Developed at the request of:

Research conducted by:

Climate: Observations, projections and impacts: South Korea

Met Office
Simon N. Gosling, University of Nottingham
Robert Dunn, Met Office
Fiona Carrol, Met Office
Nikos Christidis, Met Office
John Fullwood, Met Office
Diogo de Gusmao, Met Office
Nicola Golding, Met Office
Lizzie Good, Met Office
Trish Hall, Met Office
Lizzie Kendon, Met Office
John Kennedy, Met Office
Kirsty Lewis, Met Office
Rachel McCarthy, Met Office
Carol McSweeney, Met Office
Colin Morice, Met Office
David Parker, Met Office
Matthew Perry, Met Office
Peter Stott, Met Office
Kate Willett, Met Office
Myles Allen, University of Oxford
Nigel Arnell, Walker Institute, University of Reading
Dan Bernie, Met Office
Richard Betts, Met Office
Niel Bowerman, Centre for Ecology and Hydrology
Bastiaan Brak, University of Leeds
John Caesar, Met Office
Andy Challinor, University of Leeds
Rutger Dankers, Met Office
Fiona Hewer, Fiona's Red Kite
Chris Huntingford, Centre for Ecology and Hydrology
Alan Jenkins, Centre for Ecology and Hydrology
Nick Klingaman, Walker Institute, University of Reading
Kirsty Lewis, Met Office
Ben Lloyd-Hughes, Walker Institute, University of Reading
Jason Lowe, Met Office
Rachel McCarthy, Met Office
James Miller, Centre for Ecology and Hydrology
Robert Nicholls, University of Southampton
Maria Noguer, Walker Institute, University of Reading
Friedreike Otto, Centre for Ecology and Hydrology
Paul van der Linden, Met Office
Rachel Warren, University of East Anglia

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.

Developed at the request of:

DEPARTMENT OF ENERGY & CLIMATE CHANGE

Research conducted by:

Met Office Hadley Centre

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Walker INSTITUTE

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF LEEDS

Tyndall°Centre for Climate Change Research

Climate: Observations, projections and impacts

South Korea

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

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

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

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

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

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

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

Julia Slingo, Met Office Chief Scientist

Introduction

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

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

Each report contains:

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

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

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

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

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

Summary

Climate observations

- There has been widespread warming over the Republic of Korea since 1960.
- Between 1960 and 2003, warm days and nights have become more frequent while cool days and nights have become less frequent across the region.
- There has been a general increase in summer temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.
- There is some evidence for a decrease in consecutive dry spell length and an increase in annual precipitation total between 1960 and 2003, but uncertainties in this increase are large.

Climate change projections

- For the A1B emissions scenario projected temperature changes from CMIP3 over the Republic of Korea show increases of up to around 3-3.5°C. There is good agreement between the models in the ensemble.
- The Republic of Korea lies at the south of the widespread region across Eastern Asia where projected precipitation shows increases of 10-20% with good agreement across the CMIP3 ensemble.

Climate change impacts projections

Crop yields

- Global- and regional-scale studies included here generally project increases in the yield of rice, the country's major crop, out to the 2050s, but a potential decline towards the end of the century.

- National-scale assessments agree with the global view of a decline in rice yields towards the end of the century in the Republic of Korea.

- Brassicas and other vegetable crops constitute an important part of the country's agricultural production but crop yield changes are uncertain as these crops are not routinely included in climate change impact assessments.

Food security

- The Republic of Korea is currently a country with extremely low levels of undernourishment.

- The majority of global studies included here suggest that Republic of Korea will not face serious food security issues over the next 40 years. However, further research is needed to address knowledge gaps in projections of food security for the country.

Water stress and drought

- Global-scale studies included here indicate that the Republic of Korea currently suffers from a moderate to high level of water stress, and some project that water stress in the country could increase with climate change. However, uncertainty is high owing to the level of understanding about how the monsoon may be affected by climate change.

Pluvial flooding and rainfall

- The IPCC AR4 noted that mean and extreme precipitation for Korea was projected to increase with climate change, with stronger precipitation increases during the summer season.

- Recent studies support this, with increases in precipitation noted in a majority of the studies considered for both historic observations and future climate projections.

Fluvial flooding

- Climate change impact studies for the Republic of Korea have produced very different projections of future changes in flooding, even when the study area is the same, because of different choices of scenarios, models and simulation period.

- Simulations by the AVOID programme, based on climate scenarios from 21 GCMs, show a much greater tendency for increasing flood risk, particularly later in the century and in the A1B scenario, with some models projecting very large increases. This is consistent with the results of other global and local studies.

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.

- Projected change in the intensity of cyclones in the western Pacific basin are considered more robust than projected change in their frequency. A number of global- and regional-scale 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 the Republic of Korea.

- Estimates of future cyclone damage in the Republic of Korea are highly uncertain due to the small size of the country and the limited resolutions of the climate models used to simulate shifts in tropical-cyclone tracks under climate change.

Coastal regions

- Two recent global assessments of the impact of sea level rise on coastal regions, suggest that climate change could have major implications for the Republic of Korea's coastal populations.

- However, the magnitude of the projected impacts differs between the two assessments because of different methodological approaches.

- One of the studies shows that around 50% of the coastal population (around 863,000 people) could be affected by a 10% intensification of the current 1-in-100-year storm surge combined with a prescribed 1m SLR.

- The other study indicates that by the 2070s the exposed population to SLR could increase from 294,000 people in present to 377,000.

Table of Contents

Chapter 1 – Climate Observations ... 9

Rationale ... 10

Climate overview ... 12
Analysis of long-term features in the mean temperature ... 13

Temperature extremes ... 15
Recent extreme temperature events ... 15
Severe heat wave, July-August 1994 ... 15

Analysis of long-term features in moderate temperature extremes ... 16
Attribution of changes in likelihood of occurrence of seasonal mean temperatures ... 22
Summer 1994 ... 22

Precipitation extremes ... 24
Recent extreme precipitation events ... 25
Drought, March-May 2001 ... 25

Flooding, July 2006 ... 25

Analysis of long-term features in precipitation ... 25

Storms ... 28
Recent storm events ... 29
Typhoon Maemi, September 2003 ... 29

Typhoon Kompasu, September 2010 ... 29

Summary ... 30

The main features seen in observed climate over the Republic of Korea from this analysis are: ... 30

Methodology annex ... 31
Recent, notable extremes ... 31
Observational record ... 32
Analysis of seasonal mean temperature ... 32

Analysis of temperature and precipitation extremes using indices ... 33

Presentation of extremes of temperature and precipitation ... 43

Attribution ... 47

References ... 50

Acknowledgements ... 54

Chapter 2 – Climate Change Projections ... 55

Introduction ... 56

Climate projections ... 58
Summary of temperature change in the Republic of Korea ... 60
Summary of precipitation change in the Republic of Korea ... 60

Chapter 3 – Climate Change Impact Projections ... 61

Introduction ... 62
Aims and approach ... 62
Impact sectors considered and methods ... 62

Supporting literature ... 63
AVOID programme results ... 64
Uncertainty in climate change impact assessment ... 64
Summary of findings for each sector ... 69
Crop yields ... 72
Headline ... 72
Supporting literature ... 72
Introduction ... 72
Assessments that include a global or regional perspective ... 74
National-scale or sub-national scale assessments ... 78
AVOID programme results ... 79
Methodology ... 79
Results ... 80
Food security ... 82
Headline ... 82
Introduction ... 82
Assessments that include a global or regional perspective ... 82
National-scale or sub-national scale assessments ... 88
Water stress and drought ... 89
Headline ... 89
Introduction ... 89
Assessments that include a global or regional perspective ... 90
National-scale or sub-national scale assessments ... 94
AVOID Programme Results ... 94
Methodology ... 94
Results ... 95
Pluvial flooding and rainfall ... 97
Headline ... 97
Introduction ... 97
Assessments that include a global or regional perspective ... 97
National-scale or sub-national scale assessments ... 98
Fluvial flooding ... 100
Headline ... 100
Supporting literature ... 100
Introduction ... 100
Assessments that include a global or regional perspective ... 101
National-scale or sub-national scale assessments ... 102
AVOID Programme results ... 103
Methodology ... 104
Results ... 104
Tropical cyclones ... 106
Headline ... 106
Introduction ... 106
Assessments that include a global or regional perspective ... 106

National-scale or sub-national scale assessments 112

Coastal regions 113

Headline.. 113

Assessments that include a global or regional perspective 113

National-scale or sub-national scale assessments 121

References 122

Chapter 1 – Climate Observations

Rationale

Figure 1. Location of boxes for the regional average time series (red dashed box) in Figures 3 and 5 and the attribution region (grey box) in Figure 4.

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 1994 onwards, reported in 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) which categorises extremes of temperature and precipitation. These are core climate variables which have received significant effort from the climate research community in terms of data acquisition and processing and for which it is possible to produce long high quality records for monitoring. No new analysis is included for storms (see the methodology annex that follows for background). For seasonal temperature extremes, an attribution analysis then puts the seasons with highlighted extreme events into context of the recent climate versus a hypothetical climate in the absence of anthropogenic emissions (Christidis et al, 2011). It is important to note that we carry out our attribution analyses on seasonal mean temperatures over the entire country. Therefore these analyses do not attempt to attribute the changed likelihood of individual extreme events. The relationship between extreme events and the large scale mean temperature is likely to be complex, potentially being influenced by *inter alia* circulation changes, a greater expression of natural internal variability at smaller scales, and local processes and feedbacks. Attribution of individual extreme events is an area of developing science. The work presented here is the foundation of future plans to systematically address the region's present and projected future weather and climate, and the associated impacts.

The methodology annex 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

The Republic of Korea is a peninsula extending southwards from 38°N to 34°N on the eastern seaboard of Asia and connected, via North Korea, to north-eastern China. On account of this proximity to the vast land mass of Asia the climate has quite continental characteristics, despite the country being a peninsula, with a 22-28°C difference between mid-winter and mid-summer mean temperature. The country's climate is governed by the 'Asiatic Monsoon' which, in summer, draws warm moist winds across the peninsula from the Pacific Ocean towards low atmospheric pressure that develops over the hot Asian interior. However, in winter, winds from between north and west blow outwards from the huge high atmospheric pressure system that develops over Siberia.

Despite the winter Siberian air mass having very cold, dry and cloudless characteristics, over the Republic of Korea it regularly interacts with eastward-moving frontal weather systems bringing snowfalls and occasional thaws with rain. Winter precipitation is typically around 20-80 mm per month, much of it falling as snow. Temperatures decrease from south to north so that the average number of days on which snow falls increases from 10 in the far south to 28 in the north. Mean January temperature is around 3°C at Busan in the south, where the average daytime maximum is 7°C falling to -1°C at night, but only around -2°C at Seoul in the north where the average daytime maximum is 2°C falling to -6°C at night. A quick transition from the winter weather type to the summer weather type occurs in April/early May and vice-versa in late October/early November.

Summers are very warm and wet. Under maritime influence, the warmest month is delayed to August, when the mean temperature is around 26°C throughout the country, with daily maxima typically around 29°C, falling only to around 23°C at night. Most of the annual precipitation occurs between June and September when monthly totals range typically between 100 and 350 mm. Annual average precipitation is 1344mm at Seoul and 1492mm at Busan.

Weather hazards in The Republic of Korea include floods, droughts and heat waves. In addition, between June and September, typhoons from the South China Sea can bring very heavy rain and strong winds.

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 the Republic of Korea using the median of pairwise slopes method to fit the trend (Sen, 1968; Lanzante, 1996). The methods are fully described in the methodology annex. In concert with increasing global average temperatures (Sánchez-Lugo et al. 2011), and consistent with previous research (Jung et al. 2002), there is a spatially consistent warming signal for temperature over the Republic of Korea as shown in Figure 2. The signal is more mixed over the surrounding areas during summer (June to August). During winter (December to February) there is higher confidence in the warming signal in that the 5th to 95th percentiles of the slopes are of the same sign. Regionally averaged trends (over grid boxes included in the red dashed box in Figure 1) show warming signals but with higher confidence only for winter. This trend is greater in winter at 0.32 oC per decade (5th to 95th percentile of slopes: 0.12 to 0.53 oC per decade) than in summer at 0.07 oC per decade (5th to 95th percentile of slopes: -0.07 to 0.21 oC per decade).

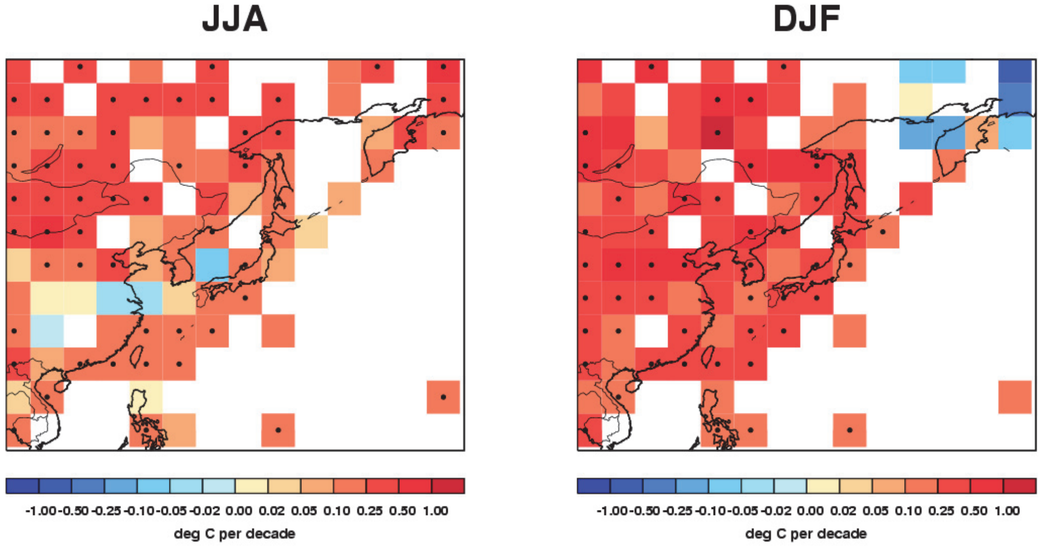


Figure 2. *Decadal trends in seasonally averaged temperatures for the Republic of Korea over the period 1960 to 2010. Monthly mean anomalies from CRUTEM3 (Brohan et al. 2006) are averaged over each 3 month season (June-July-August – JJA and December-January-February – DJF). Trends are fitted using the 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.

Very few extreme temperature events have been reported in recent years in the Republic of Korea. Table 1 shows an extreme temperature event that is reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. This event, a heat wave in July and August 1994, is highlighted below as an example of an extreme temperature event that affected the Republic of Korea.

Year	Month	Event	Details	Source
1994	Summer	Hot/dry	Severely hot and dry summer	BAMS (only evident in seasonal map)

***Table 1**. Selected extreme temperature event reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports since 1994.*

Recent extreme temperature events

Severe heat wave, July-August 1994

The heat wave that occurred during July and August, 1994, was ranked among the worst weather related disasters in East Asia. It was by far the longest and most severe heat wave observed over the Korean Peninsula since 1942, and possibly in the entire 20th century (Choi, 2004). It lasted 29 days in total in Seoul, and the highest daily maximum temperature reached 39.4˚C (daily mean temperature was 33.1 ˚C). The total death toll exceeded 3000, an order of magnitude higher than in any previously recorded heat wave for the region. The event also ranks among the worst heat waves ever documented globally, in terms of human impact, given that it also affected large populations in China and Japan (Kysely & Kim, 2009).

The weather conditions during this event, as well as the severity of impacts on human life were extremely rare, but there is some evidence that the probability of recurrence of an event such as this is sharply rising due to gradual warming of the climate (Kysely & Kim, 2009).

Analysis of long-term features in moderate temperature extremes

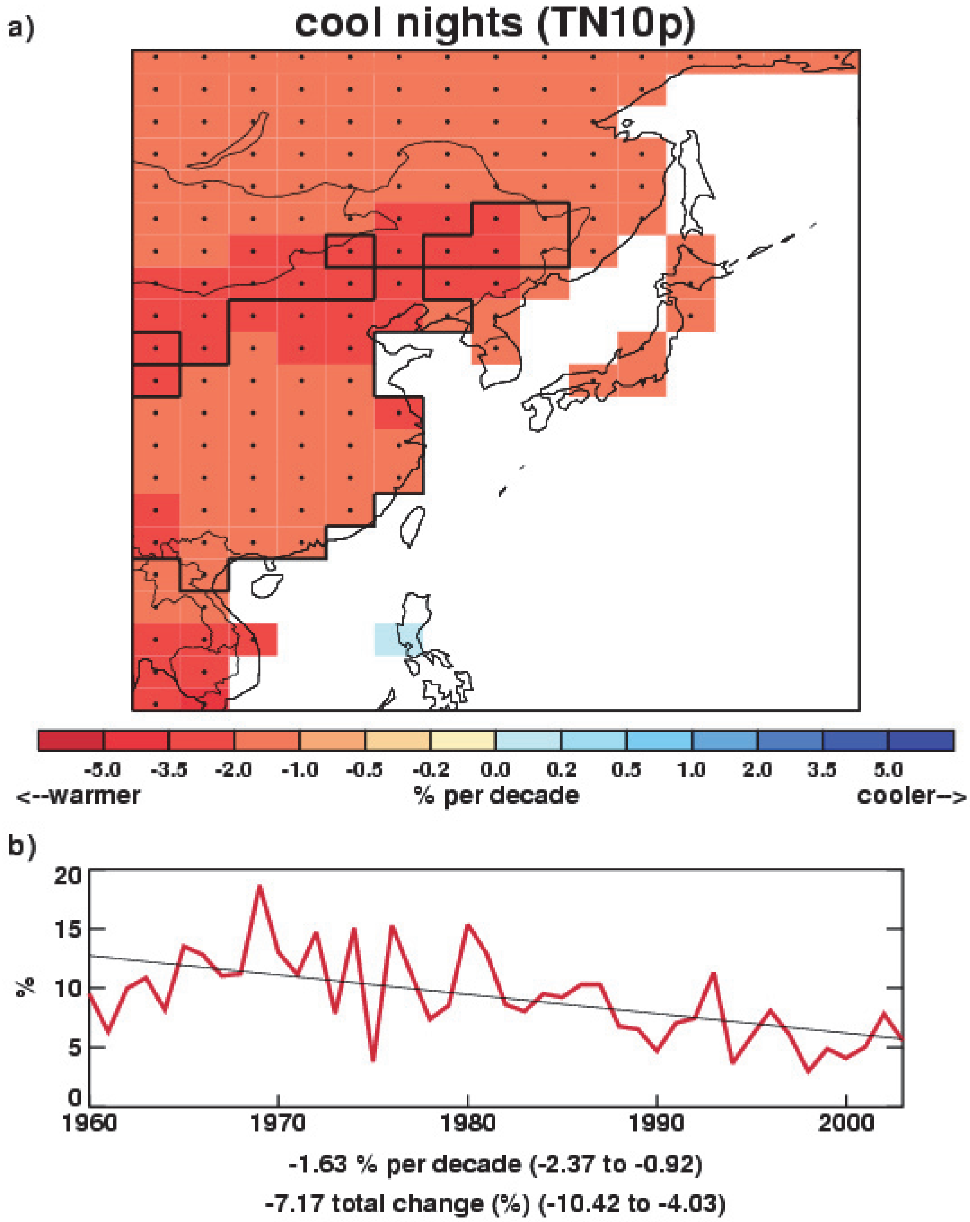
HadEX extremes indices (Alexander et al. 2006) are used here for the Republic of Korea from 1960 to 2003 using daily maximum and minimum temperatures. Here we discuss changes in the frequency of cool days and nights and warm days and nights which are moderate extremes. Cool days/nights are defined as 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.

Between 1960 and 2003, in concert with increasing mean temperature, warm days and nights have become more frequent while cool days and nights have become less frequent across the region with higher confidence. This is consistent with previous research (Jung et al. 2002; Ryoo et al. 2004). The data presented here are annual totals, averaged across all seasons, and so direct interpretation in terms of summer heat waves and winter cool snaps is not possible. Due to the land-sea mask used, the Republic of Korea is represented by a single grid box.

Night time temperatures (daily minima) show a widespread positive shift in the distribution with fewer cool nights and more warm nights. Confidence is high throughout (Figure 3 a,b,c,d). Regional averages show higher confidence signals of fewer cool nights and more warm nights.

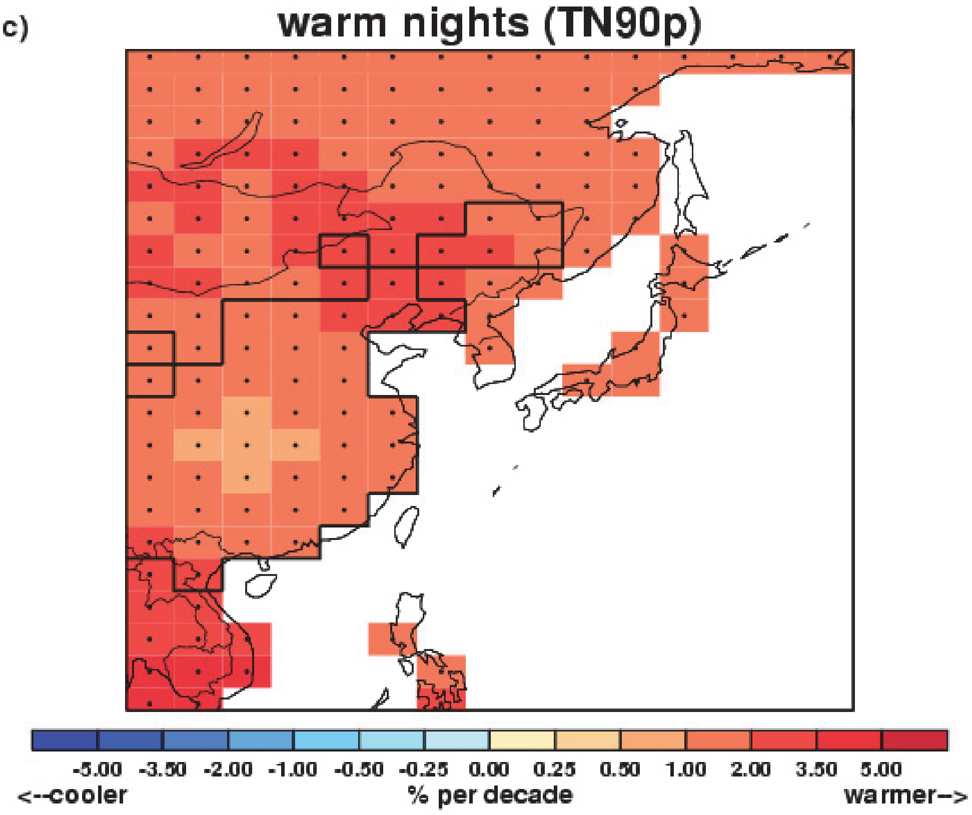
Day time temperatures (daily maxima) show a widespread positive shift in the distribution with fewer cool days and more warm days. Confidence is higher throughout (Figure 3 e,f,g,h). Regional averages show high confidence signals of fewer cool days and more warm days.

The small numbers of stations present in most grid boxes 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.



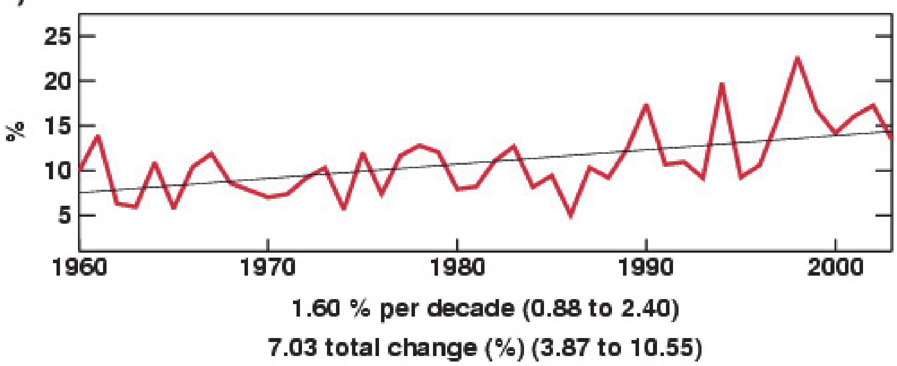
a)
cool nights (TN10p)
-5.0 -3.5 -2.0 -1.0 -0.5 -0.2 0.0 0.2 0.5 1.0 2.0 3.5 5.0
<--warmer
% per decade
cooler-->
b)
20
15
10
5
0
%
1960
1970
1980
1990
2000
-1.63 % per decade (-2.37 to -0.92)
-7.17 total change (%) (-10.42 to -4.03)

c)



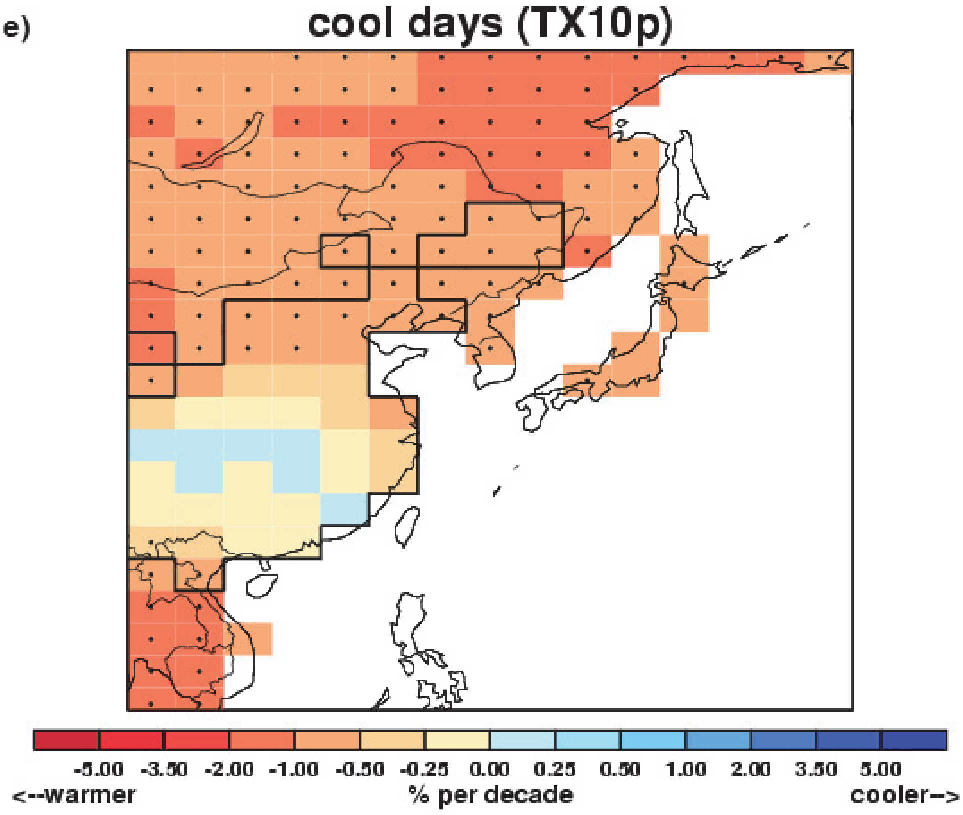
warm nights (TN90p)
-5.00 -3.50 -2.00 -1.00 -0.50 -0.25 0.00 0.25 0.50 1.00 2.00 3.50 5.00
<--cooler
% per decade
warmer-->

d)

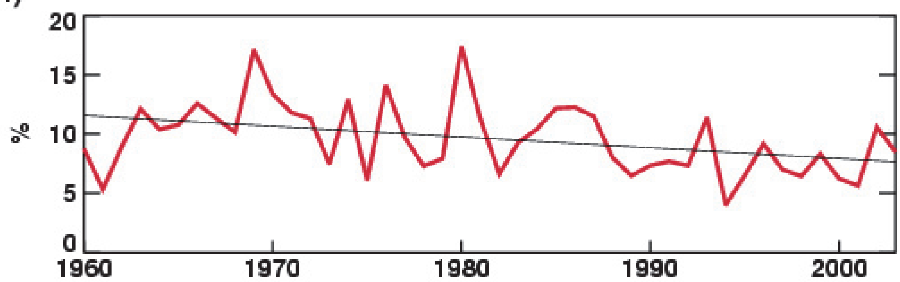


25
20
15
10
5
%
1960
1970
1980
1990
2000
1.60 % per decade (0.88 to 2.40)
7.03 total change (%) (3.87 to 10.55)

e)



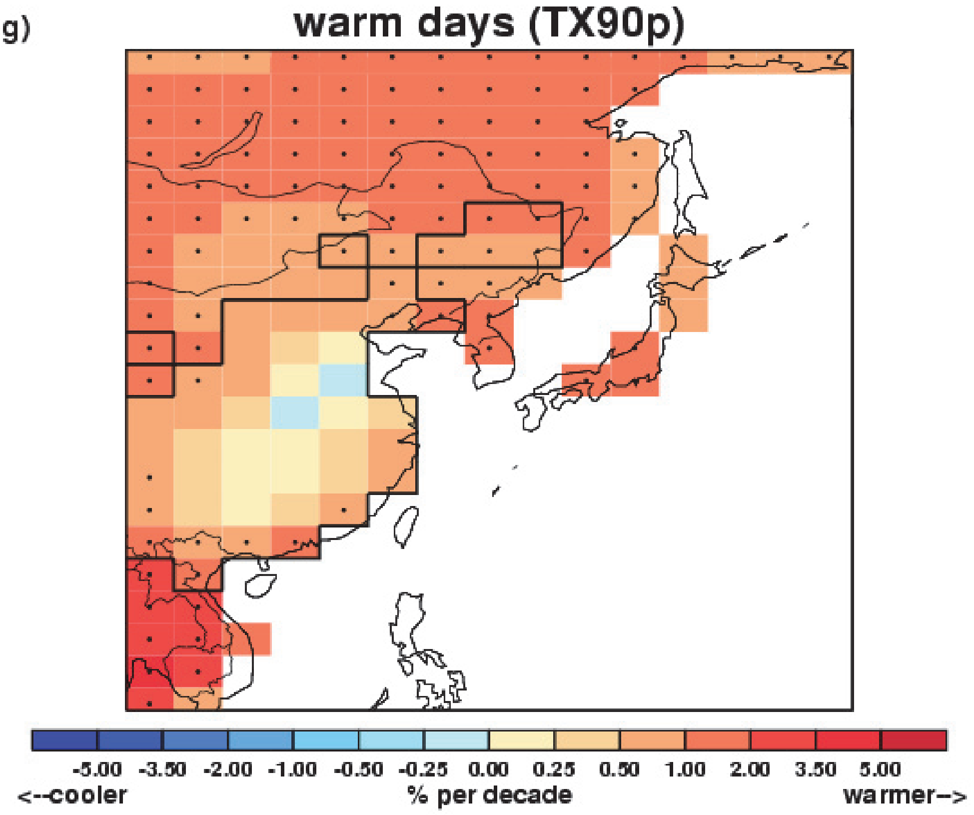
f)



-0.91 % per decade (-1.59 to -0.24)

-4.00 total change (%) (-6.99 to -1.06)

g)



h)

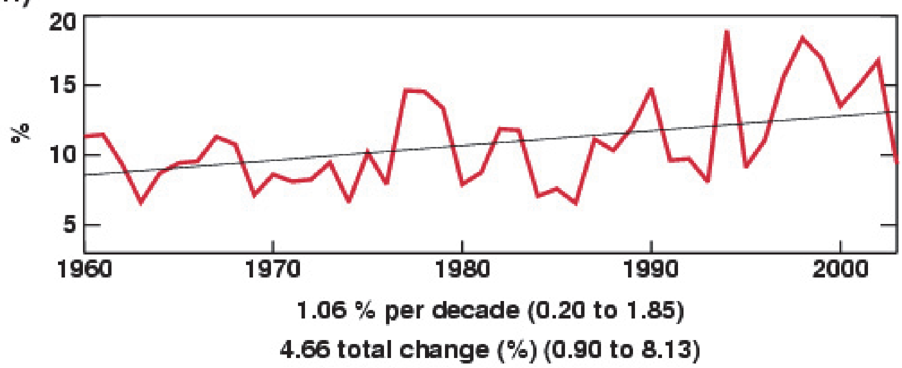


Figure 3. *Percentage change in cool nights (a,b), warm nights (c,d), cool days (e,f) and warm days (g,h) for the Republic of Korea over the period 1960 to 2003 relative to 1961-1990 from HadEX (Alexander et al. 2006). a,c,e,g) Grid box decadal trends. Grid boxes outlined in solid black contain at least 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 125.625 to 129.375^{o} E, 33.75 to 38.75^{o} N as shown in the red box in Figure 1. 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.*

Attribution of changes in likelihood of occurrence of seasonal mean temperatures

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

Summer 1994

The distributions of the summer mean regional temperature in recent years in the presence and absence of anthropogenic forcings are shown in Figure 4. Analyses with two different models suggest that human influences on the climate have shifted the distribution to higher temperatures. Considering the average over the entire region, the summer of 1994 was warm, as it lies at the warm tail of the temperature distributions for the climate influenced by anthropogenic forcings (red distributions) and is also the warmest in the CRUTEM3 dataset. The summer of 1994 was more extreme according to the MIROC model, which shows a smaller shift in the summer temperature (red dotted distribution) than the HadGEM1 model. In the absence of human influences on the climate (green distributions), the season would be even more extreme, as it lies further into the tail of the distributions plotted in green. It should be noted that the attribution results shown here refer to temperature anomalies over the entire region (as shown in Figure 1), whereas the actual extreme event affected a smaller region.

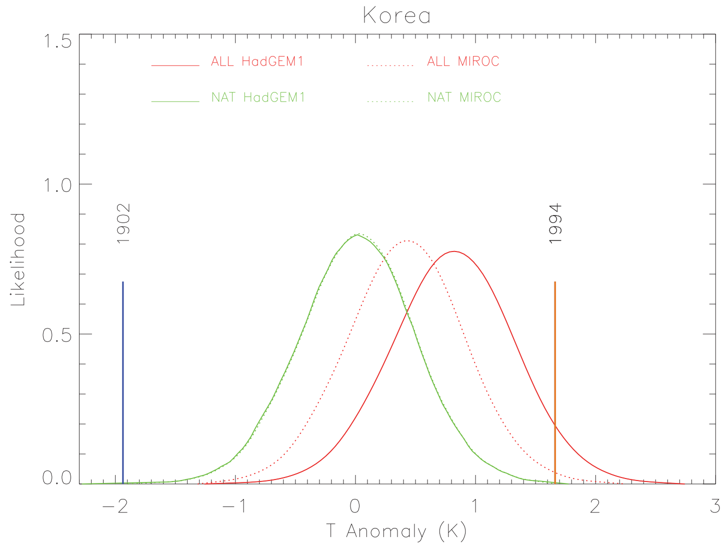


Figure 4. *Distributions of the June-July-August mean temperature anomalies (relative to 1961-1990) averaged over an East Asian region that encompasses the Republic of Korea (122-150E, 30-48N) including (red lines) and excluding (green lines) the influence of anthropogenic forcings. The distributions describe the seasonal mean temperatures expected in recent years (2000-2009) and are based on analyses with the HadGEM1 (solid lines) and MIROC (dotted lines) models. The vertical orange and blue lines correspond to the maximum and minimum anomaly in the CRUTEM3 dataset since 1900 respectively.*

Precipitation extremes

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

Table 2 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. Two events, the March-May drought of 2001 and flooding during July 2006, are highlighted below as examples of recent extreme precipitation events that affected the Republic of Korea.

Year	Month	Event	Details	Source
2000	Aug-Sep	Wet	Typhoon Prapiroon struck the west coast of the Korean Peninsula bringing heavy rainfall and flash floods.	WMO (2001)
2001	Mar-May	Drought	Severe drought	WMO (2002)
2006	Jul	Flooding	Locations record more than 500 mm of rainfall in a few days.	BAMS (Bell & Halpert, 2007))

***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

Drought, March-May 2001

Abnormally strong drought conditions hit the Korean Peninsula in 2001 (Min et al., 2003; Kang and Byun, 2001). The severity of this drought is illustrated by Figure 82 of Waple et al. (2002). During three months of drought, the Republic of Korea received only about 30 percent of the average rainfall it usually receives during the crucial spring planting season and the country's agriculture was particularly affected.

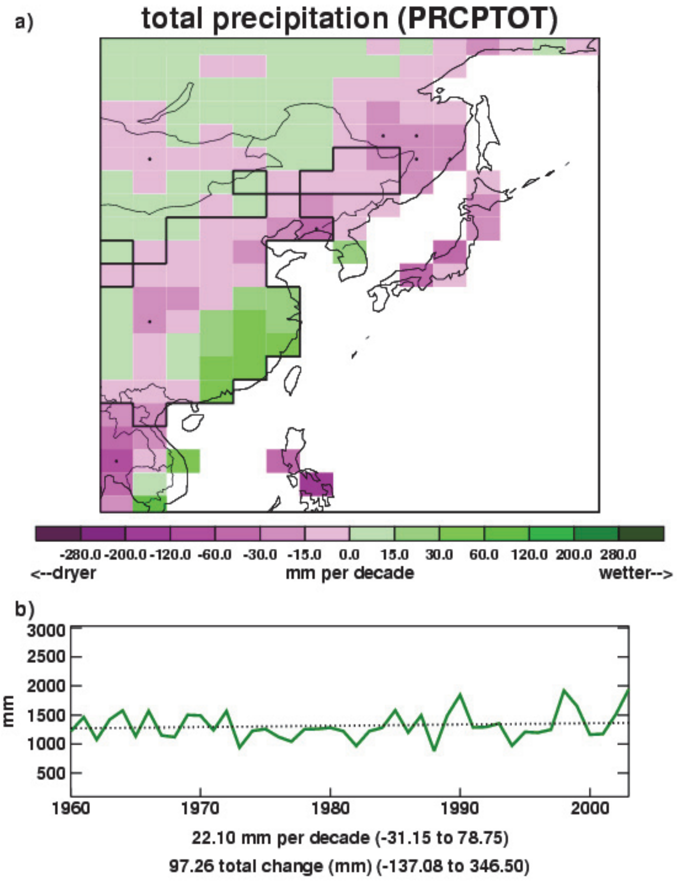
Flooding, July 2006

Heavy rains in July 2006 affected several provinces of the Republic of Korea, especially the mountainous Gangwon Province where some locations recorded more than 500 millimetres of rain in just a few days. However, the heavy rains were not sufficiently widespread and persistent to be evident on the rainfall map for June to August 2006 in Figure 7.5 of Bell and Halpert (2007) which indicates near-normal seasonal totals over the Republic of Korea.

Analysis of long-term features in precipitation

HadEX extremes indices (Alexander et al. 2006) are used here for the Republic of Korea from 1960 to 2003 using daily precipitation totals. Here we discuss changes in the annual total precipitation, and in the frequency of prolonged (greater than 6 days) dry spells. The methods are fully described in the methodology annex.

Between the 1960s and 2003 there are mixed signals for precipitation surrounding the Republic of Korea (Figure 5). There is a decrease in consecutive dry spell length and an increase in annual precipitation total. However, the signal is mixed over the wider region and confidence is low over the Republic of Korea. Previous research shows intensification of August rainfall events since the late 1970s (Ho et al. 2003).


a)
total precipitation (PRCPTOT)
-280.0 -200.0 -120.0 -60.0 -30.0 -15.0 0.0 15.0 30.0 60.0 120.0 200.0 280.0
<--dryer
mm per decade
wetter-->
b)
3000
2500
2000
1500
1000
500
mm
1960
1970
1980
1990
2000
22.10 mm per decade (-31.15 to 78.75)
97.26 total change (mm) (-137.08 to 346.50)

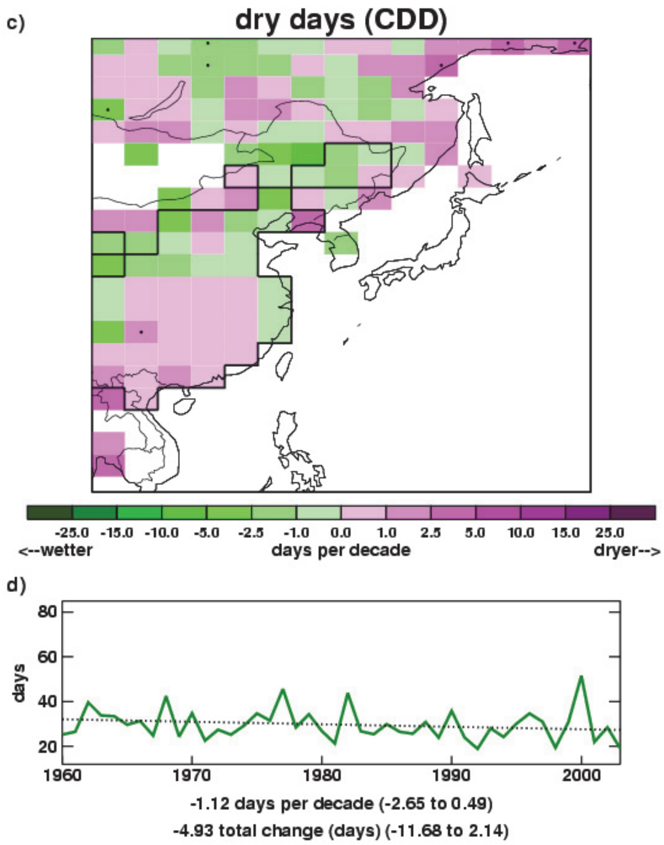


Figure 5. *Change in total annual precipitation (a, b) and continuous dry spell length (c,d) for the Republic of Korea over the period 1960 to 2003 using a base reference period of 1961-1990 from HadEX (Alexander et al. 2006). a,c) Decadal trends as described in Figure 3. b,d) Area average annual time-series for 125.625 to 129.375 ^{o} E, 33.75 to 38.75 ^{o} N as described in Figure 3. All the trends have lower confidence that they are different from zero, as their 5th to 95th percentile slopes are of different signs, and hence are marked with dotted lines.*

Storms

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

Table 3 shows selected extreme events since 2000 that are reported in WMO Statements on Status of the Global Climate and/or BAMS State of the Climate reports. Two events, Typhoon Maemi in September 2003 and Typhoon Kompasu in 2010, are highlighted below as examples of recent storm events that affected the Republic of Korea.

Year	Month	Event	Details	Source
2002	Aug	Storm	Typhoon Rusa – heavy rain, daily precipitation exceeded 870mm at Gangneung.	WMO (2003)
2003	Sep	Storm	Typhoon Maemi - high winds	WMO (2004)
2010	Sep	Storm	Typhoon Kompasu - strongest typhoon to hit Seoul in 15 years	WMO (2011)

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

Recent storm events

Typhoon Maemi, September 2003

Super-typhoon Maemi caused widespread destruction in the Republic of Korea. Maemi formed east of the Philippines and moved northwest-ward while intensifying, reaching its maximum intensity near Okinawa, Japan, and weakened before making landfall in the Republic of Korea. High winds and rainfall associated with Maemi were responsible for more than 100 deaths and destroyed more than 1.4 million houses, damaged roads and bridges, and sank at least 82 vessels (Camargo, 2004).

Typhoon Kompasu, September 2010

Typhoon Kompasu moved over the southern islands of Japan and the west coast of the Korean Peninsula before striking the Seoul Metropolitan Area on 2nd September 2010. Japan Meteorological Agency, http://www.jma.go.jp/en/typh/ provides the track and central atmospheric pressure data: the minimum was 960hPa. In the Republic of Korea, high winds and torrential rains cut power to an estimated 1.56 million residences (National Disaster Center of Korea, 2010) costing the Korea Electric Power Corporation 25.4 billion won (US$21.4 million). Due to the rapid progress made by the storm, much of the damage was due to intense winds of up to 188 km/h (117 mph), the sixth highest wind speed ever recorded in the country.

Summary

The main features seen in observed climate over the Republic of Korea from this analysis are:

- There has been widespread warming over the Republic of Korea since 1960.
- Between 1960 and 2003, warm days and nights have become more frequent while cool days and nights have become less frequent across the region.
- There has been a general increase in summer temperatures averaged over the country as a result of human influence on climate, making the occurrence of warm summer temperatures more frequent and cold summer temperatures less frequent.
- There is some evidence for a decrease in consecutive dry spell length and an increase in annual precipitation total between 1960 and 2003, but data uncertainties in this increase 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).

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

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

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

Use of HadEX for analysis of extremes

The HadEX dataset comprises all 27 ETCCDI indices calculated from station data and then smoothed and gridded onto a 2.5° x 3.75° grid, chosen to match the output from the Hadley Centre suite of climate models. To update the dataset to the present day, indices are calculated from the individual station data using the RClimDex/FClimDex software; developed and maintained on behalf of the ETCCDI by the Climate Research Branch of the

Meteorological Service of Canada. Given the timeframe of this project it was not possible to obtain sufficient station data to create updated HadEX indices to present day for a number of countries: Brazil; Egypt; Indonesia; Japan (precipitation only); South Africa; Saudi Arabia; Peru; Turkey; and Kenya. Indices from the original HadEX data-product are used here to show changes in extremes of temperature and precipitation from 1960 to 2003. In some cases the data end prior to 2003. Table 5 summarises the data used for each country. Below, we give a short summary of the methods used to create the HadEX dataset (for a full description see Alexander et al. 2006).

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

Data sources used for updates to the HadEX analysis of extremes

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

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

GHCND:

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

ECA&D and SACA&D:

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

Mexico:

The station data from Mexico has been kindly supplied by the SMN[3] and Jorge Vazquez. These daily data were then converted to the required indices using the *Fclimdex* software. There are a total of 5298 Mexican stations in the database. In order to select those which have sufficiently long data records and are likely to be the most reliable ones we performed a cross correlation between all stations. We selected those which had at least 20 years of data post 1960 and have a correlation with at least one other station with an *r*-value >0.95. This resulted in 237 stations being selected for further processing and analysis.

Indian Gridded:

The India Meteorological Department provided daily gridded data (precipitation 1951-2007, temperature 1969-2009) on a 1° x 1° grid. These are the only gridded daily data in our analysis. In order to process these in as similar a way as possible the values for each grid

---

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

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

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

were assumed to be analogous to a station located at the centre of the grid. We keep these data separate from the rest of the study, which is particularly important when calculating the decorrelation length scale, which is on the whole larger for these gridded data.

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

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

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

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

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

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

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

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

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

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

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

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

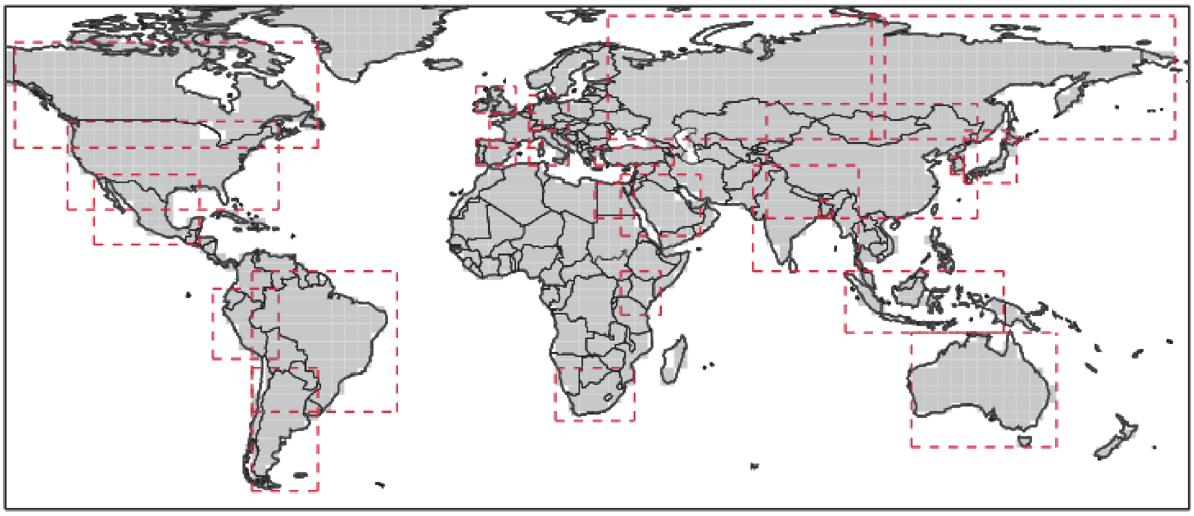


Figure 6. *Land Sea mask used for gridding the station data and regional areas allocated to each country as described in Table 5.*

Presentation of extremes of temperature and precipitation

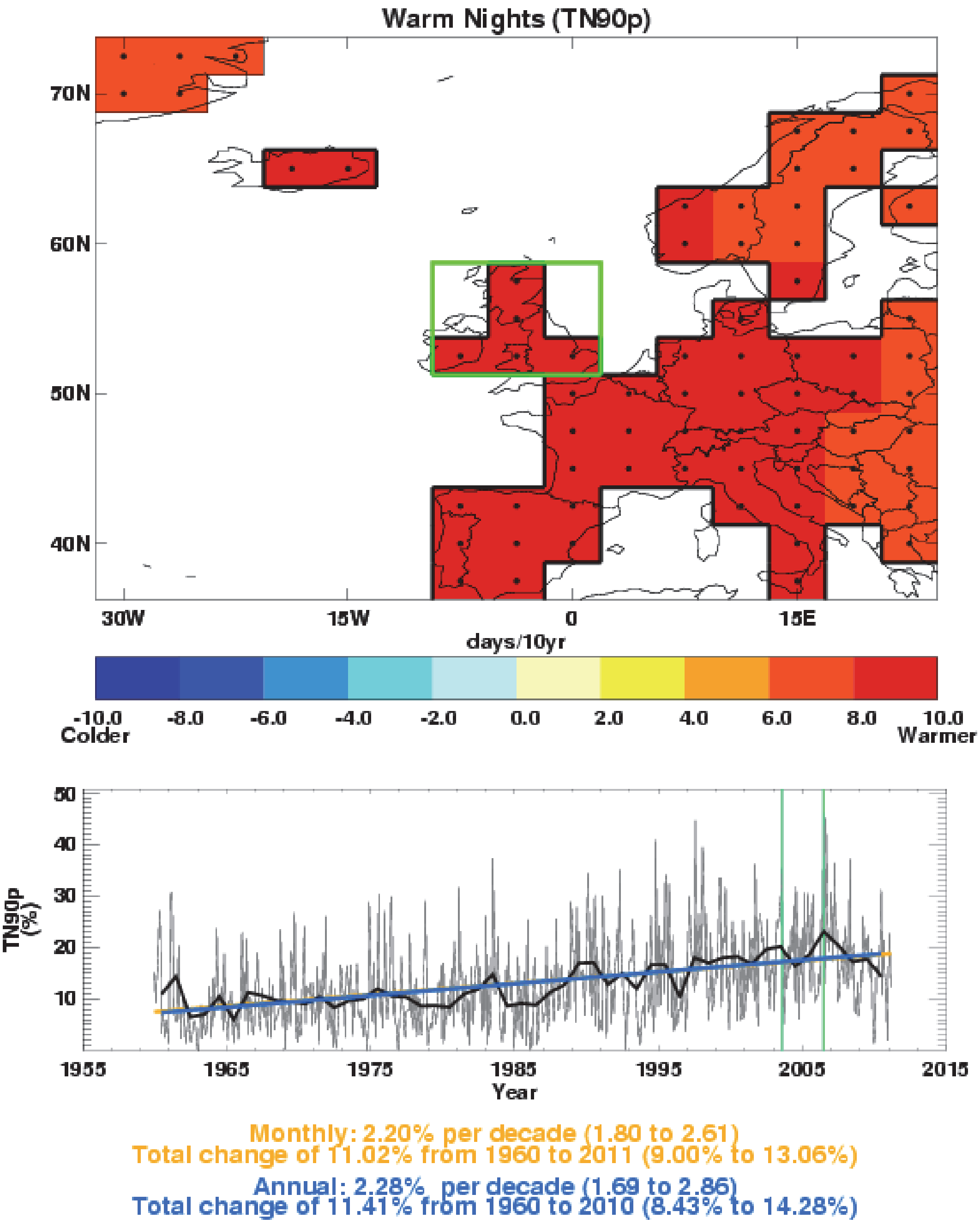
Indices are displayed as regional gridded maps of decadal trends and regional average time-series with decadal trends where appropriate. Trends are fitted using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Trends are considered to be significantly different from a zero trend if the 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 1 and listed in Table 2, which is used for the creation of the regional average. This is sometimes identical to the attribution region shown in grey on the map in Figure 1. This region is again shown on the maps accompanying the time series of the regional averages as a reminder of the region and grid boxes used in the calculation. Regional averages are created by weighting grid box values by the cosine of their grid box centre latitude. To ensure consistency over time a regional average is only calculated when there are a sufficient number of grid boxes present. The full-period median number of grid-boxes present is calculated. For regions with a median of more than six grid-boxes there must be at least 80%

of the median number of grid boxes present for any one year to calculate a regional average. For regions with six or fewer median grid boxes this is relaxed to 50%. These limitations ensure that a single station or grid box which has a longer period of record than its neighbours cannot skew the timeseries trend. So sometimes there may be grid-boxes present but no regional average time series. The trends for the regional averages are calculated in the same way as for the individual grid boxes, using the median of pairwise slopes method (Sen 1968, Lanzante 1996). Confidence in the trend is also determined if the 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.


Warm Nights (TN90p)
70N
60N
50N
40N
30W
15W
0
15E
days/10yr
-10.0
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
Colder
Warmer
TN90p (%)
50
40
30
20
10
1955
1965
1975
1985
1995
2005
2015
Year
Monthly: 2.20% per decade (1.80 to 2.61)
Total change of 11.02% from 1960 to 2011 (9.00% to 13.06%)
Annual: 2.28% per decade (1.69 to 2.86)
Total change of 11.41% from 1960 to 2010 (8.43% to 14.28%)

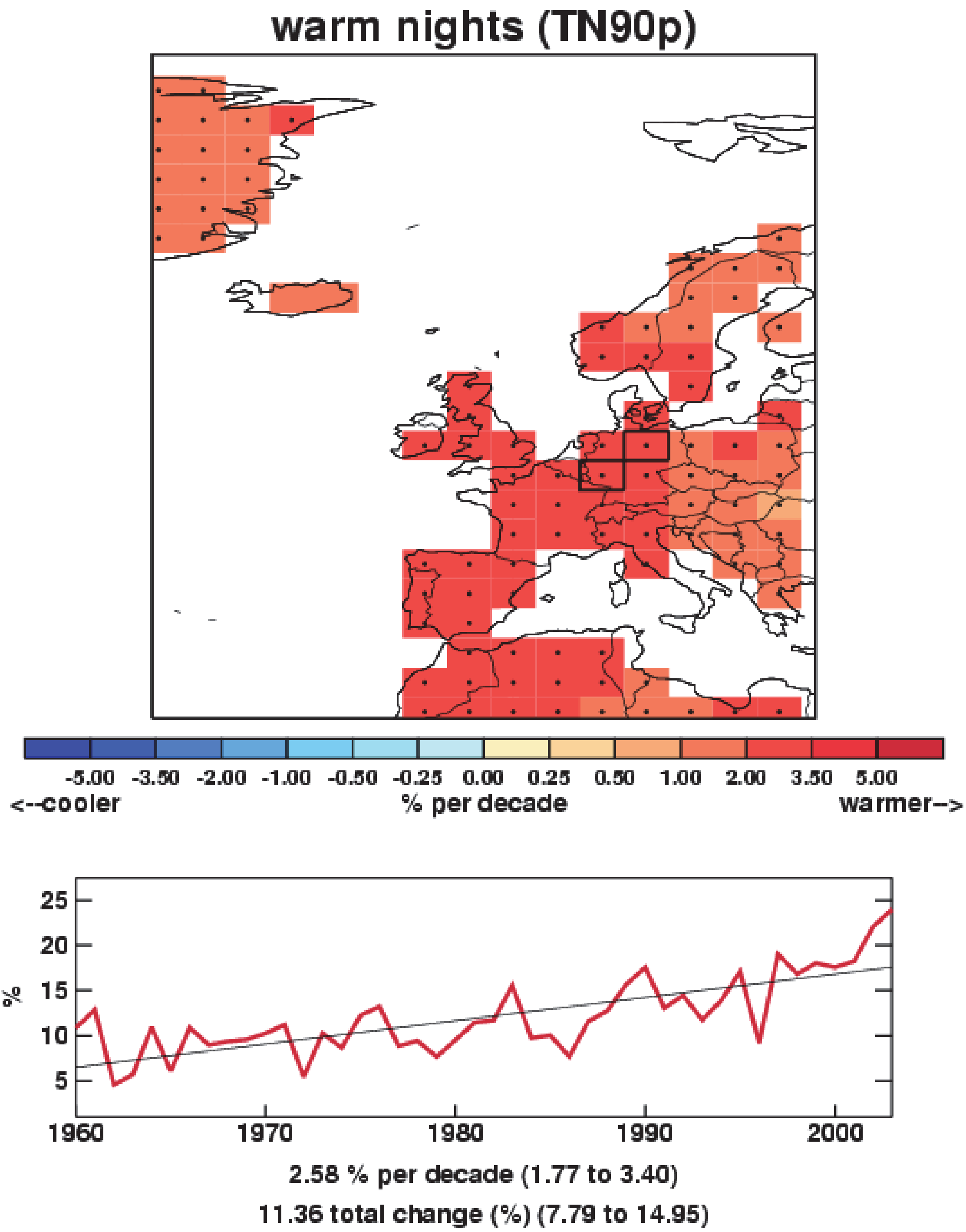


Figure 7. *Examples of the plots shown in the data section. Left: From ECA&D data between 1960-2010 for the number of warm nights, and Right: from HadEX data (1960-2003) for the total precipitation. A full explanation of the plots is given in the text below.*

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

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

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

Attribution

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

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

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

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

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

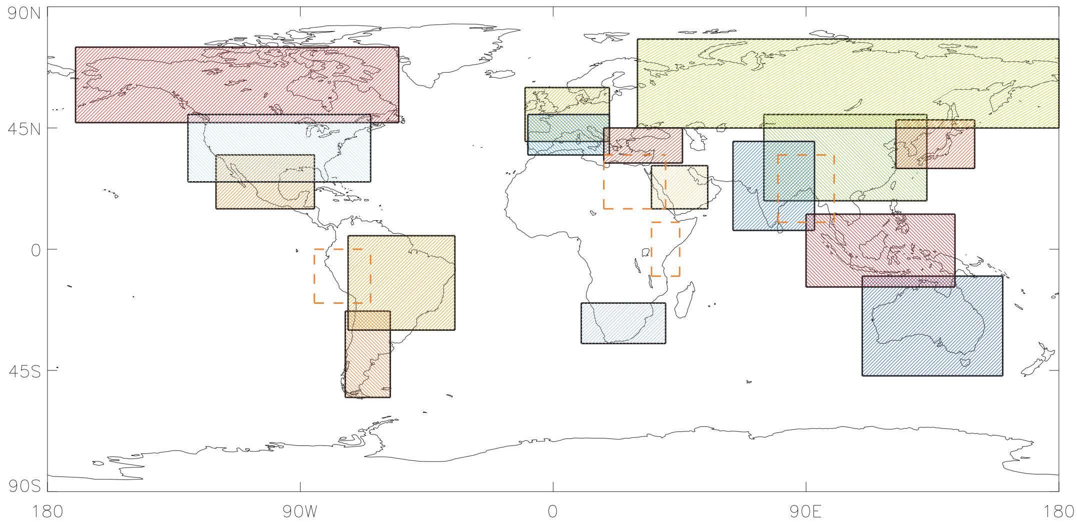


Figure 8. *The regions used in the attribution analysis. Regions marked with dashed orange boundaries correspond to non-G20 countries that were also included in the analysis.*

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

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

References

ALEXANDER, L. V., ZHANG. X., PETERSON, T. C., CAESAR, J., GLEASON, B., KLEIN TANK, A. M. G., HAYLOCK, M., COLLINS, D., TREWIN, B., RAHIMZADEH, F., TAGIPOUR, A., RUPA KUMAR, K., REVADEKAR, J., GRIFFITHS, G., VINCENT, L., STEPHENSON, D. B., BURN, J., AGUILAR, E., BRUNET, M., TAYLOR, M., NEW, M., ZHAI, P., RUSTICUCCI, M. and VAZQUEZ-AGUIRRE, J. L. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res*. 111, D05109. doi:10.1029/2005JD006290.

ALLEN, M. R., TETT S. F. B. 1999. Checking for model consistency in optimal fingerprinting. Clim Dyn 15: 419-434

ALLEN M. R., STOTT P. A. 2003. Estimating signal amplitudes in optimal fingerprinting, part I: theory. Clim Dyn 21: 477-491

BELL, G.D. and HALPERT, M.S. 2007. Seasonal Global Summaries. Supplement to State of the Climate in State of the Climate 2006. *Bulletin of the American Meteorological Society* 88 (6), S118-S121].

BROHAN, P., KENNEDY, J.J., HARRIS, I., TETT, S.F.B. and JONES, P.D. 2006. Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophys. Res* 111, D12106. doi:10.1029/2005JD006548.

CAMARGO, S.J. 2004. Pacific Tropical Storms, Western North Pacific typhoon season in State of the Climate 2003. *Bulletin of the American Meteorological Society* 85 (6), S25-S27].

CHRISTIDIS N., STOTT. P A., ZWIERS, F. W., SHIOGAMA, H., NOZAWA, T. 2010. Probabilistic estimates of recent changes in temperature: a multi-scale attribution analysis. Clim Dyn 34: 1139-1156

CHRISTIDIS, N., STOTT, P. A., ZWIERS, F. W., SHIOGAMA, H., NOZAWA, T. 2011. The contribution of anthropogenic forcings to regional changes in temperature during the last decade. *Climate Dynamics* in press.

CHOI, Y. 2004. Trends on temperature and precipitation extreme events in Korea. *Journal of the Korean Geographical Society* 39:711-721.

COMPO, G. P., J.S. WHITAKER, P.D. SARDESHMUKH, N. MATSUI, R.J. ALLAN, X. YIN, B.E. GLEASON, R.S. VOSE, G. RUTLEDGE, P. BESSEMOULIN, S. BRÖNNIMANN, M. BRUNET, R.I. CROUTHAMEL, A.N. GRANT, P.Y. GROISMAN, P.D. JONES, M.C. KRUK, A.C. KRUGER, G.J. MARSHALL, M. MAUGERI, H.Y. MOK, Ø. NORDLI, T.F. ROSS, R.M. TRIGO, X.L. WANG, S.D. WOODRUFF and S.J. WORLEY. 2011. The Twentieth Century Reanalysis Project, *Q. J. R.Met.S.* 137, 1-28, doi: 10.1002/qj.776

CORNES, R. C., and P. D. JONES. 2011. An examination of storm activity in the northeast Atlantic region over the 1851–2003 period using the EMULATE gridded MSLP data series. *J. Geophys. Res*. 116, D16110, doi:10.1029/2011JD016007.

HO, C.H., LEE, J.Y., AHN, M.H. and LEE, H.S. 2003. A sudden change in summer rainfall characteristic in Korea during the late 1970s. *Int. J. Climatology* 23, 117-128.

JUNG, H.S., CHOI, Y., OH, J.-H. and LIM, G.H. 2002. Recent trends in temperature and precipitation over South Korea. *Int. J. Climatology* 22, 1327-1337.

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

KANG K.A. and BYUN, H.R. 2001. Characteristics of East Asian drought events. *Atmosphere* 11: 286–290 (in Korean).

KYSELY, J. and KIM, J. 2009. Mortality during heat waves in South Korea, 1991 to 2005: How exceptional was the 1994 heat wave? *Climate Research* 38: 105-116.

LANZANTE, J. R. 1996. Resistant, robust and non-parametric techniques for the analysis of climate data: theory and examples, including applications to historical radiosonde station data. *Int. J. Climatology* 16, 1197–226.

MARTIN G.M., RINGER. M. A., POPE V. D., JONES, A., DEARDEN, C., HINTON, T. 2006. The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model (HadGEM1). Part I: Model description and global climatology. J Clim 19: 1274-1301

MIN, S.-K., KWON, W.-T., PARK, E.-H. AND CHOI, Y. 2003. Spatial and temporal comparisons of droughts over Korea with East Asia. *Int. J. Climatology* 23: 223–233. doi: 10.1002/joc.872

National Disaster Center of Korea (Typhoon Kompasu) 2010 [online: Accessed Sept 2011]http://www.safekorea.go.kr/dmtd/contents/room/ldstr/DmgReco.jsp?q_menuid=M_NST_SVC_01_02_03&q_flag=0&q_largClmy=24 (in Korean)

PETERSON, T.C., VAUTARD, R., McVICAR, T.R., THÉPAUT, J-N. and BERRISFORD, P. 2011. Global Climate, Surface Winds over Land in State of the Climate 2010. *Bulletin of the American Meteorological Society* 92 (6), S57.

RYOO, S.B., KWON, W.T. and JHUN, J.G. 2004. Characteristics of wintertime daily and extreme temperature over South Korea. *Int. J. Climatology* 24, 145-160.

SANCHEZ-LUGO, A., KENNEDY, J.J. AND BERRISFORD, P. 2011. Global Climate, Surface Temperatures in “State of the Climate 2010. *Bulletin of the American Meteorological Society* 92 (6), S36-S37].

SEN, P. K. 1968. Estimates of the regression coefficient based on Kendall’s tau. *J. Am. Stat. Assoc*. 63, 1379–89.

WAPLE, A. M., LAWRIMORE, J.H., HALPERT, M.S., BELL, G.D., HIGGINS, W., LYON, B., MENNE, M.J., GLEASON, K.L., SCHNELL, R.C., CHRISTY, J.R., THIAW, W., WRIGHT, W.J., SALINGER, M.J., ALEXANDER, L., STONE, R.S., and CAMARGO, S.J. 2002. Climate Assessment for 2001. *Bulletin of the American Meteorological Society* 83, 6, S1-S62.

WMO WORLD METEOROLOGICAL ORGANIZATION. 2001. Statement on Status of the Global Climate in 2000, WMO-No. 920. http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2002. Statement on Status of the Global Climate in 2001, WMO-No. 940. http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2003. Statement on Status of the Global Climate 2002, WMO-No. 949. http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2004. Statement on Status of the Global Climate in 2003, WMO-No. 966. http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

WMO WORLD METEOROLOGICAL ORGANIZATION. 2011. Statement on Status of the Global Climate in 2010, WMO-No. 1074. http://www.wmo.int/pages/prog/wcp/wcdmp/statement/wmostatement_en.html

Acknowledgements

We thank Lisa Alexander and Markus Donat (University of New South Wales) for their help and advice. We also thank the external reviewers from the Republic of Korea for their input and advice.

Chapter 2 – Climate Change Projections

Introduction

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

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

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

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

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

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

Climate projections

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

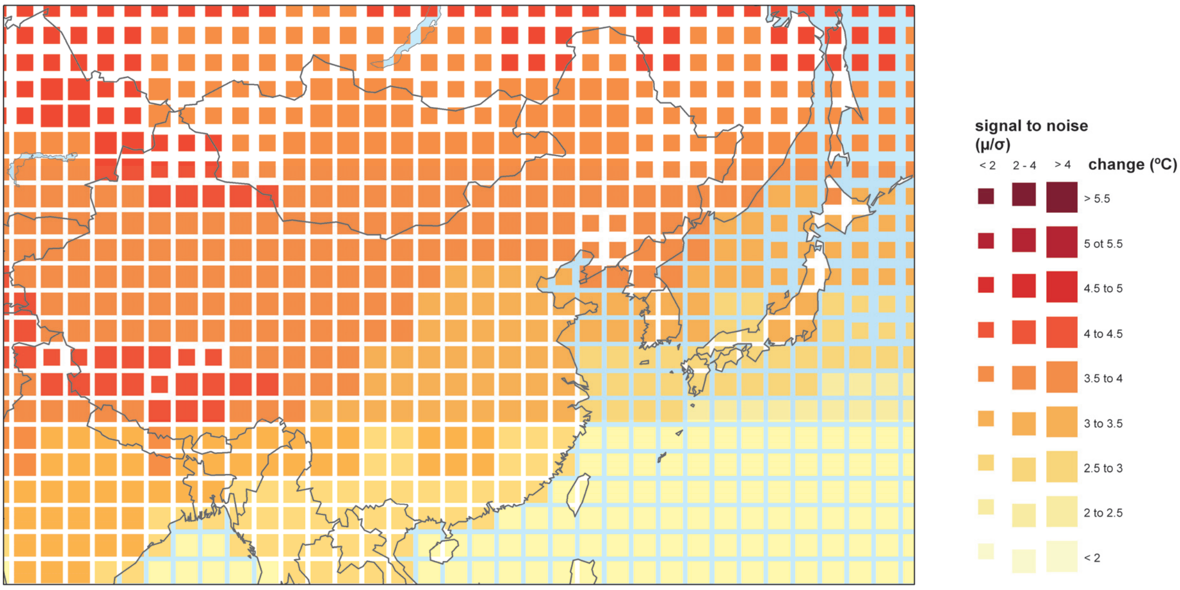


Figure 1. *Percentage change in average annual temperature by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the magnitude of the change.*

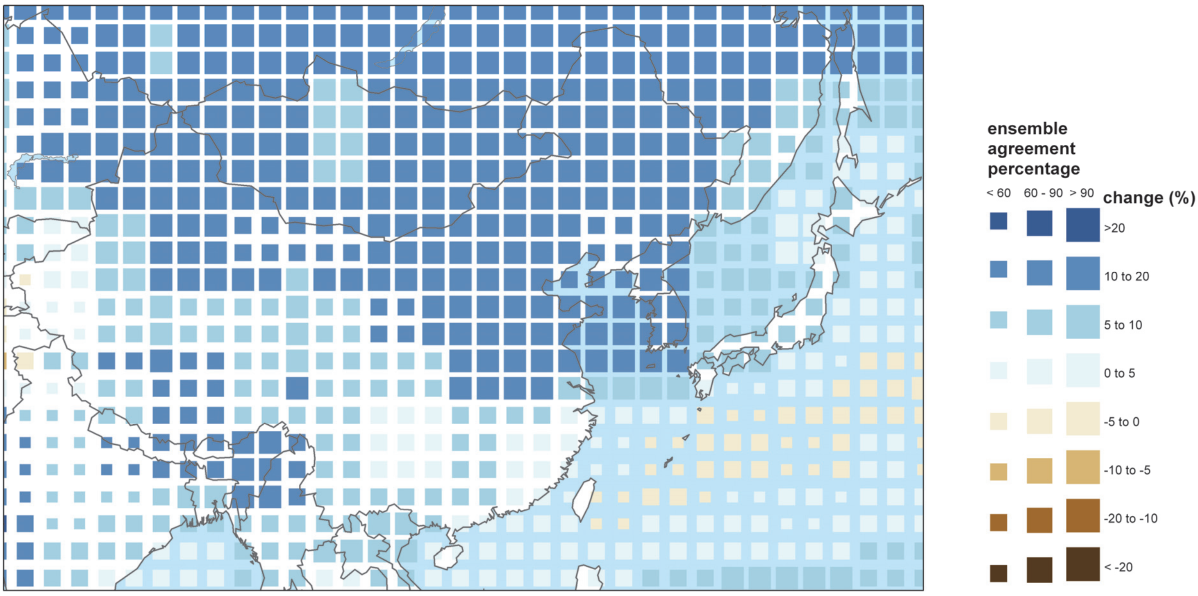


Figure 2. *Percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate, averaged over 21 CMIP3 models. The size of each pixel represents the level of agreement between models on the sign of the change.*

Summary of temperature change in the Republic of Korea

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 changes over the Republic of Korea show increases of up to around 3-3.5°C. There is good agreement between the models in the ensemble.

Summary of precipitation change in the Republic of Korea

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.

The Republic of Korea lies at the south of a widespread region across Eastern Asia where projected precipitation shows increases of 10-20% with good 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 the Republic of Korea. 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 the Republic of Korea. The following sectors are considered in turn in this report:

- Crop yields
- Food security
- Water stress and drought

- Pluvial flooding and rainfall
- Fluvial flooding
- Tropical cyclones (where applicable)
- Coastal regions

Supporting literature

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

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

AVOID programme results

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

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

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

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

Uncertainty in climate change impact assessment

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

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

- Uncertainties in translating emissions of greenhouse gases into atmospheric concentrations and radiative forcing. Atmospheric CO_2 concentrations are currently rising at approximately 50% of the rate of anthropogenic emissions, with the remaining 50% being offset by a net uptake of CO_2 into the oceans and land biosphere. However, this rate of uptake itself probably depends on climate, and evidence suggests it may weaken under a warming climate, causing more CO_2 to remain in the atmosphere, warming climate further. The extent of this feedback is highly uncertain, but it not considered in most studies. The phase 3 of the Coupled Model Intercomparison Project (CMIP3), which provided the future climate projections for the IPCC Fourth Assessment Report (AR4), used a single estimate of CO_2 concentration rise for each emissions scenario, so the CMIP3 projections (which were used in most studies presented here, including AVOID) do not account for this uncertainty.

- Uncertainty in climate response to the forcing by greenhouse gases and aerosols. One aspect of this is the response of global mean temperature ("climate sensitivity"), but a more relevant aspect for impacts studies is the response of regional climates, including temperature, precipitation and other meteorological variables. Different climate models can give very different results in some regions, while giving similar results in other regions. Confidence in regional projections requires more than just agreement between models: physical understanding of the relevant atmospheric, ocean and land surface processes is also important, to establish whether the models are likely to be realistic.

- Additional forcings of regional climate. Greenhouse gas changes are not the only anthropogenic driver of climate change; atmospheric aerosols and land cover change are also important, and unlike greenhouse gases, the strength of their influence varies significantly from place to place. The CMIP3 models used in most impacts studies generally account for aerosols but not land cover change.

- Uncertainty in impacts processes. The consequences of a given changes in weather or climatic conditions for biophysical impacts such as river flows, drought, flooding, crop yield or ecosystem distribution and functioning depend on many other processes which are often poorly-understood, especially at large scales. In particular, the extent to which different biophysical impacts interact with each other has been hardly studied, but may be crucial; for example, impacts of climate change on crop yield may depend not only on local climate changes affecting rain-fed crops, but also remote climate changes affecting river flows providing water for irrigation.

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

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

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

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

.

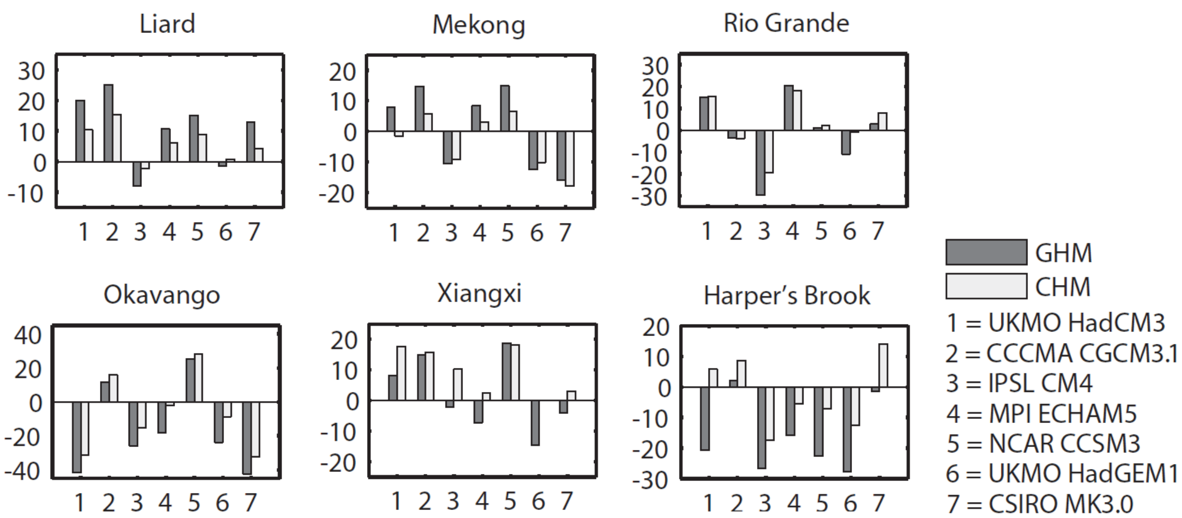


Figure 1. *Change in average annual runoff relative to present (vertical axis; %), when a global hydrological model (GHM) and a catchment-scale hydrological model (CHM) are driven with climate change projections from 7 GCMs (horizontal axis), under a 2°C prescribed global-mean warming scenario, for six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

Uncertainties in the large scale climate relevant to the Republic of Korea include 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.

The Republic of Korea is a relatively small country and this introduces an additional uncertainty when analysing Global Climate Model (GCM) results on a national scale. The average grid box size for the CMIP3 ensemble of models is comparative to the size of the Republic of Korea, such that for most models the whole country is represented by a single grid box. This has a significant impact in lowering confidence in how representative the results from GCMs are on a national scale for the Republic of Korea, and this should be borne in mind when considering all the conclusions drawn from GCM studies presented in this report.

Summary of findings for each sector

Crop yields

- Quantitative crop yield projections under climate change scenarios for the Republic of Korea vary across studies due to the application of different models, assumptions and emissions scenarios.
- Global- and regional-scale studies included here generally project increases in the yield of rice, the country's major crop, out to the 2050s, but a potential decline towards the end of the century.
- National-scale assessments agree with the global view of a decline in rice yields towards the end of the century in the Republic of Korea.
- Brassicas and other vegetable crops constitute an important part of the country's agricultural production but crop yield changes are uncertain as these crops are not routinely included in climate change impact assessments.
- Important knowledge gaps and key uncertainties include the quantification of potential yield increases due to CO_2 fertilisation, quantification of potential yield reductions due to ozone damage, and quantification of the extent to which crop diseases might affect crop yields with climate change.

Food security

- The Republic of Korea is currently a country with extremely low levels of undernourishment.
- The majority of global studies included here suggest that Republic of Korea will not face serious food security issues over the next 40 years.
- One study projects that the 10-year averaged maximum catch potential in the Republic of Korea from 2005 to 2055 could decline by 7% under SRES A1B.

Water stress and drought

- Global-scale studies included here indicate that the Republic of Korea currently suffers from a moderate to high level of water stress, and some project that water stress in the country could increase with climate change. However, uncertainty is high due to the application of different climate and hydrological models and as to how the monsoon may be affected by climate change.

Pluvial flooding and rainfall

- The IPCC AR4 noted that mean and extreme precipitation for the Republic of Korea was projected to increase with climate change, with stronger precipitation increases during the summer season.
- Recent studies support this, with increases in precipitation noted in a majority of the studies considered for both historic observations and future climate projections.

Fluvial flooding

- Climate change impact studies for the Republic of Korea have produced very different projections of future changes in flooding, even when the study area is the same, because of different choices of scenarios, models and simulation period.
- Simulations by the AVOID programme, based on climate scenarios from 21 GCMs, show a much greater tendency for increasing flood risk, particularly later in the century and in the A1B scenario, with some models projecting very large increases. This is consistent with the results of other global and local studies.
- At least one small-scale study suggests annual runoff could increase with climate change, but there is more uncertainty regarding seasonal changes.

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.

- Projected change in the intensity of cyclones in the western Pacific basin are considered more robust than projected change in their frequency. A number of global- and regional-scale 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 the Republic of Korea.

- Estimates of future cyclone damage in the Republic of Korea are highly uncertain due to the small size of the country and the limited resolutions of the climate models used to simulate shifts in tropical-cyclone tracks under climate change.

Coastal regions

- Two recent global assessments of the impact of sea level rise on coastal regions, suggest that climate change could have major implications for the Republic of Korea's coastal populations..

- However, the magnitude of the projected impacts differs between the two assessments because of different methodological approaches.

- One of the studies shows that around 50% of the coastal population (around 863,000 people) could be affected by a 10% intensification of the current 1-in-100-year storm surge combined with a prescribed 1m SLR.

- The other study indicates that by the 2070s the exposed population to SLR could increase from 294,000 people in present to 377,000.

Crop yields

Headline

The majority of crop yield projections with climate change for the Republic of Korea focus on the main staple crop, rice. Rice yield projections vary across studies due to the application of different models, assumptions, and emissions scenarios. However, a number of national studies indicate that rice yields could decline in the south of the country. Brassicas and other vegetable crops constitute an important part of the Republic of Korea's agricultural production but crop yield changes are uncertain as these crops are not routinely included in climate change impact assessments.

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 main cereal staple crop in the Republic of Korea but vegetable and fruit crops make up an important share in terms of quantity and value (see Table 1) (FAO, 2008).

Harvested area (ha)		**Quantity (Metric ton)**		**Value ($1000)**	
Rice, paddy	935000	Rice, paddy	6910000	Rice, paddy	1460000
Vegetables fresh (nes) [1]	81000	Vegetables fresh (nes) [1]	3380000	Vegetables fresh (nes) [1]	635000
Soybeans	75200	Cabbages and other brassicas	2900000	Cabbages and other brassicas	426000
Chillies and peppers, green	54800	Onions, dry	1030000	Garlic	289000
Barley	53700	Watermelons	856000	Strawberries	215000
Cabbages and other brassicas	43100	Tangerines, mandarins, clem.	636000	Onions, dry	190000
Chestnuts	38000	Potatoes	604000	Grapes	154000

[1] nes = not elsewhere specified or included

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

A number of global, regional, national and sub-national impact model studies, which include results for some of the main crops in the Republic of Korea, 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 CO_2 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 the Republic of Korea. However, the majority of studies explored in this report show that rice yields could decline in some areas.

Important knowledge gaps, which are applicable to the Republic of Korea 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 the Republic of Korea were also calculated. Lobell et all. (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 the Republic of Korea, a positive effect on rice yield but negative effects on maize, wheat and soybean yield in particular were estimated relative to what could have been achieved without the climate trends (see Table 2).

Crop	Trend
Maize	-0.2 to -0.1
Rice	0.1 to 0.2
Wheat	-0.2 to -0.1
Soybean	-0.3 to -0.2

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

Other studies have noted that many crops have seen northward shifts in the distribution of cultivation area due to recent climate change (Korea Joongang Daily, 2009, Lee et al., 2009, Kim et al., 2010, Lim et al., 2009). Citrus fruits such as tangerines, mandarins and clementine's are traditionally grown on the southern-most Jeju Island but are now grown in other provinces as well (Korea Joongang Daily, 2009). The 'safe zone' for barley cultivation has moved northwards (Shim et al., 2004) as has that for apple (Kim et al., 2010).

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 the Republic of Korea (Avnery et al., 2011, Masutomi et al., 2009, Iglesias and Rosenzweig, 2009, Shin and Lee, 1995). The process of CO_2 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.

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. The simulations showed that until 2050, rice yield was above baseline (1970-2000) yield levels under all emissions scenarios. However, from 2050 to 2080, four out of seven emission scenarios were associated with a yield decline for rice.

Scenario	Year	Rice
A1FI	2020	0.84
	2050	1.21
	2080	-4.95
A2a	2020	1.84
	2050	4.47
	2080	3.50
A2b	2020	1.60
	2050	3.01
	2080	-1.38
A2c	2020	1.79
	2050	2.90
	2080	3.57
B1a	2020	0.73
	2050	2.77
	2080	-0.89
B2a	2020	0.15
	2050	1.92
	2080	3.77
B2b	2020	0.11
	2050	0.52
	2080	3.60

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

	Rice	
	Up	**Down**
Baseline to 2020	7	0
Baseline to 2050	7	0
Baseline to 2080	4	3
2020 to 2050	7	0
2050 to 2080	3	4

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

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 CO_2 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 the Republic of Korea are presented in Table 5. The overall finding is broadly similar to that of Iglesias and Rosenzweig (2009), with projections of an increase in yield up to the 2050s under all scenarios and then two out of three projecting a decline by the 2080s.

1990s - 2020s			1990s - 2050s			1990s - 2080s		
A2	A1B	B1	A2	A1B	B1	A2	A1B	B1
-1.0	0.8	2.3	6.0	5.7	2.7	-6.0	2.5	8.2

Table 5. *Average change in rice production (%) taking CO_2 effect into consideration, for the Republic of Korea. The values represent the average across all GCMs considered in the analysis (individual GCM results are not presented in the study). Data is from Masutomi et al. (2009).*

Elsewhere, recent studies have assessed the impact of climate change on a global-scale and include impact estimates for multi-nation regions, such East Asia and the Pacific, which include the Republic of Korea as a component country (Nelson et al., 2009, Tatsumi et al., 2011). Whilst these studies provide a useful indicator of crop yields under climate change for the *region*, it should be noted that the crop yields presented in such cases are not definitive *national* estimates. This is because the yields are averaged over the entire region, which includes other countries as well as the Republic of Korea.

Nelson et al. (2009) 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 the Republic of Korea is included.

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.

GCM and CO_2 fertilisation	Rice		Maize		Soybean		Wheat		Groundnut	
	Rf.	Irr.	Rf.	Irr.	Rf.	Irr.	Rf.	Irr.	Rf.	Irr.
CSIRO NoCF	-4.5	-13.0	1.5	-1.3	-3.6	-8.2	-14.8	-2.7	-5.1	-11.1
NCAR NoCF	-5.8	-19.8	-3.9	-2.6	-8.6	-13.4	-16.1	-7.1	-6.5	-13.7
CSIRO CF	2.5	4.4	3.7	-0.8	17.0	9.1	-5.4	3.7	11.3	3.6
NCAR CF	1.8	-1.1	-2.0	-1.9	11.5	3.6	-9.2	-0.6	9.7	1.2

Table 6. *Projected yield changes (%) by 2050 compared to baseline (yields with 2000 climate) using two GCMs with (CF) and without CO_2 fertilisation effect (NoCF). Rain-fed (Rf.) and Irrigated (Irr.) crop lands were assessed separately. Data is from Nelson et al. (2009).*

Tatsumi et al. (2011) applied an improved version of the GAEZ crop model (iGAEZ) to simulate crop yields on a global scale for wheat, potato, cassava, soybean, rice, sweet potato, maize, green beans. The impact of global warming on crop yields from the 1990s to 2090s was assessed by projecting five GCM outputs under the SRES A1B scenario and comparing the results for crop yields as calculated using the iGAEZ model for the period of 1990-1999. The results for East Asia, which includes the Republic of Korea, are displayed in Table 7.

Wheat	Potato	Cassava	Soybean	Rice	Sweet potato	Maize	Green beans
4.35	6.33	-29.35	16.35	-5.60	8.96	7.23	20.31

Table 7*. Average change in yield (%), during 1990s-2090s in East Asia. Data is from Tatsumi et al. (2011).*

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 under the SRES A2 and B1 scenarios respectively. For soybeans, relative yield loss in the near future (2030) under the SRES A2 scenario was estimated to be 31% whereas under SRES B1 it was estimated to be around 27%.

National-scale or sub-national scale assessments

Climate change studies

Included in this section are results from two recent studies that have applied a crop model, alongside information from global climate models to produce sub-national projections of future rice yield in the Republic of Korea. Both these studies generally support the conclusions from larger scales studies described previously, suggesting that crop yields could decrease with climate change in the Republic of Korea

An assessment of rice yield under climate change scenarios in 2080 estimated that rice yield could decrease at the national level (Han et al., 2007), which supports the conclusions of a similar study by Shin and Lee (1995) that predates AR4. The authors of (Han et al., 2007) used the CERES crop model under the SRES A2 scenario with 1971-2000 yields by province as the baseline. Nationwide, rice yield was projected to decrease by 14.9% but the south-western coastal zone was projected to see the largest decline, 20.1%, whereas a 9.7% decline was simulated for the north-eastern coastal zone.

Another study, reported in Kim et al. (2010), which applied the same model as Han et al. (2007), emission scenario and baseline data, compared rice yield loss under temperature increases from 2°C to 5°C. Yield losses at national level were estimated to range between 4.5% and 14.9% respectively. Projected yield loss was highest in the south-western Jeonnam province, regardless of temperature increase. The lowest decrease was simulated for the three provinces in the centre-northwest; Gangwon, Chungbuk and Gyeongbuk.

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 CO2 concentrations can decrease evapotranspiration by increasing the efficiency of water use by plants (Ramankutty et al., 2002), but that aspect of the index was not included in the analysis here. Increased CO_2 can also increase photosynthesis and improve yield to a small extent, but again these effects are not included. Exclusion of these effects may lead to an overestimate of decreases in suitability.

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

Results

Crop suitability was estimated under the pattern of climate change from 21 GCMs with two emissions scenarios; 1) SRES A1B and 2) an aggressive mitigation scenario where emissions follow A1B up to 2016 but then decline at a rate of 5% per year thereafter to a low emissions floor (denoted A1B-2016-5-L). The application of 21 GCMs is an attempt to quantify the uncertainty due to climate modelling, although it is acknowledged that only one crop suitability impacts model is applied. Simulations were performed for the years 2030, 2050, 2080 and 2100. The results for the Republic of Korea are presented in Figure 2. Apart from two outliers under A1B for 2080 and 2100 for decreased suitability, none of the models project climate change has having an impact on crop suitability for the Republic of Korea with this analysis.

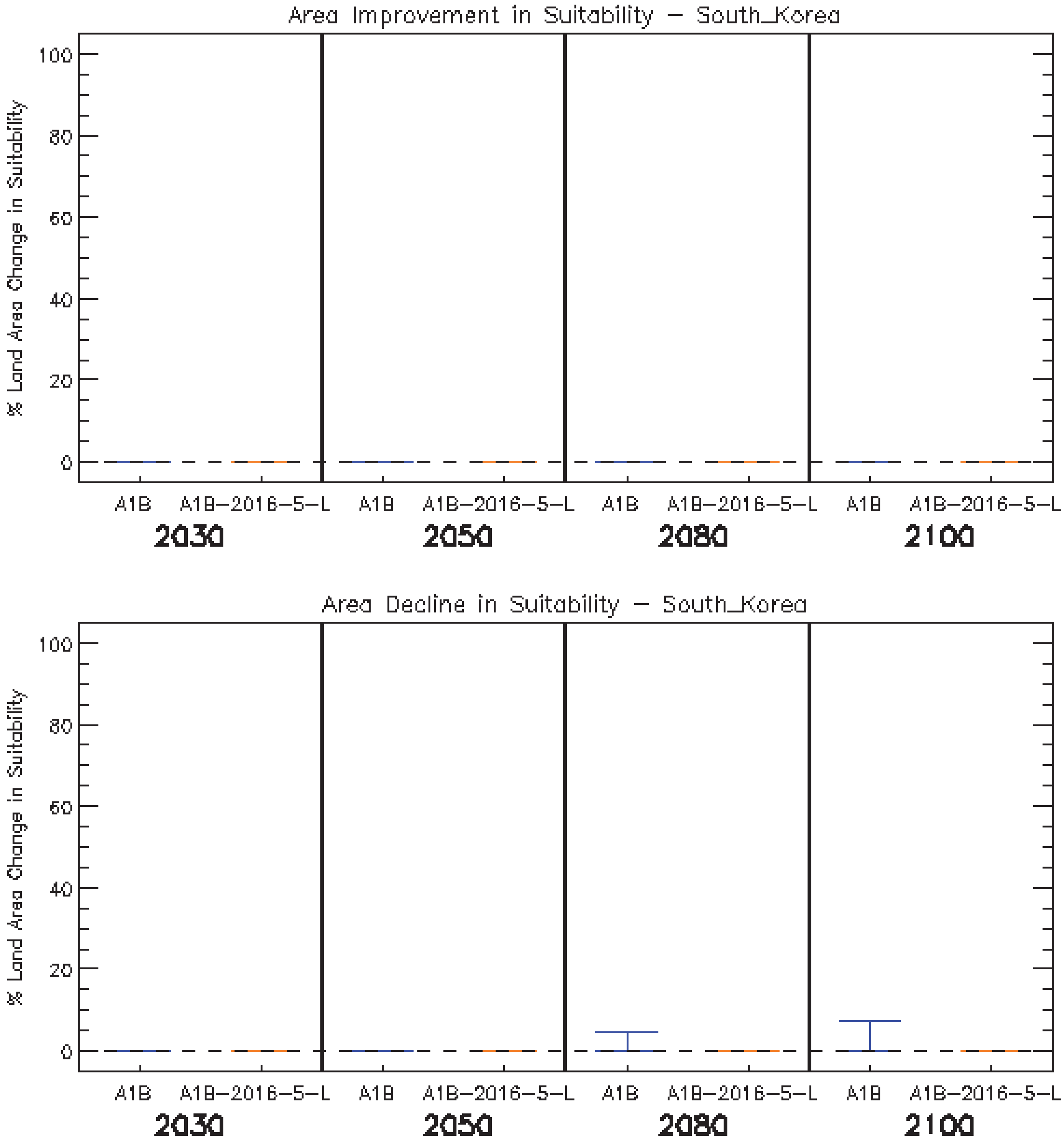


Figure 2. *Box and whisker plots for the impact of climate change on increased crop suitability (top panel) and decreased crop suitability (bottom panel) for the Republic of Korea, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum and minimum values (shown by the extent of the whiskers).*

Food security

Headline

There is no consensus across studies regarding whether food security might improve or decline with climate change for the Republic of Korea. However, studies agree that any effects of climate change may not be large. Further research should seek to address this knowledge gap.

Introduction

Food security is a concept that encompasses more than just crop production, but is a complex interaction between food availability and socio-economic, policy and health factors that influence access to food, utilisation and stability of food supplies. In 1996 the World Food Summit defined food security as existing 'when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs, and their food preferences are met for an active and healthy life'. As such this section cannot be a comprehensive analysis of all the factors that are important in determining food security, but does attempt to assess a selection of the available literature on how climate change, combined with projections of global and regional population and policy responses, may influence food security.

Assessments that include a global or regional perspective

According to the FAO's Food Security Country profiles (FAO, 2010) an extremely low proportion (<5%) of the Republic of Korea's population are currently undernourished.

A study on future food security by Wu et al. (2011) simulated crop yields with the GIS-based Environmental Policy Integrated Climate (EPIC) model. This was combined with crop areas simulated by a crop choice decision model to calculate total food production and per capita food availability across the globe, which was used to represent the status of food availability and stability. The study focussed on the SRES A1 scenario and applied climate change simulations for the 2000s (1991–2000) and 2020s (2011–2020). The climate simulations were performed by MIROC (Model for Interdisciplinary Research on Climate) version 3.2., which means the effects of climate model uncertainty were not considered. Downscaled population and GDP data from the International Institute for Applied Systems Analysis (IIASA) were applied in the simulations. Wu et al. (2011) concluded that the Republic of Korea is not likely to face severe food insecurity in the next 20 years.

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

1) how far improved land and water management might go towards achieving global food security,

2) the water deficits that would remain in regions currently experiencing water scarcity and which are aiming at food self-sufficiency,

3) how the water deficits above may be met by importing food,

4) the cropland expansion required in low income countries without the needed purchasing power for such imports, and

5) the proportion of that expansion pressure which will remain unresolved due to potential lack of accessible land.

Similar to the study presented by Wu et al. (2011), there is no major treatment of modelling uncertainty; simulations were generated by only the LPJml dynamic global vegetation and water balance model (Gerten et al. 2004) with population growth and climate change under the SRES A2 emission scenario. Falkenmark et al. (2009) summarise the impacts of future improvements (or lack thereof) in water productivity for each country across the globe and show that this generates either a deficit or a surplus of water in relation to food water requirements in each country. These can be met either by trade or by horizontal expansion (by converting other terrestrial ecosystems to crop land). The study estimated that in 2050 around one third of the world's population will live in each of three regions: those that export food, those that import food, and those that have to expand their croplands at the expense of other ecosystems because they do not have enough purchasing power to import their food. The simulations demonstrated that the Republic of Korea could be 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 CO_2 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 the Republic of Korea 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 Republic of Korea and Figure 3 displays the effect of climate change, calculated by comparing the 'perfect mitigation' scenario with each baseline, optimistic and pessimistic scenario. Whilst by 2050 climate change is attributable for up to around a 7% decline in kilocalorie availability, the absolute value of available kilocalories remains relatively high in comparison with other countries across the globe, and implies that the Republic of Korea may not face major food security issues in 2050. Figure 4 shows how the changes projected for the Republic of Korea compare with the projections for the rest of the globe (IFPRI, 2010).

Scenario	2010	2050
Baseline CSI A1B	2993	2967
Baseline CSI B1	2996	2988
Baseline MIR A1B	2979	2910
Baseline MIR B1	2986	2946
Baseline Perfect Mitigation	3031	3142
Pessimistic CSI A1B	2946	2698
Pessimistic CSI B1	2949	2717
Pessimistic MIR A1B	2932	2645
Pessimistic MIR B1	2938	2673
Pessimistic Perfect Mitigation	2983	2858
Optimistic CSI A1B	2989	3119
Optimistic CSI B1	2992	3135
Optimistic MIR A1B	2975	3053
Optimistic MIR B1	2981	3081
Optimistic Perfect Mitigation	3026	3296

Table 8. *Average daily kilocalorie availability simulated under different climate and socioeconomic scenarios, for the Republic of Korea (IFPRI, 2010).*

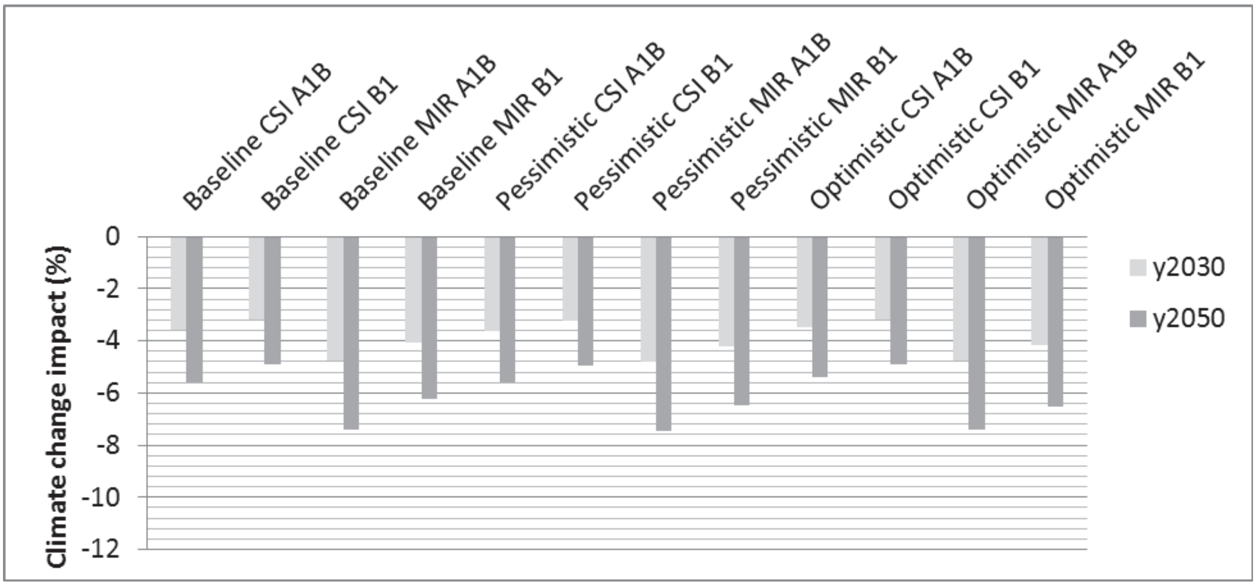


Figure 3. *The impact of climate change on average daily kilocalorie availability (IFPRI, 2010).*

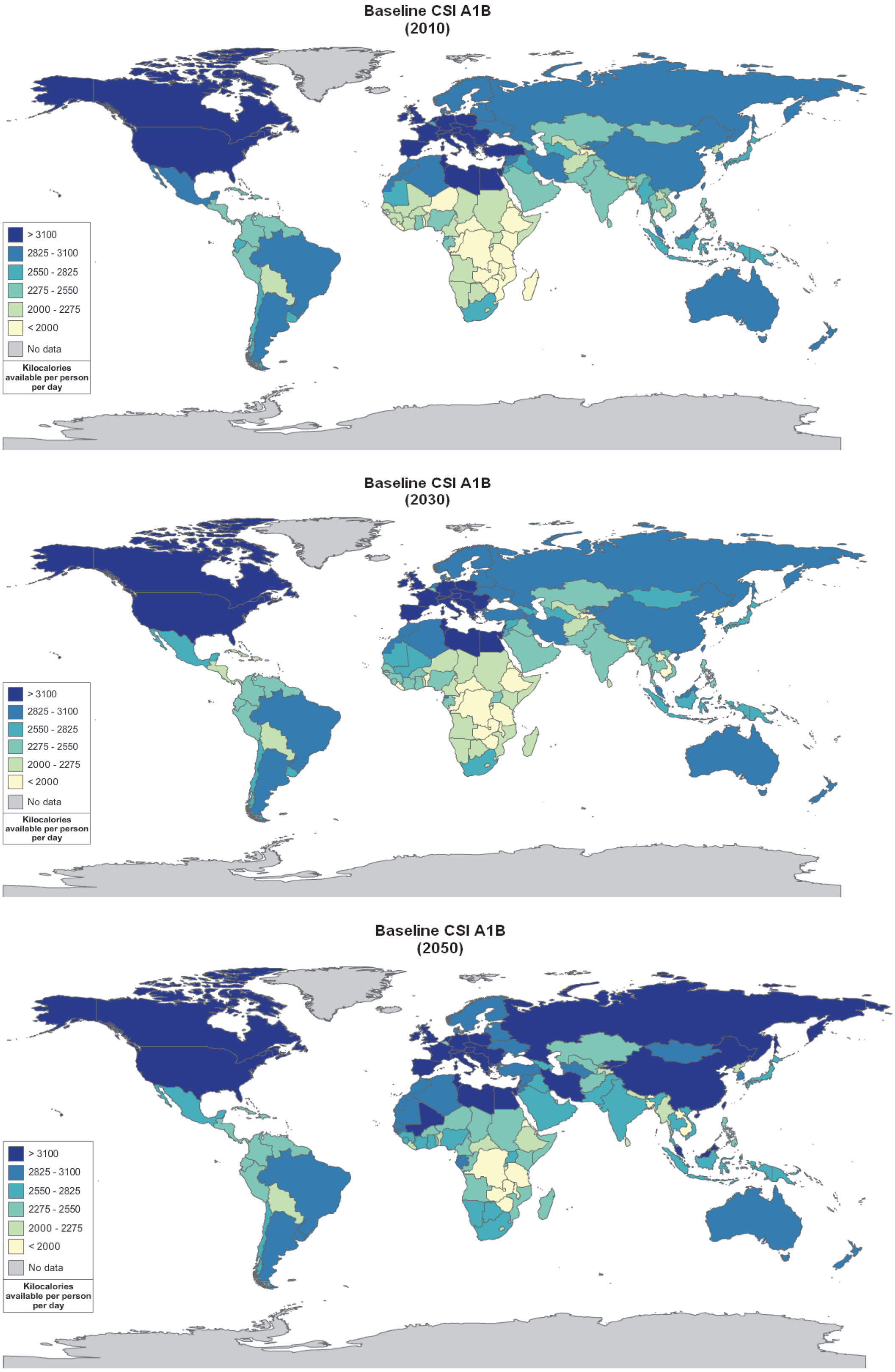


Figure 4. *Average daily kilocalorie availability simulated by the CSIRO GCM (CSI) under an A1B emissions scenario and the baseline socioeconomic scenario, for 2010 (top panel), 2030 (middle panel) and 2050 (bottom panel). Figure is from IFPRI (2010). The changes show the combination of both climate 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, Cheung et al. (2010) address this knowledge gap for the Republic of Korea. 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.

The Cheung et al. (2010) study considers 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 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 the Republic of Korea, the projected change in the 10-year averaged maximum catch potential from 2005 to 2055 was around a 7% reduction under A1B but a 4% increase under the stabilisation scenario, based upon 72 exploited species included in the analysis. These results highlight the potential benefits of global climate change mitigation for the Republic of Korea. Figure 5 demonstrates how this compares with projected changes for other countries across the globe. It should be noted, however, that results from studies that have applied only a single climate model or climate change scenario should be interpreted with caution. This is because they do not consider other possible climate change scenarios which could result in a different impact outcome, in terms of magnitude and in some cases sign of change.

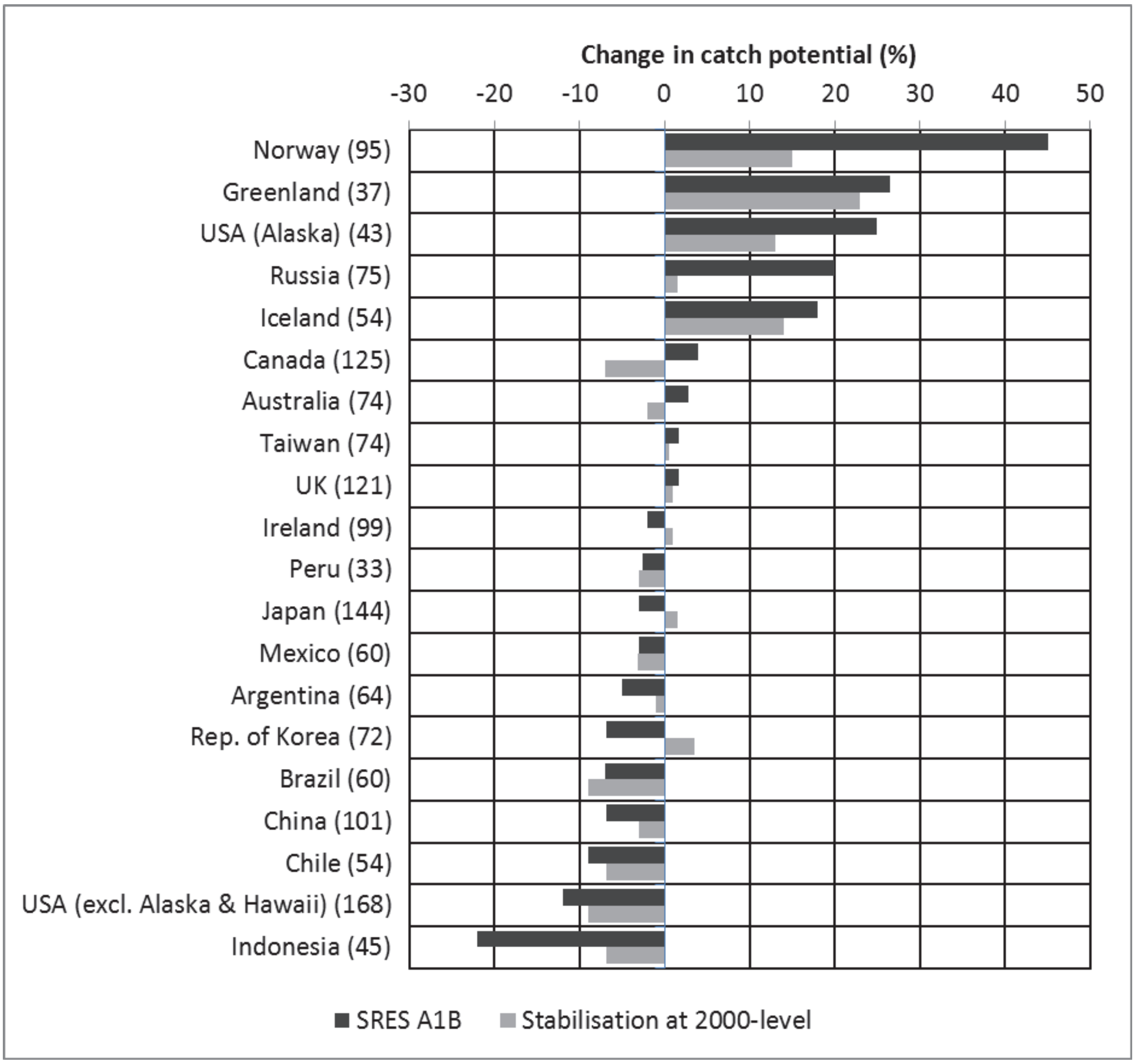


Figure 5. *Projected changes in the 10-year averaged maximum catch potential from 2005 to 2055. The numbers in parentheses represent the numbers of exploited species included in the analysis. Adapted from Cheung et al. (2010).*

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

All studies indicate that the Republic of Korea currently suffers from a high level of water stress. A number of studies present evidence to suggest that water stress could increase with climate change for the Republic of Korea. However, uncertainty is high, due to the application of different climate and hydrological models. This also complicates an assessment of the impact of climate change on drought in the country, where uncertainty is also high. This is, in part, linked to uncertainties regarding the current understanding of the monsoon under climate change scenarios.

Introduction

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

A number of impact model studies looking at water stress and drought for the present (recent past) and future (climate change scenario) have been conducted. These studies are conducted at global or national scale and include the application of global water 'availability' or 'stress' models driven by one or more climate change scenario from one or more GCM. The approaches variously include other factors and assumptions that might affect water availability, such as the impact of changing demographics and infrastructure investment, etc. These different models (hydrological and climate), assumptions and emissions scenarios mean that there are a range of water stress projections for the Republic of Korea. 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 the Republic of Korea as well as at the global-scale, include; the appropriate coupling of surface water and groundwater in hydrological models, including the recharge process, improved soil moisture and evaporation dynamics, inclusion of water quality, inclusion of water management (Wood et al. 2011) and further refinement of the down-scaling methodologies used for the climate driving variables (Harding et al., 2011).

Assessments that include a global or regional perspective

Recent past

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

Here, the present day HWS is mapped for the Republic of Korea. 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. One example is Australia, which is noted for its droughts and long dry spells, and while there are some densely populated cities in that country where water stress is a real issue, for most of the country, relative to the rest of the world, the measure suggests water stress (as measured by HWS defined by Vörösmarty et al. (2010)), is not a serious problem.

Figure 6 presents the results of this analysis for the Republic of Korea. A moderate to high level of water security threat is evident in all parts of the Republic of Korea. High levels of industrialisation in the south, and significant concentrations of population and intensive agriculture all combine.

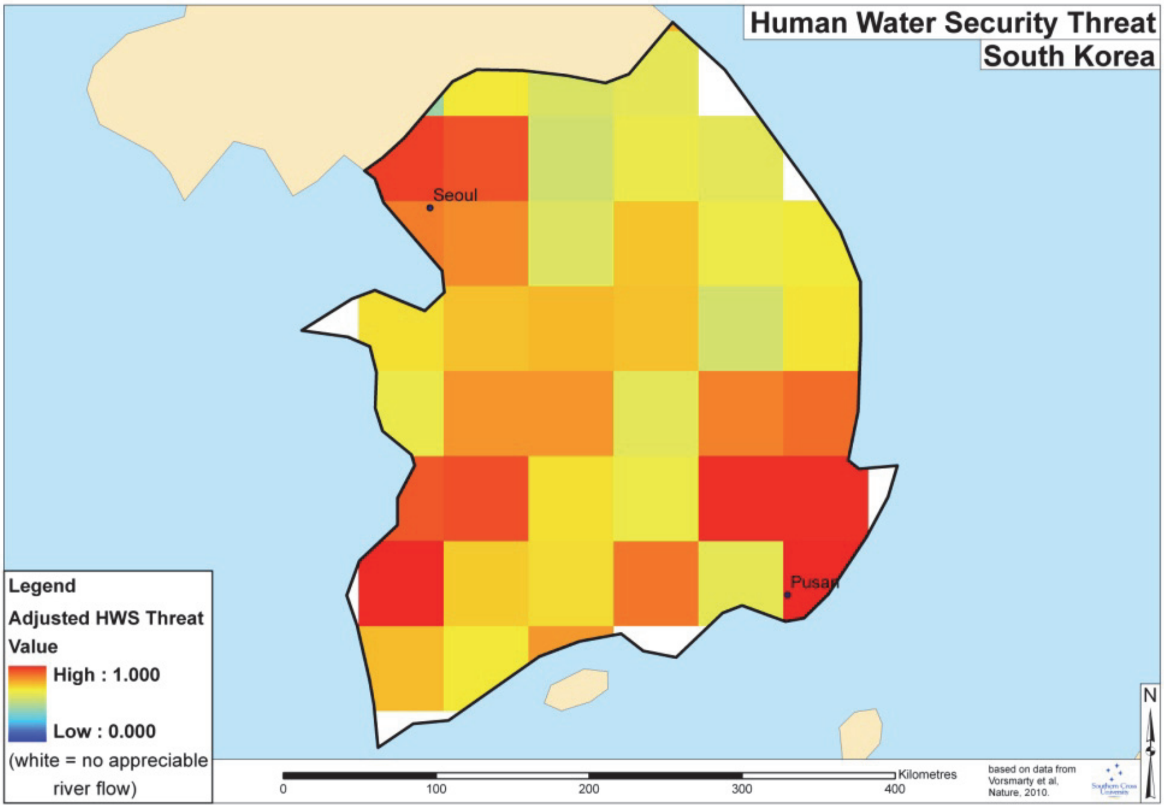


Figure 6. *Present Adjusted Human Water Security Threat (HWS) for the Republic of Korea, calculated following the method described by Vörösmarty et al. (2010).*

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 7. The results show that for the basins considered, much of the Republic of Korea presents a medium to high WSI.

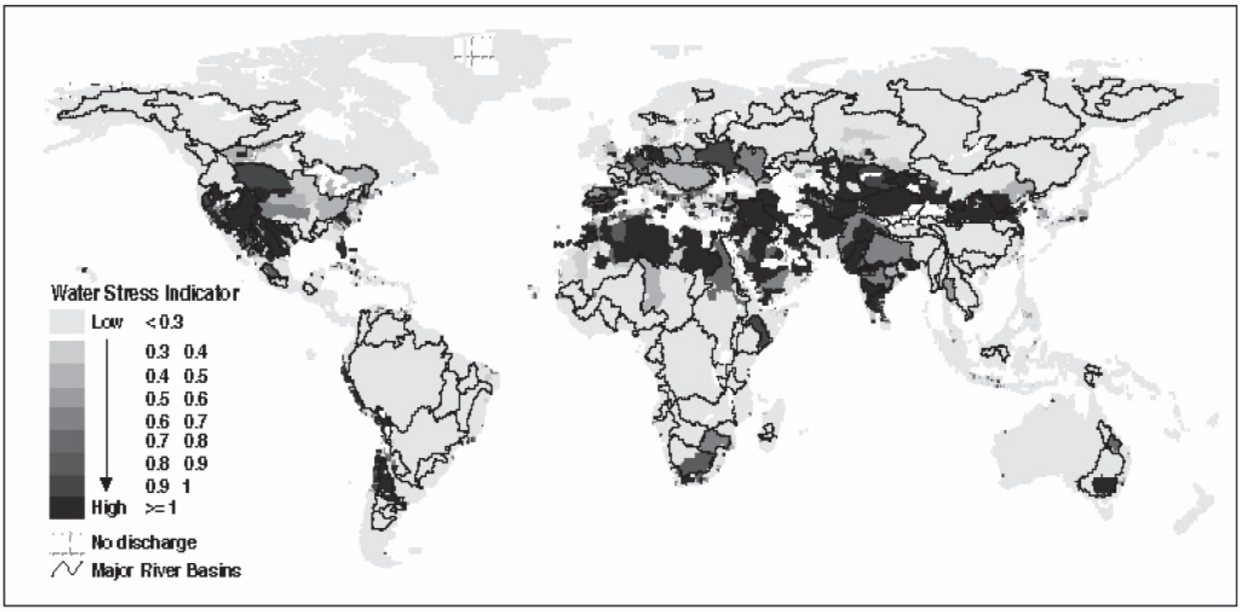


Figure 7. *A map of the major river basins across the globe and the water stress indicator (WSI) for the 1961-1990 time horizon. The figure is from Smakhtin et al. (2004).*

Climate change studies

Rockstrom et al. (2009) applied the LPJml vegetation and water balance model to assess green-blue water availability and requirements. The authors applied observed climate data from the CRU TS2.1 gridded dataset for a present-day simulation, and climate change projections from the HadCM2 GCM under the SRES A2 scenario to represent the climate change scenario for the year 2050. The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The simulations presented by Rockstrom et al. (2009) should not be considered as definitive, however, because the study only applied one climate model, which means climate modelling uncertainty was overlooked. The results from the two simulations are presented in Figure 8. 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 the Republic of Korea, Rockstrom et al. (2009) found that blue-green water availability was already close to the 1,300m^3/capita/year in the present climate, which supports the results presented in Figure 6. Under climate change, this declines to under

1,300m^3/capita/year, indicating that the Republic of Korea could be exposed to insufficient water for food security.

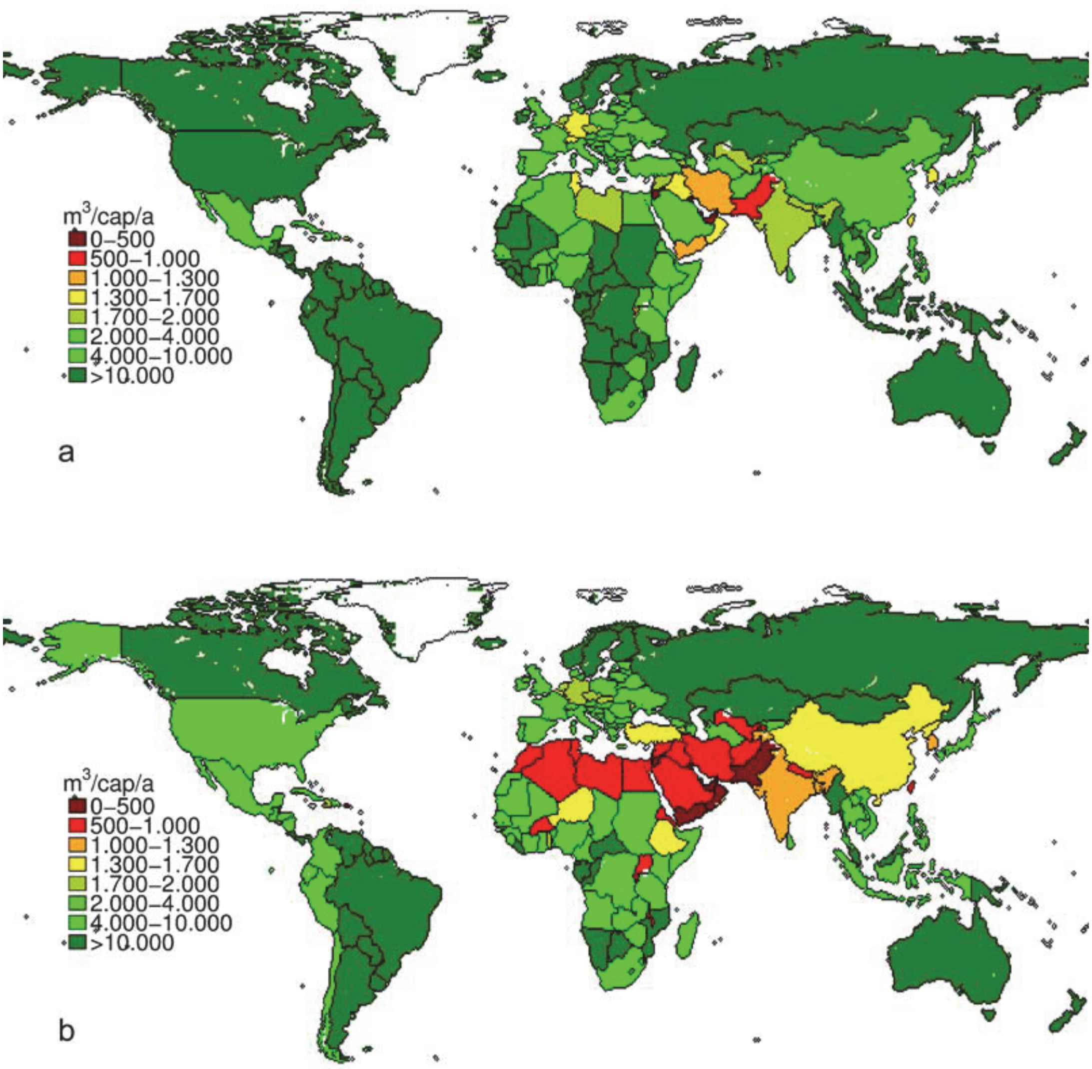


Figure 8*. Simulated blue-green water availability (m^3/capita/year) for present climate (top panel) and including both demographic and climate change under the SRES A2 scenario in 2050 (bottom panel). The study assumed that if water availability was less than 1,300m^3/capita/year, then the country was considered to present insufficient water for food self-sufficiency. The figure is from Rockstrom et al. (2009).*

Li et al. (2010a) investigated changes in the East Asian monsoon system by applying climate projections from 14 GCMs under an A1B emissions scenario. The authors demonstrate that regional-mean East Asian Summer Monsoon (EASM) rainfall is dominated by large inter-annual-to-decadal fluctuations. They show that the EASM strength does not respond with any pronounced trend to the A1B scenario during the 21st Century. Li et al. (2010a) suggest 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. Similarly, Kim and Byun (2009) explored multi-model drought projections for Asia by the end of the 21st century under the A1B emissions scenario. Precipitation was simulated to increase for most of Asia. To this end it could be expected that drought might occur less frequently and with weaker intensity and shorter duration with climate change. However, the monsoon regions (South Asia and East Asia) displayed a greater increase in the standard deviation of precipitation, with an amplified seasonal cycle. This means that parts of the monsoon regions may be affected by slight increases in drought.

National-scale or sub-national scale assessments

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

AVOID Programme Results

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

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

Results

The results for the Republic of Korea are presented in Figure 9. They show that by 2080, under A1B, the majority of GCMs are associated with no increase in water stress, with only three models indicating any increase in the proportion of population experiencing more water stress. The results for the percentage of the population experiencing a decrease in water stress are quite unusual. The same number of models show the same result, for all time periods, for both the A1B and the aggressive mitigation scenario. This signal is not necessarily a result of climate change, and could be a feature associated with the way that the model data was processed, or the fact that the driving GCMs behind the impacts model have a resolution equivalent to the size of the Republic of Korea. For this reason, these results should be treated with caution.

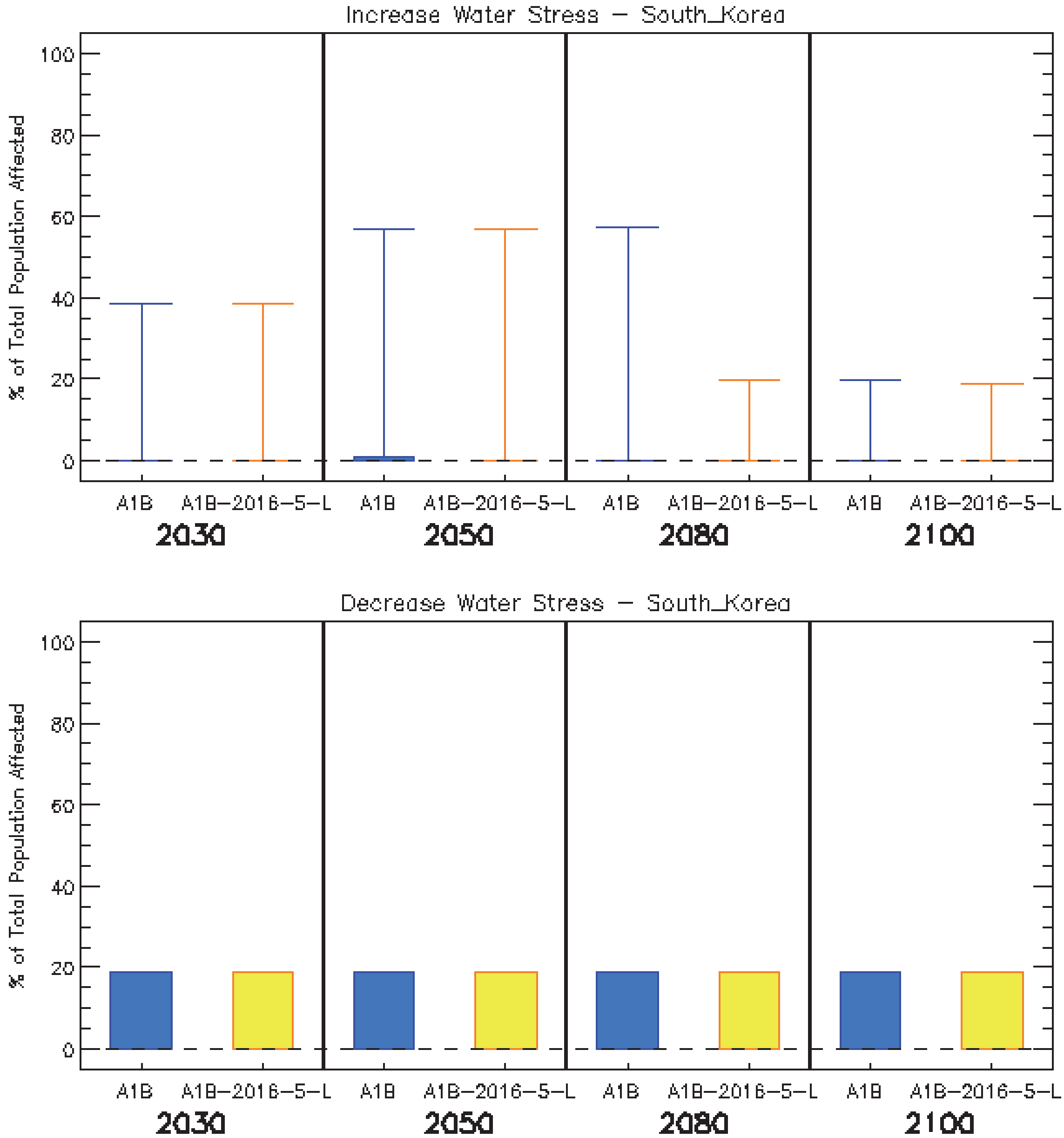


Figure 9. *Box and whisker plots for the impact of climate change on increased water stress (top panel) and decreased water stress (bottom panel) in the Republic of Korea, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th 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 noted that precipitation over the Republic of Korea was projected to increase, along with increasing extremes of precipitation. Recent studies support this, with stronger precipitation increases during the summer season.

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

A regional-scale assessment conducted Choi et al. (2009) found that trends in total precipitation for the Republic of Korea were statistically significant (at the 95% level) for the period of 1955-2007 during the summer months, with an increase of 33mm/decade. There was a small non-significant decrease in winter of -1.9mm/decade.

Climate change studies

Heavy rainfall is common in the Republic of Korea during the warm season (from late June through early September) as a result of synoptic disturbances, typhoons or convective systems. The IPCC AR4 (IPCC, 2007a) reported that the CMIP3 multi-model dataset projected precipitation increases in all seasons for East Asia under the A1B emissions scenario. The median change by the end of the 21st Century was +9% in the annual mean compared with the 1980-1999 period. with little seasonal differences. Whilst qualitative projections are consistent, there remain large quantitative differences between models (IPCC, 2007a). In terms of extremes, intense precipitation events in East Asia were very likely to increase, which is consistent with historic trends.

Yun et al. (2008) found in a high-resolution GCM study that East Asian Summer Monsoon (EASM) rainfall is projected to increase by the 2090s with climate change, while the rainfall over the northern part of the Korean Peninsula is projected to decrease with a slight southward movement of the monsoonal band.

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 EASM rainfall was dominated by large interannual-to-decadal fluctuations. They showed that the EASM strength does not respond with any pronounced trend to the A1B scenario during the 21st Century.

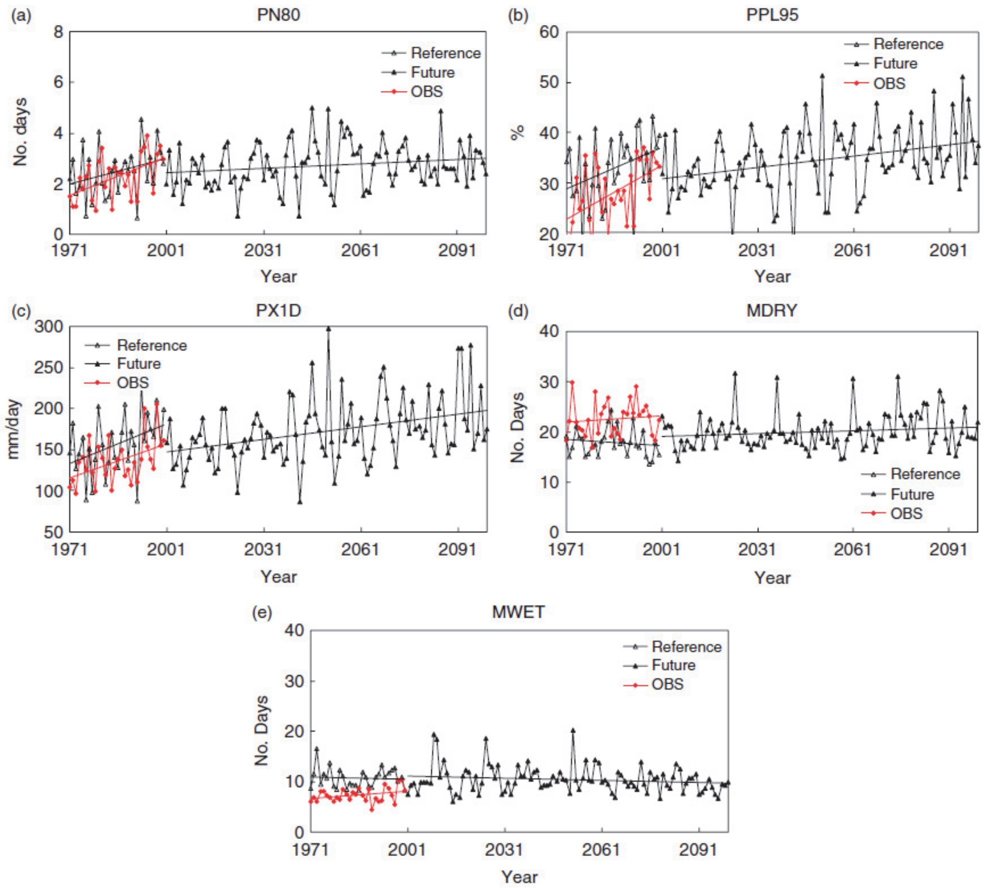
National-scale or sub-national scale assessments

Recent past

Nadarajah and Choi (2007) analysed the annual maxima of daily rainfall in the Republic of Korea from 1961 to 2001 but found no evidence for trends. In contrast, Park et al. (2010) found evidence of changes in extreme rainfall in the Republic of Korea in the form of increasing trends at a number of weather stations. Similarly, Jung et al. (2011) investigated precipitation variability in the Republic of Korea using 183 weather stations covering the 1973-2005 time horizon. They found that annual precipitation exhibited a significant positive trend, associated mainly with an increase in the frequency and intensity of heavy precipitation during the summer. Precipitation during spring and winter showed a decreasing trend, and this increasing variability could add to the risk of floods and droughts.

Climate change studies

Im et al. (2011) applied a 20km resolution RCM under the SRES A1B emissions scenario to investigate trends in climate extremes indices between 1971 and 2100 for the Republic of Korea. Observed precipitation indices for the recent past (1971-2000) showed a significant increase in the frequency and intensity of heavy precipitation. Projections of precipitation were less consistent than temperature projections, but showed a continued increase in frequency and intensity of heavy precipitation with climate change (see Figure 10). This study used a single realisation of the International Centre for Theoretical Physics (ICTP) regional climate model, RegCM3, driven by the ECHAM5/MPI-OM GCM, and therefore does not quantify uncertainty in the projections.



PN80 (days)	Number of days with precipitation above 80 mm intensity
PPL95 (%)	Percentage of total rainfall from events above long-term 95th percentile
PX1D (mm)	Greatest 1-day total precipitation
MDRY (days)	Maximum duration of consecutive dry days
MWET (days)	Maximum duration of consecutive wet days

***Figure 10**. Time series of precipitation-based indices averaged over the Republic of Korea for baseline ("Reference"), observed ("OBS") and future time horizons under an A1B emissions scenario. Indices definitions are provided in the table beneath the figure. The figure is from Im et al. (2011).*

Fluvial flooding

Headline

Climate change impact studies for the Republic of Korea have produced very different projections of future changes in flooding, even when the study area is the same, because of different choices of scenarios, models and simulation period. Simulations by the AVOID programme, based on climate scenarios from 21 GCMs, show a much greater tendency for increasing flood risk, particularly later in the century and in the A1B scenario, with some models projecting very large increases. This is consistent with the results of some other global and local studies. Although at least one small-scale study suggests annual runoff could increase with climate change, there is more uncertainty regarding seasonal changes.

Supporting literature

Introduction

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

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

Floods are a recurring problem in the Republic of Korea. Heavy rainfall amounts are common during the wet season (July to September) and are often associated with tropical cyclones. Because of the physiographical features of the Korean peninsula, these heavy rainfall events repeatedly produce high flood peaks affecting densely-populated valleys and floodplains (Jeong et al., 2007). Increases in flood damage in recent years are not only due to changes in precipitation but are also associated with deforestation in upstream areas and intensive land use and urbanisation in lowlands (Chang et al., 2009).

Assessments that include a global or regional perspective

Climate change

Because of its geography, the Republic of Korea is usually not well represented in global modelling studies of changes in flood hazard from climate change. Nevertheless, a global modelling study presented by Hirabayashi et al. (2008), which applied climate change simulations from a single GCM under the A1B emissions scenario, suggested a decrease in the return period of what was a 100-year flood event in the 20th century by the end of the century (2071-2100) to 40 years or less. This suggests a general increase in the probability of extreme flooding events, but provides little regional detail. 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.

High-resolution climate simulations over the Republic of Korea have shown a much more complex pattern of change in heavy precipitation events, suggesting the regions most prone to flooding may change substantially under climate change (Im et al., 2008; see the section on pluvial flooding for more details).

National-scale or sub-national scale assessments

Climate change

Several studies have projected changes in river flow characteristics for a number of catchments in the Republic of Korea (Bae et al., 2011, Im et al., 2010, Kang et al., 2007).

For three river catchments (Soyang, Chungju and Daecheong), Im et al. (2010) simulated changes in river discharge for the 2021-2050 time horizon under the B2 emissions scenario with an RCM. The change in the 95th percentile (i.e. the flow level that is exceeded only 5% of the time) was found to be inconsistent across the three basins, ranging from –4.6% to +1.3% in the Soyang catchment, from –2.1% to +7.5% in the Chungju basin, and from –9.6% to +7.5% in the Daecheong catchment. These results were influenced not only by the bias correction method that was applied, but also by the convection scheme that was used in the RCM to downscale the global simulations.

In a study of the Geum river basin, that feeds the Yongdam reservoir, Kang et al. (2007) found the number of flood events in the coming decade (2010-2019) under the B1 scenario could remain the same, but the magnitude of individual events could become larger especially for the largest flood events.

Bae et al. (2011) investigated the impact of climate change on water resources in the Chungju Dam basin, Republic of Korea, by applying climate change projections from 13 GCMs. Unlike the majority of climate change impact assessment studies, the authors also considered uncertainty due to impacts models. To this end they applied the climate change projections to three hydrological models (PRMS, SLURP and SWAT), and considered seven different potential evapotranspiration (PET) computation methods (Hamon and Jensen–Haise methods for PRMS, Penman–Monteith, Granger and Spittlehous-Black for SLURP, Penman–Monteith, Priestley-Taylor and Hargreaves for SWAT). Simulations were performed under A2, A1B and B1 emissions scenarios for the 2020s and 2080s. Results are presented in Figure 11. Bae et al. (2011) found that the hydrological models and PET methods can induce major differences in runoff change given the same climate change projections, and the differences are larger for the 2080s than the 2020s. Runoff projections for the dry season were highly uncertain due to the uncertainty in the hydrological modelling methods, which adds to the climate modelling uncertainty. In the (summer) high flow season on the other hand, climate modelling was the main source of uncertainty in the future projections. Similar to other studies, Bae et al. (2011) observed a tendency towards an increase in annual runoff as well as high flow season runoff with climate change.

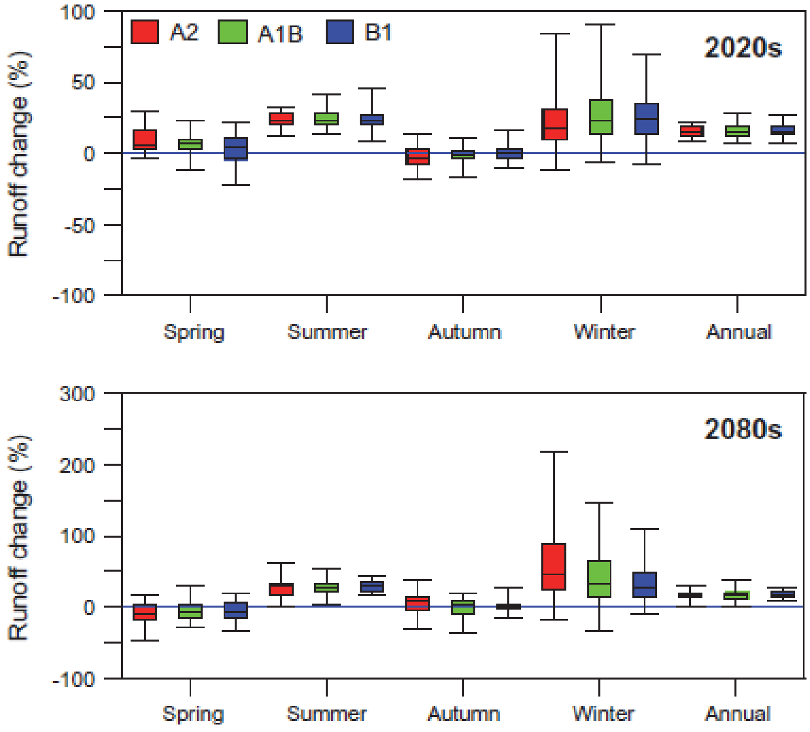


Figure 11. *Box-and-whisker plots for changes in seasonal and annual runoff under 39 simulations (13 GCMs and 3 emissions scenarios) for the 2020s and 2080s relative to the baseline time horizon (1971–2000). The figure is from Bae et al. (2011).*

As noted by Kim and Lee (2010), climate change impact studies for the Republic of Korea have produced very different projections of future changes in flooding, even when the study area is the same, because of different choices of scenarios, models and simulation period. There is therefore a need for a consistent, nation-wide assessment of flood risk in the Republic of Korea under climate change, taking into account the uncertainties associated with projections of extreme precipitation and runoff.

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°x0.00833°), 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 the Republic of Korea are presented in Figure 12. By the 2030s, the models project a range of changes in mean fluvial flooding risk over The Republic of Korea in both scenarios, with some models projecting decreases and others increases. However, the balance is much more towards increased flood risk, with 75% of models projecting an increase.

The largest decrease projected for the 2030s is −20%, while the largest increase is +170%. The mean across all projections is an increase in average annual flood risk of approximately 25%.

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, several models still project a lower flood risk (down to −10%), but more than three quarters of the models project a higher flood risk. The mean of all projections is a 50% increase, but the largest increase is approximately +340%. Under the A1B scenario, a large majority of the models project an increased flood risk, although still a few project a decline in flood risk (down to −20%). The largest projected increase is over 900%, with the mean of all projections being an increase in average annual flood risk of approximately +150%.

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

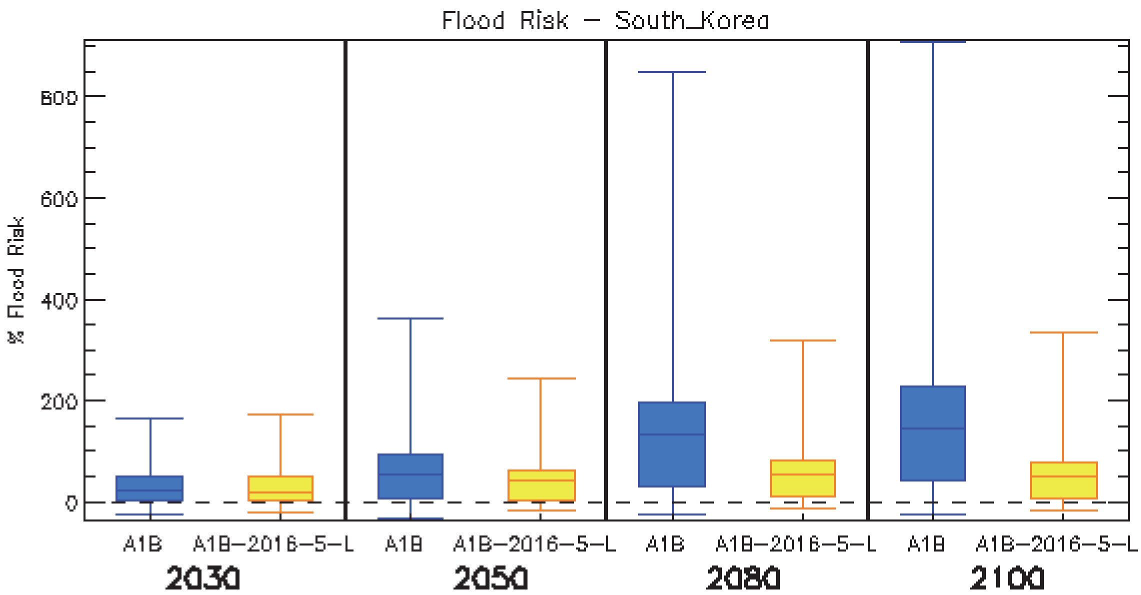


Figure 12. *Box and whisker plots for the percentage change in average annual flood risk within the Republic of Korea, from 21 GCMs under two emissions scenarios (A1B and A1B-2016-5-L), for four time horizons. The plots show the 25th, 50th, and 75th percentiles (represented by the boxes), and the maximum 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. A number of studies reviewed here suggest that the *intensity* of tropical cyclones in this basin could increase with climate change. Some studies suggest that the possible increases in intensity could be greatest for the most severe cyclones, which could lead to large increases in cyclone damages in the Republic of Korea. Estimates of damage in the Republic of Korea are highly uncertain, however, due to the small size of the country and the limited resolutions of the climate models used to simulate shifts in tropical-cyclone tracks under climate change.

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 experiments with the atmospheric component of the ECHAM5 GCM at 60km and 40km resolutions respectively. The GCM was driven by SSTs and sea ice simulated by the lower-resolution version of the GCM under the A1B emissions scenario. They study investigated the 2071-2100 time horizon for the 60km simulation and 2081-2100 for the 40km simulation. The 2081-2100 time horizon was compared with a present-day simulation using SSTs and sea ice for the 1980-2000 period. 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 measured by dry static stability, as well as reduced upward motion.

In an even finer-resolution 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 13. The authors found that the number of West Pacific tropical cyclones declined by 38%, relative to a present-day simulation using mean SSTs and sea ice for 1982-1993. In agreement with the results presented by Bengtsson et al. (2007), the authors concluded that the decreases were due to increased atmospheric stability in a warmer world; the JMA climate 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 observed by Gualdi et al. (2008), using the 120km resolution SINTEX-G climate model in a 30-year simulation under a 2xCO_2 emissions scenario.

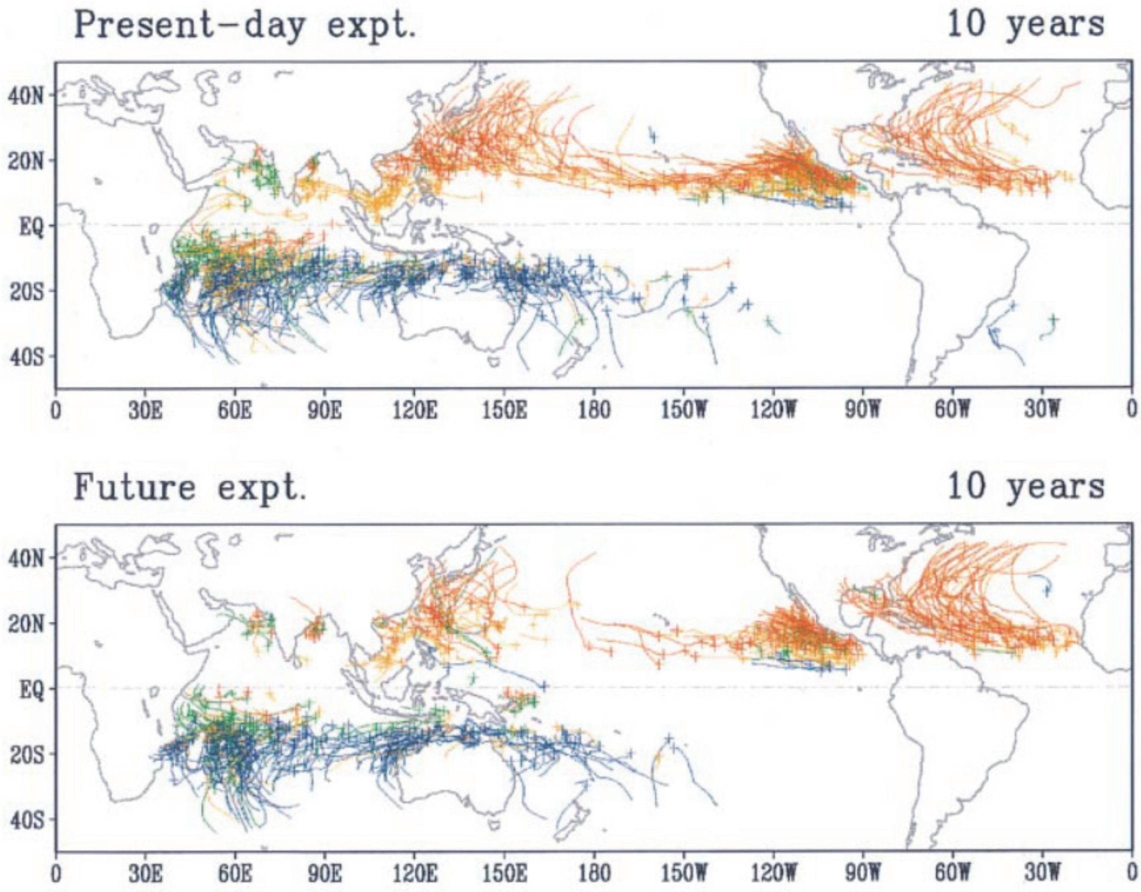


Figure 13. *Tracks of tropical cyclones simulated by the 20km resolution JMA climate model when it is driven by (top) present-day SSTs (1982-1993) and (bottom) SSTs from the MRI GCM for 2080-2099 under the A1B emissions scenario. Decreases in the number of tracks in the western Pacific and the South 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 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. 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 GCM simulated a decrease of 5%, HadCM3 a decrease of 12%, the 18 GCM ensemble-mean a decrease of 29%, and ECHAM5 a decrease of 52%.

Sugi et al. (2009) applied the JMA climate model, at 60km and 20km resolutions respectively, with SSTs and sea ice from three individual GCMs as well as the CMIP3 multi-model dataset ensemble mean, for a total of eight projections, all using 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 simulate 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 seven GCMs under the A1B emissions scenario for the 2180-2200 time horizon. The technique they applied "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 results for 2180-2200 to downscaled reanalysis data for 1980-2000, the authors concluded that West Pacific tropical-cyclone frequency could increase by 6% with climate change. All seven GCMs simulated an increase in frequencies. Importantly, Emanuel et al. (2008) observed a northward shift in the main Pacific tropical cyclogenesis (cyclone formation) region, which would imply a greater frequency of storms making landfall in the Republic of Korea.

In a study focused on the West Pacific basin, Stowasser et al. (2007) conducted an experiment with the IPRC RCM at 50km resolution, driven by SSTs and sea ice from the final 10 years of a 6xCO_2 simulation. This unrealistically large climate forcing was chosen to produce a strong climate change–related signal that may stand out among the unforced inter-annual variability in tropical cyclone statistics. The frequency of tropical cyclones remained relatively constant overall in the West Pacific, but there was approximately a doubling of the number of cyclones passing through the South China Sea, which could then track to make landfall in the Republic of Korea. The IPRC RCM 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-time increase in CO_2 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. An increase in tropical-cyclone activity in the South China Sea has also been observed over the last decade (Tu et al., 2009), although whether such a shift is due to natural variability or the result of anthropogenic climate change is currently unclear.

In contrast, Li et al. (2010b) reported 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 experiments with the 40km resolution ECHAM5 atmospheric GCM, driven by SSTs and sea-ice from the lower-resolution version of the model from two periods: one experiment used the period 1981-2000, representing the present-day climate; the other used the period 2081-2100 from the model's A1B emission scenario simulation. 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 near the Republic of Korea. Unlike the results presented by Zhao et al. (2009), Li et al. (2010b) found that the regional SST warming patterns simulated by ECHAM5 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 Niño-like basic state in ECHAM5. 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_2 conditions imposed in Stowasser et al. (2007)) or from projections of the late 22nd century (Emanuel et al., 2008). Furthermore, 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. It is therefore not possible to make a robust assessment of whether the Republic of Korea could be impacted by more or fewer tropical cyclones with climate change.

Assessment of cyclone intensity

It is, however, possible that tropical cyclones in the West Pacific could become more *intense* with climate change. Under their 6xCO_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^{-1}. 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 nine GCMs under a 1% per year CO_2 increase scenario and found that the intensity of West Pacific cyclones increased by 4-9%. The authors also used a 9km version of the GFDL hurricane model, driven by the large-scale conditions simulated by the nine GCMs under the same 1% per year CO_2 increase scenario. Across all of the nine models, the average wind speed of West Pacific cyclones increased by 5%, while central pressures fell by 13.6%. In their global experiment with the JMA 20km resolution climate model, Oouchi et al. (2006) found that cyclone intensities increased by 4.2% in the West Pacific against 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 the Republic of Korea by 2100 are also uncertain, due to both the lack of robust projections for changes in cyclone frequencies and the mismatch between the GCM resolutions and the size of the Republic of Korea. For the latter, it is important to note that there is considerably more uncertainty in projections of the changes in tropical-cyclone tracks within a particular basin than there is in the basin-wide frequency of cyclones. Given these high levels of uncertainty, projections of future damage from tropical cyclones due to climate change in the Republic of Korea should be viewed sceptically.

Mendelsohn et al. (2011) applied the cyclone "seeding" method described by Emanuel et al. (Emanuel et al., 2008) to climate change 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 employed 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 $1.27 billion in damages per year in the Republic of Korea, all four GCMs simulated an increase in cyclone damages, ranging from $0.21 billion (the CNRM GCM) to $2.05 billion (the MIROC GCM). Such large projected damage increases are 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. Thus, climate change may cause the tropical-cyclone damage in the Republic of Korea 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

Two recent global assessments of the impact of sea level rise (SLR) on coastal regions, suggest that climate change could have major implications for the country's coast. However, the magnitude of the projected impacts differ between the two assessments because of different methodological approaches. One of the studies shows that around 50% of the coastal population (around 863,000 people) could be affected by a 10% intensification of the current 1-in-100-year storm surge combined with a prescribed 1m SLR. The other study shows that by the 2070s the exposed population to SLR could increase from 294,000 people in present to 377,000.

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 Japan). 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.

Dasgupta et al. (2009) considered 84 developing countries with a 10% intensification of the current 1-in-100-year storm surge combined with a prescribed 1m SLR. GIS inundation models were applied in the analysis and the method means that uncertainty associated with the climate system is inherently overlooked. Nevertheless, the projections give a useful indicator of the possible impact of SLR in the Republic of Korea. Table 9 shows that in terms of the proportion of coastal population affected by SLR, the Republic of Korea is ranked highest of the countries considered in this review; around 50% of the coastal population (around 863,000 people) could be affected. Of the countries reviewed here, the Republic of Korea is also ranked highest for proportion of coastal land affected (62%; 902km^2), highest for proportion of coastal GDP affected (48%; \$10,670m), highest for proportion of coastal agricultural land affected (67%; 237km^2), and highest for proportion of urban extents affected (48%; 335km^2). Whilst the magnitude of the absolute impacts are generally smaller than many of the other countries considered here, it is important to note that the impacts present the largest impacts relative to the coastal area of the Republic of Korea, for all the countries considered in this review.

Country	Incremental Impact: Land Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Population	Projected Impact as a % of Coastal Total	Incremental Impact: GDP (mil. USD)	Projected Impact as a % of Coastal Total	Incremental Impact: Agricultural Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Urban Extent (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Wetlands (sq. km)	Projected Impact as a % of Coastal Total
Africa												
South Africa	607	43.09	48,140	32.91	174	30.98	70	34.48	93	48.10	132	46.23
Egypt	2,290	13.61	2,600,000	14.68	4,600	16.67	692	5.23	627	15.30	640	28.36
Kenya	274	41.93	27,400	40.23	10	32.05	40	22.13	9	38.89	177	52.51
Americas												
Argentina	2,400	18.03	278,000	19.52	2,240	16.42	157	9.93	313	27.47	459	11.30
Brazil	6,280	15.08	1,100,000	30.37	4,880	28.48	275	16.47	960	33.67	2,590	11.48
Mexico	9,130	29.04	463,000	20.56	2,570	21.22	310	10.89	701	18.35	1,760	52.25
Peru	727	36.69	61,000	46.90	177	46.18	5	26.92	54	42.72	20	37.91
Asia												
China	11,800	17.52	10,800,000	16.67	31,200	17.15	6,640	11.66	2,900	15.70	4,360	39.77
Rep. of Korea	902	61.73	863,000	50.48	10,600	47.86	237	66.75	335	48.15	77	78.81
India	8,690	29.33	7,640,000	28.68	5,170	27.72	3,740	23.64	1,290	30.04	2,510	32.31
Indonesia	14,400	26.64	5,830,000	32.75	7,990	38.71	4,110	26.12	1,280	33.25	2,680	26.97
Saudi Arabia	1,360	41.58	243,000	42.92	2,420	40.60	0	0.00	390	45.85	715	51.04
Bangladesh	4,450	23.45	4,840,000	16.01	2,220	19.00	2,710	17.52	433	18.30	3,890	24.29

Table 9. *The impact of a 1m SLR combined with a 10% intensification of the current 1-in-100-year storm surge. Impacts are presented as incremental impacts, relative to the impacts of existing storm surges. Each impact is presented in absolute terms, then as a percentage of the coastal total; e.g. 9.93% of Argentina's coastal agricultural land is impacted. The table is adapted from a study presented by Dasgupta et al. (2009), which considered impacts in 84 developing countries. Only those countries relevant to this review are presented here and all incremental impacts have been rounded down to three significant figures.*

Hanson et al. (2010) investigated 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 the Republic of Korea. 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 10 shows the aspects of SLR that were considered for various scenarios and Table 11 displays regional population exposure for each scenario in the 2030s, 2050s and 2070s. By comparing the projections in Table 11 with the estimates for exposure in the absence of climate change that are presented in Table 12, the vulnerability of the Republic of Korea to SLR is clear. For example, in present day there are around 294,000 people in the Republic of Korea exposed to SLR and in the absence of climate change in the 2070s this increases to around 303,000. With climate change in the 2070s, and under the FAC (Future City All Changes) scenario the exposed population is 377,000 under un-mitigated A1B emissions. This implies an incremental climate change impact of around 74,000 people, which is considerably smaller than the incremental impact estimated by Dasgupta et al. (2009) (863,000 people) for the Republic of Korea. The large difference is likely due to the estimates of Hanson et al. (2010) being based upon just three port cities (see Table 11) whereas Dasgupta et al. (2009) considered the entire coastline of the country. Hanson et al. (2010) also demonstrated that aggressive mitigation scenario could avoid an exposure of around 34,000 people in the Republic of Korea, relative to un-mitigated climate change (see Table 12) in 2070.

Scenario		Water levels				
		Climate			Subsidence	
Code	Description	More intense storms	Sea-level change	Higher storm surges	Natural	Anthropogenic
FNC	Future city	**V**	x	x	x	x
FRSLC	Future City Sea-Level Change	**V**	**V**	x	**V**	x
FCC	Future City Climate Change	**V**	**V**	**V**	**V**	x
FAC	Future City All Changes	**V**	**V**	**V**	**V**	**V**

***Table 10**. 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																	
2030						2050						2070					
Country	Ports	Water level projection				Country	Ports	Water level projection				Country	Ports	Water level projection			
		FAC	FCC	FRSLC	FNC			FAC	FCC	FRSLC	FNC			FAC	FCC	FRSLC	FNC
CHINA	15	17,100	15,500	15,400	14,600	**CHINA**	15	23,000	19,700	18,700	17,400	**CHINA**	15	27,700	22,600	20,800	18,600
INDIA	6	11,600	10,800	10,300	9,970	**INDIA**	6	16,400	14,600	13,600	12,500	**INDIA**	6	20,600	17,900	15,600	13,900
US	17	8,990	8,960	8,830	8,460	**US**	17	11,300	11,200	10,800	9,970	**US**	17	12,800	12,700	12,100	10,700
JAPAN	6	5,260	4,610	4,430	4,390	**JAPAN**	6	6,440	5,280	5,000	4,760	**JAPAN**	6	7,800	5,970	5,580	5,070
INDONESIA	4	1,420	1,200	1,200	1,170	**INDONESIA**	4	2,110	1,610	1,610	1,500	**INDONESIA**	4	2,680	1,830	1,830	1,530
BRAZIL	10	833	833	833	802	**BRAZIL**	10	929	929	929	879	**BRAZIL**	10	940	940	940	864
UK	2	497	497	478	459	**UK**	2	609	609	564	521	**UK**	2	716	716	640	569
CANADA	2	459	433	422	405	**CANADA**	2	549	512	486	457	**CANADA**	2	614	585	545	489
REP. OF KOREA	3	344	344	331	441	**REP. OF KOREA**	3	361	361	341	318	**REP. OF KOREA**	3	377	377	325	303
GERMANY	1	257	257	253	248	**GERMANY**	1	287	287	273	269	**GERMANY**	1	309	309	290	280
RUSSIA	1	177	177	177	177	**RUSSIA**	1	202	202	173	173	**RUSSIA**	1	226	226	197	169
AUSTRALIA	5	162	162	157	157	**AUSTRALIA**	5	197	197	191	181	**AUSTRALIA**	5	196	196	186	175
SOUTH AFRICA	2	30	30	30	29	**SAUDI ARABIA**	1	33	33	33	27	**SAUDI ARABIA**	1	38	38	38	29
SAUDI ARABIA	1	24	24	24	22	**SOUTH AFRICA**	2	28	28	28	27	**SOUTH AFRICA**	2	30	30	30	27
FRANCE	1	15	15	15	15	**FRANCE**	1	19	19	19	17	**FRANCE**	1	23	23	23	18
ITALY	1	2	2	2	2	**ITALY**	1	4	4	4	3	**ITALY**	1	6	6	6	4
MEXICO	0	0	0	0	0	**MEXICO**	0	0	0	0	0	**MEXICO**	0	0	0	0	0

***Table 11**. National estimates of 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 12. Data is from Hanson et al. (2010) and has been rounded down to three significant figures.*

Country	Ports	Population exposure				Exposure avoided
		Current	2070. Rapid urbanisation, FAC water level scenario			
			No climate change	A1B un-mitigated	Mitigated (2016-5-L)	
CHINA	15	8,740	18,600	27,700	26,500	1,140
UNITED STATES	17	6,680	10,700	12,800	12,300	505
RUSSIA	1	189	169	226	197	28
JAPAN	6	3,680	5,070	7,800	7,290	515
SOUTH AFRICA	2	24	27	30	29	0
INDIA	6	5,540	13,900	20,600	18,900	1,670
BRAZIL	10	555	864	940	926	14
MEXICO	0	0	0	0	0	0
CANADA	2	308	489	614	599	15
AUSTRALIA	5	99	175	196	190	6
INDONESIA	4	602	1,530	2,680	2,520	156
REP. OF KOREA	3	294	303	377	343	34
UK	2	414	569	716	665	51
FRANCE	1	13	18	23	20	2
ITALY	1	2	4	6	6	0
GERMANY	1	261	280	309	295	15
SAUDI ARABIA	1	15	29	38	35	3

Table 12. *Exposed 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 13.

	A1B		RCP	
	Low	**High**	**Low**	**High**
Additional people flooded (1000s)	18.55	381.56	10.30	89.49
Loss of wetlands area (% of country's total wetland)	21.96%	39.71%	21.96%	33.26%

***Table 13**. 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 for this impact sector.

References

AINSWORTH, E. A. & MCGRATH, J. M. 2010. Direct Effects of Rising Atmospheric Carbon Dioxide and Ozone on Crop Yields. *In:* LOBELL, D. & BURKE, M. (eds.) *Climate Change and Food Security.* Springer Netherlands.

ARNELL, N. W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change,* 14**,** 31-52.

AVNERY, S., MAUZERALL, D. L., LIU, J. F. & HOROWITZ, L. W. 2011. Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O_3 pollution. *Atmospheric Environment,* 45**,** 2297-2309.

BAE, D.-H., JUNG, I.-W. & LETTENMAIER, D. P. 2011. Hydrologic uncertainties in climate change from IPCC AR4 GCM simulations of the Chungju Basin, Korea. *Journal of Hydrology,* 401**,** 90-105.

BENGTSSON, L., HODGES, K. I., ESCH, M., KEENLYSIDE, N., KORNBLUEH, L., LUO, J.-J. & YAMAGATA, T. 2007. How may tropical cyclones change in a warmer climate? *Tellus A,* 59**,** 539-561.

BETTS, R. A., BOUCHER, O., COLLINS, M., COX, P. M., FALLOON, P. D., GEDNEY, N., HEMMING, D. L., HUNTINGFORD, C., JONES, C. D., SEXTON, D. M. H. & WEBB, M. J. 2007. Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature,* 448**,** 1037-1041.

BROWN, S., NICHOLLS, R., LOWE, J.A. and PARDAENS, A. (2011), Sea level rise impacts in 24 countries. Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton.

CHAKRABORTY, S. & NEWTON, A. C. 2011. Climate change, plant diseases and food security: an overview. *Plant Pathology,* 60**,** 2-14.

CHANG, H. J., FRANCZYK, J. & KIM, C. 2009. What is responsible for increasing flood risks? The case of Gangwon Province, Korea. *Natural Hazards,* 48**,** 339-354.

CHEUNG, W. W. L., LAM, V. W. Y., SARMIENTO, J. L., KEARNEY, K., WATSON, R. E. G., ZELLER, D. & PAULY, D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology,* 16**,** 24-35.

CHOI, G., COLLINS, D., REN, G., TREWIN, B., BALDI, M., FUKUDA, Y., AFZAAL, M., PIANMANA, T., GOMBOLUUDEV, P., HUONG, P. T. T., LIAS, N., KWON, W.-T., BOO, K.-O., CHA, Y.-M. & ZHOU, Y. 2009. Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007. *International Journal of Climatology,* 29**,** 1906-1925.

DASGUPTA, S., LAPLANTE, B., MURRAY, S. & WHEELER, D. 2009. Sea-level rise and storm surges: a comparative analysis of impacts in developing countries. Washington DC, USA: World Bank.

DINAS-COAST Consortium. 2006 DIVA 1.5.5. Potsdam, Germany: Potsdam Institute for Climate Impact Research (on CD-ROM)

DOLL, P. & SIEBERT, S. 2002. Global modeling of irrigation water requirements. *Water Resources Research*. Vol: 38 Issue: 4. Doi: 10.1029/2001WR000355

EMANUEL, K., SUNDARARAJAN, R. & WILLIAMS, J. 2008. Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. *Bulletin of the American Meteorological Society,* 89**,** 347-367.

FALKENMARK, M., ROCKSTRÖM, J. & KARLBERG, L. 2009. Present and future water requirements for feeding humanity. *Food Security,* 1**,** 59-69.

FAO. 2008. *Food and Agricultural commodities production* [Online]. Available: http://faostat.fao.org/site/339/default.aspx [Accessed 1 June 2011].

FAO. 2010. *Food Security country profiles* [Online]. Available: http://www.fao.org/economic/ess/ess-fs/ess-fs-country/en/ [Accessed 1 Sept 2011].

GERTEN D., SCHAPHOFF S., HABERLANDT U., LUCHT W., SITCH S. 2004 . Terrestrial vegetation and water balance: hydrological evaluation of a dynamic global vegetation model *International Journal Water Resource Development* 286:249–270

GORNALL, J., BETTS, R., BURKE, E., CLARK, R., CAMP, J., WILLETT, K., WILTSHIRE, A. 2010. Implications of climate change for agricultural productivity in the early twenty-first century. *Phil. Trans. R. Soc. B*, DOI: 10.1098/rstb.2010.0158

GOSLING, S., TAYLOR, R., ARNELL, N. & TODD, M. 2011. A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models. *Hydrology and Earth System Sciences,* 15**,** 279–294.

GOSLING, S. N. & ARNELL, N. W. 2011. Simulating current global river runoff with a global hydrological model: model revisions, validation, and sensitivity analysis. *Hydrological Processes,* 25**,** 1129-1145.

GOSLING, S. N., BRETHERTON, D., HAINES, K. & ARNELL, N. W. 2010. Global hydrology modelling and uncertainty: running multiple ensembles with a campus grid. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 368**,** 4005-4021.

GUALDI, S., SCOCCIMARRO, E. & NAVARRA, A. 2008. Changes in Tropical Cyclone Activity due to Global Warming: Results from a High-Resolution Coupled General Circulation Model. *Journal of Climate,* 21**,** 5204-5228.

HAN, W.-J., KIM, Y. E., LEE, J. T., NA, Y. E., KIM, M. H., BAE, D., JUNG, I. W. & HWANG, J. H. 2007. Climate Change Impact Assessment and Development of Adaptation Strategies in Korea: Case Studies on Agriculture and Water Resource Sectors. *In:* GARG, A., HAN, W.-J., HWANG, J. H., KIM, J. E. & HALSNAES, K. (eds.) *From Vulnerability to Resilience: The Challenge of Adaptation to Climate Change. Case studies from Bangladesh, Brazil, China, India, South Africa and Korea.* New Delhi, India: Magnum Custom Publishing (A Division of Magnum Books Pvt Ltd).

HANSON, S., NICHOLLS, R., RANGER, N., HALLEGATTE, S., CORFEE-MORLOT, J., HERWEIJER, C. & CHATEAU, J. 2011. A global ranking of port cities with high exposure to climate extremes. *Climatic Change,* 104**,** 89-111.

HANSON, S., NICHOLLS, R., S, H. & CORFEE-MORLOT, J. 2010. The effects of climate mitigation on the exposure of worlds large port cities to extreme coastal water levels. London, UK.

HIRABAYASHI, Y., KANAE, S., EMORI, S., OKI, T. & KIMOTO, M. 2008. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 53**,** 754-772.

HARDING, R., BEST, M., BLYTH, E., HAGEMANN, D., KABAT, P., TALLAKSEN, L.M., WARNAARS, T., WIBERG, D., WEEDON, G.P., van LANEN, H., LUDWIG, F., HADDELAND, I. 2011. Preface to the “Water and Global Change (WATCH)” special collection: Current knowledge of the terrestrial global water cycle. *Journal of Hydrometeorology*, DOI: 10.1175/JHM-D-11-024.1

IFPRI. 2010. *International Food Policy Research Institute (IFPRI) Food Security CASE maps. Generated by IFPRI in collaboration with StatPlanet.* [Online]. Available: www.ifpri.org/climate-change/casemaps.html [Accessed 21 June 2010].

IGLESIAS, A., GARROTE, L., QUIROGA, S. & MONEO, M. 2009. Impacts of climate change in agriculture in Europe. PESETA-Agriculture study. *JRC Scientific and Technical Reports.*

IGLESIAS, A. & ROSENZWEIG, C. 2009. Effects of Climate Change on Global Food Production under Special Report on Emissions Scenarios (SRES) Emissions and Socioeconomic Scenarios: Data from a Crop Modeling Study. . Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University.

IM, E.-S., JUNG, I.-W., CHANG, H., BAE, D.-H. & KWON, W.-T. 2010. Hydroclimatological response to dynamically downscaled climate change simulations for Korean basins. *Climatic Change,* 100**,** 485-508.

IM, E. S., AHN, J. B., KWON, W. T. & GIORGI, F. 2008. Multi-decadal scenario simulation over Korea using a one-way double-nested regional climate model system. Part 2: future climate projection (2021-2050). *Climate Dynamics,* 30**,** 239-254.

IM, E. S., JUNG, I. W. & BAE, D. H. 2011. The temporal and spatial structures of recent and future trends in extreme indices over Korea from a regional climate projection. *International Journal of Climatology,* 31**,** 72-86.

IPCC 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change *In:* SOLOMON, S., QIN, D., MANNING, M., CHEN, Z., MARQUIS, M., AVERYT, K. B., TIGNOR, M. & MILLER, H. L. (eds.). Cambridge, United Kingdom and New York, NY, USA.

IPCC 2007b. Summary for Policymakers. *In:* PARRY, M. L., CANZIANI, O. F., PALUTIKOF, J. P., VAN DER LINDEN, P. J. & HANSON, C. E. (eds.) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment*

Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

JEONG, D., STEDINGER, J., KIM, Y.-O. & SUNG, J. 2007. Bayesian GLS for Regionalization of Flood Characteristics in Korea. *World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat.* ASCE Conf. Proc.

JUNG, I. W., BAE, D. H. & KIM, G. 2011. Recent trends of mean and extreme precipitation in Korea. *International Journal of Climatology,* 31**,** 359-370.

KANG, B., LEE, S. J., KANG, D. H. & KIM, Y. O. 2007. A flood risk projection for Yongdam dam against future climate change. *Journal of Hydro-Environment Research,* 1**,** 118-125.

KIM, C.-G., LEE, S.-M., JEONG, H.-K., JANG, J.-K., KIM, Y.-H. & LEE, C.-K. 2010. Impacts of Climate Change on Korean Agriculture and Its Counterstrategies. Korea Rural Economics Institute.

KIM, D.-W. & BYUN, H.-R. 2009. Future pattern of Asian drought under global warming scenario. *Theoretical and Applied Climatology,* 98**,** 137-150.

KIM, Y. O. & LEE, J. K. 2010. Addressing heterogeneities in climate change studies for water resources in Korea. *Current Science,* 98**,** 1077-1083.

KNUTSON, T. R. & TULEYA, R. E. 2004. Impact of CO_2-Induced Warming on Simulated Hurricane Intensity and Precipitation : Sensitivity to the Choice of Climate Model and Convective Parameterization. *Journal of Climate***,** 3477-3495.

KOREA JOONGANG DAILY. 2009. *South Korea: Warmer climate moves tropical fruit cultivation northward* [Online]. Available: http://joongangdaily.joins.com/article/view.asp?aid=2907946 [Accessed 13 June 2011].

LATIF, M. & KEENLYSIDE, N. S. 2009. El Niño/Southern Oscillation response to global warming. *Proceedings of the National Academy of Sciences of the United States of America,* 106**,** 20578-20583.

LEE, D. B., SHIM, K. M. & RHO, K. A. Year. Strategy on Adapting Crop Production to Climate Change: Implications to Multi-functionality of Paddy Farming. *In:* 9th International Conference of the East and Southeast Asia Federation of Soil Science Societies, 2009. 313-314.

LI, J. P., WU, Z. W., JIANG, Z. H. & HE, J. H. 2010a. Can Global Warming Strengthen the East Asian Summer Monsoon? *Journal of Climate,* 23**,** 6696-6705.

LI, T., KWON, M., ZHAO, M., KUG, J.-S., LUO, J.-J. & YU, W. 2010b. Global warming shifts Pacific tropical cyclone location. *Geophysical Research Letters,* 37**,** 1-5.

LIM, H. C., CHUN, S. J., SEONG, K. C., SEO, H. H. & MOON, D. G. Year. Research strategies for future horticultural crops addressign climate change in Korea. *In:* 9th International Conference of the East and Southeast Asia Federation of Soil Science Societies, 2009. 324-325.

LOBELL, D. B., BANZIGER, M., MAGOROKOSHO, C. & VIVEK, B. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Clim. Change,* 1**,** 42-45.

LUCK, J., SPACKMAN, M., FREEMAN, A., TRE˛BICKI, P., GRIFFITHS, W., FINLAY, K. & CHAKRABORTY, S. 2011. Climate change and diseases of food crops. *Plant Pathology,* 60**,** 113-121.

MASUTOMI, Y., TAKAHASHI, K., HARASAWA, H. & MATSUOKA, Y. 2009. Impact assessment of climate change on rice production in Asia in comprehensive consideration of process/parameter uncertainty in general circulation models. *Agriculture, Ecosystems & Environment,* 131**,** 281-291.

MCDONALD, R. E., BLEAKEN, D. G., CRESSWELL, D. R., POPE, V. D. & SENIOR, C. A. 2005. Tropical storms: representation and diagnosis in climate models and the impacts of climate change. *Climate Dynamics,* 25**,** 19-36.

MENDELSOHN, R., EMANUEL, K. & CHONABAYASHI, S. 2011. The Impact of Climate Change on Global Tropical Cyclone Damages.

NADARAJAH, S. & CHOI, D. 2007. Maximum daily rainfall in South Korea. *Journal of Earth System Science,* 116**,** 311-320.

NELSON, G. C., ROSEGRANT, M. W., KOO, J., ROBERTSON, R., SULSER, T., ZHU, T., RINGLER, C., MSANGI, S., PALAZZO, A., BATKA, M., MAGALHAES, M., VALMONTE-SANTOS, R., EWING, M. & LEE, D. 2009. Climate change. Impact on Agriculture and Costs of Adaptation. Washington, D.C.: International Food Policy Research Institute.

NELSON, G. C., ROSEGRANT, M. W., PALAZZO, A., GRAY, I., INGERSOLL, C., ROBERTSON, R., TOKGOZ, S., ZHU, T., SULSER, T. & RINGLER, C. 2010. Food Security, Farming and Climate Change to 2050. *Research Monograph, International Food Policy Research Institute.* Washington, DC.

NICHOLLS, R. J. and LOWE, J. A. (2004). "Benefits of mitigation of climate change for coastal areas." *Global Environmental Change* **14**(3): 229-244.

NICHOLLS, R. J., MARINOVA, N., LOWE, J. A., BROWN, S., VELLINGA, P., DE GUSMÃO, G., HINKEL, J. and TOL, R. S. J. (2011). "Sea-level rise and its possible impacts given a 'beyond 4◦C world' in the twenty-first century." *Philosophical Transactions of the Royal Society A* **369**: 1-21.

OOUCHI, K., YOSHIMURA, J., YOSHIMURA, H., MIZUTA, R., KUSUNOKI, S. & NODA, A. 2006. Tropical Cyclone Climatology in a Global-Warming Climate as Simulated in a 20 km-Mesh Global Atmospheric Model: Frequency and Wind Intensity Analyses. *Journal of the Meteorological Society of Japan,* 84**,** 259-276.

PARDAENS, A. K., LOWE, J., S, B., NICHOLLS, R. & DE GUSMÃO, D. 2011. Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions. *Geophysical Research Letters,* 38**,** L12604.

PARK, J.-S., KANG, H.-S., LEE, Y. S. & KIM, M.-K. 2010. Changes in the extreme daily rainfall in South Korea. *International Journal of Climatology***,** n/a-n/a.

PARRY, M. L., ROSENZWEIG, C., IGLESIAS, A., LIVERMORE, M. & FISCHER, G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions,* 14**,** 53-67.

RAMANKUTTY, N., EVAN, A. T., MONFREDA, C. & FOLEY, J. A. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles,* 22**,** GB1003.

RAMANKUTTY, N., FOLEY, J. A., NORMAN, J. & MCSWEENEY, K. 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global Ecology and Biogeography,* 11**,** 377-392.

REICHLER, T. & KIM, J. 2008. How well do coupled models simulate today's climate? *Bulletin of the American Meteorological Society,* 89**,** 303-+.

ROCKSTROM, J., FALKENMARK, M., KARLBERG, L., HOFF, H., ROST, S. & GERTEN, D. 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research,* 45.

SHIM, K. M., LEE, J. T., LEE, Y. S. & KIM, G. Y. 2004. Reclassification of Winter Barley Cultivation Zones in Korea Based on Recent Evidences in Climate Change. *Korean Journal of Agricultural and Forest Meteorology,* 6**,** 218-234.

SHIN, J. C. & LEE, M. H. 1995. Rice production in South Korea under current and future climates. *In:* MATTHEWS, R. S., KROPFF, M. J., BACHELET, D. & VAN LAAR, H. H. (eds.) *Modeling the Impact of Climate Change on Rice production in Asia.* Oxford, UK: CAB International.

SMAKHTIN, V., REVENGA, C. & DOLL, P. 2004. A pilot global assessment of environmental water requirements and scarcity. *Water International,* 29**,** 307-317.

STOWASSER, M., WANG, Y. & HAMILTON, K. 2007. Tropical Cyclone Changes in the Western North Pacific in a Global Warming Scenario. *Journal of Climate,* 20**,** 2378-2396.

SUGI, M., MURAKAMI, H. & YOSHIMURA, J. 2009. A reduction in global tropical cyclone frequency due to global warming. *SOLA,* 5**,** 164-167.

TATSUMI, K., YAMASHIKI, Y., VALMIR DA SILVA, R., TAKARA, K., MATSUOKA, Y., TAKAHASHI, K., MARUYAMA, K. & KAWAHARA, N. 2011. Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes,* Special Issue: Japan Society of Hydrology and water resources, 25 (17), 2715-2725

TU, J.-Y., CHOU, C. & CHU, P.-S. 2009. The Abrupt Shift of Typhoon Activity in the Vicinity of Taiwan and Its Association with Western North Pacific–East Asian Climate Change. *Journal of Climate,* 22**,** 3617-3628.

VAN VUUREN, D., DEN ELZEN, M., LUCAS, P., EICKHOUT, B., STRENGERS, B., VAN RUIJVEN, B., WONINK, S. & VAN HOUDT, R. 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change,* 81**,** 119-159.

VAN VUUREN, D. P., ISAAC, M., KUNDZEWICZ, Z. W., ARNELL, N., BARKER, T., CRIQUI, P., BERKHOUT, F., HILDERINK, H., HINKEL, J., HOF, A., KITOUS, A., KRAM, T., MECHLER, R. & SCRIECIU, S. 2011. The use of scenarios as the basis for combined assessment of climate change mitigation and adaptation. *Global Environmental Change,* 21**,** 575-591.

VECCHI, G. A. & SODEN, B. J. 2007. Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature,* 450**,** 1066-70.

VOROSMARTY, C. J., MCINTYRE, P. B., GESSNER, M. O., DUDGEON, D., PRUSEVICH, A., GREEN, P., GLIDDEN, S., BUNN, S. E., SULLIVAN, C. A., LIERMANN, C. R. & DAVIES, P. M. 2010. Global threats to human water security and river biodiversity. *Nature,* 467**,** 555-561.

WARREN, R., ARNELL, N., BERRY, P., BROWN, S., DICKS, L., GOSLING, S., HANKIN, R., HOPE, C., LOWE, J., MATSUMOTO, K., MASUI, T., NICHOLLS, R., O'HANLEY, J., OSBORN, T., SCRIECRU, S. (2010) The Economics and Climate Change Impacts of Various Greenhouse Gas Emissions Pathways: A comparison between baseline and policy emissions scenarios, AVOID Report, AV/WS1/D3/R01.
http://www.metoffice.gov.uk/avoid/files/resources-researchers/AVOID_
WS1_D3_01_20100122.pdf

WOOD, E.F., ROUNDY, J.K., TROY, T.J., van BEEK, L.P.H., BIERKENS, M.F.P., BLYTH, E., de ROO, A., DOLL, P., EK, M., FAMIGLIETTI, J., GOCHIS, D., van de GIESEN, N., HOUSER, P., JAFFE, P.R., KOLLET, S., LEHNER, B., LETTENMAIER, D.P., PETERS-LIDARD, C., SIVAPALAN, M., SHEFFIELD, J., WADE, A. & WHITEHEAD, P. 2011. Hyperresolution global land surface modelling: Meeting a grand challenge for monitoring Earth's terrestrial water. *Water Resources Research,* 47, W05301.

WOS. 2011. *Web of Science* [Online]. Available:
http://thomsonreuters.com/products_services/science/science_products/a-z/web_of_science
[Accessed August 2011].

WU, W., TANG, H., YANG, P., YOU, L., ZHOU, Q., CHEN, Z. & SHIBASAKI, R. 2011. Scenario-based assessment of future food security. *Journal of Geographical Sciences,* 21**,** 3-17.

YUN, K. S., SHIN, S. H., HA, K. J., KITOH, A. & KUSUNOKI, S. 2008. East Asian Precipitation Change in the Global Warming Climate Simulated by a 20-km Mesh AGCM. *Asia-Pacific Journal of Atmospheric Sciences,* 44**,** 233-247.

ZHAO, M., HELD, I. M., LIN, S.-J. & VECCHI, G. A. 2009. Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50-km Resolution GCM. *Journal of Climate,* 22**,** 6653.

Acknowledgements

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

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

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

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

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

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

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

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

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

Produced by the Met Office.