Chapter 1

Introduction and Overview

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1.1 Rainfall Variability and Extremes: Why the Concern?

Climatic changes associated with increasing atmospheric concentrations of greenhouse gases are expected to cause changes in the mean conditions of climate, but also, and more importantly, changes in the variability of climate, such that some types of extreme events are expected become more frequent and/or severe. The damaging nature of extreme events such as tropical cyclones, storms, heavy rain, droughts and heat-waves means that this is an issue of considerable concern, prompting a recent surge in research into potential changes in climatic extremes and variability.

Precipitation is one particular element of climate which is expected to be affected by changes in variability. Physical theory (Fowler and Hennessy, 1995; Trenberth, 1998), observational evidence (e.g.Groisman *et al*.,1999, 2005; Frich *et al*., 2002 and Alexander *et al*., 2006) and model simulations (e.g. Gordon *et al*., 1992; Fowler and Hennessy, 1995; Kharin and Zwiers, 2000; Semenov and Bengtsson, 2002; Watterson and Dix , 2003), suggest that the warming of the atmosphere will result in an intensification of the hydrological cycle, bringing a mean increase in global precipitation, of which a proportionally large fraction is expected to occur through an increase in intensity of the heaviest events.

In recent years the impacts that extremely heavy rainfall can have on people and communities in the UK have been highlighted by events such as the floods of Boscastle in August 2004, and the Autumn Floods of 2000 throughout the country. The severe impacts of events such as these serve to demonstrate the importance of research into the variability and extremes of rainfall in present and future climate. This thesis addresses some of the problems that are incurred in the study of precipitation variability and extremes in the simulations of climate generated by General Circulation Models (GCMs).

1.2 Simulation of Daily Rainfall Variability and Extremes Using Climate Models

Climate change impacts research relies heavily on climate model projections of future climate. Precipitation extremes, however, pose some key difficulties due to the typically coarse spatial resolution of climate models, a limitation which is imposed by the complexity and hence, computational demand, of these models. The Hadley Centre General Circulation Model (GCM), HadCM3, for example, has a resolution of 2.5° latitude by 3.75° longitude, and even the higher resolution Regional Climate Model (RCM), HadRM3 runs at a maximum resolution of 25 by 25 km (Hulme *et al*., 2002). By comparison, mesoscale systems such as thunderstorms or small tropical storms typically range from a few kilometers to a hundred kilometers in diameter (Ahrens, 2000).

Limited resolution of climate models not only results in a number of problems relating to the physical processes modeled, but also causes problems for the assessment and application of model output, which are summarised in Figure 1-1.

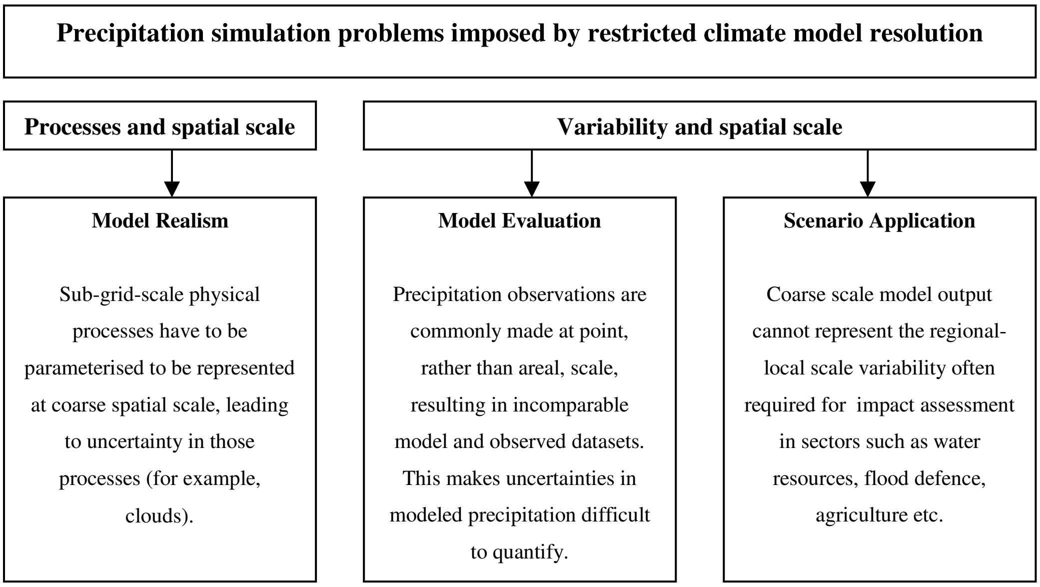

Figure 1-1: Precipitation simulation problems imposed by restricted climate model resolution.

Fundamentally, for the realism of the modeling process, the limited spatial (and temporal) resolution of climate models limits the degree to which precipitation can be modeled realistically. Processes critical to the reliable representation of moisture transport and precipitation, such as convection, evaporation and condensation, can operate at scales significantly smaller than the model grid-scale, and are therefore parameterised, introducing a significant margin for error into the model simulation, particularly with respect to precipitation (Fowler and Hennessy, 1995). The limited representation of topography also introduces errors, as rainfall caused by orographic uplift is inhibited by the inadequate detail in topography that can be included at the coarse scale of GCMs (Leung and Ghan, 1995).

Additionally, however, the coarse spatial resolution also affects the way in which the model output is interpreted, and restricts its application to impacts studies which require local-scale projections. It is with these issues that this thesis is concerned, and these are explained further below.

1.3 Temporal Variability of Daily Rainfall at Different Spatial Scales

When timeseries data are averaged spatially (for example, from a number of daily observation stations to a grid-box average), the temporal variability is smoothed. This means that the level of temporal variability in an observation of rainfall taken at a single point in space will be higher than the level of temporal variability in the average rainfall over an area surrounding that point, with the level of variability decreasing with increasing area. This means that, for an areal average rainfall series, the distribution is narrower, and the extremes at either end of the distribution (dry days with no rainfall, or very wet days with very heavy rainfall) occur with less frequency, than for the points observed within that area.

Although it is has been argued that GCM output might represent the point scale (Skelly and Henderson-Sellers, 1996), it is much more generally accepted that the output of the model represents the grid-box average, because many of the processes within the GCM are parameterised over areas not points (Osborn and Hulme, 1997). This has some significant implications for the way in which the daily rainfall generated by GCMs can be used and interpreted when the level of variability, specifically, is important. There are two substantial problems caused by this mis-match in spatial scale and thus variability:

1.) The comparison of model simulations against observed data.

The evaluation of the level of variability at daily (or at other timesteps) timescale is made difficult because the observations of rainfall that are often used to gauge how well GCMs can reproduce the characteristics of recent climate in control or present-day simulations are largely point observations made at weather stations. This means that the level of variability observed at those point observations is not directly comparable with the grid-box average series' which are simulated by GCMs.

2.) The application of model data to a context which requires point or local scale variability

The need for local and regional climate change projections, with appropriate representation of variability and extremes, is crucial to climate impact assessment in fields such as hydrology where the characteristics of the spatial and temporal variability of precipitation at the local or regional scale can be critical to the issue of whether or not climate changes poses an increased flood risk to a region (Reynard *et al.*, 2003). The requirement for climate change scenarios at local scale has led to the development of a number of disaggregation or 'downscaling' approaches, which attempt to determine the variability at points or local regions within a grid box.

1.4 Evaluation of Daily Rainfall Simulated by Climate Models

Rainfall is known to be difficult to model reliably in atmospheric models as its generation relies on the parameterisations of processes that operate on spatial scales that are too small to be modeled explicitly. This means that it is particularly important to be able to assess the level skill a model has in generating rainfall in order to ensure that those simulations are used and interpreted appropriately. The mis-match between the levels of temporal variability in point observations of rainfall to that of an areal average rainfall series, however, means that the variability and extremes of daily rainfall simulated by climate models cannot be compared directly to observations.

Areal rainfall can be estimated by averaging available station observations (a number of different interpolation techniques can be used for this) but the level of variability in the resulting areal average depends heavily on the number of stations which contribute to that mean. A sparsely distributed network may well result in an areal mean which has significantly higher levels of daily variability than that which might have come from a fully sampled grid box, and may not, therefore, represent a 'true' grid box mean (Osborn and Hulme, 1997). This means that whilst a gridded dataset based on a dense network of rain-gauges can be considered as representative an observation of the true areal mean, and thus may be comparable with climate model simulations, there are many regions and time periods for which such a network is not available.

The differences in the variability (Osborn and Hulme, 1997) and extremes (e.g. Booij, 2002; Coles and Tawn, 1996; Bell, 1976) between point and areal rainfall have been investigated by previous studies, proposing methods for estimating the characteristics of areal rainfall. Hydrological applications that require estimates of extreme rainfalls for different return periods (e.g. 20, 50 or 100 years) for the design of flood defences or the estimation of flood frequency, for example, have prompted a large amount of research in this area. Studies which have applied these techniques to the evaluation of precipitation extremes in rainfall simulated by GCMs are, however, less common; known examples include Osborn and Hulme (1997, 1998) Fowler *et al.*, (2005a) and Booij *et al*. (2002).

1.5 Daily Rainfall Simulations of Future Climate for Impacts Studies

For the purposes of climate model evaluation, previous studies (e.g. Osborn *et al*., 1997; Booij, 2002) have investigated methods to estimate the characteristics of areal rainfall using the characteristics of point station observations. The application of GCM projections of climate change, under greenhouse gas emissions scenarios, to climate impacts studies, however, often requires some estimation of the characteristics of point or local scale rainfall using the areal rainfall simulated by models. Flood-frequency estimation is one such application. A number of studies have used hydrological models to estimate changes in the frequency of peak flows that might be expected in the future, under a warmer climate with an enhanced hydrological cycle (e.g. Kay *et al*., 2006a, 2006b; Fowler and Kilsby, 2007). Many of these models require precipitation input at considerably smaller spatial scales than a GCM can provide. A variety of 'downscaling' techniques have been developed to help overcome this problem, which range in complexity, but all serve the purpose of estimating the surface conditions at a point or local area using the large-scale conditions simulated by GCMs.

The relationships between variability at the point and areal scales may therefore be usefully applied to future rainfall if they can be considered to be stationary in time, and under changed climatic conditions. As these relationships between point and areal rainfall variability are strongly dependent on the spatial variability of climate within the region (Osborn and Hulme, 1997; Booij *et al*. 2002), it is the potential for changes to this spatial variability that will determine the stationarity of those relationships. Any assumption that the spatial characteristics of rainfall, at the sub-GCM-grid-scale, will remain unchanged in a warmer climate is, however, difficult to validate. Some climate model experiments (Gordon *et al*., 1992, Hennessy *et al*., 1997; Chen *et al*., 2005) have indicated that under a warmer climate, an increased proportion of rainfall might be caused by convective processes, and less by large-scale dynamical processes. This may alter the overall spatial characteristics of rainfall because convection typically operates at small spatial scales, thus causing more localised rainfall than the larger-scale synoptic events (Osborn, 1997).

1.6 Aims and Objectives and Structure of the Thesis

The broad aims and objectives of this thesis are to address the differences in daily rainfall variability at point and areal scales, and develop solutions which will facilitate the comparison of variability between point observations of daily rainfall gauging stations with areal-average daily rainfall simulated by GCMs. The development of relationships between variability at point and areal scales will not only allow a more explicit evaluation of GCMs simulated rainfall, but also potentially provide an approach to estimating the characteristics of point rainfall in a future climate based on the characteristics of the areal-average rainfall simulated by a GCM, if the relationships developed can be demonstrated to be stationary under changed climatic conditions.

The thesis is structured as follows. **Chapter 2** reviews the literature to-date which concerns precipitation variability and extremes in present and future climate, in climate observations and modeling experiments, methods and results of previous evaluations of GCM-simulated precipitation and its daily variability, and the approaches that are used to estimate point or local scale precipitation characteristics for future climate. Areas requiring further research are identified, and the specific research objectives for this work are specified in light of these findings.

Chapter 3 describes the development of an approach for estimating **dry-day probability** in grid-box average precipitation based on the station observations of precipitation that are available. This approach is tested using station data from UK, Zimbabwe and China, and the uncertainty margins that are associated with those estimates are assessed.

Chapter 4 describes the development of an approach for estimating parameters of the **gamma distribution** of wet-day amounts for daily rainfall for a grid-box average, using information from available stations. Similarly to Chapter 3, the uncertainty associated with those estimates is also investigated. The estimates of the gamma distribution parameters are then also used to investigate the extremes of areal rainfall, using the **95th percentile** values estimated via the distribution parameters.

Chapter 5 applies the approaches developed in Chapters 3 and 4 to the **evaluation of daily rainfall** simulated by three GCMs (**HadCM3**, **CGCM3** and **PCM**) for the UK and South Africa. The latter region was selected because it is independent of those regions used to develop the relationships between point and areal scale. The approaches developed facilitate the estimation of 'observed' areal rainfall characteristics, and therefore allow quantitative assessment of model performance in terms of mean precipitation, wet/dry-day frequency, mean wet-day amount (mean intensity), the parameters of the gamma distribution of wet-day amounts and the magnitude of the 95^{th} percentile of wet-day amounts.

Chapter 6 assesses the likelihood that the relationships between variability in point and areal rainfall, developed in Chapters 3 and 4, can be assumed to be stationary in time, with a change in climate regime due to global warming. This is done by investigating the changes in the **spatial characteristics of rainfall** at the sub-GCM-grid-scale using a precipitation simulated at a higher spatial resolution by Regional Climate Model HadRM3H.

Chapter 7 presents an attempt to quantify the effect of potential changes in spatial characteristics of rainfall under a scenario of climate change, using an analogue approach. This allows the relationships developed in Chapters 3 and 4 to be applied to **scenarios of future climate**. The changes in the daily variability that might be expected under a warmer climate at point and areal scales are then compared.

Conclusions and recommendations for further work are then made in **Chapter 8**.