DOWNSCALING GLOBAL CLIMATE MODELS FOR IRELAND: PROVIDING FUTURE CLIMATE SCENARIOS

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1 INTRODUCTION

Previous work using downscaled global circulation output has examined the likely spatial characteristics of future climate change in Ireland (Sweeney and Fealy, 2003). These likely changes have been shown to have potentially large effects on water resources and especially on flood and drought frequencies with increased winter runoff in western parts and decreased summer runoff, especially in eastern Ireland. Uncertainties in projections involving only one GCM, however, limit the reliability of such climate scenarios somewhat for future water resource management. GCMs show considerable variability for areas such as Ireland arising from inherent weaknesses they possess due to problems of scale and feedback. An approach which seeks to overcome some of these uncertainties by the use of multi-model downscaling is presented here.

2 UNCERTAINTY AND MODELLING APPROACHES

2.1 Model Uncertainty: The SRES Emission Scenarios

Model projections of future climate are highly dependent on future estimates of greenhouse gas and aerosol loadings in the atmosphere. These cannot be forecast with a high degree of confidence for decades ahead, and yet this must be attempted if any modelling of future temperature and rainfall is to have credibility and to be of use for future resource and hazard management. To address this major uncertainty the Intergovernmental Panel on Climate Change commissioned a study to provide a range of plausible future socioeconomic scenarios which could be equated to particular atmospheric loadings of greenhouse gases and aerosols Nakicenovic *et al* (2000). Generally these reflected much reduced aerosol sulphate loadings from earlier efforts, reflecting growing control of these emissions on the part of the industrialised world. The consequence of this was that the cooling influence of aerosols was diminished in most GCMs and global warming estimates increased sharply in the Third Assessment Report (IPCC, 2001). A range of 'storylines' was produced of which four 'marker' scenarios were used to drive GCMs.

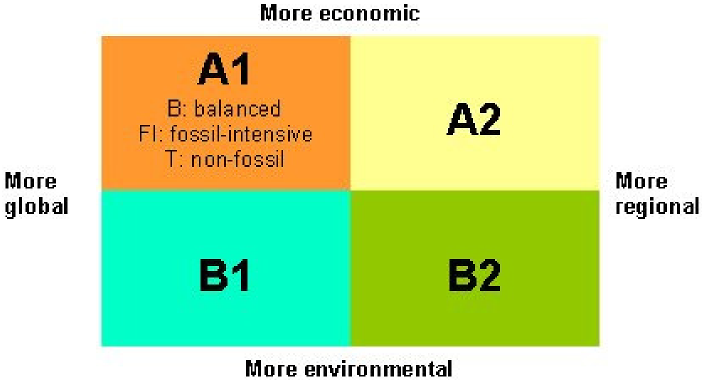

Figure 1: SRES Scenarios

The A2 and B2 scenarios were selected for this study of future Irish climate scenarios. For the A2 emissions scenario, the main emphasis is on a strengthening of regional and local culture. A very heterogeneous world is envisaged with large disparities in wealth and well-being. Population growth is high with global population reaching 15 billion by 2100. Economic growth and technological is less dramatic. Per capita income is slow to increase and less emphasis on environmental protection than the other scenarios is apparent. The A2 CO_2 emissions are the highest of all four scenario families.

The B2 world sees population reaching about 10 Billion by 2100. This is in line with both the United Nations and IIASA median projections. Global per capita income grows at a moderate rate to reach about US$12,000 by 2050. The divergence in incomes between rich and poor nations decreases, although not as rapidly as in scenarios of higher global convergence (A1, B1). While globally the energy system remains predominantly based on oil and gas to 2100, there is a gradual transition to renewables with a gradual decoupling of energy production and greenhouse gas emissions.

2.2 Downscaling Global Climate Models- Principles

The computational burden of solving equations of mass, energy and motion at thousands of grid points means that, despite major advances in computing in recent years, the horizontal resolution of Global Climate Models (GCMs) is quite coarse. Typically, grid sizes are approximately 300km, meaning that for many GCMs, Ireland is represented by only one grid square. This is unfortunate because many processes of concern to hydrologists: convective rainfall, cloud, local winds etc., typically occur on scales much finer than this. As a consequence, many important hydrometeorological processes are often parameterized (simplified or averaged) for incorporation into a GCM. Such parameterization is frequently based on present climate relationships, not necessarily applicable to future climate conditions. Clouds are particularly problematic because they occur at sub grid scale sizes and have complex feedback effects resulting from increased evapo-transpiration as global warming proceeds.

Temporal and spatial variability changes are also masked by large grid sizes. These may be crucially important for Ireland at regional or local levels. Regional changes in precipitation across Ireland will probably constitute the most important dimension of climate change and have profound effects on water distribution and availability at different seasons. There is therefore a disparity of scales between what policy makers and environmental managers need and what GCMs can deliver. A methodology which can downscale GCM output to resolutions of the order of 10kms to enable local scale impact analysis to be undertaken is thus a highly desirable research objective for Ireland.

Regional Climate Models (RCMs) have become widely used in recent years to simulate climate at resolutions of 20-50km. These are essentially nested models driven by a parent GCM. Large scale climate variables such as pressure, wind, temperature, water vapour are fed into the regional model domain space and then processed at the higher resolution by the RCM to yield a higher resolution product. The relationship is a one-way relationship. Data comes from the GCM to the RCM domain. No feedback from the RCM to the GCM occurs. This is the main area of concern for RCMs in that the quality of their prediction is determined largely by the quality of the GCM boundary information. Should for example the GCM have a major weakness in projecting storm tracks, the RCM is likely to be poor at projecting rainfall or wind parameters. Nonetheless, the advent of supercomputers and ongoing improvements in GCMs has seen the quality of RCM performance markedly improved. Multiple GCM simulations can now also be undertaken to provide better inputs.

This study employs a downscaling technique known as empirical statistical downscaling. This has become increasingly used as an alternative to RCMs where high spatial and temporal resolution climate scenarios are required. Unlike RCMs which are computationally demanding, expensive to run and difficult to use for obtaining long climate simulations, statistical downscaling requires substantially less computational resources and produces results that are comparable to that output from RCMs.. The principle underpinning this form of downscaling involves using large scale variables from a GCM via an intermediate data set to estimate small scale climatological variables.

Empirical statistical downscaling is based on the development of mathematical transfer functions or relationships between observed large-scale atmospheric variables and the surface environmental variable of interest. The transfer functions are generally regression-based and are derived between a set of atmospheric grid scale predictors, output from both reanalysis projects and GCMs, and a single predictand.

The use of statistical downscaling requires a number of assumptions, the most fundamental of which is that the derived relationships between the observed predictor and predictand will remain constant under conditions of climate change and that the relationships are` time-invariant' (Yarnal, 2001). It also assumes that the employed large-scale predictor variables are adequately modelled by the GCM for the resultant scenarios to be valid. Busuioc *et al.* (1998), in their verification of the validity of empirical downscaling techniques, found that in the case considered, GCMs were reliable at the regional scale with respect to precipitation in their study area and that the assumptions of validity of predictor-predictand relationship held up under changed climate conditions. Von Storch *et al.* (1993) suggested that if statistical downscaling is to be useful, the relationship between predictor and predictand should explain a large part of the observed variability and that the expected changes in the mean climate should lie within the range of its natural variability. This is generally true for temperature. However, for precipitation the influence of 'local' factors on occurrence and amounts can often be considerable. As a result of these site-specific considerations the relationship between the large-scale predictors and local outputs often reflects a smaller part of the actual observed variability. This situation is further complicated in areas such as Ireland due to relief effects on precipitation.

2.3 Downscaling Global Climate Models- Data Sources

Observed daily data for precipitation, temperature and sunshine hours were obtained from 14 synoptic stations from Met Éireann, for the period 1961-2000. Potential evapotranspiration, based on the Penman-Montieth formula, was obtained for the 1971-2000 period, while radiation, for the 1961-2000 period, was only available from a selection of synoptic stations. The synoptic stations are generally at low elevations and can be considered of high quality, data being collected by experienced meteorological officers. The data is, however, provided with quality control flags, indicating whether the measurement is the value as read, accumulated, trace or otherwise, thereby enabling the researcher to decide on a suitable threshold for accepting the data as valid. In the present research, all values not directly measured by the observer were removed from the analysis, with the exception of potential evapotranspiration which is a calculated variable.

Large-scale surface and atmospheric data were obtained from the NCEP/NCAR Reanalysis project. Originally at a resolution of 2.5^{o} x 2.5^{o} degrees, this data was regridded to conform with the output resolution of the HadCM3 GCM. Standardised reanalysis variables were then used as candidate predictor variables to calibrate the transfer functions, linking the large-scale surface and atmospheric variables to the daily precipitation series for each of the 14 synoptic stations.

GCM data were obtained, for three models from the Hadley Centre (HadCM3), Canadian Centre for Climate Modelling and Analysis (CCCma) (CGCM2) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO Mark 2) for both the A2 and B2 emissions scenarios. All the modelled datasets exist on a common grid resolution, that of 2.5^{o} x 3.75^{o} degrees, and were obtained for the grid box representing Ireland in the GCM domain.

3 DOWNSCALING GLOBAL CLIMATE MODELS – RESULTS FOR IRELAND

3.1 Calibration and verification

Temperature is largely a homogenous variable over space with a significant degree of its variation being accounted for by the large-scale atmospheric forcing mechanisms. Daily maximum and minimum temperature data for the 1961-2000 periods were split into two periods, one for calibration, with the remainder withheld for verification. Good results were obtained for the calibration and verification periods (Tables 1 & 2).

A Generalised Linear Model (GLM) was employed to model precipitation amounts. GLMs are particularly useful for modelling rainfall series, as they do not require the dependent variable to be normally distributed. A log link function, $g(\mu)$, and gamma distribution were employed for the purposes of modelling precipitation amounts. This has been found to be an extremely good fit to precipitation amounts in a number of regions. Acceptable results were obtained for both east coast and west coast regions (Figures 2 & 3).

Maximum Temp.	**DJF**		**MAM**		**JJA**		**SON**	
Stations	**Cal.**	**Ver.**	**Cal.**	**Ver.**	**Cal.**	**Ver.**	**Cal.**	**Ver.**
Valentia Observatory	0.88	0.87	0.89	0.90	0.83	0.84	0.88	0.86
Shannon Airport	0.89	0.88	0.89	0.91	0.82	0.84	0.88	0.87
Dublin Airport	0.82	0.81	0.87	0.89	0.80	0.82	0.87	0.87
Malin Head	0.83	0.86	0.83	0.86	0.78	0.78	0.85	0.84
Roche's Point	0.89	0.88	0.85	0.87	0.76	0.80	0.86	0.87
Belmullet	0.85	0.86	0.85	0.87	0.79	0.79	0.86	0.85
Clones	0.86	0.85	0.87	0.90	0.81	0.82	0.87	0.86
Rosslare	0.90	0.90	0.86	0.86	0.74	0.79	0.87	0.87
Claremorris	0.87	0.86	0.87	0.90	0.79	0.82	0.86	0.86
Mullingar	0.88	0.88	0.87	0.91	0.80	0.85	0.87	0.87
Kilkenny	0.90	0.89	0.89	0.91	0.83	0.85	0.87	0.87
Casement Aerodrome	0.90	0.89	0.88	0.90	0.81	0.84	0.87	0.87
Cork Airport	0.90	0.89	0.87	0.89	0.80	0.84	0.87	0.87
Birr	0.89	0.88	0.89	0.92	0.83	0.85	0.87	0.87

Table 1: Pearson's R values for the seasonal calibration and verification periods for maximum temperatures.

Minimum Temp.	**DJF**		**MAM**		**JJA**		**SON**	
Stations	**Cal.**	**Ver.**	**Cal.**	**Ver.**	**Cal.**	**Ver.**	**Cal.**	**Ver.**
Valentia Observatory	0.83	0.81	0.82	0.81	0.73	0.74	0.84	0.85
Shannon Airport	0.84	0.83	0.84	0.86	0.77	0.80	0.88	0.89
Dublin Airport	0.79	0.81	0.83	0.85	0.75	0.81	0.88	0.89
Malin Head	0.77	0.80	0.80	0.82	0.72	0.74	0.84	0.83
Roche's Point	0.85	0.84	0.88	0.89	0.82	0.85	0.90	0.90
Belmullet	0.81	0.80	0.81	0.82	0.70	0.72	0.81	0.81
Clones	0.78	0.79	0.82	0.83	0.74	0.77	0.86	0.86
Rosslare	0.81	0.82	0.86	0.88	0.81	0.84	0.89	0.89
Claremorris	0.81	0.80	0.82	0.83	0.73	0.75	0.85	0.86
Mullingar	0.79	0.78	0.83	0.82	0.75	0.76	0.87	0.87
Kilkenny	0.78	0.77	0.79	0.79	0.71	0.73	0.83	0.85
Casement Aerodrome	0.80	0.80	0.82	0.82	0.75	0.77	0.87	0.88
Cork Airport	0.85	0.85	0.87	0.88	0.83	0.84	0.91	0.91
Birr	0.82	0.82	0.84	0.82	0.74	0.77	0.87	0.88

Table 2: Pearson's R values for the seasonal calibration and verification periods for minimum temperatures.

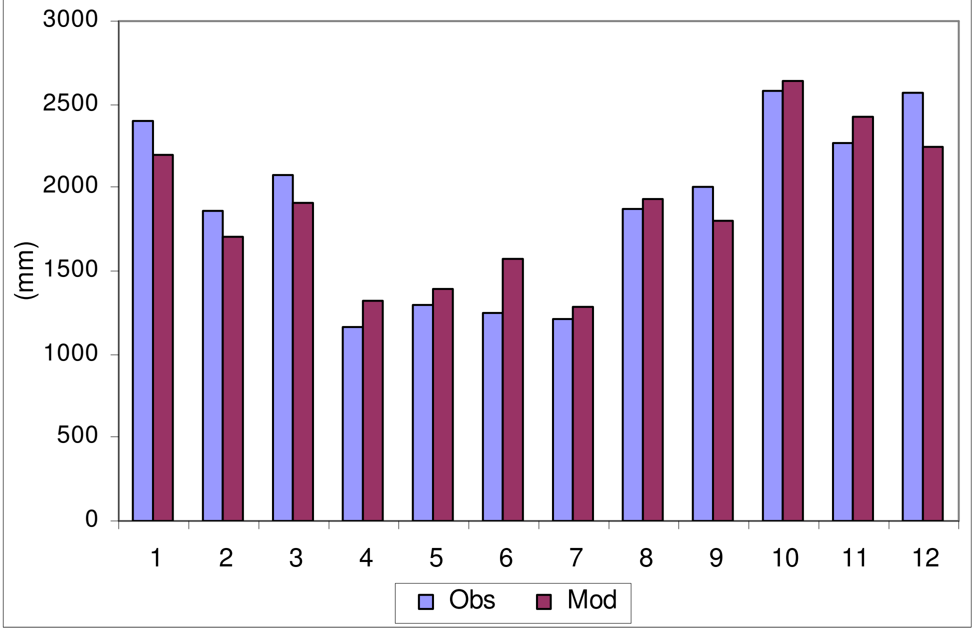

Figure 2: Comparison of observed and modelled precipitation from Valentia, a west coast station with high annual receipts, for the independent verification period 1979-1993.

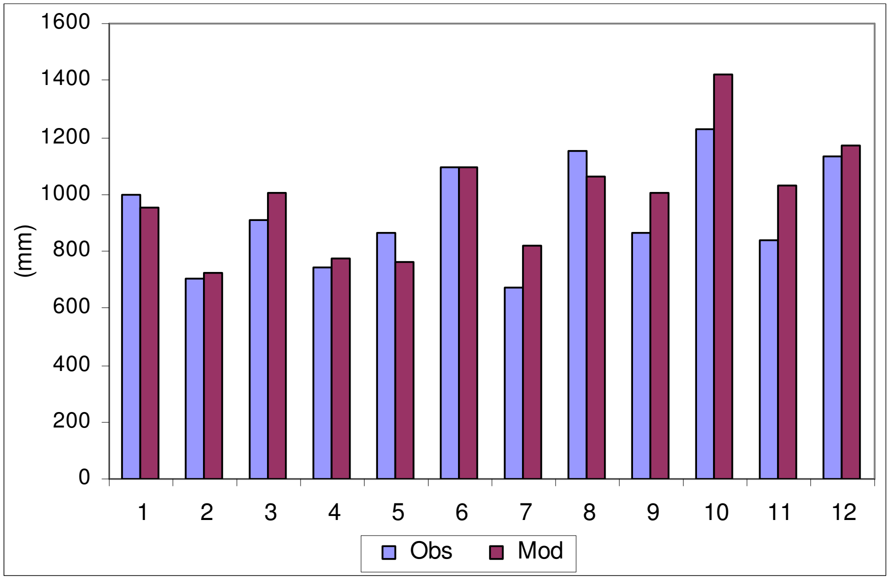

Figure 3: Comparison of observed and modelled precipitation from Dublin Airport, an east coast station with low annual receipts, for the independent verification period 1979-1993.

An alternative modelling technique to that of temperature and precipitation, but within the remit of statistical downscaling techniques, was employed to generate daily values of radiation and potential evapotranspiration (PE). As global solar radiation is only measured at a limited number of synoptic stations, sunshine hours, measured at all synoptic stations, was used in conjunction with the Angstrom formula in order to convert sun hours to radiation (Angstrom, 1924; Brock, 1981). Radiation, precipitation occurrence and precipitation amounts were then used as inputs into the regression model for calibrating potential evapotranspiration (Figure 4). While wind plays an important role in potential evapotranspiration, it has a seasonal dependence, being more influential during the winter months and diminishing during the spring, summer and autumn months. As potential evapotranspiration values are at a minimum during the winter months, the exclusion of this variable is unlikely to impact too much on the predicted values of potential evapotranspiration.

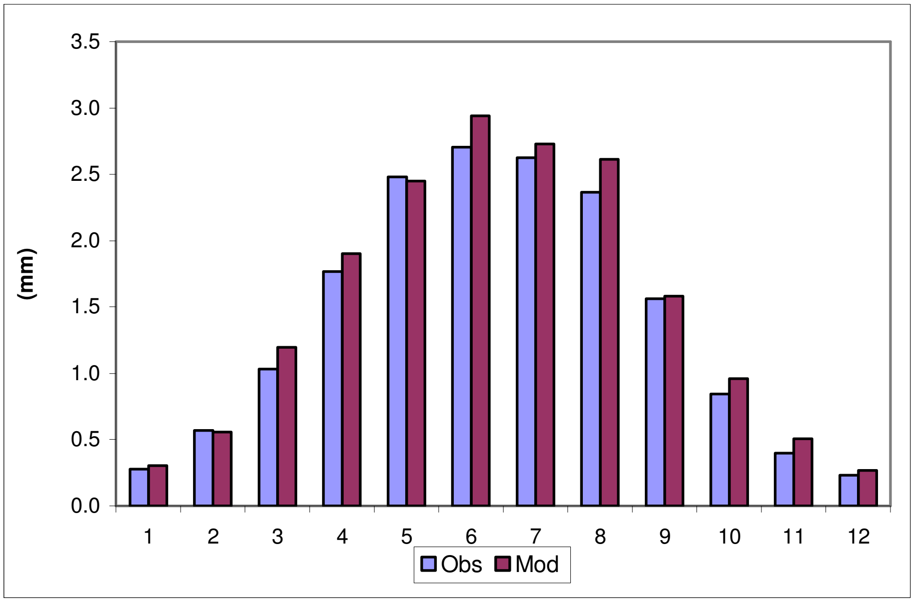

Figure 4: Comparison of observed mean daily potential evapotranspiration from Kilkenny and modelled potential evapotranspiration for an independent verification period of 1991-2000.

3.2 Scenario Results

The stations showing the largest change and the smallest change in temperature for the different GCMs are illustrated in Figures 5 for each season for the A2 emissions scenario for the 2050s. In general, the CCCM GCM is associated with the largest amount of seasonal. These differences largely arise due to different GCM model climate sensitivities or equilibrium temperatures under a doubling of the pre-1990 atmospheric CO_2 concentrations.

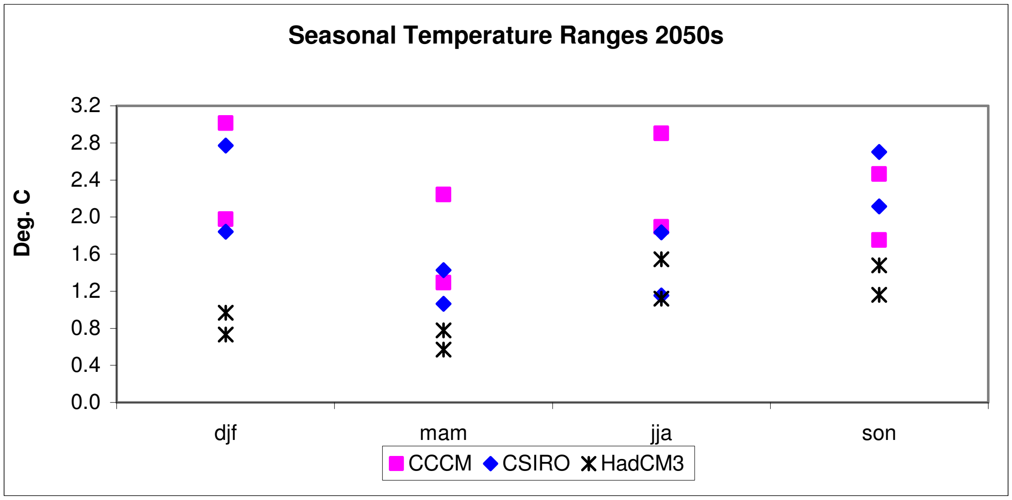

Figure 5: Seasonal temperature ranges for stations showing the smallest and greatest changes for the A2 emissions scenario

For precipitation, the stations showing the largest percent change and the smallest percent change for the different GCMs are illustrated in Figure 6 for the A2 emissions scenario. The largest increases in winter are demonstrated by the CCMA GCM All models suggest an increase in winter and a decrease in summer rain Differences in the GCM model ranges demonstrate the importance of using a number of GCMs when conducting impacts analysis due to the various uncertainties that cannot be accounted for when employing just one GCM.

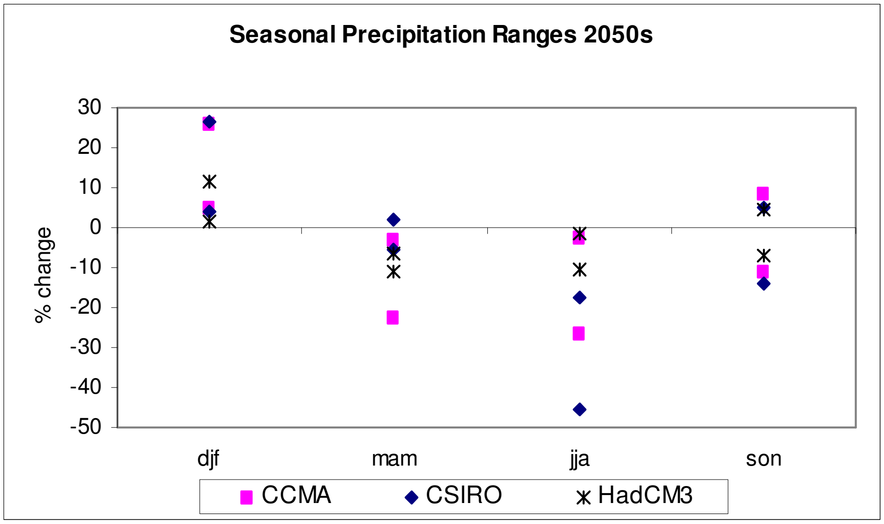

Figure 6: Seasonal precipitation ranges for stations showing the smallest and greatest changes for the A2 emissions scenario

3.3 Ensembles

Although it has long being recognised that different GCMs produce different regional climate responses even when run with the same emissions data, it was common practice until recently for many impact studies to employ only one climate change scenario, based on one emissions scenario, derived from a single GCM.. From a risk assessment perspective this could be considered unsound (Hulme and Carter, 1999). To address this problem an approach incorporating ensembles or weighting of the downscaled results was developed. This weighting was based on the individual GCMs ability to reproduce the properties of the observed climate. The modified CPI index or Impacts Relevant Climate Prediction Index (IR-CPI) is weighted based on the individual GCMs ability to reproduce the properties of the observed climate, derived from the NCEP data, and is derived from the root-mean-square difference between modelled and observed climatological means, assessed over the baseline period (Wilby and Harris, 2006).

The mean ensembles, produced from the weighted averaging described above, suggest that by the 2020s, average seasonal temperatures across Ireland will increase by between 0.75-1.0°C (Figure 8), part of which has already been experienced over the period since 1990. By the 2050s, Irish temperatures are suggested to increase by 1.4-1.8°C, with the greatest warming occurring during the autumn. Spatial differences also become more apparent, with an enhanced ‘continental’ effect occurring during all seasons.

This ‘continental’ effect is further enhanced during the 2080s period, particularly during the autumn season, which accounts for the greatest warming during the 2080s, with an increase of 2.7°C. The mean temperature in all seasons is suggested to increase by 2°C or more. Summer increases in the order of 2.5-3.0°C are indicated from the ensemble mean.

Winter precipitation is likely to increase marginally by the 2020s, by between 0.7-3.7% (Figure 9). The greatest seasonal changes are suggested for summer, with a reduction of 8.5% for the ensemble mean. However, reductions of between 10-16% are suggested for regions along the southern and eastern coasts.

Again, winter and summer during this time period experience the largest percentage changes in receipt, ranging from 10% increases in winter to reductions of between 12-17% in summer. While increases are experienced along the east coast and midlands during winter, reductions of between 20-28% are projected to occur along the southern and eastern coast during the summer season. If realised, these changes are likely to have a large impact on hydrology in Ireland. These seasonal and spatial changes in precipitation are further enhanced by the 2080s, with winter increases of 11-17% and summer reductions of between 14-25%. The largest percentage increases in winter precipitation are projected to occur in the midlands, of up to 20%, while the largest reductions during the summer months are again projected to occur along the southern and eastern coast, which are likely to experience decreases of between 30-40% during these months.

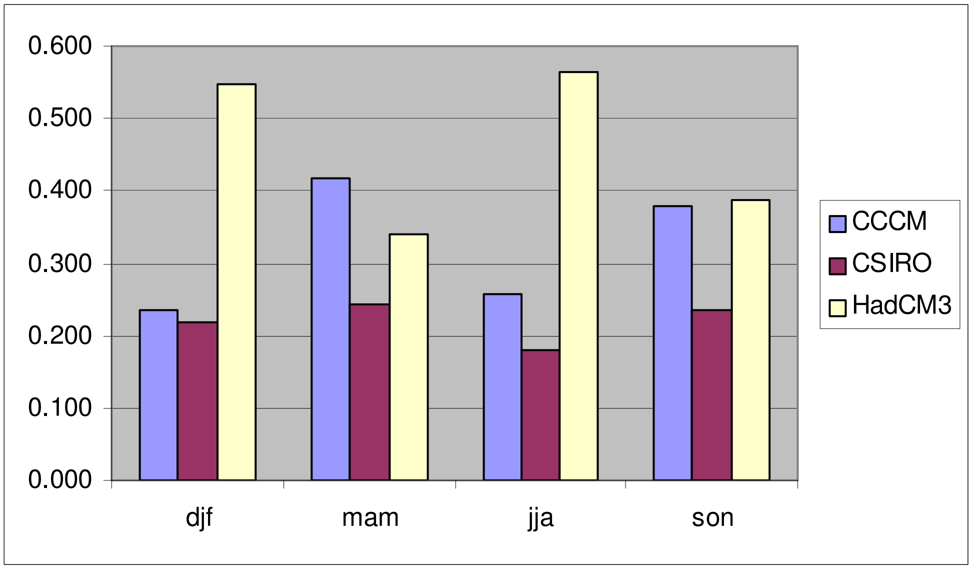

Figure 7: Seasonal weights derived from the CPI score for each of the GCMs to produce the weighted ensemble mean.

4 CONCLUSIONS

Significant changes in temperature, rainfall and potential evapotranspiration are projected for mid-century by the use of a multi model ensemble approach to downscaling GCMs. These are likely to have major impacts on streamflow, groundwater, soil moisture and generally all aspects of the hydrological cycle and will be examined in the paper by Murphy *et al* later in this publication.

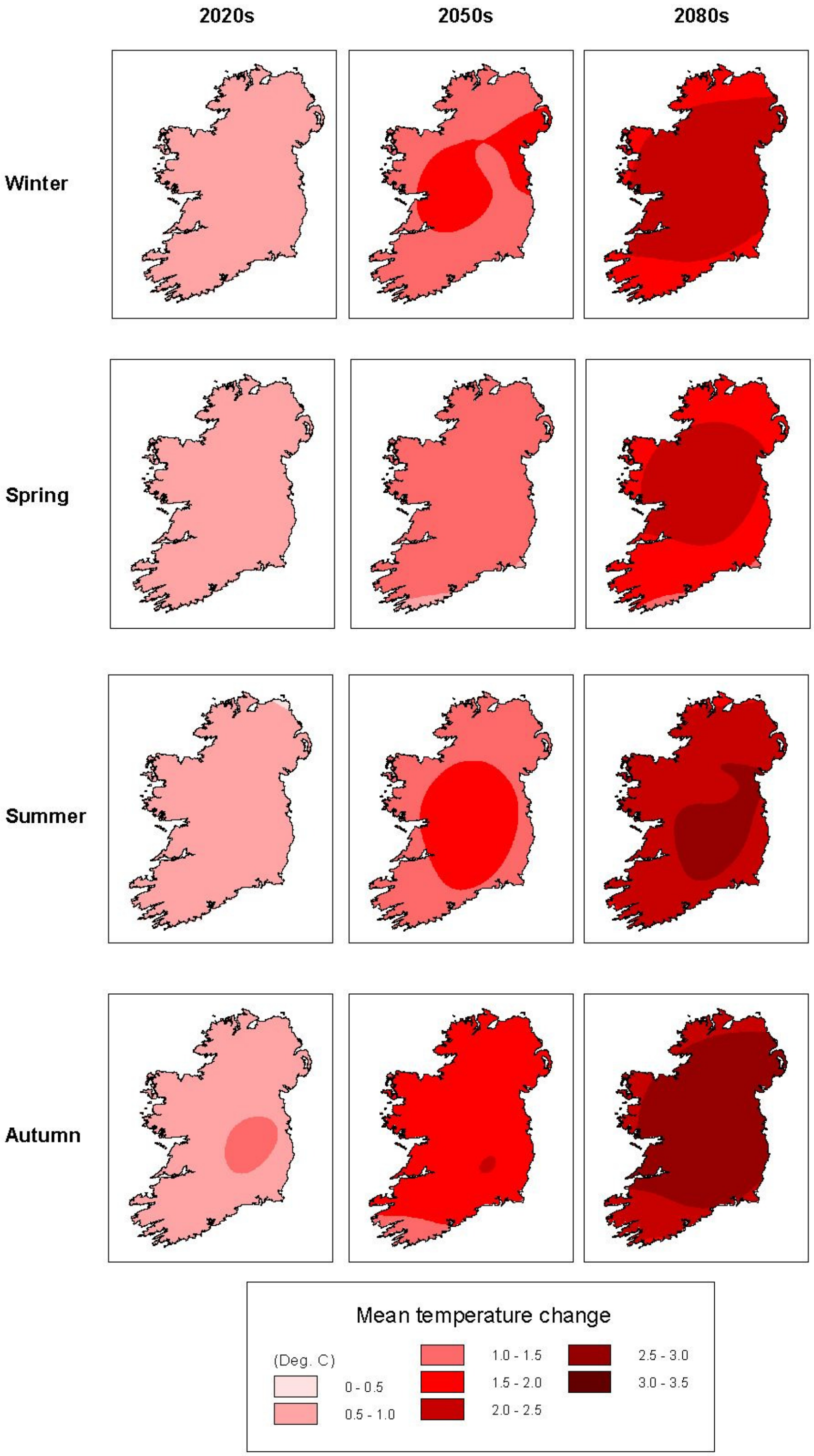

Figure 8: Mean temperature increases for each season and time period

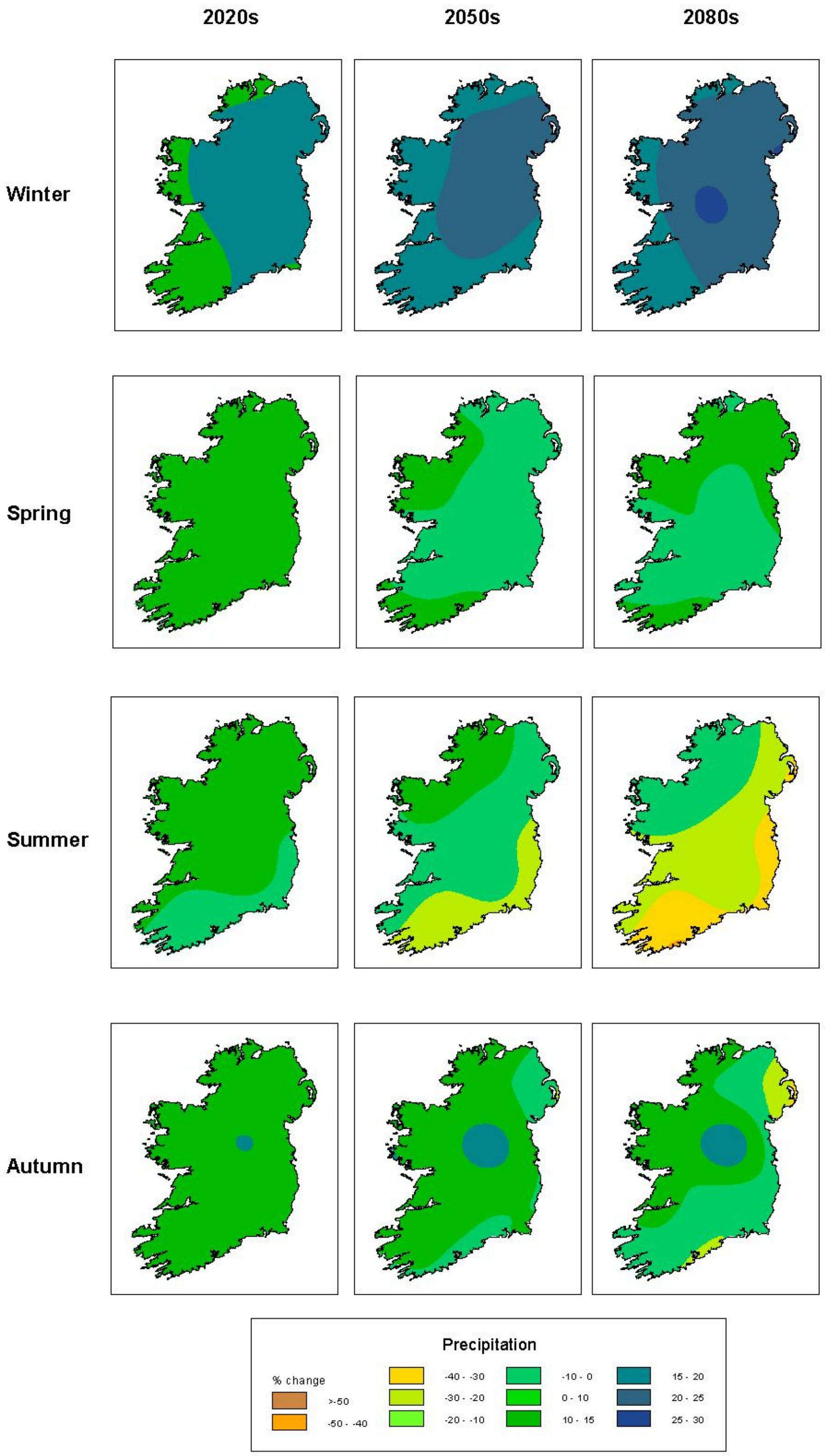

Figure 9: Percentage Changes in precipitation for each season and time period

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