Projected Changes in Extreme Weather and Climate Events in Europe

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Introduction

Extreme weather and climate events have wide ranging impacts on society as well as on biophysical systems. In 2003 for example there were several noteworthy events across Europe, including annual temperature anomalies of 1–2°C over Central and Western Europe, prolonged summer drought, a major heat wave, and severe wildfires in Portugal, France and the Mediterranean. The consequences were significant economic losses as well as human fatalities. The economic losses have been estimated at US$18,619 million with drought accounting for one third of the total (Munich Re, 2004); the majority of the fatalities are most likely attributable to the heat wave that gripped Europe for almost two weeks in early August. Clearly 2003 is a pertinent example of how the weather and climate can produce conditions that are outside the coping range of society.

That society, on occasions, is unable to cope with extreme weather and climate events is concerning, especially as increases in the frequency and intensity of certain events are predicted by some global climate change projections. The purpose of this chapter is to illustrate ways in which climate change may affect the occurrence of extreme events, consider the observational record of climate extremes for Europe and present the results of one projection of the impact of climate change on extreme events over Europe. Some of the issues associated with the analysis of extremes are presented first.

Types of Extreme Events

Extreme events come in many different shapes and sizes. Events occurring over short time scales, between less than 1 day and 6–10 days, are often referred to as extreme weather events. For example, tornadoes and thunderstorms usually have durations shorter than a day. The latter period, which is often referred to as the synoptic time scale, is typical for the weather associated with low- or high-pressure systems that usually bring unsettled (wet and windy) or settled (hot/cold and dry) weather respectively. Beyond the synoptic time scale lie extreme climate events. Examples include hot and dry summers or wet and stormy winters, which may be the product of the cumulative effect of a number of hot dry periods or a high frequency of intense rain-bearing cyclonic systems. Extreme events also occur on a range of spatial scales, from concentrated events such as tornadoes to diffuse events such as droughts. Extreme events can further be classified as simple or complex. Simple extremes are characterised by a single variable such as temperature, whereas complex extremes might involve a critical combination of variables associated with a particular weather or climate phenomenon such as a cyclone (rainfall and wind) or drought (little precipitation and high temperatures).

The different forms of extreme events have implications for monitoring. Generally it is easier to monitor acute events, such as floods or windstorms, because of their high magnitude and short duration. In contrast, the onset of chronic events such as droughts is difficult to detect because of the long lead-time and imperceptible transformation of the environment.

The multitude of extreme event types has also led to a proliferation of definitions appropriate for different applications at different times and places. For example, the Intergovernmental Panel on Climate Change (IPCC) defines an extreme weather event as 'an event that is rare within its statistical reference distribution at a particular place' and continues: 'Definitions of "rare" vary but an extreme weather event would normally be as rare or rarer than the 10^{th} or 90^{th} percentile' (IPCC, 2001, page 790). Other definitions might be more meaningful in other contexts however: an event may be considered extreme merely if some of its characteristics, such as magnitude, duration, speed of onset or intensity, lie outside a particular society's experiential or coping range, whether or not the event is rare. Applying definitions out of context can therefore be misleading and causes confusion, and attempting to formulate a universal definition of 'extreme' is misguided. Studies should simply adopt the most apposite definition and state it precisely.

Climate Change and Changes in Extreme Events

In order to gauge how extreme a particular event is, the typical values of climate variables and the relative frequencies of those values must be known. These statistical properties are captured by the probability distribution of a climate variable. For example, the distribution of temperature is often approximately Gaussian, identified with a symmetric bell-shaped curve, while precipitation approximately follows the asymmetric gamma distribution that is truncated at zero and has a longer upper tail of high values. Useful summaries of probability distributions include measures of the *location*, *scale* (or spread) and *shape* (or skewness). The mean value is a common measure of location, while the standard deviation (the square root of the variance) measures the scale. Another measure of location is the median, the level below which values from the distribution fall 50% of the time. This is also known as the 50^{th} percentile. Other percentiles are defined similarly and a small set of them can provide an informative summary of a distribution: for example, the 90^{th}, 95^{th} and 99^{th} percentiles are sometimes used to summarise the upper tail of a distribution. Percentiles can also be used to define measures of scale such as the inter-quartile range, which is the difference between the 75^{th} and 25^{th} percentiles, and measures of shape such as the Yule-Kendall skewness statistic, positive (negative) values of which indicate that the upper (lower) tail of the distribution is the longer.

The statistical characteristics of weather and climate events could be affected by climate change in a number of ways (Figure 1). For example, in the case of temperature there simply could be a shift in location towards higher (warmer) values (Figure 1a). This would result in an increase in the number of extreme events at the hot end and a decrease at the cold end of the distribution. Consequently, there would be not only more hot weather but also more record hot and less cold weather. As the probability of exceeding a fixed threshold changes non-linearly with shifts in location, a small change in the location can result in a large relative change in the probability of extremes (Mearns et al., 1984; Meehl et al., 2000; IPCC 2001).

In addition to a change in location, there may be a change in the scale of the distribution (Figure 1b). This would produce changes in the occurrence of extreme events at either end of the distribution and potentially have a greater effect on the frequency of extreme events than a simple change in location (Katz and Brown, 1992). In addition to changes in the location and scale, changes in the shape of a distribution can be envisaged such that the distribution, of temperature for example, becomes skewed to the right (Figure 1c). This would result in much more hot and record hot weather and fewer cold events. More discussion of possible changes is given in Ferro et al. (2004).

Many other types of change and combinations of changes in the distributions of climate variables are of course possible and will result in different climate outcomes (IPCC, 2001). For example, a pure shift in location is unlikely to occur in distributions of non-negative valued variables such as precipitation, for which location and scale often change simultaneously. This can alter disproportionately the occurrence of various aspects of precipitation extremes such as seasonal totals or daily intensities (Easterling, 2000).

Trends in Observed Climate Extremes

Studies concerning climate trends at various locations across Europe abound. However, results from these are not directly comparable because of the contrasts in data set length and quality and the different methods used for data processing and trend analysis (Wijngaard et al., 2003). Nevertheless, common patterns appear to be emerging. For most locations across Europe, increases in minimum temperature appear to be greater than in maximum temperature (Klein-Tank et al., 2002). In many cases this has been attributed to increasing nocturnal cloud cover (Brazdil et al., 1996; Huth, 2001; Wibig and Glowicki, 2002). In relation to human thermal comfort, McGregor et al. (2002) have noted for Athens, Greece, a tendency towards an increase in the length of the discomfort season over the period 1966–1995.

Precipitation studies have shown increases in total precipitation for some locations but decreases for others. Generally, rainfall increases have been noted for non-Mediterranean climates (New et al., 2001; González-Rouco et al., 1999; González-Hidalgo et al., 2001; Hanseen-Bauer and Forland, 1998; Windman and Schar, 1998; Garcia-Herrara et al., 2003). As well as precipitation totals, precipitation intensity has received some attention because potential increases in this precipitation characteristic have implications for flooding and soil erosion. For the UK, precipitation intensity increases have been observed and are more marked for the winter months (Osborn et al., 2000). This matches what has been found for the European Alpine region (Frei and Schar, 2001). Some studies point to intensity increases being associated with certain types of weather systems (Windman and Schar, 1998) and the changing relationships between wet day occurrence and wet day rainfall totals (Brunetti et al., 2000; 2001).

Perhaps the clearest picture of the situation concerning trends in extremes of European climate can be garnered from the analyses presented as part of the European Climate Assessment and Dataset project (Klein-Tank et al., 2002). This project has compiled numerous climate time series using consistent procedures for the period 1946–1999 (http://www.knmi.nl/samenw/eca/index.html). An analysis of these reveals that observed trends across Europe demonstrate a greater consistency with the trends predicted by climate models for temperature (Figure 2) than for precipitation. Further, in the case of both temperature and precipitation, the observed trends are far weaker in the first half of the analysis period than in the second half (1975–1999).

A limited number of studies have considered trends in storminess across Europe. Of the studies undertaken most have focused on Western Europe and have concluded that there are no discernable trends in storminess at this geographical scale. Rather inter-annual to decadal variability dominates and there is geographical variability in the temporal pattern of storminess (Alexandersson et al., 2000; Bijl, 1999; Flocas et al., 2001; Maheras et al., 2001; Pryor and Bathelmie, 2003).

Projected Changes of Extreme Events

Arriving at a climate projection involves several steps. Firstly scenarios of energy production are used to construct Greenhouse Gas Emission (GHGE) scenarios. These are then used as input into a carbon cycle model that provides estimates of the sinks and sources of carbon. The balance between these provides an estimate of the increase in carbon dioxide concentrations in the atmosphere for a certain GHGE scenario. Global climate models are then run in order to establish how higher carbon dioxide concentrations may affect, for example, changes in temperature and precipitation. Estimated changes in climate variables form the input into climate change impact models, the results of which are used to assess the economic and societal consequences of a given change in climate.

This section will present the results of just one projection of the impact of climate change on extreme events over Europe. The projection is based on a nested modelling strategy in that a high resolution Regional Climate Model (RCM) is driven by a much coarser resolution General Circulation Model (GCM); the latter provides the boundary conditions for the former. The RCM is HIRHAM4, developed at the Danish Meteorological Institute (Christensen et al., 1998). This model produces output of climatological fields at a resolution of 50km and is one of the RCMs being used to investigate climatic change over Europe as part of the European Union project PRUDENCE (http://prudence.dmi.dk). The impacts of climate change on extreme events are established by comparing the extreme event statistics for the current climate with that of the future climate. The current climate is represented by the output from a RCM simulation (a control simulation) of the climate for the period 1961–1990, which is a standard World Meteorological Organization reference period. The future climate is represented by the period of 2071–2100. In order to achieve predictions for this period, the HIRHAM4 RCM is ‘forced’ with the IPCC A2 emissions scenario (Naki´cenovi´c et al., 2000). This scenario assumes a high level of emissions throughout the 21st century, resulting from low priorities concerning greenhouse-gas abatement strategies and high population growth in the developing world. Under this scenario, atmospheric CO2 levels will reach about 800 ppmv by 2100 (three times their pre-industrial values). Projections based on this scenario therefore provide a single-model estimate of the upper bound of climate futures discussed by the IPCC (Beniston, 2004). RCM boundary conditions are supplied by the Hadley Centre's global, atmosphere-only model HadAM3H (Pope et al., 2000), which is driven by observed sea ice and sea-surface temperatures (HadISST1) in the control simulation, and by sea ice and sea-surface temperatures simulated from the coupled model HadCM3 (Johns et al., 2003) in the future climate simulation. Note that the results presented below are from only one RCM and that quantitative differences between projections from different models can differ markedly.

Figure 3 displays summary statistics for the simulated control (1961–1990) and future (2071–2100) climates for June, July and August (JJA) daily maximum temperatures (Tmax). Noticeable differences between the two climates are widespread higher median temperatures (a change in location) with increases of 4–8^{o}C over the majority of France, Spain, Switzerland, Italy and South-eastern Europe including Turkey, similarly widespread increases in the inter-quartile range (scale) and complex changes in skewness (shape). The increases in location and scale suggest that Europe will experience not only higher daily maximum temperatures but also a greater occurrence of both anomalously hot and anomalously cold summer days. However, lower skewness, in regions such as France and the UK, would tend to favour an increase in the frequency of anomalously cold summers and a decrease in the frequency of anomalously hot summers, while the opposite would be true in regions such as Eastern Europe that are predicted to experience higher skewness. An analysis of the projected changes in the 90th percentile (Figure 4a) reveals the combined effects of these location, scale and shape changes. The change in 90th percentile (Figure 4b) is almost everywhere greater than the change in median (Figure 4c). Except in regions that experience an increase in skewness, the change in 90th percentile is mostly attributable to a change in both location and scale (Figure 4d), not just location alone.

If these projected changes in summer temperatures were to materialize then the implications for human health and availability of water resources in summer could be severe. With regards to human health, an analysis of the number of days with maximum temperature above 30°C provides a crude approximation of the way in which heat-wave incidence and duration might change across Europe. According to the HIRHMAM RCM control simulation, the majority of Western Europe currently experiences about 5–10 days per summer with maximum temperatures in excess of 30°C. However, for the period 2071–2100 the situation could be quite different with the model simulation predicting increases of up to 60 days per summer in Mediterranean countries (Figure 5). By 2100, countries such as France may experience temperatures above 30°C as often as Spain and Sicily currently experience such events. Consequently, this climate model predicts increases in heat-wave frequency and duration across most of Europe, along with prolonged dry periods and increased probability of summer drought. Using a simple definition of a heat wave, based on three successive days above 30°C, a three and ten fold increase in the duration and frequency of heat waves might be expected for many places across Europe by the end of the current century (Beniston, 2004). The extent to which such projected changes in the heat wave climate of Europe would bring about increases in heat-related mortality and morbidity depends on the level of societal adaptation to such events. With respect to this, the summer of 2003 in Europe may be a harbinger of the future, as in statistical terms the maximum temperature climate of 2003 resembles far more that predicted for 2071–2100 than the current climate (Beniston, 2004).

In addition to changes in temperature, climate change is likely to bring about changes in precipitation amount and spatial distribution. Climate models show the precipitation response to be far less certain than temperature (Deque, 2003). Generally, winter precipitation increases are predicted for most of Europe apart from the far south. In summer, Europe-wide precipitation decreases are predicted apart from the far north where summer wetness may increase. Although summer precipitation amounts are predicted to reduce substantially over large parts of Central and Southern Europe, the opposite may hold true for trends in heavy precipitation amounts. This is because climate change projections point to heavier/more intense summertime precipitation events over large parts of Europe despite overall decreases in summer precipitation amounts. This has clear implications for flash flooding in summer (Christensen and Christensen, 2003) such that intense precipitation events that lead to flooding in the Elbe, Donau, Moldau and the Rhone in 2003 are likely to become more frequent. For winter, increases in precipitation, relative to the current climate, have been simulated by both GCMs and RCMs for northern Europe (Johns et al., 2003; Ferro et al., 2004). This is mainly because in a warmer climate the atmosphere will contain more water. As for summer, increases in winter precipitation have implications for flooding especially as increased precipitation will bring soil moisture capacities closer to their maximum. Thus wet antecedent conditions are likely to increase the probability of wintertime flooding.

More humidity may also provide an additional source of energy via latent heat release during cyclogenesis and could lead to the intensification of low-pressure systems and make more water available for precipitation (Frei et al., 1998). Increases in winter precipitation over Northern Europe may also be due to changes in the position of winter storm tracks (McCabe et al., 1999), which may partly account for the slight decreases in simulated precipitation for Southern Europe. The situation regarding projections of future storminess is far less clear than that for temperature and precipitation. Although there are a growing number of studies addressing changes in storm activity as a result of climate change there is little consensus yet (Meehl et al., 2000b; IPCC 2001).

Conclusions

Conceptually, climate change may lead to an alteration of extreme weather and climate events across Europe. Trends in time series of observed extreme weather and climate indices are suggestive of changes in the climatology of extreme events over Europe. Climate change projections indicate not only the likelihood of substantial warming by 2100 but also non-linear changes in the probability of extreme events relative to the mean climate. This finding lends weight to the hypothesis that increases in the probability of extreme events across Europe are likely with climate change. Changes in the climatology of extreme events holds pressing implications for European society and economy, especially in terms of the development of effective adaptation measures to reduce the vulnerability of people, property, livelihoods and infrastructure to the fatal and otherwise damaging effects of extreme weather and climate events.

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Figure 1: Theoretical changes in the distribution of climate variable values. (a) change in mean (location); (b) change in variance (scale); (c) change in mean, variance and skewness (shape)

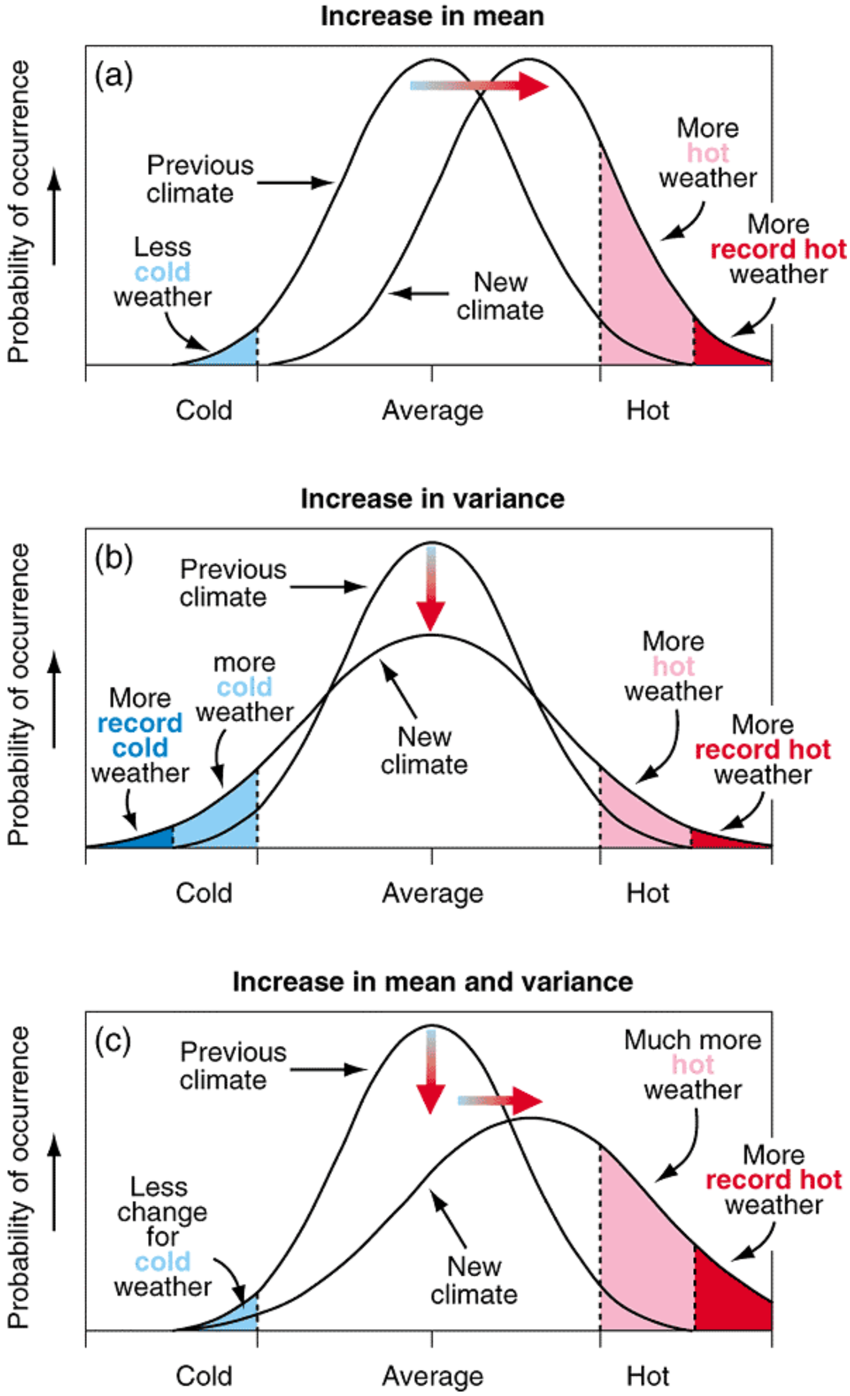
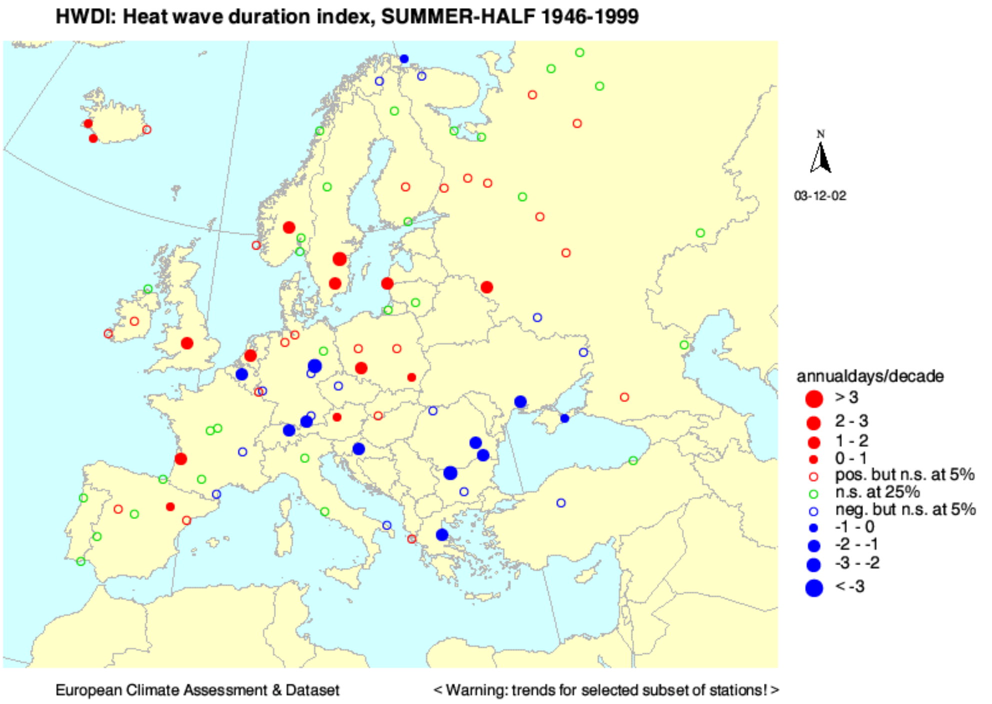


Figure 2: Observed changes in heat wave duration index, (a) 1946 – 1999; (b) 1976-1999.

(a)



(b)

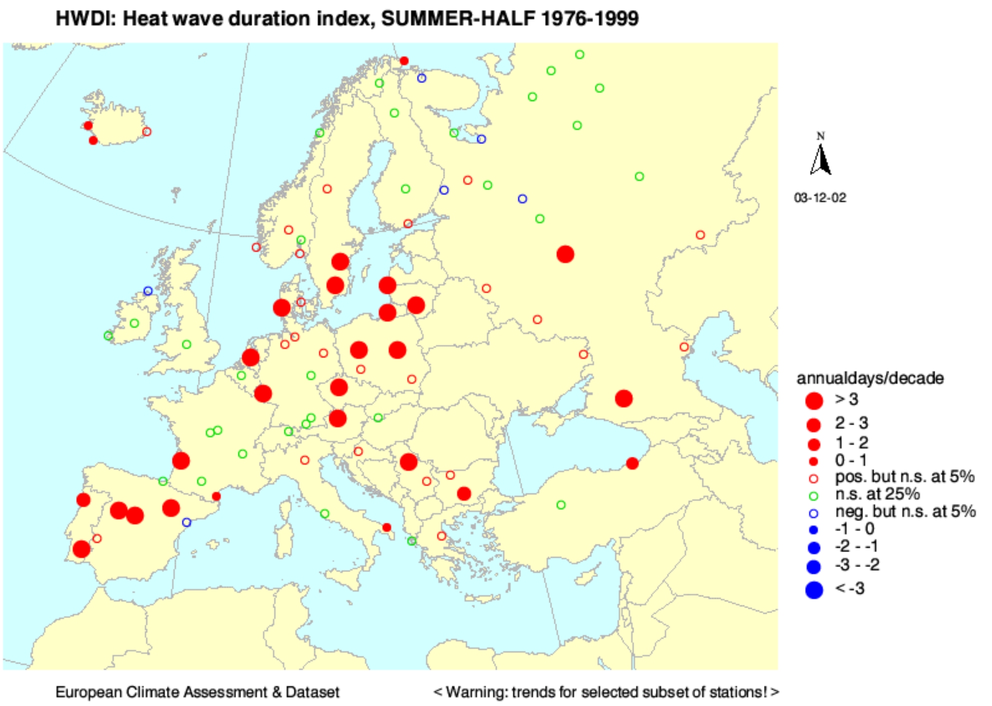


Figure 3: a) Median (°C), b) inter-quartile range (°C) and c) skewness measure for JJA daily maximum temperatures in the control; d), e) and f) the differences in the summary statistics between the scenario and control.

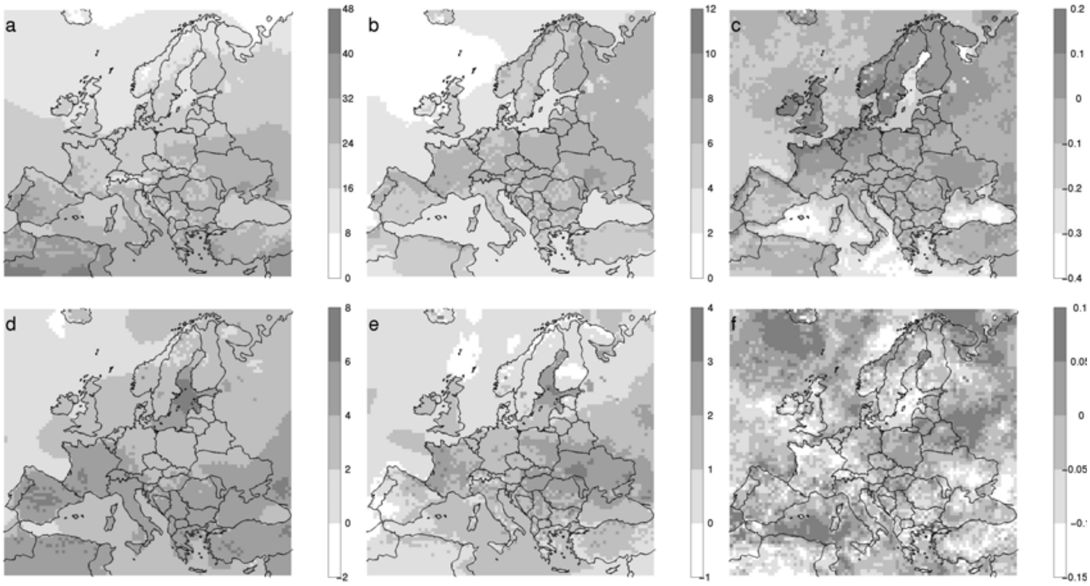


Figure 4: The 90% quantile (°C) of JJA daily maximum temperatures: a) in the control, b) the difference between the scenario and control, and the differences after adjusting for c) location, and d) both location and scale.

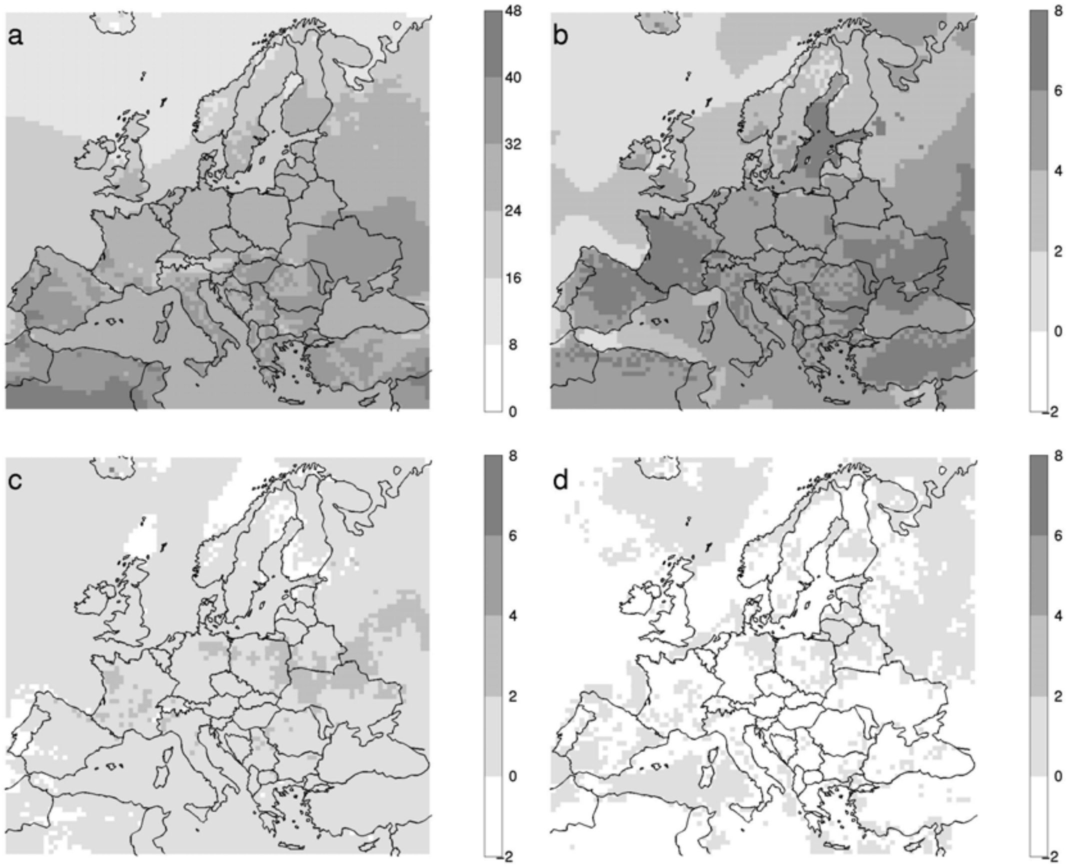


Figure 5: Difference between the mean number of JJA days with maximum temperature exceeding 30°C in the scenario (2071–2100) and the control (1961–1990).