8 Summary and conclusions

8.1 Introduction

At the beginning of this thesis, a number of Research Questions were posed (Chapter 1.2) regarding the patterns, causes, and impacts of Mediterranean extreme climate. Chapters 2 and 5 developed null hypotheses regarding these questions, which were then explored in Chapters 3 and 4 (pattern, causes), and 6 and 7 (impacts). This chapter summarises the main messages and novel findings from Chapters 3, 4, 6, and 7 as they address each of the main Research Questions and null hypotheses, and also highlights recommendations for future use of the modelling techniques developed. A summary of additional Research Questions that have risen from the thesis work, and that might be explored through further study, is provided at the end of this chapter.

8.2 Summary

What are the characteristics of the spatial and temporal variability of Mediterranean climate extremes?

In order to determine the spatial and temporal patterns evident within Mediterranean extreme climate, a new and extensive Mediterranean daily data set has been constructed (84 stations, covering 35°-45°N, 10°W-30°E, from 1958-2000), from which a number of seasonal indices of extremes have been formulated. These indices represent local (station-scale) ‘moderate’ extreme behaviour (Chapter 1.3), largely through percentile-based thresholds (Chapter 1.3, 3.4.1). Indices of extremes have then been analysed in terms of seasonally averaged spatial patterns (Chapter 3.4.2), to assess regionally persistent forcing on the order of decades, shared variance between indices via correlation analysis (Chapter 3.4.3), and inter-annual trend behaviour (Chapter 3.4.4). From these analyses, it can be seen that extreme events do not behave uniformly across the Mediterranean (null hypothesis 1, Chapter 2.5), but are highly regional in nature (Chapter 3.4.5). As a function of latitude, topography, and atmospheric circulation, a large number of Mediterranean sub-regions exist that display their own distinct climatology (e.g. central Portugal, Galicia, Catalonia, Murcia, the gulfs of

Lyons and Genoa, Sicily, north western Greece, south eastern Greece) in terms of both mean and extreme climate. A number of novel findings have also resulted from the Mediterranean-wide statistical testing, as discussed below.

Partially due to enhanced temperature gradients or airflow during extreme events, topographical effects on spatial variability may be more noticeable for extreme climate than the mean (Chapter 3.4.2). Both winter frost days (TNFD) and summer heatwaves (TXHW) are affected more by proximity to coastlines than mean temperatures (e.g. between La Coruna and Santiago in northwest Spain, Figures 3.2 and 3.6). Also, the winter contrast between west coast (mostly wet) and east coast (mostly dry) rainfall regimes (Chapter 2.2.1) is more evident in terms of extremes for both west coast (more frequent, heavier rainfall) and east coast (high proportion of rainfall from extremes, generally intense) locations (Chapter 3.4.2). In some cases, spatial consistency between extreme behaviour and the mean may disappear due to topographical or atmospheric circulation effects (Chapter 3.4.2). Although mean temperatures are generally consistent with latitude, very high summer temperatures (TX90) are generally higher in the west of each country than the east (due to south-easterly circulation) (Chapter 3.4.5), and winter warm spells and frost days are more sensitive to altitude than latitude (e.g. 65km between Llobregat and Montseny Turo in northeast Spain, difference of 1706m in altitude and 58 days of frost) (Chapter 3.4.2). Previous study has linked the length of winter warm spells to altitude for the Alps (Beniston, 2005), but this work produces additional evidence for links throughout the Mediterranean, and for all seasons.

Seasonal variability is also not uniform between regions, or between indices of extremes. Rainfall extremes display different forms of seasonal variability for different regions, and groups of indices (Chapter 3.4.2), that may not be consistent that of mean rainfall (Chapter 2.2.1). Although rainfall intensity (PINT) and the duration of dry periods (PCDD) generally display similar seasonal variability, as do the magnitude (PQ90) and persistence (PX5D) of rainfall, only the intensity (PINT, peaks in autumn), and number of heavy events (PN90, peaks in winter) show a spatially consistent seasonal cycle. The winter west coast / east coast (meridional) rainfall contrast (see above) becomes a north / south (zonal) contrast in summer. Seasonal rainfall variability therefore varies both north/south and between western / eastern coasts. In terms of temperature, stations over 900m tend to exhibit lower seasonal variability than those nearer sea level (Chapter 3.4.2), particularly in terms of persistent temperature extremes (i.e., frost days and heat waves). The variation of extreme temperature with altitude is therefore seasonally dependent and at its greatest between heat waves for winter. Very high temperatures (TX90) decline less from summer to autumn for the southern Mediterranean (-3°C) than very low temperatures (TN10) do for the north (-11°C). From winter to spring, very low temperatures (TN10) increase more for the north (+7°C) than very high temperatures (TX90) do for the south (+5°C). This behaviour (i.e. greater seasonal variability for low temperatures than high temperatures) results in seasonal differences in the range of Mediterranean extreme temperatures, with the greatest range in autumn (Chapter 3.4.5).

Extreme temperature ranges have not, however, remained constant over the last half century (null hypothesis 2, Chapter 2.5). Statistically significant trends have been found showing that summer mean temperatures have been warming across the basin, less in the east (+0.01°C yr^{-1}) than west (+0.05°C yr^{-1}), western winter mean temperatures have been warming (+0.04°C yr^{-1} on average), but that winter eastern mean temperatures have been cooling (-0.05°C yr^{-1}) (Chapter 3.4.4). Warming is not consistent across the basin. Further, where warming (cooling) has occurred, trends for very high (low) temperatures are also significant (i.e. TX90 and TN10), and are greater than for the mean by +/- 0.01-0.02°C yr^{-1}. Temperature ranges have shrunk for all seasons and locations, except for Balkan winter conditions. Where mean rainfall (PREC) trends are statistically significant, it can be seen that western and eastern Mediterranean rainfall has generally declined over the last 50 years, by more for winter (-0.03mm yr^{-1}) than summer (-0.01mm yr^{-1}). Italian rainfall, however, has been increasing, due largely to statistically significant trends in the prevalence, intensity, and magnitude of spring (+0.05 days yr^{-1} PN90, +0.06mm/wd yr^{-1} PINT, +0.16mm yr^{-1} PQ90) and autumn (+0.06 days yr^{-1} PN90, +0.15mm/wd yr^{-1} PINT, +0.38mm yr^{-1} PQ90) rainfall extremes.

It can be seen from the above summary that Mediterranean climate extremes do not vary uniformly across the basin, share little seasonal or spatial variance with the mean (less so during summer) (Chapter 3.4.3), and have changed over time in terms of both spatial and seasonal variability. Further details concerning spatial and seasonal variability of extreme climate can be found in Chapter 3.4.

Do Mediterranean climate extremes show links to synoptic or meso-scale climatology? Can circulatory factors be identified that may cause extreme climate?

A large volume of literature has been reviewed (Chapter 2) in order to identify a definitive set of indices of atmospheric circulatory behaviour that may show links with indices of Mediterranean extreme climate. These have been derived from both synoptic-scale centres of action (i.e. the NAO, MOI, SOI, ABI, EBI…) (Chapter 3.5.2), and meso-scale pressure and humidity variance (i.e. principal components calculated from 2.5°x2.5° resolution reanalysis data) (Chapter 3.5.5). Statistically significant correlations between these circulation indices and climate extremes have been assessed in order to identify shared trends (Chapter 3.6). Sophisticated statistical downscaling models have then been constructed (after comprehensive sensitivity testing) to simulate extremes from circulation indices (Chapter 4.2), using both orthogonal spatial regression (OSR, a new downscaling method) and (linear and nonlinear) artificial neural networking (ANN, substantially expanded in this study compared with previous downscaling work). Linear neural network models (LBFNN) were found to perform well when compared to other methods (Chapter 4.3), and their structure (i.e. their weights) has been analysed to provide further insight into the links between extreme climate and circulatory factors (Chapter 4.4). Through this approach, a coherent picture of both empirical and statistical links between circulatory factors and extreme climate has been developed. Although extreme events are complex and (spatially) multi-scale in origin, investigation of links with circulation has allowed exploration of their underlying causes.

Links are evident between Mediterranean climate and the movements of both hemispheric-scale air masses and more localised effects (null hypothesis 3, chapter 2.5). These links are not, however, consistent across the Mediterranean, or between seasons. Empirical evidence suggests that mean climate is heavily influenced by meridional circulation during winter, and zonal circulation in summer (Chapter 2.2.1). The results of this study suggest that these two major circulation regimes are influenced by largely distinct groups of synoptic-scale phenomena. During winter and autumn, the Atlantic pressure regime (i.e. the NAO, and North Atlantic centred principal components), the Mediterranean Oscillation, and European blocking are all correlated. During summer, the North Sea Caspian Pattern (NSCP) and Atlantic blocking are highly correlated (Chapter 3.5.8).

It has also been shown that eastern Mediterranean influences generally differ from those in the western basin (Chapter 3.6, Chapter 4.4.2). In many cases, these links are stronger for measures of extreme climate than the mean (null hypothesis 4, chapter 2.5) (Chapter 3.5.8). Major relationships between synoptic influences and climate extremes, and the regions and seasons for which they are most apparent, are summarised in Table 8.1. Particularly interesting links, supported by empirical evidence (Chapter 2), correlations, shared trends, and model weights, include:

- A link between the Mediterranean Oscillation (MO) and the magnitude of both extreme warm (TX90) and cold (TN10) events in the eastern basin, due to positive phase MO circulation drawing air upward from Africa, and negative phase circulation drawing air down from Europe. Seasonal trends in the MO are consistent with warming eastern summers and cooling eastern winters.
- Differences in African influence upon south-western and south-eastern coasts. Links are apparent between northward incursions of African air and both south-western dry conditions / heatwaves, and south-eastern low temperatures / increased rainfall. This finding expands upon the ‘Omega-wave’ circulation pattern (Chapter 2.4.3) discussed by Colacino and Conte (1995) to suggest that, depending upon location, southern Mediterranean heatwave conditions may be preceded by a decline in temperature.
- A link between western Mediterranean extreme climate and the NSCP. Until now, the NSCP has only been statistically linked to conditions in Greece, Turkey, and Israel (Kutiel *et al.* 2002). The NSCP can be described as a facet of the East Atlantic/Western Russia (EAWR) pattern, linked to southerly flow over western Europe (Panagiatopoulous *et al.*, 2002). This study shows that the NSCP also influences the western

basin, and that its (considerable) effects upon extreme climate vary between high and low phases.

- Lagged (by three months) ENSO influence is shown by this study to be stronger for extremes than the mean for both Italy (dry and hot conditions) and Greece (wet and cold conditions). Prior work (Section 2.2.3), suggests that (lagged) ENSO influence may also affect southeastern Iberia (wet and cold conditions), Sicily (dry and hot conditions), Turkey (dry and hot conditions), and Israel (wet and cold conditions). It is clear that the effect of ENSO upon the Mediterranean climate is complex, and may vary with latitude.

Although the Siberian High Index shows links to low winter temperatures and mean precipitation, confirming Panagiatopolous *et al*. (2005), its influence (more western than eastern) is rarely apparent during this study. The issue of Asian influence is generally poorly resolved. Although some of the above circulatory factors are useful in determining the causes of Greek extreme climate, further work is needed to assess the strength of eastern influences upon (particularly south-eastern) Greek climate.

Do extremes of climate have a significant impact upon Mediterranean socio-economics at the national scale? If so, where are the most important sensitivities?

The impacts of climatology are becoming increasingly important to European governments and populations (Kundzewicz *et al.*, 2001). This study assesses whether or not climate extremes are of importance to southern European countries, where mean climate has been previously shown to have some effect on socio-economic activity (Chapter 5.3). Because this thesis is focused on the construction of models concerning links associated with interannual variability timescales, certain aspects of Mediterranean vulnerability have not been considered at length. With the exception of human mortality, long-term, complex, economically ‘intangible’ impacts have not been considered here (e.g. ecosystem loss through desertification, pollution, the devaluation of other non-market goods). However, a growing body of literature concerning such phenomena exists independent of studies concerning discrete extreme events (e.g. Brandt and Thornes, 1996; Perry, 2000b; Geeson *et al.,* 2002.).

Consistent (comparable) socio-economic data have been collated (at the national level) for France, Greece, Italy, Portugal and Spain. These data have then been utilised to construct indicators (i.e. anomalies) of socio-economic activity for agricultural yield, electricity consumption, and mortality, with respect to technological progress, economic and demographic growth, and breaks or steps in activity due to other non-climatic influences (e.g. accession to the EU) (Chapter 6.2). Where possible, implicit assumptions in socio-economic index construction have been discussed and tested through correlations between non-climatic factors and anomaly indices (Chapter 6.3).

Covariance (i.e. correlation) between the resulting socio-economic indices and indices of climate extremes has been evaluated (Chapter 6.4) to identify potential sensitivities and quantitative evidence for empirical links. The modelling techniques developed in Chapter 4 have then been applied as econometric up-scaling tools with station-scale indices of climate extremes as predictors (independent variables), and national-level socio-economic indices as predictands (dependent variables) (Chapter 7.2). Again, where models have displayed high levels of performance (Chapter 7.3), their structure has been analysed to further explore sensitivity in terms of spatial consistency (Chapter 7.4.1) and magnitude (Chapter 7.4.2). It has been shown that long-term (i.e. decadal) trends in socio-economic activity are generally consistent with non-climatic influence (e.g. changes in GDP), and that after controlling for such influence, different sectors of socio-economic activity show varying sensitivities to interannual climate variability, as discussed below (null hypothesis 1, Chapter 5.4). Even when using nationally aggregated socio-economic indices (as forced to by data availability issues) it has been shown that the use of fine spatial scale climate data may offer distinct advantages over nationally aggregated measures of climate. Mediterranean climate is not spatially uniform (Chapter 3.4.2), thus aggregating data would reduce the representation of extreme behaviour (Chapter 3.4.1). Due to regional sensitivities, it may also be much more efficient (in terms of data) to consider one or a small number of stations, rather than nationally aggregated data, although spatial analysis may be required to determine those regional sensitivities, and may occasionally reveal that aggregation is appropriate (Chapter 7.4.1).

For agriculture, having first removed linear increases in yield with time due to the technological improvement of farming methods, the greatest levels of climate sensitivity have been shown for permanent crops (i.e., citrus, and grape), particularly in Italy and Spain (null hypothesis 2, Chapter 5.4). Permanent crops have a greater exposure to climate risk (particularly frosts and scorching) than other crops due to a longer growth period (Chapter 5.3.3). It is evident that the model functions (e.g. linear or nonliear, Gaussian or Quadratic) most useful for modelling agricultural crop yield vary seasonally and regionally. Critical temperatures, fixed for each crop type (Rosenzweig and Liverman, 1992), may be exceeded more or less depending on seasonal and regional climate. Where such temperatures are not exceeded, relationships between climate and yield may be linear. Where they are exceeded, nonlinearities are likely to occur (Chapter 5.3.3)- certain crops may respond non-linearly in regions that generally display conditions at the warmer (enhanced growth or scorching) or colder (greater vernalization or freezing) end of their response to climate. A series of seasonal responses are also important, and yields therefore show lags with different climate conditions throughout the year. Some crops may require vernalisation (cold temperatures) during spring before flowering (warm temperatures) can occur properly. Although effects are regionally complex, sensitivities to changes in climate imply that in the future, a warming basin would generally benefit citrus and maize yields for most regions (except for the south east of Iberia and Greece), but harm grape, potato and wheat yields. A cooling of the eastern basin during winter is likely to benefit wheat yields and potato yields and declining rainfall may negatively affect maize yield (particularly during summer).

The most sensitive sector considered here is electricity consumption (measured per capita), which generally responds linearly to high temperatures for summer, and mean temperatures, low temperatures and frost days for winter (null hypothesis 3, Chapter 5.4), and more for urban regions than rural areas. For Mediterranean regions that display the coldest extremes (i.e. during winter for France and Greece), winter commercial energy may be sensitive to temperature in a nonlinear fashion. Commercial usage must scale appropriately to extremely cold conditions because of (legally enforceable) constraints on environmental requirements for workers. Residential concerns may more rapidly deploy additional (less economically expensive in the long term) measures (e.g. changes in clothing, changes in movement, changes in housing insulation) to adapt to temperature changes, thus reducing the need for changes in electricity consumption under very cold conditions. The implications of changes in extreme and mean climate suggest that as Mediterranean summers become increasingly warm (over time) the need for residential cooling will increase. However, during winter the need for warming is likely to decrease in the western basin and increase in the east, generally consistent with trends in low, but not extremely low temperatures (Chapter 7.4).

Correlations and modelling results suggest a high level of climate sensitivity for winter excess mortality in Italy and Spain, summer excess mortality in Spain, and Greek elderly mortality (null hypothesis 4, Chapter 5.4). It has been suggested that acclimatization to cold and damp winter conditions may result in increased sensitivity to climate, and that acclimatization to hot summer conditions is likely to decrease sensitivity (Kalkstein and Davis, 1989). Also, that acclimatization and avoidance processes are weaker for the old than the young (Chapter 5.3.5). When compared to the variation of climate across the Mediterranean (Chapter 3.4.2), the sensitivities described above (Chapter 7.3) are consistent with the acclimatization process (Chapter 5.3.5) and (generally) population density (Chapter 7.4.1). It can be seen that winter mortality is likely to decrease in response to western and central winter warming, but that summer mortality is likely to increase due to summer warming, more so for Spain than Greece. Accurately capturing the sensitivity of mortality to climate may require the use of functions that vary both seasonally and regionally (as for agriculture), although in general non-linear models are more appropriate than linear functions. Non-linearities are likely to appear in the sensitivity of mortality to climate with respect to zones of comfort, critical temperatures, and the proportion of population (e.g. those over 65) susceptible to climate (Chapter 5.3.5), all of which may alter with acclimatization.

Current evidence suggests that past variations in EU GDP are inflexible to climate (Munich Re, 2003). The sectors shown to be sensitive to climate variability in this study are not consistent with the most economically important (in terms of GDP generation) activities in the EU (this may not be the case for developing countries). However, the results presented here clearly show that sensitivities to extreme climate do exist within sectors of the Mediterranean economy, and that (for certain regions), complex relationships may be observed with extremes of climate even within nationally aggregated measures of socio-economic activity. Serious implications for adaptation policy can therefore be drawn from these results, and some level of co-ordinated national response is required if the effects of regional climate extremes upon the sectors under consideration are to be minimised. Areas which display strong trends in extreme behaviour, and significant links to sensitive sectors, may be particularly important to decision makers (Table 8.2). Although the EU currently favours the application of unilateral policy, this study suggests that a Mediterranean-wide response to socio-economic climate sensitivities cannot work efficiently. Policy must be specified with regional concerns in mind. Adaptation policy prepared for Mediterranean warming, for instance, is likely to fail if Greek temperatures continue to decrease during winter. If the trends shown in this study continue in the future, an increasing contrast between winter conditions for the eastern and western basins is only likely to exacerbate the need to consider adaptation at a regional level (Section 8.4).

8.3 Recommendations for model use

Two statistical models, Orthogonal Spatial Regression (OSR) and Artificial Neural Networking (ANN), have been developed in this study (Chapter 4.2 and 7.2) for application to both the downscaling of climate extremes (from synoptic scale circulation) (Chapter 4.3) and the upscaling of socio-economic indices (from indices of climate extremes) (Chapter 7.3). Both of these models have been tested for systematic sensitivities (to changes in predictor and predictand sets, and in neural network starting values) in order to develop objective, optimal parameters, rather than use arbitrary values (Chapter 4.2.3 and Chapter 7.3.1). When applied with objectively identified parameter values, with respect to the statistical assumptions that statistical (regressive) models must conform to (Chapter 1.3), these models possess a variety of useful qualities. Due to its PCA core, OSR (a regressive method) includes spatial analysis, automatic aggregation of data based upon variance, rather than mean values, and an ability to utilise predictands and predictors that display multi-collinearity (Chapter 4.2.1). The application of an array of ANN models (which interpolate relationships in a multi-dimensional space) results in a set of models calibrated to regional data over a large number of iterations, that automatically weight irrelevant predictors to zero, and that may display non-linearity if used with an appropriate basis function (Chapter

4.2.2). Issues may arise when applying these (or other) models however, and the following recommendations for use apply.

Model performance varies systematically by season (Chapter 4.2.3). Seasonally dominant forms of climate, such as winter low temperatures and heavy rainfall, or summer high temperatures and heat waves, are relatively well modelled in every season, but other types of extreme climate (e.g. winter warm spells, summer low temperatures), are not as skilfully reproduced. This seasonal variation in skill is less apparent when using non-linear ANN models than linear models, and is generally smaller for ANN models than OSR models. If considering climate conditions outside of the dominant mode of variability (such as winter warm spells), non-linear ANN models are therefore recommended as a more appropriate approach than other modelling methods. However, seasonal variability in performance may cause non-linear ANN models to fail for certain conditions (Chapter 4.3.3), particularly for summer rainfall indices. Therefore, as for other forms of downscaling (Goodess *et al.*, 2006), a multi-model approach is recommended that uses different forms of model (e.g., both linear and non-linear ANNS, both ANN and OSR)

The overdispersion problem (Katz and Zheng, 1999) causes underestimation of variance for both of the models used in this study (Chapter 4.3.2), for both statistical downscaling, and socio-economic upscaling. However, ANN models are generally less susceptible to the underestimation of variance than OSR methods (Chapter 4.3.2). When considering variables for which overdispersion may be a serious issue, i.e. rainfall data, or data regarding Mediterranean autumn climate conditions (which display a greater range than other seasons) ANN models may be more appropriate (Chapter 4.3.2). However, ANN models both over- and underestimate variance, and the underestimation of variance by OSR models is generally more predictable. When applied to socio-economic indices, however, this contrast becomes less distinct.

For modelling Mediterranean climate or socio-economic activity, it has been found that the most appropriate set of model predictors varies depending upon season, country, and the predictand under consideration. Pre-selection of predictors (through step-wise regression, or correlation, or some other technique) may hamper ANN models, but benefit the performance of regressive models (including OSR) (Chapter

4.2.2). OSR requires only one model to encompass an array of spatially distributed predictors and/or predictands (rather than an array of models, e.g. ANN) through the construction of principal components (Chapter 4.2.1). To take advantage of this quality, a predictor/predictand set that is consistent across space is recommended. The selection of OSR predictors should be a careful balance between this, and the use of only relevant predictors. The pre-selection process for OSR predictors may, therefore, prove difficult, but gains in performance can be found as a result.

When using climate indices as predictors (i.e. in econometric upscaling) it has been demonstrated that the use of aggregate indices is largely unnecessary (Chapter 7.4.2). Climate extremes are relevant to socio-economic activity (occasionally more so than the mean), and information regarding them may be lost through spatial aggregation (Chapter 1.3, Chapter 3.2.1). Furthermore, ANN arrays benefit from local calibration of individual models upon station-scale data (Chapter 4.2.2, Chapter 4.2.3), the OSR approach automatically aggregates data based upon variance (rather than the mean, more appropriate for the application of extreme data) (Chapter 4.2.1), and in many cases (such as for electricity consumption) the use of single stations (e.g. those close to urban centres) as predictors can be more effective than the use of large-spatial-scale indices (As generated by OSR), which may contain redundant or confounding information (Chapter 7.4.2). In some cases, however (e.g. for Italian Grape Yield), the most (spatially) appropriate predictors are not obvious (Chapter 7.4.2), and either some level of spatial analysis, or a modelling technique capable of discriminating the relevance of regional predictors (such as OSR) is necessary. OSR is only capable of forming aggregate predictors (Chapter 4.2.1), and where the majority of spatial variance is irrelevant to a given predictand, skill is likely to suffer. In such instances, the ANN approach is more appropriate, as each location in the array is assessed individually. Spatial issues concerning the choice of predictors for econometric upscaling are non-trivial and should not be dismissed through the arbitrary use of aggregate indices of climate.

Socio-economic sensitivity is highly complex, and the functional form (i.e. the selection of predictors, and underlying mathematical function) required for best model performance varies depending on regions, seasons, and the predictand under consideration (e.g. between different crop types) (Chapter 7.3.2). In this study the use of multiple functional forms has allowed for high levels of skill in replicating some socio-economic data, particularly for electricity consumption (largely linear), and permanent crop yield (non-linear) (Chapter 7.3.2), but significant uncertainties still exist. For one region / set of climate conditions, relationships with a given socio-economic sector may approximate linearity, while for the same relationship but a different region, non-linearities may appear. Critical levels in relationships (i.e. ‘turning points’) have not been identified in this study, and the forms of modelling developed here are not ideal for doing so. Further, non-climatic differences in sensitivity exist between different aspects of socio-economic activity (e.g. between commercial and residential electricity consumption) that may introduce further uncertainty. However, where the underlying functional form is unknown, the use of multi-model ensembles may help to partially constrain uncertainties (as for climate downscaling). The application of an array of ANN models is intensive in terms of time and computational power. Although OSR models generally display lower levels of skill, due (in part) to their ability to cope with multi-collinearity, they can be applied to many variables simultaneously, and are therefore far more efficient. As OSR models are also relatively simple to configure (with few starting parameters to adjust) they should be considered when deploying multi-model ensembles for either statistical downscaling or socio-economic upscaling.

It has been demonstrated that there is scope for the statistical downscaling of Mediterranean climate extremes from circulation indices, and the upscaling of certain socio-economic forms of activity from climate extremes (most notably for electricity consumption). When analysing links between atmospheric circulation and extremes of Mediterranean climate, linear neural networks have been found to give the best performance, and their use is recommended for future work. For socio-economic upscaling it has been found that there is a greater distinction in performance between linear and nonlinear methods than between different forms of nonlinear model, although nonlinearities may be apparent for one region and not for another. When modelling socio-economic activity the consideration of nonlinear methods is therefore recommended as part of a multi-model approach.

8.4 Future research

Many parts of this thesis act as a foundation for work that may help to predict extreme climate behaviour and its impacts given a change in global climate and atmospheric circulation. If the relationships explored in this study (see above) remain stationary in the future, then there is substantial scope for improvement of the methods developed here through further work on data availability, the characteristics of Asian and Middle-eastern synoptic-scale circulation, the limitation of variance underestimation, the use of GCM output, development of the use of econometric theory, regional sensitivities to climate change, and nonlinearities evident in relationships between climatology and socioeconomic activity.

Although the station data set compiled in Chapter 3.2.1 is the most comprehensive Mediterranean extreme climate data set used to date, a number of countries that possess (at least in part) a Mediterranean climate (as defined by the Cs Koppen climate type) (Chapter 2.2.1) have not been adequately represented by either climatological or socio-economic data (Chapter 3.2.1). With additional eastern data, the role of both the NSCP and Asian circulation, and the influences of ENSO, the NSCP and the MO, could be explored in greater depth. The NSCP, particularly, may have wider applications than previously identified, including a link between positive phases of the NSCP and powerful eastern basin winds (the Bora and Vardarac) (Chapter 4.4.2). The role of the Asiatic summer thermal pressure system is poorly constrained in this study due to a lack of empirical relationships or representative indices of circulatory behaviour (Chapter 3.5.2). The causes of extreme climate for the eastern and south eastern Balkans still require further analysis (Chapter 4.4.3), and the construction of new circulation indices (from centres of action evident within pressure or humidity data) representative of Middle Eastern and south west Asian influence (e.g. the Asiatic or Indian monsoons) is likely to aid such study.

Although the use of percentile-based thresholds has proven useful in defining extremes (Chapter 3.4.1) across a distinctly heterogeneous climate (Chapter 2.2.1, Chapter 3.4.2), a recalculation of the frost days (TNFD) index to make null values less common (Chapter 4.2.3) would be desirable. If interested in coldsnaps, an inversion of the heatwave duration index (Chapter 3.4.1) may prove useful, although this approach would not specifically quantify frost conditions. Further, it can be seen that certain aspects of both coldsnap and heatwave behaviour require further attention (Chapter 3.4.2): Warming behaviour has been shown to be more exaggerated for the south of Spain and Italy than the north, and the duration of summer heat waves appears to be increasing in northern Spain and Italy faster than the south. The number of winter frost days is also increasing in southern Greece faster than for the north. Regions currently affected by heatwave or coldsnap conditions may be larger than those in the recent past (Chapter 3.4.2). Research concerning Mediterranean heatwaves and their behaviour over time should therefore consider changes in both their magnitude / duration, and their spatial scale.

From the models developed here, it is possible to construct a hybrid method of statistical downscaling to combine the features of both OSR and ANN techniques (Chapter 4.2). There is no statistical reason why the regression part of the newly adapted OSR technique could not be replaced by a neural network form of surface fitting, allowing for a nonlinear approach to the modelling of orthogonal spatial variance. Although it has been shown for the Mediterranean climate that linear neural networks outperform non-linear networks (Chapter 4.3.3), this may not be the case for other regions, and for socio-economic upscaling OSR and ANN models have shown distinct levels of skill for different applications (i.e. different sectors of socio-economic activity and different seasons) (Chapter 7.3.5) that could be beneficially combined in a hybrid technique. Both the under- and over-estimation of variance (Chapter 4.3.2) may be reduced for a hybrid method, but if not then downscaling studies must consider dispersion (Katz and Zheng, 1999) issues further. If dispersion can be resolved (e.g. through a more appropriate ANN basis function, or possibly logits) (Chapter 7.2.3) then there is definite scope for the modelling of changes in extreme behaviour at the regional level for future time periods using GCM output (consistent with reanalysis data in terms of resolution, and most reliable parameters, Chapter 3.2.2) (Abaurrea and Asin, 2005) and the methods developed in this thesis.

Further, there is the potential to use modelled extremes to estimate changes in selected socio-economic impacts (e.g. at least for electricity consumption) over relatively large areas (Chapter 7.3.3). As demonstrated in this study, the statistical models used for climate downscaling can be appropriate for use in econometric applications, and econometrics has much to offer climatology (Chapter 7.2). This study has bypassed the complex issue of temporally lagged dependent variables but econometric theory suggests techniques for the inclusion of lagged dependent variables in econometric models (through adjustment and expectation techniques) (Johnston, 1972; Anderson and Hsiao, 1982; Gujurati, 2003). This thesis leaves great potential for further collaboration between researchers in the statistical downscaling of climate, and practitioners of econometrics, beyond the application of Ordinary Least Squares methodology (Galeotti et al., 2004; Bigano et al., 2005).

However, this study highlights the fact that although national level sensitivity analyses are feasible (and that the impacts of climate change upon socio-economic activity do not necessarily balance at the national level), they may indicate a requirement for more localised analysis (Chapter 7.4.2). Quantative studies of the kind developed here require much more data (i.e. demographic, land use, and financial) where the need to normalise socio-economic data between small-scale regions is evident (Chapter 6.2.2), and it has been illustrated that such data is not (generally) currently available (Chapter 6.2.1). In some circumstances, the use of nationally aggregated socio-economic data may be particularly undesirable, (e.g. between north / south Italy and France, both of which show distinct socio-economic and climatic behaviour). The need for intense development of socio-economic data provision is evident.

There are a number of socio-economic factors that have not been considered in this study. Although indices of activity have been chosen to minimise the problem (e.g. electricity consumption, rather than supply) (Chapter 6.2.2), each country has been treated as an isolated body, and the interactions between them (e.g. the European electricity market generally involves large companies providing to more than one country) may be of interest to further work. Furthermore, although the models developed in Chapter 7.2 do allow for the effects of multiple forms of climate extreme simultaneously, the effects of multiple (within one season) or compound extreme events (e.g the occurrence of flooding shortly after drought conditions) have not been a focus of this study, and should be considered further in future work, if such effects can be represented adequately in predictor sets.

The models and analyses developed here have provided fundamental input into a future vulnerability assessment of the Mediterranean region and, in particular, have opened up scope for the study of nonlinear links between climate and socio-economic activity (as seen in every sector under consideration), that may vary between countries (Chapter 7.3). If the trends in Mediterranean climate extremes identified in this thesis persist into the future and relationships remain stationary (Chapter 3.3.5), then as Mediterranean extremes of climate increase in magnitude and affect a wider area (Chapter 3.4.4), nonlinearities in energy use, agriculture, and mortality, may appear or become more relevant to socio-economic development within the basin (Chapter 7.3). Future work is required to characterise these non-linearities further, but this study shows where such issues are already relevant (Chapter 7.3). A number of specific circumstances of concern, toward which further research and adaptation efforts should be focused, have been highlighted (Table 8.2).

Table 8.1: Summary of major synoptic influences relevant to Mediterranean extreme climate. For acronyms see Table 3.5.

Synoptic Influence		Seasons	Regions	Indices
Atlantic Pressure regime	-ve phase NAO	DJF	West	+TX90, +PCDD, +PN90, -PX5D
	+ve phase NAO	DJF, SON	West	-TN10, +TNFD, +PF90, +PN90
	Atlantic blocking	DJF	West, Central	-TN10, +TNFD, +HWDI, +PCDD
		JJA	West	+TX90, +HWDI, +PCDD
		MAM, SON	Central	+TNFD, +HWDI, +PCDD
	Euro-atlantic blocking	DJF	West	+TX90, +PQ90, +PF90, +PX5D
		SON	East	
European blocking		DJF	West	+TX90, +PQ90, +PINT, +PCDD
		MAM	East	+TNFD, +HWDI, +PQ90, +PINT, +PCDD
		JJA	East	+TX90, +PCDD, +PN90
Mediterranean Oscillation		DJF, SON	West	+PCDD
		DJF, JJA	East	+TAVG, +TX90, -TN10
African airmass		All year	West	+TX90
		DJF	West	+PCDD, +PINT, -TNFD, +PN90, +PF90
		SON	West	+HWDI
		JJA	East	+HWDI, +TN10, -PREC
North Sea Caspian Pattern	-ve phase NSCP	DJF	West	+TX90, -TNFD, +PREC, -PCDD, -PN90, -PX5D
	+ve phase NSCP	MAM	West, Central	+TX90, -TNFD, -PREC, +PCDD, +PN90, +PX5D
El Nino Southern Oscillation		DJF	Central	+TX90, +PCDD
		SON	Eastern	+TNFD, +PF90,

Table 8.2: Areas of high sensitivity and interest to decision makers.

Region	Climate trend	Risk	Sensitivity
Northern Iberia	Increasing summer heatwaves	Heat wave	Electricity consumption, Citrus, Grape, Potato, and Wheat yield, summer mortality
North west Spain	Increasing magnitude and persistence of winter extreme rainfall	Flooding	Maize yield, Grape yield, Wheat yield
Southern Iberia	Increasing summer high temperatures	Heat wave	Electricity consumption, Citrus and Maize yields
Southern Portugal	Increasing length of dry spells	Drought	Maize yield, Elderly mortality
South east Spain	Increasing proportion and frequency of extreme winter rainfall, decreasing mean rainfall.	Flooding	Maize yield, Grape yield, Wheat yield
South east Spain	Increasing length of dry spells	Drought	Maize yield, Potato yield, Wheat yield
Gulf of Genoa (France and Spain)	Increasing magnitude, intensity, and frequency of extreme spring rainfall.	Flooding	Spring mortality, Grape yield, Wheat yield, Citrus yield, Elderly mortality,
Western Italy	Increasing rainfall	Flooding	Grape yield, Potato yield, Wheat yield, Spring mortality, Autumn mortality
Southern Greece	Increasing winter frost conditions	Cold-snap	Electricity consumption, Potato yields, Wheat yields
Southern Greece	Increasing summer heat wave conditions	Heat wave	Electricity consumption, Elderly Mortality
South West Greece	Decreasing mean rainfall.	Drought	Maize yield, Grape yield, Wheat yield
High altitude stations (>900m)	Increasing winter warm spells	Flooding	