Climate: Observations, projections and impacts: Japan

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The country reports were written by a range of climate researchers, chosen for their subject expertise, who were drawn from institutes across the UK. Authors from the Met Office and the University of Nottingham collated the contributions in to a coherent narrative which was then reviewed. The authors and contributors of the reports are as above.
Climate: Observations, projections and impacts
We have reached a critical year in our response to climate change. The decisions that we made in Cancun 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

- Over the period 1960 to 2010 there was a widespread warming trend over Japan
- Since 1960 there has been a widespread increase in the frequency of warm days and nights and a decrease in the frequency of cool days and nights.
- 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.
- Between the 1960s and 2003 there is some evidence for a decrease in annual total precipitation across Japan although data uncertainties are large.

Climate change projections

- For the A1B emissions scenario projected temperature increases over Japan show changes of which range between around 2.5-3°C in the south, and up to 3.5-4°C in the north, with lower agreement between CMIP3 models in the north of the country.
- Projected precipitation over Japan indicates increases of up to 10% with generally moderate agreement across the CMIP3 ensemble.

Climate impact projections

Crop yields

- There is a general consensus across global- and regional-scale studies that the yields of Japan’s main crop, rice, could increase until 2050 but depending on the emission scenario, may decrease after that.
- One national study included projects rice yields to increase in the north of Japan and remain stable or decrease in the southwest throughout the coming century.

Food security

- Japan is currently a country of extremely low levels of undernourishment. Several global-scale studies included here project that Japan will not face serious food security issues over the next 40 years. This is largely as a result of Japan’s high adaptive capacity and ability to afford to import food to offset potential deficits in food production.
Water stress and drought

- There are currently few studies on the impact of climate change on water stress and drought in Japan, especially at the national scale.
- Studies of the recent past provide evidence that the area around Tokyo may be vulnerable to water stress.
- From the few global-scale studies available to this report, climate change projections suggest that Japan may not experience an increase in water stress under climate change.
- Recent simulations by the AVOID programme broadly agree, simulating a small post-2080 increase of no more than approximately 10% of Japan's population experiencing an increase in exposure to water stress by 2100 under SRES A1B. Furthermore, simulations under an aggressive mitigation scenario suggest that mitigation could avoid all effects of climate change on increased water stress in Japan.

Pluvial flooding and rainfall

- The IPCC AR4 projected precipitation increases under climate change for Japan, along with increases in intense precipitation.
- More recent research has highlighted uncertainties in rainfall projections partly as a result of inter-annual decadal variability of the East Asian monsoon, and also projections of changes in tropical cyclones.

Fluvial flooding

- Most national- and sub-national scale assessments suggest that the magnitude of floods and the costs associated with them could increase with climate change in Japan.
- This is further confirmed by recent simulations by the AVOID programme, where most models show a tendency for increasing flood risk, particularly later in the century and under the A1B scenario, with some models showing very large increases.
- At least one study has suggested that in Hokkaido the month of peak flow occurrence could shift from April (i.e. the snowmelt season) to July or August.

Tropical cyclones

- There remains large uncertainty in the current understanding of how tropical cyclones might be affected by climate change. To this end, caution should be applied in interpreting model-based results, even where the models are in agreement.
- There is relatively less uncertainty regarding the intensity of cyclones in the western Pacific basin, compared to their frequency. A number of global and regional studies
included here project that cyclone intensity could increase considerably in the future in this basin. These increases in intensity could be greatest for the most severe cyclones, which could lead to large increases in cyclone damages in Japan.

Coastal regions

- Research on the impact of climate change on coastal regions in Japan is severely limited.
- Results from one recent global-scale assessment suggest that Japan could experience some of the largest impacts from sea level rise (SLR) across the globe.
- For example, 3.7 million people are currently exposed to SLR in Japan; with climate change up to 7.8 million people could be exposed in the 2070s. Aggressive climate change mitigation policy could avoid an exposure of around 515,000 people in the 2070s.
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Chapter 1 – Climate Observations
Rationale

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 the HadEX extremes database (Alexander et al., 2006), updated for temperature, 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. 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 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

Japan is a group of islands, aligned from south-west to north-east, between 30°N and 45°N off the eastern seaboard of Asia. All the islands are hilly or mountainous. The country’s climate is governed by the ‘Asiatic Monsoon’. In summer this draws warm moist winds across the islands from the Pacific Ocean towards low atmospheric pressure that develops over the hot Asian interior. In winter the prevailing wind reverses and blows from the north-west, bringing air of very cold origin from the intense high atmospheric pressure system that develops over Siberia. The contrast between these two weather regimes results in a large seasonal range in mean temperature of about 24°C between the warmest and coldest months. The considerable latitudinal span of the country also means that temperatures in the north are generally several degrees lower than in the south, especially in winter.

Winters are severe in the north, especially on the more northerly island of Hokkaido, with heavy snowfall. Further south winters are mild. Mean January temperature is around 7°C at Fukuoka in the south and only a degree lower at Tokyo, near the centre of the island chain but with a longer sea track from the cold Asian mainland. By contrast, the mean January temperature at Sapporo, on Hokkaido and with a shorter sea track from the Asian mainland, is only -4°C with a typical daily maximum around -1°C. Average daily maxima in the southern half of Japan in January are around 10°C. Winter precipitation is typically 50-80mm per month, much of it falling as snow in the north. The very cold, dry air mass leaving Siberia picks up moisture and heat as it crosses the relatively warm Sea of Japan, becoming very unstable and depositing particularly heavy snowfall along the western sides of Hokkaido and Honshu – the two more northerly islands. For instance at Sapporo, November, December and January each have more than 100mm precipitation.

In summer, under maritime influence, the warmest month is delayed to August, when the mean temperature is around 28°C in the southern half of the country (Fukuoka and Tokyo), decreasing to 23°C at Sapporo. Typical daily maxima in August reach 32°C in Fukuoka, 31°C in Tokyo and 26°C in Sapporo. With the exceptions of some north-western locations, summer is the wetter season. Much of the annual precipitation falls between March and October which have, typically, 100-200mm each month and more in places. Annual average precipitation is 1613mm at Fukuoka, 1529mm at Tokyo and 1107mm at Sapporo.

Japan is located in one of the most active tropical cyclone regions in the world. Much of the heavy rain in late summer and early autumn is brought by typhoons (tropical cyclones) curving northwards from the region of the Philippines. In some parts of central and southern
Japan there is a double rainfall maximum; one in early summer and a second in late summer or early autumn, brought by typhoons. This is slightly evident at Tokyo which has a minor rainfall peak in June (170mm) and a stronger peak in September (210mm). Apart from flooding and wind damage from these typhoons, other climate hazards in Japan include droughts and heat waves, snow storms and severe cold.

**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 Japan using the median of pairwise slopes method to fit the trend (Sen, 1968; Lanzante, 1996). The methods are fully described in the methodology annex and Brohan et al. (2006) provide a detailed discussion on uncertainty and the CRUTEM3 data. In agreement with increasing global average temperatures (Sánchez-Lugo et al., 2011), there is a widespread warming signal for temperature over Japan (Figure 2). This is consistent with previous research (Cruz et al., 2007). During winter (December to February) there is greater spatial consistency in the warming with higher confidence across the vast majority of grid boxes in that the 5th to 95th percentiles of the slopes are of the same sign. The signal is more mixed and higher confidence grid boxes more sporadic during summer (June to August). Regionally averaged trends (over grid boxes included in the red dashed box in Figure 1) show warming signals with higher confidence. This trend is larger in winter at 0.33 °C per decade (5th to 95th percentile of slopes: 0.16 to 0.50 °C per decade) than in summer at 0.14 °C per decade (5th to 95th percentile of slopes: 0.16 to 0.36 °C per decade).
Figure 2. Decadal trends in seasonally averaged temperatures for Japan 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 higher confidence in the trends shown if the 5th to 95th 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. Two events, the severe winter of 2005-2006 and the heat wave during summer 2007, are highlighted as examples of recent extreme temperature events.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
<th>Details</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005/06</td>
<td>Dec-Feb</td>
<td>Snow</td>
<td>Heavy snowfall. Deepest on record in some areas (106 stations). Deadliest winter since 1983-4.</td>
<td>WMO (2007)</td>
</tr>
<tr>
<td>2007</td>
<td>Aug-Sep</td>
<td>Heat wave</td>
<td>Extremely warm in parts of Japan.</td>
<td>WMO (2008)</td>
</tr>
<tr>
<td>2010</td>
<td>Jul-Sep</td>
<td>Heat wave</td>
<td>Warmest summer since national records began in 1898</td>
<td>WMO (2011)</td>
</tr>
</tbody>
</table>

*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

**Severe Winter (snow), December 2005 – February 2006**

The deepest snow on record (Arguez et al., 2007) combined with a severely cold winter caused 151 deaths in Japan in the winter of 2005-6, making it the deadliest winter since 1983-4. Record snowfall was experienced for December by 106 meteorological stations in Japan (JMA, Disaster summaries, 2011).

The total injured was 2136 and 18 houses were destroyed with a further 4,800 damaged or flooded as snows melted. The snow also caused damage to the transport network and disrupted electricity provision for thousands (JMA, Disaster summaries, 2011).
**Heat wave, summer 2007**

In August and September 2007, monthly mean temperatures were significantly above normal in many parts of Japan. On 16th August new national record temperatures of 40.9°C were recorded in Kumagaya, Saitama Prefecture near Tokyo and Tajimi in Gifu Prefecture (Suda et al., 2008).

**Analysis of long-term features in moderate temperature extremes**

GHCND data (Durre et al., 2010) have been used to update the HadEX extremes analysis for Japan 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.

As shown in Figure 3, there is a spatially consistent signal of increased warm day and warm night frequency, and decreased cool day and cool night frequency with higher confidence throughout the country. This is consistent with the overall warming shown in the mean temperature in Figure 2. The regional average time series also exhibit clear changes in agreement with the changes determined from the maps. The annual time series for the number of cool days and nights (based on daily minimum temperature) terminates before the monthly one, in around 2001, because there are fewer data provided post-2001. There is a restriction on the number of grid boxes present in order for an area average to be calculated. As each month has its own decorrelation length scale, some months still have sufficient valid grid boxes in the region of interest, whereas others will not. This results in the rather odd time-series for the monthly data beyond 2001 and so any features present therein should not be taken at face value. The small numbers of stations available for calculating most grid box averages means that even if there is higher confidence in the signals shown, uncertainty in the signal being representative of the wider grid box is large.
**Cool Nights (TN10p)**

- Monthly: -1.95% per decade (-2.29 to -1.63)
- Total change: -9.77% from 1950 to 2010 (-11.42% to -8.16%)
- Annual: -3.41% per decade (-3.84 to -3.19)
- Total change: -8.37% from 1950 to 2003 (-11.38% to -5.95%)

**Warm Nights (TN90p)**

- Monthly: 1.17% per decade (0.72 to 1.63)
- Total change: 5.85% from 1960 to 2010 (3.95% to 8.16%)
- Annual: 1.60% per decade (0.64 to 2.64)
- Total change: 6.42% from 1960 to 2000 (2.38% to 10.72%)
Figure 3. Change in cool nights (a,b), warm nights (c,d), cool days (e,f) and warm days (g,h) for Japan over the period 1960 to 2010 relative to 1961-1990 from the GHCND dataset (Durre et al., 2010). 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 129.375° to 144.375° E and 31.25° to 46.25° N as shown by the green box on the map and in the red box in Figure 1. Monthly (orange) and annual (blue) trends are fitted as described above. The decadal trend and its 5th to 95th percentile pairwise slopes are shown as well as the change over the period for which there are data. 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 locations of the cold winter of 2005-06 and the heat wave of 2007.
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.

Winter 2005/06

The distribution of the winter mean (December-January-February) regional temperature for 2000-2009 in the presence and absence of anthropogenic forcings are shown using distributions in Figure 4. Analyses with two independent CMIP3 coupled atmosphere and ocean general circulation models (HadGEM1 and MIROC) suggest that human influences on the climate have shifted the distribution towards higher temperatures than would be expected under natural influences alone. Considering the average over the entire region, the 2005/06 winter is cold, as it lies near the cold tail of the temperature distributions for the climate influenced by anthropogenic forcings (distributions plotted in red). However, in the absence of human influences on the climate (green distributions) the season would be average, as it lies in the central sector of the temperature distributions plotted in green. The winter of 2005/06 is considerably warmer than the winter of 1944/45, the coldest in the CRUTEM3 dataset.

It should be noted that the attribution results shown here refer to temperature anomalies averaged over the entire region and over an entire season. As such, they do not rule out the occurrence of an extreme event that has a shorter duration and affects a smaller region such as the 2005/06 winter over Japan.
**Figure 4.** Distributions of the December-January-February mean temperature anomalies (relative to 1961-1990) averaged over an East Asian region that encompasses Japan (122-150 °E, 30-48 °N – 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 black line marks the observed anomaly in 2005/06 and the vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.

**Summer 2007**

The distribution of the summer mean (June-July-August) regional temperature for 2000-2009 in the presence and absence of anthropogenic forcings are shown using distributions in Figure 5. Both models suggest that human influences on the climate have shifted the distribution to higher temperatures. Considering the average over the entire region, the 2007 summer is average as it lies in the central sector of the temperature distributions for the climate influenced by anthropogenic forcings (red distributions), albeit in the cooler half. It is not as extreme as the summer of 1994, which is the hottest since 1900 in the CRUTEM3 dataset. In the absence of human influences on the climate, the season would be warm, as it lies near the warm tail of the distributions plotted in green.

The attribution results shown here refer to temperature anomalies averaged over the entire region and over an entire season and do not rule out the occurrence of a heat wave event that has a shorter duration and affects a smaller region.
Figure 5. Distributions of the June-July-August mean temperature anomalies (relative to 1961-1990) averaged over an East Asian region that encompasses Japan (122-150°E, 30-48°N – 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 black line marks the observed anomaly in 2007 and 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 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. Flooding during October 2009 is highlighted below as an example of a recent extreme precipitation event affecting Japan.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
<th>Details</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Summer</td>
<td>Flooding</td>
<td>Localised torrential rain caused widespread flooding.</td>
<td>Guo et al. (2009)</td>
</tr>
<tr>
<td>2009</td>
<td>Jul</td>
<td>Flooding</td>
<td>Torrential rain led to flooding and landslides. The area had a record amount of rainfall in July.</td>
<td>WMO (2010)</td>
</tr>
</tbody>
</table>

*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

**Flooding, July 2009**

Heavy rain brought unusually wet conditions in July, setting a new record for monthly total precipitation for July on the Pacific side of northern Japan (209% of the 1971-2000 normal) (Osawa et al., 2010). Torrential rain caused floods which resulted in a landslide in Yamaguchi, western Japan. The BBC reported that at least 8 people were killed and many missing due to this landslide (BBC, 2009). Some crop damage and a rise in vegetable prices were also associated with this unsettled weather (Osawa et al., 2010).
Analysis of long-term features in precipitation

HadEX extremes indices (Alexander et al., 2006) are used here for Japan from 1960 to 2003 using daily precipitation totals. Here we discuss changes in the annual total precipitation. The methods are fully described in the methodology annex.

Between the 1960s and 2003, using the HadEX dataset (Alexander et al., 2006) there is a spatially consistent decrease in annual total precipitation across Japan (Figure 6 a,b). However, there is lower confidence in this signal, even when averaged across the region. Furthermore, the small numbers of stations present in most grid boxes means that even if there were higher confidence in the signals shown, uncertainty in the signal being representative of the wider grid box is large. Previous research found increases in extreme rainfall frequency over the last century and magnitude during recent decades (Cruz et al., 2007).

![Figure 6. Total annual precipitation for Japan over the period 1960 to 2003 relative to 1961-1990 from HadEX (Alexander et al., 2006). a) Decadal trends as shown in Figure 3. b) Area average annual time series for 129.375° to 144.375° E, 31.25° to 46.25° N as described in Figure 3. There is lower confidence that the trend in the total precipitation is different from zero, and hence it is marked with a dotted line.](image-url)
**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 & Jones, 2011), wind data are not yet adequate for worldwide robust analysis. 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. Typhoon Tokage in 2004, is highlighted here as an example of a recent storm event over Japan.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
<th>Details</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Sep</td>
<td>Storm</td>
<td>Typhoon Saomai caused record-breaking rainfall. September totals up to 500mm above normal.</td>
<td>WMO (2001)</td>
</tr>
<tr>
<td>2004</td>
<td>Jun-Oct</td>
<td>Storms</td>
<td>10 tropical cyclones made landfall, breaking the previous record of six, established in 1990 and repeated in 1993. Typhoon Tokage was the deadliest typhoon to affect Japan since 1979. 209 people were killed in Japan by floods, landslides, strong wind and storm surge caused by the tropical cyclones. They also caused damage to infrastructures worth around US$ 10 billion.</td>
<td>WMO (2005)</td>
</tr>
<tr>
<td>2005</td>
<td>Sep</td>
<td>Storm</td>
<td>Typhoon Nabi caused severe damage and brought a record heavy precipitation of 1321 mm in three days in western Japan.</td>
<td>WMO (2006)</td>
</tr>
</tbody>
</table>

*Table 3. 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 storm events**

**Typhoon Tokage, 2004**

One of the most striking features of the 2004 typhoon season in the western North Pacific basin were the 10 landfalls in Japan, which shattered the previous record of 6. This uncharacteristically large number of landfalls was accompanied by anomalous southeasterly winds which propagated the tropical cyclones toward Japan, generating many
impacts. Although typhoon Tokage was not the most intense storm during this period, its impacts were substantial, causing at least 69 deaths due to the high winds, flooding, and mudslides (Camargo, 2005). The highest measured wind gust was 229 km/h at Unzendake, Nagasaki, and the highest rainfall amount noted in Japan was 550 mm at Fukuherasahi, with 470 mm falling within a 24 hour period. Tokage weakened by the time it passed over Japan’s capital, Tokyo, where it caused little damage. Damage from the storm amounted to US$3.23 billion, 907 houses were destroyed, and a further 74,790 were damaged or flooded by the strong winds and flooding as coastal defences were destroyed (JMA Disaster Summaries, 2011).
Summary

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

- Over the period 1960 to 2010 there were widespread warming trends over Japan.

- Since 1960 there has been a widespread increase in the frequency of warm days and nights and a decrease in the frequency of cool days and nights.

- 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.

- Between the 1960s and 2003 there is some evidence for a decrease in annual total precipitation across Japan although data uncertainties are large.
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).

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

*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 2 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\textsuperscript{1} and the BMKG\textsuperscript{2} for their assistance in obtaining these data.

\begin{footnotesize}
\begin{enumerate}
\item Koninklijk Nederlands Meteorologisch Instituut – The Royal Netherlands Meteorological Institute
\item Badan Meteorologi, Klimatologi dan Geofisika – The Indonesian Meteorological, Climatological and Geophysical Agency
\end{enumerate}
\end{footnotesize}
Mexico:

The station data from Mexico has been kindly supplied by the SMN\textsuperscript{3} and Jorge Vazquez. These daily data were then converted to the required indices using the \textit{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 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 $1\degree \times 1\degree$ 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.

\textsuperscript{3} Servicio Meteorológico Nacional de México – The Mexican National Meteorological Service
<table>
<thead>
<tr>
<th>Country</th>
<th>Region box (red dashed boxes in Fig. 1 and on each map at beginning of chapter)</th>
<th>Data source (T = temperature, P = precipitation)</th>
<th>Period of data coverage (T = temperature, P = precipitation)</th>
<th>Indices included (see Table 1 for details)</th>
<th>Temporal resolution available</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>73.125 to 54.375 °W, 21.25 to 56.25 °S</td>
<td>Matilde Rusticucci (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>annual</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>114.375 to 155.625 °E, 11.25 to 43.75 °S</td>
<td>GHCND (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td>Land-sea mask has been adapted to include Tasmania and the area around Brisbane</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>88.125 to 91.875 °E, 21.25 to 26.25 °N</td>
<td>Indian Gridded data (T,P)</td>
<td>1960-2007 (P), 1970-2009 (T)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td>Interpolated from Indian Gridded data</td>
</tr>
<tr>
<td>Brazil</td>
<td>73.125 to 31.875 °W, 6.25 °N to 33.75 °S</td>
<td>HadEX (T,P)</td>
<td>1960-2000 (P) 2002 (T)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>annual</td>
<td>Spatial coverage is poor</td>
</tr>
<tr>
<td>China</td>
<td>73.125 to 133.125 °E, 21.25 to 53.75 °N</td>
<td>GHCND (T,P)</td>
<td>1960-1997 (P) 1960-2003 (T&lt;sub&gt;min&lt;/sub&gt;) 1960-2010 (T&lt;sub&gt;max&lt;/sub&gt;)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td>Precipitation has very poor coverage beyond 1997 except in 2003-04, and no data at all in 2000-02, 2005-11</td>
</tr>
<tr>
<td>Egypt</td>
<td>24.375 to 35.625 °E, 21.25 to 31.25 °N</td>
<td>HadEX (T,P)</td>
<td>No data</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>annual</td>
<td>There are no data for Egypt so all grid-box values have been interpolated from stations in Jordan, Israel, Libya and Sudan</td>
</tr>
<tr>
<td>France</td>
<td>5.625 °W to 9.375 °E, 41.25 to 51.25 °N</td>
<td>ECA&amp;D (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>5.625 to 16.875 °E, 46.25 to 56.25 °N</td>
<td>ECA&amp;D (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Latitude/Longitude</td>
<td>Data Source and Periods</td>
<td>Variables</td>
<td>Spatial Coverage Notes</td>
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<tr>
<td>-------------</td>
<td>-----------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>69.375 to 99.375° E, 6.25 to 36.25° N</td>
<td>Indian Gridded data (T,P), 1970-2009 (T)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>95.625 to 140.625° E, 6.25° N to 11.25° S</td>
<td>HadEX (T,P), 1968-2003 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT,</td>
<td>annual</td>
<td>Spatial coverage is poor</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>5.625 to 16.875° E, 36.25 to 46.25° N</td>
<td>ECA&amp;D (T,P), 1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td>Land-sea mask has been adapted to improve coverage of Italy</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>129.375 to 144.375° E, 31.25 to 46.25° N</td>
<td>HadEX (P), GHCND (T), 1960-2003 (P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT,</td>
<td>annual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenya</td>
<td>31.875 to 43.125° E, 6.25° N to 6.25° S</td>
<td>HadEX (T,P), 1960-1999 (P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT</td>
<td>annual</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td>Peru</td>
<td>84.735 to 65.625° W, 1.25° N to 18.75° S</td>
<td>HadEX (T,P), 1960-2002 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>annual</td>
<td>Intermittent coverage in TX90p, CDD and CWD</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>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</td>
<td>ECA&amp;D (T,P), 1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td>monthly, seasonal and annual</td>
<td>Country split for presentation purposes only.</td>
<td></td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>31.875 to 54.375° E, 16.25 to 33.75° N</td>
<td>HadEX (T,P), 1960-2000 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT</td>
<td>annual</td>
<td>Spatial coverage is poor</td>
<td></td>
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<tr>
<td>Country</td>
<td>Coordinates</td>
<td>Dataset</td>
<td>Time Period</td>
<td>Data Details</td>
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<td>------------------------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>13.125 to 35.625 ° W, 21.25 to 36.25 ° S</td>
<td>HadEX (T,P)</td>
<td>1960-2000 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>annual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>125.625 to 129.375 ° E, 33.75 to 38.75 ° N</td>
<td>HadEX (T,P)</td>
<td>1960-2003 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>annual</td>
<td>There are too few data points for CWD to calculate trends or regional timeseries</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>9.375 ° W to 1.875 ° E, 36.25 to 43.75 ° N</td>
<td>ECA&amp;D (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>monthly, seasonal and annual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turkey</td>
<td>24.375 to 46.875 ° E, 36.25 to 43.75 ° N</td>
<td>HadEX (T,P)</td>
<td>1960-2003 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>annual</td>
<td>Intermittent coverage in CWD and CDD with no regional average beyond 2000</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>9.375 ° W to 1.875 ° E, 51.25 to 58.75 ° N</td>
<td>ECA&amp;D (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>monthly, seasonal and annual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>United States of America</td>
<td>125.625 to 65.625 ° W, 23.75 to 48.75 ° N</td>
<td>GHCND (T,P)</td>
<td>1960-2010 (T,P)</td>
<td>TN10p, TN90p, TX10p, TX90p, PRCPTOT, CDD, CWD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>monthly, seasonal and annual</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*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 7).

![Figure 7. Land Sea mask used for gridding the station data and regional areas allocated to each country as described in Table 5.](image)

**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 5th to 95th 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 5th to 95th 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 7 and listed in Table 5 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 7. 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 5th to 95th 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.
Figure 8. 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 7. 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 7 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 9. These are also identified as grey boxes on the maps in Figure 7. 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.9 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 9. 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.

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

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


K-1 Model Developers (2004) K-1 coupled GCM (MIROC) description, K-1 Tech Rep, H Hasumi and S Emori (eds), Centre for Clim Sys Res, Univ of Tokyo


Acknowledgements

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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 Japan 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.*
Summary of temperature change in Japan

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.

Projected temperature increases over Japan show changes of which range between around 2.5-3°C in the south, and up to 3.5-4°C in the north, with lower agreement between models in the north of the country.

Summary of precipitation change in Japan

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 precipitation over Japan indicates increases of up to 10% with generally moderate ensemble agreement.
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 Japan. 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 Japan. 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 CO₂ 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, CO₂ exerts physiological influences on plants, affecting photosynthesis and transpiration. Under higher CO₂ 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 CO₂ affects crop yields and natural vegetation functioning remains uncertain and controversial. Many impacts
projections assume CO₂ 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 Japan includes changes in the El Niño-Southern Oscillation (ENSO) which could undergo rapid change with climate change. This could have a serious impact on large-scale atmospheric circulation, rainfall and seasonality in many parts of the world. Latif and Keenlyside (2009) concluded that, at this stage of understanding, it is not known how climate change might affect the tropical Pacific climate system. None of the global climate models (GCMs) they analysed showed rapid changes in behaviour. However, a threshold of abrupt change cannot be ruled out because whilst the GCMs that Latif and Keenlyside (2009) analysed (the CMIP3 multi-model dataset) are better than the previous generation of models (Reichler and Kim, 2008), these same models all show large biases in simulating the contemporary tropical Pacific, with no consensus on the sign of change in ENSO-like response.
Summary of findings for each sector

Crop yields

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

- There is a general consensus across global- and regional-scale studies included here that the yields of Japan’s main crop, rice, could increase until 2050 but, depending on the emission scenario, may decrease after that.

- The national study included here projects rice yields to increase in the north of Japan and remain stable or decrease in the southwest throughout the coming century.

- Important knowledge gaps and key uncertainties include the quantification of yield increases due to CO$_2$ fertilisation, quantification of yield reductions due to ozone damage and the extent to which crop diseases might affect crop yields with climate change.

Food security

- Japan is currently a country of extremely low levels of undernourishment. Several global-scale studies included here project that Japan will not face serious food security issues over the next 40 years. This is largely as a result of Japan’s high adaptive capacity and ability to afford to import food to offset potential deficits in food production.

- The national economy of Japan presents a low vulnerability to climate change impacts on fisheries by the 2050s. The 10-year averaged maximum catch potential from 2005 to 2055 in Japan could decline by 3% under SRES A1B.
Water stress and drought

- There are currently few studies on the impact of climate change on water stress and drought in Japan, especially at the national scale, so additional research efforts should be focussed here.

- Studies of the recent past provide evidence that the area around Tokyo may be vulnerable to water stress.

- From the few global-scale studies available, climate change projections suggest that Japan may not experience an increase in water stress under climate change.

- Recent simulations by the AVOID programme broadly agree, simulating a small post-2050 increase of no more than approximately 10% of Japan’s population presenting an increase in exposure to water stress by 2100 under SRES A1B. Furthermore, simulations under an aggressive mitigation scenario suggest that mitigation could avoid all effects of climate change on increased water stress in Japan.

Pluvial flooding and rainfall

- The IPCC AR4 projected precipitation increases under climate change for Japan, along with increases in intense precipitation.

- More recent research has highlighted uncertainties in rainfall projections partly as a result of inter-annual decadal variability of the East Asian monsoon, and also projections of changes in tropical cyclones.

- This adds detail to the current state of knowledge reported in the IPCC AR4.

Fluvial flooding

- Most national- and sub-national scale assessments suggest that the magnitude of floods and the costs associated with them could increase with climate change in Japan.

- This is further confirmed by recent simulations by the AVOID programme, where most models show a tendency for increasing flood risk, particularly later in the century and under the A1B scenario, with some models showing very large increases.
• At least one study has suggested that in Hokkaido the month of peak flow occurrence could shift from April (i.e. the snowmelt season) to July or August.

Tropical cyclones

• There remains large uncertainty in the current understanding of how tropical cyclones might be affected by climate change, including in the western Pacific, as conclusions are based upon a limited number of studies whose projections are from either coarse-resolution global models or from statistical or dynamical downscaling techniques. To this end, caution should be applied in interpreting model-based results, even where the models are in agreement.

• There is relatively less uncertainty regarding the intensity of cyclones in the western Pacific basin, compared to their frequency. A number of global and regional studies included here project that cyclone intensity could increase considerably in the future in this basin. These increases in intensity could be greatest for the most severe cyclones, which could lead to large increases in cyclone damages in Japan.

Coastal regions

• Research on the impact of climate change on coastal regions in Japan is severely limited.

• Results from one recent global-scale assessment suggest that Japan could experience some of the largest impacts from sea level rise (SLR) across the globe.

• For example, 3.7 million people are currently exposed to SLR in Japan; with climate change up to 7.8 million people could be exposed in the 2070s. An aggressive climate change mitigation scenario could avoid an exposure of around 515,000 people in the 2070s.

Crop yields

Headline

Crop yield projections under climate change scenarios for Japan vary across studies due to the application of different models, assumptions, emissions scenarios. For the main crop, rice, there is a general consensus across studies that yields could increase until 2050 but
depending on the emission scenario, may decrease after that. Yields are projected to increase in the north of Japan and remain stable or decrease in the southwest.

Results from the AVOID programme for Japan indicate that no cropland was projected to undergo a decline in productivity for either scenario. So, for Japan, the climate change is projected here to lead to improve suitability for cultivation in current croplands regardless of which of the two emissions scenarios applies.

**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 CO₂ 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.

Rice is the most important (staple) crop in Japan, but a range of temperate crops such as apples, potato, sugar beet and cabbages are also important (FAO, 2008); see Table 1.
Table 1. The top 7 crops by harvested area, quantity and value according to the FAO (2008) in Japan. 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.

<table>
<thead>
<tr>
<th>Harvested area (ha)</th>
<th>Quantity (Metric ton)</th>
<th>Value ($1000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice, paddy</td>
<td>1620000</td>
<td>Rice, paddy</td>
</tr>
<tr>
<td>Wheat</td>
<td>208000</td>
<td>Sugar beet</td>
</tr>
<tr>
<td>Soybeans</td>
<td>147000</td>
<td>Vegetables fresh (nes)</td>
</tr>
<tr>
<td>Vegetables fresh (nes)</td>
<td>117000</td>
<td>Potatoes</td>
</tr>
<tr>
<td>Potatoes</td>
<td>84900</td>
<td>Sugar cane</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>66000</td>
<td>Cabbages and other brassicas</td>
</tr>
<tr>
<td>Barley</td>
<td>56600</td>
<td>Onions, dry</td>
</tr>
</tbody>
</table>

* nes = not elsewhere specified or included

A number of global, regional, national and sub-national scale impact model studies, which include results for some of the main crops in Japan, have been conducted. They applied 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 CO2 in the atmosphere on plant growth and adaption of agricultural practises to changing climate conditions. These different models, assumptions and emissions scenarios mean that there are a range of crop yield projections for Japan. However, the majority of studies explored in this report show that wheat yield, in particular, could decline strongly over the coming decades.

Important knowledge gaps, which are applicable to Japan as well as at the global-scale, include; the quantification of 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). 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 Japan 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 overall. 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 Japan a positive effect on rice but a negative effect on soybean yield was estimated relative to what could have been achieved without climate trends (see Table 2).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>n/a</td>
</tr>
<tr>
<td>Rice</td>
<td>0.1 to 0.2</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.0 to 0.1</td>
</tr>
<tr>
<td>Soybean</td>
<td>-0.3 to -0.2</td>
</tr>
</tbody>
</table>

Table 2. The estimated net impact of climate trends for 1980-2008 on crop yields. Climate-induced yield trend divided by overall yield trend. Data is from Lobell et al. (2011).

Climate change studies

Included in this section are results from recent studies that 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, and which include impact estimates at the national-scale for Japan (Avnery et al., 2011, Iglesias and Rosenzweig, 2009, Masutomi et al., 2009). The process of CO₂ fertilisation of some crops is usually included in climate impact studies of yields. However, other gases can influence crop growth, and are not always included in impact model projections. An example of this is ozone, (O₃) and so a study which attempts to quantify the potential impact of changes in the atmospheric concentration of this gas 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 countries included 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 consistent crop simulation methodology and climate change
scenarios globally, and weighted the model site results by their contribution to regional and
national, 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 potential of the country or region to reach optimal crop yield. The results from
the study are presented in Table 3 and Table 4. Iglesias and Rosenzweig (2009) found that
wheat and rice yield were projected to increase above baseline (1970-2000) levels under
each emissions scenario until 2050. By 2080, wheat and rice yield were projected to remain
above baseline levels in six and four (out of seven) emissions scenarios respectively, which
implies there is greater uncertainty in crop response later in the century.
### Table 3
National wheat and rice yield changes (%) relative to baseline scenario (1970-2000) for different emission scenarios and future time periods in Japan. Some emissions scenarios were run in an ensemble simulation (e.g. A2a, A2b, A2c). Data is from Iglesias and Rosenzweig (2009).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>Wheat</th>
<th>Rice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
<td>1.95</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1.77</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>-4.16</td>
<td>-4.95</td>
</tr>
<tr>
<td>A1F1</td>
<td>2020</td>
<td>1.75</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>3.51</td>
<td>4.47</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>3.70</td>
<td>3.50</td>
</tr>
<tr>
<td>A2a</td>
<td>2020</td>
<td>1.73</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>3.25</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>2.71</td>
<td>-1.38</td>
</tr>
<tr>
<td>A2b</td>
<td>2020</td>
<td>1.19</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1.80</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>0.96</td>
<td>3.57</td>
</tr>
<tr>
<td>A2c</td>
<td>2020</td>
<td>1.44</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1.54</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>0.15</td>
<td>-0.89</td>
</tr>
<tr>
<td>B1a</td>
<td>2020</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>0.31</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>2.33</td>
<td>3.77</td>
</tr>
<tr>
<td>B2a</td>
<td>2020</td>
<td>0.99</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>0.90</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>1.05</td>
<td>3.60</td>
</tr>
<tr>
<td>B2b</td>
<td>2020</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>0.31</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>2.33</td>
<td>3.77</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Wheat</th>
<th>Rice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up</td>
<td>Down</td>
</tr>
<tr>
<td>Baseline to 2020</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Baseline to 2050</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Baseline to 2080</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>2020 to 2050</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>2050 to 2080</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Masutomi et al. (2009) comprehensively assessed the impact of climate change on rice production in Asia considering the process/parameter uncertainty in GCMs. The authors created climate scenarios based on the projections of GCMs for three emissions scenarios (18 GCMs for A1B, 14 GCMs for A2, and 17 GCMs for B1). The climate scenarios were then used as input to the M-GAEZ crop model to calculate the average change in production (ACP) and other parameters taking into account the effect of CO₂ fertilisation. Since land-use change was not considered in the study, changes in crop production actually equate to changes in crop yield and the country-level results for Japan are presented in Table 5. The overall finding is broadly similar to that of Iglesias and Rosenzweig (2009) with rice yield.
being above the 1990 baseline up to the 2050s, but in two out of three of the emissions scenarios used, falling to below the baseline by the 2080s.

Nelson et al. (2009) assessed the impact of climate change on a global-scale and included impact estimates for the East Asia and Pacific region as a whole. The authors applied two GCMs in combination with the DSSAT crop model under the SRES A2 emissions scenario to project future yields of rice, maize, soybean, wheat and groundnut with and without CO$_2$ enrichment, and for rain-fed and irrigated lands, for several regions across the globe. Table 6 represents the results for East Asia and the Pacific, the World Bank regional grouping in which Japan is included. Whilst this study provides a useful indicator of crop yields under climate change for the region, it should be noted that the crop yields presented are not definitive national estimates. This is because the yields are averaged over the entire region, which includes other countries as well as Japan.

It can be seen that increased CO$_2$ levels were of benefit to all crops simulated, whether rain-fed or irrigated. However the effects of CO$_2$ fertilisation in the case of irrigated maize and rain-fed wheat in particular are not projected to be large enough to fully compensate for factors which could lead to yield reductions, such as increasing temperatures, out to 2050.

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 results for Japan are presented in Table 7.

<table>
<thead>
<tr>
<th>Crop</th>
<th>A2 M12</th>
<th>A2 AOT40</th>
<th>B1 M12</th>
<th>B1 AOT40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wheat</td>
<td>4-6</td>
<td>15-20</td>
<td>4-6</td>
<td>15-20</td>
</tr>
</tbody>
</table>

**Table 7. 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

#### Climate change studies

Included in this section are results from a recent study that has applied a crop model, alongside information from global climate models to produce sub-national projections of future rice yield in Japan.

Iizumi et al. (2011) applied an ensemble-based approach to estimate paddy rice yield change in Japan in the 2050s (2046–2065) and 2090s (2081–2100) relative to the 1990s (1981–2000), under climate change scenarios. Seventeen climate projections were applied; eight projections from six GCMs with the SRES A2 scenario and nine climate projections from seven GCMs with the SRES A1B scenario. In addition, 50 sets of biophysical and empirical parameter values of PRYSBI, a large-scale process-based crop model for irrigated paddy rice, were included to represent the uncertainties of crop parameter values. The planting windows, cultivation practices, and crop cultivars in the future were assumed to be the same as the level in the baseline period (1990s). The resulting probability density functions conditioned on A2 and A1B project, despite shortening growing periods, median yield increases of +26.9% and +17.2% in Hokkaido, the northern part of Japan, in the 2050s and 2090s with 90% probability intervals of (+40.3%, −5.2%) and (+51.2%, +6.3%), relative to the 1990s mean yield, respectively. The corresponding values in Aichi, on the Pacific side of Western Japan, are -0.8% and 2.2%, with 90% probability intervals of (+14.9%, −15.0%) and (+17.9%, −33.4%), respectively. The reason for the substantial projected yield increase in the north is the drastic decrease in the frequency and intensity of cool-summer damage.

#### 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 as 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 Japan are presented in Figure 2.

By 2030 in both emissions scenarios, models projected between 25% and 28% of current Japanese cropland areas to undergo an improvement of suitability of cultivation. Over the 21st Century this changes only slightly for both scenarios, with the range of croplands showing improving suitability narrowing to approximately 28% by 2100.

No cropland in Japan was projected to undergo a decline in productivity for either scenario. So, for Japan, the climate change is projected here to lead to improve suitability for cultivation in current croplands regardless of which of the two emissions scenarios applies.
Figure 2. Box and whisker plots for the impact of climate change on increased crop suitability (top panel) and decreased crop suitability (bottom panel) for Japan, 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

Several global-scale assessments point towards a generally optimistic and positive outlook for the impact of climate change on food security in Japan. This is largely as a result of Japan's high adaptive capacity and its ability to be able to afford to import food to offset potential deficits in food production. The national economy of Japan presents a low vulnerability to climate change impacts on fisheries.

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’ (World Food Summit, 1996).

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.

Assessments that include a global or regional perspective

Climate change studies

According to the FAO’s Food Security Country profiles (FAO, 2010) an extremely low level(<5%) of Japan’s population are currently undernourished.

A number of global studies point towards a generally optimistic and positive outlook for the impact of climate change on food security in Japan, largely as a result of Japan's high adaptive capacity and its ability to be able to afford to import food to offset potential deficits in food production. For example, 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. Whilst parts of Japan were highlighted as hot spots for food security vulnerability between 2000 and 2020, Wu et al. (2011) note that Japan’s population may still be food-secure because it’s population is less reliant on subsistence agriculture and the country possesses a high capability for importing food due to strong purchasing power and financial support. Furthermore, Japan has substantial adaptive capacity and proactive food management systems in place.

A global analysis of food security under climate change scenarios for the 2050s by Falkenmark et al. (2009) considered 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 Japan was a food importing country in 2050.

The International Food Policy Research Institute (IFPRI) have produced a report and online tool that describes the possible impact of climate change on two major indicators of food security; 1) the number of children aged 0-5 malnourished, and 2) the average daily kilocalorie availability (Nelson et al., 2010, IFPRI, 2010). The study considered three broad socio-economic scenarios; 1) a ‘pessimistic’ scenario, which is representative of the lowest of the four GDP growth rate scenarios from the Millennium Ecosystem Assessment GDP scenarios and equivalent to the UN high variant of future population change, 2) a ‘baseline’ scenario, which is based on future GDP rates estimated by the World Bank and a population change scenario equivalent to the UN medium variant, and 3) an ‘optimistic’ scenario that is representative of the highest of the four GDP growth rate scenarios from the Millennium Ecosystem Assessment GDP scenarios and equivalent to the UN low variant of future population change. Nelson et al. (2010) also considered climate modelling and emission uncertainty and included a factor to account for CO₂ fertilisation in their work. The study applied two GCMs, the CSIRO GCM and the MIROC GCM, and forced each GCM with two SRES emissions scenarios (A1B and B1). They also considered a no climate change emissions scenario, which they called ‘perfect mitigation’ (note that in most other climate change impact studies that this is referred to as the baseline). The perfect mitigation scenario is useful to compare the effect of climate change against what might have happened without, but is not a realistic scenario itself. IFPRI have not published projections for child malnourishment in Japan but information on average daily kilocalorie availability has been made available. Table 8 displays the average daily kilocalorie availability simulated under different climate and socioeconomic scenarios for Japan and Figure 3 displays the effect of climate change, calculated by comparing the ‘perfect mitigation’ scenario with each baseline, optimistic and pessimistic scenario. Climate change is attributable for up to around a 7% decline in kilocalorie availability and the effect of climate change and socioeconomic changes is a decline in overall kilocalorie availability during 2010-2050 under the baseline and pessimistic scenarios. Figure 4 shows, however, that kilocalorie availability remains at a moderate level relative to other countries across the globe, which suggests that Japan may not face major food security issues in 2050.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>2010</th>
<th>2050</th>
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<tbody>
<tr>
<td>Baseline CSI A1B</td>
<td>2746</td>
<td>2679</td>
</tr>
<tr>
<td>Baseline CSI B1</td>
<td>2749</td>
<td>2699</td>
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<tr>
<td>Baseline MIR A1B</td>
<td>2732</td>
<td>2626</td>
</tr>
<tr>
<td>Baseline MIR B1</td>
<td>2739</td>
<td>2658</td>
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<tr>
<td>Baseline Perfect Mitigation</td>
<td>2772</td>
<td>2808</td>
</tr>
<tr>
<td>Pessimistic CSI A1B</td>
<td>2760</td>
<td>2494</td>
</tr>
<tr>
<td>Pessimistic CSI B1</td>
<td>2763</td>
<td>2511</td>
</tr>
<tr>
<td>Pessimistic MIR A1B</td>
<td>2747</td>
<td>2447</td>
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<tr>
<td>Pessimistic MIR B1</td>
<td>2752</td>
<td>2470</td>
</tr>
<tr>
<td>Pessimistic Perfect Mitigation</td>
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</tr>
<tr>
<td>Optimistic CSI A1B</td>
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<td>Optimistic MIR B1</td>
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<td>2818</td>
</tr>
<tr>
<td>Optimistic Perfect Mitigation</td>
<td>2773</td>
<td>2993</td>
</tr>
</tbody>
</table>

Table 8. Average daily kilocalorie availability simulated under different climate and socioeconomic scenarios, for Japan (IFPRI, 2010).

Figure 3. The impact of climate change on average daily kilocalorie availability (IFPRI, 2010).
**Figure 4.** Average daily kilocalorie availability simulated by the CSIRO GCM (CSI) under an A1B emissions scenario and the baseline socioeconomic scenario, for 2010 (top panel), 2030 (middle panel) and 2050 (bottom panel). Figure is from IFPRI (2010). The changes show the combination of both climate change and socio-economic changes.
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 (Allison et al. 2009, Cheung et al., 2010). 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 Japan presented a low vulnerability to climate change impacts on fisheries. In contrast, countries in Central and Western Africa (e.g. Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in north-western South America, and five tropical Asian countries (Bangladesh, Cambodia, Vietnam, Pakistan, and Yemen) were identified as most vulnerable (see Figure 5). 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.
Cheung et al. (2010) also consider marine capture fisheries at the global scale for several countries. The study projected changes in global catch potential for 1066 species of exploited marine fish and invertebrates from 2005 to 2055 under climate change scenarios. Cheung et al. (2010) found that climate change may lead to large-scale redistribution of global catch potential, with an average of 30–70% increase in high-latitude regions and a decline of up to 40% in the tropics. The simulations were based on climate simulations from a single GCM (GFDL CM2.1) under a SRES A1B emissions scenario (CO$_2$ concentration at 720ppm in 2100) and a stable-2000 level scenario (CO$_2$ concentration maintains at year 2000 level of 365 ppm). For Japan, the projected change in the 10-year averaged maximum catch potential from 2005 to 2055 was around a 3% decrease under A1B and a 1% increase under the stabilisation scenario, based upon 144 exploited species included in the analysis. Figure 6 demonstrates how this compares with projected changes for other countries across the globe. However, the limitations of applying a single GCM have been noted previously.
Figure 6. Projected changes in the 10-year averaged maximum catch potential from 2005 to 2055. The numbers in parentheses represent the numbers of exploited species included in the analysis. Adapted from Cheung et al. (2010).

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

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.

There are few assessments of the impact of climate change on drought and water stress in Japan. Nevertheless, results from a small number of global-scale assessments suggest that Japan as a whole may not experience an increase in water stress under climate change scenarios. Recent simulations by the AVOID programme support this. There is, however, evidence to suggest that the area around Tokyo may be vulnerable to human water security threat and water stress in future under climate change.

Supporting literature

Introduction

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 for Japan. 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 Japan 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 km². 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 Japan. 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 Japan. Japan is a densely populated country with advanced infrastructure. This in some ways has increased water security in most areas, but in others, a moderate level of stress is observed with the area around Tokyo being the most at threat. The large forests and well established environmental policy of the country
have also helped to maintain high levels of water security in most areas, and low water stress.

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

Smakhtin et al. (2004) present 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. For Japan, the results show that for the
basins considered around Tokyo, environmental water stress is high, although basins for the remainder of the country were not included in the analysis.

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 1,300 m$^3$/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 Japan, Rockstrom et al. (2009) found that blue-green water availability was well above the 1,300 m$^3$/capita/year threshold at present and under climate change.
Figure 9. Simulated blue-green water availability (m³/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 1,300m³/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The figure is from Rockstrom et al. (2009).

National-scale or sub-national scale assessments

Climate change studies

A regional climate model study for one hundred years ahead finds that there will be an increasing occurrence of water shortages in the southern Kyushu region of Japan (Project Team for Comprehensive Projection of Climate Change Impacts, 2008). The study was conducted with the Japanese Meteorological Research Institute’s RCM20 (20km horizontal resolution) model driven by the couple atmosphere-ocean model, CGCM2 (280km resolution) for the SRES A2 scenario. Several different social conditions were tested. Uncertainties in this conclusion are high as it is for only one model and one scenario. There is an overall lack of studies uncovered on assessing water stress post AR4, however it must be considered.
that there may exist significant literature in the Japanese language that has not been considered.

**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° 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 Japan are presented in Figure 10. They show that with exception to a simulation with one climate model, no more than around 7% of Japan’s population presents an increase in exposure to water stress with climate change by 2080 under A1B. Prior to 2080, no change in increased water stress is simulated. In 2080 and 2100, an aggressive climate change mitigation scenario has the effect of avoiding all effects of climate change on increased water stress in Japan. The simulations are in broad agreement with results presented by Rockstrom et al. (2009).
Figure 10. Box and whisker plots for the impact of climate change on increased water stress (top panel) and decreased water stress (bottom panel) in Japan, 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

The IPCC AR4 reported projections of precipitation increases over Japan, along with increases in intense precipitation under climate change scenarios. More recent research has highlighted uncertainties in rainfall projections partly as a result of inter-annual decadal variability of the East Asian monsoon, and also projections of changes in tropical cyclones.

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

Recent past

The IPCC AR4 (2007a) noted an observed increase in frequency of extreme precipitation in 20th century attributed to frontal systems and typhoons and a serious flood in 2004 due to heavy rains brought by 10 typhoons. More recently, Choi et al. (2009) found that observed trends in total precipitation for Japan for the period of 1955-2007 show an annual decrease of -17.5mm/decade, with -3.2mm/decade in winter, and -6.8 in summer. These trends are not statistically significant at the 95% level.
Climate change studies

The IPCC AR4 (2007b) showed that with the CMIP3 multi-model dataset, under the SRES A1B emissions scenario, projected precipitation increases in all seasons for East Asia. The median change is +9% in the annual mean, with little seasonal difference. Whilst qualitative projections are consistent, there remain large quantitative differences between models (IPCC, 2007b). The IPCC AR4 (2007b) stated that intense precipitation events in East Asia are very likely to increase, which is consistent with historic trends. Li et al. (2010a) investigated changes in the East Asian monsoon system under an A1B emissions scenario with 14 GCMs. They demonstrated that regional-mean East Asian Summer Monsoon (EASM) rainfall is dominated by large inter-annual to decadal fluctuations. Li et al. (2010a) showed that the EASM strength does not respond with any pronounced trend to the A1B scenario during the 21st century. The suggested that the response of the EASM to a warming climate may be through the form of a change in position rather than a change in intensity, which could lead to the spatial coexistence of floods and droughts in East Asia as observed over recent decades. A global-scale assessment presented by Sillmann and Roeckner (2008) found increases in extreme precipitation indices of maximum 5-day rainfall (RX5day), and very wet days (R95p) over Japan during the 21st Century in GCM simulations. They found that increases were larger under the A1B emissions scenario compared with the B1 scenario.

National-scale or sub-national scale assessments

Climate change studies

Mizuta et al. (2005) found significantly more days with heavy precipitation and stronger average precipitation intensity in western Japan and Hokkaido Island with climate change. Similarly, Kimoto et al. (2005) suggest an increase in the frequency of non-precipitation and heavy precipitation days (>=30mm/day), with a reduction in relatively weak rainfall days (1-20 mm/day) in Japan, with climate change. Hasegawa and Emori (2005) show that daily precipitation associated with tropical cyclones over the western North Pacific could increase with climate change. This supports simulations presented by Hasumi and Emori (2004), which showed that extreme daily precipitation, including that associated with typhoons, could be enhanced over Japan with climate change (see Figure 11). Moreover, a recent report for the Ministry of Environment of Japan (2008) found that increases in heavy rainfall could increase with climate change but may vary with the region and may tend to increase more in mountainous regions. They note, however, that the degree of uncertainty associated with these results is high.
Figure 11. Number of days of heavy rainfall (>100 mm/day) over Japan simulated with a high resolution GCM described in Hasumi and Emori (2004).
Fluvial Flooding

Headline

Most national- and sub-national scale assessments suggest that the magnitude of floods and the costs associated with them could increase with climate change in Japan. This is further confirmed by simulations by the AVOID programme, based on 21 GCMs. Most models show a tendency for increasing flood risk, particularly later in the century and under the A1B scenario, with some models showing very large increases. Also, at least one study has suggested that in Hokkaido the peak flow occurrence could shift from April (i.e. the snowmelt season) to July or August.

Supporting literature

Introduction

This section summarises findings from a number of post IPCC AR4 assessments on river flooding in Japan 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° 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.

Japan is particularly vulnerable to flooding because of its steep geography and humid climate characterized by typhoons. Moreover, the number of floods, and hence the damage due to flooding, has increased in recent years (Kazama et al., 2009). Flood damage in the Tokyo Metropolitan area over the period 1995 to 2004 amounted to 108.2 billion Yen (Oshikawa et al., 2009).

Assessments that include a global or regional perspective

Climate change studies

Numerous national-scale and sub-national-scale studies have assessed the impact of climate change on fluvial flooding in Japan. One global modelling study based on simulations from a single GCM under the A1B emissions scenario (Hirabayashi et al., 2008) found mostly little change in flood hazard across Japan in the coming decades (2001-2030). 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. By the end of the century (2071-2100) however, the return period of what was a 100-year flood event in the 20th century was generally projected to decrease significantly to 40 years or less, suggesting an increase in the frequency of extreme floods.

Generally, this supports the results from several small-scale studies (Dairaku et al., 2008, Ma et al., 2010, Ministry of Land Infrastructure Transport and Tourism, 2008, Project Team for Comprehensive Projection of Climate Change Impacts, 2008, Project Team for Comprehensive Projection of Climate Change Impacts, 2009, Sayama et al., 2008). For Hokkaido, which historically is not affected by the summer wet season, the simulations presented by Hirabayashi et al. (2008) suggest a shift in the peak flow occurrence from April (i.e. the snowmelt season) to July or August, implying a wholly different flood regime with climate change.
National-scale or sub-national scale assessments

Climate change studies

Estimates of changes in flooded area from climate and the expected annual damage from river flooding have been made in two recent national assessment reports. Both foresee an increase in flood damages due to a projected increase in the intensity of heavy rainfall events. The first study (Project Team for Comprehensive Projection of Climate Change Impacts, 2008) anticipated an increase in heavy rainfall especially along the Pacific coast and in mountainous regions. The study estimated the expected annual damage from flooding if the probability of an extreme rainfall event with a 100-year return period increases to a 50-year return period, which under the A1B scenario may be the case around 2030. It was found that the expected annual damage may increase to approximately 1 trillion Yen, and expensive flood protection measures may be necessary in the three largest urban areas that have extensive lowlands and flatlands and high levels of economic activity (Kazama et al., 2009).

The second study (Project Team for Comprehensive Projection of Climate Change Impacts, 2009) applied projections from an integrated assessment model for three different scenarios. Due to a rise in rainfall intensity with climate change it was found that an increase in flooded area may be expected, which was larger for the scenarios with higher atmospheric concentrations of greenhouse gases. However, even in the lowest stabilisation scenario (450ppm CO₂ equivalent concentration), the expected annual damage from flooding was expected to increase significantly. Up to around 2050 there were in fact no significant differences between the three concentration scenarios, thereafter the maximum flooded area was expected to reach up to 1,200km² on average per year under the “business as usual” (BaU) scenario. By 2090, the flood damage cost potential was projected to reach approximately 6.4 trillion Yen per year under the 450ppm scenario, up to 8.7 trillion Yen per year under the BaU scenario. Major damage was expected in each region, with increases in the flooded area expected in the Kanto/Koshinetsu/Hokuriku region in particular.

However, in both studies changes in flood hazard were estimated based on changes in extreme (annual maximum) precipitation characteristics as simulated by (a limited set of) climate models, and not on dynamical rainfall-runoff modelling. In other words, changes in rainfall variability, snowmelt and antecedent moisture conditions were not taken into account so these inferences about changes to flood risk should be treated with appropriate caution. In a separate study, the Ministry of Land, Infrastructure, Transport and Tourism (2008) found that in 47 river basins across Japan the return period of what is a 100-year flood under
current climate conditions may reduce to 25 to 90 years in the future. Also in this study the projected changes in flood risk were based only on changes in extreme precipitation.

Sub-national-scale studies for Japan have mostly confirmed this general projection of increasing flood hazard. For the Yodo Basin, the principle river in the Osaka Prefecture on Honshu, Sayama et al. (2008) projected an increase in the intensity of rare but extreme floods by the end of the century. The frequency of medium magnitude floods was found to increase by the 2040s. In the Tama Basin near Tokyo, Dairaku et al. (2008) found that for precipitation events with a return period of 200 years, high water discharge may rise by 10-26% and flood volume may increase by 46-131% under the A1B emissions scenario. Ma et al. (2010) simulated snowmelt and river discharge in the Agano River basin, the second largest river in Japan in terms of annual runoff. Under the A2 emissions scenario they found a strong increase in winter discharge of 43% in January and 55% in February, and a shift in the annual flood peak from April under current conditions to March in the 2070s.

**AVOID Programme results**

To quantify the impact of climate change on fluvial flooding and the inherent uncertainties, the AVOID programme calculated an indicator of flood risk 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 fluvial flooding is shown here using an indicator representing the percentage change in average annual flood risk within a country, calculated by assuming a standardised relationship between flood magnitude and loss. The indicator is based on the estimated present-day (1961-1990) and future flood frequency curve, derived from the time series of runoff simulated at a spatial resolution of 0.5°x0.5° using a global hydrological model, MacPDM (Gosling and Arnell, 2011). The flood frequency curve was combined with a generic flood magnitude–damage curve to estimate the average annual flood damage in each grid cell. This was then multiplied by grid cell population and summed across a region, producing in effect a population-weighted average annual damage. Flood damage is thus assumed to be proportional to population in each grid cell, not the value of exposed assets, and the proportion of people exposed to flood is assumed to be constant across each grid cell (Warren et al., 2010).
The national values are calculated across major floodplains, based on the UN PREVIEW Global Risk Data Platform (preview.grid.unep.ch). This database contains gridded estimates, at a spatial resolution of 30 arc-seconds (0.00833° x 0.00833°), of the estimated frequency of flooding. From this database the proportion of each 0.5°x0.5° grid cell defined as floodplain was determined, along with the numbers of people living in each 0.5°x0.5° grid cell in flood-prone areas. The floodplain data set does not include “small” floodplains, so underestimates actual exposure to flooding. 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. The result represents the change in flood risk due to climate change, not the change in flood risk relative to present day (Warren et al., 2010).

Results

The results for Japan are presented in Figure 12. By the 2030s, the models project a range of changes in mean fluvial flooding risk over Japan in both scenarios, with some models projecting decreases and others increases. However, the balance is much more towards higher flood risk, with three quarters of the models projecting an increase. The largest decrease projected for the 2030s is −30%, while the largest increase is +150%. The mean across all projections is an increase in annual average flood risk of approximately 10%.

By 2100 the balance shifts even more towards increased flood risk in both scenarios, and the difference in projections from the different models also becomes greater. Both these aspects of the results are more pronounced for the A1B scenario than the mitigation scenario. Under the mitigation scenario, about a quarter of the models still project a lower flood risk (down to −40%), but three quarters project an increase. The mean of all projections is still a 10% increase, but the upper projection is now an increase of approximately 250%. Under the A1B scenario, most models project an increased flood risk, but still a small number of models project a decrease (down to −50%). The largest projected increase is approximately +750%, with the mean of all projections being an increase in average annual flood risk of approximately 100%.

So for Japan, the models show a much greater tendency for increasing flood risk, particularly later in the century and particularly in the A1B scenario, with some models showing very
large increases. Differences between the model projections are also greater later in the century and particularly for A1B.

**Figure 12.** Box and whisker plots for the percentage change in average annual flood risk within Japan, 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).
Tropical cyclones

Headline

As reported in the IPCC AR4, there remains considerable uncertainty in projections of tropical-cyclone frequency changes in the Western Pacific under climate change scenarios. However, a number of studies reviewed here suggest that the intensity of tropical cyclones in this basin might increase. Studies imply that it is possible that these increases in intensity could be greatest for the most severe cyclones, which could lead to large increases in cyclone damages in Japan.

Introduction

Tropical cyclones are different in nature from those that exist in mid-latitudes in the way that they form and develop. There remains an overall large uncertainty in the current understanding of how tropical cyclones might be affected by climate change because conclusions are based upon a limited number of studies. Moreover, the majority of tropical-cyclone projections are from either coarse-resolution global models or from statistical or dynamical downscaling techniques. The former are unable to represent the most-intense storms, whereas the very patterns used for the downscaling may change in itself under climate change. To this end, caution should be applied in interpreting model-based results, even where the models are in agreement.

Assessments that include a global or regional perspective

Assessment of cyclone frequency

Projections of changes in tropical-cyclone frequency in the West Pacific basin remain highly uncertain, even on the sign of the change. Bengtsson et al. (2007) conducted timeslice experiments (experiments over a short period of time to enable ensemble simulations using reasonable amounts of computational power) with the atmospheric component of the ECHAM5 GCM model at 60km and 40km resolutions respectively. The model was driven by the SSTs and sea ice predicted by the lower-resolution version of the GCM under the A1B emissions scenario, using the 2071-2100 time horizon for the 60km simulation and 2081-2100 for the 40 km simulation. The 2081-2100 period was compared to a present-day simulation using the SSTs and sea ice for the 1980-2000 period. The simulations results are summarised in Figure 13. The two climate-change experiments simulated a decrease in Western Pacific tropical cyclones, with a 20% decrease in the 60km model and a 28%
decrease in the 40km model. The authors attributed the decrease to a more stable atmosphere in the West Pacific as well as reduced upward motion.

Figure 13. Tracks of tropical cyclones simulated by the 60km resolution ECHAM5 GCM for the present-day climate (top panel; 1980-2000), under the A1B emissions scenario for the 2071-2100 time horizon (middle), and the difference between the two (bottom panel). The units are cyclones per year per unit area, where the unit area is approximately $10^6 \text{ km}^2$. The prominent features are the shift in tropical-cyclone tracks away from the western coast of Mexico and the decrease in tracks in the South China Sea and near Japan. The figure is adapted from Bengtsson et al. (2007).

In an even finer-resolution timeslice experiment, Oouchi et al. (2006) applied the JMA climate model at 20km resolution, using mean SSTs and sea ice projections from the MRI GCM for the 2080-2099 time horizon under the A1B emissions scenario. The results from the simulations are presented in Figure 14. The authors found that the number of West Pacific tropical cyclones declined by 38%, relative to a present-day simulation using the mean SSTs and sea ice for 1982-1993. In agreement with Bengtsson et al. (2007), the authors concluded that the decreases were due to increased atmospheric stability in a warmer world. The model simulated a 10% increase in the dry static stability, defined as the difference in potential temperature between the 250hPa level of the atmosphere and the land surface. Similarly, modest decreases in West Pacific cyclone frequency were found by Gualdi et al. (2008), using the 120km resolution SINTEX-G model in a 30-year simulation under a 2xCO$_2$ emissions scenario.
Figure 14. Tracks of tropical cyclones simulated by the 20km resolution JMA climate model when it is driven by (top) present-day SSTs (1982-1993) and (bottom) SSTs from the MRI GCM for 2080-2099 under the A1B emissions scenario. Decreases in the number of tracks in the western Pacific and the South China Sea were observed, suggesting fewer tropical cyclones making landfall in East Asia. The figure is from Oouchi et al. (2006).

Zhao et al. (2009) applied the 50km resolution GFDL GCM with four future SST and sea ice distributions; 1) the ensemble mean from 18 GCMs, 2) the HadCM3 GCM, 3) the GFDL GCM, and 4) the ECHAM5 GCM, respectively. The SST distributions were for the A1B emissions scenario for the 2081-2100 time horizon. In all four experiments, the frequencies of cyclones in the West Pacific basin decreased, but the magnitude varied considerably; the GFDL model simulated a decrease of 5%; HadCM3 simulated a decrease of 12%; the ensemble mean from 18 GCMs simulated a 29% decrease; and ECHAM5 simulated a 52% decrease.

Sugi et al. (2009) applied the JMA climate model, driven at 60km and 20km resolutions respectively, with SSTs and sea ice from three individual GCMs and the CMIP3 multi-model dataset ensemble mean, for a total of eight simulations, all under the A1B emissions scenario. The West Pacific showed considerable variation in projected tropical-cyclone frequencies, with three experiments simulating increases (13-64%) and five simulating decreases (14-36%). It is worth noting that three out of the four finer-resolution, 20km experiments simulated a decrease of at least 26%, including the experiment driven by the
CMIP3 multi-model dataset ensemble mean SST field. The authors attributed the variations between the driving models to the variations in regional SST changes simulated by those models. Those models which simulated an SST warming in the West Pacific that was greater than the global-mean warming tended to produce increases in cyclone frequency, while those models that simulated a relatively cooler West Pacific tended to reduce the number of cyclones relative to the present-day climate.

Emanuel et al. (2008) applied a hybrid statistical-dynamical downscaling method to seven GCMs under the A1B emissions scenario for the 2180-2200 time horizon. The technique “seeds” large numbers of tropical-cyclone vortices into each basin, then uses the models' large-scale climate fields (e.g., SSTs, wind shear, relative humidity) to determine whether the storms grow into cyclones or simply decay. The technique has shown considerable skill at simulating both frequency and intensity of storms over the past several decades. By comparing the A1B scenario simulation for 2180-2200 to downscaled reanalysis data for 1980-2000, the authors concluded that West Pacific tropical-cyclone frequency could increase by 6%. All seven GCMs that Emanuel et al. (2008) applied simulated an increase in tropical cyclone frequency. Importantly, Emanuel et al. (2008) observed a northward shift in the main Pacific tropical cyclogenesis region in their simulations, which would imply a greater frequency of storms making landfall in Japan.

In a study that focussed on the West Pacific basin, Stowasser et al. (2007) conducted a timeslice experiment with the IPRC RCM at 50km resolution, driven by the SSTs and sea ice from the final 10 years of a 6xCO₂ simulation with the NCAR CCSM2 GCM. The frequency of tropical cyclones remained relatively constant overall in the West Pacific. The IPRC model simulated large increases in relative humidity and decreases in vertical wind shear in this region, both of which are conducive to tropical-cyclone genesis and maintenance. The scenario considered in this study (a six-times increase in CO₂ concentrations) is extreme, but the increases in South China storms agree with those from the broader study of Emanuel et al. (2008) based on the A1B emissions scenario.

In contrast, Li et al. (2010b) found a substantial shift in cyclone activity away from the West Pacific and towards the central part of the basin with climate change. The authors conducted 20-year timeslice experiments with the 40km resolution ECHAM5 GCM, driven by SSTs and sea-ice from the lower-resolution version of the GCM. Li et al. (2010b) conducted one experiment used the 1981-2000 time horizon to represent the present-day climate, and another experiment that used the 2081-2100 time horizon under the A1B emissions scenario. The model simulated a 31% decrease in cyclone numbers in the West Pacific and a 65% increase in the Central Pacific, with a considerable decrease in the number of cyclones.
tracking near Japan. Unlike the simulations presented by Zhao et al. (2009), Li et al. (2010b) found that the regional sea surface temperature (SST) warming patterns simulated by the ECHAM5 GCM in the Pacific could not explain the shift of cyclone tracks toward the Central Pacific. Rather, the reduction in cyclone numbers in the West Pacific was due to a weakening of the Pacific trade winds and a more El Nino-like basic state in the ECHAM5 GCM. This resulted in changes in the mean-state vertical wind shear that suppressed nascent tropical cyclones in the West Pacific and enhanced tropical cyclogenesis in the centre of the basin.

There is therefore considerable uncertainty in projections of tropical-cyclone frequency change in the West Pacific under climate change. There are some suggestions that the number of storms in the South China Sea could dramatically increase, but these come from either extreme scenarios (e.g., the 6xCO\textsubscript{2} conditions imposed by Stowasser et al. (2007)) or from simulations of the late 22\textsuperscript{nd} century (Emanuel et al., 2008). Further, these are balanced by several studies showing basin-scale reductions in cyclone activity in the West Pacific (Bengtsson et al., 2007, Oouchi et al., 2006), e.g. see Figure 13 and Figure 14. It is therefore not possible to make a robust assessment of whether Japan could be impacted by more or fewer tropical cyclones with climate change.

**Assessment of cyclone intensity**

It is, however, likely that tropical cyclones in the West Pacific could become more intense as a result of climate change. Under their 6xCO\textsubscript{2} scenario, Stowasser et al. (2007) found a mean increase in the intensity of North Pacific storms, with a doubling in the frequency of storms exceeding 35 m s\textsuperscript{-1}. However, due to the unrealistic high CO\textsubscript{2} scenario this only hints at the sign of the intensity change due to a global warming trend and not the magnitude of the increase. Further evidence for increases in tropical-cyclone intensity comes from the application of theoretical relationships between cyclone intensity and climate variables (e.g., SST, wind shear) to coarse-resolution climate models. For instance, Vecchi and Soden (2007) applied 18 GCMs under the A1B emissions scenario and found that on average, West Pacific cyclone intensities increased by 3.5% by 2100. Knutson and Tuleya (2004) applied several CMIP2 GCMs under a 1% per year CO\textsubscript{2} increase emissions scenario, and found that the intensity of West Pacific cyclones increased by 4-9%, by the end of an 80-year simulation. The authors also applied a very high resolution 9km version of the GFDL hurricane model, driven by the large-scale conditions simulated by the CMIP2 GCMs under the same 1% per year CO\textsubscript{2} increase scenario. Across all of the models, the average wind speed of West Pacific cyclones increased by 5%, while central pressures decreased by 13.6%, by the end of an 80-year simulation. In their global
timeslice experiment with the JMA 20km resolution climate model, Oouchi et al. (2006) found that cyclone intensities increased by 4.2% in the West Pacific for the 2080-2099 time horizon under the A1B emissions scenario, relative to the present-day climate. These intensity changes are expected to be strongest for the most extreme storms, as suggested by Stowasser et al. (2007) for the West Pacific and by many global-scale studies (McDonald et al., 2005, Oouchi et al., 2006).

**Assessment of cyclone damages**

Projections of climate-change-related tropical-cyclone damages in Japan by 2100 are also uncertain, largely due to the lack of robust projections for changes in cyclone frequencies. Mendelsohn et al. (2011) applied the cyclone “seeding” method described by Emanuel et al. (2008) to climate simulations from four GCMs under the A1B emissions scenario. They then constructed a damage model to estimate the damages from each landfalling storm. The method applied by Mendelsohn et al. (2011) separates the additional damages from the impact of climate change on tropical cyclones from the additional damages due to future economic development. This is accomplished by applying the damages from both present-day and future tropical cyclones to the projected economic conditions in 2100 (the “future baseline”). Against a future baseline of $6.74 billion in damages per year in Japan, three of the four GCMs simulated an increase in cyclone damages: the ECHAM GCM ($4.5 billion), the GFDL GCM ($4.9 billion) and the MIROC GCM ($26.0 billion). The fourth GCM (CNRM), simulated a $0.45 billion decrease in damages with climate change. The MIROC GCM simulation presented very large damages and they are out-of-character with the other three simulations. The large increases in damage are likely due to the increased frequencies of the strongest tropical cyclones. Mendelsohn et al. (2011) found that, globally, the most extreme 1% of storms accounted for 64% of the damages in 2100, as opposed to 58% of damages in the present-day climate. To this end, climate change may cause tropical-cyclone damage in Japan to increase even if the frequency of tropical cyclones decreases.

**National-scale or sub-national scale assessments**

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

Headline

Research on the impact of climate change on coastal regions in Japan is severely limited. Future research priorities should address this. Results from one recent global-scale assessment suggest that Japan could experience some of the largest impacts from sea level rise (SLR) across the globe. For example, 3.7 million people are currently exposed to SLR in Japan; with climate change up to 7.8 million people could be exposed in the 2070s. An aggressive climate change mitigation scenario could avoid an exposure of around 515,000 people in the 2070s.

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 21st 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 (IPCCa) 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 East Asia 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 China and Republic of Korea). 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 East Asia region suggest an approximate 15 million additional people could be flooded for a 0.5 m SLR (assuming no additional protection). 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.

Hanson et al. (2010) present the only global-scale analysis of the impact of SLR on coastal regions that includes national-scale estimates for Japan and it suggests that Japan could experience some of the most severe impacts from SLR, relative to other countries across the globe. The study investigated port city population exposure to global SLR, natural and human subsidence/uplift, and more intense storms and higher storm surges, for 136 port cities across the globe. Future city populations were calculated using global population and economic projections, based on the SRES A1 scenario up to 2030. The study accounted for uncertainty on future urbanization rates, but estimates of population exposure were only presented for a rapid urbanisation scenario, which involved the direct extrapolation of population from 2030 to 2080. All scenarios assumed that new inhabitants of cities in the future will have the same relative exposure to flood risk as current inhabitants. The study is similar to a later study presented by Hanson et al. (2011) except here, different climate change scenarios were considered, and published estimates of exposure are available for more countries, including Japan. Future water levels were generated from temperature and thermal expansion data related to greenhouse gas emissions with SRES A1B (un-mitigated climate change) and under a mitigation scenario where emissions peak in 2016 and decrease subsequently at 5% per year to a low emissions floor (2016-5-L). Table 9 shows the aspects of SLR that were considered for various scenarios and Table 10 displays
regional port city population exposure for each scenario in the 2030s, 2050s and 2070s. The results show that Japan was ranked the 4th highest among the countries that Hanson et al. (2010) investigated, for magnitude of SLR impact. The effect of climate change is observed by comparing the projections in Table 10 with the estimates for exposure in the absence of climate change that is presented in Table 11. At present, 3.7 million people are exposed to SLR in Japan’s port cities. By the 2070s in the absence of climate change 5.0 million are exposed. With climate change in the 2070s, under the FAC (Future City All Changes) scenario, up to 7.8 million people are exposed. Hanson et al. (2010) also demonstrated that aggressive mitigation scenario could avoid an exposure of around 515,000 people in Japan, relative to un-mitigated climate change (see Table 11).

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Table 9. Summary of the aspects of SLR considered by Hanson et al. (2010). ‘V’ denotes that the aspect was considered in the scenario and ‘x’ that it was not.
### Rapid urbanisation projection

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Table 10. National estimates of port city population exposure (1,000s) for each water level projection (ranked according to exposure with the FAC (Future City All Changes) scenario) under a rapid urbanisation projection for the 2030s, 2050s and 2070s. Estimates for present day exposure and in the absence of climate change (for 2070 only) for comparison are presented in Table 11. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.
<table>
<thead>
<tr>
<th>Country</th>
<th>Ports</th>
<th>Current</th>
<th>2070. Rapid urbanisation, FAC water level scenario</th>
<th>Exposure avoided</th>
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<tr>
<td></td>
<td></td>
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<td>No climate change</td>
<td>A1B un-mitigated</td>
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<td>18,600</td>
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</table>

Table 11. Exposed port city population (1,000s) in present (current), and in the 2070s in the absence of climate change (no climate change), with unmitigated climate change (A1B un-mitigated), and mitigated climate change (mitigated 2016-5-L), under the rapid urbanisation and FAC (Future City All Changes) water level scenarios. The final column shows the potential avoided exposure, as a result of mitigation. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.
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 12.

<table>
<thead>
<tr>
<th></th>
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<th>RCP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Additional people flooded (1000s)</td>
<td>13.58</td>
<td>894.29</td>
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<tr>
<td>Loss of wetlands area (% of country’s total wetland)</td>
<td>41.50%</td>
<td>53.06%</td>
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</tbody>
</table>

**Table 12.** 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**

Literature searches yielded no results for national-scale or sub-national scale studies here.
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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.

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