1 Introduction

1.1 The Mediterranean and climate extremes

The Mediterranean basin is well known for possessing a relatively mild climate, and a long-lived culture that is partially due to the area's suitability for human habitation. Within these favourable climate conditions long periods of civilised human history have been recorded. Today, much of modern European tourism is focused upon the Mediterranean, and the economic development of the Mediterranean region is still reliant upon the favourable climate (Palutikof and Holt, 2004). In broad terms, southern European summers are long and dry, and winters are wet and relatively mild (Rudloff, 1981). Temperatures are generally higher and rainfall less frequent than for the rest of Europe (Barry and Chorley, 1998). However, the local topography, influence of the Mediterranean Sea, and a number of different circulation regimes (e.g. Mediterranean African, European, Atlantic, Asian) provide a wide range of climatic conditions over relatively short distances. Both temperature and precipitation may vary with latitude, longitude, altitude, proximity to coastlines, proximity to mountains, and the orientation of both coastlines and mountain ranges (Trewartha, 1962; Wallen, 1970; Lagouvardos *et al.,* 1996; Barry and Chorley, 1998; Bolle, 2003).

In addition to the climatic range that exists between regions, all of Europe experiences occasional problematic environmental conditions at the extreme ends of the distribution of climate through time. These climate extremes include increasingly hot summers (Colacino and Conte, 1995; Piñol *et al.,* 1998; Brunetti *et al.,* 2000a), warm (Beniston, 2005) or very cold winters (Maheras *et al.,* 1999a; Klein-Tank *et al.,* 2002), and large-scale flooding (Romero *et al.,* 1998b; Russo *et al.,* 2000; Brunetti *et al.,* 2001a; Brunetti *et al.,* 2001b; Llasat *et al.,* 2003). Furthermore, the disparity that exists between northern and southern European temperatures and precipitation means that extremely warm and dry seasons (and particularly heatwaves) may affect the already stressed Mediterranean region more than other parts of Europe (Maracchi *et al.,* 2005). In the Mediterranean, typically long summers often qualify under northern European definitions of drought (Colacino and Conte, 1995). In some parts of southern Spain, dry periods (defined as a consecutive sequence of days for which no single day accrues more than 1mm of rainfall) may persist for up to five months (Martín-Vide and Gomez, 1999). Intense bursts of precipitation are often supplied to the Mediterranean during spring and autumn by cyclogenesis and convective processes. Every year multiple rainfall events occur in Spain that supply more than 100 mm/day (Egozcue and Ramis, 2001), and northern Italy commonly experiences heavy flooding (Brunetti *et al.,* 2001b).

Partially due to multiple intense environmental pressures including drought, forest fire, and flooding (i.e. hazards), the Mediterranean region can be described as the most vulnerable region within Europe (Kundzewicz *et al.*, 2001; Schröeter *et al.*, 2004). However, exposure to environmental hazard is only part of the definition of Mediterranean climate vulnerability, which also includes the social resilience of Mediterranean societies to exposure (Adger, 1999). The 2004/2005 Spanish drought illustrates the results of additional stress produced by extreme dry conditions combined with low levels of resilience, including (among other effects) agricultural water shortages and power failures (Garcia-Herrera *et al.,* 2006). In Greece, 30% of the population is concentrated within the Athens metropolitan area, a region that has been described as environmentally, structurally, and socio-economically stressed, and having little resilience (i.e a high vulnerability) to natural hazards (Karavitis, 1998).

Climate change is likely to have a substantial influence on a future Mediterranean (Kundzewicz *et al.*, 2001). The Schengen agreement (implemented for Mediterranean countries at various times between 1995 and 2000) has loosened border control between the states of the EU (for EU nationals), and the foundation of the Euro has simplified European trade. Should Mediterranean social resilience to extreme temperatures, drought, or flood conditions decrease (Kunkel *et al.,* 1999b), or should such events become more frequent (Houghton *et al.,* 2001), populations, tourism, agriculture and other concerns may eventually migrate toward a warmer and more economically stable northern Europe (Fantechi *et al.,* 1995; Goria, 1999; Kundzewicz *et al.,* 2001) or instigate other adaptation measures (Kundzewicz *et al.,* 2001).

Future resilience to climate extremes within the Mediterranean can be seen as a series of interdependent socio-economic factors that include demographic change (e.g.

aging populations) (McMichael *et al.,* 2001), policy implementation (e.g. the Water Framework Directive, 2000), economic and infrastructural development (e.g. as part of EU accession) (Sorsa, 2006), and the reaction of both local and northern European populations to the regional impacts of climate change in sectors such as agriculture (Xoplaki *et al.,* 2001; Iglesias *et al.,* 2003; Cantelaube and Terres, 2005) and human health (Kalkstein and Davis, 1989; Koppe *et al.,* 2004; Conti *et al.,* 2005). This study does not attempt to forecast the development of policy, the complexities of regional development, or the influence of political factors external to Europe. However, for the ability to minimize vulnerability to climate extremes in the future, through appropriate responses to risk and the implementation of effective policies, populations and their governments must be fully aware of the behaviour of both mean and extreme climate (i.e. their exposure) (Koppe *et al.,* 2004). Further, where potential risks have been identified, policy makers should have a detailed grasp of the sensitivity of relevant socio-economic systems, which may vary from sector to sector, and region to region.

1.2 Aims and approaches

This study is concerned with extremes of heat, extremes of cold, excessive rainfall, and prolonged periods without rain. These forms of extreme climate, as experienced through heatwaves, floods, droughts, and less commonly, cold snaps, are the dynamic basis for the largest weather-related impacts (in terms of mortality and economic cost) upon Mediterranean society and economy (Colacino and Conte, 1995; Lagouvardos *et al.,* 1998; Em-dat, 2006; Delrieu *et al.,* 2005; Garcia-Herrera, 2006). Each of these climate phenomena may be represented by temperature and rainfall data, routinely measured across the Mediterranean (Klein-Tank and Können, 2003; Haylock and Goodess, 2004). Links between mean climate and synoptic-scale atmospheric circulation indices are well documented (Hurrell and Van Loon, 1997; Rodo *et al.,* 1997; Marshall *et al.,* 2001), as are links between synoptic-scale circulation types and mean climate (Corte-real *et al.,* 1995; Maheras *et al.,* 1999a; Quadrelli *et al.,* 2001). A large portion of the work presented here aims to expand the literature concerned with circulation and mean climate to include extremes of climate. Spatial patterns, temporal trends, and statistical relationships (e.g. correlations) of regional Mediterranean extremes are all explored with a view to the analysis of links with larger (synoptic, meso-) scale climate.

Up until now, most climate scenario or impact studies have been concerned with long-term growth or adaptation, and relatively few to date take into account extreme climate due to a lack of information regarding extreme behaviour or a lack of either the required spatial (e.g. 1-100 km) or temporal (e.g. daily) resolution (Easterling *et al.*, 2000). The problem of resolution can be met by either dynamical or statistical downscaling (von Storch *et al.*, 1993). Dynamical downscaling utilises Regional Climate Models (RCMs) nested within reanalysis data or General Circulation Models (GCMs) (Schmidli *et al.*, 2006). RCMs may utilise output from GCMs (starting, and meteorological boundary conditions) to simulate fine-scale physical processes (e.g. surface energy balance, evaporation, etc.), and thus high-resolution (10-20km) climatology (Mearns *et al.*, 2003; Schmidli *et al.*, 2006). Statistical downscaling allows for the direct modelling of point or station-scale climatology (e.g. rainfall, temperature) from large-scale climatology (e.g. atmospheric circulation) through empirically derived atmospheric processes and statistical relationships (von Storch *et al.,* 1993; Wilby *et al.,* 1998; Murphy, 1999; Schmidli *et al.*, 2006), and is increasingly being applied to extremes of climate (Haylock and Goodess, 2004; Goodess *et al.,* 2006). Essentially, statistical downscaling provides a framework for cross-spatial-scale analysis (Haylock and Goodess, 2004). The majority of this thesis is concerned with the characterisation of Mediterranean extreme climate and the subsequent generation of statistical downscaling models that are explicitly concerned with station-scale climate extremes. This approach allows for a statistical assessment of both patterns evident within extreme climate and, through an analysis of the structure and results of the downscaling models used, the potential causes of extreme climate, while offering recommendations on statistical downscaling methodology appropriate to the Mediterranean. This work does not utilise GCM output for the construction of scenarios of change (Haylock *et al.*, 2006; Schmidli *et al.*, 2006), but does provide a comprehensive basis for doing so in future studies of Mediterranean extreme climate.

As mentioned above (Section 1.1), the potential for climate extreme impacts (i.e. climate vulnerability) may be defined in terms of physical risk and social resilience (Schneider *et al.*, 2001; Adger *et al.*, 2004). In this study 'physical' vulnerability is assessed, as a function of hazard, exposure, and sensitivity (Schneider *et al.*, 2001; Adger *et al.*, 2004). A hazard can be defined as a purely physical extreme climate event (e.g. a heatwave), or (potentially) a change in the mean climate regime. Exposure is the occurrence of hazard in regions of importance to human activity (e.g. a heatwave affecting Athens), and sensitivity can be defined as the degree of first-order (i.e. immediate) response to exposure for a given socio-economic system (e.g. the number of people in Athens who are susceptible to heatwave induced mortality) (IPCC, 2001; Adger *et al.*, 2004). Having determined the exposure of Mediterranean society to changes in extreme climate hazards in the first part of this thesis, the second part is concerned with quantifying the sensitivity of social and economic systems to that exposure (Adger and Kelly, 1999). This work considers sectors of activity (health, agriculture, energy use) that are known to be sensitive to mean climate change, and for which a body of work (Chapter 5.3) and contemporary evidence (e.g. the 2003 European heatwave) suggests areas of sensitivity to extreme climate.

Existing impact studies are often based on the output of climate models that do not explicitly deal with extreme behaviour, and are biased in terms of simulated means and variability (Goodess *et al.,* 2003). This study aims to partially address the lack of regionally quantitative impact studies focussed on short-lived, discrete, and relatively moderate extremes (Klein-Tank and Können, 2003), it is not, however, a 'social' vulnerability study, in which the coping or adaptive capacity of a system may be assessed (Blaikie *et al.,* 1994; Adger and Kelly, 1999). Recommendations to decision makers regarding the adaptation of social or economic activity to reduce the impacts of extreme climate are likely to be poorly constrained (and eventually, have more costly ramifications) if the degree of exposure is unknown and relevant sensitivities are ignored (Connell and Willows, 2003). Important considerations regarding sensitivity to climate extremes include whether changes in extremes or mean behaviour result in the greatest overall impacts, whether any given societal-climate relationship is linear or non-linear, and whether or not extreme climate events (hazards) that create socio-economic impact (sensitivities) are evenly distributed over a given area. These concerns are addressed in this study, but socio-economic data availability constrains analysis to the national level. However, where sensitivities are identified at the national and seasonal level, it can be assumed that in the short term (i.e. over seasonal periods), socio-economic gains or losses (in agricultural yield, or energy consumption, or mortality) in one sub-national region do not offset those in another.

Leading on from the above issues, the aims of this thesis can be summarised through the following Research Questions:

1. What are the characteristics of the spatial and temporal variability of Mediterranean climate extremes? Are extremes changing in frequency, extent, or both?
2. Do Mediterranean climate extremes show links to synoptic or meso-scale climatology?
3. Can circulatory factors be identified that may cause extreme climate?
4. Do extremes of climate have a significant impact upon Mediterranean socio-economics at the national scale?
5. If so, where are the most important sensitivities? Are certain forms of extreme behaviour responsible for greater magnitude impacts than others, are relationships linear, and is the climate behaviour of some Mediterranean regions more relevant to socio-economic impacts than others?

1.3 Data, tools, and challenges

It is important to choose a method of quantification for extreme climate behaviour that is representative of the (temporal) distribution of extreme events (Wilks, 1995), continuous (to allow for time series analysis), and consistent across the target region and throughout time. Rather than choosing absolute maximum temperatures, or complex measures of drought, a set of simple statistical indices that typify the extremes of the climate probability distributions have been selected (Suppiah and Hennesy, 1998; Jones *et al.,* 1999a; Klein-Tank and Können, 2003; Haylock and Goodess, 2004). These indices include statistically defined thresholds (except for frost days, a physical threshold) and periods of exceedance for both temperature and precipitation (Klein-Tank and Können, 2003), representing locally relative extremes (Yan *et al.,* 2002; Klein-Tank and Können, 2003) while avoiding arbitrary values and compensating for spatial variability (Jones *et al.,* 1999a; Klein-Tank and Können, 2003). When considering the Mediterranean climate, influenced by spatial variations in topography and prevailing winds to create surface climate conditions that may vary dramatically over short distances (Fotiadi *et al.,* 1999; Romero *et al.,* 1999; Gonzales-Hidalgo *et al.,* 2001a), arbitrary thresholds for the whole region are inappropriate. Here statistical thresholds are defined at levels (i.e., the 10th and 90th percentiles) to provide event return periods of the order of weeks, rather than years (Suppiah and Hennesy, 1998; Jones *et al.,* 1999a; Horton *et al.,* 2001). These are not (for example) 1 in 10 year events, but 'moderate' extreme events. This definition allows for simple trend analysis over a 50-year period (Horton *et al.,* 2001; Klein-Tank and Können, 2003), and a greater likelihood of detection than for truly extreme extremes that may occur only a few times within the climate record (Frei and Schar, 2001). In order to construct the indices of extreme climate discussed above for the target region, daily data have been drawn from a number of meteorological bodies and quality-controlled to form the most comprehensive Mediterranean-wide data set currently available.

A large number of different modelling techniques exist to produce the statistical equations required for downscaling (e.g. multiple regression, canonical correlation analaysis, stochastic weather generators, neural networks), many of which are based upon the principles of regression (Wilby *et al.,* 1998; Goodess, 2000). However, for a given region it can be difficult to assess *a priori* whether one method will be more successful than another (Goodess *et al.,* 2006). Therefore, two very different methods are utilised in this study, both of which are quite complex and sophisticated. Orthogonal spatial regression (OSR) couples principal component analysis to regression (Briffa *et al.,* 1983; Jones and Salmon, 2005), while artificial neural networks (ANNs) utilise an iterative machine learning approach to approximate a surface-fitting function (McCulloch and Pitts, 1943; Harpham, 2005). Between them these methods account for regressive and near-regressive behaviour, linear and non-linear approaches, and statistical methods based around variance maximisation and interpolation in a multi-dimensional space. OSR was originally designed for use as a dendroclimatology tool (Briffa *et al.*, 1983), and its use as a downscaling method is new to this study. ANN methodology has been utilised for the downscaling of Mediterranean climatology by Trigo (2000b), although only for a single site (Coimbra, Portugal) and temperature variability. His research showed improvements over direct GCM output, but highlighted the need for additional work before ANNs could be reliably applied to replicate extremes of temperature. Goodess *et al.* (2006) show improvements in ANN application that are more appropriate to the downscaling of extremes, particularly for Iberian rainfall. This study expands upon previous research in terms of both geographical extent and application. In the following work ANNs are utilised on a multi-site basis for both temperature and rainfall extremes, using a predictor set specifically constructed for the Mediterranean, with a comprehensive model sensitivity test used to constrain application (also conducted for OSR, Figure 1.1), and a full comparison between linear and non-linear ANN results.

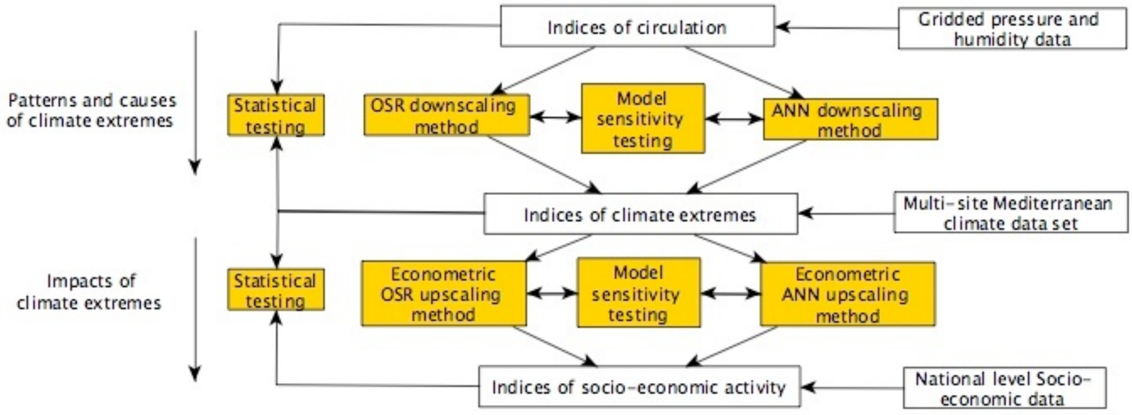

Figure 1.1: Flow diagram of modelling process

When attempting to statistically relate locally-derived independent variables (such as extreme climate) to national scale socio-economic variables (i.e. socio-economic ‘upscaling’), a form of modelling that may prove useful, in this context potentially equivalent to climatological statistical downscaling methods, is econometrics (Gujurati, 2003). Econometrics introduces quantitative analysis to economics by statistically relating socio-economic quantities of interest to independent socio-economic or environmental predictor variables (e.g. prices, demographics, temperature, precipitation), generally via classical linear regression (Gujurati, 2003). Climate-related econometric studies include those concerned with energy (Anderson, 1973; Galeotti *et al.,* 2004; Amato, 2005), agriculture (Chen *et al.,* 2004; Galeotti *et al.,* 2004), economic losses (Choi and Fisher, 2003), and health (Galeotti *et al.,* 2004). Econometric techniques may therefore contain knowledge useful to the study of extreme climate, even though they traditionally belong to a discipline outside of climatology. Econometric models generally use the same structural equations and obey the same statistical rules as those required for climatological models (see below). This study utilises the statistical downscaling techniques described above (i.e. OSR and ANN) combined with econometric theory (in addition to linear regression) in order to model the effects climate variability may have upon socio-economic factors (Galeotti *et al.,* 2004; Bigano *et al.,* 2005).

In the first part of this study, indices of extreme climate are modelled from atmospheric predictands, but in the second part the same indices of climate extremes are used as predictors for socio-economic indices (Figure 1.1). Due to mismatches in spatial scale between sets of predictors and predictands, the first part of this process therefore involves downscaling from the synoptic-scale to the station-scale, whereas the second part requires upscaling from the station-scale to national-level indices. Although this study largely utilises classical econometrics (Gujurati, 2003), prior econometric work is expanded through the use of station-scale indices of climate extremes as econometric predictors, the application of econometric theory to certain Mediterranean sectors (e.g. Greek mortality, Spanish maize yields), the geographical scope of application, and in some cases (e.g. for mortality) the model methodology used (i.e. OSR, ANN).

The consideration of functional form has important ramifications for any given climatic or econometric model, and if the researcher is not careful with the choice of independent variables and the underlying function then biases and errors may occur due to the specification of the model (Gujuratti, 2003). The functional form of a model is generally a reflection of the underlying theory on which the model is constructed. Functional forms may be linear (Galeotti *et al.*, 2004), log-linear, log-likelihood (Chen *et al.*, 2004), semi-log (Amato *et al.*, 2005), inverse, polynomial, or logit functions, among others (Kennedy, 2003). Both the forms of statistical modelling technique used within this study and the majority of econometric theory are loosely based upon the requirements of a classical linear (least-squares) regression (CLR) model (Kotz and Johnson, 1981; Kennedy, 2003). Although terminology may vary between the two disciplines (i.e. climatology and econometrics), requirements of CLR include the appropriate choice of exogenous predictors, a lack of measurement bias in the data, a linear and stationary relationship, homoscedastic errors (i.e. errors that have the same variance), and a lack of multicollinearity (Kennedy, 2003). If these conditions are met statisticians refer to the resulting model parameters as BLUE (Best Linear Unbiased Parameters), but in both climatology and econometrics a long history of mathematical technique has been developed to meet the assumptions listed above even when approaching relationships that are implicitly problematic (e.g. nonlinear). In this study, a literature review of the empirical links between both large-scale circulation and regional extreme climate, and between climate extremes and socio-economic factors, an exploration of the underlying data (in terms or spatial and temporal variability), and an analysis of relevant statistical relationships, allows for confidence in meeting the majority of relevant assumptions (e.g. stationarity, appropriate regressors). Other assumptions, including the need for linearity and an avoidance of multicollinearity, are conformed to or bypassed through the use of appropriate modelling techniques. A selection of linear and non-linear functional forms are utilised in order to estimate underlying relationships between extreme climate and socio-economic activity, which may vary both regionally and seasonally.

1.4 Thesis structure

Chapter 2 describes the Mediterranean climate in detail, and places Mediterranean extreme climate events in context. Following a definition of the target area under consideration, (Chapter 2.1), mean Mediterranean climate characteristics (Chapter 2.2.1) and influences (Chapter 2.2.2, 2.2.3, and 2.3) are reviewed. Mediterranean extreme climate events are then discussed in relation to mean climate (Chapter 2.4.1, 2.4.2) and related to localised circulation (Chapter 2.4.3), before a review of trends over the last 50 years (Chapter 2.4.4). Chapter 2 ends with a refinement of the first two research questions given above (Section 1.2) and the presentation of null hypotheses that can be experimentally pursued in Chapter 3.

Both climate data (Chapter 3.2) and statistical techniques (Chapter 3.3) must be identified and utilised appropriately. Given a robust data set, a selection of indices of climate extremes is defined (Chapter 3.4.1), as discussed above (Section 1.3). These are then used to characterise extreme behaviour in terms of seasonal and spatial variation

(Chapter 3.4.2), inter-correlation (Chapter 3.4.3), and trend behaviour (Chapter 3.4.4). Chapter 3.5 defines a set of synoptic and meso-scale oscillation and circulation indices (Chapter 3.5.2 and 3.5.5), and then explores their behaviour over time and as related to each other (Chapter 3.5). An overview of statistical links between the oscillation and circulation indices and the indices of extremes is given in Chapter 3.6. Chapter 3 ends with a summary of novel findings and their ramifications when applied to the null hypotheses of Chapter 2.

Chapter 4 introduces the two climate downscaling techniques utilised in this study in greater detail, explores their sensitivities to changing parameters, and formulates a subset of model variants appropriate to the data described in the previous chapter (Chapter 4.2). The performance of these variants is then tested in terms of skill and replicated variance (Chapter 4.3). In Chapter 4.4, recommendations from the discussion of performance and sensitivity are presented, and the internal structure of the variant that most skillfully replicates Mediterranean extreme climate is analysed. When studied in combination with the correlations and trends of the previous chapter, the importance each model places on certain predictors may help to understand the circulatory factors that cause extreme climate. Factors that show both an empirical relationship and statistical importance are summarised before socio-economic impacts are discussed in the following chapters.

In Chapter 5, the Mediterranean is introduced in terms of its socio-economic context (Chapter 5.2). Literature is reviewed that discusses how mean climate may affect finance, agriculture, and health and, where it exists, literature that concerns the impacts of extreme climate is also discussed (Chapter 5.3). There are, however, few Mediterranean specific studies. This material helps to form a foundation of evidence and methodology that can be utilised to model the socio-economic impacts of Mediterranean extremes.

Appropriate data is then compiled and utilised to construct socio-economic indices (Chapter 6.2) that characterise national-scale behaviour and aid the construction of econometric equations. Correlations between socio-economic indices and indices of extreme climate are discussed in Chapter 6.3 to provide a statistical foundation for further impact analysis. However, socio-economic relationships can be confounded by other factors (e.g. irrigation and carbon dioxide levels for agriculture), which are discussed before moving on to Chapter 7 and an analysis of sensitivities that may vary by region and type of extreme.

Chapter 7 introduces econometrics (Chapter 7.1), and the econometric application of the climate modelling methodology developed in Chapter 4 (Chapter 7.2). Both the performance (Chapter 7.3) and structure (Chapter 7.4) of the resulting econometric models are then analysed. Chapter 7.4.1 analyses the extreme climate conditions that different forms of socio-economic activity are most sensitive to, and Chapter 7.4.2 examines whether socio-economic indices are more sensitive to climate at a single site (e.g. heavy rainfall for Rome) or spatially aggregated climate (e.g. heavy rainfall variance for Italy). The implications of these conclusions for Mediterranean extreme events are discussed in Chapter 7.5.

Chapter 8 summarises the main messages from Chapters 3, 4, 6, and 7, as they apply to spatial and temporal patterns, causes and impacts (Chapter 8.2) of changing climate extremes. Chapter 8.3 describes recommendations for future use of the modelling methodology applied in Chapters 4 and 7. A number of further research questions that have been highlighted throughout the analysis conducted in previous chapters are then summarised to provide avenues of future research (Chapter 8.4).