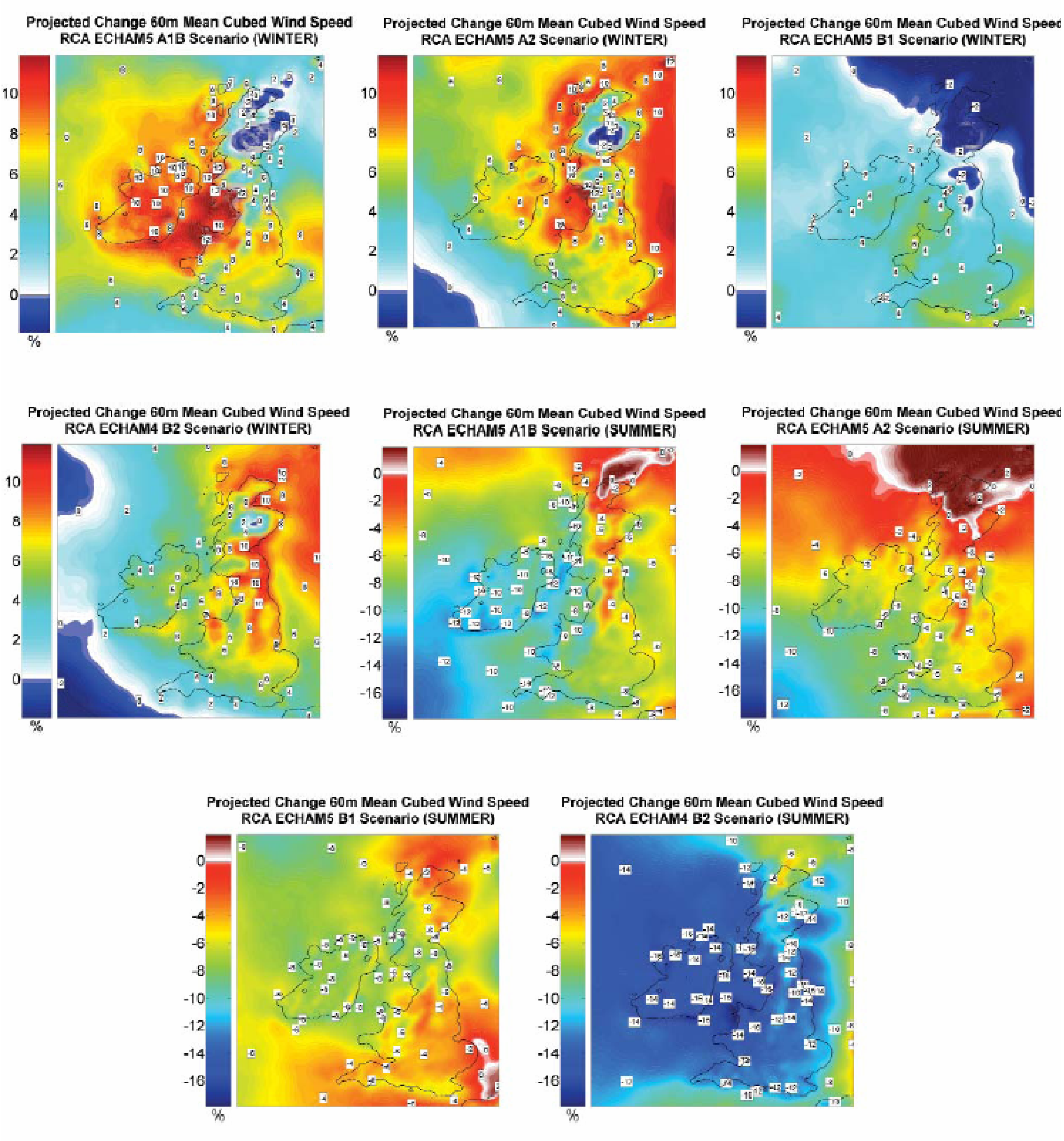


Figure 8 Projected change in wind power by season (2021-2060 relative to 1961-2000): % change in the mean annual cubed wind speed at 60 m level for 4 climate simulations. (McGrath et al., 2008)

8. River Flow

Using conceptual rainfall-runoff models to simulate river flow for a number of catchments in Ireland, Murphy and Charlton (2008) and Steele-Dunne et al. (2008) have identified a number of consistent signals for changes in hydrological regimes most prominently driven by changes in precipitation patterns, while uncertainty remains in others (Murphy and Charlton, in press, Steele-Dunne et al., 2008).

Based on the climate scenarios outlined, both Murphy and Charlton and Steele-Dunne et al. reveal that robust increases in winter and spring streamflow are apparent. All of the catchments assessed in both of these studies show substantial increases in winter and spring flows and decreases in summer and autumn. In winter, increases of up to 20% in the amount of water flowing in rivers are expected in the majority of catchments by mid-to-late century, with greatest increases occurring in January and February. Such increases would have major implications for flooding.

Reductions in summer months reach over 40% in surface water dominated catchments using ensemble averages, with uncertainty bounds reaching as much as -70% in the Boyne by the end of the century. Murphy and Charlton (2008) highlight that reductions during summer will not be as substantial in groundwater dominated catchments due to the sustaining nature of larger baseflows. While there is good agreement between both studies in terms of winter and summer simulations there are substantial disparities between both approaches in relation to autumn changes. Murphy and Charlton suggest that large reductions continue well into autumn months, while Steele-Dunne et al. suggest less severe reductions. This disparity is likely due to the difference in rainfall scenarios used (as highlighted above there are particular uncertainties regarding the direction of rainfall changes in autumn) as well as in the structures and processes represented by the rainfall-runoff models employed. Further work is required and ongoing in relation to the latter.

What is consistent between the two sets of results is that greatest uncertainty in modeling future flow regimes is associated with the lower flow seasons of summer and autumn. The most notable reductions in surface water are simulated for the Ryewater and Boyne. These catchments are the most heavily populated in the country and comprise a substantial proportion of the Greater Dublin Area (GDA). Significant reductions in the Boyne are suggested by the 2020s in early summer and autumn with reductions becoming more pronounced as the century progresses. By the end of the century reductions of up to 70% are simulated in August. Such reductions in surface water availability would have substantial implications for the entire water environment – from water supply to quality issues to loss of habitat.

In terms of water resources it is important to recognize that climate change is only one pressure, with other main drivers of demand including population growth and development. Therefore the impacts and vulnerabilities due to climate change are themselves closely linked to non-climatic factors. Furthermore, characteristics of the water resource system dictate vulnerability to climate change. In some circumstances, a large physical effect can have a very small impact, for example, where there is currently plenty of excess slack in the management system. In other cases a very small effect can have a significant impact, where the management system is already under extreme pressure (Arnell, 1998; Arnell and Delaney, 2006).

As mentioned above, higher winter flow is associated with implications for river flooding, with a reduction in return periods for floods of a particular magnitude. Almost all the catchments studied confirm a decrease in return periods. In the case of the River Barrow for example the once-in-a-fifty year flood has fallen to an 18-year event by mid century, and for the Blackwater to just over an 11-year event by mid century. These changes are consistent with Steele-Dunne et al., who for the Blackwater by mid-century suggest that the current 40 year return period is likely to be associated with a 9 year recurrence interval. These changes raise concerns regarding the integrity of flood defenses, the capacity of urban storm drainage systems, the need for greater caution concerning planning and development of vulnerable areas as well as insurance implications for commercial and private properties. In a situation where more frequent winter flooding is likely, concerns regarding the maintenance of water quality also arise. It must be pointed out that confidence in relation to extreme flood events is lessened due to the assumptions regarding stationarity in a changing climate and the noise introduced by calculating return periods for low frequency events on relatively short datasets.

In assessing specific flow percentiles Murphy and Charlton (2008) found that substantial increases are likely for Q5 (the flow exceeded 5% of the time) with some catchments showing increases of between 20-30% relative to the baseline by mid to late century. Q95 (the flow exceeded 95% of the time) shows significant reductions for some catchments with reductions of between 20-50% by mid to late century. It should be noted that there is a large difference in magnitude of changes between catchments. Changes in the variability of flow regimes are also likely as a result of climate change. By the 2050s increases in variability are simulated for the majority of catchments. By the end of the century further increases in the variability of daily streamflow are likely. The catchments showing the least change in variability are the groundwater-dominated catchments

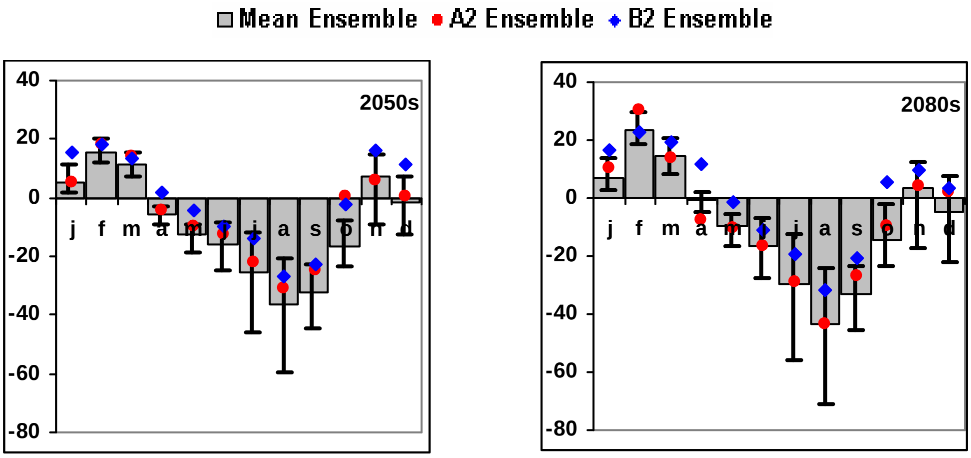


Figure 9 Percent change in monthly streamflow for the Boyne by the 2050s and 2080s. The grey columns represent changes of the Fealy and Sweeney (2008) mean ensemble used to force the rainfall runoff model. Error bars represent uncertainty in rainfall runoff model projections. Simulations have been conducted for 8 other catchments throughout Ireland. (Murphy and Charlton, 2008)

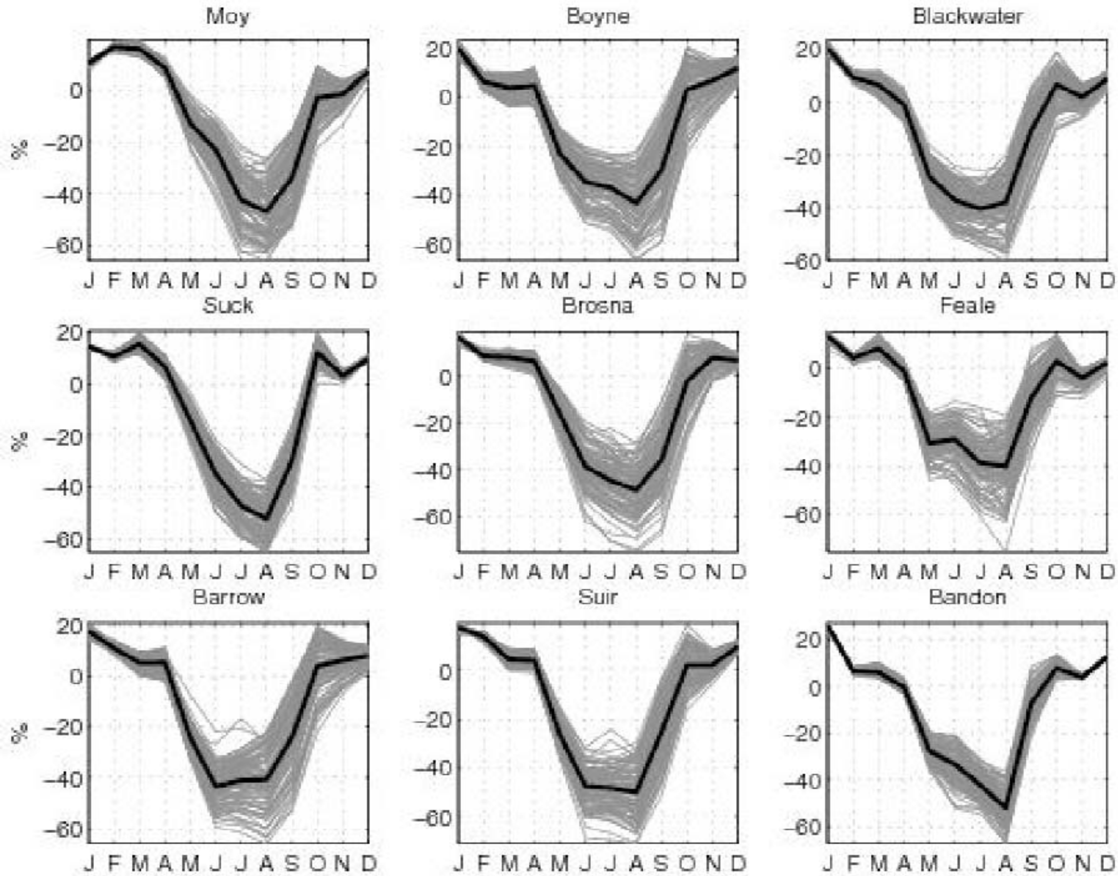


Figure 10 Change in monthly mean daily flow due to climate change under the SRES A1B scenario. Grey bars show uncertainty in rainfall-runoff model, with the mean shown as a black dashed line. (Steele-Dunne et al, 2008)

9. SEA LEVEL RISE

Relative sea level, or the height of the sea relative to the land, ultimately determines the location of the shoreline and any fluctuations in relative sea level will affect the coastal morphology. Globally, sea level has been rising over the 20th century at a rate of 1-2 mm yr^{-1}, resulting in a total rise of 0.17 m. Over the period 1961-2003, sea level rose at an average rate of 1.8 mm yr^{-1}. However, an increase in this rate, to 3.1 mm yr^{-1}, was observed over the 1993-2003 period. Evidence from observations indicate that warming of the oceans has occurred to depths of at least 3000 m. This warming has resulted in the thermal expansion of the oceans. Over the 1993-2003 period, the contribution from thermal expansion to sea level rise is estimated to have been 0.42 mm yr^{-1}. Figures 11 and 12 illustrate the increase in sea surface temperatures for the Northern hemisphere and Port Erin, Irish Sea.

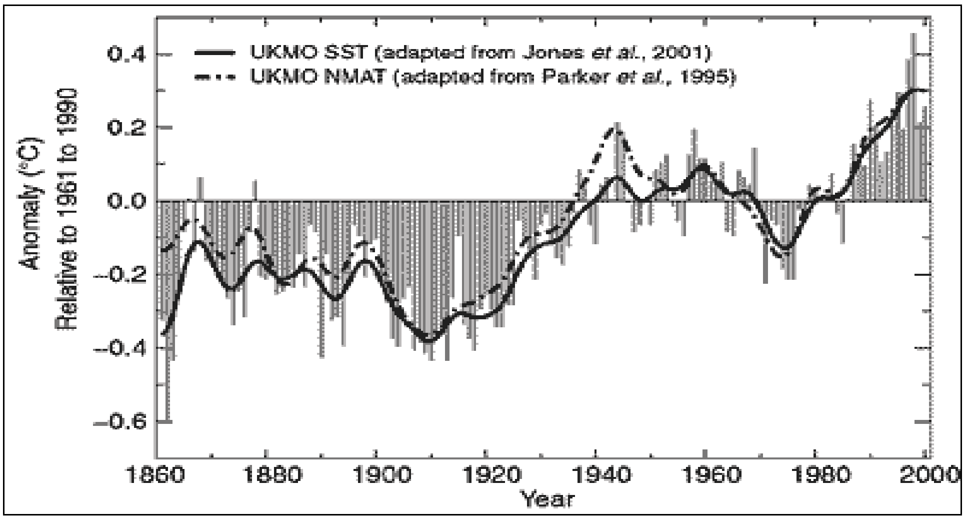


Figure 11 Sea surface temperature anomaly for the Northern Hemisphere (IPCC, 2001).

Continuing thermal expansion, melting of terrestrial glaciers and snow cover and contributions from the large ice sheets of Greenland and Antarctica are likely to result in a sea level rise of between 0.28 to 0.43 m by the end of the present century, relative to 1980-1999 (IPCC, 2007). However, these ranges may significantly underestimate the future increase in globally averaged sea level, as they do not include important uncertainties in the carbon-cycle feedback. Hansen (2007) argues that sea level rise is likely to be much greater, in the order of metres over the century timescale, due to the non-linear response of ice sheets to climate forcing. In order to prevent such a scenario occurring, global temperatures would need to be stabilised at less than 1^{o}C above the year 2000 levels (Hansen, 2007).

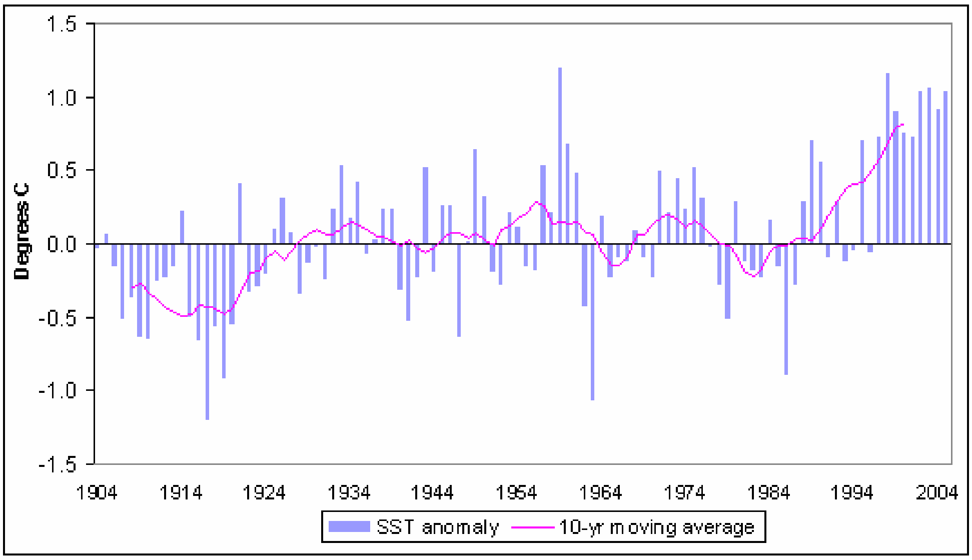


Figure12 Annual average anomalies (1904-2005) of Irish Sea sea surface temperatures from Port Erin, Isle of Man, relative to the 1961-1990 period (Data reproduced with kind permission of the Port Erin Marine Laboratory, Isle of Man).

Sea temperature and sea level in Irish waters have been rising slowly in recent decades with satellite and in situ coastal observations shwing a general warming trend of 0.3-0.4^{o}C per decade since the 1980s (McGrath et al. 2008). McGrath et al also highlight a more rapid rate of warming of 0.6-0.7^{o}C has been suggested for the Irish Sea. These trends are consistent with what has been observed globally. Rising sea levels in recent decades are linked to warming of the oceans and the resulting thermal expansion of seawater and the influx of freshwater from melting land ice. McGrath et al (2008) highlight that from satellite observations sea levels are rising on average 3.5cm per decade around Ireland, well in excess of ongoing isostatic adjustment.

Rates of highest rebound are associated with locations where the greatest mass of ice was located, approximately north of a line from north Wexford to south Donegal (Edwards and O'Sullivan, 2007), while south of this line rebound rates are slight or negative. As a consequence of isostatic rebound, mean sea level at Malin Head appears to be decreasing, while at Dublin it appears relatively stable.

Regional projections of sea level rise for the present century are subject to a high degree of uncertainty as warming of the surface layers of the oceans is not likely to be uniformly distributed across the ocean surface. Regional changes in atmospheric pressure and ocean circulation will also affect the distribution of sea level rise (Hulme *et al*., 2002). Due to the uncertainties in regional projections of sea level rise, global projections are employed to assess the likely impacts of sea level rise on the Irish coast. However, caution must be exercised in interpreting the results as these estimates may under or over estimate regional sea level rise by up to ±50% (Hulme *et al*., 2002).

Global projections, from a range of global climate models, suggest that globally averaged sea level will rise by between 0.28 and 0.43 m (IPCC, 2007), indicating an annual rate of increase of between 2.8 to 4.3 mm yr^{-1}, assuming a linear increase, over the course of the present century (1980-1999 to 2080-2099). If a wider range of emissions scenarios is included, a range of between 0.18 to 0.59 m is considered more likely. A higher rate of sea level rise cannot be excluded, but due to a limited understanding of key processes, such as the potential for increased flow rates of ice from Greenland and Antarctica, our ability to quantify an upper value is limited (IPCC, 2007).

Combining these sea level projections with isostatic rebound rates for Ireland (After Edwards and O'Sullivan, 2006), projected rates of relative sea level vary substantially around the Irish coast. Locations in the extreme southwest, from the Dingle Peninsula to Cape Clear are likely to experience the largest increases in relative sea level, at a rate of between 3.3 to 4.8 mm yr^{-1}, while on the north east coast, from Malin Head to north of Dundalk, a rate of between 2.2 to 3.7 mm yr^{-1} is likely.

Based on previous estimates of sea level rise (IPCC, 2001), Fealy (2003) calculated the potential area of land likely to be inundated due to a sea level rise of 0.48 m, and found that over 380 km^2 of the land area of Ireland had a greater than 10% risk of inundation due to sea level rise over the present century (Figure 13). While this figure represents a lowering of previous estimates of land area vulnerable to inundation, vulnerable locations represent areas with significant land values, such as Dublin, Cork and Wexford and the Shannon Estuary.

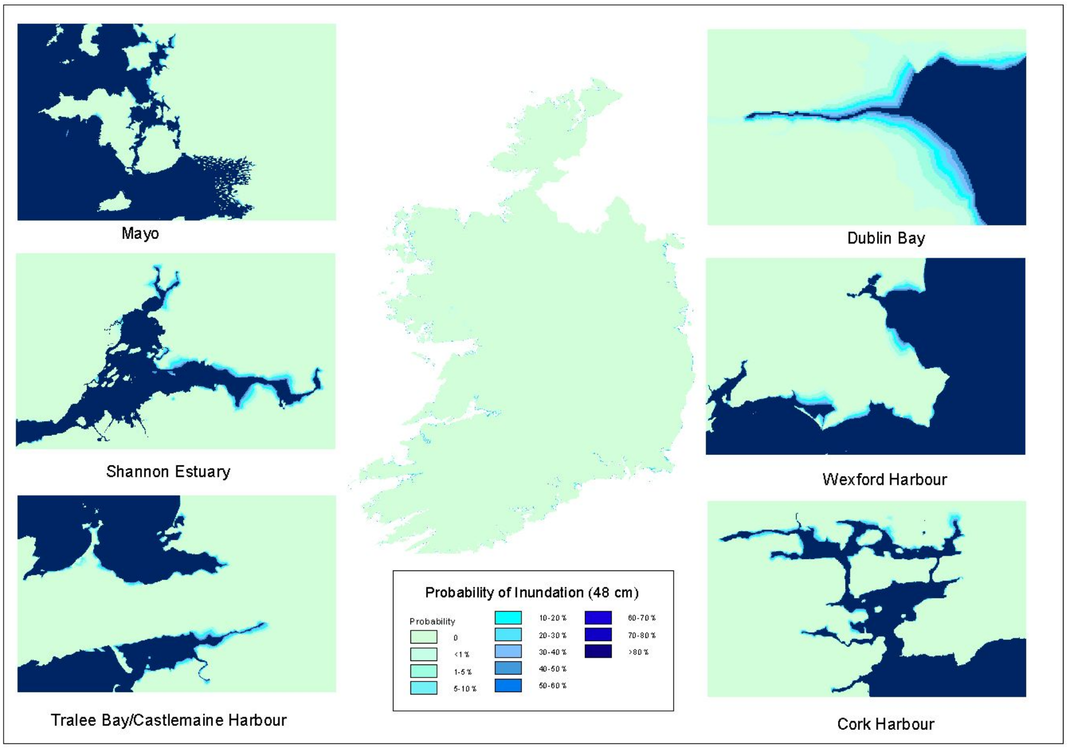


Figure 13 Probability of inundation associated with a sea level rise of 0.48 m (Source: Fealy, 2003)

The projected increase in relative sea level is also likely to result in an increase in wave energy being transmitted to the shoreline (Hulme *et al.*, 2002). In addition to an increased vulnerability of inundation due to a rise in relative sea level, coastal locations are also likely to be impacted due to changes in erosion and deposition rates.

In terms of wave heights, preliminary results from McGrath et al. (2008) show that there is some evidence of significant increases in Atlantic wave heights for the period 2031-2060, with extreme wave heights showing an increase of up to 10%, except in parts of the south and west. However, the authors highlight that these results are based on the data from only one GCM and one future greenhouse gas emission scenario and should therefore be treated with caution. Also, the resolution of the data (0.25°) is too coarse for a detailed analysis around the Irish coastline. In spite of these limitations, the basic data do provide a qualitative description of the possible impacts of climate change on wave heights around Irish coastal waters. Current work to refine these findings is ongoing between the Coastal and Marine Resources Centre (CMRC) in UCC and Met Eireann.

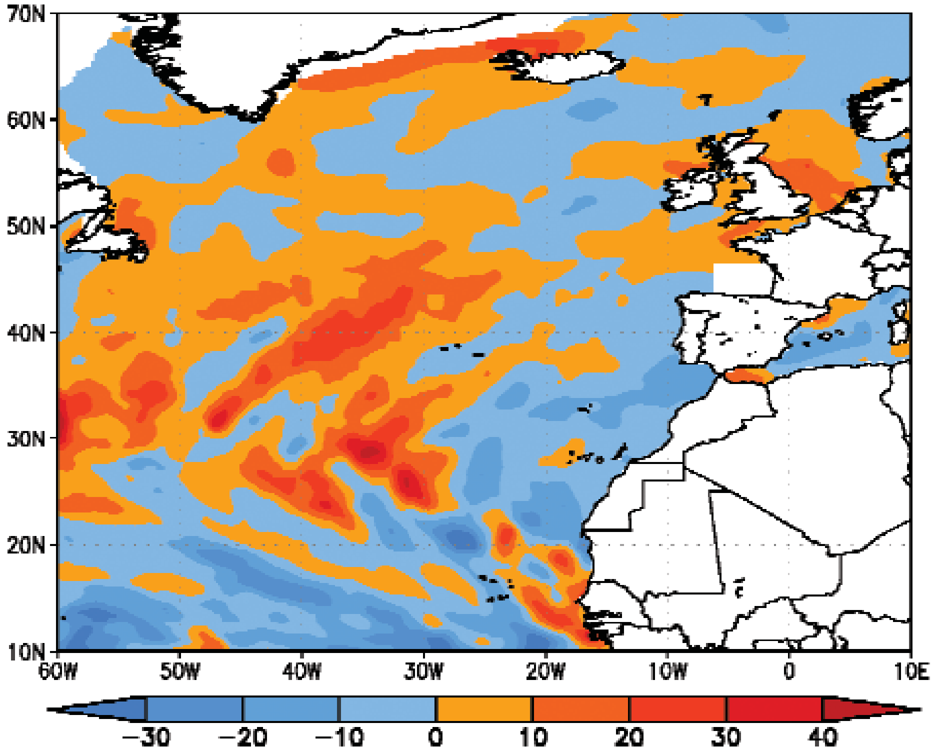


Figure 14 Relative changes (%) in the 10-year return value of annual maximum significant wave height between the future (2031-2060) and past (1961-1990) control run.

10. Storm Surges

An increase in relative sea level over the present century will mean that low-lying coastal areas will be increasingly susceptible to permanent inundation with subsequent changes in erosion and deposition. While temporary changes in extreme water levels, resulting from storm surge events particularly if coupled with high astronomical tides, are likely to present a much greater potential for damage through overtopping of coastal defences with resultant flooding. Additionally, storm surge events can have a significant and lasting impact on the coastal morphology as a temporary increase in water levels and wave energy will impact on the processes of erosion, transportation and deposition, through the reworking of material which may be in equilibrium with the existing coastal energy regime.

Due to projected increases in tropical sea surface temperatures, climate models indicate that it is very likely that tropical cyclones (typhoons and hurricanes) will become more intense, with higher wind speeds and more intense precipitation, while extra tropical storm tracks are projected to move polewards (IPCC, 2007). While Ireland is not directly affected by hurricane activity, due to insufficient temperatures of the sea surface off the coast required for hurricane formation, the remnants of Atlantic hurricanes can become rejuvenated as they cross the Atlantic from west to east and pass over the warmer sea surface temperatures associated with the Gulf Stream. Due to the model projected changes in storm intensity and associated increases in wind speeds, a significant enhancement of wave heights is likely as these low pressure systems pass over the Atlantic. For countries along the eastern Atlantic seaboard, such as Ireland, an increase in surge elevation is likely to lead to increased vulnerability from flooding and storm damage. An increase in relative sea level is likely to further exacerbate increased surge levels associated with more intense extra tropical storm activity.

In an analysis of extreme water levels and sea level rise, Fealy (2003) assessed the probability of inundation associated with an increase in sea level of 0.48 m and an extreme water level of 2.6 m, which represents a 1-in-100 year event on the east coast and 1-in12 year event on the west coast (Figure 15) (Carter, 1991). The return period associated with an extreme water level of 2.6 m is likely to decrease as a consequence of sea level rise, for example, the current 1-in-100 year event is likely to become a 1-in-10 year (or less) event. An extreme water level of 2.6 m combined with an increase in sea level of 0.48 m, is likely to place approximately 680 km^2 of land at risk of inundation (>10% probability) (Fealy, 2003).

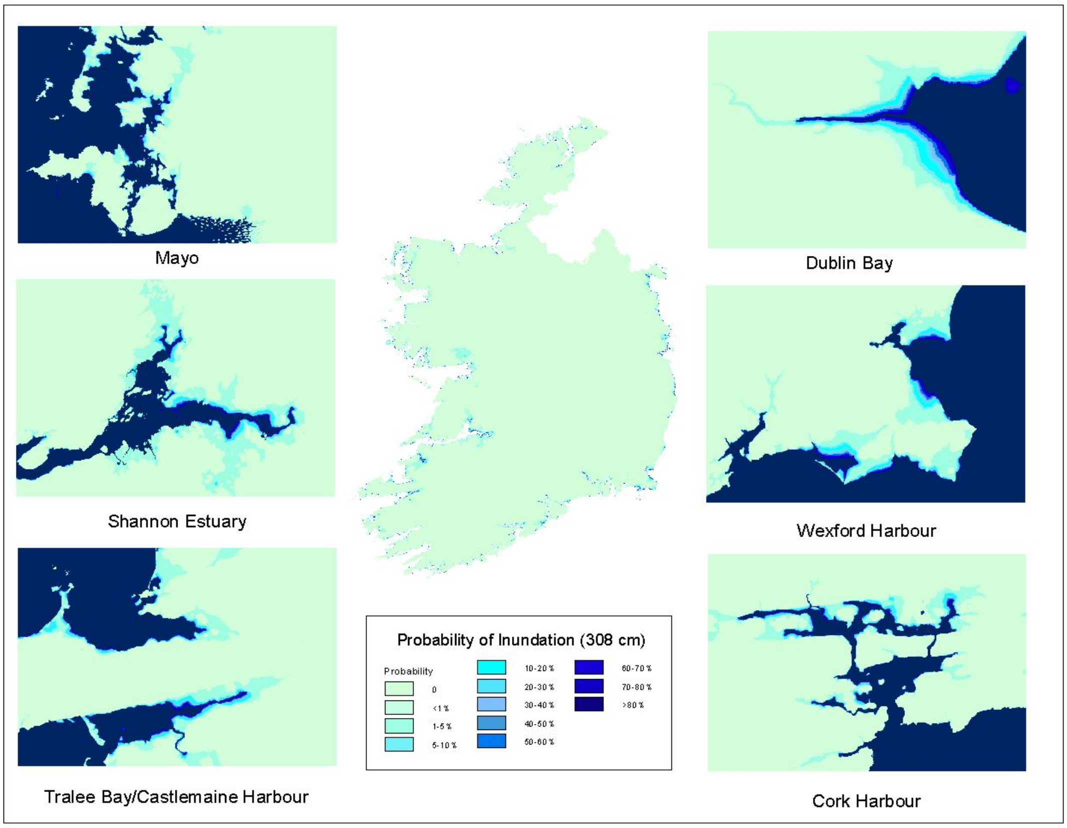


Figure 15 Probability of inundation with an extreme water level of 2.6 m and sea level rise of 0.48m (Source: Fealy, 2003)

11. Key Questions for Discussion

The likely changes in future climate and its impacts identified above raise serious questions of how we should adapt to meet these challenges in the areas of water services, flood alleviation and energy. While they are serious the impacts identified are not exhaustive. Few sectors are charged with as much responsibility as engineering for ensuring effective adaptation to climate change and in this light some points are highlighted that may spark further discussion during the workshop.

- Do we need an industry standard set of climate scenarios that incorporates as many sources of uncertainty as possible?
- What are the key data constraints in moving state of the art forward?
- How can climate researchers provide information to meet the needs of the engineering profession?
- Do we need to move towards a probabilistic approach akin to UKCIP09?
- Are we close to the point where we can attribute likelihoods to key impacts?
- What are the key gaps in knowledge that remain?
- What are the critical pieces of infrastructure that must be protected at all costs and are we in a position to produce risk assessments for these?
- Can we produce simulations for key design standards used in the engineering profession?

SRES Emissions Scenarios

The **A1** emissions scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

The **A2** emissions scenario describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The **B1** emissions scenario describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The **B2** emissions scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with a continuously increasing global population at a rate lower than in A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

In 1992, the Intergovernmental Panel on Climate Change (IPCC) published the first emissions scenarios, which were the precursor to the present SRES (Special Report on Emissions Scenarios) emissions scenarios employed in both the Third (IPCC, 2001) and Fourth Assessment Reports (IPCC, 2007). These scenarios assume varying levels of future demographic, technological, environmental, societal and economic developments that result in different future emissions scenarios for the main greenhouse gases and aerosols. While over 40 emissions scenarios were developed, four central 'families' or sets of equally probable scenarios, namely A1, A2, B1 and B2 which span approximately 80% of the range of future emissions contained in the SRES. Modelling the future climate for a given emissions scenario will always result in a range of future scenarios being simulated due to uncertainties inherent in the climate and modelling system (Hulme and Carter, 1999).

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