Developed at the request of:

Research conducted by:

Climate: Observations, projections and impacts

Spain

We have reached a critical year in our response to climate change. The decisions that we made in Cancún put the UNFCCC process back on track, saw us agree to limit temperature rise to 2 °C and set us in the right direction for reaching a climate change deal to achieve this. However, we still have considerable work to do and I believe that key economies and major emitters have a leadership role in ensuring a successful outcome in Durban and beyond.

To help us articulate a meaningful response to climate change, I believe that it is important to have a robust scientific assessment of the likely impacts on individual countries across the globe. This report demonstrates that the risks of a changing climate are wide-ranging and that no country will be left untouched by climate change.

I thank the UK's Met Office Hadley Centre for their hard work in putting together such a comprehensive piece of work. I also thank the scientists and officials from the countries included in this project for their interest and valuable advice in putting it together. I hope this report will inform this key debate on one of the greatest threats to humanity.

The Rt Hon. Chris Huhne MP, Secretary of State for Energy and Climate Change

There is already strong scientific evidence that the climate has changed and will continue to change in future in response to human activities. Across the world, this is already being felt as changes to the local weather that people experience every day.

Our ability to provide useful information to help everyone understand how their environment has changed, and plan for future, is improving all the time. But there is still a long way to go. These reports – led by the Met Office Hadley Centre in collaboration with many institutes and scientists around the world – aim to provide useful, up to date and impartial information, based on the best climate science now available. This new scientific material will also contribute to the next assessment from the Intergovernmental Panel on Climate Change.

However, we must also remember that while we can provide a lot of useful information, a great many uncertainties remain. That's why I have put in place a long-term strategy at the Met Office to work ever more closely with scientists across the world. Together, we'll look for ways to combine more and better observations of the real world with improved computer models of the weather and climate; which, over time, will lead to even more detailed and confident advice being issued.

Julia Slingo, Met Office Chief Scientist

Introduction

Understanding the potential impacts of climate change is essential for informing both adaptation strategies and actions to avoid dangerous levels of climate change. A range of valuable national studies have been carried out and published, and the Intergovernmental Panel on Climate Change (IPCC) has collated and reported impacts at the global and regional scales. But assessing the impacts is scientifically challenging and has, until now, been fragmented. To date, only a limited amount of information about past climate change and its future impacts has been available at national level, while approaches to the science itself have varied between countries.

In April 2011, the Met Office Hadley Centre was asked by the United Kingdom's Secretary of State for Energy and Climate Change to compile scientifically robust and impartial information on the physical impacts of climate change for more than 20 countries. This was done using a consistent set of scenarios and as a pilot to a more comprehensive study of climate impacts. A report on the observations, projections and impacts of climate change has been prepared for each country. These provide up to date science on how the climate has already changed and the potential consequences of future changes. These reports complement those published by the IPCC as well as the more detailed climate change and impact studies published nationally.

Each report contains:

- A description of key features of national weather and climate, including an analysis of new data on extreme events.
- An assessment of the extent to which increases in greenhouse gases and aerosols in the atmosphere have altered the probability of particular seasonal temperatures compared to pre-industrial times, using a technique called 'fraction of attributable risk.'
- A prediction of future climate conditions, based on the climate model projections used in the Fourth Assessment Report from the IPCC.
- The potential impacts of climate change, based on results from the UK's Avoiding Dangerous Climate Change programme (AVOID) and supporting literature. For details visit: http://www.avoid.uk.net

The assessment of impacts at the national level, both for the AVOID programme results and the cited supporting literature, were mostly based on global studies. This was to ensure consistency, whilst recognising that this might not always provide enough focus on impacts of most relevance to a particular country. Although time available for the project was short, generally all the material available to the researchers in the project was used, unless there were good scientific reasons for not doing so. For example, some impacts areas were omitted, such as many of those associated with human health. In this case, these impacts are strongly dependant on local factors and do not easily lend themselves to the globally consistent framework used. No attempt was made to include the effect of future adaptation actions in the assessment of potential impacts. Typically, some, but not all, of the impacts are avoided by limiting global average warming to no more than 2 °C.

The Met Office Hadley Centre gratefully acknowledges the input that organisations and individuals from these countries have contributed to this study. Many nations contributed references to the literature analysis component of the project and helped to review earlier versions of these reports.

We welcome feedback and expect these reports to evolve over time. For the latest version of this report, details of how to reference it, and to provide feedback to the project team, please see the website at www.metoffice.gov.uk/climate-change/policy-relevant/obs-projections-impacts

In the longer term, we would welcome the opportunity to explore with other countries and organisations options for taking forward assessments of national level climate change impacts through international cooperation.

Summary

Climate observations

- Widespread warming has been observed over Spain since 1960 with greater warming in summer than winter.

- There is a clear trend to fewer cool nights and more warm nights since 1960, and also to fewer cool days and more warm days.

- There has been a general increase in summer temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.

- There has been a reduction in the amount of annual rainfall in the Iberian Peninsula since 1960 with the largest reduction in the northwest and the lowest reduction in the east.

Climate change projections

- For the A1B emissions scenario increases in temperature of up to around 4°C are projected over Spain, with the highest agreement between models towards the south of the country.

- Projected rainfall decreases over Spain could be over 20% in the southwest of the country, and between 10% and 20% over other parts. Spain has good ensemble agreement between the ensemble members over these projected decreases.

Climate change impacts projections

Crop yields

- A definitive conclusion on the impact of climate change on crop yields in Spain cannot be drawn from the studies included here.

- The majority of global- and regional-scale studies surveyed generally project an increase in the yield of wheat, one of Spain's major crops, over the century.

- However, simulations by the AVOID programme indicate that, of the area currently cultivated in Spain, much of it could become less suitable for agricultural production as a result of climate change.

Food security

- Spain is presently a country with extremely low levels of undernourishment. Global-scale studies included here generally project that Spain will face adverse affects on food security as a consequence of climate change over the next 40 years, but could remain food-secure largely as a result of its strong economic position in global food markets and high adaptive capacity.

Water stress and drought

- Several global-scale and national-scale studies included here project that droughts in the country could increase in frequency and magnitude with climate change, with the greatest impacts projected for the south of the country, along the Mediterranean coast.

- Similarly global-, national-, and sub-national-scale studies project increases in water stress in the country with climate change.

- Recent simulations by the AVOID programme project a median increase of around 60% of Spain's population to be exposed to water stress increases by 2100 under the A1B emissions scenario. Under an aggressive mitigation scenario, this is 25%. None of the models included in the AVOID study simulated decreases in water stress with climate change for Spain.

Pluvial flooding and rainfall

- Recent studies support conclusions from the IPCC AR4 that mean rainfall is projected to decrease over the Mediterranean area.

- There remains uncertainty over whether extreme short-term precipitation, and associated pluvial flooding, may either increase or decrease with climate change.

Fluvial flooding

- Few studies have assessed the impact of climate change on fluvial flooding in Spain. Moreover, large climate model uncertainty presently inhibits any firm conclusions with regards to changes in fluvial flood hazard in Spain under climate change scenarios.

- Simulations by the AVOID programme show a much greater tendency towards decreasing flood risk throughout the 21st century under both the A1B and a mitigation emissions scenario.

Coastal regions

- Recent studies show that sea level rise (SLR) impacts in Spain could be large in the absence of adaptation.

- For example, one study shows that by the 2080s under a high SLR scenario and without adaptation, the average annual number of people flooded could be around 321,800; with adaptation (raising of flood dykes and the application of beach nourishment), this is greatly reduced to 1,100.

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Chapter 1 – Climate Observations

Rationale

Figure 1. Location of boxes for the regional average time series (red dashed box) in Figures 3 and 5 and the attribution region (grey box) in Figure 7.

Present day weather and climate play a fundamental role in the day to day running of society. Seasonal phenomena may be advantageous and depended upon for sectors such as farming or tourism. Other events, especially extreme ones, can sometimes have serious negative impacts posing risks to life and infrastructure, and significant cost to the economy. Understanding the frequency and magnitude of these phenomena, when they pose risks or when they can be advantageous and for which sectors of society, can significantly improve societal resilience. In a changing climate it is highly valuable to understand possible future changes in both potentially hazardous events and those reoccurring seasonal events that are depended upon by sectors such as agriculture and tourism. However, in order to put potential future changes in context, the present day must first be well understood both in terms of common seasonal phenomena and extremes.

The purpose of this chapter is to summarise the weather and climate from 1960 to present day. This begins with a general climate overview including an up to date analysis of changes in surface mean temperature. These changes may be the result of a number of factors including climate change, natural variability and changes in land use. There is then a focus on extremes of temperature, precipitation and storms selected from 2000 onwards, reported to the World Meteorological Organization (WMO) Annual Statement on the Status of the Global Climate and/or the Bulletin of the American Meteorological Society (BAMS) State of the Climate reports. This is followed by a discussion of changes in moderate extremes from 1960 onwards using an updated version of the HadEX extremes database (Alexander et al., 2006) which categorises extremes of temperature and precipitation. These are core climate variables which have received significant effort from the climate research community in terms of data acquisition and processing and for which it is possible to produce long high quality records for monitoring. No new analysis is included for storms (see the methodology annex that follows for background). For seasonal temperature extremes, an attribution analysis then puts the seasons with highlighted extreme events into context of the recent climate versus a hypothetical climate in the absence of anthropogenic emissions (Christidis et al., 2011). It is important to note that we carry out our attribution analyses on seasonal mean temperatures over the entire country. Therefore these analyses do not attempt to attribute the changed likelihood of individual extreme events. The relationship between extreme events and the large scale mean temperature is likely to be complex, potentially being influenced by *inter alia* circulation changes, a greater expression of natural internal variability at smaller scales, and local processes and feedbacks. Attribution of individual extreme events is an area of developing science. The work presented here is the foundation of future plans to systematically address the region's present and projected future weather and climate and the associated impacts.

The methodology annex that follows provides details of the data shown here and of the scientific analyses underlying the discussions of changes in the mean temperature and in temperature and precipitation extremes. It also explains the methods used to attribute the likelihood of occurrence of seasonal mean temperatures.

Climate overview

Mainland Spain is situated between the latitudes of 36°N and 44°N, so that in summer high pressure usually dominates. Much of the interior of the country is a plateau with an altitude of at least 500 m above sea level. The central city Madrid has an annual mean temperature of 15°C, with a large range between 6°C in January and 25°C in July. There is only a narrow low-lying coastal plain, except in the south-west around Seville where the low-lying area reaches further inland. Here, the annual mean temperature is 19°C and winters are relatively warm. On the Mediterranean coast, sea breezes keep temperatures bearable in the summer, for example at Valencia where the mean annual temperature is 18°C, but the mean daily maximum temperature in July is 30°C, lower than at Madrid. In the north-west, the Atlantic Ocean has an influence on the climate, and summer temperatures are reduced. For example, at La Coruña the annual mean temperature is 14°C with a summer peak of only 19°C. There are mountain ranges, including the Pyrenees along the north-east border and the Sierra Nevada in the south, where temperatures decrease with altitude up to 3500m. Spain also includes the Balearic and Canary Islands. The Canary Islands, at latitude 28°N, have an annual mean temperature of 20°C close to sea level, with volcanic mountains rising over 3000m.

Overall, the largest concentration of rainfall occurs during the winter half of the year (October to March), but the seasonal variability is more marked in some regions than others. The north-west is the wettest region because it is most affected by the dominant westerlies from the Atlantic during winter. Santander, on the north-west coast, has an average annual rainfall of 1246 mm, with 60% of this falling in the winter half-year. Inland and further east, precipitation is much lower and with less seasonal variability because these areas are protected from the Atlantic influence. For example at Zaragoza in the north-east the average annual precipitation is 318 mm, and at Madrid 436 mm. In the southern coastal plain, the summer is very dry, especially in the far south-east which has an arid climate. Here, the summer is characterised by dry, sunny weather, with only 20 mm expected from June to August and approximately 50 cloudless days during these months. There is still an annual average rainfall of 533 mm at Seville however, with a relatively wet winter period.

As summer precipitation is mainly convective, it is more localised spatially and temporally, and this leads to the hazard of flooding. By contrast, the high inter-annual variability of precipitation can lead to periods of drought. Southern Spain is also prone to being affected by a heat wave hazard.

Analysis of Long-term Features in the Mean Temperature

CRUTEM3 data (Brohan et al., 2006) have been used to provide an analysis of mean temperatures from 1960 to 2010 over Spain using the median of pairwise slopes method to fit the trend (Sen, 1968; Lanzante, 1996). The methods are fully described in the methodology annex. In agreement with increasing global average temperatures (Sánchez-Lugo et al., 2011), there is a spatially consistent warming signal for temperature over mainland Spain as shown in Figure 2, consistent with previous research (UNFCCC, 2009). For the summer (June to August), there is high confidence in the warming signal throughout as the 5^{th} to 95^{th} percentiles of the slopes are of the same sign. For winter (December to February) there is a less robust warming signal with higher confidence shown in only three of the five Spanish grid-boxes. Regionally averaged trends (over grid boxes included in the red dashed box in Figure 1) calculated by the median of pairwise slopes show warming signals but with higher confidence only for summer. For winter this is 0.16 °C per decade (5^{th} to 95^{th} percentile of slopes: -0.01 to 0.33 °C per decade) and for summer this is 0.35 °C per decade (5^{th} to 95^{th} percentile of slopes: 0.24 to 0.47 °C per decade).

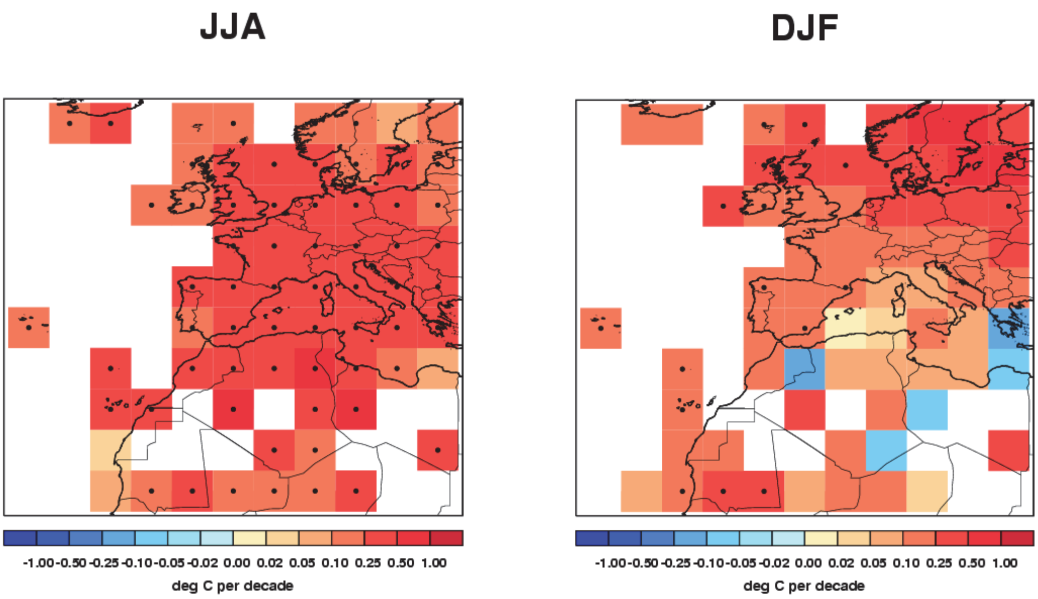

Figure 2. *Decadal trends in seasonally averaged temperatures for Spain and the surrounding regions over the period 1960 to 2010. Monthly mean anomalies from CRUTEM3 (Brohan et al. 2006) are averaged over each 3 month season (June-July-August – JJA and December-January-February – DJF). Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). There is high confidence in the trends shown if the* 5^{th} *to* 95^{th} *percentiles of the pairwise slopes do not encompass zero because here the trend is considered to be significantly different from a zero trend (no change). This is shown by a black dot in the centre of the respective grid-box.*

Temperature extremes

Both hot and cold temperature extremes can place many demands on society. While seasonal changes in temperature are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), extreme heat or cold can have serious negative impacts. Importantly, what is 'normal' for one region may be extreme for another region that is less well adapted to such temperatures.

Table 1 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The summer heat wave event during 2003 is highlighted as an example of an extreme temperature event that affected Spain.

Year	Month	Event	Details	Source
2001	Dec	Cold and snow	The northeastern region of Catalonia experienced extreme cold and snow and was virtually cut off from the rest of the country.	BAMS (Waple et al., 2002)
2003	Jul-Aug	Heat wave	Severe heat. Intense forest fires. Daily maximum temperatures in August averaged more than 40°C across most of Spain's interior.	WMO (2004) BAMS (Bell & Eichler, 2004)
2004	Jun-Jul	Heat wave	Heat wave - max temps reaching 40°C.	WMO (2005)
2006	Jul	Heat wave	Warmest European mean temperature for July	WMO (2007)

Table 1. *Selected extreme temperature events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 2000*

Recent extreme temperature events

Heat wave, summer 2003

The summer of 2003 was one of the warmest on record across parts of Europe, and in parts of Central Europe was likely the warmest since 1540 (Levinson and Waple, 2004). Two distinct periods of exceptional heat occurred during the summer season— the first in June and the second during the first half of August. The heat waves resulted from strong high pressure over western Europe. Such “blocking highs” can persist for many days in Europe during summer. In 2003, heated air from the south reinforced the strength and persistence of the heat wave, and nearly all the sun’s radiation was converted to heat because of the soil and vegetation dryness (WMO, 2004). The August heat wave was the more serious of the two, because it coincided with the normal peak in summer temperatures and was accompanied by an almost complete absence of rainfall. Daily maximum temperatures during this period averaged more than 40°C across most of interior Spain (Bell & Eichler, 2004).

The financial impact of the 2003 heat wave and drought on Spanish agriculture and forestry is estimated to have been € 810 million with 127,525 ha of forest destroyed by wildfires (UNEP, 2004).

Analysis of long-term features in moderate temperature extremes

ECA&D data (Klein Tank et al., 2002) have been used to update the HadEX extremes analysis for mainland Spain from 1960 to 2010 using daily maximum and minimum temperatures. Here we discuss changes in the frequency of cool days and nights and warm days and nights which are moderate extremes. Cool days/nights are defined as being below the 10th percentile of daily maximum/minimum temperature and warm days/nights are defined as being above the 90th percentile of the daily maximum/minimum temperature. The methods are fully described in the methodology annex.

Over the period analysed (1960-2009) there is a clear trend to fewer cool nights and more warm nights, and also to fewer cool days and more warm days (Figure 3). This matches the trend in the mean temperatures outlined in the previous section. This implies that there is a shift in the temperature distribution, with very little change in its shape. The warming signal is very coherent over the Iberian Peninsula. There is high confidence that the trends are different from zero for all grid boxes and all indices.

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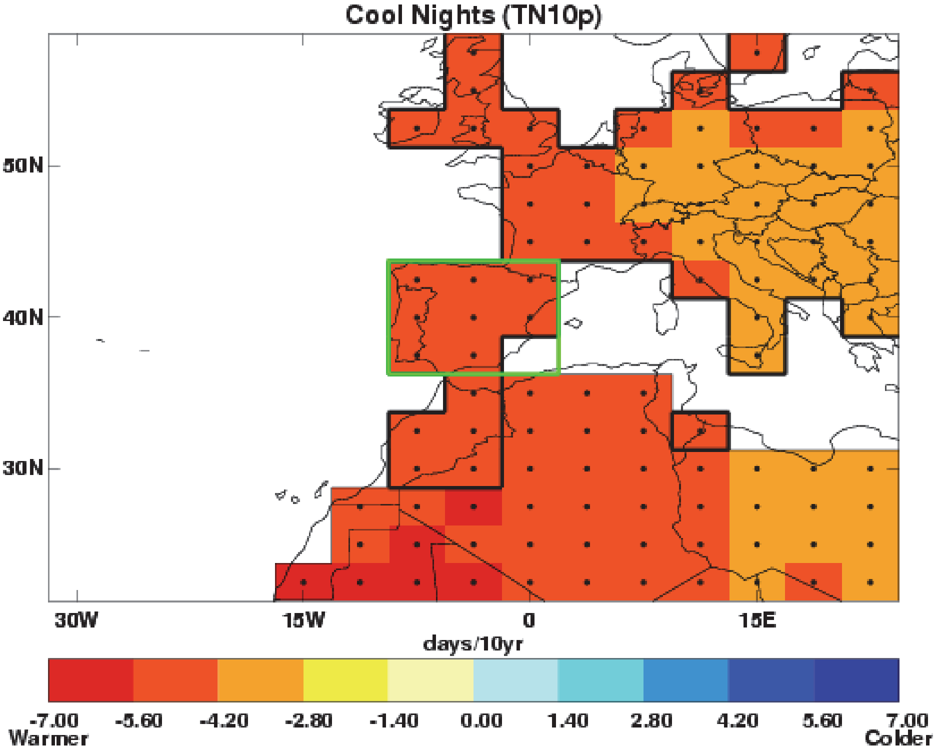

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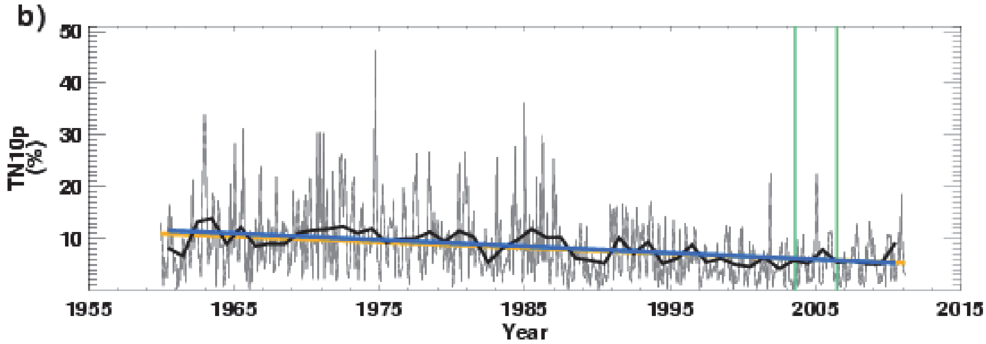

Monthly: -1.11% per decade (-1.39 to -0.84)
Total change of -5.53% from 1960 to 2011 (-6.94% to -4.18%)

Annual: -1.26% per decade (-1.71 to -0.85)
Total change of -6.28% from 1960 to 2010 (-8.54% to -4.25%)

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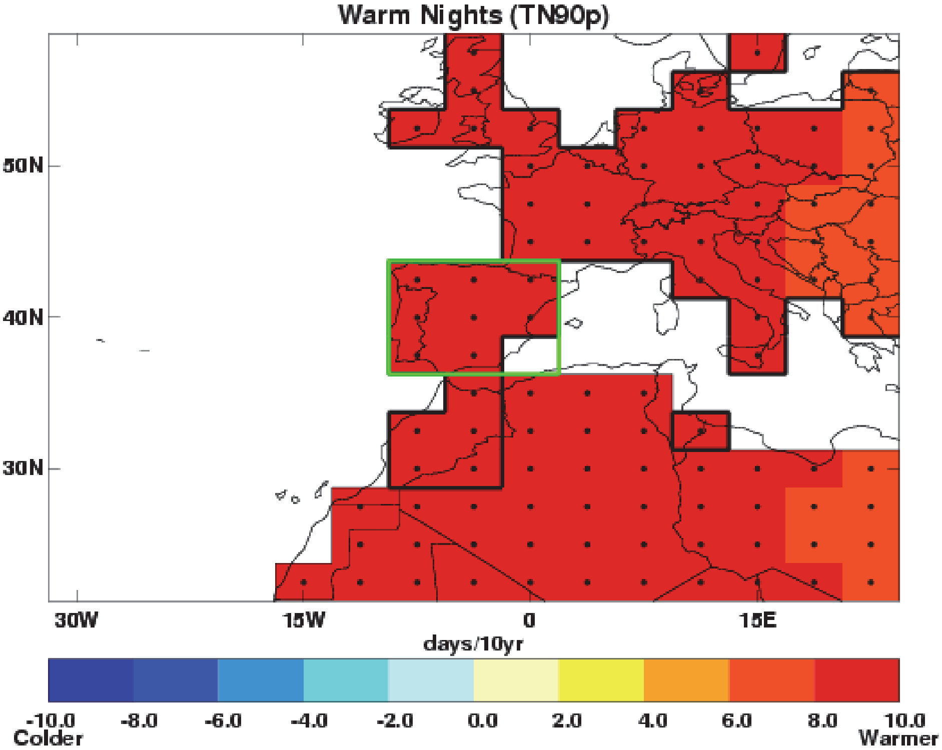

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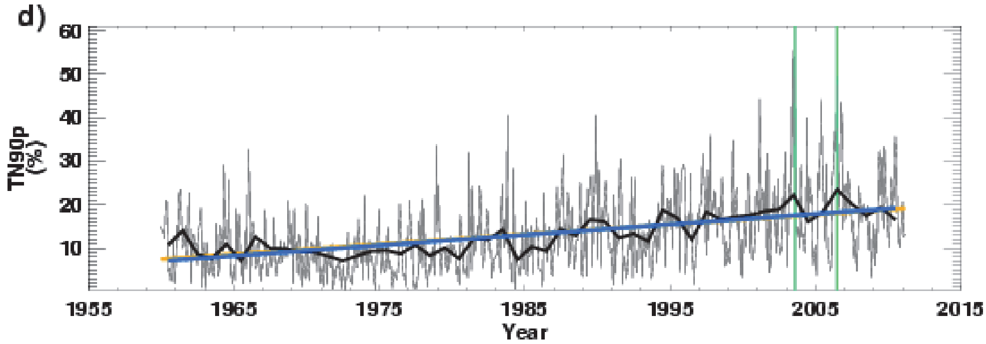
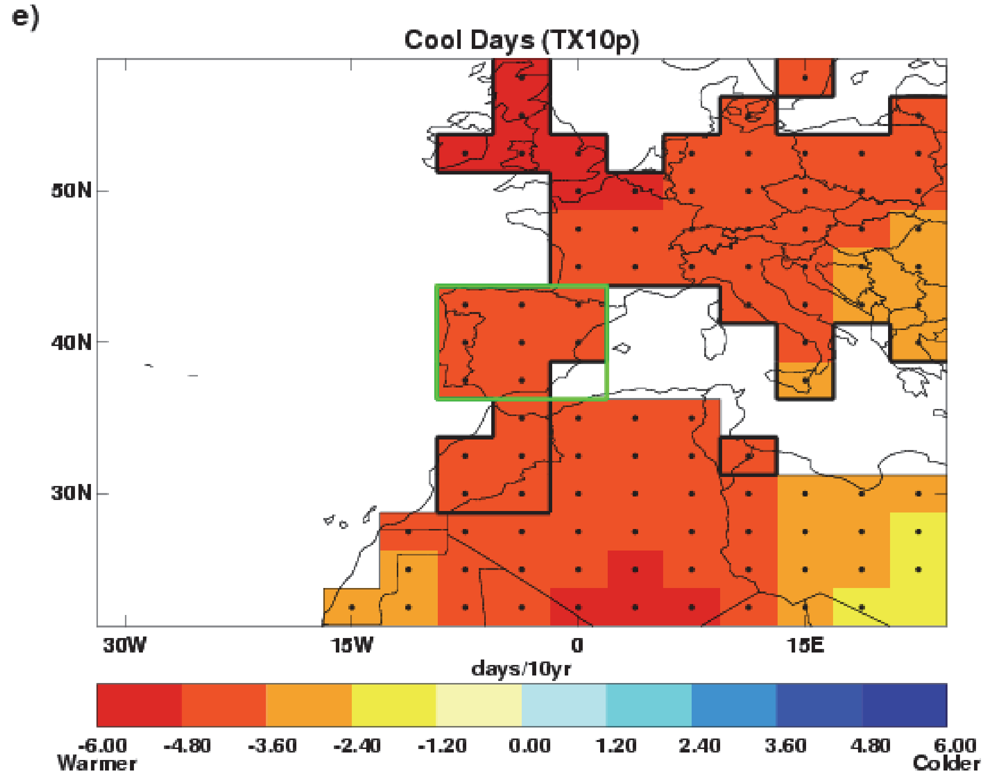


Monthly: 2.28% per decade (1.86 to 2.71)
Total change of 11.41% from 1960 to 2011 (9.31% to 13.55%)

Annual: 2.40% per decade (1.80 to 2.94)
Total change of 12.01% from 1960 to 2010 (8.99% to 14.69%)

e)



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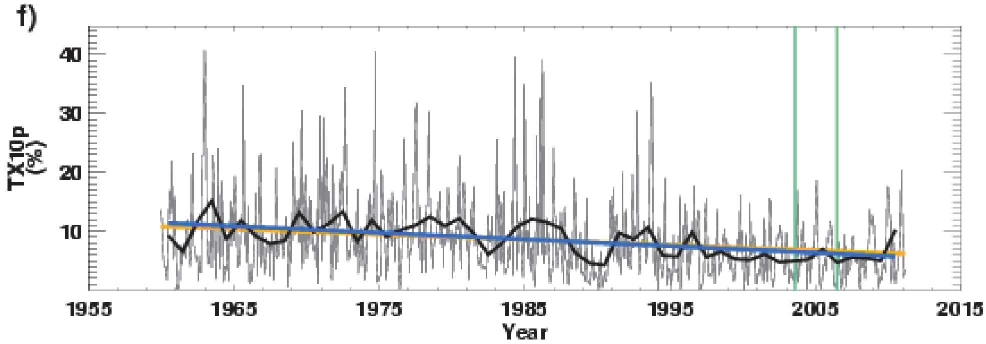

Monthly: -0.90% per decade (-1.20 to -0.63)
Total change of -4.52% from 1960 to 2011 (-5.98% to -3.13%)

Annual: -1.12% per decade (-1.67 to -0.73)
Total change of -5.62% from 1960 to 2010 (-8.33% to -3.66%)

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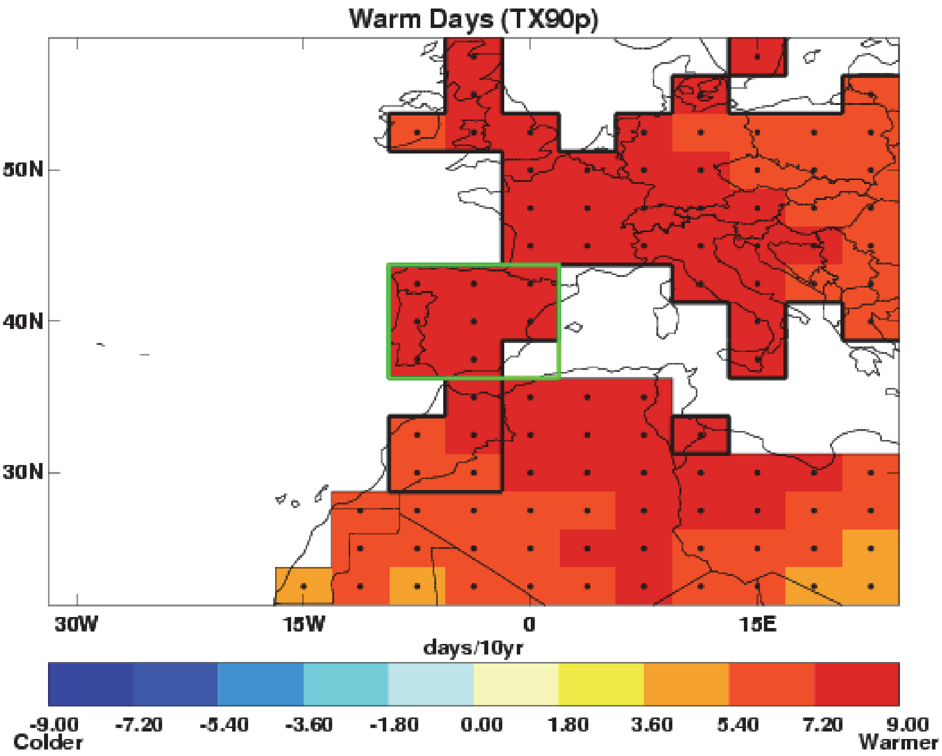

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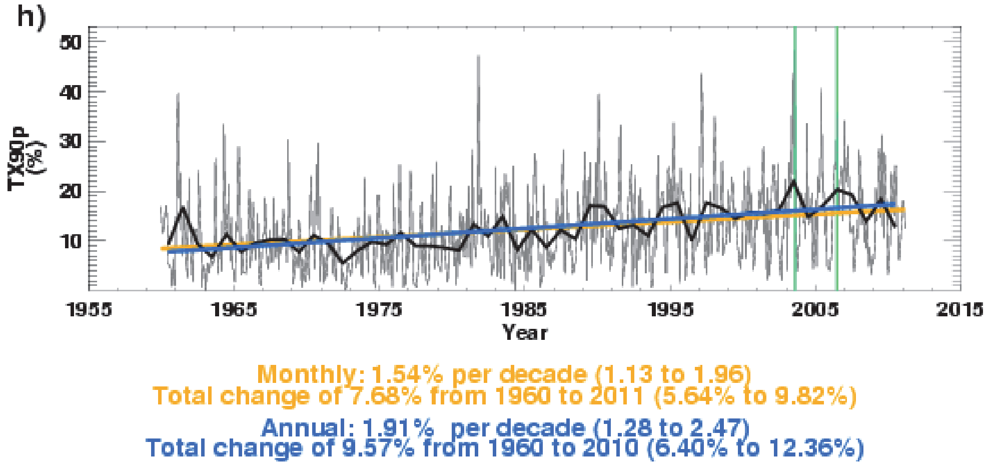

Figure 3. *Change in cool nights (a,b), warm nights (c,d), cool days (e,f) and warm days (g,h) for Spain over the period 1960 to 2010 relative to 1961-1990 from the ECA&D dataset (Klein Tank et al., 2002). a,c,e,g) Grid box decadal trends. Grid boxes outlined in solid black contain at least 3 stations and so are likely to be more representative of the wider grid-box. Trends are fitted using the median of pairwise slopes method (Sen, 1968;Lanzante, 1996). Higher confidence in a long-term trend is shown by a black dot if the 5th to 95th percentile slopes are of the same sign. Differences in spatial coverage occur because each index has its own decorrelation length scale (see methodology annex). b,d,f,h) Area averaged annual time series for 9.375° to 1.875° W and 36.25° to 43.75° N as shown by the green box on the map and red box in Figure 1. Thin and thick black lines show the monthly and annual variation respectively. Monthly (orange) and annual (blue) trends are fitted as described above. The decadal trend and its 5th to 95th percentile confidence intervals are stated along with the change over the period for which there are data available. All the trends have higher confidence that they are different from zero as their 5th to 95th percentile slopes are of the same sign. The green vertical lines show the dates of the heat waves in 2003 and 2006.*

The regional average time series show a large amount of annual and monthly variability, with an apparent increase for the warm percentiles and a decrease for the cool percentiles over the period of record. The heat wave of 2003 can clearly be seen as a strong signal in the frequency of warm nights and warm days. Indeed, over the period of record, the greatest number of warm days occurs during 2003. The notable heat wave of 2006 (see Table 1) is also present, but to a lesser extent.

Attribution of changes in likelihood of occurrence of seasonal mean temperatures

Today's climate covers a range of likely extremes. Recent research has shown that the temperature distribution of seasonal means would likely be different in the absence of anthropogenic emissions (Christidis et al., 2011). Here we discuss the seasonal means, within which the highlighted extreme temperature events occur, in the context of recent climate and the influence of anthropogenic emissions on that climate. The methods are fully described in the methodology annex.

Summer 2003

The distributions of the summer mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 4. Analyses with both models suggest that human influences on the climate have shifted the distribution to higher temperatures. Considering the average over the entire region, the 2003 summer is exceptionally hot, as it lies at the far end of the warm tail of the temperature distributions for the climate influenced by anthropogenic forcings (red distributions) and is the hottest since 1900 in the CRUTEM3 dataset. In the absence of human influences on the climate (green distributions), the season would be even more extreme. It should be noted that the attribution results shown here refer to temperature anomalies over the entire region and over an entire season, whereas the actual extreme event had a shorter duration and affected a smaller region.

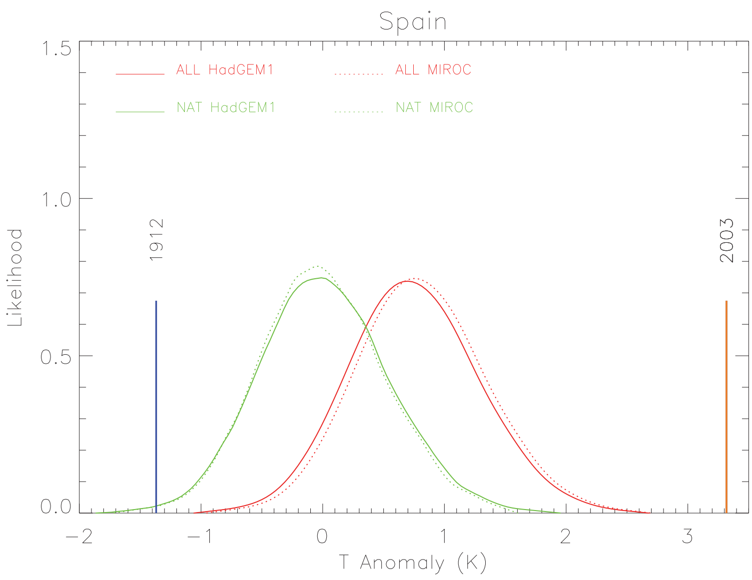

Figure 4. *Distributions of the June-July-August mean temperature anomalies (relative to 1961-1990) averaged over a Southern European region that encompasses Spain (9W-20E, 35-50N – as shown in Figure 1) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.*

Precipitation extremes

Precipitation extremes, either excess or deficit, can be hazardous to human health, societal infrastructure, and livestock and agriculture. While seasonal fluctuations in precipitation are normal and indeed important for a number of societal sectors (e.g. tourism, farming etc.), flooding or drought can have serious negative impacts. These are complex phenomena and often the result of accumulated excesses or deficits or other compounding factors such as spring snow-melt, high tides/storm surges or changes in land use. This section below deals purely with precipitation amounts.

Table 2 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The severe drought in Catalunya in 2008 is highlighted below as an example extreme event which affected Spain.

Year	Month	Event	Details	Source
2000	Oct	Flooding	Torrential rainstorms caused major flooding in eastern Spain, where some stations recorded monthly totals greater than 500 mm. Some coastal areas received more than 275 mm of rainfall in the four days from 22-25 October.	BAMS (Lawrimore et al., 2001)
2005	Summer	Drought	Severe summer drought. Forest fires. Worst drought conditions since the late 1940s.	WMO (2006)
2007	Sept	Hail/flooding	On 21 September, Andalucia (southern Spain) was hit by thunderstorms with severe hail and rainfall producing floods and crop damage.	BAMS (Trigo et al., 2008)
2008	Winter	Drought	Worst drought for decades	WMO (2009) BAMS (Trigo et al., 2009)

Table 2. *Selected extreme precipitation events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 2000.*

Recent extreme precipitation events

Severe drought, 2005

During the period October 2004 to June 2005, Madrid experienced record dry conditions (WMO, 2006; Trigo et al., 2006). The drought had major socioeconomic impacts, where hydroelectricity decreased to 40% and cereals production decreased to 60% of their long-term average values. It was estimated that agricultural losses due to the drought resulting in diminished pasture land came to $2 billion USD (Trigo et al., 2006). The dry conditions also aggravated wildfires in the region (WMO, 2006).

All major droughts in this region are characterised by a lack of rainfall between October and March, which is the normal rainy season for Iberia, as the rest of the year the region experiences relatively arid conditions (Trigo et al., 2006).

Analysis of Observed Precipitation from 1960

ECA&D data (Klein Tank et al., 2002) have been used to update the HadEX extremes analysis for mainland Spain from 1960 to 2010 for daily precipitation totals. Here we discuss changes in the annual total precipitation, and in the frequency of prolonged (greater than 6 days) wet and dry spells. The methods are fully described in the methodology annex.

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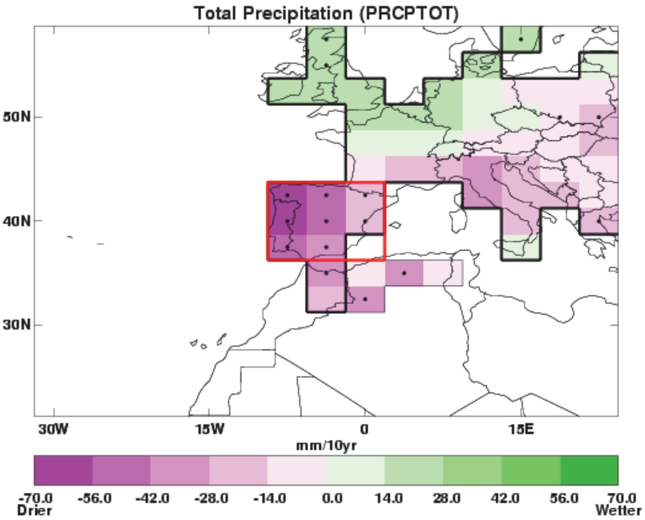

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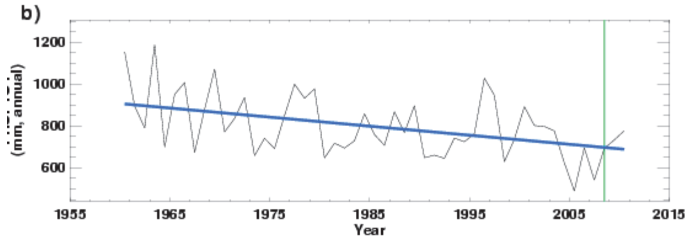

Annual: -43.16mm per decade (-71.67 to -14.19)
Total change of -215.80mm from 1960 to 2010 (-358.35mm to -70.96mm)

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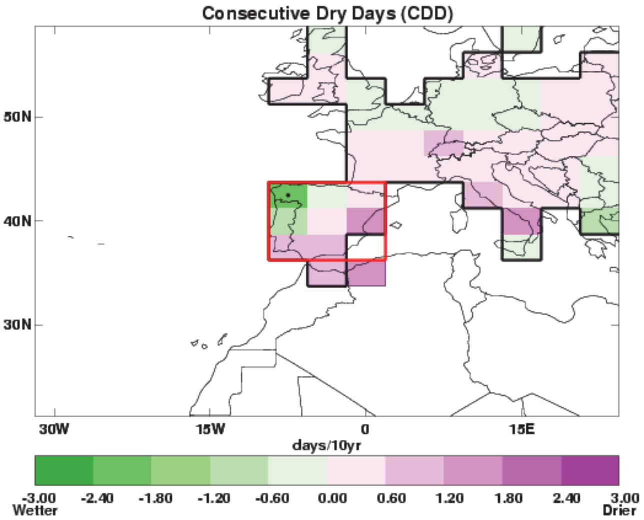

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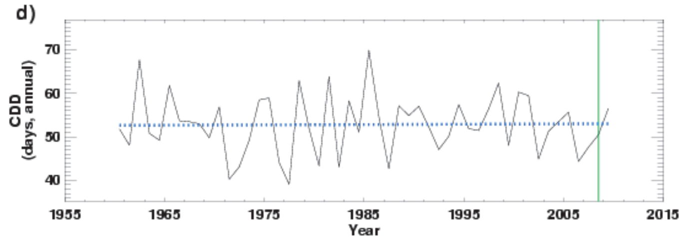


Annual: 0.08days per decade (-1.38 to 1.50)
Total change of 0.30days from 1960 to 2009 (-5.51days to 6.00days)

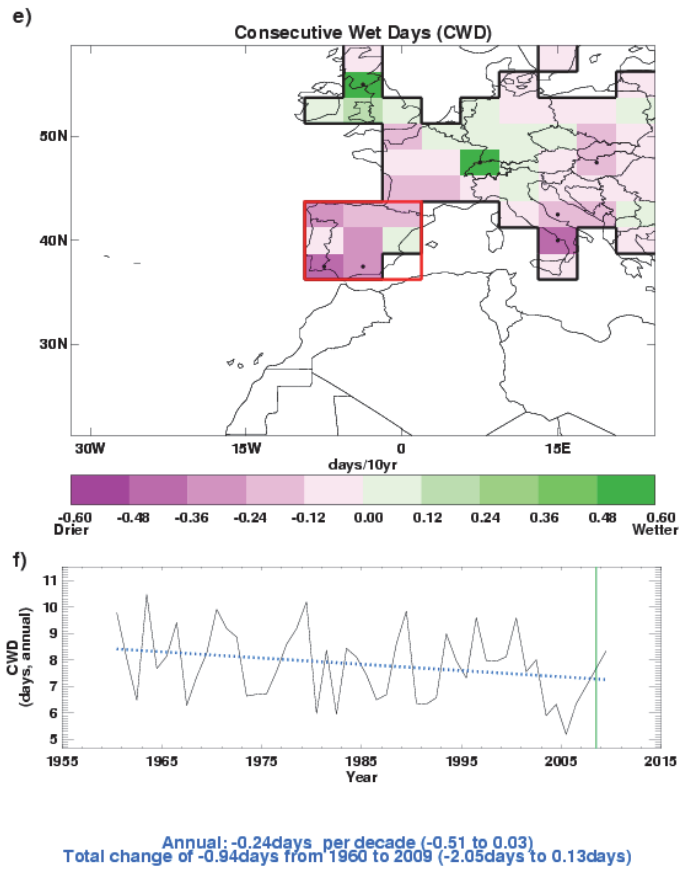


Figure 5. *The change in the annual total rainfall (a,b), the annual number of continuous dry days (c,d) and the annual number of continuous wet days (e,f) over the period 1960-2010. The maps and time series have been created in exactly the same way as Figure 3. The vertical green lines show the dates of the drought of 2008 (see Table 2). Only annual regional averages are shown in b,d,f). The trends which have lower confidence that they are different from zero as their 5th to 95th percentile slopes are of different signs are marked with a dotted line.*

The signal from the total annual precipitation (Figure 5) shows a reduction in the amount of annual rainfall in the Iberian Peninsula over the period 1960 to 2009, with the largest reduction in the northwest and the lowest in the east. There is higher confidence that this signal is different from zero, both across the region and in trend for the regional average. Although with lower confidence, this variation is also seen in the length of continuous dry days which shows an increase over the north-west. The signal for the continuous wet days shows a reduction, but with low confidence for all apart from the two southernmost grid boxes.

Storms

Storms can be very hazardous to all sectors of society. They can be small with localised impacts or spread across multiple states. There is no systematic observational analysis included for storms because, despite recent progress (Peterson et al., 2011; Cornes and Jones, 2011), land surface wind data are not yet adequate for worldwide robust analysis (see methodology annex). Further progress awaits studies of the more reliable barometric pressure data through the new 20th Century Reanalysis (Compo et al., 2011) and its planned successors.

Table 3 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. The extra-tropical storm Klaus which struck mainland Spain in 2009 is highlighted below as an example.

Year	Month	Event	Details	Source
2009	January	Storm	Extra-tropical Storm Klaus - worst storm since 1999 The strongest winds induced by Klaus were felt in northern Spain, including the large populated cities of Santander, Bilbao, and Barcelona. Strongest gusts reached 190km per hour	BAMS (Trigo et al., 2010)

Table 3. *Selected extreme storm events reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 2000.*

Extra-tropical Storm Klaus, January 2009

On 23-24 January 2009, Spain and France were severely affected by winter storm *Klaus*, the worst extra-tropical storm in a decade, with wind speeds equivalent to a Category 3 hurricane (WMO, 2010). It was the costliest weather event in the world in 2009, estimated at a total of US$6.0 billion (Liberato, 2011). The strongest winds induced by Klaus were felt in northern Spain, including the large populated cities of Santander, Bilbao, and Barcelona. Maximum wind speeds of over 180 km/hour ion the north coast (Trigo et al., 2010). The Spanish Oceanographic Institute measured record wave heights in Spanish waters (Liberato, 2011).

Summary

The main features seen in observed climate over Spain from this analysis are:

- Widespread warming has been observed over Spain since 1960 with greater warming in summer than winter.
- There is a clear trend to fewer cool nights and more warm nights since 1960, and also to fewer cool days and more warm days.
- There has been a general increase in summer temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.
- There has been a reduction in the amount of annual rainfall in the Iberian Peninsula since 1960 with the largest reduction in the northwest and the lowest reduction in the east.

Methodology annex

Recent, notable extremes

In order to identify what is meant by ‘recent’ events the authors have used the period since 1994, when WMO Status of the Global Climate statements were available to the authors. However, where possible, the most notable events during the last 10 years have been chosen as these are most widely reported in the media, remain closest to the forefront of the memory of the country affected, and provide an example likely to be most relevant to today’s society. By ‘notable’ the authors mean any event which has had significant impact either in terms of cost to the economy, loss of life, or displacement and long term impact on the population. In most cases the events of largest impact on the population have been chosen, however this is not always the case.

Tables of recent, notable extreme events have been provided for each country. These have been compiled using data from the World Meteorological Organisation (WMO) Annual Statements on the Status of the Global Climate. This is a yearly report which includes contributions from all the member countries, and therefore represents a global overview of events that have had importance on a national scale. The report does not claim to capture all events of significance, and consistency across the years of records available is variable. However, this database provides a concise yet broad account of extreme events per country. This data is then supplemented with accounts from the monthly National Oceanic and Atmospheric Administration (NOAA) State of the Climate reports which outline global extreme events of meteorological significance.

We give detailed examples of heat, precipitation and storm extremes for each country where these have had significant impact. Where a country is primarily affected by precipitation or heat extremes this is where our focus has remained. An account of the impact on human life, property and the economy has been given, based largely on media reporting of events, and official reports from aid agencies, governments and meteorological organisations. Some data has also been acquired from the Centre for Research on Epidemiological Disasters (CRED) database on global extreme events. Although media reports are unlikely to be completely accurate, they do give an indication as to the perceived impact of an extreme event, and so are useful in highlighting the events which remain in the national psyche.

Our search for data has not been exhaustive given the number of countries and events included. Although there are a wide variety of sources available, for many events, an official account is not available. Therefore figures given are illustrative of the magnitude of impact only (references are included for further information on sources). It is also apparent that the reporting of extreme events varies widely by region, and we have, where possible, engaged with local scientists to better understand the impact of such events.

The aim of the narrative for each country is to provide a picture of the social and economic vulnerability to the current climate. Examples given may illustrate the impact that any given extreme event may have and the recovery of a country from such an event. This will be important when considering the current trends in climate extremes, and also when examining projected trends in climate over the next century.

Observational record

In this section we outline the data sources which were incorporated into the analysis, the quality control procedure used, and the choices made in the data presentation. As this report is global in scope, including 23 countries, it is important to maintain consistency of methodological approach across the board. For this reason, although detailed datasets of extreme temperatures, precipitation and storm events exist for various countries, it was not possible to obtain and incorporate such a varied mix of data within the timeframe of this project. Attempts were made to obtain regional daily temperature and precipitation data from known contacts within various countries with which to update existing global extremes databases. No analysis of changes in storminess is included as there is no robust historical analysis of global land surface winds or storminess currently available.

Analysis of seasonal mean temperature

Mean temperatures analysed are obtained from the CRUTEM3 global land-based surface-temperature data-product (Brohan et al. 2006), jointly created by the Met Office Hadley Centre and Climatic Research Unit at the University of East Anglia. CRUTEM3 comprises of more than 4000 weather station records from around the world. These have been averaged together to create 5° by 5° gridded fields with no interpolation over grid boxes that do not contain stations. Seasonal averages were calculated for each grid box for the 1960 to 2010 period and linear trends fitted using the median of pairwise slopes (Sen 1968; Lanzante 1996). This method finds the slopes for all possible pairs of points in the data, and takes their median. This is a robust estimator of the slope which is not sensitive to outlying points. High confidence is assigned to any trend value for which the 5th to 95th percentiles of the pairwise slopes are of the same sign as the trend value and thus inconsistent with a zero trend.

Analysis of temperature and precipitation extremes using indices

In order to study extremes of climate a number of indices have been created to highlight different aspects of severe weather. The set of indices used are those from the World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI). These 27 indices use daily rainfall and maximum and minimum temperature data to find the annual (and for a subset of the indices, monthly) values for, e.g., the 'warm' days where daily maximum temperature exceeds the 90th percentile maximum temperature as defined over a 1961 to 1990 base period. For a full list of the indices we refer to the website of the ETCCDI (http://cccma.seos.uvic.ca/ETCCDI/index.shtml).

Index	Description	Shortname	Notes
Cool night frequency	Daily minimum temperatures lower than the 10th percentile daily minimum temperature using the base reference period 1961-1990	TN10p	---
Warm night frequency	Daily minimum temperatures higher than the 90th percentile daily minimum temperature using the base reference period 1961-1990	TN90p	---
Cool day frequency	Daily maximum temperatures lower than the 10th percentile daily maximum temperature using the base reference period 1961-1990	TX10p	---
Warm day frequency	Daily maximum temperatures higher than the 90th percentile daily maximum temperature using the base reference period 1961-1990	TX90p	---
Dry spell duration	Maximum duration of continuous days within a year with rainfall <1mm	CDD	Lower data coverage due to the requirement for a 'dry spell' to be at least 6 days long resulting in intermittent temporal coverage
Wet spell duration	Maximum duration of continuous days with rainfall >1mm for a given year	CWD	Lower data coverage due to the requirement for a 'wet spell' to be at least 6 days long resulting in intermittent temporal coverage
Total annual precipitation	Total rainfall per year	PRCPTOT	---

Table 4. *Description of ETCCDI indices used in this document.*

A previous global study of the change in these indices, containing data from 1951-2003 can be found in Alexander et al. 2006, (HadEX; see http://www.metoffice.gov.uk/hadobs/hadex/). In this work we aimed to update this analysis to the present day where possible, using the most recently available data. A subset of the indices is used here because they are most easily related to extreme climate events (Table 4).

Use of HadEX for analysis of extremes

The HadEX dataset comprises all 27 ETCCDI indices calculated from station data and then smoothed and gridded onto a 2.5° x 3.75° grid, chosen to match the output from the Hadley Centre suite of climate models. To update the dataset to the present day, indices are calculated from the individual station data using the RClimDex/FClimDex software; developed and maintained on behalf of the ETCCDI by the Climate Research Branch of the Meteorological Service of Canada. Given the timeframe of this project it was not possible to obtain sufficient station data to create updated HadEX indices to present day for a number of countries: Brazil; Egypt; Indonesia; Japan (precipitation only); South Africa; Saudi Arabia; Peru; Turkey; and Kenya. Indices from the original HadEX data-product are used here to show changes in extremes of temperature and precipitation from 1960 to 2003. In some cases the data end prior to 2003. Table 5 summarises the data used for each country. Below, we give a short summary of the methods used to create the HadEX dataset (for a full description see Alexander et al., 2006).

To account for the uneven spatial coverage when creating the HadEX dataset, the indices for each station were gridded, and a land-sea mask from the HadCM3 model applied. The interpolation method used in the gridding process uses a decorrelation length scale (DLS) to determine which stations can influence the value of a given grid box. This DLS is calculated from the e-folding distance of the individual station correlations. The DLS is calculated separately for five latitude bands, and then linearly interpolated between the bands. There is a noticeable difference in spatial coverage between the indices due to these differences in decorrelation length scales. This means that there will be some grid-box data where in fact there are no stations underlying it. Here we apply black borders to grid-boxes where at least 3 stations are present to denote greater confidence in representation of the wider grid-box area there. The land-sea mask enables the dataset to be used directly for model comparison with output from HadCM3. It does mean, however, that some coastal regions and islands over which one may expect to find a grid-box are in fact empty because they have been treated as sea.

Data sources used for updates to the HadEX analysis of extremes

We use a number of different data sources to provide sufficient coverage to update as many countries as possible to present day. These are summarised in Table 5. In building the new datasets we have tried to use exactly the same methodology as was used to create the original HadEX to retain consistency with a product that was created through substantial international effort and widely used, but there are some differences, which are described in the next section.

Wherever new data have been used, the geographical distributions of the trends were compared to those obtained from HadEX, using the same grid size, time span and fitting method. If the pattern of the trends in the temperature or precipitation indices did not match that from HadEX, we used the HadEX data despite its generally shorter time span. Differences in the patterns of the trends in the indices can arise because the individual stations used to create the gridded results are different from those in HadEX, and the quality control procedures used are also very likely to be different. Countries where we decided to use HadEX data despite the existence of more recent data are Egypt and Turkey.

GHCND:

The Global Historical Climate Network Daily data has near-global coverage. However, to ensure consistency with the HadEX database, the GHCND stations were compared to those stations in HadEX. We selected those stations which are within 1500m of the stations used in the HadEX database and have a high correlation with the HadEX stations. We only took the precipitation data if its $r>0.9$ and the temperature data if one of its r-values >0.9. In addition, we required at least 5 years of data beyond 2000. These daily data were then converted to the indices using the *fclimdex* software.

ECA&D and SACA&D:

The European Climate Assessment and Dataset and the Southeast Asian Climate Assessment and Dataset data are pre-calculated indices comprising the core 27 indices from the ETCCDI as well as some extra ones. We kindly acknowledge the help of Albert Klein Tank, the KNMI[1] and the BMKG[2] for their assistance in obtaining these data.

Mexico:

The station data from Mexico has been kindly supplied by the SMN[3] and Jorge Vazquez. These daily data were then converted to the required indices using the *Fclimdex* software. There are a total of 5298 Mexican stations in the database. In order to select those which have sufficiently long data records and are likely to be the most reliable ones we performed a cross correlation between all stations. We selected those which had at least 20 years of data post 1960 and have

[1] Koninklijk Nederlands Meteorologisch Instituut – The Royal Netherlands Meteorological Institute

[2] Badan Meteorologi, Klimatologi dan Geofisika – The Indonesian Meteorological, Climatological and Geophysical Agency

[3] Servicio Meteorológico Nacional de México – The Mexican National Meteorological Service

a correlation with at least one other station with an *r*-value >0.95. This resulted in 237 stations being selected for further processing and analysis.

Indian Gridded:

The India Meteorological Department provided daily gridded data (precipitation 1951-2007, temperature 1969-2009) on a 1° x 1° grid. These are the only gridded daily data in our analysis. In order to process these in as similar a way as possible the values for each grid were assumed to be analogous to a station located at the centre of the grid. We keep these data separate from the rest of the study, which is particularly important when calculating the decorrelation length scale, which is on the whole larger for these gridded data.

Country	**Region box** (red dashed boxes in Fig. 1 and on each map at beginning of chapter)	**Data source** (T = temperature, P = precipitation)	**Period of data coverage** (T = temperature, P = precipitation)	**Indices included** (see Table 4 for details)	**Temporal resolution available**	**Notes**
Argentina	73.125 to 54.375 ^{o} W, 21.25 to 56.25 ^{o} S	Matilde Rusticucci (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	
Australia	114.375 to 155.625 ^{o} E, 11.25 to 43.75 ^{o} S	GHCND (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Land-sea mask has been adapted to include Tasmania and the area around Brisbane
Bangladesh	88.125 to 91.875 ^{o} E, 21.25 to 26.25 ^{o} N	Indian Gridded data (T,P)	1960-2007 (P), 1970-2009 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Interpolated from Indian Gridded data
Brazil	73.125 to 31.875 ^{o} W, 6.25 ^{o} N to 33.75 ^{o} S	HadEX (T,P)	1960-2000 (P) 2002 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Spatial coverage is poor
China	73.125 to 133.125 ^{o} E, 21.25 to 53.75 ^{o} N	GHCND (T,P)	1960-1997 (P) 1960-2003 (T_{min}) 1960-2010 (T_{max})	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Precipitation has very poor coverage beyond 1997 except in 2003-04, and no data at all in 2000-02, 2005-11
Egypt	24.375 to 35.625 ^{o} E, 21.25 to 31.25 ^{o} N	HadEX (T,P)	No data	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	annual	There are no data for Egypt so all grid-box values have been interpolated from stations in Jordan, Israel, Libya and Sudan
France	5.625 ^{o} W to 9.375 ^{o} E, 41.25 to 51.25 ^{o} N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	

Germany	5.625 to 16.875 ° E, 46.25 to 56.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
India	69.375 to 99.375 ° E, 6.25 to 36.25 ° N	Indian Gridded data (T,P)	1960-2003 (P), 1970-2009 (T)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Indonesia	95.625 to 140.625 ° E, 6.25 ° N to 11.25 ° S	HadEX (T,P)	1968-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	annual	Spatial coverage is poor
Italy	5.625 to 16.875 ° E, 36.25 to 46.25 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Land-sea mask has been adapted to improve coverage of Italy
Japan	129.375 to 144.375 ° E, 31.25 to 46.25 ° N	HadEX (P) GHCND (T)	1960-2003 (P) 1960-2000 (T_{min}) 1960-2010 (T_{max})	TN10p, TN90p, TX10p, TX90p, PRCPTOT,	monthly, seasonal and annual (T), annual (P)	
Kenya	31.875 to 43.125 ° E, 6.25 ° N to 6.25 ° S	HadEX (T,P)	1960-1999 (P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT	annual	There are no temperature data for Kenya and so grid-box values have been interpolated from neighbouring Uganda and the United Republic of Tanzania. Regional averages include grid-boxes from outside Kenya that enable continuation to 2003
Mexico	118.125 to 88.125 ° W, 13.75 to 33.75 ° N	Raw station data from the Servicio Meteorológico Nacional (SMN) (T,P)	1960-2009 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	237/5298 stations selected. Non uniform spatial coverage. Drop in T and P coverage in 2009.
Peru	84.735 to 65.625 ° W, 1.25 ° N to 18.75 ° S	HadEX (T,P)	1960-2002 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Intermittent coverage in TX90p, CDD and CWD

Russia	West Russia 28.125 to 106.875 ° E, 43.75 to 78.75 ° N, East Russia 103.125 to 189.375 ° E, 43.75 to 78.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	Country split for presentation purposes only.
Saudi Arabia	31.875 to 54.375 ° E, 16.25 to 33.75 ° N	HadEX (T,P)	1960-2000 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT	annual	Spatial coverage is poor
South Africa	13.125 to 35.625 ° W, 21.25 to 36.25 ° S	HadEX (T,P)	1960-2000 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	---
Republic of Korea	125.625 to 129.375 ° E, 33.75 to 38.75 ° N	HadEX (T,P)	1960-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD	annual	There are too few data points for CWD to calculate trends or regional timeseries
Spain	9.375 ° W to 1.875 ° E, 36.25 to 43.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
Turkey	24.375 to 46.875 ° E, 36.25 to 43.75 ° N	HadEX (T,P)	1960-2003 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	annual	Intermittent coverage in CWD and CDD with no regional average beyond 2000
United Kingdom	9.375 ° W to 1.875 ° E, 51.25 to 58.75 ° N	ECA&D (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	
United States of America	125.625 to 65.625 ° W, 23.75 to 48.75 ° N	GHCND (T,P)	1960-2010 (T,P)	TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD	monthly, seasonal and annual	

Table 5. *Summary of data used for each country.*

Quality control and gridding procedure used for updates to the HadEX analysis of extremes

In order to perform some basic quality control checks on the index data, we used a two-step process on the indices. Firstly, internal checks were carried out, to remove cases where the 5 day rainfall value is less than the 1 day rainfall value, the minimum T_min is greater than the minimum T_max and the maximum T_min is greater than the maximum T_max. Although these are physically impossible, they could arise from transcription errors when creating the daily dataset, for example, a misplaced minus sign, an extra digit appearing in the record or a column transposition during digitisation. During these tests we also require that there are at least 20 years of data in the period of record for the index for that station, and that some data is found in each decade between 1961 and 1990, to allow a reasonable estimation of the climatology over that period.

Weather conditions are often similar over many tens of kilometres and the indices calculated in this work are even more coherent. The correlation coefficient between each station-pair combination in all the data obtained is calculated for each index (and month where appropriate), and plotted as a function of the separation. An exponential decay curve is fitted to the data, and the distance at which this curve has fallen by a factor 1/*e* is taken as the decorrelation length scale (DLS). A DLS is calculated for each dataset separately. For the GHCND, a separate DLS is calculated for each hemisphere. We do not force the fitted decay curve to show perfect correlation at zero distance, which is different to the method employed when creating HadEX. For some of the indices in some countries, no clear decay pattern was observed in some data sets or the decay was so slow that no value for the DLS could be determined. In these cases a default value of 200km was used.

We then perform external checks on the index data by comparing the value for each station with that of its neighbours. As the station values are correlated, it is therefore likely that if one station measures a high value for an index for a given month, its neighbours will also be measuring high. We exploit this coherence to find further bad values or stations as follows. Although raw precipitation data shows a high degree of localisation, using indices which have monthly or annual resolution improves the coherence across wider areas and so this neighbour checking technique is a valid method of finding anomalous stations.

We calculate a climatology for each station (and month if appropriate) using the mean value for each index over the period 1961-1990. The values for each station are then anomalised using this climatology by subtracting this mean value from the true values, so that it is clear if the station values are higher or lower than normal. This means that we do not need to take differences in elevation or topography into account when comparing neighbours, as we are not comparing actual values, but rather deviations from the mean value.

All stations which are within the DLS distance are investigated and their anomalised values noted. We then calculate the weighted median value from these stations to take into account the decay in the correlation with increasing distance. We use the median to reduce the sensitivity to outliers.

If the station value is greater than 7.5 median-absolute-deviations away from the weighted median value (this corresponds to about 5 standard deviations if the distribution is Gaussian, but is a robust measure of the spread of the distribution), then there is low confidence in the veracity of this value and so it is removed from the data.

To present the data, the individual stations are gridded on a 3.75° x 2.5° grid, matching the output from HadCM3. To determine the value of each grid box, the DLS is used to calculate which stations can reasonably contribute to the value. The value of each station is then weighted using the DLS to obtain a final grid box value. At least three stations need to have valid data and be near enough (within 1 DLS of the gridbox centre) to contribute in order for a value to be calculated for the grid point. As for the original HadEX, the HadCM3 land-sea mask is used. However, in three cases the mask has been adjusted as there are data over Tasmania, eastern Australia and Italy that would not be included otherwise (Figure 6).

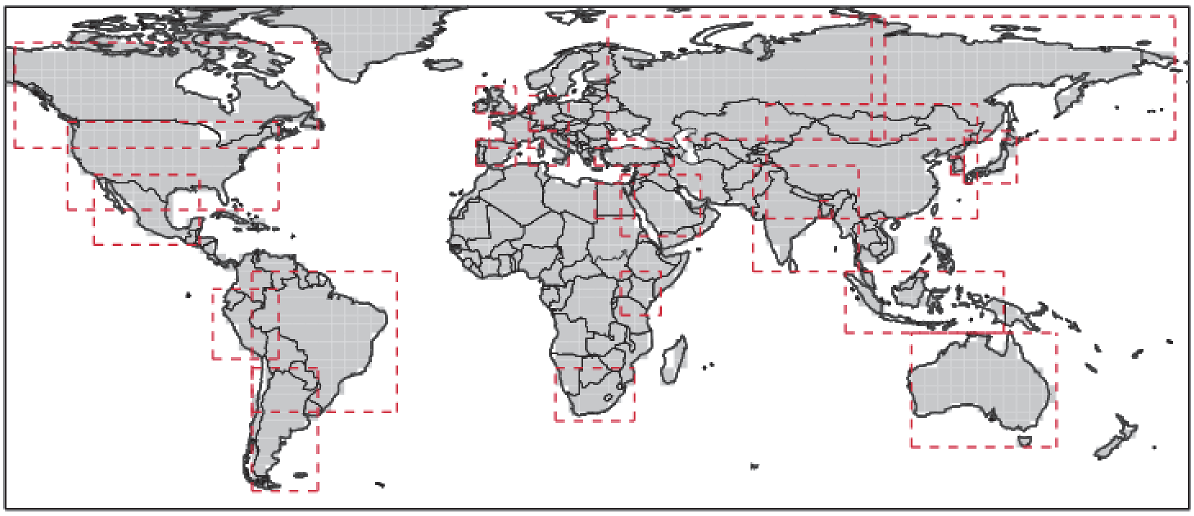


Figure 6. *Land-sea mask used for gridding the station data and regional areas allocated to each country as described in Table 5.*

Presentation of extremes of temperature and precipitation

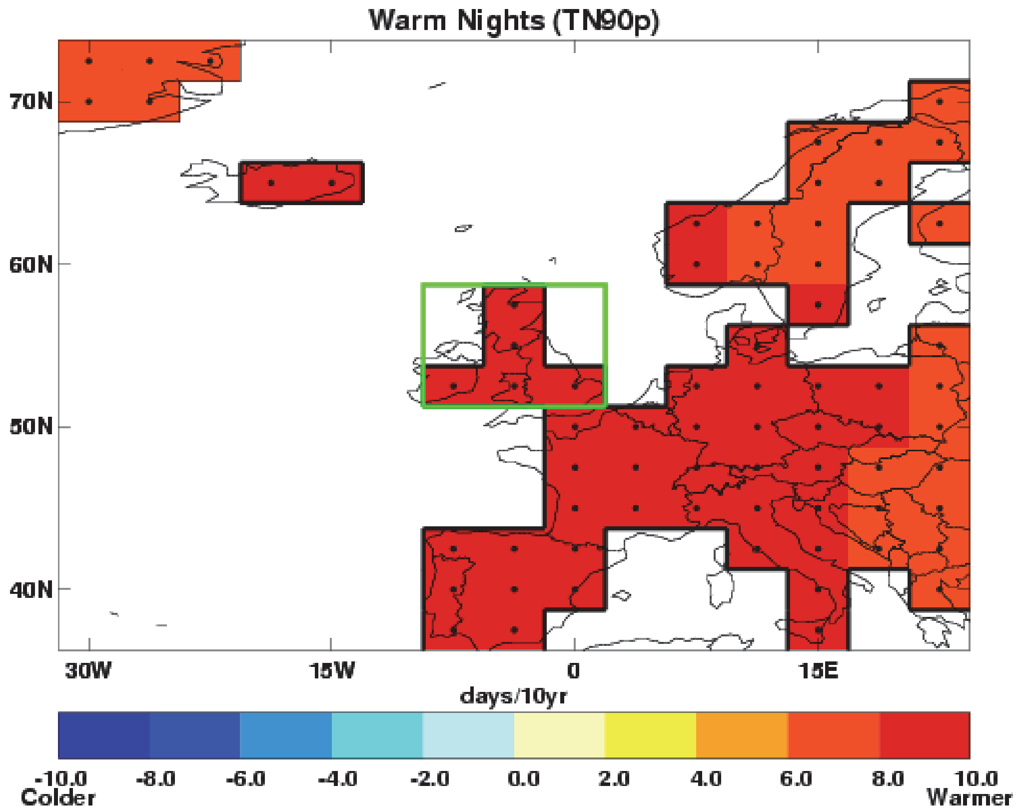
Indices are displayed as regional gridded maps of decadal trends and regional average time-series with decadal trends where appropriate. Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Trends are considered to be significantly different from a zero trend if the 5^{th} to 95^{th} percentiles of the pairwise slopes do not encompass zero. This is shown by a black dot in the centre of the grid-box or by a solid line on time-series plots. This infers that there is high confidence in the sign (positive or negative) of the sign. Confidence in the trend magnitude can be inferred by the spread of the 5^{th} to 95^{th} percentiles of the pairwise slopes which is given for the regional average decadal trends. Trends are only calculated when there are data present for at least 50% of years in the period of record and for the updated data (not HadEX) there must be at least one year in each decade.

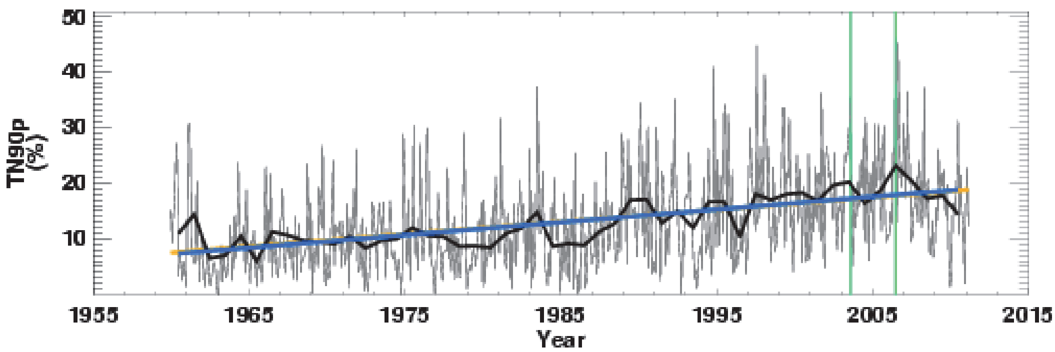
Due to the practice of data-interpolation during the gridding stage (using the DLS) there are values for some grid boxes when no actually station lies within the grid box. There is more confidence in grid boxes for which there are underlying data. For this reason, we identify those grid boxes which contain at least 3 stations by a black contour line on the maps. The DLS differs with region, season and index which leads to large differences in the spatial coverage. The indices, by their nature of being largely threshold driven, can be intermittent over time which also effects spatial and temporal coverage (see Table 4).

Each index (and each month for the indices for which there is monthly data) has a different DLS, and so the coverage between different indices and datasets can be different. The restrictions on having at least 20 years of data present for each input station, at least 50% of years in the period of record and at least one year in each decade for the trending calculation, combined with the DLS, can restrict the coverage to only those regions with a dense station network reporting reliably.

Each country has a rectangular region assigned as shown by the red dashed box on the map in Figure 1 and listed in Table 2, which is used for the creation of the regional average. This is sometimes identical to the attribution region shown in grey on the map in Figure 1. This region is again shown on the maps accompanying the time series of the regional averages as a reminder of the region and grid boxes used in the calculation. Regional averages are created by weighting grid box values by the cosine of their grid box centre latitude. To ensure consistency over time a regional average is only calculated when there are a sufficient number of grid boxes present. The full-period median number of grid-boxes present is calculated. For regions with a median of more than six grid-boxes there must be at least 80%

of the median number of grid boxes present for any one year to calculate a regional average. For regions with six or fewer median grid boxes this is relaxed to 50%. These limitations ensure that a single station or grid box which has a longer period of record than its neighbours cannot skew the timeseries trend. So sometimes there may be grid-boxes present but no regional average time series. The trends for the regional averages are calculated in the same way as for the individual grid boxes, using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Confidence in the trend is also determined if the 5^{th} to 95^{th} percentiles of the pairwise slopes are of the same sign and thus inconsistent with a zero trend. As well as the trend in quantity per decade, we also show the full change in the quantity from 1960 to 2010 that this fitted linear trend implies.





Monthly: 2.20% per decade (1.80 to 2.61)
Total change of 11.02% from 1960 to 2011 (9.00% to 13.06%)

Annual: 2.28% per decade (1.69 to 2.86)
Total change of 11.41% from 1960 to 2010 (8.43% to 14.28%)

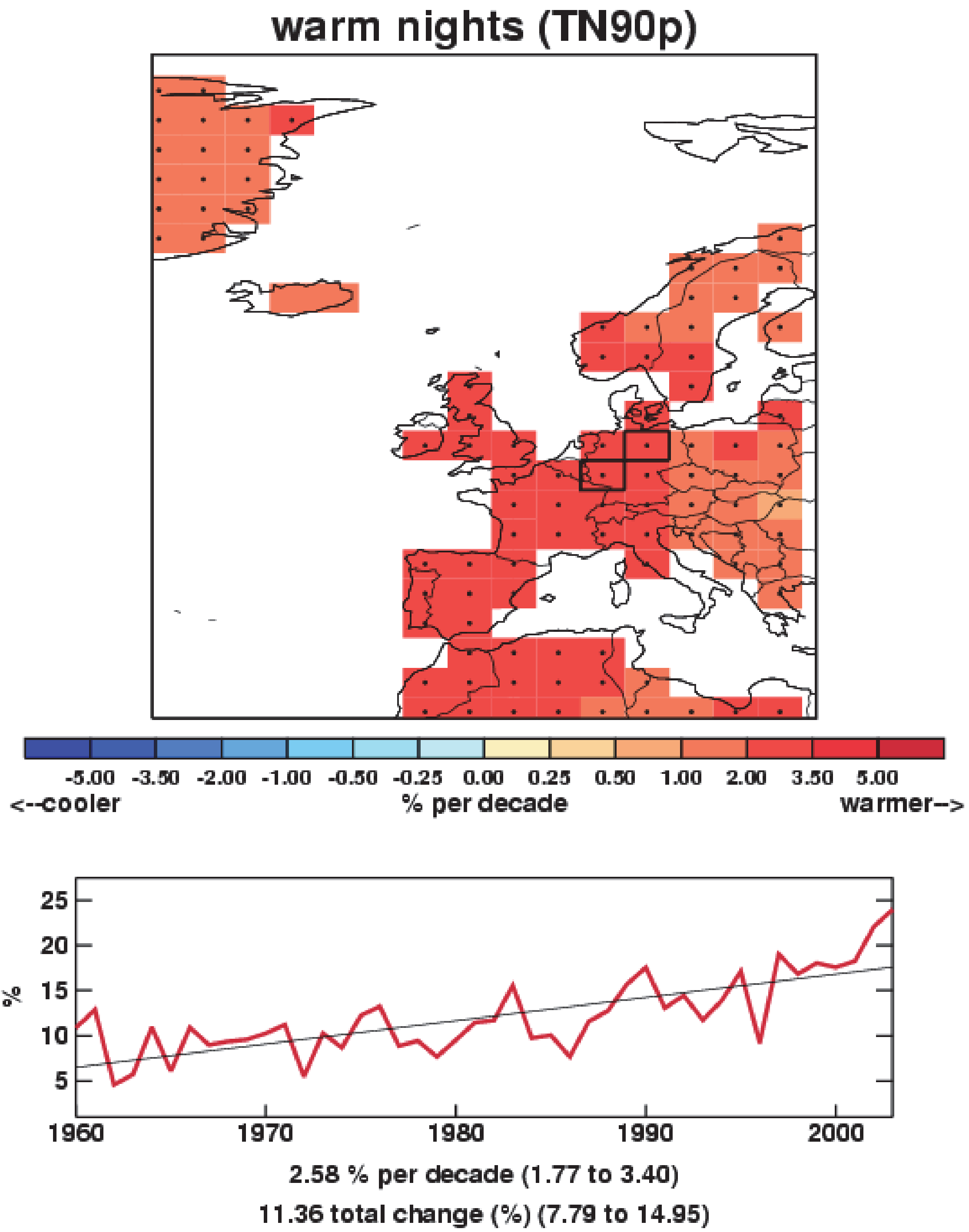


Figure 7. *Examples of the plots shown in the data section. Left: From ECA&D data between 1960-2010 for the number of warm nights, and Right: from HadEX data (1960-2003) for the total precipitation. A full explanation of the plots is given in the text below.*

The results are presented in the form of a map and a time series for each country and index. The map shows the grid box decadal trend in the index over the period for which there are data. High confidence, as determined above, is shown by a black dot in the grid box centre. To show the variation over time, the values for each year (and month if available) are shown in a time series for a regional average. The values of the indices have been normalised to a base period of 1961-1990 (except the Indian gridded data which use a 1971 to 1990 period), both in HadEX and in the new data acquired for this project. Therefore, for example, the percentage of nights exceeding the 90th percentile for a temperature is 10% for that period.

There are two influences on whether a grid box contains a value or not – the land-sea mask, and the decorrelation length scale. The land-sea mask is shown in Figure 6. There are grid boxes which contain some land but are mostly sea and so are not considered. The decorrelation length scale sets the maximum distance a grid box can be from stations before no value is assigned to it. Grid boxes containing three or more stations are highlighted by a thick border. This indicates regions where the value shown is likely to be more representative of the grid box area mean as opposed to a single station location.

On the maps for the new data there is a box indicating which grid boxes have been extracted to calculate the area average for the time series. This box is the same as shown in Figure 1 at the beginning of each country's document. These selected grid boxes are combined using area (cosine) weighting to calculate the regional average (both annual [thick lines] and monthly [thin lines] where available). Monthly (orange) and annual (blue) trends are fitted to these time series using the method described above. The decadal trend and total change over the period where there are data are shown with 5th to 95th percentile confidence intervals in parentheses. High confidence, as determined above, is shown by a solid line as opposed to a dotted one. The green vertical lines on the time series show the dates of some of the notable events outlined in each section.

Attribution

Regional distributions of seasonal mean temperatures in the 2000s are computed with and without the effect of anthropogenic influences on the climate. The analysis considers temperatures averaged over the regions shown in Figure 8. These are also identified as grey boxes on the maps in Figure 1. The coordinates of the regions are given in Table 6. The methodology combines information from observations and model simulations using the approach originally introduced in Christidis et al., 2010 and later extended in Christidis et al., 2011, where more details can be found. The analysis requires spatial scales greater than about 2,500 km and for that reason the selected regions (Fig.8 and Table 6) are often larger than individual countries, or include several smaller countries in a single region (for example UK, Germany and France are grouped in one region).

Observations of land temperature come from the CRUTEM3 gridded dataset (Brohan et al., 2006) and model simulations from two coupled GCMs, namely the Hadley Centre HadGEM1 model (Martin et al., 2006) and version 3.2 of the MIROC model (K-1 Developers, 2004). The use of two GCMs helps investigate the sensitivity of the results to the model used in the analysis. Ensembles of model simulations from two types of experiments are used to partition the temperature response to external forcings between its anthropogenic and natural components. The first experiment (ALL) simulates the combined effect of natural and anthropogenic forcings on the climate system and the second (ANTHRO) includes anthropogenic forcings only. The difference of the two gives an estimate of the effect of the natural forcings (NAT). Estimates of the effect of internal climate variability are derived from long control simulations of the unforced climate. Distributions of the regional summer mean temperature are computed as follows:

a) A global optimal fingerprinting analysis (Allen and Tett, 1999; Allen and Stott, 2003) is first carried out that scales the global simulated patterns (fingerprints) of climate change attributed to different combinations of external forcings to best match them to the observations. The uncertainty in the scaling that originates from internal variability leads to samples of the scaled fingerprints, i.e. several realisations that are plausibly consistent with the observations. The 2000-2009 decade is then extracted from the scaled patterns and two samples of the decadal mean temperature averaged over the reference region are then computed with and without human influences, which provide the Probability Density Functions (PDFs) of the decadal mean temperature attributable to ALL and NAT forcings.

b) Model-derived estimates of noise are added to the distributions to take into account the uncertainty in the simulated fingerprints.

c) In the same way, additional noise from control model simulations is introduced to the distributions to represent the effect of internal variability in the annual values of the seasonal mean temperatures. The result is a pair of estimated distributions of the annual values of the seasonal mean temperature in the region with and without the effect of human activity on the climate. The temperatures throughout the analysis are expressed as anomalies relative to period 1961-1990.

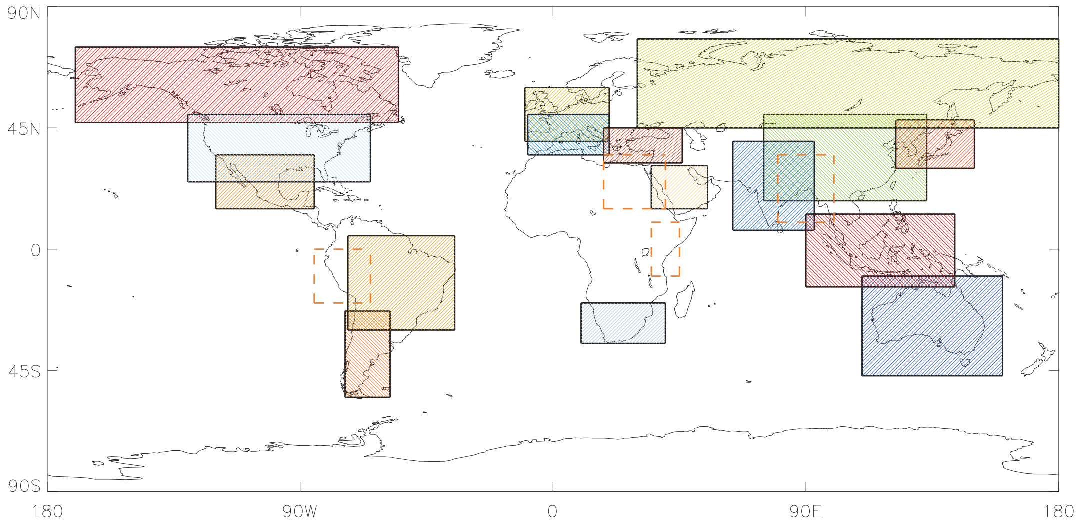


Figure 8. *The regions used in the attribution analysis. Regions marked with dashed orange boundaries correspond to non-G20 countries that were also included in the analysis.*

Region	Region Coordinates
Argentina	74-58W, 55-23S
Australia	110-160E, 47-10S
Bangladesh	80-100E, 10-35N
Brazil	73-35W, 30S-5N
Canada-Alaska	170-55W, 47-75N
China	75-133E, 18-50N
Egypt	18-40E, 15-35N
France-Germany-UK	10W-20E, 40-60N
India	64-93E, 7-40N
Indonesia	90-143E, 14S-13N
Italy-Spain	9W-20E, 35-50N
Japan-Republic of Korea	122-150E, 30-48N
Kenya	35-45E, 10S-10N
Mexico	120-85W, 15-35N
Peru	85-65W, 20-0S
Russia	30-185E, 45-78N
Saudi Arabia	35-55E, 15-31N
South Africa	10-40E, 35-20S
Turkey	18-46E, 32-45N

Table 6. *The coordinates of the regions used in the attribution analysis.*

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Acknowledgements

Data for this work were taken from the ECA&D dataset (Klein Tank et al., 2002). We thank Lisa Alexander and Markus Donat (University of New South Wales) for their help and advice. We also thank reviewers from Spain for their valuable input and advice.

Chapter 2 – Climate Change Projections

Introduction

Climate models are used to understand how the climate will evolve over time and typically represent the atmosphere, ocean, land surface, cryosphere, and biogeochemical processes, and solve the equations governing their evolution on a geographical grid covering the globe. Some processes are represented explicitly within climate models, large-scale circulations for instance, while others are represented by simplified parameterisations. The use of these parameterisations is sometimes due to processes taking place on scales smaller than the typical grid size of a climate model (a Global Climate Model (GCM) has a typical horizontal resolution of between 250 and 600km) or sometimes to the current limited understanding of these processes. Different climate modelling institutions use different plausible representations of the climate system, which is why climate projections for a single greenhouse gas emissions scenario differ between modelling institutes. This gives rise to "climate model structural uncertainty".

In response to a proposed activity of the World Climate Research Programme's (WCRP's; http://www.wcrp-climate.org/) Working Group on Coupled Modelling (WGCM), the Program for Climate Model Diagnosis and Intercomparison (PCMDI; http://www-pcmdi.llnl.gov/) volunteered to collect model output contributed by leading climate modelling centres around the world. Climate model output from simulations of the past, present and future climate was collected by PCMDI mostly during the years 2005 and 2006, and this archived data constitutes phase 3 of the Coupled Model Intercomparison Project (CMIP3). In part, the WGCM organised this activity to enable those outside the major modelling centres to perform research of relevance to climate scientists preparing the IPCC Fourth Assessment Report (AR4). This unprecedented collection of recent model output is commonly known as the "CMIP3 multi-model dataset". The GCMs included in this dataset are referred to regularly throughout this review, although not exclusively.

The CMIP3 multi-model ensemble has been widely used in studies of regional climate change and associated impacts. Each of the constituent models was subject to extensive testing by the contributing institute, and the ensemble has the advantage of having been constructed from a large pool of alternative model components, therefore sampling alternative structural assumptions in how best to represent the physical climate system. Being assembled on an opportunity basis, however, the CMIP3 ensemble was not designed to represent model uncertainties in a systematic manner, so it does not, in isolation, support robust estimates of the risk of different levels of future climate change, especially at a regional level.

Since CMIP3, a new (CMIP5) generation of coupled ocean-atmosphere models has been developed, which is only just beginning to be available and is being used for new projections for the IPCC Fifth Assessment Report (AR5).

These newer models typically feature higher spatial resolution than their CMIP3 counterparts, including in some models a more realistic representation of stratosphere-troposphere interactions. The CMIP5 models also benefit from several years of development in their parameterisations of small scale processes, which, together with resolution increases, are expected to result in a general improvement in the accuracy of their simulations of historical climate, and in the credibility of their projections of future changes. The CMIP5 programme also includes a number of comprehensive Earth System Models (ESMs) which explicitly simulate the earth's carbon cycle and key aspects of atmospheric chemistry, and also contain more sophisticated representations of aerosols compared to CMIP3 models.

The CMIP3 results should be interpreted as a useful interim set of plausible outcomes. However, their neglect of uncertainties, for instance in carbon cycle feedbacks, implies that higher levels of warming outside the CMIP3 envelope cannot be ruled out. In future, CMIP5 coupled model and ESM projections can be expected to produce improved advice on future regional changes. In particular, ensembles of ESM projections will be needed to provide a more comprehensive survey of possible future changes and their relative likelihoods of occurrence. This is likely to require analysis of the CMIP5 multi-model ESM projections, augmented by larger ensembles of ESM simulations in which uncertainties in physical and biogeochemical feedback processes can be explored more systematically, for example via ensembles of model runs in which key aspects of the climate model are slightly adjusted. Note that such an exercise might lead to the specification of wider rather than narrower uncertainties compared to CMIP3 results, if the effects of representing a wider range of earth system processes outweigh the effects of refinements in the simulation of physical atmosphere-ocean processes already included in the CMIP3 models.

Climate projections

The Met Office Hadley Centre is currently producing perturbed parameter ensembles of a single model configuration known as HadCM3C, to explore uncertainties in physical and biogeochemical feedback processes. The results of this analysis will become available in the next year and will supplement the CMIP5 multi-model ESM projections, providing a more comprehensive set of data to help progress understanding of future climate change. However, many of the studies covered in the chapter on climate impacts have used CMIP3 model output. For this reason, and because it is still the most widely used set of projections available, the CMIP3 ensemble output for temperature and precipitation, for the A1B emission scenario, for Spain and the surrounding region is shown below.

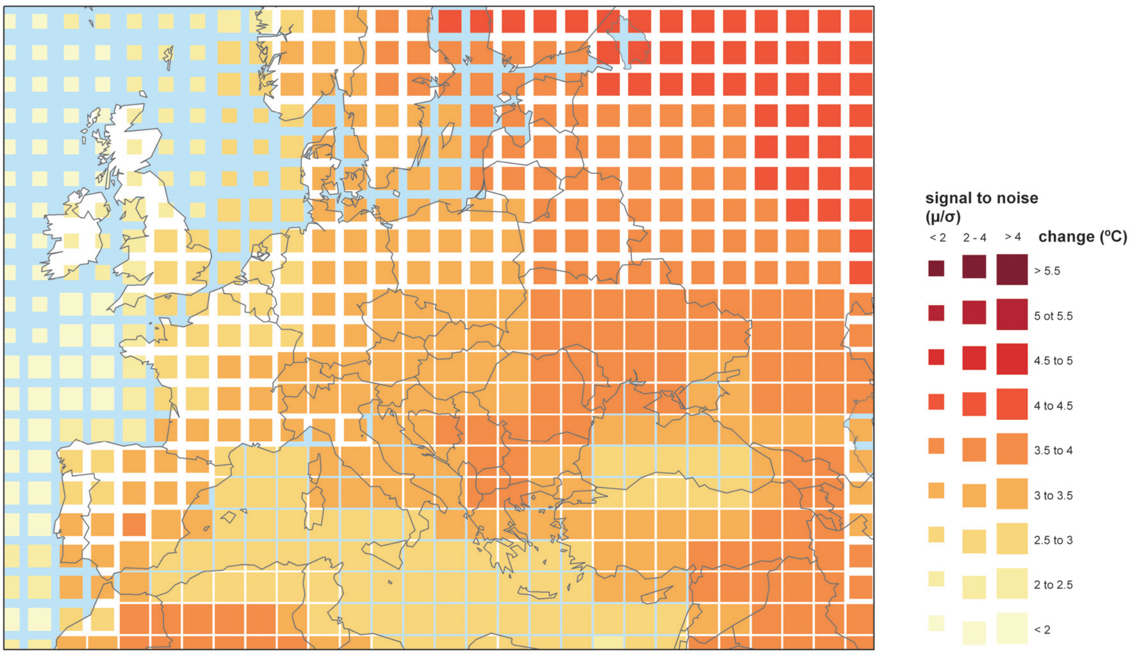

***Figure 1**. Percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the magnitude of the change.*

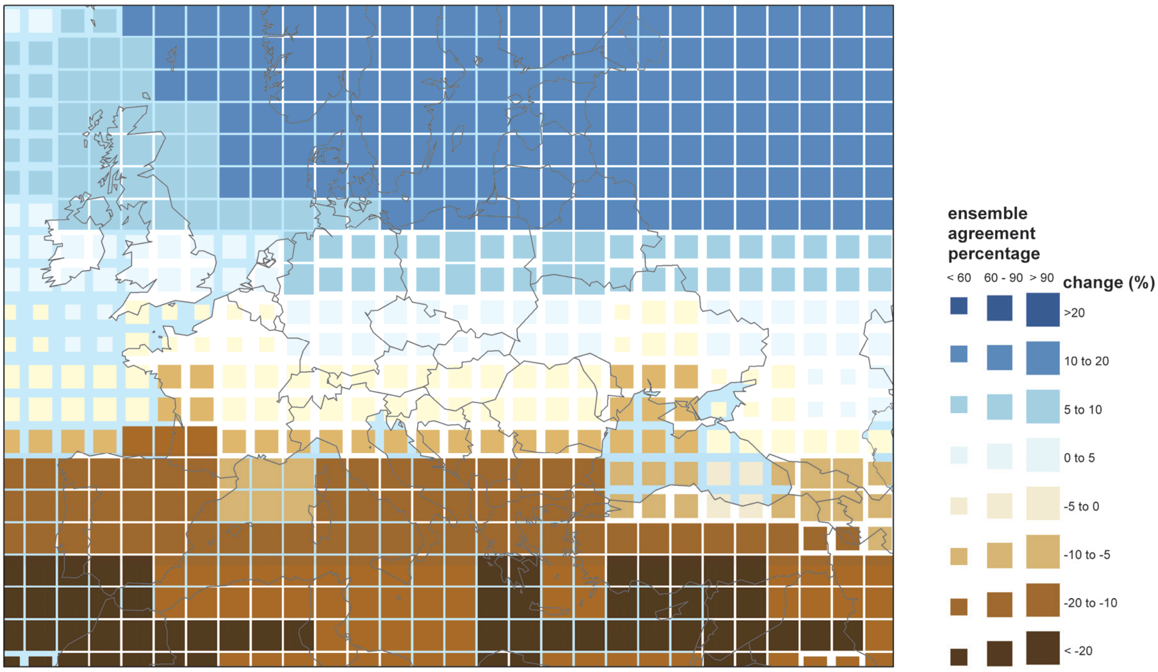

Figure 2. *Percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the sign of the change.*

Summary of temperature change in Spain

Figure 1 shows the percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. All of the models in the CMIP3 ensemble project increased temperatures in the future, but the size of each pixel indicates how well the models agree over the magnitude of the increase.

Increases in temperature of up to around 4°C are projected over Spain, with the highest agreement between models towards the south of the country.

Summary of precipitation change in Spain

Figure 2 shows the percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. Unlike for temperature, the models sometimes disagree over whether precipitation is increasing or decreasing over a region, so in this case the size of each pixel indicates the percentage of the models in the ensemble that agree on the sign of the change in precipitation.

Projected rainfall decreases over Spain could be over 20% in the southwest of the country, and between 10% and 20% over other parts. Spain has good ensemble agreement between the ensemble members over these projected decreases.

Chapter 3 – Climate Change Impact Projections

Introduction

Aims and approach

This chapter looks at research on a range of projected climate change impacts, with focus on results for Spain. It includes projections taken from the AVOID programme, for some of the impact sectors.

The aim of this work is to take a 'top down' approach to assessing global impacts studies, both from the literature and from new research undertaken by the AVOID programme. This project covers 23 countries, with summaries from global studies provided for each of these. This global approach allows some level of comparison between countries, whilst presenting information on a scale most meaningful to inform international policy.

The literature covered in this chapter focuses on research published since the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) and should be read in conjunction with IPCC AR4 WG1 and WG2 reports. For some sectors considered, an absence of research developments since the IPCC AR4, means earlier work is cited as this helps describe the current level of scientific understanding. This report focuses on assessing scientific research about climate change impacts within sectors; it does not present an integrated analysis of climate change adaptation policies.

Some national and sub-national scale literature is reported to a limited extent to provide some regional context.

Impact sectors considered and methods

This report reviews the evidence for the impact of climate change on a number of sectors, for Spain. The following sectors are considered in turn in this report:

- Crop yields
- Food security
- Water stress and drought
- Pluvial flooding and rainfall

- Fluvial flooding
- Tropical cyclones (where applicable)
- Coastal regions

Supporting literature

Literature searches were conducted for each sector with the Thomson Reuters Web of Science (WoS., 2011) and Google Scholar academic search engines respectively. Furthermore, climate change impact experts from each of the 23 countries reviewed were contacted. These experts were selected through a combination of government nomination and from experts known to the Met Office. They were asked to provide literature that they felt would be of relevance to this review. Where appropriate, such evidence has been included. A wide range of evidence was considered, including; research from international peer-reviewed journal papers; reports from governments, non-governmental organisations, and private businesses (e.g. reinsurance companies), and research papers published in national journals.

For each impact sector, results from assessments that include a global- or regional-scale perspective are considered separately from research that has been conducted at the national- or sub-national-scale. The consideration of global- and regional-scale studies facilitates a comparison of impacts across different countries, because such studies apply a consistent methodology for each country. While results from national- and sub-national-scale studies are not easily comparable between countries, they can provide a level of detail that is not always possible with larger-scale studies. However, the national- and sub-national scale literature included in this project does not represent a comprehensive coverage of regional-based research and cannot, and should not, replace individual, detailed impacts studies in countries. The review aims to present an up-to-date assessment of the impact of climate change on each of the sectors considered.

AVOID programme results

Much of the work in this report is drawn from modelling results and analyses coming out of the AVOID programme. The AVOID programme is a research consortium funded by DECC and Defra and led by the UK Met Office and also comprises the Walker Institute at the

University of Reading, the Tyndall Centre represented through the University of East Anglia, and the Grantham Institute for Climate Change at Imperial College. The expertise in the AVOID programme includes climate change research and modelling, climate change impacts in natural and human systems, socio-economic sciences, mitigation and technology. The unique expertise of the programme is in bringing these research areas together to produce integrated and policy-relevant results. The experts who work within the programme were also well suited to review the literature assessment part of this report. In this report the modelling of sea level rise impacts was carried out for the AVOID programme by the University of Southampton.

The AVOID programme uses the same emissions scenarios across the different impact sectors studied. These are a business as usual (IPCC SRES A1B) and an aggressive mitigation (the AVOID A1B-2016-5-L) scenario. Model output for both scenarios was taken from more than 20 GCMs and averaged for use in the impact models. The impact models are sector specific, and frequently employ further analytical techniques such as pattern scaling and downscaling in the crop yield models.

Data and analysis from AVOID programme research is provided for the following impact sectors:

- Crop yields
- Water stress and drought
- Fluvial flooding
- Coastal regions

Uncertainty in climate change impact assessment

There are many uncertainties in future projections of climate change and its impacts. Several of these are well-recognised, but some are not. One category of uncertainty arises because we don't yet know how mankind will alter the climate in the future. For instance, uncertainties in future greenhouse gas emissions depends on the future socio-economic pathway, which, in turn, depends on factors such as population, economic growth, technology development, energy demand and methods of supply, and land use. The usual approach to dealing with this is to consider a range of possible future scenarios.

Another category of uncertainties relate to our incomplete understanding of the climate system, or an inability to adequately model some aspects of the system. This includes:

- Uncertainties in translating emissions of greenhouse gases into atmospheric concentrations and radiative forcing. Atmospheric CO_2 concentrations are currently rising at approximately 50% of the rate of anthropogenic emissions, with the remaining 50% being offset by a net uptake of CO_2 into the oceans and land biosphere. However, this rate of uptake itself probably depends on climate, and evidence suggests it may weaken under a warming climate, causing more CO_2 to remain in the atmosphere, warming climate further. The extent of this feedback is highly uncertain, but it not considered in most studies. The phase 3 of the Coupled Model Intercomparison Project (CMIP3), which provided the future climate projections for the IPCC Fourth Assessment Report (AR4), used a single estimate of CO_2 concentration rise for each emissions scenario, so the CMIP3 projections (which were used in most studies presented here, including AVOID) do not account for this uncertainty.
- Uncertainty in climate response to the forcing by greenhouse gases and aerosols. One aspect of this is the response of global mean temperature ("climate sensitivity"), but a more relevant aspect for impacts studies is the response of regional climates, including temperature, precipitation and other meteorological variables. Different climate models can give very different results in some regions, while giving similar results in other regions. Confidence in regional projections requires more than just agreement between models: physical understanding of the relevant atmospheric, ocean and land surface processes is also important, to establish whether the models are likely to be realistic.
- Additional forcings of regional climate. Greenhouse gas changes are not the only anthropogenic driver of climate change; atmospheric aerosols and land cover change are also important, and unlike greenhouse gases, the strength of their influence varies significantly from place to place. The CMIP3 models used in most impacts studies generally account for aerosols but not land cover change.
- Uncertainty in impacts processes. The consequences of a given changes in weather or climatic conditions for biophysical impacts such as river flows, drought, flooding, crop yield or ecosystem distribution and functioning depend on many other processes which are often poorly-understood, especially at large scales. In particular, the extent to which different biophysical impacts interact with each other has been hardly studied, but may be crucial; for example, impacts of climate change on crop yield may depend not only on local climate changes affecting rain-fed crops, but also remote climate changes affecting river flows providing water for irrigation.

- Uncertainties in non-climate effects of some greenhouse gases. As well as being a greenhouse gas, CO_2 exerts physiological influences on plants, affecting photosynthesis and transpiration. Under higher CO_2 concentrations, and with no other limiting factors, photosynthesis can increase, while the requirements of water for transpiration can decrease. However, while this has been extensively studied under experimental conditions, including in some cases in the free atmosphere, the extent to which the ongoing rise in ambient CO_2 affects crop yields and natural vegetation functioning remains uncertain and controversial. Many impacts projections assume CO_2 physiological effects to be significant, while others assume it to be non-existent. Studies of climate change impacts on crops and ecosystems should therefore be examined with care to establish which assumptions have been made.

In addition to these uncertainties, the climate varies significantly through natural processes from year-to-year and also decade-to-decade, and this variability can be significant in comparison to anthropogenic forcings on shorter timescales (the next few decades) particularly at regional scales. Whilst we can characterise the natural variability it will not be possible to give a precise forecast for a particular year decades into the future.

A further category of uncertainty in projections arises as a result of using different methods to correct for uncertainties and limitations in climate models. Despite being painstakingly developed in order to represent current climate as closely as possible, current climate models are nevertheless subject to systematic errors such as simulating too little or too much rainfall in some regions. In order to reduce the impact of these, '*bias correction*' techniques are often employed, in which the climate model is a source of information on the *change* in climate which is then applied to the observed present-day climate state (rather than using the model's own simulation of the present-day state). However, these bias-corrections typically introduce their own uncertainties and errors, and can lead to inconsistencies between the projected impacts and the driving climate change (such as river flows changing by an amount which is not matched by the original change in precipitation). Currently, this source of uncertainty is rarely considered

When climate change projections from climate models are applied to climate change impact models (e.g. a global hydrological model), the climate model structural uncertainty carries through to the impact estimates. Additional uncertainties include changes in future emissions and population, as well as parameterisations within the impact models (this is rarely considered). Figure 1 highlights the importance of considering climate model structural uncertainty in climate change impacts assessment. Figure 1 shows that for 2°C prescribed global-mean warming, the magnitude of, and sign of change in average annual runoff from present, simulated by an impacts model, can differ depending upon the GCM that provides the climate change projections that drive the impact model. This example also shows that the choice of impact model, in this case a global hydrological model (GHM) or catchment-scale hydrological model (CHM), can affect the magnitude of impact and sign of change from present (e.g. see IPSL CM4 and MPI ECHAM5 simulations for the Xiangxi). To this end, throughout this review, the number of climate models applied in each study reviewed, and the other sources of uncertainty (e.g. emissions scenarios) are noted. Very few studies consider the application of multiple impacts models and it is recommended that future studies address this.

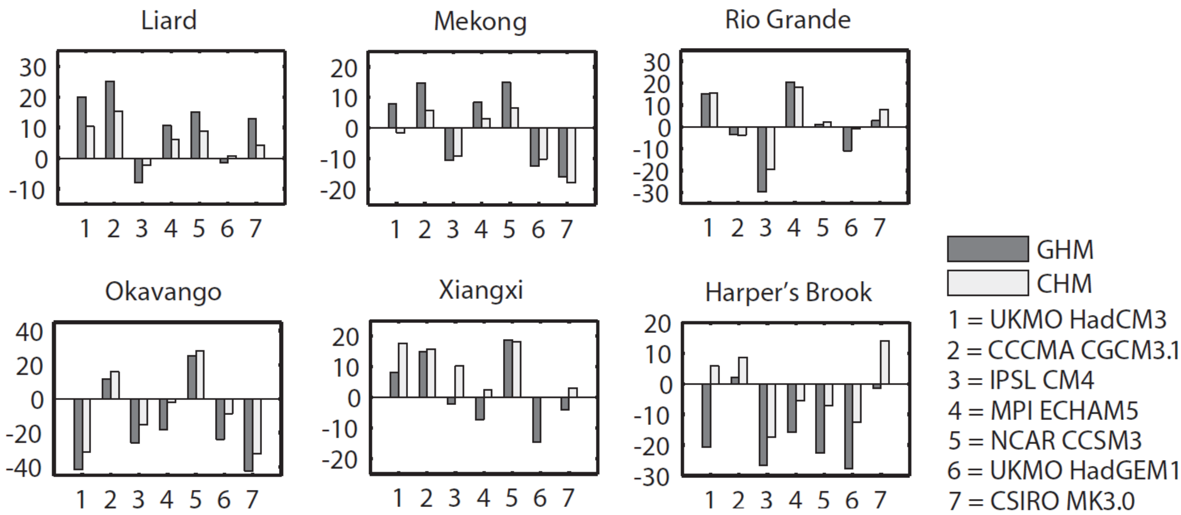

Figure 1. *Change in average annual runoff relative to present (vertical axis; %), when a global hydrological model (GHM) and a catchment-scale hydrological model (CHM) are driven with climate change projections from 7 GCMs (horizontal axis), under a 2°C prescribed global-mean warming scenario, for six river catchments. The figure is from Gosling et al. (2011).*

Uncertainties in the large scale climate relevant to Spain include the Atlantic Ocean has a Meridional Overturning Circulation (MOC) which transports large amounts of heat northwards in the Atlantic from the Equator. A key part of this is called the thermohaline circulation (THC). Disruption of the MOC could have a major impact on the Northern Hemisphere climate, including that of Spain, with likely detrimental impacts on human and animal systems. The IPCC AR4 concluded that "… it is very likely that the Atlantic Ocean Meridional Overturning Circulation could slow down during the course of the 21st century. A multi-model ensemble shows an average reduction of 25% with a broad range from virtually no change to a reduction of over 50% averaged over 2080 to 2099" (IPCC, 2007a).

Schneider et al. (2007) analysed simulations from several GCMs that were reviewed in the IPCC AR4 and found that projections of MOC change indicate it may weaken by 25-30% by the year 2100. Recent monitoring (Cunningham et al., 2007, Kanzow et al., 2007) has revealed large variability in the strength of the MOC on daily to seasonal timescales. This significant variability casts doubt on a previous report of decreases in MOC transport from several hydrographic sections (Bryden et al., 2005), although it does not explain the observed water mass changes below 3000m. Recent results based on radar altimeter and Argo data also suggest that there has been no slowdown, at least over the altimeter era (1993-present) (Willis, 2010). In contrast, two ocean state estimation studies (Balmaseda et al., 2007, Wunsch and Heimbach, 2006) indicated an MOC slow down. It has been suggested, based on model studies, that anthropogenic aerosols have slowed the weakening of the MOC and such weakening might only become significant several decades into the 21st century (Delworth and Dixon, 2006).

Regarding the possibility of MOC shutdown, a recent study presented by Swingedouw et al. (2007) with one climate model found that additional melt from Greenland could lead to complete AMOC shutdown in a CO_2 stabilisation experiment. However, a previous study with a different model (Ridley et al., 2005) found no effect from similar levels of meltwater input. Mikolajewicz et al. (2007) coupled an earth system model with atmospheric and ocean GCMs and observed a complete shutdown of the AMOC under a high emission scenario (SRES A2), but not before 2100. Moreover, Mikolajewicz et al. (2007) observed only a temporary weakening of the deep water formation in the North Atlantic by 2100 under a low emission scenario (B1).

Reversibility following AMOC shutdown is a key issue. Hofmann and Rahmstorf (2009) showed that hysteresis still occurs in a new low-diffusivity model. This is contrary to previous theoretical arguments that hysteresis is a product of diffusivity of the low-resolution simplified ocean models which are applied to perform the long-term simulations that are required to investigate this issue.

There is some new work on the impacts of AMOC weakening. Two studies (Kuhlbrodt et al., 2009, Vellinga and Wood, 2008) found SLR of several tens of cm along parts of the North Atlantic coast. They studies found that regional cooling could partially offset the greenhouse gas warming, and various other impacts may be substantial but hard to quantify such as change in tropical precipitation patterns and change in ocean currents leading to declining fish stocks and ecosystems (Schmittner, 2005).

In conclusion, large uncertainty remains in the probability of a complete MOC shutdown (Kriegler et al., 2009, Zickfeld et al., 2007). However, for the high temperature scenario considered by a recent expert elicitation exercise (centred on 4.5°C by 2100, 6.5°C by 2200) (Kriegler et al., 2009), the probability of complete shutdown was assessed to be at least 10% (according to several experts). Comparable results were found by the exercise reported by Zickfeld et al. (2007). To this end, it is thought unlikely that the AMOC could significantly weaken with 2°C global-mean warming.

Summary of findings for each sector

Crop yields

- Quantitative crop yield projections under climate change scenarios for Spain vary across studies due to the application of different models, assumptions and emissions scenarios.

- A definitive conclusion on the impact of climate change on crop yields in Spain cannot be drawn from the studies included here. However the majority, but not all, of global- and regional-scale studies surveyed generally project an increase in the yield of wheat, one of Spain's major crops, over the century.

- However, simulations by the AVOID programme indicate that much of the area currently cultivated could become less suitable for agricultural production as a result of climate change.

- Important knowledge gaps and key uncertainties include the quantification of yield increases due to CO_2 fertilisation, the quantification of yield reductions due to ozone damage and the extent to which crop diseases might affect crop yields with climate change.

Food security

- Spain is presently a country with extremely low levels of undernourishment. Global-scale studies included here generally project that Spain will face adverse affects on food security as a consequence of climate change over the next 40 years, but could remain food-secure largely as a result of its strong economic position in global food markets and high adaptive capacity.

- One study concluded that the national economy of Spain presents a moderate vulnerability to climate change impacts on fisheries by the 2050s.

Water stress and drought

- Several global-scale and national-scale studies included here project that droughts in the country could increase in frequency and magnitude with climate change, with the greatest impacts projected for the south of the country, along the Mediterranean coast.
- Similarly global-, national-, and sub-national-scale studies project increases in water stress in the country with climate change.
- Recent simulations by the AVOID programme project a median increase of around 60% of Spain's population to be exposed to water stress increases by 2100 under SRES A1B. Under the aggressive mitigation scenario, this is 25%. None of the models included simulated decreases in water stress with climate change for Spain.

Pluvial flooding and rainfall

- Recent studies support conclusions from the IPCC AR4 that mean rainfall is projected to decrease over the Mediterranean area.
- There remains uncertainty over whether extreme short-term precipitation, and associated pluvial flooding, may either increase or decrease with climate change.

Fluvial flooding

- Few studies have assessed the impact of climate change on fluvial flooding in Spain. Moreover, large climate model uncertainty presently inhibits any firm conclusions with regards to changes in fluvial flood hazard in Spain under climate change scenarios.
- Simulations by the AVOID programme, based on climate projections from 21 GCMs, show a much greater tendency towards decreasing flood risk throughout the 21st century under both the A1B and a mitigation emissions scenario.
- Better quantification and understanding of uncertainties is a requirement for future research.

Tropical cyclones

- Spain is not impacted by tropical cyclones.

Coastal regions

- Recent studies show that sea level rise (SLR) impacts in Spain could be large in the absence of adaptation.
- For example, one study shows that by the 2080s under a high SLR scenario and without adaptation, the average annual number of people flooded could be around 321,800; with adaptation (raising of flood dykes and the application of beach nourishment), this is greatly reduced to 1,100.
- This adds detail to knowledge reported in the IPCC AR4.

Crop yields

Headline

Crop yield projections under climate change scenarios for Spain vary across studies due to the application of different models, assumptions, and emissions scenarios. This precludes the formulation of a robust and definitive conclusion on the impact of climate change on crop yields in Spain. The majority, but not all, of global- and regional-scale studies surveyed generally project an increase in the yield of wheat, one of Spain's major crops, over the century. However, simulations by the AVOID programme indicate that much of the areas currently cultivated could become meteorologically less suitable for agricultural production as a result of climate change.

Supporting literature

Introduction

The impacts of climate change on crop productivity are highly uncertain due to the complexity of the processes involved. Most current studies are limited in their ability to capture the uncertainty in regional climate projections, and often omit potentially important aspects such as extreme events and changes in pests and diseases. Importantly, there is a lack of clarity on how climate change impacts on drought are best quantified from an agricultural perspective, with different metrics giving very different impressions of future risk. The dependence of some regional agriculture on remote rainfall, snowmelt and glaciers adds to the complexity - these factors are rarely taken into account, and most studies focus solely on the impacts of local climate change on rain-fed agriculture. However, irrigated agricultural land produces approximately 40-45 % of the world's food (Doll and Siebert 2002), and the water for irrigation is often extracted from rivers which can depend on climatic conditions far from the point of extraction. Hence, impacts of climate change on crop productivity often need to take account of remote as well as local climate changes. Indirect impacts via sea-level rise, storms and diseases have also not been quantified. Perhaps most seriously, there is high uncertainty in the extent to which the direct effects of CO_2 rise on plant physiology will interact with climate change in affecting productivity. Therefore, at present, the aggregate impacts of climate change on large-scale agricultural productivity cannot be reliably quantified (Gornall et al, 2010). This section summarises findings from a range of post IPCC AR4 assessments to inform and contextualise the analysis performed by AVOID programme for this project. The results from the AVOID work are discussed in the next section.

The FAO (2008) showed that Barley is the most important food crop in Spain, followed by wheat (see Table 1). Other important crops, especially in monetary terms, include grapes, olives, tomatoes and oranges.

Harvested area (ha)		Quantity (Metric ton)		Value ($1000)	
Barley	3460000	Barley	11200000	Grapes	2790000
Olives	2450000	Wheat	6710000	Olives	2730000
Wheat	2060000	Grapes	5950000	Tomatoes	905000
Grapes	1100000	Olives	5570000	Oranges	591000
Sunflower seed	730000	Tomatoes	4040000	Tangerines, mandarins, clem.	501000
Almonds	566000	Sugar beet	3980000	Peaches and nectarines	463000
Oats	505000	Oranges	3410000	Chillies and peppers, green	342000

Table 1. *The top 7 crops by harvested area, quantity and value according to the FAO (2008) in Spain. Crops that feature in all lists are shaded green; crops that feature in two top 7 lists are shaded amber. Data is from FAO (2008) and has been rounded down to three significant figures.*

A number of impact model studies looking at crop yield which include results for some of the main crops in Spain have been conducted. They apply a variety of methodological approaches, including using different climate model inputs and treatment of other factors that might affect yield, such as impact of increased CO_2 in the atmosphere on plant growth and adaption of agricultural practises to changing climate conditions. Some studies report projections for geographic or climatic areas larger than Spain alone and it is not always clear to what extent the crop yield projections are representative for Spain only in these cases. These different models, assumptions and emissions scenarios mean that there are a range of crop yield projections for Spain.

Important knowledge gaps and key uncertainties which are applicable to Spain as well as at the global-scale, include; the quantification of yield increases due to CO_2 fertilisation and yield reductions due to ozone damage (Ainsworth and McGrath, 2010, Iglesias et al., 2009), and the extent crop diseases could affect crop yields with climate change (Luck et al., 2011). Recent work has highlighted that repeated small water stresses during the growing season may have a strong impact on yields. However, the magnitude to which climate change might exacerbate this phenomenon remains poorly understood.

Most crop simulation models do not include the direct effect of extreme temperatures on crop development and growth, thus only changes in mean climate conditions are considered to affect crop yields for the studies included here.

Assessments that include a global or regional perspective

Recent Past

Crop yield changes could be due to a variety of factors, which might include, but not be confined to, a changing climate. In order to assess the impact of recent climate change (1980-2008) on wheat, maize, rice and soybean, Lobell et al. (2011) looked at how the overall yield trend in these crops changed in response to changes in climate over the period studied. The study was conducted at the global-scale but national estimates for Spain were also calculated. Lobell et al. (2011) divided the climate-induced yield trend by the overall yield trend for 1980–2008, to produce a simple metric of the importance of climate relative to all other factors. The ratio produced indicates the influence of climate on the productivity trend. So for example a value of –0.1 represents a 10% reduction in yield gain due to climate change, compared to the increase that could have been achieved without climate change, but with technology and other gains. This can also be expressed as 10 years of climate trend being equivalent to the loss of roughly 1 year of technology gains. For Spain, rice yield was estimated to have benefited relative to what could have been achieved without the climate trends (see Table 2).

Crop	Trend
Maize	-0.1 to 0
Rice	0.1 to 0.2
Wheat	-0.1 to 0
Soybean	n/a

***Table 2**. The estimated national net impact of climate trends for 1980-2008 on crop yields in Spain. Climate-induced yield trend divided by overall yield trend. 'n/a' infers zero or insignificant crop production or unavailability of data. Data is from Lobell et al. (2011).*

Climate change studies

Several recent studies have applied climate projections from Global Climate Models (GCMs) to crop yield models to assess the global-scale impact of climate change on crop yields (Iglesias and Rosenzweig, 2009, Giannakopoulos et al., 2005, Moriondo et al., 2010, Olesen et al., 2007). Most of these studies include impact estimates at the national-scale for Spain which are presented in this section. The process of CO_2 fertilisation of some crops is usually included in most climate impact studies of yields. However, other gases can influence crop yield and are not always included in impacts models. An example of this is ozone (O_3) and so a study which attempts to quantify the potential impact on crop yield of changes in ozone in the atmosphere is also included (Avnery et al. 2011). In addition to these studies, the AVOID programme analysed the patterns of climate change for 21 GCMs, to establish an index of 'climate suitability' of agricultural land. Climate suitability is not directly equivalent to crop yields, but is a means of looking at a standard metric across all the countries including in this project, and of assessing the level of agreement on variables that affect crop production, between all 21 GCMs.

Iglesias and Rosenzweig (2009) repeated an earlier study presented by Parry et al. (2004) by applying climate projections from the HadCM3 GCM (instead of HadCM2, which was applied by Parry et al. (2004)), under seven SRES emissions scenarios and for three future time periods. This study used a globally consistent crop simulation methodologies and climate change scenarios, and weighted the model site results by their contribution to regional and national, and rain-fed and irrigated production. The study also applied a quantitative estimation of physiological CO_2 effects on crop yields and considered the affect of adaptation by assessing the country or regional potential for reaching optimal crop yield. The results from the study for Spain are presented in Table 3 and Table 4. Wheat yield was projected above baseline (1970-2000) levels for each future time horizon and under all emissions scenarios and this trend continued throughout the 21st century.

Scenario	Year	Wheat
A1FI	2020	4.19
	2050	9.28
	2080	7.48
A2a	2020	5.67
	2050	9.20
	2080	13.14
A2b	2020	3.49
	2050	8.92
	2080	13.15
A2c	2020	3.34
	2050	9.07
	2080	13.51
B1a	2020	1.61
	2050	5.28
	2080	6.86
B2a	2020	3.66
	2050	5.13
	2080	7.24
B2b	2020	3.16
	2050	5.50
	2080	8.85

***Table 3**. Wheat yield changes (%) in Spain relative to baseline scenario (1970-2000) for different emission scenarios and future time periods. Some emissions scenarios were run in an ensemble simulation (e.g. A2a, A2b, A2c). Data is from Iglesias and Rosenzweig (2009).*

	Wheat	
	Up	**Down**
Baseline to 2020	7	0
Baseline to 2050	7	0
Baseline to 2080	7	0
2020 to 2050	7	0
2050 to 2080	6	1

***Table 4.** The number of emission scenarios that predict yield gains ("Up") or yield losses ("Down") in Spain for wheat between two points in time. Data is from Iglesias and Rosenzweig (2009).*

Giannakopoulos et al. (2005, 2009) applied climate projections with the HadCM3 GCM under the SRES A2 and B2 emissions scenarios to assess climate change impacts for the Mediterranean basin for the period 2031-2060 under the A2 and B2 emissions scenarios. Climate data were used as input to the CROPSYST (Cropping Systems Simulation Model) (Stockle et al., 2003) crop model to project crop productivity changes (compared to 1961-1990) for a range of different crop types. The crop types were divided into 'C4' summer crop, 'C3' summer crop, legumes, tuber crops and cereals, where 'C4' and 'C3' refer to two plant physiology types that affect the way plants take up CO_2 from the atmosphere. 'C3' crops are able to benefit from CO_2 enrichment of the atmosphere, whereas 'C4' crops are not. This process is simulated by CROPSYST. The process is important because the benefit from CO_2 enrichment can potentially off-set some of the negative impacts of climate change for that crop. For Spain the 'C4' summer crop studied was irrigated maize, the 'C3' summer crop was rain-fed sunflowers, the legume was rain-fed lentils, the tuber crop was irrigated potato and the cereal was rain-fed barley. Giannakopoulos et al. (2005) observed that the difference in crop productivity between emissions scenarios was large. B2 was associated with positive changes in crop productivity for all crops whereas the changes with A2 were less positive (potato and barley), or adverse (maize, sunflower and lentil).

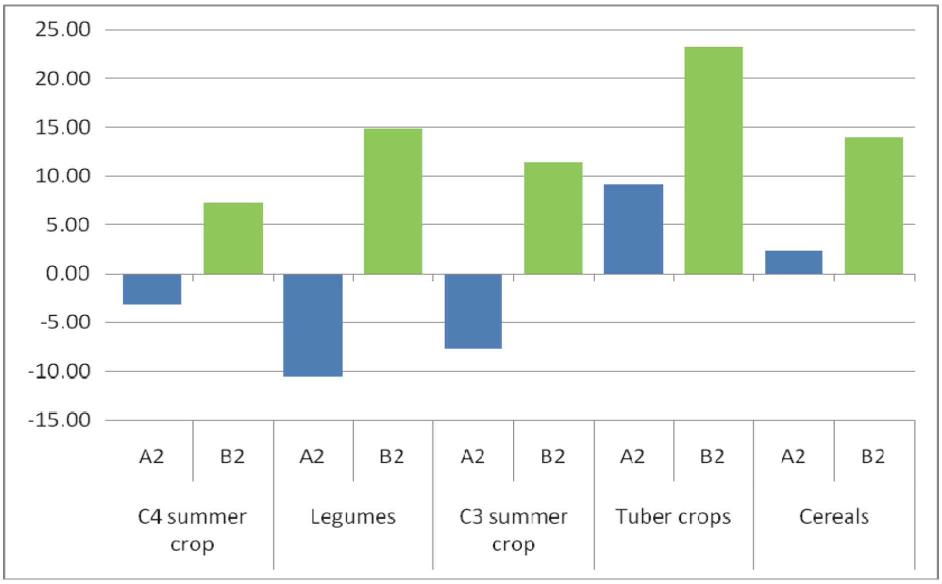

Figure 2. *Impact of climate change on crop productivity for different types of crops for Spain. The Y-axis is expressed as percentage difference between future (A2 and B2 scenarios respectively) and present yields. After Giannakopoulos et al. (2005).*

Moriondo et al. (2010) simulated relative changes in crop yield for sunflower, soybean, spring wheat and durum wheat for a global mean warming of 2°C warmer than present climate change scenario with A2 socioeconomics. The study accounted for changes in extreme events such as droughts and the CO_2 fertiliser effect. Moriondo et al. (2010) compared the effectiveness of various adaptation options relative to no adaptation. No quantitative information on impacts is available from the study but estimates can be made whether, on average, a relative yield loss or a yield gain was projected for a given crop, adaptation method and country (see Table 5). The results indicate that for the 2030-2060 time horizon, on average, climate change is associated with yield gains for durum wheat without adaptation and for all crops if the specified irrigation is implemented.

	No adaptation[1]	Advanced sowing	Delayed sowing	Shorter cycle varieties	Longer cycle varieties	Irrigation
Sunflower	-	+	-	-	+-	+
Soybean	-	+	-	+ -	-	+
Spring wheat	-	+	-	-	+-	+
Durum wheat	+ -	+	-	-	+	+

[1] Yield changes with respect to the present period, not considering adaptation methods

Table 5. *Relative change in yield of four crops in a +2 °C world under SRES A2 socioeconomics for Spain. The relative change is calculated with respect to the same +2°C scenario without adaptation (left column). "+" = relative yield gain, "-" = relative yield loss, "+ -" = high spatial variability and uncertainty over sign of average yield change. After Moriondo et al. (2010).*

Olesen et al. (2007) addressed the issue of uncertainty in projecting impacts of climate change on agriculture. They projected rain-fed winter wheat yield across the European domain using nine different RCMs with HadAM3H as the bounding GCM, under SRES A2 emissions. For more than 75% of the cropping area, all RCMs were associated with decreases in wheat yields for Spain. This presents a higher degree of certainty about the sign of yield changes, relative to the simulations presented by Moriondo et al. (2010).

Elsewhere, several recent studies have assessed the impact of climate change on a global-scale or regional-scale and include impact estimates for Southern Europe as a whole (Ciscar et al., 2009, Ferrise et al., 2011, Iglesias et al., 2009, Tatsumi et al., 2011). Whilst these studies provide a useful indicator of crop yields under climate change for the larger *region*, it should be noted that the crop yields presented in such cases are not definitive *national* estimates. This is because the yields are averaged over the entire region, which includes other countries as well as Spain.

Tatsumi et al. (2011) applied an improved version of the GAEZ crop model (iGAEZ) to simulate crop yields on a global scale for wheat, potato, cassava, soybean, rice, sweet potato, maize, green beans. The impact of global warming on crop yields from the 1990s to 2090s was assessed by projecting five GCM outputs under the SRES A1B scenario and comparing the results for crop yields as calculated using the iGAEZ model for the period of 1990-1999. The results for Southern Europe, the regional grouping which included Spain, are displayed in Table 6 and suggest increased yields for wheat, potato and rice, but a decline for sweet potato, green beans and maize.

Wheat	Potato	Cassava	Soybean	Rice	Sweet potato	Maize	Green beans
10.80	7.30	-	-0.24	3.46	-2.00	-2.42	-2.34

Table 6. *Average change in yield (%), during 1990s-2090s in Southern Europe. Data is from Tatsumi et al. (2011).*

Ferrise et al. (2011) developed a probabilistic framework for evaluating the risk of durum wheat yield shortfall for the Mediterranean Basin. An artificial neural network, trained to emulate the outputs of a process-based crop growth model, was adopted to create yield response surfaces which were then overlaid with probabilistic projections of future temperature and precipitation changes in order to estimate probabilistic projections of future yields. To estimate the climatic risk of durum wheat shortfall in the next century, the future yield projections were compared with a critical threshold, calculated as the 30-year mean yield for the reference period (1961–1990). The climatic risk of durum wheat yield shortfall was then defined as the relative frequency of future yield projections below the threshold. Results were only presented as plotted maps of the spatial distribution of climatic risk of durum wheat shortfall (see Figure 3) but it is evident nonetheless that the projected probability of future yield being below the baseline is higher than 50% for most locations and time slices. Assuming crop yield probability distributions do not deviate much from normality it can be inferred that for most grid cells in Spain (though not for the Galicia region), durum wheat yield declines with climate change.

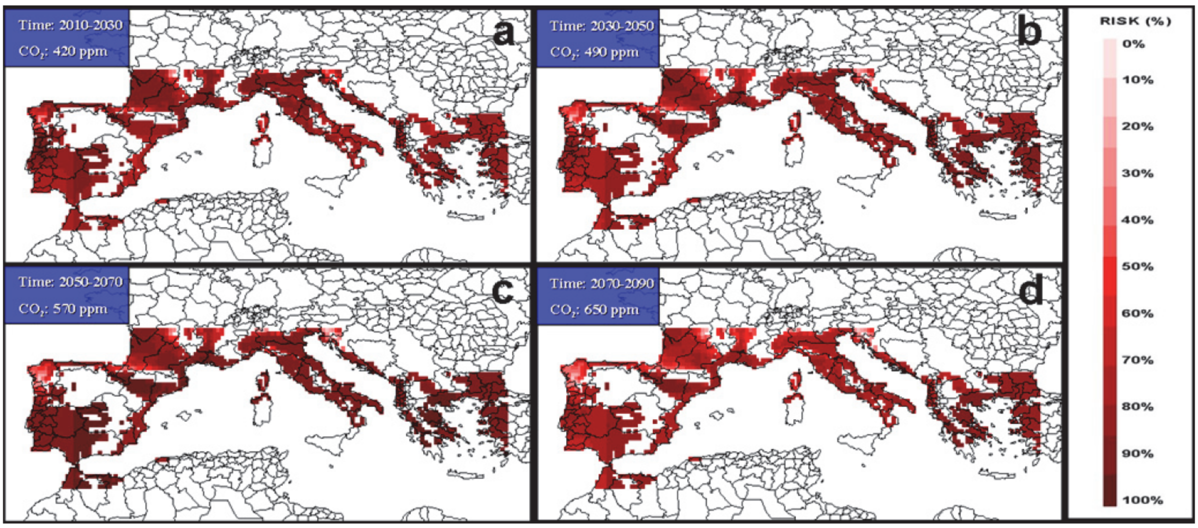

Figure 3. *Spatial distribution of risk of durum wheat yield shortfall by: (a) 2010–2030, (b) 2030–2050, (c) 2050–2070 and (d) 2070–2090. Risk is defined as the relative frequency of future projected yields that are lower than the selected threshold (30-year mean yield for 1961-1990). Figure is from Ferrise et al. (2011).*

The PESETA project estimated the impacts of climate change on crop yields for different regions in the EU (Ciscar et al., 2009, Iglesias et al., 2009). Climate scenarios were created for the 2070-2100 time horizon using a combination of two GCMs and SRES emissions scenarios (A2 and B2). Crop yield simulations (winter wheat, spring wheat, rice, grassland, maize and soybeans) were then conducted using the DSSAT suite of crop models. The results for the "Southern Europe" region, which includes Spain and other countries, are displayed in Table 7. As mentioned previously, it should be noted that the projected yield changes may vary widely within a geographic region. The Southern Europe average not fully representative for Spain. Nevertheless, the PESETA project includes useful maps that show projected changes in crop yield for each emissions scenario, from which impacts for Spain can be inferred (see Figure 4). These show that the projected crop yield change in Spain under the SRES A2 emissions scenario is more adverse than for Southern Europe as a whole.

2011-2040	**2071-2100**			
A2 ECHAM4	A2 HadAM3h	B2 HadAM3h	A2 ECHAM4	B2 ECHAM4
15	-12	0	-27	-4

***Table 7**. Projected crop yield changes (%), compared to 1961-1990 period for the "Southern Europe" region, which includes Spain. Data is from Ciscar et al. (2009).*

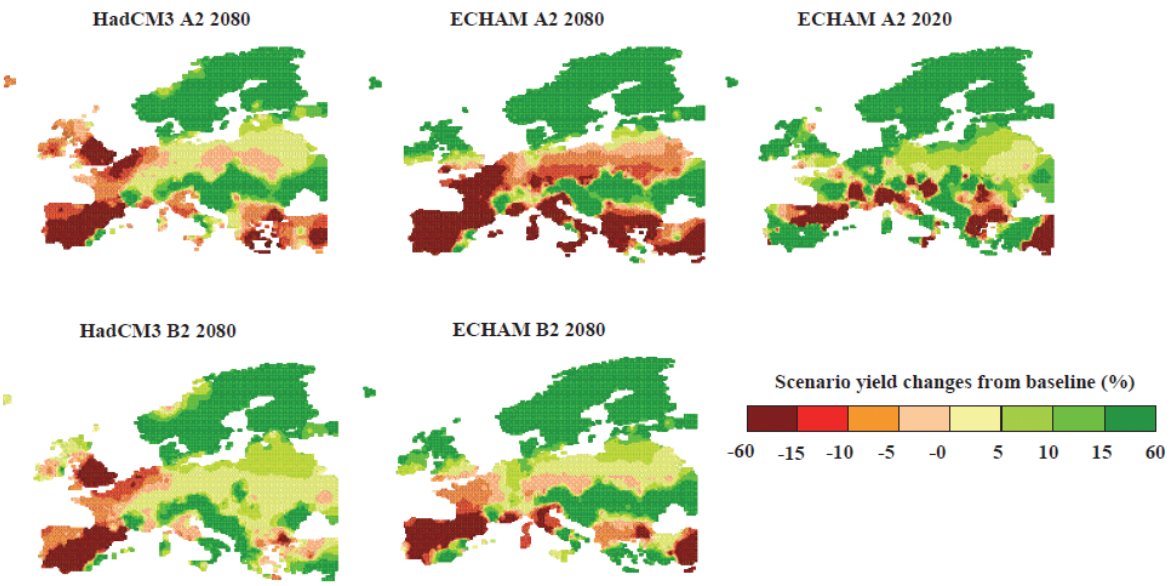

***Figure 4.** Crop yield changes under the HadCM3/HIRHAM A2 and B2 scenarios for the period 2071 - 2100 and for the ECHAM4/RCA3 A2 and B2 scenarios for the period 2011 – 2040 compared to baseline. The figure is from (Iglesias et al., 2009), p.31.*

In addition to the studies looking at the effect of changes in climate and CO_2 concentrations on crop yield, Avnery et al. (2011) investigated the effects of ozone surface exposure on crop yield losses for soybeans, maize and wheat under the SRES A2 and B1 scenarios respectively. Two metrics of ozone exposure were investigated; seasonal daytime (08:00-19:59) mean O_3 ("M12") and accumulated O_3 above a threshold of 40 ppbv ("AOT40"). The effect of the ozone exposure was considered in isolation from climate and other changes. The results for Spain are presented in Table 8.

	A2		B1	
	M12	AOT40	M12	AOT40
Soybeans	-	-	-	-
Maize	10-15	6-8	8-10	2-4
Wheat	6-8	20-25	4-6	10-15

Table 8. *National relative crop yield losses (%) for 2030 under A2 and B1 emission scenarios according to the M12 (seasonal daytime (08:00–19:59) mean) and AOT40 (accumulated O_3 above a threshold of 40 ppbv) metrics of O_3 exposure. Data is from Avnery et al. (2011).*

National-scale or sub-national scale assessments

Literature searches yielded no results for national-scale or sub-national scale studies for this impact sector.

AVOID programme results

To further quantify the impact of climate change on crops, the AVOID programme simulated the effect of climate change on the suitability of land for crop cultivation for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The effect of climate change on the suitability of land for crop cultivation is characterised here by an index which defines the percentage of cropland in a region with 1) a decrease in suitability or 2) an increase in suitability. A threshold change of 5% is applied here to characterise decrease or increase in suitability. The crop suitability index is calculated at a spatial resolution of 0.5°x0.5°, and is based on climate and soil properties Ramankutty et al., (2002). The baseline crop suitability index, against which the future changes are measured, is representative of conditions circa 2000. The key features of the climate for the crop suitability index are temperature and the availability of water for plants. Changes in these were derived from climate model projections of future changes in temperature and precipitation, with some further calculations then being used to estimate actual and potential evapotranspiration as an indicator of water availability. It should be noted that changes in atmospheric CO_2 concentrations can decrease evapotranspiration by increasing the efficiency of water use by plants Ramankutty et al., (2002), but that aspect of the index was not included in the analysis here. Increased CO_2 can also increase photosynthesis and improve yield to a small extent, but again these effects are not included. Exclusion of these effects may lead to an overestimate of decreases in suitability.

The index here is calculated only for grid cells which contain cropland circa 2000, as defined in the global crop extent data set described by Ramankutty et al. (2008) which was derived from satellite measurements. It is assumed that crop extent does not change over time. The crop suitability index varies significantly for current croplands across the world Ramankutty et al., (2002), with the suitability being low in some current cropland areas according to this index. Therefore, while climate change clearly has the potential to decrease suitability for cultivation if temperature and precipitation regimes become less favourable, there is also scope for climate change to increase suitability in some existing cropland areas if conditions become more favourable in areas where the suitability index is not at its maximum value of 1. It should be noted that some areas which are not currently croplands may already be suitable for cultivation or may become suitable as a result of future climate change, and may become used a croplands in the future either as part of climate change adaptation or changes in land use arising for other reasons. Such areas are not included in this analysis.

Results

Crop suitability was estimated under the pattern of climate change from 21 GCMs with two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one crop suitability impacts model is applied. Simulations were performed for the years 2030, 2050, 2080 and 2100. The results for Spain are presented in Figure 5.

All models projected only up to 1%-2% of current Spanish cropland areas to undergo an improvement of suitability of cultivation, under both scenarios and across the entire 21st

century. In contrast, the models showed a very high degree of consensus towards a large proportion of current croplands undergoing declining suitability from 2030 onwards. In 2030, approximately 90%-95% of current croplands experienced declining suitability in both scenarios, and by 2100 this had risen to 92%-98% in the mitigation scenario, and 92%-100% under A1B. So for Spain, there is a strong consensus between models of climate change giving declining suitability for cultivation over most current croplands.

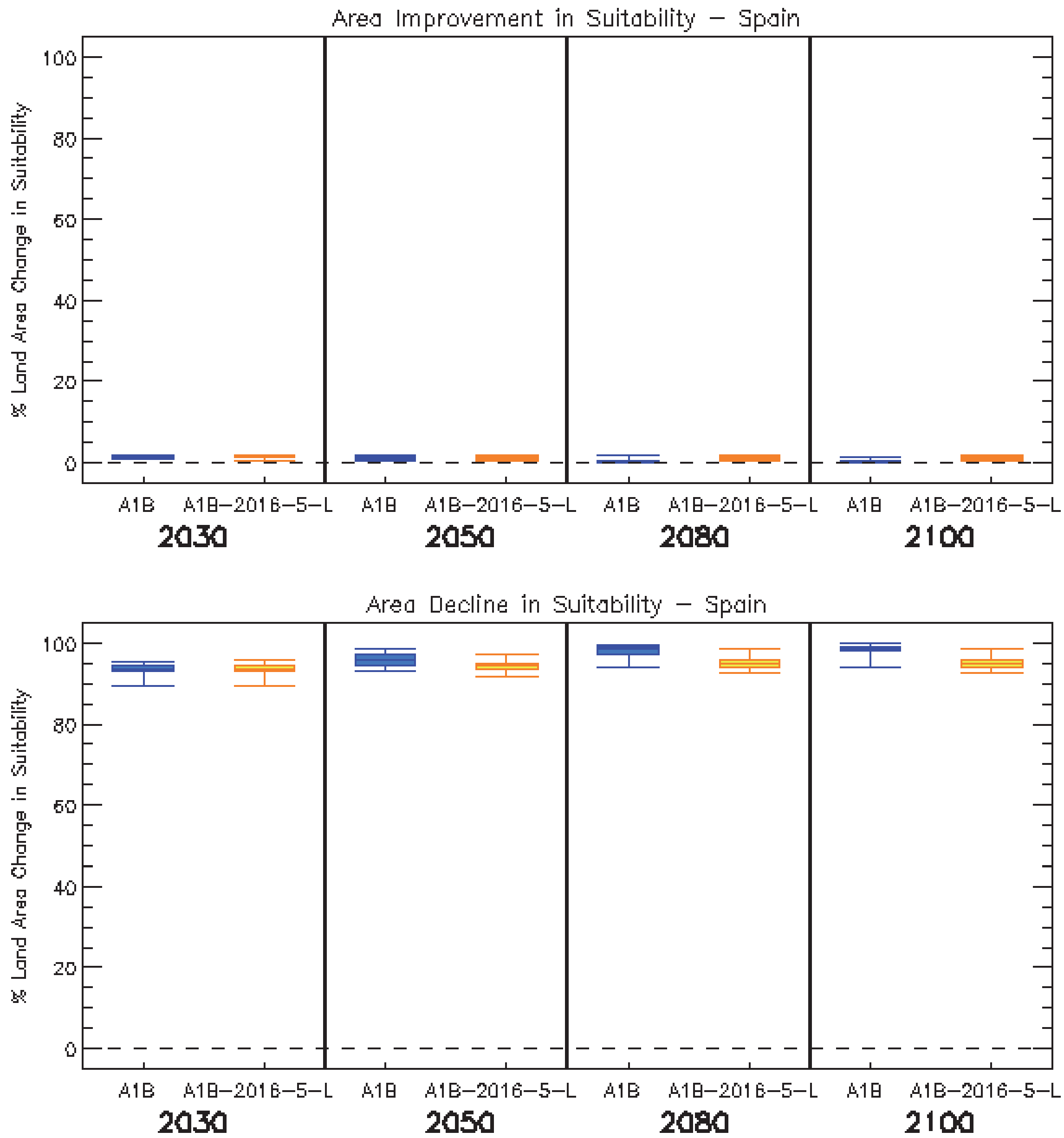

Figure 5. *Box and whisker plots for the impact of climate change on increased crop suitability (top panel) and decreased crop suitability (bottom panel) for Spain, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Food security

Headline

A number of global-scale assessments suggest that Spain is at risk of facing food security issues under climate change scenarios, but that their strong economic position in global food markets means that they may largely be able to offset these risks against increased food imports. The national economy of Spain presents a moderate vulnerability to climate change impacts on fisheries. These results add detail to knowledge reported in the IPCC AR4.

Supporting literature

Introduction

Food security is a concept that encompasses more than just crop production, but is a complex interaction between food availability and socio-economic, policy and health factors that influence access to food, utilisation and stability of food supplies. In 1996 the World Food Summit defined food security as existing 'when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs, and their food preferences are met for an active and healthy life'

As such this section cannot be a comprehensive analysis of all the factors that are important in determining food security, but does attempt to assess a selection of the available literature on how climate change, combined with projections of global and regional population and policy responses, may influence food security.

With regards to food security Spain is a country of very low concern, relative to other countries across the globe. According to FAO statistics (FAO, 2010) Spain has an extremely low level of undernourishment (less than 5% of the population). Global studies indicate food security in Spain potentially faces adverse effects of climate change, but the country could remain food secure largely as a result of its high adaptive capacity.

Assessments that include a global or regional perspective

Climate change studies

Several recent studies have analysed food security under climate change across the globe. Wu et al. (2011) simulated crop yields with the GIS-based Environmental Policy Integrated Climate (EPIC) model. This was combined with crop areas simulated by a crop choice decision model to calculate total food production and per capita food availability across the globe, which was used to represent the status of food availability and stability. The study focussed on the SRES A1 scenario and applied climate change simulations for the 2000s (1991–2000) and 2020s (2011–2020). The climate simulations were performed by MIROC (Model for Interdisciplinary Research on Climate) version 3.2., which means the effects of climate model uncertainty were not considered. Downscaled population and GDP data from the International Institute for Applied Systems Analysis (IIASA) were applied in the simulations. Wu et al. (2011) concluded that between 2000 and 2020, Spain could become a potential hotspot for food insecurity but importantly, Spain's population could likely remain food-secure, because they are less reliant on subsistence agriculture and because the country possesses a high capability for importing food due to strong purchasing power and financial support. Moreover, Wu et al. (2011) argue that Spain's substantial adaptive capacity and proactive food management systems mean the country may be able to avoid food security issues under climate change.

Falkenmark et al. (2009) present a global analysis of food security under climate change scenarios for the 2050s that considers the importance of water availability for ensuring global food security. The study presents an analysis of water constraints and opportunities for global food production on current croplands and assesses five main factors:

1) how far improved land and water management might go towards achieving global food security,
2) the water deficits that would remain in regions currently experiencing water scarcity and which are aiming at food self-sufficiency,
3) how the water deficits above may be met by importing food,
4) the cropland expansion required in low income countries without the needed purchasing power for such imports, and
5) the proportion of that expansion pressure which will remain unresolved due to potential lack of accessible land.

Similar to the study presented by Wu et al. (2011), there is no major treatment of modelling uncertainty; simulations were generated by only the LPJml dynamic global vegetation and water balance model (Gerten et al. 2004) with population growth and climate change under the SRES A2 emission scenario. Falkenmark et al. (2009) summarise the impacts of future improvements (or lack thereof) in water productivity for each country across the globe and show that this generates either a deficit or a surplus of water in relation to food water requirements in each country. These can be met either by trade or by horizontal expansion (by converting other terrestrial ecosystems to crop land). The study estimated that in 2050 around one third of the world's population will live in each of three regions: those that export food, those that import food, and those that have to expand their croplands at the expense of other ecosystems because they do not have enough purchasing power to import their food. The simulations demonstrated that Spain was a food exporting country in 2050.

It is important to note that up until recently, projections of climate change impacts on global food supply have tended to focus solely on production from terrestrial biomes, with the large contribution of animal protein from marine capture fisheries often ignored. However, recent studies have addressed this knowledge gap (e.g., Allison et al., 2009). In addition to the direct affects of climate change, changes in the acidity of the oceans, due to increases in CO_2 levels, could also have an impact of marine ecosystems, which could also affect fish stocks. However, this relationship is complex and not well understood, and studies today have not been able to begin to quantify the impact of ocean acidification on fish stocks.

Allison et al. (2009) present a global analysis that compares the vulnerability of 132 national economies to potential climate change impacts on their capture fisheries. The study considered a country's vulnerability to be a function of the combined effect of projected climate change, the relative importance of fisheries to national economies and diets, and the national societal capacity to adapt to potential impacts and opportunities. Climate change projections from a single GCM under two emissions scenarios (SRES A1FI and B2) were used in the analysis. Allison et al. (2009) concluded that the national economy of Spain presented a moderate vulnerability to climate change impacts on fisheries (see Figure 6). It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution. This is because they do not consider other possible climate change scenarios which could result in a different impact outcome, in terms of magnitude and in some cases sign of change.

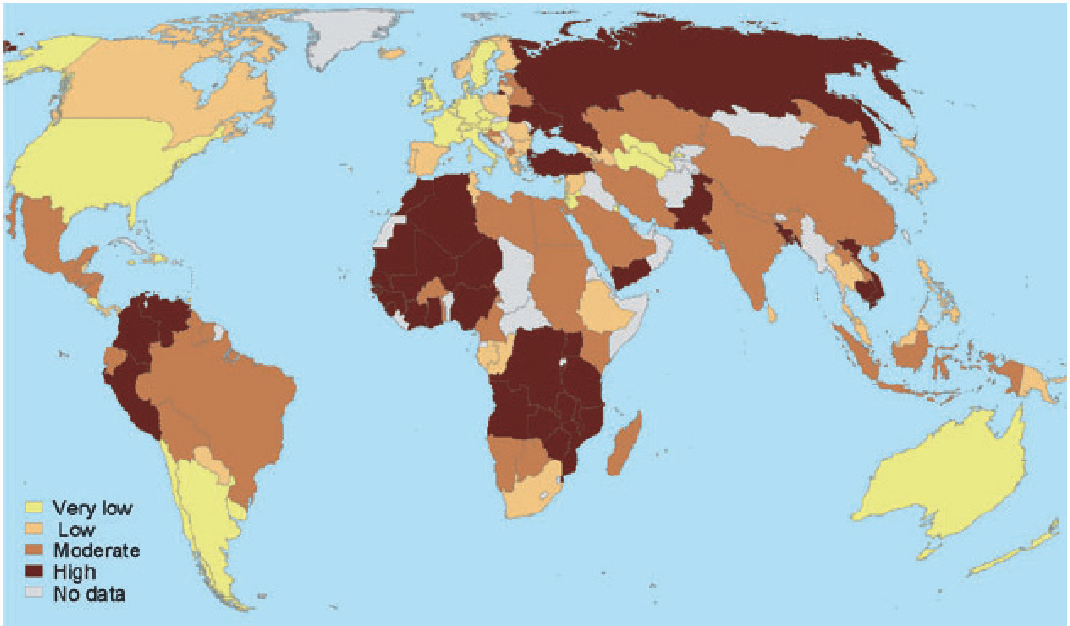

Figure 6. *Vulnerability of national economies to potential climate change impacts on fisheries under SRES B2 (Allison et al., 2009). Colours represent quartiles with dark brown for the upper quartile (highest index value), yellow for the lowest quartile, and grey where no data were available.*

National-scale or sub-national scale assessments

Literature searches yielded no results for national-scale or sub-national scale studies for this impact sector.

Water stress and drought

Headline

Several global-scale and national-scale assessments indicate that droughts could increase in frequency and magnitude with climate change. The greatest effects are reported for the south of the country, along the Mediterranean coast. Similarly, several studies show that water stress may increase significantly in Spain with climate change. This is further supported by recent simulations by the AVOID programme.

Supporting literature

Introduction

For the purposes of this report droughts are considered to be extreme events at the lower bound of climate variability; episodes of prolonged absence or marked deficiency of precipitation. Water stress is considered as the situation where water stores and fluxes (e.g. groundwater and river discharge) are not replenished at a sufficient rate to adequately meet water demand and consumption.

A number of impact model studies looking at water stress and drought for the present (recent past) and future (climate change scenario) have been conducted. These studies are conducted at global or national scale and include the application of global water 'availability' or 'stress' models driven by one or more climate change scenario from one or more GCM. The approaches variously include other factors and assumptions that might affect water availability, such as the impact of changing demographics and infrastructure investment, etc. These different models (hydrological and climate), assumptions and emissions scenarios mean that there are a range of water stress projections Spain. This section summarises findings from these studies to inform and contextualise the analysis performed by the AVOID programme for this project. The results from the AVOID work and discussed in the next section.

Important knowledge gaps and key uncertainties which are applicable to Spain as well as at the global-scale, include; the appropriate coupling of surface water and groundwater in hydrological models, including the recharge process, improved soil moisture and evaporation dynamics, inclusion of water quality, inclusion of water management (Wood et al. 2011) and further refinement of the down-scaling methodologies used for the climate driving variables (Harding et al. 2011).

Assessments that include a global or regional perspective

Recent Past

Recent research presented by Vörösmarty et al. (2010) describes the calculation of an '*Adjusted Human Water Security Threat'* (HWS) indicator. The indicator is a function of the cumulative impacts of 23 biophysical and chemical drivers simulated globally across 46,517 grid cells representing 99.2 million km^2. With a digital terrain model at its base, the calculations in each of the grid boxes of this model take account of the multiple pressures on the environment, and the way these combine with each other, as water flows in river basins. The level of investment in water infrastructure is also considered. This infrastructure measure (the *investment benefits factor*) is based on actual existing built infrastructure, rather than on the financial value of investments made in the water sector, which is a very unreliable and incomplete dataset. The analysis described by Vörösmarty et al. (2010) represents the current state-of-the-art in applied policy-focussed water resource assessment. In this measure of water security, the method reveals those areas where this is lacking, which is a representation of human water stress. One drawback of this method is that no analysis is provided in places where there is 'no appreciable flow', where rivers do not flow, or only do so for such short periods that they cannot be reliably measured. This method also does not address places where water supplies depend wholly on groundwater or desalination, being piped in, or based on wastewater reuse. It is based on what is known from all verified peer reviewed sources about surface water resources as generated by natural ecosystem processes and modified by river and other hydraulic infrastructure (Vörösmarty et al., 2010).

Here, the present day HWS is mapped for Spain. The model applied operates at 50km resolution, so, larger countries appear to have smoother coverage than smaller countries, but all are mapped and calculated on the same scale, with the same data and model, and thus comparisons between places are legitimate. It is important to note that this analysis is a comparative one, where each place is assessed *relative* to the rest of the globe. In this way, this presents a realistic comparison of conditions across the globe. As a result of this, however, some places may seem to be less stressed than may be originally considered.

Figure 7 presents the results of this analysis for Spain. Spain is often thought of as one of the driest parts of Europe, but the level of water security in some areas is high, with little water stress. Much of this results from the large extent of water infrastructure, and the well developed water governance system. Nevertheless, there are certain areas of the country which have no surface water and must rely on groundwater and other sources, and climate warming could increase agricultural water stress.

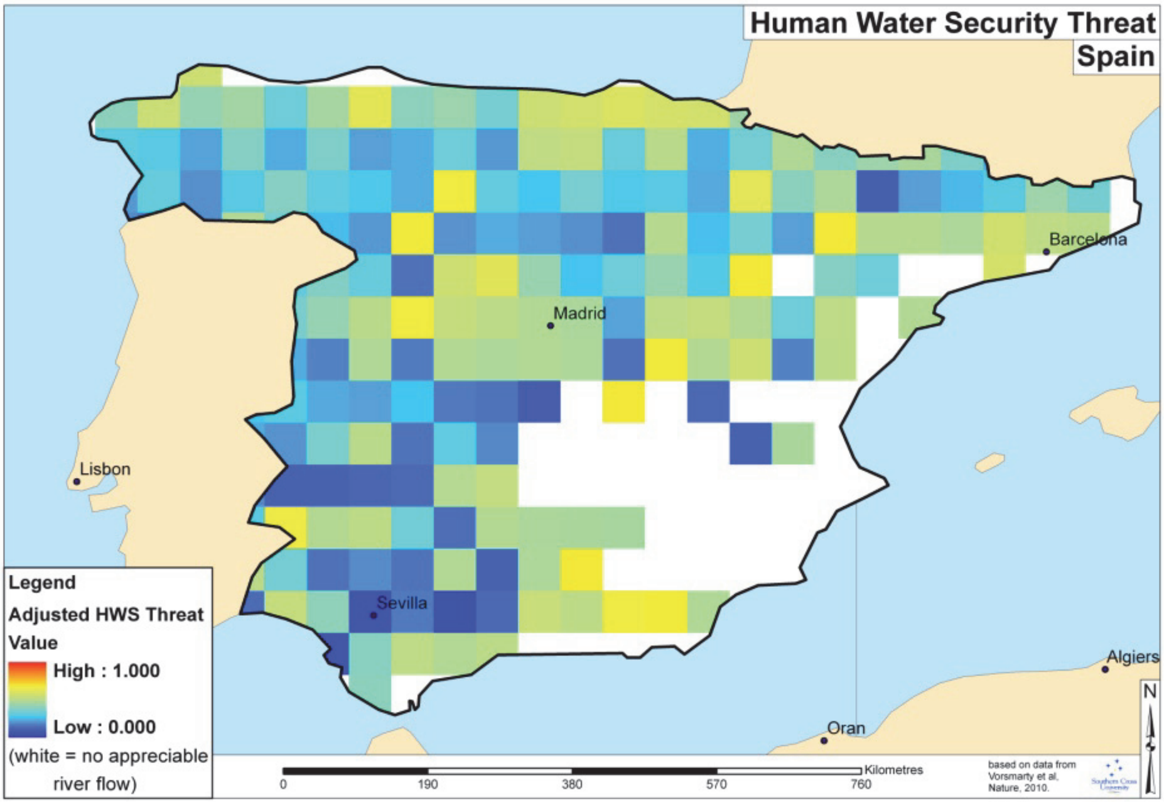

***Figure 7**. Present Adjusted Human Water Security Threat (HWS) for Spain, calculated following the method described by Vörösmarty et al. (2010).*

Smakhtin et al. (2004) present a more pessimistic overview of water stress for Spain. The authors describe a first attempt to estimate the volume of water required for the maintenance of freshwater-dependent ecosystems at the global scale. This total environmental water requirement (EWR) consists of ecologically relevant low-flow and high-flow components. The authors argue that the relationship between water availability, total use and the EWR may be described by the water stress indicator (WSI). If WSI exceeds 1.0, the basin is classified as “environmentally water scarce”. In such a basin, the discharge has already been reduced by total withdrawals to such levels that the amount of water left in the basin is less than EWR. Smaller index values indicate progressively lower water resources exploitation and lower risk of “environmental water scarcity.” Basins where WSI is greater than 0.6 but less than 1.0 are arbitrarily defined as heavily exploited or “environmentally water stressed” and basins where WSI is greater than 0.3 but less than 0.6 are defined as moderately exploited. In these basins, 0-40% and 40-70% of the utilizable water respectively is still available before water withdrawals come in conflict with the EWR. Environmentally “safe” basins are defined as those where WSI is less than 0.3. The global distribution of WSI for the 1961-1990 time horizon is shown in Figure 8. The results show that for the basins considered, much of Spain presents a high WSI.

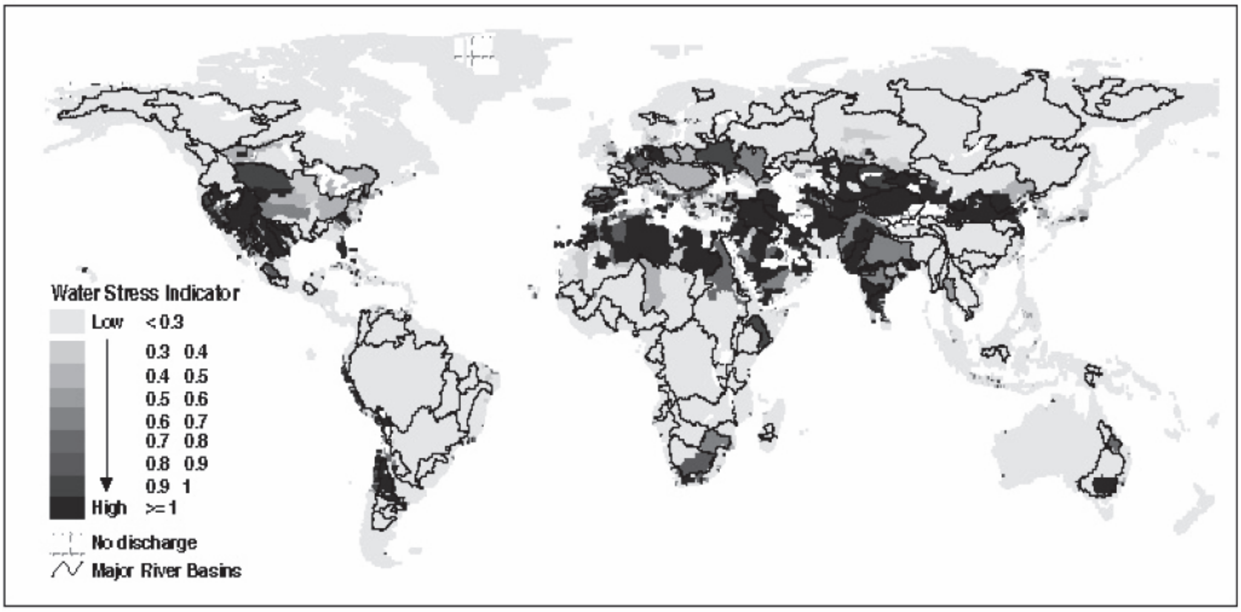

Figure 8. *A map of the major river basins across the globe and the water stress indicator (WSI) for the 1961-1990 time horizon. The figure is from Smakhtin et al. (2004).*

Climate Change Studies

Rockstrom et al. (2009) applied the LPJml vegetation and water balance model (Gerten et al. 2004) to assess green-blue water (irrigation and infiltrated water) availability and requirements. The authors applied observed climate data from the CRU TS2.1 gridded dataset for a present-day simulation, and climate change projections from the HadCM2 GCM under the SRES A2 scenario to represent the climate change scenario for the year 2050. The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The simulations presented by Rockstrom et al. (2009) should not be considered as definitive, however, because the study only applied one climate model, which means climate modelling uncertainty was overlooked. The results from the two simulations are presented in Figure 9. Rockstrom et al. (2009) found that globally in 2050 and under the SRES A2 scenario, around

59% of the world's population could be exposed to "blue water shortage" (i.e. irrigation water shortage), and 36% exposed to "green water shortages" (i.e. infiltrated rain shortage). For Spain, Rockstrom et al. (2009) found that blue-green water availability was well above the 1,300m^3/capita/year threshold in present conditions and under climate change. This indicates that at a national level, Spain's water resource requirements should be met by 2050 but significant regional differences could be masked at this spatial scale.

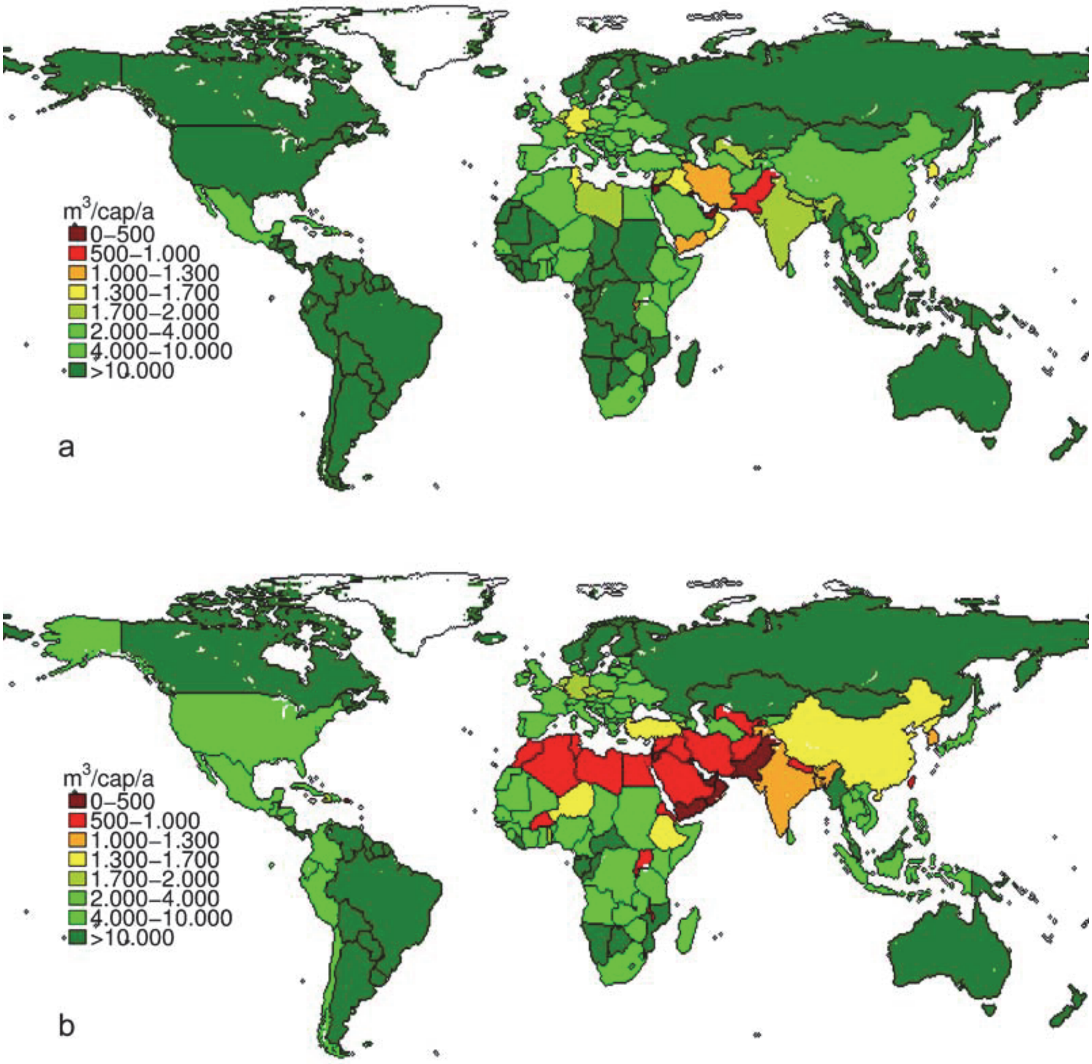

Figure 9. *Simulated blue-green water availability (m^3/capita/year) for present climate (top panel) and including both demographic and climate change under the SRES A2 scenario in 2050 (bottom panel). The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The figure is from Rockstrom et al. (2009).*

Doll (2009) presents updated estimates of the impact of climate change on groundwater resources by applying a new version of the WaterGAP hydrological model. The study accounted for the number of people affected by changes in groundwater resources under climate change relative to present (1961-1990). To this end, the study provides an assessment of the vulnerability of humans to decreases in available groundwater resources (GWR). This indicator was termed the “Vulnerability Index” (VI), defined as; VI = -% change GWR * Sensitivity Index (SI). The SI component was a function of three more specific sensitivity indicators that include an indicator of water scarcity (calculated from the ratio between consumptive water use to low flows), an indicator for the dependence upon groundwater supplies, and an indicator for the adaptive capacity of the human system. Doll (2009) applied climate projections from two GCMs (ECHAM4 and HadCM3) to WaterGAP, for two scenarios (SRES A2 and B2), for the 2050s. Figure 10 presents each of these four simulations respectively. There is variation across scenarios and GCMs. For Spain, the simulations with HadCM3 display small or no decreases in GWR with associated increases in VI under climate change. However, with the ECHAM4 simulations, GWR does decrease with climate change and southern Spain presents a very high VI; one of the highest in Europe with southern Italy and southern Turkey.

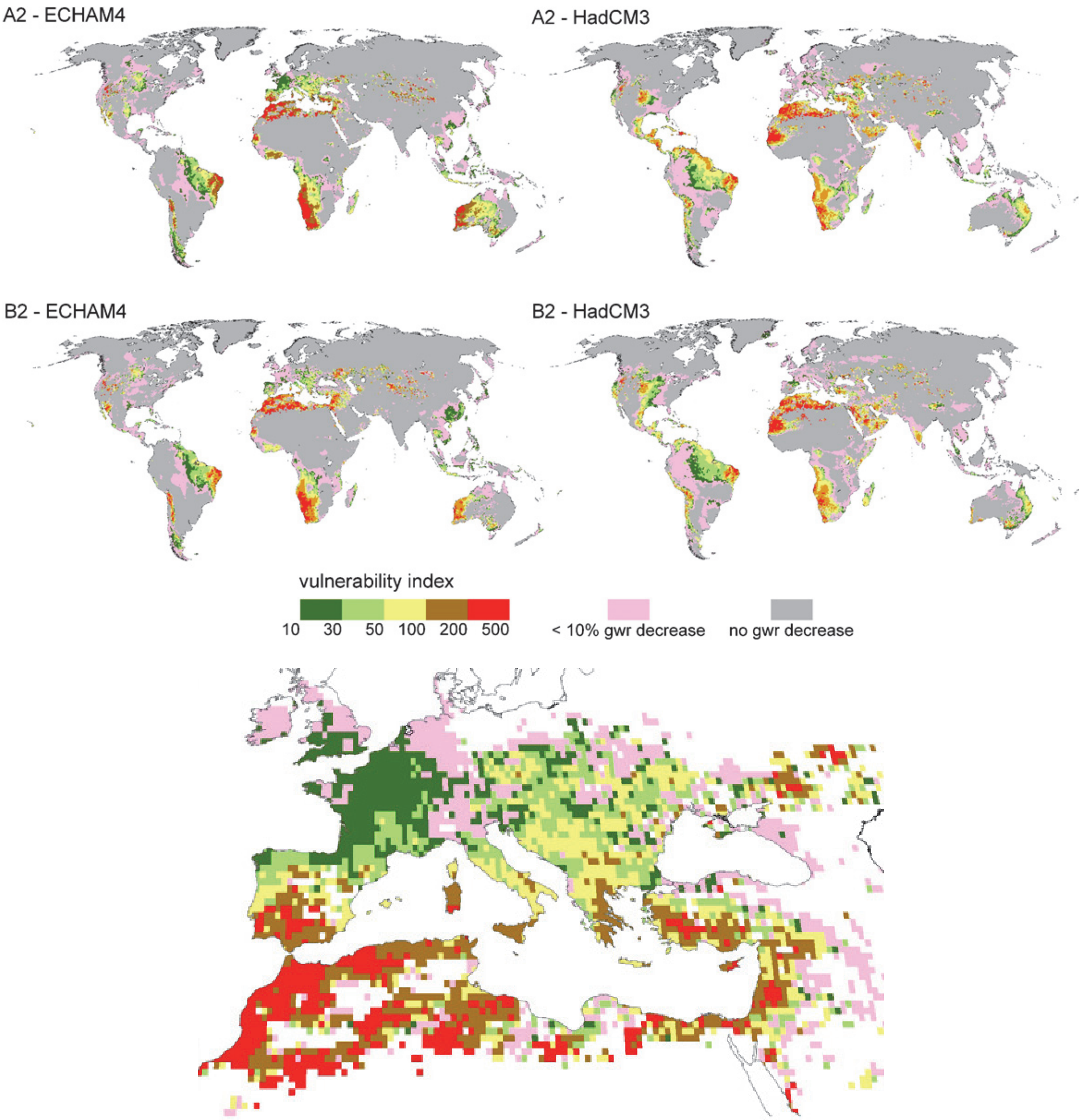

Figure 10. *Vulnerability index (VI) showing human vulnerability to climate change induced decreases of renewable groundwater resources (GWR) by the 2050s under two emissions scenarios for two GCMs. VI is only defined for areas with a GWR decrease of at least 10% relative to present (1961-1990). Also shown is VI for the Mediterranean region with ECHAM4 under A2 emissions. The figure is from Doll (2009).*

Lehner et al. (2006) assessed the impact of climate change on European drought risk. The authors accounted for future human water use and assessed future flood and drought frequencies by applying the WaterGAP hydrological model, driven by climate projections from the HadCM3 and ECHAM4 GCMs, under a 1%/year CO_2 increase emissions scenario. The simulations are presented in Figure 11 and Figure 12. The results reflect the general consensus from other studies that southern and south-eastern Europe could experience increased drought frequencies, leading to water stress. This in part due to increased water use but the impacts are much more pronounced and wide spread when climate change is factored in (Lehner et al., 2006). Long term projections indicate those drought events expected to occur once every 100 years could become much more frequent, to around every 40 years in the most extreme areas, including much of the Mediterranean. For Spain, both GCMs simulated that the current 100-year drought could be expected to occur more frequently with climate change. Moreover, the results show that the 100-year drought could become more intense with climate change, increasing in intensity by over 25% from present magnitude

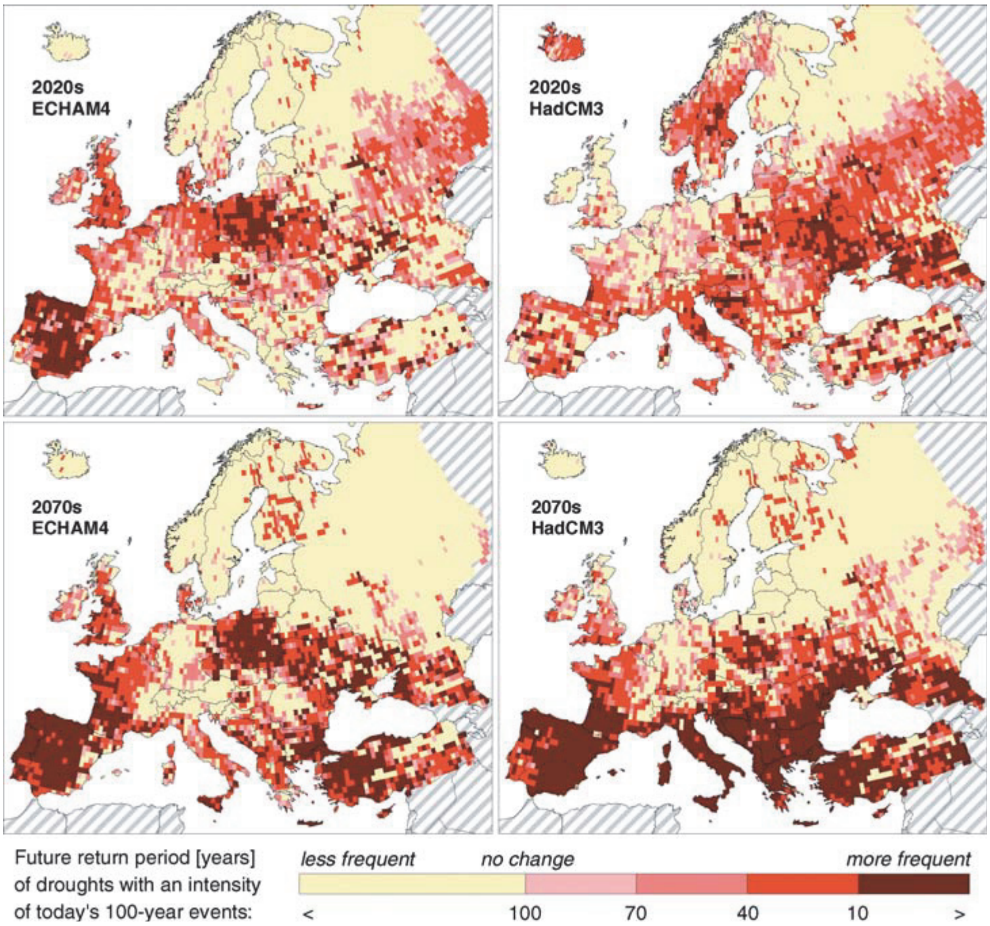

Figure 11. *Change in recurrence of 100-year droughts, based on comparisons between today's climate and water use (1961–1990) and simulations for the 2020s and 2070s (ECHAM4 and HadCM3 GCMs), under a 1%/year* CO_2 *increase emissions scenario. The figure is from Lehner et al. (2006).*

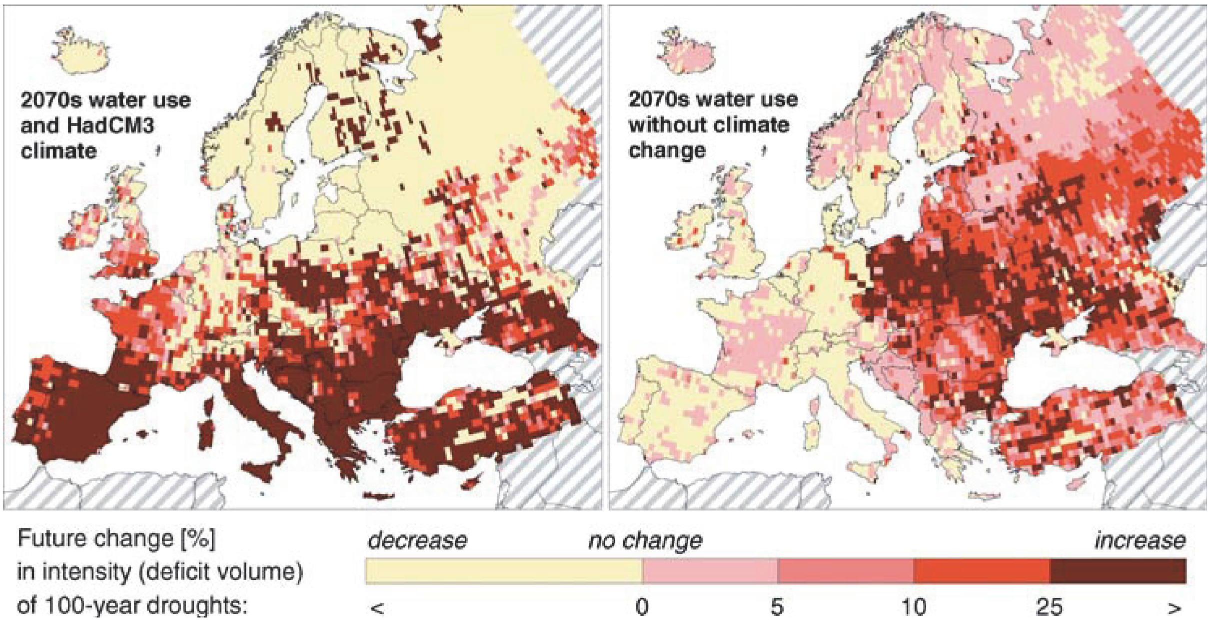

Figure 12. *Change in intensity of 100-year droughts, based on comparison between today's climate and water use (1961–1990) and simulations for the 2070s (left map: HadCM3 GCM; right map: only water use scenario, no climate change), under a 1%/year CO_2 increase emissions scenario.*

The simulated increase in frequency and magnitudes of droughts for Spain, which are presented by Lehner et al. (2006), are supported by a more recent study presented by Giannakopoulos et al. (2009). The authors found increases in the number of dry days to the order of 3-4 weeks for Spain during the 2031-60 time horizon (compared to 1961-90), and also an increase in the longest dry spell under a 2°C warming scenario.

National-scale or sub-national scale assessments

Several smaller-scale assessments point towards more severe droughts and increases in water stress with climate change for Spain, which supports the results from larger-scale studies (Doll, 2009, Lehner et al., 2006).

Beniston et al. (2007) found that the RCMs they analysed all simulated earlier and longer droughts in the Mediterranean. The drought indices indicated considerable drying over much of the Mediterranean under the A2 emissions scenario. The main contributing factors are reduced rainfall intensity, and an early onset and longer duration of drought. Regions most affected include the southern Iberian Peninsula and eastern Adriatic seaboard. Under the A2 scenario, drought over southern Iberia was projected to last over a month longer than at present, similar to the results presented by Giannakopoulos et al. (2009). Under the B2 scenario, drought length increased by about 20 days. Similarly, Lopez-Moreno et al. (2008) investigated a set of climate parameters (including mean precipitation, number of wet days, daily intensity, and number of days with more than 50 mm rainfall) over the Pyrenees for the

21st Century using a set of RCMs under the A2 emissions scenario. For the Pyrenees they observed a tendency towards increasing drought periods.

Diaz et al. (2007) focussed on the Guadalquivir basin in Spain, where water resources are reported to be under severe pressure from irrigated production. The study highlights an increasing supply-demand imbalance. Climate change impacts were assessed using GIS techniques, with maps showing increased need for irrigation of 15-20% by the 2050's. Gao and Giorgi (2008) calculated aridity indices for climate simulations under A2 and B2 emissions scenarios. Results indicated that by 2100 southern portions of the Iberian Peninsula could experience a northward expansion of arid areas suffering water stress.

AVOID Programme Results

To further quantify the impact of climate change on water stress and the inherent uncertainties, the AVOID programme calculated water stress indices for all countries reviewed in this literature assessment based upon the patterns of climate change from 21 GCMs (Warren et al., 2010), following the method described by Gosling et al. (2010) and Arnell (2004). This ensures a consistent methodological approach across all countries and takes consideration of climate modelling uncertainties.

Methodology

The indicator of the effect of climate change on exposure to water resources stress has two components. The first is the number of people within a region with an *increase in exposure to stress*, calculated as the sum of 1) people living in water-stressed watersheds with a significant reduction in runoff due to climate change and 2) people living in watersheds which become water-stressed due to a reduction in runoff. The second is the number of people within a region with a *decrease in exposure to stress*, calculated as the sum of 1) people living in water-stressed watersheds with a significant increase in runoff due to climate change and 2) people living in watersheds which cease to be water-stressed due to an increase in runoff. It is not appropriate to calculate the net effect of "increase in exposure" and "decrease in exposure", because the consequences of the two are not equivalent. A water-stressed watershed has an average annual runoff less than 1000m^3/capita/year, a widely used indicator of water scarcity. This indicator may underestimate water stress in watersheds where per capita withdrawals are high, such as in watersheds with large withdrawals for irrigation.

Average annual runoff (30-year mean) is simulated at a spatial resolution of 0.5x0.5^{o} using a global hydrological model, MacPDM (Gosling and Arnell, 2011), and summed to the watershed scale. Climate change has a "significant" effect on average annual runoff when the change from the baseline is greater than the estimated standard deviation of 30-year mean annual runoff: this varies between 5 and 10%, with higher values in drier areas.

The pattern of climate change from 21 GCMs was applied to MacPDM, under two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). Both scenarios assume that population changes through the 21st century following the SRES A1 scenario as implemented in IMAGE 2.3 (van Vuuren et al., 2007). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one impacts model is applied (MacPDM). Simulations were performed for the years 2030, 2050, 2080 and 2100. Following Warren et al. (2010), changes in the population affected by increasing or decreasing water stress represent the additional percentage of population affected due to climate change, not the absolute change in the percentage of the affected population relative to present day.

Results

The results for Spain are presented in Figure 13. None of the 21 GCMs are associated with simulated decreases in water stress under climate change. By 2100 and under A1B, the median population across 21 GCMs exposed to an increase in water stress due to climate change is 60%. Under the mitigation scenario, this is 25%. The simulations show that Spain's population could experience a large increase in water stress with climate change.

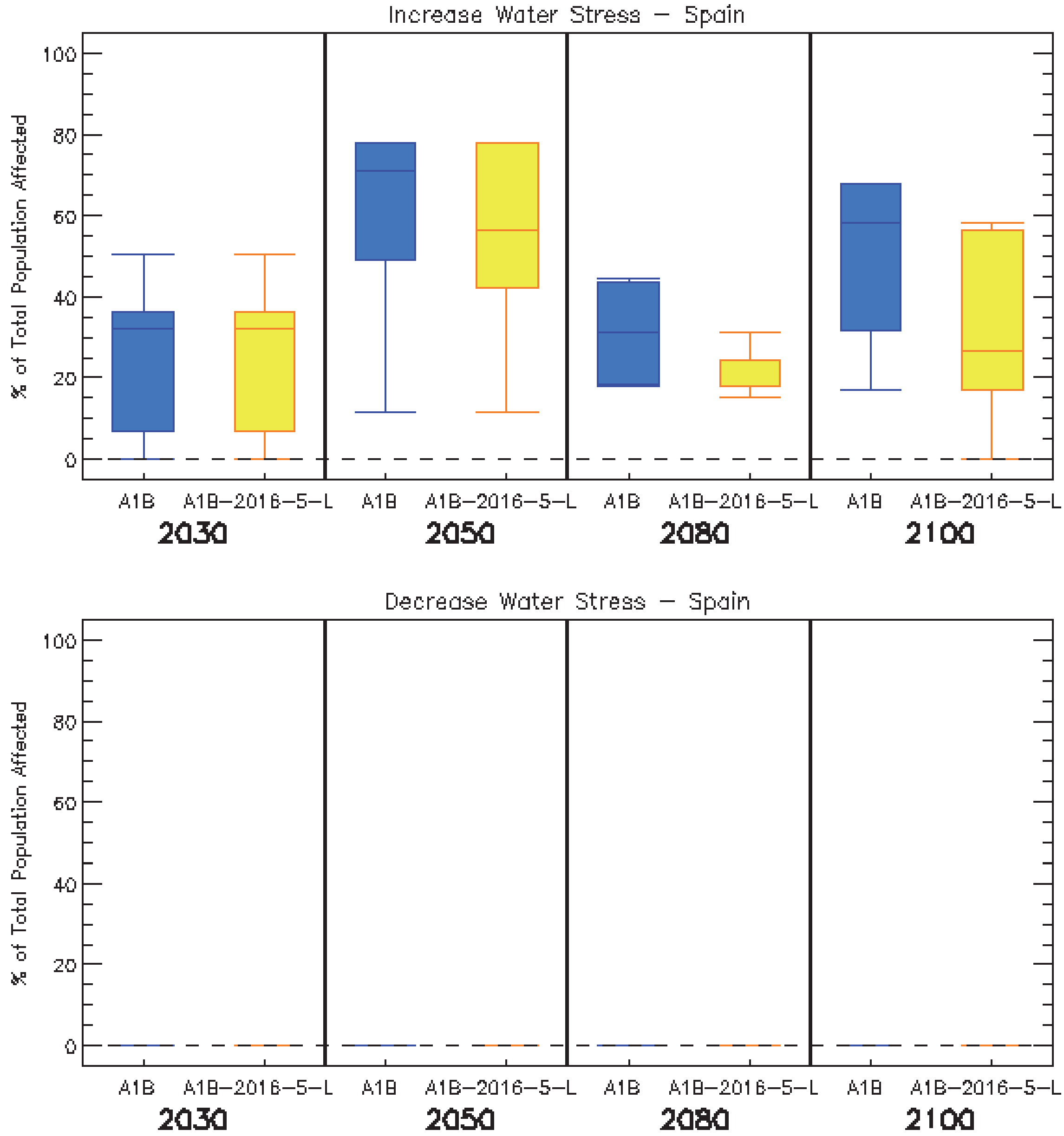

Figure 13. *Box and whisker plots for the impact of climate change on increased water stress (top panel) and decreased water stress (bottom panel) in Spain, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Pluvial flooding and rainfall

Headline

Recent studies support conclusions from the IPCC AR4 that extreme short-term precipitation may either increase or decrease with climate change for Spain. To this end, large uncertainties remain in quantifying pluvial flooding under climate change scenarios for Spain.

Supporting literature

Introduction

Pluvial flooding can be defined as flooding derived directly from heavy rainfall, which results in overland flow if it is either not able to soak into the ground or exceeds the capacity of artificial drainage systems. This is in contrast to fluvial flooding, which involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. Pluvial flooding can occur far from river channels, and is usually caused by high intensity, short-duration rainfall events, although it can be caused by lower intensity, longer-duration events, or sometimes by snowmelt. Changes in mean annual or seasonal rainfall are unlikely to be good indicators of change in pluvial flooding; changes in extreme rainfall are of much greater significance. However, even increases in daily rainfall extremes will not necessarily result in increases in pluvial flooding, as this is likely to be dependent on the sub-daily distribution of the rainfall as well as local factors such as soil type, antecedent soil moisture, land cover (especially urbanisation), capacity and maintenance of artificial drainage systems etc. It should be noted that both pluvial and fluvial flooding can potentially result from the same rainfall event.

Assessments that include a global or regional perspective

Climate change studies

The IPCC AR4 (2007a) noted that for the Mediterranean area, annual precipitation is very likely to decrease, the annual number of precipitation days is very likely to decrease, and the risk of summer drought is likely to increase. Extreme short-term precipitation may either increase (due to the increased water vapour content of a warmer atmosphere) or decrease (due to a decreased number of precipitation days, which if acting alone could also make heavy precipitation less common) (IPCC, 2007a).

In a global-scale assessment, Bates et al. (2008) found that for Europe, under various emissions scenarios from the ECHAM4 and HadCM3 GCMs for the 2020s, an increased risk of flash floods over the whole of Europe was possible. Moreover, they found that by the 2070s, today's 100-year return period floods could become more frequent in Spain.

Beniston et al. (2007) applied GCMs and RCMs under A2 and B2 emissions scenarios to assess the impact of climate change on precipitation for Europe. They found that heavy winter and summer precipitation could decrease in the south of Europe with climate change. The authors found that these changes were weaker for the B2 than for the A2 emissions scenario. However, model choices had greater effects on the magnitude (RCM) and pattern (GCM) of response than the choice of emissions scenario. When analysing projections under the A2 and B2 scenarios from an ensemble of four RCMs, Beniston et al. (2007) found that changes in maximum 5-day rainfall (R5d) simulated under the B2 scenario were smaller than those simulated under the A2 scenario in two cases, and similar in the other two cases. In parts of southern Europe, projected summer changes in maximum 1-day rainfall ranged between -60 and +10%. In most cases the reductions were smaller for the B2 scenario than the A2 scenario, but the results generally point to high uncertainty.

Goubanova and Li (2007) used a variable grid atmospheric GCM with a zoom over the Mediterranean region run with the A2 emissions scenario. They found that projections for the 21st Century showed an increase in precipitation extremes and variability over the Mediterranean region in winter, spring and autumn seasons. This is despite an overall decrease in mean precipitation.

National-scale or sub-national scale assessments

Recent past

De Luis et al. (2010) undertook an observation analysis of changing rainfall between 1946 and 2005, for Spain. They found a general reduction of precipitation amounts from winter to summer, and an increase in autumn rainfall percentage. An observational study by Gonzalez-Hidalgo et al. (2010) also found a redistribution of precipitation through the year, with a reduction during March-June and in increase during October.

Herrera et al. (2010) evaluated the performance of RCMs in simulating mean and extreme precipitation for Spain. They found a good agreement with observations for mean precipitation. The main limitation was in the representation of extremes, in particular the upper percentile tended to be underestimated, and also the amounts of rainfall coming from extreme events were poor.

Climate change studies

López-Moreno and Beniston (2009) investigated a set of climate parameters (including mean precipitation, number of wet days, daily intensity, and number of days with more than 50 mm rainfall) over the Pyrenees for the 21st century with a set of RCMs under the A2 emissions scenario. The climate of this region is very complex, but the projections indicated an intensification of extremes, increasing daily rainfall intensity, and increasing contribution of intense events to total precipitation.

Fluvial flooding

Headline

Few studies have assessed the impact of climate change on fluvial flooding for Spain. Moreover, large climate model uncertainty presently inhibits any firm conclusions with regards to changes in flood hazard in Spain under climate change scenarios. However, simulations by the AVOID programme, based on climate projections from 21 GCMs, show a much greater tendency towards decreasing flood risk throughout the 21st century under both the A1B and a mitigation emissions scenario Better quantification and understanding of uncertainties is a requirement for future research.

Supporting literature

Introduction

This section summarises findings from a number of post IPCC AR4 assessments on river flooding in Spain to inform and contextualise the analysis performed by the AVOID programme for this project. The results from the AVOID work are discussed in the next section.

Fluvial flooding involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. A complex set of processes is involved in the translation of precipitation into runoff and subsequently river flow (routing of runoff along river channels). Some of the factors involved are; the partitioning of precipitation into rainfall and snowfall, soil type, antecedent soil moisture, infiltration, land cover, evaporation and plant transpiration, topography, groundwater storage. Determining whether a given river flow exceeds the channel capacity, and where any excess flow will go, is also not straightforward, and is complicated by the presence of artificial river embankments and other man-made structures for example. Hydrological models attempt to simplify and conceptualise these factors and processes, to allow the simulation of runoff and/or river flow under different conditions. However, the results from global-scale hydrological modelling need to be interpreted with caution, especially for smaller regions, due to the necessarily coarse resolution of such modelling and the assumptions and simplifications this entails (e.g. a 0.5^{o} grid corresponds to landscape features spatially averaged to around 50-55km for mid- to low-latitudes). Such results provide a consistent, high-level picture, but will not show any finer resolution detail or variability. Smaller-scale or catchment-scale hydrological modelling can allow for more local factors affecting the hydrology, but will also involve further sources of uncertainty, such as in the downscaling of global climate model data to the necessary scale for the hydrological models. Furthermore, the application of different hydrological models and analysis techniques often makes it difficult to compare results for different catchments.

Assessments that include a global or regional perspective

Recent past

Benito (2006) noted that in the Atlantic river basins in Spain the frequency of extraordinary floods has declined throughout the instrumental record (since 1910), but that the magnitude of the most catastrophic floods has remained the same despite the buffering effect of dams and reservoirs that have been built. Furthermore, evidence from the existing records and paleo-reconstructions suggests that future climate change could increase the irregularity of flood and drought occurrence and lead to the generation or intensification of flash floods in the Mediterranean basins as well as further inland in the Iberian Peninsula (Benito, 2006).

Climate change studies

There have been very few modelling studies of changes in flood hazard in Spain under climate change. In a European-scale study, Dankers and Feyen (2008) applied climate change projections from a very high resolution (~12 km) RCM for the end of the century (2071-2100) under the A2 emissions scenario to drive a flood forecasting model. For most of the main westward-flowing rivers of Spain (Duero, Tajo, Guadiana, Guadalquivir), the authors found little change in the 100-year flood level or a (sometimes strong) decrease. The only exception was the Ebro where some of the smaller tributaries showed an increase in the 100-year return level. As a consequence, the return period of the current (1961-1990) 100-year flood level was projected to stay more or less the same, or increase considerably in most rivers, but to decrease in the upstream reaches of the Duero basin and in the Ebro to less than 50 years (Dankers and Feyen, 2008).

However, in a follow-up study that applied two RCMs, each driven with boundary conditions from two different GCMs and for two different emissions scenarios, Dankers and Feyen (2009) found that the projected changes in flood levels were not consistent across all model experiments. Some model simulations driven by a different combination of GCMs and RCMs projected increases in flood hazard towards the west of the Peninsula, for example in the

Tajo and Guadiana rivers. At least one model experiment showed a strong decrease in extreme discharges in the Ebro. As a result, the projected changes were very small when averaged over the ensemble. These results suggest large uncertainties in the projections of changes in extreme precipitation and river discharge over Spain, arising from modelling uncertainty in both RCMs and the driving GCMs. This large climate model uncertainty presently inhibits any firm conclusions with regards to future changes in flood hazard in the country.

National-scale or sub-national scale assessments

Literature searches yielded no results for national-scale or sub-national scale studies for this impact sector.

Tropical cyclones

Mainland Spain is not impacted by tropical cyclones.

Coastal regions

Headline

Recent studies show that sea level rise (SLR) impacts in Spain could be large in the absence of adaptation. For example, one study shows that by the 2080s under a high SLR scenario and without adaptation, the average annual number of people flooded could be around 321,800; with adaptation (raising of flood dykes and the application of beach nourishment), this is greatly reduced to 1,100. This adds detail to knowledge reported in the IPCC AR4.

Assessments that include a global or regional perspective

The IPCC AR4 concluded that at the time, understanding was too limited to provide a best estimate or an upper bound for global SLR in the twenty-first century (IPCC, 2007b). However, a range of SLR, excluding accelerated ice loss effects was published, ranging from 0.19m to 0.59m by the 2090s (relative to 1980-2000), for a range of scenarios (SRES A1FI to B1). The IPCC AR4 also provided an illustrative estimate of an additional SLR term of up to 17cm from acceleration of ice sheet outlet glaciers and ice streams, but did not suggest this is the upper value that could occur. Although there are published projections of SLR in excess of IPCC AR4 values (Nicholls et al., 2011), many of these typically use semi-empirical methods that suffer from limited physical validity and further research is required to produce a more robust estimate. Linking sea level rise projections to temperature must also be done with caution because of the different response times of these two climate variables to a given radiative forcing change.

Nicholls and Lowe (2004) previously showed that mitigation alone would not avoid all of the impacts due to rising sea levels, adaptation would likely be needed too. Recent work by van Vuuren et al. (2011) estimated that, for a world where global mean near surface temperatures reach around 2°C by 2100, global mean SLR could be 0.49m above present levels by the end of the century. Their sea level rise estimate for a world with global mean temperatures reaching 4°C by 2100 was 0.71m, suggesting around 40% of the future increase in sea level to the end of the 21^{st} century could be avoided by mitigation. A qualitatively similar conclusion was reached in a study by Pardaens et al. (2011), which examined climate change projections from two GCMs. They found that around a third of global-mean SLR over the 21st century could potentially be avoided by a mitigation scenario under which global-mean surface air temperature is near-stabilised at around 2°C relative to pre-industrial times. Under their baseline business-as-usual scenario the projected increase in temperature over the 21st century is around 4°C, and the sea level rise range is 0.29-0.51m (by 2090-2099 relative to 1980-1999; 5% to 95% uncertainties arising from treatment of land-based ice melt and following the methodology used by the IPCC AR4). Under the mitigation scenario, global mean SLR in this study is projected to be 0.17-0.34m.

The IPCC 4th assessment (IPCCb) followed Nicholls and Lowe (2004) for estimates of the numbers of people affected by coastal flooding due to sea level rise. Nicholls and Lowe (2004) projected for the North and West Europe region that an additional 100 thousand people per year could be flooded due to sea level rise by the 2080s relative to the 1990s for the SRES A2 Scenario (note this region also includes other countries, such as UK and Norway). For the North Mediterranean region, this figure is less than 200 thousand people per year. However, it is important to note that this calculation assumed that protection standards increased as GDP increased, although there is no additional adaptation for sea level rise. More recently, Nicholls et al. (2011) also examined the potential impacts of sea level rise in a scenario that gave around 4°C of warming by 2100. Readings from Figure 3 from Nicholls et al. (2011) for the North and West Europe region suggest that less than an approximate 1 million additional people could be flooded for a 0.5 m SLR (assuming no additional protection), with less than 2 million addition people flooded in the north Mediterranean region. Nicholls et al. (2011) also looked at the consequence of a 2m SLR by 2100, however as we consider this rate of SLR to have a low probability we don't report these figures here.

The European Commission (2009) assessed the vulnerability of several European countries to SLR. Their study found that less than 5% of this Spain's coastline comprises 10km long stretches that are below 5m elevation and that 757km is subject to erosion. The study also calculated that 22,866,485 people live within 50km of the coast.

Recent results from the PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis) project have afforded consistent quantitative projections of the impact of SLR for several European countries (Richards and Nicholls, 2009). These are advantageous because previous European assessments have tended to be more qualitative in nature (Nicholls, 2000). The results show that while Europe is potentially highly threatened by SLR, adaptation (in the form of the two protection options considered) can greatly reduce these impacts to levels which appear manageable. The adaptation methods and costs assessed were the raising of flood dykes and the application of beach nourishment. Richards and Nicholls (2009) show that there are almost immediate benefits of adaptation, and the analysis suggests that widespread adaptation to SLR across Europe could be prudent. The assessment considered SLR projections from two GCMs, ECHAM4 and HadCM3. For each of these, SLR estimates for low, medium and high climate sensitivities were applied, and under the A2 and B2 emissions scenarios. To further quantify uncertainty, the upper and lower estimates of global SLR from the IPCC Third Assessment Report (IPCC, 2001) were also applied. The estimates of global SLR considered by Richards and Nicholls (2009) are summarised in Table 9.

GCM	**ECHAM4**		**HadCM3**		**IPCC TAR**
SRES scenario	**A2**	**B2**	**A2**	**B2**	**A2/B2**
Climate sensitivity					
Low	*29.2*	*22.6*	*25.3*	*19.4*	*9*
Medium	*43.8*	*36.7*	*40.8*	*34.1*	
High	*58.5*	*50.8*	*56.4*	*48.8*	*88*

Table 9. *Global SLR (cm) for low, medium and high climate sensitivities at 2100, for the A2 and B2 SRES scenarios, that were applied by Richards and Nicholls (2009).*

Given that the IPCC TAR estimates of SLR encompass the full range of uncertainty that Richards and Nicholls (2009) considered, impacts for the IPCC TAR low and high scenarios are presented in Table 10. The results show that by the 2080s under the high SLR scenario and without adaptation, the average annual number of people flooded is around 321,800. This is greatly reduced with adaptation, to 1,100. Under the low SLR scenario, 1,100 people are flooded annually without adaptation and 700 are flooded with adaptation. The results highlight the importance of climate sensitivity in determining the impacts as well as demonstrating clear potential benefits of adaptive measures, which by the 2080s can almost completely remove any incremental climate change effect.

Country	Indicator	Baseline (1995)	**IPCC** A2 2020s **Low SLR**		**IPCC** A2 2020s **High SLR**		**IPCC** A2 2080s **Low SLR**		**IPCC** A2 2080s **High SLR**	
			No adaptation	**With adaptation**	**No adaptation**	**With adaptation**	**No adaptation**	**With adaptation**	**No adaptation**	**With adaptation**
France	Total damage costs (millions €/year)	253.2	362.7	228.8	434.9	291.7	673.3	220.9	3359.8	456.6
	Land loss (submergence) (km^2/year)	0	0.2	0.2	0.6	0.6	0.2	0.2	130.8	1.6
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	19.5	0
	Net loss of wetland area (km^2/year)	12.4	300.7	300.7	688.7	688.7	950.9	950.9	1963.8	1963.8
	People actually flooded (1000s/year)	1.96	2.4	2.0	2.9	2.1	3.0	1.8	463.7	2.5
	Salinity intrusion costs (millions €/year)	135.85	145.3	145.3	153.5	153.5	199.9	199.9	268.7	268.7
Germany	Total damage costs (millions €/year)	428.1	473.7	398.9	590.3	448.3	782.2	344.6	2607.6	686.9
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	178.1	0
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	14.3	0.1
	Net loss of wetland area (km^2/year)	0.3	146.4	146.4	418.3	418.3	673.2	673.2	1938.5	1938.5
	People actually flooded (1000s/year)	2.23	2.6	2.3	3.7	2.5	4.4	2.1	293.3	2.9
	Salinity intrusion costs (millions €/year)	274.78	240.8	240.8	251.2	251.2	343.3	343.3	431.4	431.4
Italy	Total damage costs (millions €/year)	8.5	18.5	6.6	271.9	7.1	444.2	9.6	8044.2	17.0
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	188.5	0.1
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	55.2	0
	Net loss of wetland area (km^2/year)	9.6	78.2	78.2	155.5	155.5	221.8	221.8	393.7	393.7
	People actually flooded (1000s/year)	1.49	1.9	1.5	3.1	1.6	3.3	1.5	512.9	2.3
	Salinity intrusion costs (millions €/year)	5.84	6.4	6.4	6.7	6.7	9.2	9.2	11.9	11.9

Spain	Total damage costs (millions €/year)	15.3	23.6	9.4	55.6	14.5	75.6	3.9	749.7	32.0
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	38.3	0.1
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	7.0	0
	Net loss of wetland area (km^2/year)	0.2	64.4	64.4	174.3	174.3	242.5	242.5	659.8	659.8
	People actually flooded (1000s/year)	0.73	0.9	0.7	1.3	0.8	1.1	0.7	321.8	1.1
	Salinity intrusion costs (millions €/year)	0.92	1.0	1.0	1.0	1.0	1.4	1.4	1.8	1.8
UK	Total damage costs (millions €/year)	189.5	414.2	50.1	743.5	136.4	1087.0	6.3	10062.6	155.1
	Land loss (submergence) (km^2/year)	0	0	0	0	0	0	0	239.3	0
	Migration due to land loss (1000s of people/year)	0	0	0	0	0	0	0	73.6	0
	Net loss of wetland area (km^2/year)	8.5	175.1	175.1	522.6	522.6	789.4	789.4	1690.2	1690.2
	People actually flooded (1000s/year)	4.85	5.7	4.4	6.1	4.9	6.8	4.3	986.3	5.6
	Salinity intrusion costs (millions €/year)	2.32	2.5	2.5	2.8	2.8	3.6	3.6	5.7	5.7

Table 10. *Estimates of the impact of SLR with the low and high estimates of SLR from the IPCC TAR in the 2020s and 2080s, and assuming no adaptation or adaptation. Baseline impacts (1995) are also presented. Data is from Richards and Nicholls (2009).*

To further quantify the impact of SLR and some of the inherent uncertainties, the DIVA model was used to calculate the number of people flooded per year for global mean sea level increases (Brown et al., 2011). The DIVA model (DINAS-COAST, 2006) is an integrated model of coastal systems that combines scenarios of water level changes with socio-economic information, such as increases in population. The study uses two climate scenarios; 1) the SRES A1B scenario and 2) a mitigation scenario, RCP2.6. In both cases an SRES A1B population scenario was used. The results are shown in Table 11. While globally there is evidence that the impacts results are not significantly affected by driving DIVA with global mean sea level rise, there are regions where may make a difference. Once such region is the Mediterranean.

	A1B		**RCP**	
	Low	**High**	**Low**	**High**
Additional people flooded (1000s)	3.53	95.60	2.18	27.32
Loss of wetlands area (% of country's total wetland)	34.02%	41.70%	28.05%	40.95%

Table 11*. Number of additional people flooded (1000s), and percentage of total wetlands lost by the 2080s under the high and low SRES A1B and mitigation (RCP 2.6) scenarios (Brown et al., 2011).*

National-scale or sub-national scale assessments

A national assessment of the impact of SLR for Spain (Uceda et al., 2005) supports the contention from global-scale assessments; that SLR impacts in Spain could be large in the absence of adaptation (Richards and Nicholls, 2009). Uceda et al. (2005) suggest that a hypothetical 0.5m SLR could mean the disappearance of around 30% of the beaches in the eastern part of the bay of Biscay, if no natural or artificial nourishment of sediments takes place. Furthermore, this magnitude of SLR could be associated with a sediment response that is associated with the disappearance of around 50% of the Ebro delta. The secondary effects of this could include the flooding of coastal lowlands (deltas, coastal wetlands and agricultural and built up areas in the vicinity of deltas or on coastal alluvial plains). In the Mediterranean and the Balearic Isles, Uceda et al. (2005) found that the most threatened areas, apart from the aforementioned deltas (Ebro and Llobregat), are the Manga del Mar Menor (around 20 km), the Cabo de Gata lagoons (5 km) and, in the Gulf of Cadiz, around 10 km of the coast of Doñana and around 100 km^2 of marshland.

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Acknowledgements

Funding for this work was provided by the UK Government Department of Energy and Climate Change, along with information on the policy relevance of the results.

The research was led by the UK Met Office in collaboration with experts from the University of Nottingham, Walker Institute at the University of Reading, Centre for Ecology and Hydrology, University of Leeds, Tyndall Centre — University of East Anglia, and Tyndall Centre — University of Southampton.

Some of the results described in this report are from work done in the AVOID programme by the UK Met Office, Walker Institute at the University of Reading, Tyndall Centre — University of East Anglia, and Tyndall Centre — University of Southampton.

The AVOID results are built on a wider body of research conducted by experts in climate and impact models at these institutions, and in supporting techniques such as statistical downscaling and pattern scaling.

The help provided by experts in each country is gratefully acknowledged — for the climate information they suggested and the reviews they provided, which enhanced the content and scientific integrity of the reports.

The work of the independent expert reviewers at the Centre for Ecology and Hydrology, University of Oxford, and Fiona's Red Kite Climate Consultancy is gratefully acknowledged.

Finally, thanks go to the designers, copy editors and project managers who worked on the reports.

Met Office
FitzRoy Road, Exeter
Devon, EX1 3PB
United Kingdom

Tel: 0870 900 0100
Fax: 0870 900 5050
enquiries@metoffice.gov.uk
www.metoffice.gov.uk

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