Climate Change Impacts for Ireland
Part 2: Changes in Key Climatic Variables

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Abstract: Over the past five years or so research into the impacts of climate change in Ireland has been developing rapidly and we now have more information than ever before on the likely magnitudes and the spatial distribution of change in Ireland. Part One of this paper provided an overview of the steps and challenges involved in developing future climate scenarios. This paper draws together the main findings for changes in key climatic variables and impacts from recent reports on climate change in Ireland over the coming century. It also asks where the focus of climate change research needs to be pointed next in order to ensure successful adaptation to what are likely to be substantial changes.

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1. INTRODUCTION

Part One of this paper highlighted the likely global impacts of climate change. The magnitude of these changes has seen the need to adapt to the impacts of climate change in Ireland become increasingly recognised in recent years. For many 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. In order to ensure robustness to climate change, a greater handle on future changes and impacts are required at a local scale. In meeting this demand 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 simple climate scenarios for impact modellers to use. The second main assessment; Climate Change, Impacts and Scenarios for Ireland (Sweeney *et al.*, 2003) was published in 2003 using downscaled (see paper one) global climate data as input to impact 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 the island, it is limited in that key uncertainties are omitted, with results being based on output from only one Global Climate Model (GCM).

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 research centres nationwide, most notably at the Irish Climate Analysis and Research Units (ICARUS) in the Department of Geography, NUI Maynooth and through the C4I project at Met Eireann. 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 (see paper one) that exists in assessing climate change impacts, thereby providing policy and decision makers 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, 2007) and 'Climate Change: Regional Climate Model Predictions for Ireland' (McGrath *et al.*, 2005). 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).

As a result of this surge in recent information on climate change impacts, this is an opportune time to review the results derived to date and to ask where research needs to be focused next. As such this paper provides an overview of the likely changes for key climatic variables and impacts for Ireland over the coming century. Section 2 outlines the sources of uncertainty that have been accounted for in recent work, while sections 3-7 detail likely changes in temperature, precipitation, catchment hydrology, sea level rise and storm surges. The paper concludes with a discussion of the key gaps in knowledge that remain and where current research is going.

2. ACCOUNTING FOR UNCERTAINTY

The future impacts of climate change presented in this paper are based on two recent national reports produced by ICARUS and C4I. So as to ensure transparency regarding the uncertainties captured in the most up to date research for Ireland, 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 periods of simulation in the future and control periods from which future changes are derived. Therefore, together they provide a comprehensive 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. The results presented here are thus based on output from seven different Global Climate Models that have been forced with a total of four emissions scenarios and have been downscaled using both statistical and dynamical techniques. Unfortunately, the different time periods defined for future simulations (from 2021 - 2060 in the case of C4I and the 2020s, 2050s and 2080s for ICARUS) and the different control periods from which future changes are calculated make it difficult to directly compare and contrast the output from each report. In spite of these difficulties, the results gleamed from each scenario goes a long way to increasing confidence in the changes that will take place in our climate, as well as highlighting areas that remain uncertain and require further research.

Scenarios	GCMs	Emissions Scenarios (See box 1, Part 1)	Downscaling Approach	Control and future time periods
C4I (McGrath *et al.*, 2008)	ECHAM4 ECHAM5 HadCM3L HadCM3H	A2 SRES A1B SRES B1 SRES B2 SRES	Regional Climate Modelling & Statistical Downscaling	1961-2000 2021-2060
ICARUS Fealy and Sweeney (2008)	HadCM3 CCCma CSIRO (Mark2)	A2 B2	Statistical Downscaling	1961-1990 thirty year time period centred around the 2020s, 2050s, 2080s

Table 1: Approaches to generating future scenarios used for impact assessment in key reports produced for Ireland.

Box 1: Summary of key impacts of climate change for Ireland

- Temperatures are likely to increase everywhere relative to the present with greatest increases suggested for the summer and autumn of up to 3.4°C by the end of the century.
- With increasing temperature, 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; however, a strong signal of increased seasonality is evident with wetter winters and drier summers likely. No clear direction of change is evident for spring and autumn.
- Considerable uncertainty remains in relation to future precipitation extremes.
- Increases of 8-11% in 60m average wind speeds are likely in winter by mid-century, with decreases of between 14-16% in summer; however, assessment of this variable to date has been subject to high levels of uncertainty.
- River flows show robust increases in winter and spring in the order of 20% in winter by mid to late century. Reductions in summer and autumn months of over 40% are likely in many catchments.
- Flood events are likely to become more frequent with the extreme flood currently expected once in every 50 years likely to occur once every ~10 years by mid to late century.
- 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.

3. FUTURE CHANGES IN TEMPERATURE

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 consistency between the different projections made for Ireland, uncertainties exist depending on the GCMs, emission scenarios and downscaling approaches.

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). These changes show 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°C is expected with greatest increases again evident for the east and south east.

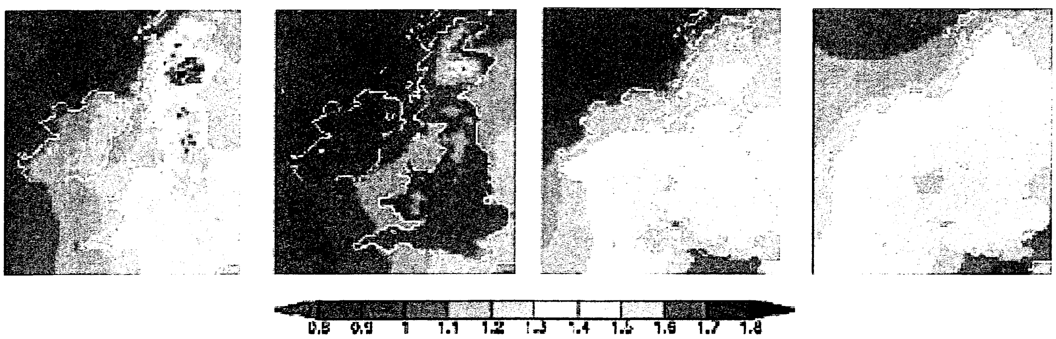

Figure 1: Seasonal warming: mean of 8 ensemble simulations showing the temperature change (°C) between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). The warming is greatest in the summer/autumn (1.2-1.4°C) (Caption and Figure after McGrath *et al.*, 2008).

Based on the multi-model ensemble simulations derived by ICARUS (Fealy and Sweeney, 2008), results for seasonal changes in temperature and precipitation are presented for three 30-year time slices centred on the 2020s, 2050s and 2080s. These model projections suggest that warming is likely to take place at a rate of between 0.2-0.3°C/decade. As a consequence, an increase of between 0.7-1.0°C is likely to occur in all seasons by the 2020s. This increase is projected to be more or less uniform across Ireland (Figure 2).

By the 2050s, seasonal temperatures are projected to increase by between 1.4 to 1.8°C, with 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°C to 2.7°C. Seasonally, summer and autumn show likely temperature increases of between 2.5-3.0°C, very much in line with C4I projections, although direct comparison is not fully justified.

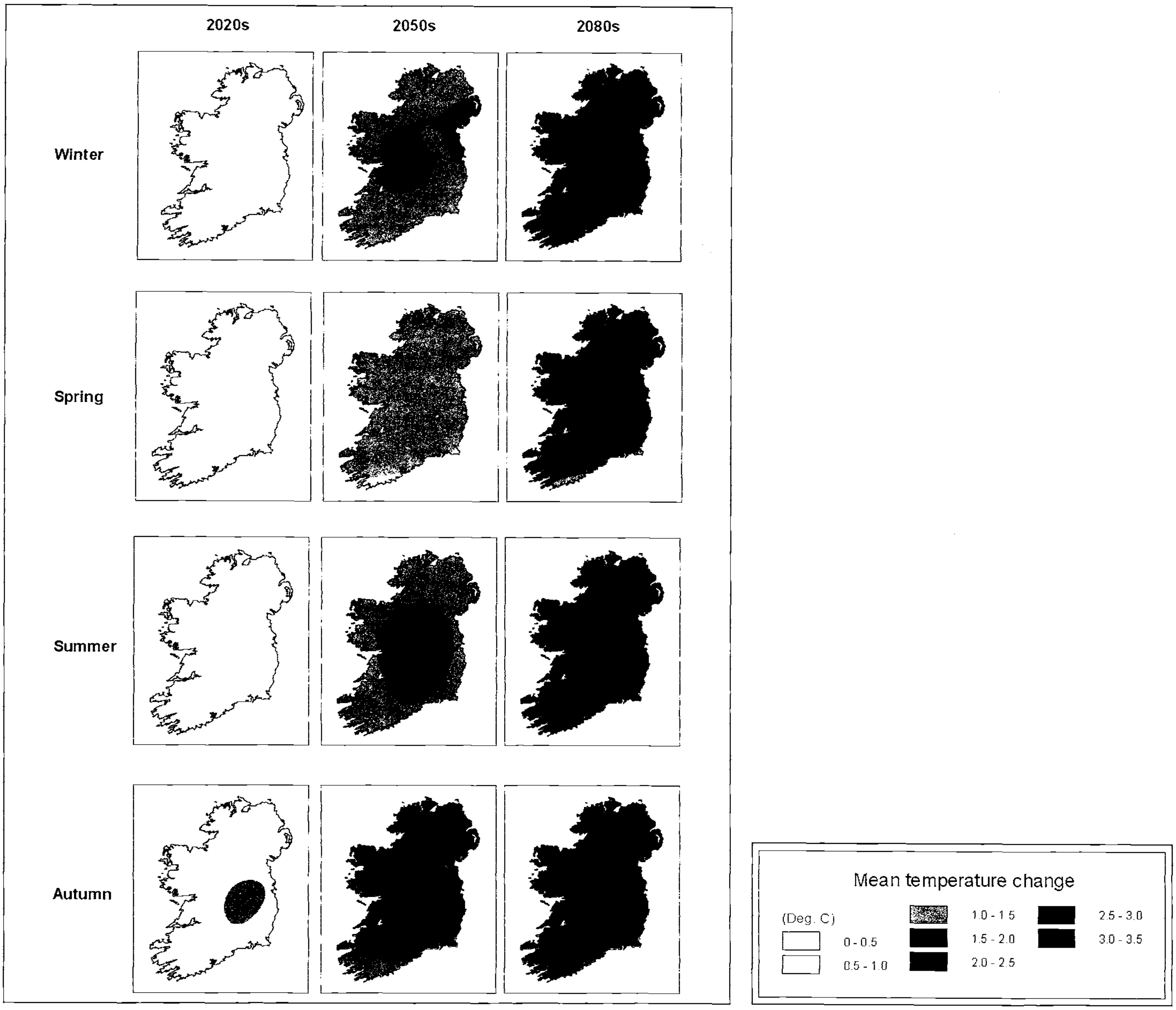

Figure 2: Changes in temperature by Fealy and Sweeney (2008). Results based on a mean ensemble of output from three GCMs forced with two emissions scenarios (SRES A2 and B2).

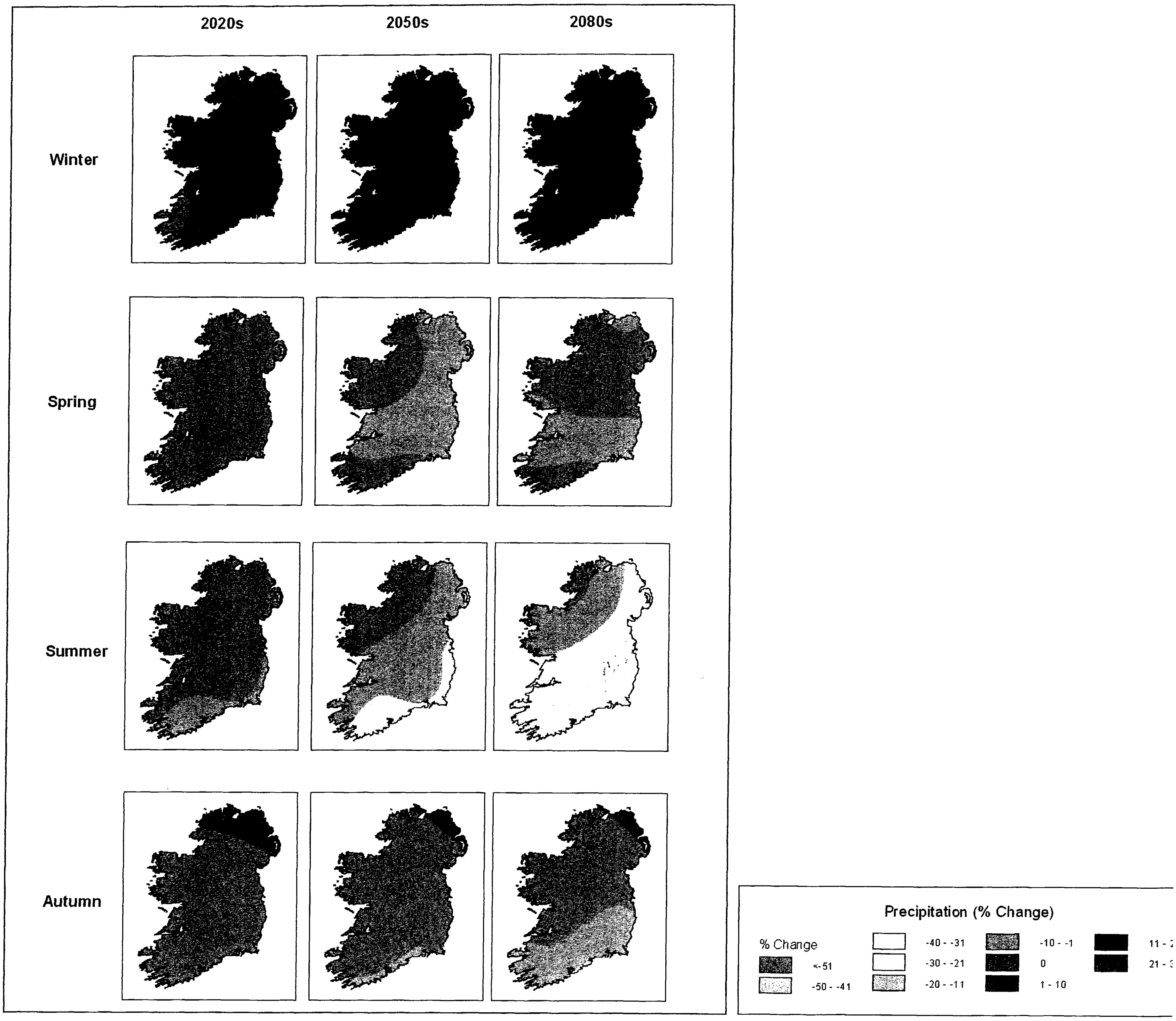

Figure 3 Percent changes in precipitation by Fealy and Sweeney (2008). Results based on a mean ensemble of output from three GCMs forced with two emissions scenarios (SRES A2 and B2)

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.

3.1 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. During the summer months of 2006, above average mean temperatures, which were over 1°C higher than the 'normal' 1961-1990 period (nearly 2°C higher than 'normal' in the midland stations of Clones and Kilkenny), combined with below average precipitation, resulted in significant soil moisture deficits throughout much of the southern part of Ireland with resultant impacts on agriculture (Met Éireann, 2006).

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).

Fealy and Sweeney (2008), in an analysis of likely future changes in extremes highlight that an increase in the intensity of extreme temperatures is indicated for all stations (synoptic weather stations), 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. These projected changes are consistent with the observational records, indicating that a good degree of confidence can be placed in these findings.

4. FUTURE CHANGES IN PRECIPITATION

Changes in precipitation over the course of the present century are likely to have a greater impact on Ireland than changes in temperature, due to the potential of increased flooding during the winter months and reductions in river 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 of the rainfall we receive are likely for all future time periods.

Dealing firstly with the *ICARUS* scenarios produced by Fealy and Sweeney (2008) ensemble changes by the 2020s suggest that winter precipitation is likely to increase by approximately 3%. A similar magnitude decrease in 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 3).

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. If realised, these changes in 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.

Differences in simulated precipitation are apparent between both the C4I (McGrath et al., 2008) and ICARUS (Fealy and Sweeney, 2008) simulations for the middle of the century. The C4I simulations project a greater decrease in summer precipitation along the west coast of Ireland, with reductions in the order of 6 to 9% (Figure 4), while the ICARUS projections suggest the greatest decrease in summer precipitation will be experienced along the east and south coast.

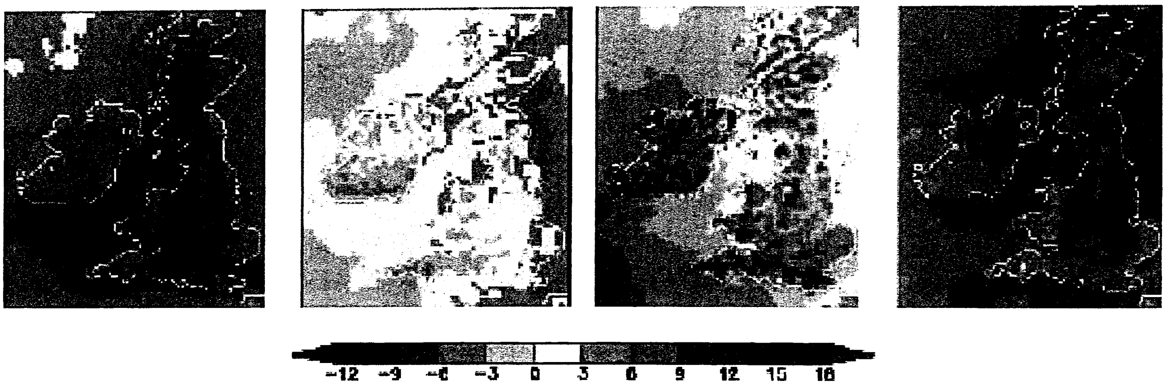

Figure 4: Seasonal changes in precipitation: mean of 8 ensemble simulations showing the percentage change between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). Autumn and winter are wetter (5-10%), summer drier (5-10%); spring is also slightly drier (2-5%). (Caption and Figure after McGrath *et al.*, 2008).

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 season of autumn with no clear and robust changes forthcoming. Both ICARUS and C4I scenarios suggest decreases in spring precipitation for mid-century however, in autumn the ICARUS scenarios suggest decreases while the C4I scenarios suggest increases. These differences largely reflect uncertainties in generating climate scenarios and the difficultly in modelling precipitation as compared to temperature. Such divergence between results of two key reports stresses the importance of employing multiple model simulations in order to develop robust adaptation strategies for the future.

5. CATCHMENT HYDROLOGY

Using impacts models (conceptual rainfall runoff models) to simulate river flow for river 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 with the broad pattern of change consistent with changes in precipitation once catchment storage and losses from evaporation are accounted for.

Based on the climate scenarios outlined above, both Murphy and Charlton and Steele-Dunne *et al.* reveal that robust increases in winter and spring river flow 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.

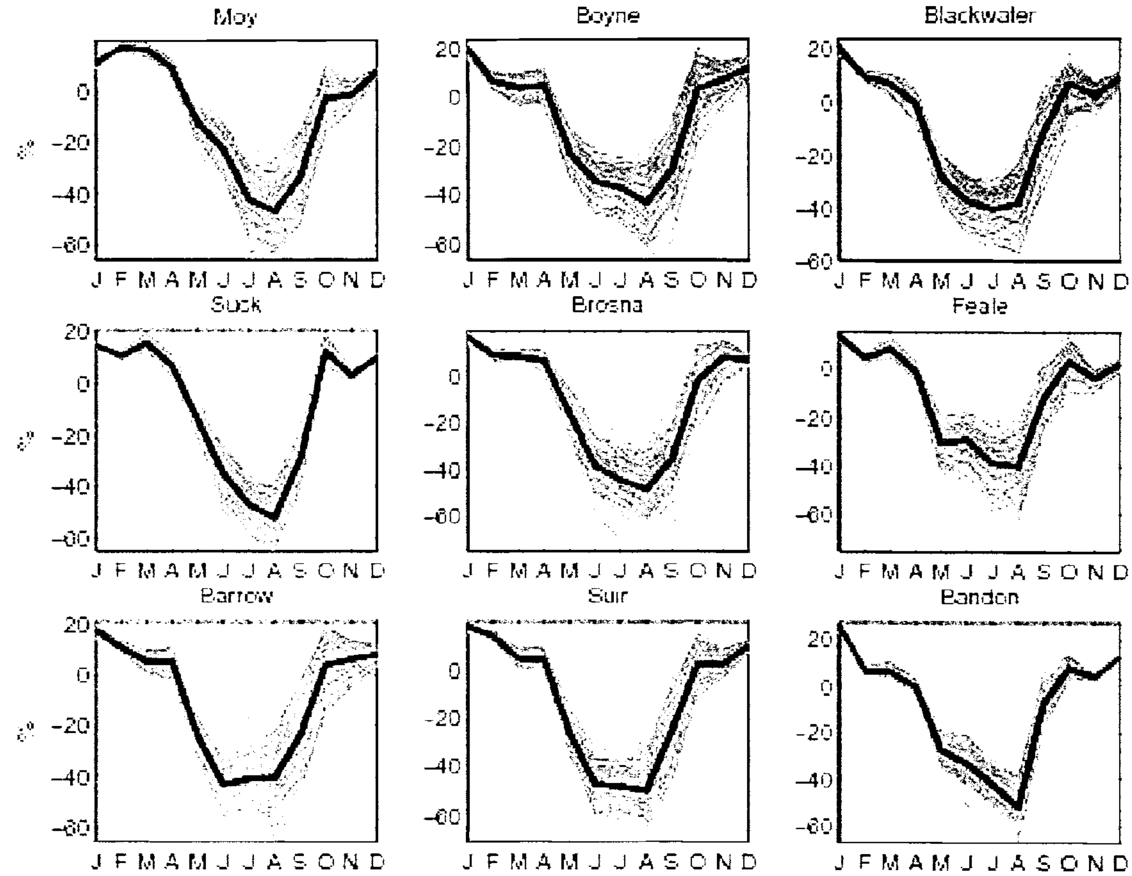

Figure 5: Change in monthly mean flow due to climate change under the SRES A1B scenario. Grey bars show uncertainty in rainfall-runoff model, with the mean shown as a black dashed line. (Steele-Dunne et al, 2008).

Reductions in river flow for summer months reach over 40% in surface water dominated catchments (those with little groundwater storage in particular) with some simulations 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 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 different impacts models employed. Further work is required and ongoing in relation to the latter. Figure 5 depicts the changes for selected catchments simulated by Steele-Dunne *et al.*

5.1 Water Resources

Murphy and Charlton (2008) highlight that substantial reductions in summer and autumn flow would have potentially serious implications for water supply and water resource management. 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 serious implications for the entire water environment – from water supply to quality issues, to loss of habitat.

In relation to water resources, non-climatic drivers such as changes in population, consumption, economy, technology and lifestyle predominantly govern water use. In the GDA for example, due to the extent of population growth, water provision is coming under increasing pressure. Taking account of projected population growth, with the population of the region projected to double by 2031, existing primary sources of water supply from the Liffey at Ballymore Eustace and the Ryewater at Leixlip will be unable to cope with projected demands by as early as 2013. Work is currently underway to supplement sources of water supply in the medium term through the extraction of water from the Shannon basin to increase resources in the GDA.

Added to this is the fact that non-climatic drivers of water demand in the past will be supplemented by climate change. Herrington (1996) in studying the impact of climate change on water consumption in the UK suggests that a rise in temperature of about 1.1°C would lead to an increase in average domestic per capita demands of approximately 5% with increased demand greatest for personal washing and gardening. Peak demands are likely to increase by a greater magnitude, while the frequency of occurrence of current peak demand also likely to increase (Zhou *et al.*, 2001). From the simulations conducted it is during times of the year that demand is greatest (summer and autumn), when the greatest reductions in surface water resources are likely. Increases in evaporation are likely to result in increased losses from storage reservoirs.

When considering the vulnerability of water supply to future climate change it is also important to note that it is not just the domestic sector from which pressures are likely to increase with agricultural demand being particularly sensitive to climate change. Characteristics of the water resource system itself also 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 water supply system. In other cases a very small effect can have a significant impact, where the supply system is already under extreme pressure (Arnell, 1998; Arnell and Delaney, 2006).

5.2 Flooding

As mentioned above, higher winter flow is associated with an increase in flooding, one of the most common natural hazards experienced in Ireland. From the results obtained flood events are likely to become more common, particularly the more extreme and currently rare events like the flood expected once every 100 years. In the case of the River Barrow for example, a flood of magnitude expected to occur once every fifty years under current climatic conditions is likely to occur on average, once every 18 years by mid century, and in the Munster Blackwater the same flood is likely to occur every 10 years (Murphy and Charlton 2008). These changes are consistent with Steele-Dunne *et al.*, who for the Blackwater by mid-century suggest that the current 40 year flood is likely to be associated with a 9 year recurrence interval.

These changes raise concerns regarding the integrity of flood defences, 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 flooding is likely, concerns regarding the maintenance of water quality also arise.

6. SEA LEVEL RISE

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 indicates 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 6 and 7 illustrate the increase in sea surface temperatures for the Northern hemisphere and Port Erin in the Irish Sea respectively.

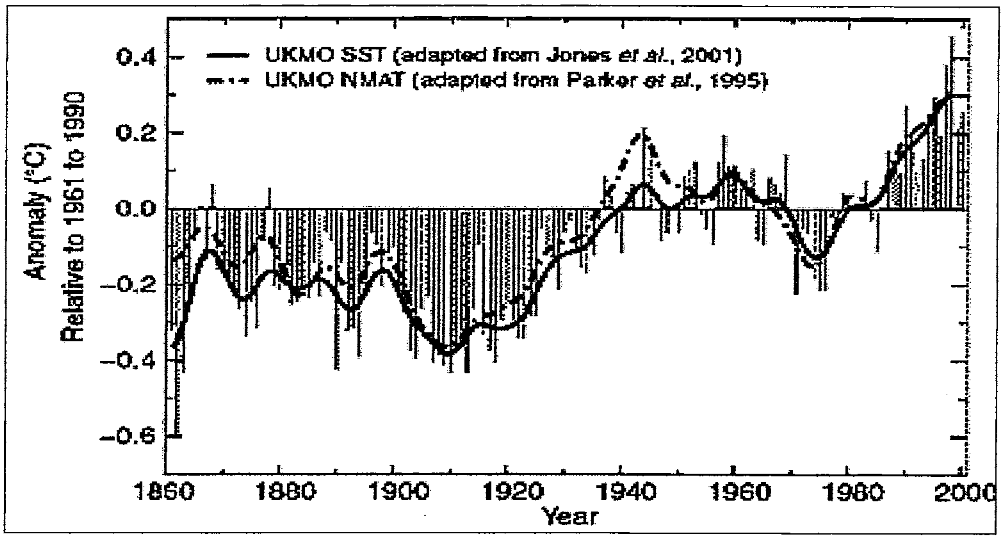

Figure 6: Sea surface temperature anomaly (yearly departures from the 1961-1990 mean) for the Northern Hemisphere (IPCC, 2001).

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). This is likely to be a conservative estimate. 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°C above the year 2000 levels (Hansen, 2007).

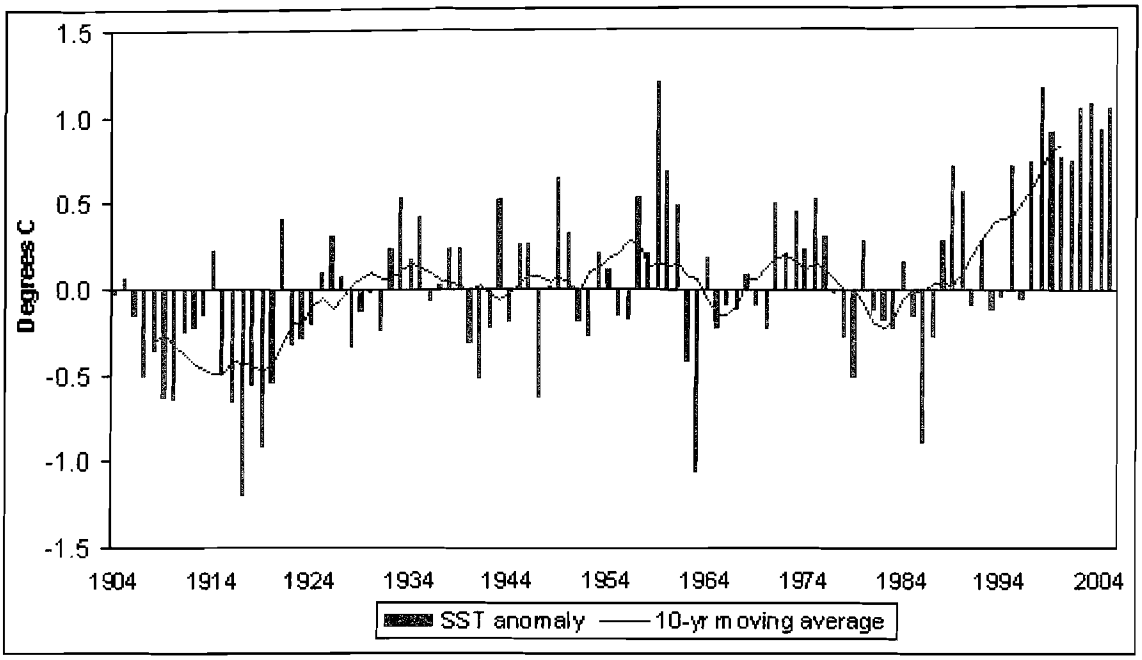

Figure 7 Annual average anomalies (1904-2005) of Irish Sea sea surface temperatures from Port Erin, Isle of Man, relative to the 1961-1990 period (Data reproduced with kind permission of the Port Erin Marine Laboratory, Isle of Man).

Sea temperature and sea level in Irish waters have been rising slowly in recent decades with satellite and in situ coastal observations showing a general warming trend of 0.3-0.4°C per decade since the 1980s (McGrath *et al.,* 2008). McGrath *et al.* also highlight that a more rapid rate of warming of 0.6-0.7°C has been suggested for the Irish Sea, while satellite observations highlight that sea levels are rising on average 3.5 cm per decade around Ireland, well in excess of ongoing isostatic adjustment.

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 8). 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.

6.1 Wave Energy

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. Current work to refine these findings is ongoing between the Coastal and Marine Resources Centre (CMRC) in UCC and Met Eireann.

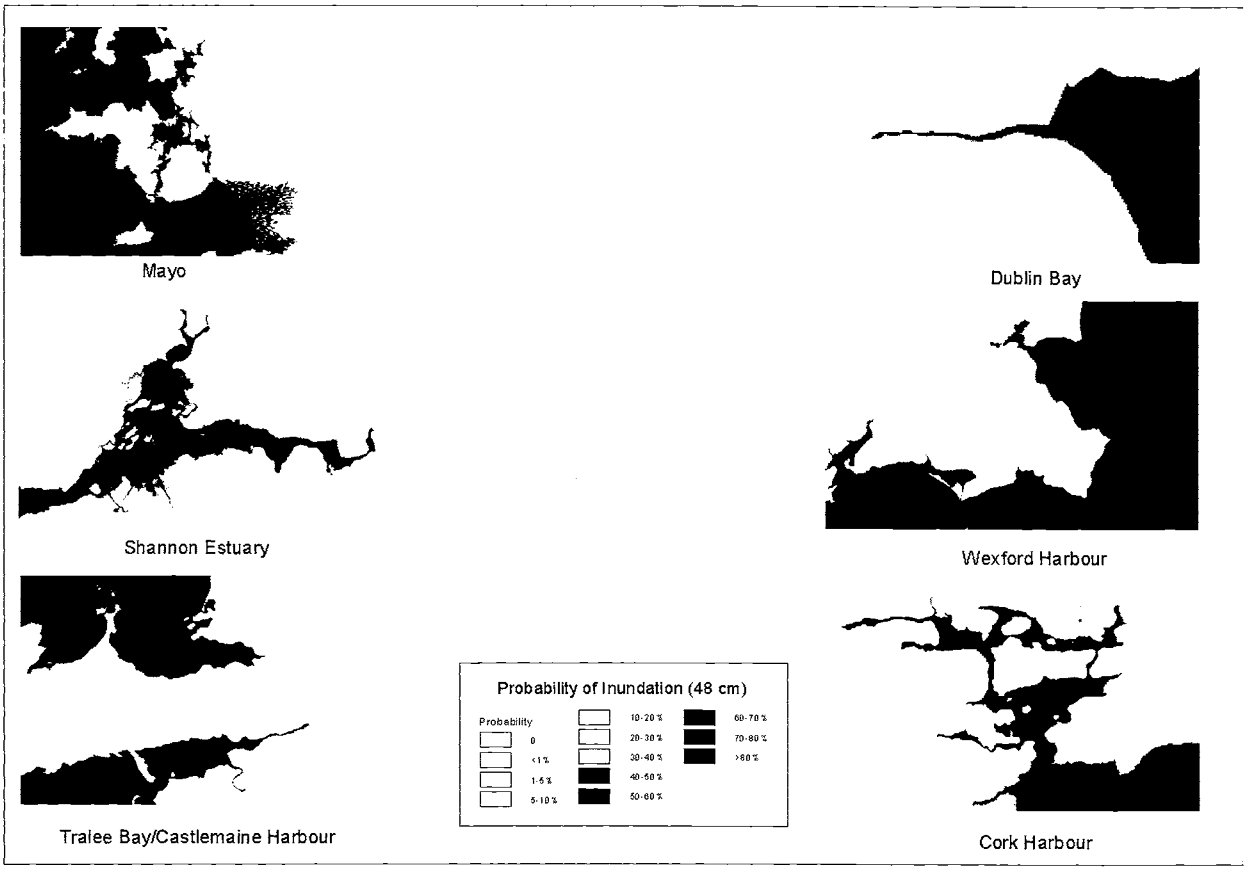

Figure 8: Risk of inundation associated with a sea level rise of 0.48 m (Source: Fealy, 2003)

7. 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. 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.

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 sea surface temperatures required for hurricane formation and sustenance, 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 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-in-12 year event on the west coast (Figure 9) (Carter, 1991). The return period or frequency of occurrence, 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 (Fealy, 2003). When placed in context of the major cities, valuable land, key infrastructure and important habitats that exist in these areas, the weight that needs to be given to effective adaptation becomes evident.

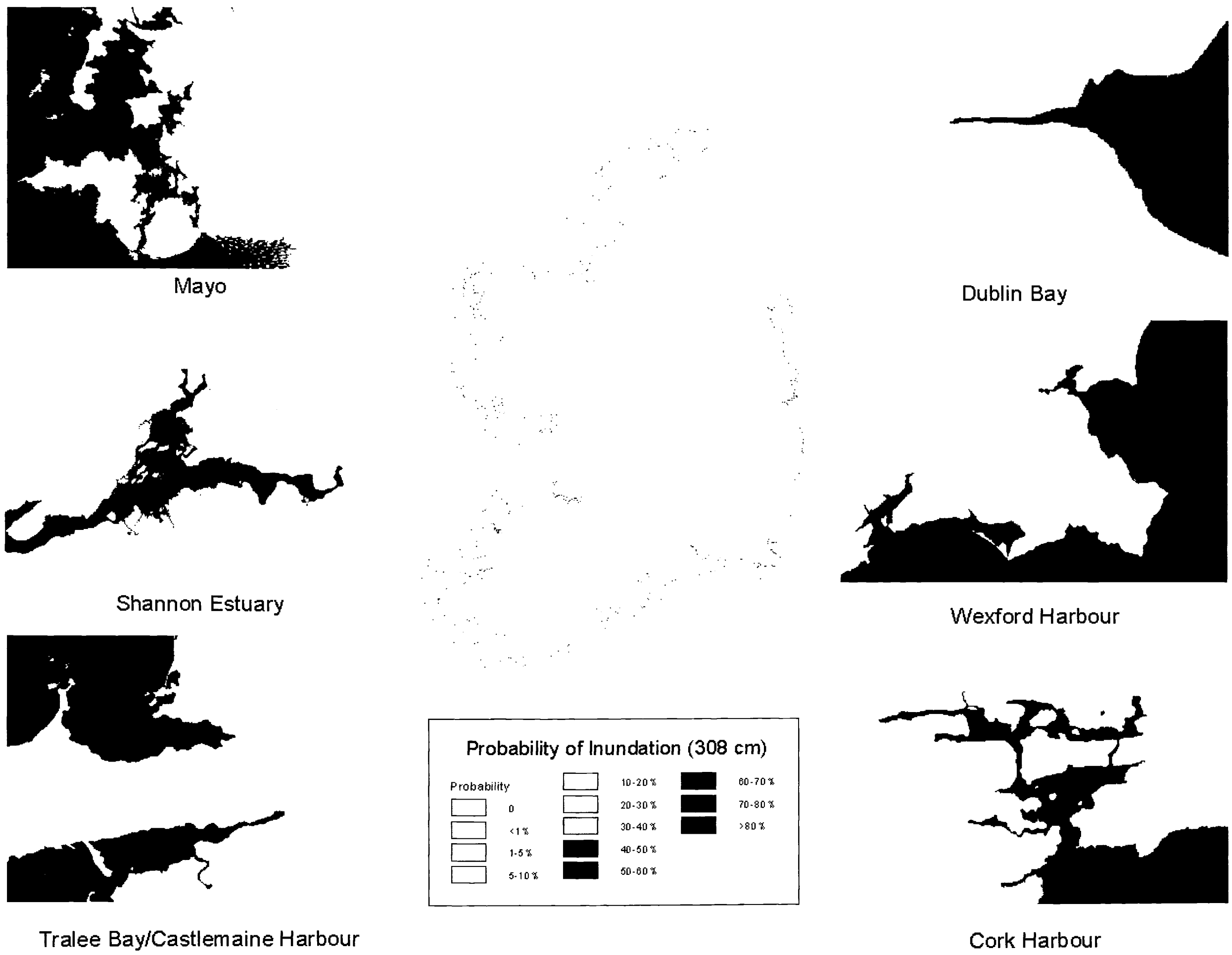

Figure 9: Risk of inundation with an extreme water level of 2.6 m and sea level rise of 0.48m Dark blue represents areas most at risk (Source: Fealy, 2003)

8. DISCUSSION: CRITICAL GAPS REMAINING

Despite the substantial developments that have taken place in recent climate change research in Ireland, critical gaps still exist around the provision of robust information for decision makers and risk managers. Burton *et al.* (2002) highlight a number of reasons for this with the central issues being the wide range of potential impacts derived from uncertainty in modelling climate change. Such uncertainty exists at every scale and is visible in areas such as likely future development pathways and future emissions of greenhouse gases, uncertainty in modelling complex environmental systems; from the global climate system to individual catchment processes, as well as a mismatch in scales between global change and local impacts.

In an effort to deal with such uncertainty impact assessment has evolved to deal with scenarios of change so that a number of possible realisations can be accounted for. However large ranges of uncertainty make decision making difficult. The focus of Irish and international research has thus turned to bridging the gap between impacts and the information required by decision makers. Central to this task is the role of probability through the determination of likelihoods and the construction of confidence intervals for simulated impacts. The ability to attribute probabilities to impacts offers huge potential to decision making approaches, with risks defined as the probability of hazard times the vulnerability. The use of probabilities in this way offers the potential for decision makers to account not only for the most likely impacts, but also low probability, high impact, surprise events while accounting for the vulnerability of stakeholders.

Additionally, more substantial work is required on the social side of vulnerabilities to climate change and how adaptation actually takes place from the point of view of the individual and communities. On this side of the equation very interesting work is beginning to emerge on deciphering the limits to adaptation (see for example Adger *et al.*, 2009). In order to deliver successful adaptation we need to be more explicit on what we define as 'successful'. This is a major challenge when extremely diverse values are at play which are not static and are contingent on ethics, knowledge, attitudes to risk and culture. As we move towards delivering the required local information on climate change and as our foresight into the future becomes further tuned, we seem to be lagging behind in determining vulnerability to change. It is critically important that we view climate change as occurring not in isolation, but rooted within the myriad pressures and dynamics that give communities and individuals a sense of space and place. This is an area in which Geographers have a key role to play.

REFERENCES

Adger, N.W., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D.R., Naess, L.O., Wolf, J., Wreford, A. (2009) Are there social limits to adaptation to climate change. Climatic Change, 93: 335-354.

Arnell, N.W. (1998) Climate change and water resources in Britain. Climatic Change, 39, 83–110.

Arnell, N.W. and Delaney, E.K. (2006) Adapting to climate change: Public water supply in England and Wales. Climatic Change, 78, 227-255.

Burton, I., Huq, S., Lim, B., Pilifosova, O., and Schipper, E. L. (2002) From impacts assessment to adaptation priorities: the shaping of adaptation policy. Climate Policy 2, 145-159.

Carter, R.W.G. (1991) Sea level changes in McWilliams, B.E. (ed) Climate Change: Studies on the implications for Ireland, Stationary Office, Dublin, Ireland.

Edwards, R. and O'Sullivan, A. (2006) A vulnerability assessment of Ireland's coastal archaeological heritage, The Heritage Council.

Fealy R. and Sweeney, J. (2008) Climate Scenarios for Ireland. In Sweeney et al. (2008) Climate Change: Refining the Impacts. STRIVE Report, Environmental Protection Agency, Johnstown Castle, Wexford (2001-CD-C3-M1), 5-38.

Fealy, R., (2003) The impacts of climate change on sea level and the Irish coast, in Sweeney, J. (ed.) Climate Change: Scenarios and Impacts for Ireland. Report prepared for the Environmental Protection Agency, Johnstown Castle, Wexford, 189-222.

Hansen, J.E. (2007) Scientific reticence and sea level rise, Environmental Research Letters, 2.

Herrington, P. (1996) Climate Change and the Demand for Water, Her Majesty's Stationery Office, London, United Kingdom, 164 pp.

Hulme,M.,Jenkins,G.J.,Lu,X.,Turnpenny,J.R.,Mitchell,T.D.,Jones,R. G., Lowe,J., Murphy,J.M., Hassell,D., Boorman,P., McDonald,R. and Hill,S. (2002) Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. 120pp

IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Houghton, J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P. J. and Xiaosu, D. (eds.). Cambridge University Press, UK. 944 pp.

IPCC (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry M.L., O.F. Canziani, P Palutikof, P. van der Linden and C.E. Hanson, (eds.). Cambridge University Press, Cambridge, UK, 982pp.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

McElwain, L. and Sweeney, J. (2006) Key Meteorological Indicators of climate change for Ireland. Environmental Protection Agency, Ireland.

McElwain, L. and Sweeney, J. (2007) Implications of the EU climate protection target for Ireland. Environmental Protection Agency, Ireland

McGrath, R., Lynch, P., Dunne, S., Hanafin, J., Nishimura, E., Nolan, P., Venkata J.R., Semmler, T., Sweeney, C., and Wang, S. (2008) Ireland in a Warmer World. Scientific Predictions of the Irish Climate in the Twenty-First Century. Final report of C4I, Dublin.

McGrath, R., Nishimura, E., Nolan, P., Semmler, T., Sweeney, C. and Wang, S., (2005) Climate Change: Regional Climate Model Predictions for Ireland. Environmental Protection Agency, ERTDI Report Series No. 36, 45 pp.

McWilliams, B.E. (ed) (1991) Climate Change: Studies on the implications for Ireland, Stationary Office, Dublin, Ireland.

Murphy, C. and Charlton, R. (2008) Climate Change and Water Resources in Ireland In Sweeney et al. (2008) Climate Change: Refining the Impacts. STRIVE Report, Environmental Protection Agency, Johnstown Castle, Wexford (2001-CD-C3-M1), 39-81.

Steele-Dunne, S., Lynch, P., McGrath, R., Semmler T.,Wang, S., Hanafin, J., Nolan, P. (2008) The impacts of climate change on hydrology in Ireland. Journal of Hydrology 356, 28– 45

Sweeney, J., Albanito, F., Brereton, A., Caffarra, A., Charlton, R., Donnelly, A., Fealy, R., Fitzgerald, J., Holden, N., Jones, M., Murphy, C. (2008) Climate Change: Refining the Impacts. STRIVE Report, Environmental Protection Agency, Johnstown Castle, Wexford (2001-CD-C3-M1)

Sweeney, J., Brerton, T., Byrne, C., Charlton, C., Emblow, C., Fealy, R., Holden, N., Jones, M., Donnelly, A., Moore, S., Purser, P., Byrne, K., Farrell, E., Mayes, E., Minchin, D., Wilson, J., Wilson, J. (2003) Climate Change: Scenarios and Impact for Ireland. Report prepared for the Environmental Protection Agency. (2000-LS-5.2.1-M1)

Sweeney, J.C., Fealy, R. (2003) Establishing Reference Climate Scenarios in Sweeney, J. et al. Climate Change: Scenarios and Impacts for Ireland, EPA Publication, 81-102.

Zhou, S L., McMahon, T. A. Wang Q. J. (2001) Frequency analysis of water consumption for metropolitan area of Melbourne, Journal of Hydrology 247, 72-84.